City of Tacoma Environmental Services

Please see the attached City of Tacoma Environmental Services comment letter and attachments 1 - 39. Please note that a second submission with the letter and attachment 40 will be submitted separately due to the file size and number of files limitation.

City of Tacoma
Environmental Services Department

Submitted via Rulemaking Comment Portal

Marla Koberstein
State of Washington Department of Ecology
Water Quality Program
P.O. Box 47600
Olympia, WA 98504-7600

May 22, 2025

Re: City of Tacoma Comments on Draft Performance-Based Approach

Dear Ms. Koberstein:

The City of Tacoma ("Tacoma", "City") appreciates the opportunity to comment on the Washington State Department of Ecology ("Ecology") draft performance-based approach guidance document ("Performance-Based Approach") that will steer Ecology determinations for site-specific natural conditions standards.

Environmental health is a priority for the City of Tacoma. For over a decade, we have been a leader and steadfast partner in regional discussions on finding the right balance when it comes to nutrients and protecting the health of the Puget Sound. We are continuing to work collaboratively on sensible and sustainable long-term solutions that protect the Puget Sound. We also want to ensure that measures that are put into place will actually have the potential to make a measurable positive impact to the environment, and that we are using reliable science and the best available data to determine the appropriate actions at a sustainable cost for our ratepayers, particularly when there is a potential to significantly impact the housing supply and affordability for many households in Tacoma.

For decades, the mission of Puget Sound clean water utilities has been focused on protection of water quality and successful compliance with regulatory requirements for secondary treatment, wet weather controls, toxics reduction, stormwater management, and beneficial use of biosolids. These water quality protection efforts require utilities to extensively plan, fund, construct, operate, and maintain billions of dollars in investments in their complex wastewater infrastructure. New regulatory requirements with the potential to add significant technical, operational, and economic impacts need to be carefully balanced with the understanding of the necessity and expected benefits. It is especially important that uncertainties are addressed with permit structures that provide opportunities for adaptive management over time to ensure that investments are on-target, effective, and produce tangible results.

The City supports water quality standards, including those which will be calculated using the Performance-Based Approach, for dissolved oxygen that are protective of aquatic life and supported by sound science. Developing updated biologically based dissolved oxygen standards should be considered together with natural conditions criteria since natural conditions considerations only take effect when biologically based numeric criteria are not met. Such an approach might even negate the need for natural condition criteria in some circumstances.

Tacoma provides the following comments regarding the Performance-Based Approach:

The City reviewed the following Ecology documents regarding the new natural conditions regulations.

- A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington (24-10-017, May 2024)
- A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington (Second Draft) (25-10-022, March 2025)
- Performance-based approach methods document: marine dissolved oxygen. Public workshop and hearing. May 15, 2025.
- Concise Explanatory Statement Chapter 173-201A WAC Water Quality Standards for Surface Waters of the State of Washington – Natural Conditions: Summary of Rulemaking and Response to Comments (24-10-057, November 2024)
- Comment Letter from EPA Region 10 on the Washington State Department of Ecology's proposed amendments and additions to Chapter 173-201A Washington Administrative Code – Water Quality Standards for Surface Waters of the State of Washington, filed on May 10, 2024, and incorporation by reference the adoption of Ecology publication *A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington*.

The following review comments were focused on applying the Performance-Based Approach to develop standards for marine dissolved oxygen (DO), as that is the only parameter for which this draft provides a method of calculation; however, the City anticipates an opportunity to provide comment on future chapters Ecology issues addressing other conventional pollutants such as temperature and pH level.

1. **Ecology's performance-based approach is overly complex and based on an entirely hypothetical natural condition that depends upon the assumptions made about pre-anthropogenic conditions, which cannot be known, measured, or verified.**

Developing pre-anthropogenic conditions as part of setting natural conditions criteria is unlikely to meet Ecology's objectives that the process should result in predictable and repeatable criteria. This is because developing pre-anthropogenic conditions will require many assumptions in estimating load reductions from land-based sources (including groundwater and river/tributary inputs), atmospheric deposition, and ocean boundary conditions. In addition, human-induced structural changes will need to be estimated to remove impacts associated with shoreline hardening, dredging activities, and river control structures such as dams and diversions. Most likely a model (e.g., watershed, such as the Salish Sea Model) will need to be used to estimate the natural conditions criteria associated with the pre-anthropogenic conditions, which will have its own set of application assumptions.

It appears that Ecology has introduced an additional level of complexity in the March 2025 Second Draft of the performance-based approach that would require the development of individual natural conditions criteria for each layer of the 10 layers in the marine water column from top to bottom of Puget Sound. This appears complex and Ecology has not provided an explanation for how this will be applied in practice to Puget Sound. The March 2025 Second Draft does reference volume weighting horizontally, but notes that no vertical aggregation is allowed. No explanation is provided in the March 2025 Second Draft for how volume weighted horizontal aggregation of the various layers would be accomplished across the entire geography of Puget Sound, or by subbasin, or by embayment. Further, the Salish Sea Model includes 10 layers from top to bottom, but water depths vary throughout Puget Sound. So, while the surface layer may be common across Puget Sound, lower water depth layers at various locations would not align with each other.

EPA acknowledges that the performance-based approach Ecology is proposing has limited application in other States[1], so an established precedent that the process is predictable and repeatable is also limited and may not exist. This suggests that Ecology's novel application of the performance-based approach may result in unpredictable outcomes when applied to Washington waters. It is unlikely that Ecology's performance-based approach meets Ecology's own stated goal to "Increase clarity and transparency on the process we use to determine natural conditions in surface waters" given the complexity of the process and challenges in characterizing and accounting for pre-anthropogenic conditions predating European settlement, agricultural development, climate change, etc. The assumptions made to conduct the natural conditions

[1] EPA, 2015. A Framework for Defining and Documenting Natural Conditions for Development of Site-Specific Natural Background Aquatic Life Criteria for Temperature, Dissolved Oxygen, and pH: Interim Document. Office of Water, EPA 820-R- 15-001. February 2015.

analysis are likely to vary depending upon the individuals or institutions conducting the analysis and their opinions.

2. **Limited Opportunity for Public Comment and Transparency**

If the Performance-Based Approach is approved by EPA, the criteria derived from the methods in the approach become applicable for CWA purposes and remain the applicable criteria until EPA approves a change, deletion, or until EPA promulgates more stringent criteria if necessary to meet CWA requirements (40 CFR 131.21(c), (e)). The draft Performance-Based Approach states that, "aquatic life water quality criteria values developed using the performance-based approach are applicable to the waterbody immediately following the performance-based approach derivation process." The City is generally concerned that if the Performance-Based Approach is implemented, there will be a significant lack of transparency and opportunities for independent, scientific peer review and public input as Ecology works to set standards for a water body. There is additionally limited opportunity for public comment and transparency regarding the Salish Sea Model. Although Ecology anticipates publishing the model in June, Ecology is not offering any opportunity for public comment at that time. This is a critical point, as Ecology has made clear it intends to use the Salish Sea Model as an integral component of its Performance-Based Approach to set DO standards in Puget Sound; these standards will have a significant impact on municipalities and thus the public deserves an opportunity for input on this part of the approach. This is a theme that is brought up continually in our comments below.

3. **Ecology has not addressed the spatial and temporal applicability or the frequency of exceedance of the natural conditions criteria in order to establish a transparent process for interpretation of where and when and how often natural conditions apply.**

EPA recommends a performance-based approach call for definition of the spatial (e.g., monitoring location, embayment, assessment unit) and temporal (e.g., summer, low flow, diurnal) boundaries of natural conditions criteria. For example, the DO standards in Chesapeake Bay established designated use areas (e.g., open-water fish and shellfish use, deep-water seasonal fish and shellfish use, deep channel seasonal refuge use) with associated temporal, concentration, and duration definitions. In its Performance-Based Approach guidance document, Ecology mentions that "developing and calibrating a model of the existing conditions of the waterbody or watershed, including defining temporal and spatial boundaries" is a step in the process of developing natural conditions criteria, and boundary information used to develop site boundaries must include geospatial information and be documented in the QAPP. However, Ecology provides no further detail on the topic. Ecology also stated in its response to comments on its first draft of the Performance-Based Approach that defining spatial boundaries will be a part of natural conditions criteria development, so the agency is unable to provide an exact timeline of when that step of the process will be undertaken and when the natural conditions criteria will be available.

Further, Ecology has not addressed the allowable exceedance frequency of the natural conditions criteria that would allow a transparent interpretation of the *de minimis* impact to natural conditions criteria due to anthropogenic sources. For example, the EPA proposed DO rulemaking for the tidal Delaware River[2] and the Florida Department of Environmental Protection DO standards[3] use an acceptable criteria exceedance frequency of 10% (i.e., the DO magnitude can be exceeded 10% of the time in a season). These missing considerations are needed to develop natural conditions criteria that include the required magnitude, duration, and frequency components of water quality standards.

These omissions may result in Ecology's additional DO decrease (i.e., 10% or 0.2 mg/L) below the natural conditions criteria due to anthropogenic sources being interpreted as a not to exceed value at any point and at any time, which constitutes an extremely high bar for water quality assessments. It would be inappropriate to consider a numerical value which has simply been selected as a representation of a *de minimis* impact (i.e., within monitoring measurement error) that is not linked to maintenance of a specific aquatic life beneficial use.

Further, it would be inconsistent with the level of accuracy of water quality model predictions with and without anthropogenic sources when model skill assessment results exceed the selected *de minimis* DO decrease of 0.2 mg/L. Model skill assessment of the Salish Sea Model presented in the Journal of Geophysical Research[4] and in Ecology's Model Updates and Bounding Scenarios report[5] indicate overall Sound wide mean error (bias) ranging for DO from -0.7 to 1.0 mg/L and root mean square error (RMSE) ranging from 0.6 to 1.6 mg/L. These two statistics measure the difference between observed data and the model predictions with the model performance varying in the different regions of the Sound (i.e., Bellingham, Samish and Padilla Bays, Whidbey Basin, Admiralty Inlet, Main Basin, Hood Canal, South Sound). Although these model statistics results are similar to other complex marine DO modeling studies, the accuracy of the model needs to be accounted for when evaluating natural conditions DO criteria and the allowable DO decrease associated with anthropogenic sources.

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[2] Federal Register, 2023. Water Quality Standards To Protect Aquatic Life in the Delaware River. EPA–HQ–OW–2023–0222. Vol. 88, No. 244, December 21, 2023.

[3] FDEP, Dissolved Oxygen Criteria for Class I, Class II, Class III, and Class III-Limited Waters. Chapter 62-302.533.

[4] Khangaonkar, T., Nugraha, A., Xu, W., Long, W., Bianucci, L., Ahmed, A., Mohamedali, T., & Pelletier, G., 2018. Analysis of hypoxia and sensitivity to nutrient pollution in Salish Sea. Journal of Geophysical Research: Oceans, 123, 4735–4761. https://doi.org/10.1029/2017JC013650.

[5] Washington State Department of Ecology, 2019. Puget Sound Nutrient Source Reduction Project, Volume 1: Model Updates and Bounding Scenarios. Publication No. 19-03-001, January 2019.

4. **Ecology must fully comply with state rulemaking requirements.**

The adoption of water quality standards is subject to the significant legislative rule (SLR) requirements of the state Administrative Procedures Act (APA). RCW 34.05.328. These include the following:[6]

- Statement of general goals and objectives. A detailed statement of the general goals and objectives of the statute that the rule implements. RCW 34.05.328 (1)(a).

- Statement of necessity and alternatives analysis. A determination that the rule is necessary to achieve the general goals and specific objectives, an analysis of alternatives to rulemaking, and analysis of the consequences of not adopting the rule. RCW 34.05.328 (1)(b).

- Preliminary and final cost-benefit analysis. A preliminary cost-benefit analysis must be prepared at the time a draft rule is published for public comment. A final cost-benefit analysis must be issued when the rule is adopted. RCW 34.05.328 (1)(c). The cost-benefit analysis must include a determination that the "probable benefits of the rule are greater than its probable costs, taking into account both the qualitative and quantitative benefits and costs and the specific directives of the statute being implemented." RCW 34.05.328 (1)(d).

- Least burdensome alternative analysis. A determination, after considering alternative versions of the rule, that the rule being adopted is the least burdensome alternative for those required to comply with it that will achieve the general goals and specific objectives identified under RCW 34.05.328 (1)(a). RCW 34.05.328(1)(e).

- Justification for more stringent requirements than federal law. Ecology must determine if the rule is more stringent than federal standards. If so, Ecology must determine that the difference is justified either by a state statute that explicitly allows the agency to differ from federal standards or by "substantial evidence" that the difference is necessary to achieve the general goals and specific objectives stated under RCW 34.05.328 (1)(a). RCW 34.05.328(1)(h).

- Implementation plan. Prior to adoption, Ecology must provide an implementation plan that describes how the agency intends to implement and enforce the rule

[6] In addition to these elements, the SLR also requires determinations that the rule does not require actions that violate the requirements of other state or federal laws, RCW 34.05.328 (1)(f), and that the rule does not impose more stringent requirements on private entities than on public entities unless required by federal law. RCW 34.05.328(1)(g).

including a description of the resources the agency intends to use, how the agency will inform and educate affected persons about the rule, how the agency will promote and assist voluntary compliance, and an evaluation of whether the rule achieves the purpose for which it was adopted. RCW 34.05.328 (3).

- Report to joint administrative rules review committee. After adopting a rule regulating the same subject matter as another provision of federal law, Ecology will be required to submit a report to the legislature identifying the existence of any overlap, duplication, or difference with federal law and making recommendations for any legislation necessary to eliminate or mitigate any adverse effects of such overlap, duplication or difference. RCW 34.05.328 (4).

The APA also requires that the Ecology water quality program identify the sources of information reviewed and relied upon by the agency in preparing a SLR. RCW 34.05.272. The APA further requires that a draft rule package include a small business economic impact statement (SBEIS) that complies with RCW 19.85.040. RCW 34.05.320 (1)(j). RCW 34.05.320. The SBEIS must include an evaluation of compliance impacts on small businesses and provide a determination of whether the rule will have a disproportionate cost impact on small businesses.

The draft Performance-Based Approach is not in full compliance with these important rulemaking requirements under state law as discussed in the following comments. Ecology claims that, since the Performance-Based Approach is only referenced and not part of the Water Quality Standards regulations, and revisions to the document would not change the adopted rule language, the agency is not required nor will be conducting a separate formal rulemaking for this document. However, if adopted, the Performance-Based Approach will be used to develop new standards that will have a significant impact on the operation, management, and financial capacity of municipalities across the state, and the violation of such standards would subject municipalities to penalty. RCW 34.05.328 (5)(c)(iii). Ecology is first and foremost an agency that promotes and enforces compliance with environmental regulations and permits. The department should take as equally important its obligations to fully comply with the significant legislative rule requirements. These requirements were first adopted as part of the 1995 Regulatory Reform Act under Governor Lowry. Ch. 403, Sec. 201, Laws of 1995. They serve to promote notice to the public and a necessary opportunity to fully understand and comment on the reasonableness of a proposed rule. These requirements are no less important to the legislative oversight of rulemaking under RCW 34.05.610-681. That oversight cannot function unless Ecology fully complies with the APA requirements for its rulemaking. Tacoma requests that Ecology address these deficiencies in a revised draft rule package that is subject to public notice and comment.

5. Ecology has failed to reasonably consider alternatives.

Before adopting a rule, agencies are required to analyze alternative versions of the rule, the consequences of not adopting the rule, and alternatives to rule making. RCW 34.05.328(1). A reasonable consideration of alternatives under the APA is akin to requirements under the State Environmental Policy Act (SEPA). Under SEPA, if an agency proposal may have significant adverse environmental impacts, the agency is required to prepare an Environmental Impact Statement (EIS) that includes an analysis of alternatives. RCW 43.21C.030. Washington courts have equated this alternatives analysis to be "one of the key building blocks, if not the heart of SEPA." *Escala Owners Association v. City of Seattle*, 2022 WL 2915536, at *8 (2022) (unpublished). Similarly, the National Environmental Policy Act (NEPA) requires the federal government to consider a "reasonable range of alternatives" to any proposed agency action that may have a significant impact on the environment. 42 USCA § 4332 (C)(3). NEPA requires that agencies, "give full and meaningful consideration to all reasonable alternatives," and "the existence of a viable but unexamined alternative renders an [assessment] inadequate." *N. Idaho Cmty. Action Network v. U.S. Dep't of Transp.*, 545 F.3d 1147, 1153 (9th Cir. 2008); *Wetlands Water Dist. V. U.S. Dep't of Interior*, 376 F.3d 853, 868 (9th Cir. 2004); *Western Watersheds Project v. Abbey*, 719 F.3d 1035, 1050-1052 (9th Cir. 2013) (the court was troubled by BLM's decision not to consider a reduced- or no-grazing alternative at a site- specific level and by the way BLM dismissed other alternatives without any detailed analysis.)

Ecology has failed to issue an alternatives analysis for its Performance-Based Approach. Importantly, by not issuing the required analysis, Ecology fails to consider one essential alternative: developing a biologically-based and site specific marine DO criteria to replace the current DO criteria (WAC 173-201A-210) or a Puget Sound biologically-based and site specific marine DO criteria. Ecology has ignored inputs from EPA, multiple municipalities, Tribes, and other parties urging the adoption of such a standard.[7] The current DO water quality standard is outdated (over 55 years old) and fails to consider the geography and hydrology of the Puget Sound.[8] Puget Sound is comprised of multiple deep-water basins separated by shallow sills, and many basins terminate in shallow inlets; the current marine DO standards are neither reasonable nor realistic in many locations due to these physical factors.[9] The state has identified waters not meeting the DO standard, but that determination does not confirm the waters are truly

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[7] On multiple occasions, EPA has communicated to Ecology that it understood Ecology was only interested in pursuing a performance-based approach, Ecology "Modeling Considerations Checklist" with comments from EPA (internally circulated by Kalman Bugica on April 17, 2023); Letter from Sara Thitipraserth, Director, Stillaguamish Tribe Natural Resources Department to Washington Department of Ecology and EPA (May 26, 2023); Letter from EPA to Vince McGowan, Water Quality Program Manager, Washington State Department of Ecology (Nov. 19, 2021); City of Tacoma, Comment Letter on the Department of Ecology's draft Puget Sound Nutrient General Permit and draft Fact Sheet (Aug. 16, 2021); Email from Chad Brown to Ronald L. Lavigne (Nov. 21, 2022); Michael Connor and William Stelle, *Elements of a Comprehensive Puget Sound Nutrients Program*; Petition to the Department of Ecology from Tad Shimazu and Lincoln Loehr (Jul. 17, 1998).

[8] Lincoln Loehr, Comment Letter on Proposed 2018 303(d) List of Impaired Waters (June 4. 2021); Gordon Holtgrieve, Comment Letter on Proposed Puget Sound Nutrient General Permit (August 16, 2021).

[9] Letter from Sara Thitipraserth, Director, Stillaguamish Tribe Natural Resources Department to Washington Department of Ecology and EPA (May 26, 2023).

impaired.[110] Currently, marine waters with 5 mg/L DO in many deep-water basins are considered non-compliant, when in fact this oxygen level poses no threat to affected organisms.[11] A DO concentration of 5 mg/L is identified as protective for most uses, included fish migration, rearing, and spawning; however, the proposed rule may trigger natural conditions criteria if a sector of water is below even 6 or 7 mg/L. One cannot justifiably assert there is impairment when DO is less than 6 or 7 mg/L but still meets the 5 mg/L level. Ecology intends to extend its proposed Performance-Based Approach to aquatic life criteria[12]; this will ultimately result in many areas qualifying as "impaired" without any scientific basis.[13]

Additionally, Ecology has acknowledged that the 0.2 mg/L human-caused difference is not biologically based.[14] The nutrient criteria were adopted in 1967 by a predecessor agency that made no effort to understand DO levels throughout the inland marine waters before adopting the criteria.[15] In 1985, the Chairman of the Pollution Control Hearings Board, in a decision to deny waiver appeals from wastewater treatment plants (WWTPs), stated that evidence supported the position that the WWTPs' primary-treated effluents were not significantly impacting the marine environment, but there were significant impacts related to economic costs and the added requirements of disposing additional sludge, which, "outweighed the undefined benefits of secondary treatment."[16] Further, the toxic hot spots of pollution in the Puget Sound are site-specific and largely unrelated to a majority of the wastewater (sewer) outfalls in Puget Sound, due to the active circulation within the Puget Sound and the tremendous volume of deep water

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[10] *Id*.

[11] *Id*.

[12] E-mail from Kalman Bugia, Wastewater Quality Standards Scientist, Washington State Dep't of Ecology, to Lincoln Loehr (Apr. 16, 2024).

[13] *See* Lincoln Loehr, Comment Letter on Proposed 2018 303(d) List of Impaired Waters (June 4. 2021); *See also* Gordon Holtgrieve, Comment Letter on Proposed Puget Sound Nutrient General Permit (August 16, 2021).

[14] Department of Ecology Water Quality Standards staff Mark Hicks admitted Ecology does not have supporting information on the technical basis for Ecology's existing criteria, and stated archive staff had the relevant records destroyed, Letter from Mark Hicks, Water Quality Standards Scientist, Washington Dep't of Ecology, to Lincoln Loehr, Environmental Analyst, Heller, Ehrman, White and McAuliffe (Jul. 8, 1998); *See also* Department of Ecology Nutrient Forum presentation on May 30, 2018.

[15] Letter from Mark Hicks, Water Quality Standards Scientist, Washington Dep't of Ecology, to Lincoln Loehr, Environmental Analyst, Heller, Ehrman, White and McAuliffe (Jul. 8, 1998); To contrast, Chesapeake Bay confronted the same need for nutrient reductions and developed new DO criteria with EPA's help based on sound scientific rationale, Memorandum from Lincoln Loehr, Oceanographer and Water Quality/Permitting Consultant, to Scott Redman (Feb. 29, 2020).

[16] Lincoln Loehr, The Exclusion of Science from Major Water Quality Decisions, 17 Marine Pollution Bulletin 489, 492 (1986).

which acts as a nutrient and DO buffer.[17] A glacial fjord with good tidal circulation, like the Puget Sound, is considerably different from a shallow river valley type of estuary.[18]

Despite these facts, Ecology has chosen to implement nutrient criteria and modeling that is incompatible with the state of science. Ecology justifies this decision by asserting EPA and Ecology staff have "vetted" the marine DO criteria. However, more is needed than having these agencies "verify" the criteria or "check for accuracy." The Clean Water Act requires that water quality criteria "based on sound scientific rationale" and establish numeric criteria based on "scientifically defensible methods." 40 CFR 131.11(a)(1)-(b)(1). Rather than address the concerns voiced by numerous parties and evaluate the implications of using a biologically-based standard instead of a performance-based approach that does not accord with sound scientific rationale, Ecology is attempting to reestablish the nutrient program it had in place previously without considering other, more sound alternatives.

Ecology failed to conduct a reasonable analysis of all alternatives and must therefore address these deficiencies in a revised draft rule package that is subject to public notice and comment.

6. **Ecology failed to conduct an analysis to determine whether its Performance-Based Approach is the least burdensome alternative.**

To adopt a significant legislative rule, an agency must determine it is the least burdensome alternative to achieve the goals and objectives of the authorizing statute. RCW 34.05.328(1). Ecology has not published a least burdensome alternatives analysis to conclude its Performance-Based Approach is the least-burdensome alternative to achieve the goal of nutrient reduction in the Puget Sound. The Performance-Based Approach will inevitably overburden WWTPs with the costs of implementing advanced treatment technology and in turn overburden communities that must absorb the costs through higher wastewater rates and housing prices.

7. **Ecology has failed to conduct a proper cost-benefit analysis in accordance with the APA.**

Ecology cannot adopt a significant legislative rule if it fails to properly conduct the analysis required under RCW 34.05.328. Ecology is required to conduct a preliminary cost-benefit analysis and determine that the probable benefits of the rule are greater than its probable costs, accounting for both the qualitative and quantitative benefits and costs and the specific directives

[17] *Id.*
[18] *Id.*

of the statute being implemented. RCW 34.05.328(1)(d). Ecology failed to conduct a cost-benefit analysis for its Performance-Based Approach.

The City, other utilities, and non-utility organizations[19] have shared with Ecology the significant cost concerns associated with nutrient regulations and the ultimate cost implications for the respective impacted communities. It appears that Ecology has not considered this raised concern and is attempting to use its proposed Performance-Based Approach to reestablish its previous nutrient program. It is important that Ecology consider the cost effectiveness and cost impacts for any regulatory program, including nutrients. Ecology should consider the potential costs through its ongoing refinement of the Salish Sea Model (SSM) and plans to impose numeric water quality based effluent limits on Puget Sound WWTPs in the upcoming voluntary Puget Sound Nutrient General Permit (PSNGP). The proposed Performance-Based Approach will result in standards requiring WWTPs to implement cost-prohibitive advanced treatment technologies to reduce nitrogen and limit nutrient discharges in the Puget Sound. Ecology should evaluate the cost benefit effectiveness as part of its consideration to implement of a Performance-Based Approach, in collaboration with WWTPs to better understand the site-specific cost impacts, as Ecology's nutrient program continues to evolve and shift.

Ecology has published its own technical and economic evaluation of nitrogen removal at municipal WWTPs that outlines the costs of treatment technologies.[20] Additionally, environmental and engineering consulting firm, HDR, published a "Treatment Technology Review and Assessment" that analyzes treatment technologies applicable to nitrogen removal and related costs of implementation.[21] Ecology can also compare costs to the "Nitrogen Optimization Plan and Report", which Ecology has indicated that it will require under the voluntary PSNGP, which could cost cities tens of millions of dollars to implement over the first two years.[22] Municipalities have frequently expressed such concerns over the cost of reducing nitrogen discharges; these are also costs that municipalities will then need to pass onto ratepayers.[23] Further, Ecology has published guidance for WWTPs to estimate the costs of

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[19] *See* Burke et al., *Puget Sound Wastewater Service Affordability Analysis: Implications for Implementation Strategies* (May 17, 2023).

[20] Department of Ecology, *Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities* (June 2011).

[21] The report estimates that, "the incremental unit costs to implement an advanced treatment retrofit for 0.5 mgd would range between $30 to $96 per gallon per day of treatment capacity,", HDR, *Treatment Technology Review and Assessment* (Dec. 4, 2013), pg. 41.

[22] Declaration of Christie True, ¶¶ 9-10, *King County v. Dept. of Ecology*, No. 21-083 (PCHB 2021); Mot. For Stay, 2021-12-28 King County Motion for Stay, pg. 5, *King County v. Dept. of Ecology*, No. 21-083 (PCHB 2021).

[23] To comply with a TIN cap rule under the PSGNP, King County estimated it will need to spend between $25 and $150 million over the next five years, $100 to $200 million in the next 10 to 15 years, and between $9 billion and $14 billion on future nitrogen removal. This results in monthly sewer rate increases of between $20 and $130 per month per household, Brief for King County as Amicus Curiae, pg. 3, *City of Tacoma v. Ecology*,

treatment technology required for nitrogen removal; there is no reason the agency cannot use that same guidance to conduct its own analysis for the Performance-Based Approach. Ecology published its Final Treatment Plant Financial Capability Assessment Guidance Puget Sound Nutrient General Permit (Financial Guidance) for WWTPs to use when preparing reasonable treatment alternatives as a part of the upcoming PSNGP's required AKART analysis.[24] In this Financial Guidance, Ecology lays out the tools for performing this type of economic impact analysis. At both the Mt. Vernon and Olympia workshops provided to outline and answer questions regarding the Financial Guidance, Utility representatives heard Ecology make it clear that the agency is fully aware of how expensive it will be to implement a Performance-Based Approach under its Natural Conditions Rule.

Ecology intends for its Performance-Based Approach, in association with the Natural Conditions Rule, to simply be another step in reinstituting its nutrient program. It has published guidelines for performing compliance analyses that outlined specific requirements for nutrient reduction evaluations for WWTPs to analyze and implement. There is a multitude of resources, prepared by both Ecology and third parties, that preview the exorbitant costs of treatment technologies WWTPs will need to implement in response to the anticipated standards Ecology will set using the Performance-Based Approach.

Ecology specifically fails to account for both the qualitative and quantitative costs and benefits of its Performance-Based Approach, as required under RCW 34.05.328 (1)(d). It fails to provide any discussion of environmental justice impacts, environmental concerns apart from aquatic impacts, or the generation of additional waste, among other relevant issues. Ecology has previously recognized the potential environmental impacts of requiring WWTPs to adopt additional nutrient removal technology, including the likelihood that tertiary treatment will not only generate more effluent sludge that will require disposal, but will also require two to three times the amount of electrical energy currently used in WWTPs. *Nw. Env't Advocs. v. Dep't of Ecology*, 18 Wn. App. 2d 1005, 2021 WL 2556573, at *9 (2021) (unpublished). Ecology also ignored climate change impacts of its Performance-Based Approach, including the fact that nitrogen removal from wastewater converts some nitrogen in the wastewater to nitrous oxide, a greenhouse gas that is 300 more potent than carbon dioxide.[25] Ecology also fails to consider the

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28 Wn. App. 2d 221 P.3d 462 (2023) ("King County Amicus Brief"); If Ecology implements a new Total Inorganic Nitrogen loading limits of less than 3 mg/L year-round, estimated monthly wastewater rates could double in cost (even a limit of less than 8 mg/L year-round would increase rates by about $25/month), Puget Sound Clean Water Alliance Presentation on February 28, 2023.

[24] Department of Ecology, *Final Treatment Plant Financial Capability Assessment Guidance Puget Sound Nutrient General Permit (24-10-034)* (Oct. 2024).
[25] U.S. EPA, *Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* (Aug. 2021), pg. 4-7, https://www.epa.gov/system/files/documents/2023-06/life-cycle-nutrient-removal.pdf.

impact its Performance-Based Approach will have on increased wastewater utility rates.[26] This is both an economic and environmental issue; WWTPs will necessarily pass the cost of new treatment technology onto ratepayers and when living expenses increase in urban areas, housing development sprawls to rural areas where urban wastewater systems do not reach and rural septic can be far more polluting. *City of Tacoma v. Dep't of Ecology*, 28 Wn. App. 2d 221, 234 P.3d 462 (2023). Ecology also failed to evaluate qualitative or quantitative impacts on low-income and environmental justice communities.[27]

8. Ecology has failed to assess compliance costs to small businesses as required under the Regulatory Fairness Act.

Ecology cannot adopt a significant legislative rule if it fails to properly conduct the analysis required under the Regulatory Fairness Act (RFA), Ch. 19.85 RCW. The RFA requires agencies to evaluate the relative impact of proposed rules that impose costs on businesses in an industry and compare the relative compliance costs for small businesses to those of the largest businesses affected. RCW 19.85.

Implementation of the Performance-Based Approach will undeniably impose costs on any entity discharging to a WWTP on Puget Sound, and this group includes many entities that qualify as "small businesses." Ecology can readily assess the impact of its nutrient program on wastewater utility rates and needs to do so as part of this rulemaking.

9. Ecology has failed to comply with SEPA.

SEPA environmental review is required for any state agency decision on policies, plans, and programs, including adopting or amending rules, ordinances, or regulations to regulate future projects such as water quality rules, critical area ordinances, and other state and local regulations. RCW 43.21C.030. Lead agencies, such as Ecology, are required to review the SEPA environmental checklist and other available information to evaluate a proposed rule's likely environmental impacts. The agency must consider environmental information, along with technical and economic information, when deciding whether to approve a proposal. In every recommendation or report on proposals or major actions affecting the quality of the environment, the responsible agency official must submit a detailed statement on the environmental impact of the proposed action, any adverse environmental effects which cannot be avoided should the proposal be implemented, and alternatives to the proposed action. RCW 43.21C.030(c).

Ecology has failed to complete a SEPA environmental checklist for its Performance-Based Approach, despite its influence on future regulations. There is ample evidence supporting the

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[26] King County Amicus Brief.

[27] The number of ratepayers being billed more than 5% of their income for sewer services will increase with Ecology's proposed nutrient loading requirements, Puget Sound Clean Water Alliance Presentation on February 28, 2023.

probable impacts of the proposed approach on public services and utilities, namely the increased costs of treatment technologies that will necessarily be required to comply with the anticipated standards set by the Performance-Based Approach. These costs are well-documented by both Ecology and third-party studies.[28] Ecology is required to submit mitigation measures in response to anticipated impacts.

Ecology is required to submit an EIS in accordance with SEPA. It appears that Ecology plans to require advanced (tertiary) treatment as a result of the anticipated standards set using the Performance-Based Approach, which will have profound potential adverse impacts to the environment. Ecology has even previously recognized the potential environmental impacts of requiring WWTPs to adopt additional nutrient removal technology, including the likelihood that tertiary treatment will not only generate more effluent sludge that will require disposal, but will also require two to three times the amount of electrical energy currently used in WWTPs. *Nw. Env't Advocs. v. Dep't of Ecology*, 18 Wn. App. 2d 1005, 2021 WL 2556573, at *9 (2021) (unpublished). Ecology also ignored climate change impacts of its Performance-Based Approach, including the fact that nitrogen removal from wastewater converts some nitrogen in the wastewater to nitrous oxide, a greenhouse gas that is 300 more potent than carbon dioxide.[29] Additionally, the treatment technology required to comply with the proposed rule will ultimately increase wastewater utility rates and housing prices across the state, and when living expenses increase in urban areas, housing development sprawls to rural areas where urban wastewater systems do not reach and rural septic can create significant levels of pollution. *City of Tacoma v. Dep't of Ecology*, 28 Wn. App. 2d 221, 234 P.3d 462 (2023). Given that the Performance-Based Approach will necessarily require WWTPs implement advanced treatment technology that will have significant potential for adverse environmental impacts, Ecology is required to submit a full EIS analyzing the rule's probable environmental impacts.

In its required EIS, Ecology must also identify and assess the impacts of reasonable alternatives. RCW 43.21C.030. Washington courts have equated this alternatives analysis to be "one of the key building blocks, if not the heart of SEPA." *Escala Owners Association v. City of Seattle*, 2022 WL 2915536, at *8 (2022) (unpublished). The required discussion of alternatives to a proposal, "is of major importance, because it provides a basis for a reasoned decision among alternatives having differing environmental impacts." *Weyerhaeuser v. Pierce County*, 124

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[28] Declaration of Christie True, ¶¶ 9-10, *King County v. Dept. of Ecology*, No. 21-083 (PCHB 2021); Mot. For Stay, 2021-12-28 King County Motion for Stay, pg. 5, *King County v. Dept. of Ecology*, No. 21-083 (PCHB 2021); King County Amicus Brief; Puget Sound Clean Water Alliance Presentation on February 28, 2023; Department of Ecology, *Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities* (June 2011).
[29] U.S. EPA, *Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* at 4-7 (Aug. 2021), https://www.epa.gov/system/files/documents/2023-06/life-cycle-nutrient-removal.pdf.

Wn.2d 26, 38, 873 P.2d 498 (1994). Ecology is required to submit an EIS complete with a full alternatives analysis.

10. Ecology has failed to comply with obligations to conduct an environmental justice assessment in accordance with RCW 70A.02.060.

When considering a significant agency action, an agency must conduct an environmental justice assessment to inform and support its consideration of overburdened communities and vulnerable populations and to assist the agency with the equitable distribution of environmental benefits, the reduction of environmental harms, and the identification and reduction of environmental and health disparities. RCW 70A.02.060(1)(a). Ecology has failed to prepare an environmental justice assessment as required under RCW 70A.02.060(1)(a), despite the impacts its Performance-Based Approach will inevitably impart on overburdened and vulnerable communities.

By increasing compliance costs to WWTPs, the Performance-Based Approach will have a profound impact on utility rates and housing affordability; these consequences will create environmental justice disparities throughout Puget Sound. Using King County as an example, implementing treatment technology to remove nitrogen in compliance with the proposed performance-based DO rule could cost counties between $25 and $50 million in the next five years, $100 to $200 million in the next 10 to 15 years, and between $9 billion and $14 billion in total future expenses.[30] This could result in monthly wastewater rate increases of between $20 and $130 per month per household, representing a 40% to 230% increase to county residents' current monthly wastewater rates.[31] Rate increases of this staggering magnitude will impact housing affordability.[32] This rulemaking will make it increasingly difficult for Washington citizens, especially racial and social minorities, to be able to purchase or rent homes in the communities where they currently live and work.[33] Additionally, the Washington State Court of Appeals has acknowledged how a requirement (or necessity to comply with a state regulation) for advanced treatment technology may result in the unintended consequence of halting development, including affordable housing, shelters, and accessory dwelling units, while a WWTP raises funds necessary to implement the technology.[34]

In the utility industry, rates are established based on the cost of service, which is heavily influenced by treatment costs.[35] Any increased costs incurred by municipal utilities to comply

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[30] King County Amicus Brief at 3.
[31] *Id*.
[32] *Id*.; Brief for the Washington Association of Sewer and Water Districts as Amicus Curiae, pg. 9, *City of Tacoma v. Ecology*, 28 Wn. App. 2d 221 P.3d 462 (2023) ("WASWD Amicus Brief").
[33] Brief for the Building Industry Association of Washington, pg. 2, *City of Tacoma v. Ecology*, 28 Wn. App. 2d 221 P.3d 462 (2023) ("BIAW Amicus Brief").
[34] *See City of Tacoma*, 28 Wn. App. 2d at 234.
[35] WASWD Amicus Brief at 11-12.

with an Ecology rulemaking will be paid by their respective customers in the form of increased wastewater rates.[36] In some cases, smaller utility districts with fewer customers end up being impacted more by increased regulatory costs because they have a smaller customer base over which to share the financial burden.[37] Nearly all WWTPs in Washington do not currently have the advanced treatment that will likely be necessary for compliance with anticipated standards set through the Performance-Based Approach available at their plant, and do not have the current infrastructure to add the treatment technology without passing on significant costs to the customers they serve unless there is state or federal funding available.[38] The Building Industry Association of Washington and National Association of Home Builders estimate that a change of less than $1,000 to monthly bills would result in home ownership and renting being entirely unaffordable to most Americans, resulting in increased debt and homelessness.[39] Across Washington, the shortage of affordable homes to own and rent impacts extremely low-income households. Several factors play into housing affordability; the cost of monthly, recurring bills such as wastewater bills can place housing in jeopardy if increased.[40] Given the nature of the current treatment technology utilized by most WWTPs, it is not an exaggeration to say that every resident within the greater Puget Sound region is going to experience substantial rate increases associated with the Performance-Based Approach.[41] These rate increases and resulting increase in housing costs will inevitably have the greatest impact on vulnerable communities that likely already struggle with utility costs and housing affordability.

Ecology has failed to consider the impact its rulemaking will have on vulnerable communities, and it is required to conduct a full environmental justice assessment under RCW 70A.02.060.

11. Salish Sea Model Evaluation and Proposed Actions to Improve Confidence in Model Application in Context of Proposed Performance-Based Approach

The "Salish Sea Model Evaluation and Proposed Actions to Improve Confidence in Model Application" memorandum by University of Washington Puget Sound Institute (PSI) includes a general discussion of continued Salish Sea Model (SSM) improvements, as well as better communications with the public, stakeholders, and decision makers to gain broader acceptance

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[36] *Id*. at 13.
[37] *Id*. at 11.
[38] One of the only WWTP in Washington to have advanced technology is the Riverside Park Water Reclamation Facility in Spokane and the addition of advanced treatment was estimated to cost $126 million for the construction alone, not including additional maintenance, testing, and other associated costs, *The Riverside Park Water Reclamation Facility*, Spokane City (last viewed July 21, 2024), https://my.spokanecity.org/publicworks/wastewater/treatment-plant/; The City of Tacoma estimates the addition of advanced treatment will cost anywhere from $250 million to $750 million (2020 costs) in construction costs alone, *See*, *City of Tacoma*, 28 Wn. App. 2d at 233.
[39] BIAW Amicus Brief at 7.
[40] *Id*. at 13-14.
[41] *See* Burke et al., *Puget Sound Wastewater Service Affordability Analysis: Implications for Implementation Strategies* (May 17, 2023).

of the Salish Sea Model. The following comments are focused on dissolved oxygen in context of the proposed Department of Ecology Performance-Based Approach.

SSM Model Performance Statistics

A key focus of the PSI report was on model skill assessment in the shallow areas and at specific stations in Puget Sound. Most of the model statistics reported are domain/basin wide and consequently tend to be better as the +/- statistics average out across the entire Sound.

Figure 1 below presents root mean square error (RMSE) values from the report and plots them in comparison to the entire waterbody wide average. The horizontal line (orange) in the graph is the domain wide average RMSE. It is apparent from the figure that in some areas, the RMSE performance is similar to the overall average RMSE, but in other areas it is not. The RMSE is higher than the average in a number of the inlets to Puget Sound.

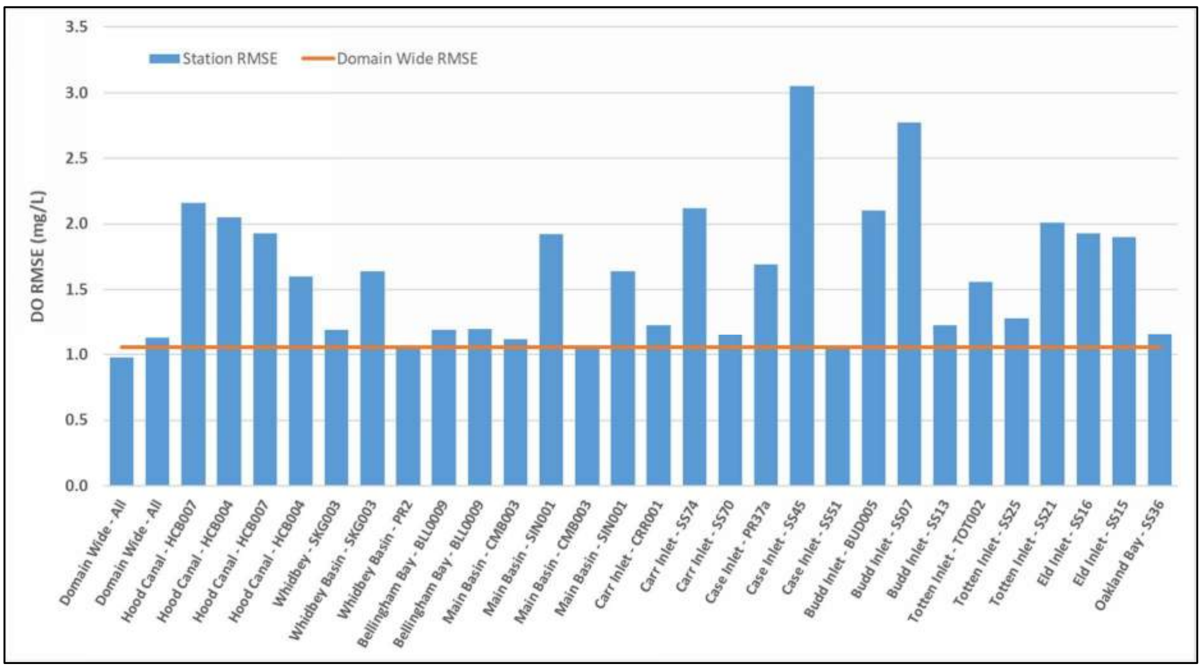

Figure 1. Comparison of Basin Wide Average RMSE with Specific Locations in Puget Sound

The Memorandum discusses the accuracy of the model-model calculations for the reference condition representing natural conditions versus the existing conditions, or the load reduction scenario SSM runs. One reference argued that the model accuracy between the 2 runs could cancel each other out and, therefore, the delta results are accurate. The Memorandum cautions that this is only one approach to the assessment and the topic should be explored further.

The Memorandum also addresses the sediment flux model and calculation of sediment oxygen demand (SOD) and nutrient fluxes. The SSM seems to calculate lower SOD than observed data.

Further, the model calculation of gross primary production was also less than observed. There are some issues with the data and model years that don't overlap.

SSM Natural Conditions Scenario

A question that may require further research into Ecology's Bounding Scenarios Report and examination of the SSM is whether the Natural Conditions scenario used in the SSM model is consistent with what Ecology is now proposing for its Performance-Based Approach. The Memorandum reports the Reference Condition Scenario as making changes to wastewater treatment plants and rivers. It has been understood that the municipal WWTP point source nutrient discharges to Puget Sound were removed from the Reference Condition in the SSM. However, the Memorandum notes that nutrients from Canadian sources and industrial treatment plants that not included in the Puget Sound Nutrient General Permit (PSNGP) are kept the same in the Reference Condition Scenario (see Figure 2 for insert from Memorandum below). This is inconsistent with Ecology's proposed Performance-Based Approach.

In Step 8 Estimating Natural Conditions of the March 2025 Second Draft, Ecology states that "All human-caused impacts must be accounted for and removed using all existing, readily available, and credible information to develop the natural conditions scenarios." The approach taken to the use of the Salish Sea Model for natural conditions does not appear to conform with this approach.

It appears that to be consistent with Ecology's proposed Performance-Based Approach, the SSM Reference Condition Scenario would need to be revised to remove both Canadian nutrient sources and industrial treatment plant discharges.

Figure 2. "Salish Sea Model Evaluation and Proposed Actions to Improve Confidence in Model Application" Technical Memorandum, page 10.

Reference Condition Scenario

What is changed from existing conditions?

- Natural loads of nitrogen and carbon for Washington's wastewater treatment plants and rivers are estimated from observations in pristine watersheds. These represent a pre-anthropogenic or pre-industrial nutrient loading.

What is kept the same?

- Nutrient inputs from:
  - Canadian sources including the Fraser River
  - Washington's industrial treatment plants and those not under the general permit
- Climate, hydrology, and ocean, and all other boundary and forcing conditions
- A unique reference condition is created for each year the model is run

12. The Proposed Performance-Based Approach Lacks Necessary Detail to Ensure Predictable, Repeatable Outcomes.

Tacoma echoes the concerns EPA voiced in its comments on the previous iteration of the Performance-Based Approach; many of these concerns are still apparent in the currently proposed draft. There are numerous steps and important details missing from the proposed Performance-Based Approach; as written, most sections lack necessary explanation of certain methods and procedures to implement the approach. Without such detail, the Performance-Based Approach lacks suitable safeguards to ensure predictable, repeatable outcomes.

First, the Performance-Based Approach includes a step to "Define site boundaries and model domain" but does not include sufficient detail on the parameters of such. For example, EPA stresses that the procedures in this step must include setting up the model grid and include the principle that the model grid accurately represents the physical characteristics of the waterbody. Procedures for documenting the decisions in translating bathymetric data to the model grid must also be included, including identifying data sources, procedures to analyze the data, and procedures for how to link the bathymetry to the model grid. This is an important step for building a water quality model. In its current form, the Performance-Based Approach appears to defer many of these additional steps to be conducted during QAPP development, as establishing the model grid is "project specific". However, even when providing guidance for establishing the model grid in a QAPP, the Performance-Based Approach lacks the requirements noted by EPA. Further, data selected for populating boundary conditions must represent seasonal variability that impacts the waterbody and parameter of interest. The Performance-Based Approach currently contains no bounds on calibration or certainty that the model performance will be adequate for the purpose of establishing current conditions and natural conditions. EPA commented that Ecology must add text to the effect that models must only be calibrated to reflect the expected range in variability of conditions at a site. EPA specifically noted that the phrase stating that calibration can be done "…by comparing to documented model fit statistics from other similar applications using the same model" could be interpreted broadly in terms of accepting any application calibration no matter how good, and therefore must be revised. EPA commented that this calibration section must also state that the model must be able to simulate current and natural conditions. As this current phrase in the Performance-Based Approach could allow inappropriate model calibration, this language does not meet the federal requirement for a sound scientific rationale (40 CFR section 131.11(a)(1)). Despite these comments clearly illustrating the present concerns, this phrase remains in the proposed Performance-Based Approach and Ecology has not revised the section according to EPA's comments.

Additionally, the Performance-Based Approach does not include a step to create a conceptual model specific to model application. For additional transparency, EPA recommended adding a requirement to develop a conceptual model by water body type and parameter, but Ecology did not follow suit. Further, the Performance-Based Approach fails to include necessary additional information on selection of a mechanistic model. EPA recommended including a list of models Ecology intends to use and procedures for identification of the appropriate model for a given application (including model selection criteria), as well as identifying any model limitations and ways to account for and address limitations. A section on model selection should also include Ecology peer-review requirements and open-source code. In addition, several other requirements for selecting a model must be added, such as sufficient resolution and processes/dynamics to capture all aspects of the interaction between the hydrodynamics/physical dynamics and biogeochemical processes, sources, cycling, and drivers. In its current form, the Performance-Based Approach simply states that, “model selection must be from a set of best-available modeling tools applicable for the specific purpose to estimate current and natural conditions based on the project requirements,” which, “includes, but is not limited to, the Salish Sea Model and other models of comparable rigor.” The Performance-Based Approach includes some criteria for model selection, but not nearly the amount of detail requested by EPA.

EPA also recommended including a model requirements review, which includes review of various model predications to assess performance. Further, this section should include the strengths and limitations of each model and procedures to address or compensate for those limitations. The Performance-Based Approach also lacks sufficient detail on model application and use; procedures must be added or minimum requirements included regarding how the model will be applied so that the Performance-Based Approach is transparent and repeatable. Specifically, the draft document lacks detail on what anthropogenic sources are removed, including process for removing both point and nonpoint sources. Ecology also fails to describe the methods and procedures for removal of anthropogenic sources that are not technically feasible to simulate in the model. There is also insufficient detail in the Performance-Based Approach section on site characterization data, which currently lacks the requirement to evaluate legacy effects resulting from past silviculture, agriculture, mining, and development. These activities influence channel form and thus, light, substrate, riparian growth, in-stream cover, sediment transport/turbidity and productivity. The EPA recommended including this information as a data requirement and evaluating the impact from these activities when establishing the natural conditions estimate.

Another concern shared between EPA and Tacoma is that the required elements section of the Performance-Based Approach includes a list of elements that need to be evaluated by the model but does not include the methods to do those evaluations or how they will be accounted for when modeling the natural conditions. EPA has recommended Ecology conduct a substantial re-write of this section for that reason, but the proposed Performance-Based Approach does not reflect such revision.

The Performance-Based Approach must also include certain general revisions across the entire document, such as additional binding language, procedures for how the steps will be executed, and minimum data requirements. Additionally, EPA has recommended substantial organizational revisions to ensure the approach provides a clear, sequential, and repeatable process, and Ecology has appeared to ignore these recommendations.

The Performance-Based Approach as it is drafted does not address the myriad of EPA concerns, which are shared by the City, and thus is not sufficient to produce predictable, repeatable outcomes. Ecology must address these concerns before moving forward with the approach.

1. Reference Attachments

As part of this review, the City referenced the documents attached to this letter. The City requests that Ecology review and consider these reference documents (and recommendations) as part of the proposed Performance-Based Approach revision efforts.

Thank you for this opportunity to comment on the draft documents for the proposed draft performance-based approach guidance document. We trust our comments are useful. If you have any questions or would like additional information please contact Teresa Peterson, P.E. at 253.591.5766 or tpeterson@cityoftacoma.org.

Sincerely,

Signed by:
Geoffrey M. Smyth, P.E.
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Initial
KF

Geoffrey M. Smyth, P.E.

Interim Director, Environmental Services

Attachments 1-40:

Attached as Separate Files with Comment Letter (File Names):

1. Modeling_Considerations_Checklist__R10_comments_ (1).docx
2. SEPADNS_NaturalConditions.pdf

Attached as One Combined File Named “Attachments 3-5”:

3. Publication no. 11-10-060_Tetra Tech Report on Nutrient Upgrades Costs
4. EPA life-cycle-nutrient-removal

5. May 2025 PBA Public Webinar and Hearing slides (2025_05_NCC_PBA_Public_Webinar 4930-9195-0662 version 1)

Attached as One Combined File Named "Attachments 6 – 9

6. Ex. A to Petition - 2019 01-15 WDOE Salish Sea Model Bounding Scenarios Report 1903001 4810-7635-6819_1 (copy)
7. 2024.06.26_Salish-Sea-Model-Evaluation-and-Proposed-Actions-to-Improve-Confidence-in-Model-Application
8. "Researchers zero in on low-oxygen areas of concern in Puget Sound_ Encyclopedia of Puget Sound" article
9. "Natural Conditions" are at the center of disputes over dissolved oxygen standards_ Encyclopedia of Puget Sound article

Attached with Comment Letter PDF File:

10. 06.04.21 Loehr Comment on Draft PSNGP
11. 07.17.1998 Everett Petition to Revise DO Standards
12. 08.16.21 Holtgrieve Comment on Draft PSNGP
13. 1998-07-08 Mark Hicks Letter to Loehr re State Standards for Dissolved Oxygen (copy)
14. 2013 12-04 HDR Treatment Technology Review and Assessment 4852-0702-5351_1 (copy)
15. 2021-08-16 City of Tacoma Comment Letter PSNGP (copy)
16. 2021 12-28 King County's Declaration of Christie True (King Cty v. Dept of Ecology 4892-0931-6616_1
17. 2021 12-28 King County's Motion for Stay 4866-0819-2776_1
18. 2022-12-07 Notes on EPA Ecology Discussion of NC Process.msg
19. 2023-02-28 UW Puget Sound Institute - Puget Sound Clean Water Alliance (CWA) Affordability + Modeling Presentation (copy)
20. 2023 05-23 Stillaguamish Tribe of Indians ltr to Ecology re DO Criteria
21. 2024-04-12 Amicus Curiae Brief by Building Industry Association of Washington
22. 2024-04-15 Brief of Amicus Curiae from King County (copy)
23. 2024-04-15 Washington Association of Sewer & Water Districts' Motion for Leave to Join in Amicus Brief Filed by King County (copy)
24. 2024-04-16 Ecology Response to Natural Conditions Criteria Questions by Lincoln Loehr
25. 2410022 - Preliminary Regulatory Analysis

26. BrysonFinch_Marine DO Criteria Presentation 2018
27. Burke_et_al_2023_Wastewater_Affordability_Critical_Analysis_Summary_Report_05.017.23
28. City of Tacoma v. Dep't of Ecology (2023) (copy)
29. Connor & Stelle_Elements of a Comprehensive Puget Sound Nutrient Alternative
30. Ecology Final Treatment Plant Financial Capability Assessment Guidance Puget Sound Nutrient General Permit (24-10-034) (Oct. 2024).
31. Environmental Checklist 2023
32. EPA_ActionsNCC_Nov192021
33. Holtgrieve Scheuerell_Detailed Critique of Ahmed et al 2019
34. Holtgrieve & Scheuerell_Appendix
35. Loehr MPB 1986 article re 301(h) in Washington (2)
36. Loehr 2020.02.29 memo to Scott Redman
37. wawqs-action-letter-11-19-2021 (copy)
38. 2024 Draft PBA Guidance
39. 2025 Draft PBA Guidance

Attached as Separate File with Comment Letter (as a second submission online):

40. 2025 Draft PBA Guidance EPA Comment Letter on Natural Conditions Rulemaking

LINCOLN LOEHR

I submitted comments on the 2018 draft 303(d) list of impaired waters to Ecology on June 4, 2021. I am attaching them here as they are also relevant to the proposed Nutrient General Permit.

P. O. Box 226
Winthrop, WA 98862
June 4, 2021

Washington State Department of Ecology
Jeremy Reiman
PO Box 47600
Olympia, WA 98504-7600
303(d)@ecy.wa.gov

Subject: Comments on proposed 2018 303(d) list of impaired waters

Dear Mr. Reiman,

This comment pertains to all of the marine water category 5 (impaired) listings for dissolved oxygen. The listings are based on 53 year old dissolved oxygen criteria that are not biologically based, are lacking in any identified scientific rationale, are not scientifically defensible, and are not based on credible information and literature for developing and reviewing a surface water quality standard.

The dissolved oxygen criteria do not meet the federal requirements of 40 CFR 131.11, nor do they meet the requirements found in Chapter 2 of WQP Policy 1-11 "Ensuring Credible Data for Water Quality Management". Since Ecology is using non-credible criteria, there is no basis for asserting that the waters are impaired. The 0.2 mg/l change component of the criteria is not biologically based. The listings should be changed to Category 2 (unsure) and notation provided that the listings will be re-evaluated after Ecology goes through a credible process to develop new criteria involving scientific input and public and scientific review. EPA should be involved since they have experience with marine DO criteria development.

I urge Ecology to start with the Marine Dissolved Oxygen Criteria developed by EPA and adopted by three states for Chesapeake Bay, which EPA says "may also apply to other estuarine and coastal systems, with appropriate modifications." There are important considerations in the Chesapeake Bay criteria including differences in depth, duration of exposure (averaging periods), and seasonality that are lacking in our criteria.

To prescribe significant wastewater treatment changes for assumed impairment based on ancient, overly protective, non-credible criteria is essentially malpractice. Ecology likes to assert that they are confident that our criteria are protective. I would agree, but they are also needlessly over-protective and therefore not representative of impairment.

To illustrate the overly protective aspect of the criteria, the Good classification includes a numeric criterion of 5 mg/l which "meet or exceed the requirements for all uses including but not limited to, salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning." The Excellent quality classification includes a higher numeric criteria of 6 mg/l which meets all the same requirements protected by 5 mg/l. Similarly, the Extraordinary quality classification includes a higher numeric criteria of 7 mg/l which meets all the same requirements protected by 5 mg/l. The only function served by the Excellent and Extraordinary criteria is to be more protective than necessary. When the numeric criteria are crossed, that triggers the natural condition and the human caused decrease of 0.2 mg/l components of the criteria. So, a water with a designated criteria of 7, might be at 6.5 with more than 0.2 mg/l of that attributed to human caused decrease. We currently call that impaired, yet it is still higher than 5 mg/l which our criteria assert protects all uses.

I note that the freshwater dissolved oxygen criteria are similarly flawed, should be changed to Category 2 and notation provided to re-evaluate after a credible process to develop freshwater dissolved oxygen criteria. Ecology could start with EPA's freshwater dissolved oxygen criteria recommendations.

Ecology has asserted that effects levels documented in a 2008 report by Vaquer-Sunyer and Duarte support our criteria and even indicate that our criteria should be more stringent.[1] They further discuss a report by John Davis (1975)[2] as additional information also supporting our criteria. The data reviewed by Davis are also included in the Vaquer-Sunyer and Duarte report, so it isn't additional information. However, Vaquer-Sunyer and Duarte do not give specifics on what effects were measured in different tests. Davis does. Some effects have no significance for the well-being of the tested species, and therefore are not relevant to criteria development or assertions of impairment.

For example, the Ratfish (*Hydrolagus colliei*) is shown as having a DO threshold of 8.54 mg/l. Davis shows that below that threshold, the blood is less than 100% saturated. The Ratfish has large eyes, the better to see with in low light conditions. It lives in deep water in Puget Sound and along the continental shelf and slope along the west coast. In Puget Sound it makes up about 80% of the fish biomass in demersal trawl surveys. It makes up a sizeable percentage of the fish biomass in trawl surveys on the continental shelf as well. The deep water where it resides is substantially lower than 8.54 mg/l. If one was developing water quality criteria for marine dissolved oxygen, studies using blood oxygen saturation of less than 100% as a threshold would not be used. Criteria development has to consider what effects are most relevant to the survival of the species.

Chesapeake Bay states had DO criteria of 5 mg/l as an average and 4 mg/l as a minimum. Those criteria probably did go back to the 1968 Department of Interior water quality criteria recommendations. With help from EPA they developed newer, better criteria that recognized different types of water (surface, deep, bottom, nearshore, heads of tidal inlets) and had different criteria for each. Criteria had averaging periods, seasonality and depth considerations. The biological basis for the criteria were spelled out in detail. The new criteria were less stringent than the old criteria. The EPA recommendations were adopted by the states. The states did not choose to keep their more stringent criteria, which they could have said were more protective.

Sincerely yours,

Lincoln Loehr

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[1] See power point from May 30, 2018 Nutrient Forum meeting, and also DOE's August 2018 report, Washington State's Marine Dissolved Oxygen Criteria; Application to Nutrient. An Overview of the Purpose and Application of the Criteria in the Surface Water Quality Standards.

[2] John Davis. (1975). Minimal Dissolved Oxygen Requirements of Aquatic Life with Emphasis on Canadian Species: a Review.

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ANCHORAGE
LOS ANGELES
PALO ALTO
PORTLAND
SAN FRANCISCO
TACOMA

July 17, 1998

17278-0001

Mr. Jerry Thielen
Rules Coordinator
Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600

Re: **Petition to the Department of Ecology to revise the dissolved oxygen standards and to halt dissolved oxygen related TMDL development and implementation until the revisions are complete.**

Dear Mr. Thielen:

In accordance with RCW 34.05.330, and on behalf of the City of Everett, we are submitting the attached petition for adoption of EPA's dissolved oxygen criteria as state water quality standards to replace those presently in rule at WAC 173-201A-030. We believe that there is no known technical basis to support our present standards and that EPA's criteria offer the best technical basis available. This petition carries ramifications to the State's 303(d) List and to the ongoing TMDL activities related to Dissolved Oxygen. We ask that all TMDL activities related to Dissolved Oxygen be curtailed until the state completes adoption of scientifically defensible Dissolved Oxygen standards.

As per RCW 34.05.330, the Department is required to respond to this petition within 60 days, by either (1) denying the petition in writing, stating its reasons for denial and specifically addressing the concerns raised by the petitioner, stating the alternative means by which it will address those concerns, or (2) initiating rulemaking proceedings.

We urge the Department to act on this petition by addressing this issue during the current triennial review of water quality standards.

Sincerely yours,

Tad H. Shimazu

Lincoln C. Loehr

cc: Mr. Tom Fitzsimmons

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07/17/98 3:29 PM

Petition to the Washington State Department of Ecology to revise the State's Surface Water Quality Standards for Dissolved Oxygen and to curtail further TMDL development for water bodies listed for Dissolved Oxygen until such revisions are completed

The existing Dissolved Oxygen standards are found in WAC 173-201A-030 (see Attachment A). The Dissolved Oxygen standards were adopted on or before 1967 (see Attachment B). At that time there was no EPA criteria document to help summarize the science or to provide a technical basis for the standard. (At that time there was no EPA.)

The state has no records identifying the basis behind the Dissolved Oxygen standards (see Attachment B). The implementation of the present Dissolved Oxygen standards has been simply habitual and unquestioned. The Dissolved Oxygen standards have not been reviewed or revised in any triennial review. Apparently neither the Department of Ecology nor the regulated community have thought to examine or question the Dissolved Oxygen standards in the last 30 years. In this regard, we accept that we all bear some responsibility for this omission.

In accordance with RCW 34.05.330 we petition the Department of Ecology to undergo rulemaking to update the Dissolved Oxygen standards with the objective being to use new science to develop defensible Dissolved Oxygen standards which may be similar to EPA's dissolved oxygen criteria. Our petition is now timely because the state has listed numerous water bodies on the 303(d) list specifically for Dissolved Oxygen. The state is now expending much effort at developing TMDLs because of the Dissolved Oxygen listings. These endeavors are in turn imposing substantial costs on the regulated communities for compliance. Appendix I to the 1998 Section 303(d) List submittal to EPA identifies TMDL activities specific to Dissolved Oxygen for 89 waterbodies (see Attachment C for a listing of those specific waterbodies.) The list presented in Attachment C does not represent all of the waterbodies listed for Dissolved Oxygen. It only represents those for which there have been TMDL activities. There are other listed waterbodies for which Dissolved Oxygen TMDL activities are yet to begin.

Because of the high costs to Ecology to develop TMDLs and the much higher costs to the regulated (and unregulated) community for implementing TMDLs, it is appropriate to examine the standards to assure they are based on scientifically sound and up-to-date technical information. The present Dissolved Oxygen standards are more than 30 years old, lack any identified technical basis and obviously cannot represent current science.

We ask that Ecology halt all Dissolved Oxygen related TMDL developments and implementation until the state adopts scientifically defensible Dissolved Oxygen standard. At the moment, the state has no such standards. We propose that the state could rapidly adopt EPA's freshwater Dissolved Oxygen criteria for both freshwater and saltwater. Alternatively, for saltwater, the state could simply adopt a standard that "the dissolved oxygen concentration shall not at any time be depressed more than 10 percent from that which occurs naturally, as the result of the discharge of oxygen demanding waste materials." This approach is what California uses, and is also in agreement with EPA's freshwater Dissolved Oxygen Criteria. We further ask that DOE immediately amend the 1998 303(d) List that was submitted to EPA to reflect the indefensibility of the present Dissolved Oxygen Standard and to later adjust the 303(d) List when Ecology completes the rulemaking.

The process we are requesting (both the standard revision, the TMDL moratorium and the 303(d) revision) must include a public education component to emphasize that this is needed to correct an old standard that is evidently without basis. The positive benefits should be emphasized. These benefits include 1) our waters are probably not as bad as had been previously indicated 2) both state and local resources may be more available to address other pressing needs instead and 3) a better standard will result.

<u>The EPA Dissolved Oxygen criteria.</u>

EPA published their criteria document in 1986 (see Attachment D), and also included a summary of the criteria in *Quality Criteria for Water, 1986* (also known as the "Goldbook") (see Attachment E). The criteria are specific to the protection of early life stages and other life stages for coldwater organisms and for warmwater organisms. The criteria (in mg/L) are:

Coldwater Criteria	Early Life Stages	Other Life Stages
30 day mean	NA	6.5
7 day mean	9.5(6.5)	NA
7 day mean minimum	NA	5.0
1 day minimum	8.0(5.0)	4.0
Warmwater Criteria		
30 day mean	NA	5.5
7 day mean	6.0	NA
7 day mean minimum	NA	4.0
1 day minimum	5.0	3.0

EPA's criteria include footnotes that explain that

- The early life stage values are water column concentrations recommended to achieve the required intergravel dissolved oxygen concentrations shown in the parentheses. For species that have early life stages exposed directly to the water column, the figures in parentheses apply.
- The 1 day minimum values should be considered as instantaneous concentrations to be achieved at all times.

The EPA criteria also discuss when natural conditions alone create dissolved oxygen concentrations less than 110 percent of the applicable criteria means or minima or both, the minimum acceptable concentration is 90 percent of the natural concentration. Note that this allows a much greater decrease than the State's 0.2 mg/L allowable drop from the natural. Also note that this is in agreement with the state of California's marine water Dissolved Oxygen standard.

STATE OF WASHINGTON
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July 8, 1998

Mr. Lincoln Loehr
Environmental Analyst
Heller, Ehrman, White and McAuliffe
6100 Columbia Center\701 Fifth Avenue
Seattle, WA 98104-7098

Dear Mr. Loehr:

I am writing in response to your June 12 letter concerning our state standards for dissolved oxygen. As I discussed with you on the phone, we do not have supporting information on the technical basis for our existing criteria.

This last year I personally went through all of the files stored at Ecology and downtown in the state central archives. I examined these files with the intent to document the basis for our various water criteria. Little information exists in general regarding the water quality standards. This leaves me with the disappointing conclusion that the archive staff decided these records were not historically critical and had them destroyed. All I found in relation to dissolved oxygen was a comment letter sent by a pulp mill stating the need to allow some human degradation beyond natural levels in marine waters during periods of upwelling.

The existing dissolved oxygen criteria thresholds have existed in the state standards as far back as 1967 and is the oldest copy of the standards in my possession. The criteria has never been expressed other than an absolute threshold value, even though many other criteria have been and continue to include averaging periods. Let me know if you have any further questions or issues needing clarification (360) 407-6477.

Sincerely,

Mark Hicks

Mark Hicks
Water Quality Standards

MPh:mh

Shared.../section/wm/mark/loehr1.doc

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
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September 16, 1998

Mr. Tad H. Shimazu
Heller Ehrman White & McAuliffe
6100 Columbia Center
701 Fifth Avenue
Seattle, WA 98104-7098

Dear Mr. Shimazu:

Thank you for your July 17, 1998 petition to revise our state's water quality standards for dissolved oxygen. Ecology is required by RCW 34.05.330 to respond to your petition within 60 days by either (1) denying the petition in writing or (2) initiating rule-making proceedings. We have reviewed your petition and find that we must deny your request at this time.

Our denial is based in part on our having already committed to undertake a review of our freshwater dissolved oxygen criteria as part of the current efforts investigating the potential conversion of the standards to a use-based approach. Following completion of these efforts, targeted for December 1999, we will evaluate whether state and agency priorities and the availability of resources allow us to initiate a similar review of our marine criteria.

We also find your request to be inconsistent with our understanding of procedural and technical issues associated with the standards, and the dissolved oxygen criteria in particular, as well as being inconsistent with our overall strategy for the surface water quality standards. For example, you suggest in the petition that our dissolved oxygen criteria are inappropriate due to their age and lack of administrative record. We disagree with your assumption that the age of the criteria and the lack of documentation in state archives indicates these standards lack scientific validity. We also find fault with the assumption that not having conducted a formal review of these criteria since their adoption is the result of an oversight. No basis has been provided to scientifically challenge our existing standards.

You also suggest that we should, and easily could, adopt the guidance values for freshwater dissolved oxygen from the U.S. Environmental Protection Agency's (EPA)

1986 Quality Criteria for Water and apply them to both fresh and marine waters. We disagree with this assumption for several reasons. First, EPA's guidance was developed specifically for fresh waters and did not consider or evaluate use impacts for marine waters. Second, EPA's guidance includes only limited evaluations of impacts to non-fish species and of sub-lethal or cumulative effects. Finally, any criteria change requires a review by the federal fisheries agencies as part of the Endangered Species Act consultative process. Based on the information provided to date by the resource agencies participating in the use-based criteria effort, we doubt whether EPA's 1986 dissolved oxygen criteria would be considered as adequately protective of the salmon species currently listed or proposed for listing as threatened or endangered in Washington waters.

Your petition includes a request that we suspend the development of Total Maximum Daily Loads (TMDLs) for dissolved oxygen until such time as we have adopted new dissolved oxygen criteria. Our existing state standards were developed and adopted in accordance with state rules and regulations and have been approved by EPA consistent with federal regulations and statutes. These regulations and statutes also require that we use them for setting permit limits, for establishing the 303(d) list, and for conducting TMDLs. We cannot legally or in good conscience waive the use of our current dissolved oxygen criteria. The enclosed letter from EPA Region 10 confirms that our current standards are legally binding and are to be used for TMDL development as well for other water pollution control efforts.

Ecology remains fully committed to maintaining accurate and defensible water quality criteria for all parameters, and dissolved oxygen is no exception. In fact, we have made many improvements to the Surface Water Quality Standards rule during the past twenty-five years in order to better protect Washington's waters. These improvements have incorporated new scientific information and advances in our understanding of aquatic systems as well as new state and national environmental policies. Recent improvements in the standards program have included the adoption of nutrient criteria for lakes and refinements to criteria for several metals and toxic chemicals. We are developing language to clarify how the state's antidegradation policy will be implemented and converting the standards to a use-based approach. The use-based approach will allow us to better customize the criteria for temperature, bacteria, dissolved oxygen, and fish habitat in order to protect the specific uses of a waterbody.

After these improvements to the standards are in place, we will need to switch our emphasis from rule development to implementing the nutrient criteria, antidegradation policy, and use-based criteria as part of the agency's watershed approach. We recognize that the standards program is very dynamic and there are many standards issues being discussed at the national level, including new requirements for nutrient criteria and biocriteria. We will, of course, continue to monitor developments on the national level with interest. It may make sense to adopt certain federal proposals in the future.

However, because we believe it is now our highest priority to implement the recent and pending changes to the standards, we do not anticipate initiating further changes to the standards in the foreseeable future.

We encourage you to remain involved with our current efforts to enhance the surface water quality standards, specifically development of an antidegradation implementation plan and conversion of the standards to a use-based approach. Mark Hicks, at (360) 407-6477 in our Water Quality Program, is leading this effort and can provide you with additional information regarding these activities.

Sincerely,

Tom Fitzsimmons
Director

TF:MH:kh
Enclosure

cc: Lincoln Loehr Heller Ehrman White & McAuliffe

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 10
1200 Sixth Avenue
Seattle, Washington 98101

SEP 1 4 1998

REPLY TO
ATTN. OF: OW-134

OPTIONAL FORM 99 (7-90)

FAX TRANSMITTAL	# of pages ► 2
To Steve Saunders	From Shirley
Dept./Agency DOE	Phone # 553-8512
Fax # 407-7162	Fax # -0165
NSN 7540-01-317-7368 5099-101	GENERAL SERVICES ADMINISTRATION

Mr. Steve Saunders
Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600

Re: Petition to Ecology submitted by Heller Ehrman White & McAuliffe to revise dissolved oxygen standards and to halt related TMDL development

Dear Mr. Saunders:

Thank you for forwarding a copy of the referenced July 17, 1998 petition. We have reviewed this document and find no basis for a favorable response. Washington's Surface Water Quality Standards (WQS) have been adopted by the state as Chapter 173-201A WAC and approved by the Environmental Protection Agency, Region 10 (EPA) in accordance with all applicable state and federal regulations and statutes. This approval includes Washington State's current standards for Dissolved Oxygen.

The petitioners are also requesting that Ecology replace the state's current Dissolved Oxygen criteria with those referenced in EPA's 1986 Quality Criteria for Water (Gold Book). Although we support the general use and adoption of the 1986 criteria, EPA policy as well as federal regulations and statutes encourage states to adopt criteria that are equal to or more protective of existing and designated uses. We believe Ecology's Dissolved Oxygen criteria provide better protection of the uses identified for each of the classifications in Washington's standards than would the single Dissolved Oxygen criteria set forth in the Gold Book. This is particularly true regarding the protection of marine uses in that the Gold Book criteria addresses only the protection of freshwater uses while Ecology has adopted separate criteria for both fresh and marine waters.

Federal Regulations and statutes also require that the approved standards be used as the basis for identifying water quality limited waters, establishing Total Maximum Daily Loads (TMDLs), and permitting decisions. Furthermore, approved standards must be used until such time that revised standards have been formally adopted by the state and approved by EPA. EPA's approval of new or revised standards also includes consultation with the federal resource agencies to ensure adequate protection for listed or threatened species under the federal Endangered Species Act. Therefore, we can not support the petitioner's request to suspend the application of approved standards during reviews of proposed revisions to the standards.

If you have any questions concerning this letter please contact Fletcher G. Shives of my staff at (206) 553-8512.

Sincerely,

[signature] for TH

Timothy Hamlin
Manager, Water Quality Unit

Gordon Holtgrieve

Please see attached file.

SCHOOL OF AQUATIC AND FISHERY SCIENCES
UNIVERSITY of WASHINGTON

August 16, 2021

Eleanor Ott, PSNGP Permit Writer
Department of Ecology
Water Quality Program
PO Box 47600
Olympia, WA 98504-7600

Regarding: Puget Sound Nutrient General Permit

The Scientific Basis for Regulation is Flawed
The Washington State Department of Ecology (hereafter Ecology), intends to implement the Nutrient General Permit on the basis that the state's water quality standard for dissolved oxygen is not being met, due in part to nitrogen discharge from wastewater treatment plants (WWTP). Ecology has used its implementation of the Salish Sea Model (SSM) to determine: a) the dissolved oxygen water quality standard is not being met, and b) WWTP are contributing to this non-compliance. These two factors are the basis for the Nutrient General Permit and, as such, questions about the SSM and the compliance determination process are relevant to the Nutrient General Permit under consideration. As detailed in my letter regarding the Draft Nutrient Permit dated 15 March 2021, I and other independent scientists with relevant expertise have repeatedly and publicly challenged Ecology's assertion that the SSM is sufficiently precise and accurate to determine compliance with the standard. In short, we believe that model uncertainty when predicting current conditions is too large to say that the standard is likely not being met. The response to my letter, provided by Ecology in the General Nutrient Permit Fact Sheet, fails to adequately address the issue of model uncertainty in determining compliance to the standard. *This use of the SSM to determine compliance to the water quality standard needs independent review by qualified scientists without conflicts of interest.*

Public Messaging from Ecology on Puget Sound Water Quality is Misleading and Not Based on Facts
Ecology's recent public messaging campaign that describes "dead zones" in Puget Sound (either current or future) as a meaningful problem for the ecosystem necessitating action[i] is not based on any published study or report. Ecology representatives have been on the record stating that salmon are suffocating because of nutrients from WWTP[ii], yet there is no scientific evidence pointing to low oxygen from nutrients as a cause of salmon mortality in Puget Sound. *Simply put, this public messaging campaign is a dishonest misrepresentation of the impacts WWTP are having on Puget Sound and should be immediately retracted.*

Here are the facts: Between 0.25% and 1% of the volume of Puget Sound is hypoxic[iii] during part of the summer, of which 80% to 85% of this hypoxia is due to natural processes outside of

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human control (Ahmed et al. 2019, MacCready 2019). That means between 0.03% and 0.2% of the Puget Sound is becoming hypoxic due to humans, for part of the year, and actions to reduce nutrients from WWTP will not have a meaningful impact on hypoxia (MacCready 2019).

Effectiveness and Tradeoffs Must be Considered

The Puget Sound Ecosystem faces numerous challenges from myriad of stressors. This reality dictates that proposed solutions must be evaluated both on their likelihood of effecting change and the opportunity costs of actions that will not occur because the proposed policy. Ecology has never considered these critical factors in their decision-making around this issue! Given the high natural variability in dissolved oxygen in Puget Sound, it is a near certainty that there will be no observable change in dissolved oxygen as a result of this policy. Furthermore, because the SSM is a deterministic model, it is an absolute certainty it will indicate a water quality improvement, even if there is not an observable change, because it is written into the model. Will the public accept that the money they have spent on this action does not result in an observable change in dissolved oxygen even if the model says it should be there? *At a minimum, Ecology should detail how the effectiveness of this policy will be evaluated.*

Finally, the list of issues and potential actions to improve the health of Puget Sound is long – far longer than is possible, given available resources. Consideration of tradeoffs and optimization of actions is therefore a must. Recent research by King County suggests that actions to reduce stormwater runoff and improve habitat result in a far greater "bang for the buck" than nutrient reduction.[iv] Ecology must take seriously the reality that resources are limiting and restoration actions must be prioritized. Otherwise, there is the substantial risk that money will be spent on this issue in vain and, even worse, the public will pull their support for future environmental initiatives. *As environmental scientists, engineers and policy-makers, have a responsibility spend the public's money wisely.*

Recommendations

1. Delay implementation of the Nutrient General Permit until it is clear that: a) there is an ecologically meaningful problem as the result of nutrients from WWTP, b) the proposed action will provide ecological benefits to the Puget Sound, and c) critical funds are not better spent on alternative actions with higher likelihoods of success.

2. Revise Ahmed et al. (2019) to include the model uncertainties in a transparent and scientifically-defensible way that specifically includes the range of likely values (i.e., confidence intervals), not just a single number, for each model-generated result. When determining compliance to the dissolved oxygen standard, present the areas deemed to be out of compliance with an associated type I error probability.

3. Conduct a multi-model comparison of Puget Sound water quality, as is the current best practice. There are at least three existing models of water quality for Puget Sound that can easily be compared to one another as a means to assess model uncertainty.

4. Solicit an independent review of the science related to compliance standards and incorporate all relevant suggestions into a new presentation of results. The Washington State Academy of Sciences frequently conducts this type of scientific review for issues of high policy

importance such as this. It is therefore recommended that Ecology requests a full scientific review from the Academy.

5. Publicly retract all statements that suggest "dead zones" are a meaningful problem in Puget Sound that can be corrected by regulating nutrients from WWTP. Furthermore, Ecology should publicly retract all statements that suggest salmon are being impacted by "dead zones" in the Puget Sound (i.e., suffocating). Neither of these statements can be supported by data or modeling.

Sincerely,

Gordon W. Holtgrieve
Associate Professor
School of Aquatic & Fishery Sciences
University of Washington

References Cited

Ahmed, A., Figueroa-Kaminsky, C. Gala, J., Mohamedali, T., Pelletier, G., and McCarthy, S. 2019. Puget Sound Nutrient Source Reduction Project. Volume 1: Model Updates and Bounding Scenarios. Washington State Department of Ecology, Publication 19-03-001.

MacCready, P. 2019. External Review of the Bounding Scenarios Report by Ahmed et al. Obtained by public records request.

Diaz, RJ and R Rosenberg. 2008. Spreading Dead Zones and Consequences for Marine Ecosystems. *Science* 321(5891): 926-929. DOI: 10.1126/science.1156401

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[i] https://ecology.wa.gov/Blog/Posts/June-2021/To-prevent-dead-zones-in-Puget-Sound,-communities

[ii] Puget Sound Partnership Leadership Council Meeting (open to the public) 18 February 2021.

[iii] The term "dead zone" is poorly defined, but at a minimum it implies lethal consequences for marine life due to low oxygen. "Hypoxia"—typically defined as dissolved oxygen less than or equal to 2 mg/L—is a term used to indicate low oxygen that can negatively impact marine life, while mass mortality events are expected to occur at dissolved oxygen values of 0.5 mg/L or less (Diaz and Rosenberg 2008).

[iv] Presentation by Dow Constantine, Abigail Hook, and colleagues at the Puget Sound Partnership Leadership Council Meeting (open to the public) 18 February 2021.

STATE OF WASHINGTON

DEPARTMENT OF ECOLOGY

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July 8, 1998

Mr. Lincoln Loehr
Environmental Analyst
Heller, Ehrman, White and McAuliffe
6100 Columbia Center\701 Fifth Avenue
Seattle, WA 98104-7098

Dear Mr. Loehr:

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Sincerely,

Mark Hicks

Mark Hicks
Water Quality Standards

MPh:mh

Treatment Technology Review and Assessment

Association of Washington Business
Association of Washington Cities
Washington State Association of Counties

December 4, 2013

HDR

500 108th Avenue NE
Suite 1200
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04594

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Acronyms

Acronym	Definition
AACE	Association for the Advancement of Cost Engineering
AOP	advanced oxidation processes
AWB	Association of Washington Businesses
BAC	biological activated carbon
BAP	benzo(a)pyrene
BOD	biochemical oxygen demand
BTU	British thermal unit
CEPT	Chemically-enhanced primary treatment
cf	cubic feet
CIP	clean in place
CRITFC	Columbia River Inter-Tribal Fish Commission
Ecology	Washington Department of Ecology
EPA	U.S. Environmental Protection Agency
FCR	fish consumption rate
g/day	grams per day
GAC	granular activated carbon
gal	gallon
gfd	gallons per square foot per day
GHG	greenhouse gas
gpd	gallons per day
gpm	gallons per minute
GWh	giga watt hours
HDR	HDR Engineering, Inc.
HHWQC	human health water quality criteria
HRT	hydraulic residence time
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
KWh/MG	kilowatt-hours per million gallons
lb	pound
MBR	membrane bioreactor
MCL	maximum contaminant level
MF	microfiltration
mgd	million gallons per day
mg/L	milligrams per liter
MMBTU	million British thermal units
MWh/d	megawatt-hours per day
NF	nanofiltration
ng/L	nanograms per liter
NPDES	National Pollutant Discharge Elimination System
NPV	net present value
O&M	operations and maintenance
ODEQ	Oregon Department of Environmental Quality
PAC	powdered activated carbon
PAH	polycyclic aromatic hydrocarbons
PCB	polychlorinated biphenyls
PE	population equivalents
PIX	potable ion exchange

Acronym	Definition
ppm	parts per million
RO	reverse osmosis
SDWA	Safe Drinking Water Act
sf	square feet
SGSP	salinity gradient solar pond
SRT	solids retention time
Study Partners	Association of Washington Businesses/Association of Washington Cities and Washington State Association of Counties consortium
TDS	total dissolved solids
TMDL	total maximum daily load
TSS	total suspended solids
UF	ultrafiltration
µg/L	micrograms per liter
USDA	U.S. Department of Agriculture
UV	ultraviolet
WAC	Washington Administrative Code
WAS	waste activated sludge
WLA	waste load allocation
WWTP	wastewater treatment plant
ZLD	zero liquid discharge

Executive Summary

This study evaluated treatment technologies potentially capable of meeting the State of Washington Department of Ecology's (Ecology) revised effluent discharge limits associated with revised human health water quality criteria (HHWQC). HDR Engineering, Inc. (HDR) completed a literature review of potential technologies and an engineering review of their capabilities to evaluate and screen treatment methods for meeting revised effluent limits for four constituents of concern: arsenic, benzo(a)pyrene (BAP), mercury, and polychlorinated biphenyls (PCBs). HDR selected two alternatives to compare against an assumed existing baseline secondary treatment system utilized by dischargers. These two alternatives included enhanced secondary treatment with membrane filtration/reverse osmosis (MF/RO) and enhanced secondary treatment with membrane filtration/granulated activated carbon (MF/GAC). HDR developed capital costs, operating costs, and a net present value (NPV) for each alternative, including the incremental cost to implement improvements for an existing secondary treatment facility.

Currently, there are no known facilities that treat to the HHWQC and anticipated effluent limits that are under consideration. Based on the literary review, research, and bench studies, the following conclusions can be made from this study:

- Revised HHWQC based on state of Oregon HHWQC (2001) and U.S. Environmental Protection Agency (EPA) "National Recommended Water Quality Criteria" will result in very low water quality criteria for toxic constituents.
- There are limited "proven" technologies available for dischargers to meet required effluent quality limits that would be derived from revised HHWQC.
  - Current secondary wastewater treatment facilities provide high degrees of removal for toxic constituents; however, they are not capable of compliance with water quality-based National Pollutant Discharge Elimination System (NPDES) permit effluent limits derived from the revised HHWQC.
  - Advanced treatment technologies have been investigated and candidate process trains have been conceptualized for toxics removal.
    - Advanced wastewater treatment technologies may enhance toxics removal rates; however, they will not be capable of compliance with HHWQC-based effluent limits for PCBs. The lowest levels achieved based on the literature review were between <0.00001 and 0.00004 micrograms per liter (µg/L), as compared to a HHWQC of 0.0000064 µg/L.
    - Based on very limited performance data for arsenic and mercury from advanced treatment information available in the technical literature, compliance with revised criteria may or may not be possible, depending upon site specific circumstances.
      - Compliance with a HHWQC for arsenic of 0.018 µg/L appears unlikely. Most treatment technology performance information available in the literature is based on drinking water treatment applications targeting a much higher Safe Drinking Water Act (SDWA) maximum contaminant level (MCL) of 10 µg/L.
      - Compliance with a HHWQC for mercury of 0.005 µg/L appears to be potentially attainable on an average basis, but perhaps not if effluent limits are structured on a maximum monthly, maximum weekly or maximum daily basis. Some secondary treatment facilities attain average effluent mercury levels of 0.009 to 0.066 µg/L. Some treatment facilities with effluent filters attain average effluent mercury levels of 0.002 to 0.010 µg/L. Additional

advanced treatment processes are expected to enhance these removal rates, but little mercury performance data is available for a definitive assessment.

  - Little information is available to assess the potential for advanced technologies to comply with revised BAP criteria. A municipal wastewater treatment plant study reported both influent and effluent BAP concentrations less than the HHWQC of 0.0013 ug/L (Ecology, 2010).

  - Some technologies may be effective at treating identified constituents of concern to meet revised limits while others may not. It is therefore even more challenging to identify a technology that can meet all constituent limits simultaneously.
  - A HHWQC that is one order-of-magnitude less stringent could likely be met for mercury and BAP; however, it appears PCB and arsenic limits would not be met.

- Advanced treatment processes incur significant capital and operating costs.
  - Advanced treatment process to remove additional arsenic, BAP, mercury, and PCBs would combine enhancements to secondary treatment with microfiltration membranes and reverse osmosis or granular activated carbon and increase the estimated capital cost of treatment from $17 to $29 in dollars per gallon per day of capacity (based on a 5.0-million-gallon-per-day (mgd) facility).
  - The annual operation and maintenance costs for the advanced treatment process train will be substantially higher (approximately $5 million - $15 million increase for a 5.0 mgd capacity facility) than the current secondary treatment level.
- Implementation of additional treatment will result in additional collateral impacts.
  - High energy consumption.
  - Increased greenhouse gas emissions.
  - Increase in solids production from chemical addition to the primaries. Additionally, the membrane and GAC facilities will capture more solids that require handling.
  - Increased physical space requirements at treatment plant sites for advanced treatment facilities and residuals management including reverse osmosis reject brine processing.
- It appears advanced treatment technology alone cannot meet all revised water quality limits and implementation tools are necessary for discharger compliance.
  - Implementation flexibility will be necessary to reconcile the difference between the capabilities of treatment processes and the potential for HHWQC driven water quality based effluent limits to be lower than attainable with technology

Table ES-1 indicates that the unit NPV cost for baseline conventional secondary treatment ranges from $13 to $28 per gallon per day of treatment capacity. The unit cost for the advanced treatment alternatives increases the range from the low $20s to upper $70s on a per gallon per-day of treatment capacity. The resulting unit cost for improving from secondary treatment to advanced treatment ranges between $15 and $50 per gallon per day of treatment capacity. Unit costs were also evaluated for both a 0.5 and 25 mgd facility. The range of unit costs for improving a 0.5 mgd from secondary to advanced treatment is $60 to $162 per gallon per day of treatment capacity. The range of unit costs for improving a 25 mgd from secondary to advanced treatment is $10 to $35 per gallon per day of treatment capacity.

Table ES-1. Treatment Technology Costs in 2013 Dollars for a 5-mgd Facility

Alternative	Total Construction Cost, 2013 dollars ($ Million)	O&M Net Present Value, 2013 dollars ($ Million)***	Total Net Present Value, 2013 dollars ($ Million)	NPV Unit Cost, 2013 dollars ($/gpd)
Baseline (Conventional Secondary Treatment)*	59 - 127	5 - 11	65 - 138	13 - 28
Incremental Increase to Advanced Treatment - MF/RO	48 - 104	26 - 56	75 - 160	15 - 32
Advanced Treatment - MF/RO**	108 - 231	31 - 67	139 - 298	28 - 60
Incremental Increase to Advanced Treatment - MF/GAC	71 - 153	45 - 97	117 - 250	23 - 50
Advanced Treatment - MF/GAC	131 - 280	50 - 108	181 - 388	36 - 78

* Assumed existing treatment for dischargers. The additional cost to increase the SRT to upwards of 30-days is about $12 - 20 million additional dollars in total project cost for a 5 mgd design flow.

** Assumes zero liquid discharge for RO brine management, followed by evaporation ponds. Other options are available as listed in Section 4.4.2.

*** Does not include the cost for labor.

mgd=million gallons per day
MG=million gallons
MF/RO=membrane filtration/reverse osmosis
MF/GAC=membrane filtration/granulated activated carbon
O&M=operations and maintenance
Net Present Value = total financed cost assuming a 5% nominal discount rate over an assumed 25 year equipment life.

Costs presented above are based on a treatment capacity of 5.0 mgd, however, existing treatment facilities range dramatically across Washington in size and flow treated. The key differences in cost between the baseline and the advanced treatment MF/RO are as follows:

- Larger aeration basins than the baseline to account for the longer SRT (>8 days versus <8 days).
- Additional pumping stations to pass water through the membrane facilities and granulated activated carbon facilities. These are based on peak flows.
- Membrane facilities (equipment, tanks chemical feed facilities, pumping, etc.) and replacement membrane equipment.
- Granulated activated carbon facilities (equipment, contact tanks, pumping, granulated activated carbon media, etc.)
- Additional energy and chemical demand to operate the membrane and granulated activated carbon facilities
- Additional energy to feed and backwash the granulated activated carbon facilities.
- Zero liquid discharge facilities to further concentrate the brine reject.
  - Zero liquid discharge facilities are energy/chemically intensive and they require membrane replacement every few years due to the brine reject water quality.
- Membrane and granulated activated carbon media replacement represent a significant maintenance cost.

- Additional hauling and fees to regenerate granulated activated carbon off-site.

The mass of pollutant removal by implementing advanced treatment was calculated based on reducing current secondary effluent discharges to revised effluent limits for the four pollutants of concern. These results are provided in Table ES-2 as well as a median estimated unit cost basis for the mass of pollutants removed.

Table ES-2. Unit Cost by Contaminant for a 5-mgd Facility Implementing Advanced Treatment using Membrane Filtration/Reverse Osmosis

Component	PCBs	Mercury	Arsenic	BAPs
Required HHWQC based Effluent Quality (µg/L)	0.0000064	0.005	0.018	0.0013
Current Secondary Effluent Concentration (µg/L)	0.002	0.025	7.5	0.006
Total Mass Removed (lbs) over 25 year Period	0.76	7.6	2,800	1.8
Median Estimated Unit Cost (NPV per total mass removed in pounds over 25 years)	$290,000,000	$29,000,000	$77,000	$120,000,000

µg/L=micrograms per liter
lbs=pounds
NPV=net present value

Collateral adverse environmental impacts associated with implementing advanced treatment were evaluated. The key impacts from this evaluation include increased energy use, greenhouse gas production, land requirements and treatment residuals disposal. Operation of advanced treatment technologies could increase electrical energy by a factor of 2.3 to 4.1 over the baseline secondary treatment system. Direct and indirect greenhouse gas emission increases are related to the operation of advanced treatment technologies and electrical power sourcing, with increases of at least 50 to 100 percent above the baseline technology. The energy and air emission implications of advanced treatment employing granulated activated carbon construction of advanced treatment facilities will require additional land area. The availability and cost of land adjacent to existing treatment facilities has not been included in cost estimates, but could be very substantial. It is worthwhile noting residual materials from treatment may potentially be hazardous and their disposal may be challenging to permit. Costs assume zero liquid discharge from the facilities.

1.0 Introduction

Washington's Department of Ecology (Ecology) has an obligation to periodically review waterbody "designated uses" and to modify, as appropriate, water quality standards to ensure those uses are protected. Ecology initiated this regulatory process in 2009 for the human health-based water quality criteria (HHWQC) in Washington's *Surface Water Quality Standards* (Washington Administrative Code [WAC] 173-201A). HHWQC are also commonly referred to as "toxic pollutant water quality standards." Numerous factors will influence Ecology's development of HHWQC. The expectation is that the adopted HHWQC will be more stringent than current adopted criteria. National Pollutant Discharge Elimination System (NPDES) effluent limits for permitted dischargers to surface waters are based on U.S. Environmental Protection Agency (EPA) and state guidance. Effluent limits are determined primarily from reasonable potential analyses and waste load allocations (WLAs) from total maximum daily loads (TMDLs), although the permit writer may use other water quality data. Water quality-based effluent limits are set to be protective of factors, including human health, aquatic uses, and recreational uses. Therefore, HHWQC can serve as a basis for effluent limits. The presumption is that more stringent HHWQC will, in time, drive lower effluent limits. The lower effluent limits will require advanced treatment technologies and will have a consequent financial impact on NPDES permittees. Ecology anticipates that a proposed revision to the water quality standards regulation will be issued in first quarter 2014, with adoption in late 2014.

The Association of Washington Businesses (AWB) is recognized as the state's chamber of commerce, manufacturing and technology association. AWB members, along with the Association of Washington Cities and Washington State Association of Counties (collectively referred to as Study Partners), hold NPDES permits authorizing wastewater discharges. The prospect of more stringent HHWQC, and the resulting needs for advanced treatment technologies to achieve lower effluent discharge limits, has led this consortium to sponsor a study to assess technology availability and capability, capital and operations and maintenance (O&M) costs, pollutant removal effectiveness, and collateral environmental impacts of candidate technologies.

The "base case" for the study began with the identification of four nearly ubiquitous toxic pollutants present in many industrial and municipal wastewater discharges, and the specification of pollutant concentrations in well-treated secondary effluent. The pollutants are arsenic, benzo(a)pyrene (BAP), mercury and polychlorinated biphenyls (PCBs), which were selected for review based on available monitoring data and abundant presence in the environment. The purpose of this study is to review the potential water quality standards and associated treatment technologies able to meet those standards for four pollutants.

A general wastewater treatment process and wastewater characteristics were used as the common baseline for comparison with all of the potential future treatment technologies considered. An existing secondary treatment process with disinfection at a flow of 5 million gallons per day (mgd) was used to represent existing conditions. Typical effluent biochemical oxygen demand (BOD) and total suspended solids (TSS) were assumed between 10 and 30 milligrams per liter (mg/L) for such a facility and no designed nutrient or toxics removal was assumed for the baseline existing treatment process.

Following a literature review of technologies, two advanced treatment process options for toxics removal were selected for further evaluation based on the characterization of removal effectiveness from the technical literature review and Study Partners' preferences. The two tertiary treatment options are microfiltration membrane filtration (MF) followed by either reverse osmosis (RO) or granular activated carbon (GAC) as an addition to an existing secondary treatment facility.

The advanced treatment technologies are evaluated for their efficacy and cost to achieve the effluent limitations implied by the more stringent HHWQC. Various sensitivities are examined, including for less stringent adopted HHWQC, and for a size range of treatment systems. Collateral environmental impacts associated with the operation of advanced technologies are also qualitatively described.

2.0 Derivation of the Baseline Study Conditions and Rationale for Selection of Effluent Limitations

2.1 Summary of Water Quality Criteria

Surface water quality standards for toxics in the State of Washington are being updated based on revised human fish consumption rates (FCRs). The revised water quality standards could drive very low effluent limitations for industrial and municipal wastewater dischargers. Four pollutants were selected for study based on available monitoring data and abundant presence in the environment. The four toxic constituents are arsenic, BAP, mercury, and PCBs.

2.2 Background

Ecology is in the process of updating the HHWQC in the state water quality standards regulation. Toxics include metals, pesticides, and organic compounds. The human health criteria for toxics are intended to protect people who consume water, fish, and shellfish. FCRs are an important factor in the derivation of water quality criteria for toxics.

The AWB/City/County consortium (hereafter "Study Partners") has selected four pollutants for which more stringent HHWQC are expected to be promulgated. The Study Partners recognize that Ecology probably will not adopt more stringent arsenic HHWQC so the evaluation here is based on the current arsenic HHWQC imposed by the National Toxics Rule. Available monitoring information indicates these pollutants are ubiquitous in the environment and are expected to be present in many NPDES discharges. The four pollutants include the following:

- Arsenic
    - Elemental metalloid that occurs naturally and enters the environment through erosion processes. Also widely used in batteries, pesticides, wood preservatives, and semiconductors. Other current uses and legacy sources in fungicides/herbicides, copper smelting, paints/dyes, and personal care products.
- Benzo(a)pyrene (BAP)
    - Benzo(a)pyrene is a polycyclic aromatic hydrocarbon formed by a benzene ring fused to pyrene as the result of incomplete combustion. Its metabolites are highly carcinogenic. Sources include wood burning, coal tar, automobile exhaust, cigarette smoke, and char-broiled food.
- Mercury
    - Naturally occurring element with wide legacy uses in thermometers, electrical switches, fluorescent lamps, and dental amalgam. Also enters the environment through erosion processes, combustion (especially coal), and legacy industrial/commercial uses. Methylmercury is an organometallic that is a bioaccumulative toxic. In aquatic systems, an anaerobic methylation process converts inorganic mercury to methylmercury.
- Polychlorinated Biphenyls (PCBs)
    - Persistent organic compounds historically used as a dielectric and coolant in electrical equipment and banned from production in the U.S. in 1979. Available information indicates continued pollutant loadings to the environment as a byproduct from the use of some pigments, paints, caulking, motor oil, and coal combustion.

2.3 Assumptions Supporting Selected Ambient Water Quality Criteria and Effluent Limitations

Clean Water Act regulations require NPDES permittees to demonstrate their discharge will "not cause or contribute to a violation of water quality criteria." If a "reasonable potential analysis" reveals the possibility of a standards violation, the permitting authority is obliged to develop "water quality-based effluent limits" to ensure standards achievement. In addition, if ambient water quality monitoring or fish tissue assessments reveal toxic pollutant concentrations above HHWQC levels, Ecology is required to identify that impairment ("303(d) listing") and develop corrective action plans to force reduction in the toxic pollutant discharge or loading of the pollutant into the impaired water body segment. These plans, referred to as total maximum daily loads (TMDLs) or water cleanup plans, establish discharge allocations and are implemented for point discharge sources through NPDES permit effluent limits and other conditions.

The effect of more stringent HHWQC will intuitively result in more NPDES permittees "causing or contributing" to a water quality standards exceedance, and/or more waterbodies being determined to be impaired, thus requiring 303(d) listing, the development of TMDL/water cleanup plans, and more stringent effluent limitations to NPDES permittees whose treated wastewater contains the listed toxic pollutant.

The study design necessarily required certain assumptions to create a "baseline effluent scenario" against which the evaluation of advanced treatment technologies could occur. The Study Partners and HDR Engineering, Inc (HDR) developed the scenario. Details of the baseline effluent scenario are presented in Table 1. The essential assumptions and rationale for selection are presented below:

- Ecology has indicated proposed HHWQC revisions will be provided in first quarter 2014. A Study Partners objective was to gain an early view on the treatment technology and cost implications. Ecology typically allows 30 or 45 days for the submission of public comments on proposed regulations. To wait for the proposed HHWQC revisions would not allow sufficient time to complete a timely technology/cost evaluation and then to share the study results in the timeframe allowed for public involvement/public comments.
- Coincident with the issuance of the proposed regulation, Ecology has a statutory obligation to provide a Significant Legislative Rule evaluation, one element of which is a "determination whether the probable benefits of the rule are greater than its probable costs, taking into account both the qualitative and quantitative benefits and costs and the specific directives of the statute being implemented" (RCW 34.05.328(1)(d)). A statutory requirement also exists to assess the impact of the proposed regulation to small businesses. The implication is that Ecology will be conducting these economic evaluations in fourth quarter 2013 and early 2014. The Study Partners wanted to have a completed technology/cost study available to share with Ecology for their significant legislative rule/small business evaluations.
- The EPA, Indian tribes located in Washington, and various special interest groups have promoted the recently promulgated state of Oregon HHWQC (2011) as the "model" for Washington's revisions of HHWQC. The Oregon HHWQC are generally based on a increased FCR of 175 grams per day (g/day) and an excess cancer risk of 10^{-6}. While the Study Partners do not concede the wisdom or appropriateness of the Oregon criteria, or the selection of scientific/technical elements used to derive those criteria, the Study Partners nevertheless have selected the Oregon HHWQC as a viable "starting point" upon which this study could be based.

- The scenario assumes generally that Oregon's HHWQC for ambient waters will, for some parameters in fact, become effluent limitations for Washington NPDES permittees. The reasoning for this important assumption includes:
  - The state of Washington's NPDES permitting program is bound by the *Friends of Pinto Creek vs. EPA* decision in the United States Court of Appeals for the Ninth Circuit (October 4, 2007). This decision held that no NPDES permits authorizing new or expanded discharges of a pollutant into a waterbody identified as impaired; i.e., listed on CWA section 303(d), for that pollutant, may be issued until such time as "existing dischargers" into the waterbody are "subject to compliance schedules designed to bring the (waterbody) into compliance with applicable water quality standards." In essence, any new/expanded discharge of a pollutant causing impairment must achieve the HHWQC at the point of discharge into the waterbody.
  - If a waterbody segment is identified as "impaired" (i.e., not achieving a HHWQC), then Ecology will eventually need to produce a TMDL or water cleanup plan. For an existing NPDES permittee with a discharge of the pollutant for which the receiving water is impaired, the logical assumption is that any waste load allocation granted to the discharger will be at or lower than the numeric HHWQC (to facilitate recovery of the waterbody to HHWQC attainment). As a practical matter, this equates to an effluent limit established at the HHWQC.
  - Acceptance of Oregon HHWQC as the baseline for technology/cost review also means acceptance of practical implementation tools used by Oregon. The HHWQC for mercury is presented as a fish tissue methyl mercury concentration. For the purposes of NPDES permitting, however, Oregon has developed an implementation management directive which states that any confirmed detection of mercury is considered to represent a "reasonable potential" to cause or contribute to a water quality standards violation of the methyl mercury criteria. The minimum quantification level for total mercury is presented as 0.005 micrograms per liter (µg/L) (5.0 nanograms per liter (ng/L)).
  - The assumed effluent limit for arsenic is taken from EPA's *National Recommended Water Quality Criteria* (2012) (inorganic, water and organisms, 10^{-6} excess cancer risk). Oregon's 2011 criterion is actually based on a less protective excess cancer risk (10^{-4}). This, however, is the result of a state-specific risk management choice and it is unclear if Washington's Department of Ecology would mimic the Oregon approach.
  - The assumption is that no mixing zone is granted such that HHWQC will effectively serve as NPDES permit effluent limits. Prior discussion on the impact of the Pinto Creek decision, 303(d) impairment and TMDL Waste Load Allocations processes, all lend support to this "no mixing zone" condition for the parameters evaluated in this study.
- Consistent with Ecology practice in the evaluation of proposed regulations, the HHWQC are assumed to be in effect for a 20-year period. It is assumed that analytical measurement technology and capability will continue to improve over this time frame and this will result in the detection and lower quantification of additional HHWQC in ambient water and NPDES dischargers. This knowledge will trigger the Pinto Creek/303(d)/TMDL issues identified above and tend to pressure NPDES permittees to evaluate and install advanced treatment technologies. The costs and efficacy of treatment for these additional HHWQC is unknown at this time.

Other elements of the Study Partners work scope, as presented to HDR, must be noted:

- The selection of four toxic pollutants and development of a baseline effluent scenario is not meant to imply that each NPDES permittee wastewater discharge will include those pollutants at the assumed concentrations. Rather, the scenario was intended to represent a composite of many NPDES permittees and to facilitate evaluation of advanced treatment technologies relying on mechanical, biological, physical, chemical processes.
- The scalability of advanced treatment technologies to wastewater treatment systems with different flow capacities, and the resulting unit costs for capital and O&M, is evaluated.
- Similarly, a sensitivity analysis on the unit costs for capital and O&M was evaluated on the assumption the adopted HHWQC (and effectively, NPDES effluent limits) are one order-of-magnitude less stringent than the Table 1 values.

Table 1: Summary of Effluent Discharge Toxics Limits

Constituent	Human Health Criteria based Limits to be met with no Mixing Zone (µg/L)	Basis for Criteria	Typical Concentration in Municipal Secondary Effluent (µg/L)	Typical Concentration in Industrial Secondary Effluent (µg/L)	Existing Washington HHC (water + org.), NTR (µg/L)
PCBs	0.0000064	Oregon Table 40 Criterion (water + organisms) at FCR of 175 grams/day	0.0005 to 0.0025[b,c,d,e,f]	0.002 to 0.005[i]	0.0017
Mercury	0.005	DEQ IMD[a]	0.003 to 0.050[h]	0.010 to 0.050[h]	0.140
Arsenic	0.018	EPA National Toxics Rule (water + organisms)[k]	0.500 to 5.0[j]	10 to 40[j]	0.018
Benzo(a)Pyrene	0.0013	Oregon Table 40 Criterion (water + organisms) at FCR of 175 grams/day	0.00028 to 0.006[b,g]	0.006 to1.9	0.0028

[a] Oregon Department of Environmental Quality (ODEQ). Internal Management Directive: Implementation of Methylmercury Criterion in NPDES Permits. January 8, 2013.
[b] Control of Toxic Chemicals in Puget Sound, Summary Technical Report for Phase 3: Loadings from POTW Discharge of Treated Wastewater, Washington Department of Ecology, Publication Number 10-10-057, December 2010.
[c] Spokane River PCB Source Assessment 2003-2007, Washington Department of Ecology, Publication No. 11-03-013, April 2011.
[d] Lower Okanogan River Basin DDT and PCBs Total Maximum Daily Load, Submittal Report, Washington Department of Ecology, Publication Number 04-10-043, October 2004.
[e] Palouse River Watershed PCB and Dieldrin Monitoring, 2007-2008, Wastewater Treatment Plants and Abandoned Landfills, Washington Department of Ecology, Publication No. 09-03-004, January 2009
[f] A Total Maximum Daily Load Evaluation for Chlorinated Pesticides and PCBs in the Walla Walla River, Washington Department of Ecology, Publication No. 04-03-032, October 2004.
[g] Removal of Polycyclic Aromatic Hydrocarbons and Heterocyclic Nitrogenous Compounds by A POTW Receiving Industrial Discharges, Melcer, H., Steel, P. and Bedford, W.K., Water Environment Federation, 66th Annual Conference and Exposition, October 1993.
[h] Data provided by Lincoln Loehr's summary of WDOE Puget Sound Loading data in emails from July 19, 2013.
[i] NCASI memo from Larry Lefleur, NCASI, to Llewellyn Matthews, NWPPA, revised June 17, 2011, summarizing available PCB monitoring data results from various sources.
[j] Professional judgment, discussed in August 6, 2013 team call.
[k] The applicable Washington Human Health Criteria cross-reference the EPA National Toxics Rule, 40 CFR 131.36. The EPA arsenic HHC is 0.018 ug/L for water and organisms.

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3.0 Wastewater Characterization Description

This section describes the wastewater treatment discharge considered in this technology evaluation. Treated wastewater characteristics are described, including average and peak flow, effluent concentrations, and toxic compounds of concern.

3.1 Summary of Wastewater Characterization

A general wastewater treatment process and wastewater characteristics were developed as the common baseline to represent the existing conditions as a starting point for comparison with potential future advanced treatment technologies and improvements. A secondary treatment process with disinfection at a flow of 5 mgd as the current, baseline treatment system for existing dischargers was also developed. Typical effluent biochemical oxygen demand (BOD) and total suspended solids (TSS) were assumed between 10 to 30 mg/L from such a facility and no nutrient or toxics removal was assumed to be accomplished in the existing baseline treatment process.

3.2 Existing Wastewater Treatment Facility

The first step in the process is to characterize the existing wastewater treatment plant to be evaluated in this study. The goal is to identify the necessary technology that would need to be added to an existing treatment facility to comply with revised toxic pollutant effluent limits. Rather than evaluating the technologies and costs to upgrade multiple actual operating facilities, the Study Partners specified that a generalized municipal/industrial wastewater treatment facility would be characterized and used as the basis for developing toxic removal approaches. General characteristics of the facility's discharge are described in Table 2.

Table 2. General Wastewater Treatment Facility Characteristics

Average Annual Wastewater Flow, mgd	Maximum Month Wastewater Flow, mgd	Peak Hourly Wastewater Flow, mgd	Effluent BOD, mg/L	Effluent TSS, mg/L
5.0	6.25	15.0	10 to 30	10 to 30

mgd=million gallons per day
mg/L=milligrams per liter
BOD=biochemical oxygen demand
TSS=total suspended solids

In the development of the advanced treatment technologies presented below, the capacity of major treatment elements are generally sized to accommodate the maximum month average wastewater flow. Hydraulic elements, such as pumps and pipelines, were selected to accommodate the peak hourly wastewater flow.

The general treatment facility incorporates a baseline treatment processes including influent screening, grit removal, primary sedimentation, suspended growth biological treatment (activated sludge), secondary clarification, and disinfection using chlorine. Solids removed during primary treatment and secondary clarification are assumed to be thickened, stabilized, dewatered, and land applied to agricultural land. The biological treatment process is assumed to be activated sludge with a relatively short (less than 10-day) solids retention time. The baseline secondary treatment facility is assumed not to have processes dedicated to removing nutrients or toxics. However, some coincident removal of toxics will occur during conventional treatment.

3.3 Toxic Constituents

As described in Section 2.3, the expectation of more stringent HHWQC will eventually trigger regulatory demands for NPDES permittees to install advanced treatment technologies. The Study Group and HDR selected four specific toxic pollutants reflecting a range of toxic constituents as the basis for this study to limit the constituents and technologies to be evaluated to a manageable level.

The four toxic pollutants selected were PCBs, mercury, arsenic, and BAP, a polycyclic aromatic hydrocarbon (PAH). Mercury and arsenic are metals, and PCBs and PAHs are organic compounds. Technologies for removing metals and organic compounds are in some cases different. Key information on each of the compounds, including a description of the constituent, the significance of each constituent, proposed HHWQC, basis for the proposed criteria, typical concentration in both municipal and industrial secondary effluent, and current Washington state water quality criteria, are shown in Table 1. It is assumed that compliance with the proposed criteria in the table would need to be achieved at the “end of pipe” and Ecology would not permit a mixing zone for toxic constituents. This represents a “worst–case,” but a plausible assumption about discharge conditions.

4.0 Treatment Approaches and Costs

4.1 Summary of Treatment Approach and Costs

Two advanced treatment process options for toxics removal for further evaluation based on the characterization of removal effectiveness from the technical literature review and Study Group preferences. The two tertiary treatment options are microfiltration MF followed by either RO or GAC as an addition to an existing secondary treatment facility. Based on the literature review, it is not anticipated that any of the treatment options will be effective in reducing all of the selected pollutants to below the anticipated water quality criteria. A summary of the capital and operations and maintenance costs for tertiary treatment is provided, as well as a comparison of the adverse environmental impacts for each alternative.

4.2 Constituent Removal – Literature Review

The evaluation of treatment technologies relevant to the constituents of concern was initiated with a literature review. The literature review included a desktop search using typical web-based search engines, and search engines dedicated to technical and research journal databases. At the same time, HDR's experience with the performance of existing treatment technologies specifically related to the four constituents of concern, was used in evaluating candidate technologies. A summary of the constituents of concern and relevant treatment technologies is provided in the following literature review section.

4.2.1 Polychlorinated Biphenyls

PCBs are persistent organic pollutants that can be difficult to remove in treatment. PCB treatment in wastewater can be achieved using oxidation with peroxide, filtration, biological treatment or a combination of these technologies. There is limited information available about achieving ultra-low effluent PCB concentrations near the 0.0000064 µg/L range under consideration in the proposed rulemaking process. This review provides a summary of treatment technology options and anticipated effluent PCB concentrations.

Research on the effectiveness of ultraviolet (UV) light and peroxide on removing PCBs was tested in bench scale batch reactions (Yu, Macawile, Abella, & Gallardo 2011). The combination of UV and peroxide treatment achieved PCB removal greater than 89 percent, and in several cases exceeding 98 percent removal. The influent PCB concentration for the batch tests ranged from 50 to 100 micrograms per liter (µg/L). The final PCB concentration (for the one congener tested) was <10 µg/L (10,000 ng/L) for all tests and <5 µg/L (5,000 ng/L) for some tests. The lowest PCB concentrations in the effluent occurred at higher UV and peroxide doses.

Pilot testing was performed to determine the effectiveness of conventional activated sludge and a membrane bioreactor to remove PCBs (Bolzonella, Fatone, Pavan, & Cecchi 2010). EPA Method 1668 was used for the PCB analysis (detection limit of 0.01 ng/L per congener). Influent to the pilot system was a combination of municipal and industrial effluent. The detailed analysis was for several individual congeners. Limited testing using the Aroclor method (total PCBs) was used to compare the individual congeners and the total concentration of PCBs. Both conventional activated sludge and membrane bioreactor (MBR) systems removed PCBs. The effluent MBR concentrations ranged from <0.01 ng/L to 0.04 ng/L compared to <0.01 ng/L to 0.88 ng/L for conventional activated sludge. The pilot testing showed that increased solids retention time (SRT) and higher mixed liquor suspended solids concentrations in the MBR system led to increased removal in the liquid stream.

Bench scale studies were completed to test the effectiveness of GAC and biological activated carbon (BAC) for removing PCBs (Ghosh, Weber, Jensen, & Smith 1999). The effluent from the

GAC system was 800 ng/L. The biological film in the BAC system was presumed to support higher PCB removal with effluent concentrations of 200 ng/L. High suspended sediment in the GAC influent can affect performance. It is recommended that filtration be installed upstream of a GAC system to reduce solids and improve effectiveness.

Based on limited available data, it appears that existing municipal secondary treatment facilities in Washington state are able to reduce effluent PCBs to the range approximately 0.10 to 1.5 ng/L. It appears that the best performing existing municipal treatment facility in Washington state with a microfiltration membrane is able to reduce effluent PCBs to the range approximately 0.00019 to 0.00063 µg/L. This is based on a very limited data set and laboratory blanks covered a range that overlapped with the effluent results (blanks 0.000058 to 0.00061 µg/L).

Addition of advanced treatment processes would be expected to enhance PCB removal rates, but the technical literature does not appear to provide definitive information for guidance. A range of expected enhanced removal rates might be assumed to vary widely from level of the reference microfiltration facility of 0.19 to 0.63 ng/L.

Summary of PCB Technologies

The literature review revealed there are viable technologies available to reduce PCBs **but no research was identified with treatment technologies capable of meeting the anticipated human health criteria based limits for PCB removal**. Based on this review, a tertiary process was selected to biologically reduce PCBs and separate the solids using tertiary filtration. Alternately, GAC was investigated as an option to reduce PCBs, although it is not proven that it will meet revised effluent limits.

4.2.2 Mercury

Mercury removal from wastewater can be achieved using precipitation, adsorption, filtration, or a combination of these technologies. There is limited information available about achieving ultra-low effluent mercury concentrations near the 5 ng/L range under consideration in the proposed rulemaking process. This review provides a summary of treatment technology options and anticipated effluent mercury concentrations.

Precipitation (and co-precipitation) involves chemical addition to form a particulate and solids separation, using sedimentation or filtration. Precipitation includes the addition of a chemical precipitant and pH adjustment to optimize the precipitation reaction. Chemicals can include metal salts (ferric chloride, ferric sulfate, ferric hydroxide, or alum), pH adjustment, lime softening, or sulfide. A common precipitant for mercury removal is sulfide, with an optimal pH between 7 and 9. The dissolved mercury is precipitated with the sulfide to form an insoluble mercury sulfide that can be removed through clarification or filtration. One disadvantage of precipitation is the generation of a mercury-laden sludge that will require dewatering and disposal. The mercury sludge may be considered a hazardous waste and require additional treatment and disposal at a hazardous waste site. The presence of other compounds, such as other metals, may reduce the effectiveness of mercury precipitation/co-precipitation. For low-level mercury treatment requirements, several treatment steps will likely be required in pursuit of very low effluent targets.

EPA compiled a summary of facilities that are using precipitation/co-precipitation for mercury treatment (EPA 2007). Three of the full-scale facilities were pumping and treating groundwater and the remaining eight facilities were full-scale wastewater treatment plants. One of the pump and treat systems used precipitation, carbon adsorption, and pH adjustment to treat groundwater to effluent concentrations of 300 ng/L.

Adsorption treatment can be used to remove inorganic mercury from water. While adsorption can be used as a primary treatment step, it is frequently used for polishing after a preliminary treatment step (EPA 2007). One disadvantage of adsorption treatment is that when the adsorbent is saturated, it either needs to be regenerated or disposed of and replaced with new adsorbent. A common adsorbent is GAC. There are several patented and proprietary adsorbents on the market for mercury removal. Adsorption effectiveness can be affected by water quality characteristics, including high solids and bacterial growth, which can cause media blinding. A constant and low flow rate to the adsorption beds increases effectiveness (EPA 2007). The optimal pH for mercury adsorption on GAC is pH 4 to 5; therefore, pH adjustment may be required.

EPA compiled a summary of facilities that are using adsorption for mercury treatment (EPA 2007). Some of the facilities use precipitation and adsorption as described above. The six summarized facilities included two groundwater treatment and four wastewater treatment facilities. The reported effluent mercury concentrations were all less than 2,000 ng/L (EPA 2007).

Membrane filtration can be used in combination with a preceding treatment step. The upstream treatment is required to precipitate soluble mercury to a particulate form that can be removed through filtration. According to the EPA summary report, ultrafiltration is used to remove high-molecular weigh contaminants and solids (EPA 2007). The treatment effectiveness can depend on the source water quality since many constituents can cause membrane fouling, decreasing the effectiveness of the filters. One case study summarized in the EPA report showed that treatment of waste from a hazardous waste combustor treated with precipitation, sedimentation, and filtration achieved effluent mercury concentrations less than the detection limit of 200 ng/L.

Bench-scale research performed at the Oak Ridge Y-12 Plant in Tennessee evaluated the effectiveness of various adsorbents for removing mercury to below the NPDES limit of 12 ng/L and the potential revised limit of 51 ng/L (Hollerman et al. 1999). Several proprietary adsorbents were tested, including carbon, polyacrylate, polystyrene, and polymer adsorption materials. The adsorbents with thiol-based active sites were the most effective. Some of the adsorbents were able to achieve effluent concentrations less than 51 ng/L but none of the adsorbents achieved effluent concentrations less than 12 ng/L.

Bench-scale and pilot-scale testing performed on refinery wastewater was completed to determine treatment technology effectiveness for meeting very low mercury levels (Urgun-Demirtas, Benda, Gillenwater, Negri, Xiong & Snyder 2012) (Urgun-Demirtas, Negri, Gillenwater, Agwu Nnanna & Yu 2013). The Great Lakes Initiative water quality criterion for mercury is less than 1.3 ng/L for municipal and industrial wastewater plants in the Great Lakes region. This research included an initial bench scale test including membrane filtration, ultrafiltration, nanofiltration, and reverse osmosis to meet the mercury water quality criterion. The nanofiltration and reverse osmosis required increased pressures for filtration and resulted in increased mercury concentrations in the permeate. Based on this information and the cost difference between the filtration technologies, a pilot-scale test was performed. The 0.04 um PVDF GE ZeeWeed 500 series membranes were tested. The 1.3 ng/L water quality criterion was met under all pilot study operating conditions. The mercury in the refinery effluent was predominantly in particulate form which was well-suited for removal using membrane filtration.

Based on available data, it appears that existing municipal treatment facilities are capable of reducing effluent mercury to near the range of the proposed HHWQC on an average basis. Average effluent mercury in the range of 1.2 to 6.6 ng/L for existing facilities with secondary treatment and enhanced treatment with cloth filters and membranes. The Spokane County plant data range is an average of 1.2 ng/L to a maximum day of 3 ng/L. Addition of advanced treatment processes such as GAC or RO would be expected to enhance removal rates. Data from the West Basin treatment facility in California suggests that at a detection limit of 7.99 ng/L mercury is not detected in the effluent from this advanced process train. A range of expected enhanced removal rates from the advanced treatment process trains might be expected to ranged from meeting the proposed standard at 5 ng/L to lower concentrations represented by the Spokane County performance level (membrane filtration) in the range of 1 to 3 ng/L, to perhaps even lower levels with additional treatment. For municipal plants in Washington, this would suggest that effluent mercury values from the two advanced treatment process alternatives might range from 1 to 5 ng/L (0.001 to 0.005 µg/L) and perhaps substantially better, depending upon RO and GAC removals. It is important to note that industrial plants may have higher existing mercury levels and thus the effluent quality that is achievable at an industrial facility would be of lower quality.

Summary of Mercury Technologies

The literature search revealed limited research on mercury removal technologies at the revised effluent limit of 0.005 µg/L. Tertiary filtration with membrane filters or reverse osmosis showed the best ability to achieve effluent criteria less than 0.005 µg/L.

4.2.3 Arsenic

A variety of treatment technologies can be applied to capture arsenic (Table 3). Most of the information in the technical literature and from the treatment technology vendors is focused on potable water treatment for compliance with a Safe Drinking Water Act (SDWA) maximum contaminant level (MCL) of 10 µg/L. The most commonly used arsenic removal method for a wastewater application (tertiary treatment) is coagulation/ flocculation plus filtration. This method by itself could remove more than 90 to 95 percent of arsenic. Additional post-treatment through adsorption, ion exchange, or reverse osmosis is required for ultra-low arsenic limits in the 0.018 µg/L range under consideration in the proposed rulemaking process. In each case it is recommended to perform pilot-testing of each selected technology.

Table 3: Summary of Arsenic Removal Technologies[1]

Technology	Advantages	Disadvantages
Coagulation/filtration	• Simple, proven technology • Widely accepted • Moderate operator training	• pH sensitive • Potential disposal issues of backwash waste • As^{+3} and As^{+5} must be fully oxidized
Lime softening	• High level arsenic treatment • Simple operation change for existing lime softening facilities	• pH sensitive (requires post treatment adjustment) • Requires filtration • Significant sludge operation
Adsorptive media	• High As^{+5} selectivity • Effectively treats water with high total dissolved solids (TDS)	• Highly pH sensitive • Hazardous chemical use in media regeneration • High concentration SeO_4^{-2}, F^-, Cl^-, and SO_4^{-2} may limit arsenic removal

Table 3: Summary of Arsenic Removal Technologies[1]

Technology	Advantages	Disadvantages
Ion exchange	• Low contact times • Removal of multiple anions, including arsenic, chromium, and uranium	• Requires removal of iron, manganese, sulfides, etc. to prevent fouling • Brine waste disposal
Membrane filtration	• High arsenic removal efficiency • Removal of multiple contaminants	• Reject water disposal • Poor production efficiency • Requires pretreatment

[1]Adapted from WesTech

The removal of arsenic in activated sludge is minimal (less than 20 percent) (Andrianisa et al. 2006), but biological treatment can control arsenic speciation. During aerobic biological process As (III) is oxidized to As (V). Coagulation/flocculation/filtration removal, as well as adsorption removal methods, are more effective in removal of As(V) vs. As (III). A combination of activated sludge and post-activated sludge precipitation with ferric chloride (addition to MLSS and effluent) results in a removal efficiency of greater than 95 percent. This combination could decrease As levels from 200 µg/L to less than 5 µg/L (5,000 ng/L) (Andrianisa et al. 2008) compared to the 0.018 µg/L range under consideration in the proposed rulemaking process.

Data from the West Basin facility (using MF/RO/AOP) suggests effluent performance in the range of 0.1 to 0.2 µg/L, but it could also be lower since a detection limit used there of 0.15 µg/l is an order of magnitude higher than the proposed HHWQC. A range of expected enhanced removal rates might be assumed to equivalent to that achieved at West Basin in 0.1 to 0.2 µg/L range.

Review of Specific Technologies for Arsenic Removal

Coagulation plus Settling or Filtration

Coagulation may remove more than 95 percent of arsenic through the creation of particulate metal hydroxides. Ferric sulfite is typically more efficient and applicable to most wastewater sources compared to alum. The applicability and extent of removal should be pilot-tested, since removal efficiency is highly dependent on the water constituents and water characteristics (i.e., pH, temperature, solids).

Filtration can be added after or instead of settling to increase arsenic removal. Example treatment trains with filtration are shown in Figures 1 and 2, respectively.

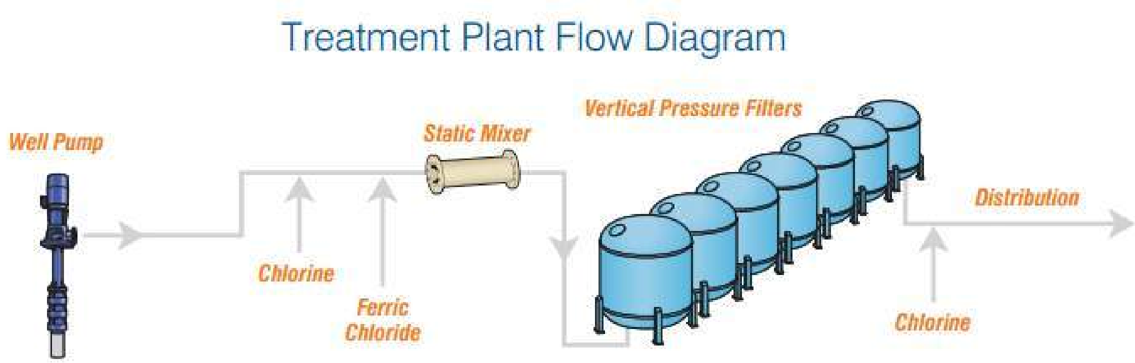

Figure 1. Water Treatment Configuration for Arsenic Removal (WesTech)

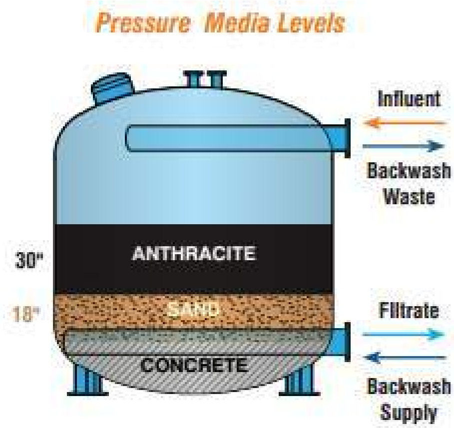

Figure 2. WesTech Pressure Filters for Arsenic Removal

One system for treatment of potable water with high levels of arsenic in Colorado (110 parts per million [ppm]) consists of enhanced coagulation followed by granular media pressure filters that include anthracite/silica sand/garnet media (WesTech). The arsenic levels were reduced to less than the drinking water MCL, which is 10 µg/L (10,000 ng/L). The plant achieves treatment by reducing the pH of the raw water to 6.8 using sulfuric acid, and then adding approximately 12 to 14 mg/L ferric sulfate. The water is filtered through 16 deep bed vertical pressure filters, the pH is elevated with hydrated lime and is subsequently chlorinated and fed into the distribution system.
(http://www.westechinc.com/public/uploads/global/2011/3/Fallon%20NV%20Installation%20ReportPressureFilter.pdf).

Softening (with lime)

Removes up to 90 percent arsenic through co-precipitation, but requires pH to be higher than 10.2.

Adsorption processes

Activated alumina is considered an adsorptive media, although the chemical reaction is an exchange of arsenic ions with the surface hydroxides on the alumina. When all the surface hydroxides on the alumina have been exchanged, the media must be regenerated. Regeneration consists of backwashing, followed by sodium hydroxide, flushing with water and neutralization with a strong acid. Effective arsenic removal requires sufficient empty bed contact time. Removal efficiency can also be impacted by the water pH, with neutral or slightly acidic conditions being considered optimum. If As (III) is present, it is generally advisable to increase empty bed contact time, as As (III) is adsorbed more slowly than As (V). Alumina dissolves slowly over time due to contact with the chemicals used for regeneration. As a result, the media bed is likely to become compacted if it is not backwashed periodically.

Granular ferric hydroxide works by adsorption, but when the media is spent it cannot be regenerated and must be replaced. The life of the media depends upon pH of the raw water, the concentrations of arsenic and heavy metals, and the volume of water treated daily. Periodic backwashing is required to prevent the media bed from becoming compacted and pH may need to be adjusted if it is high, in order to extend media life. For maximum arsenic removal, filters operate in series. For less stringent removal, filters can operate in parallel.

One type of adsorption media has been developed for application to non-drinking water processes for arsenic, phosphate and for heavy metals removal by sorption (Severent Trent Bayoxide® E IN-20). This granular ferric oxide media has been used for arsenic removal from mining and industrial wastewaters, selenium removal from refinery wastes and for phosphate polishing of municipal wastewaters. Valley Vista drinking water treatment with Bayoxide® E IN-20 media achieves removal from 31-39 µg/L (31,000-39,000 ng/L) to below 10 µg/L MCL (http://www.severntrentservices.com/News/Successful_Drinking_Water_Treatment_in_an_Arsenic__Hot_Spot__nwMFT_452.aspx).

Another adsorptive filter media is greensand. Greensand is available in two forms: as glauconite with manganese dioxide bound ionically to the granules and as silica sand with manganese dioxide fused to the granules. Both forms operate in pressure filters and both are effective. Greensand with the silica sand core operates at higher water temperatures and higher differential pressures than does greensand with the glauconite core. Arsenic removal requires a minimum concentration of iron. If a sufficient concentration of iron is not present in the raw water, ferric chloride is added.

WesTech filters with greensand and permanganate addition for drinking water systems can reduce As from 15-25 µg/L to non-detect. Sodium hypochlorite and/or potassium permanganate are added to the raw water prior to the filters. Chemical addition may be done continuously or intermittently, depending on raw water characteristics. These chemicals oxidize the iron in the raw water and also maintain the active properties of the greensand itself. Arsenic removal is via co-precipitation with the iron.

Ion Exchange

Siemens offers a potable ion exchange (PIX) arsenic water filtration system. PIX uses ion exchange resin canisters for the removal of organic and inorganic contaminants, in surface and groundwater sources to meet drinking water standards.

Filtronics also uses ion exchange to treat arsenic. The technology allows removal for below the SWDA MCL for potable water of 10 µg/L (10,000 ng/L).

Reverse osmosis

Arsenic is effectively removed by RO when it is in oxidative state As(V) to approximately 1,000 ng/L or less (Ning 2002).

Summary of Arsenic Technologies

The current state of the technology for arsenic removal is at the point where all the processes target the SWDA MCL for arsenic in potable water. Current EPA maximum concentration level for drinking water is 10 ug/l; much higher than 0.0018 µg/L target for arsenic in this study. The majority of the methods discussed above are able to remove arsenic to either EPA maximum contaminant level or to the level of detection. The lowest detection limit of one of the EPA approved methods of arsenic measurements is 20 ng/l (0.020 µg/l) (Grosser, 2010), which is comparable to the 0.018 µg/L limit targeted in this study.

4.2.1 Polycyclic Aromatic Hydrocarbons

BAP During Biological Treatment

During wastewater treatment process, BAP tends to partition into sludge organic matter (Melcer et al. 1993). Primary and secondary processing could remove up to 60 percent of incoming PAHs and BAP in particular, mostly due to adsorption to sludge (Kindaichi et al., NA, Wayne et al. 2009). Biodegradation of BAP is expected to be very low since there are more than five benzene rings which are resistant to biological degradation. Biosurfactant addition to biological process could partially improve biodegradation, but only up to removal rates of 50 percent (Sponza et al. 2010). Existing data from municipal treatment facilities in Washington state have influent and effluent concentrations of BAP of approximately 0.30 ng/L indicating that current secondary treatment has limited effectiveness at BAP removal.

Methods to Enhance Biological Treatment of BAP

Ozonation prior to biological treatment could potentially improve biodegradability of BAP (Zeng et al. 2000). In the case of soil remediation, ozonation before biotreatment improved biodegradation by 70 percent (Russo et al. 2012). The overall removal of BAP increased from 23 to 91 percent after exposure of water to 0.5 mg/L ozone for 30 minutes during the simultaneous treatment process and further to 100 percent following exposure to 2.5 mg/L ozone for 60 minutes during the sequential treatment mode (Yerushalmi et al. 2006). In general, to improve biodegradability of BAP, long exposure to ozone might be required (Haapea et al. 2006).

Sonication pre-treatment or electronic beam irradiation before biological treatment might also make PAHs more bioavailable for biological degradation..

Recent studies reported that a MBR is capable of removing PAHs from wastewater (Rodrigue and Reilly 2009; Gonzaleza et al. 2012). None of the studies listed the specific PAHs constituents removed.

Removal of BAP from Drinking Water

Activated Carbon

Since BAP has an affinity to particulate matter, it is removed from the drinking water sources by means of adsorption, such as granular activated carbon (EPA). Similarly, Oleszczuk et al. (2012) showed that addition of 5 percent activated carbon could remove 90 percent of PAHs from the wastewater.

Reverse Osmosis

Light (1981) (referenced by Williams, 2003) studied dilute solutions of PAHs, aromatic amines, and nitrosamines and found rejections of these compounds in reverse osmosis to be over 99 percent for polyamide membranes. Bhattacharyya et al. (1987) (referenced by Williams, 2003) investigated rejection and flux characteristics of FT30 membranes for separating various pollutants (PAHs, chlorophenols, nitrophenols) and found membrane rejections were high (>98 percent) for the organics under ionized conditions.

Summary of BAP Technologies

Current technologies show that BAP removal may be 90 percent or greater. The lowest detection limit for BAP measurements is 0.006 µg/L, which is also the assumed secondary effluent BAP concentration assumed for this study. If this assumption is accurate, it appears technologies may exist to remove BAP to a level below the proposed criteria applied as an effluent limit of 0.0013 µg/L; however, detection limits exceed this value and it is impossible to know this for certain. A municipal wastewater treatment plant study reported both influent and effluent BAP concentrations less than the HHWQC of 0.0013 ug/L (Ecology, 2010).

4.3 Unit Processes Evaluated

Based on the results of the literature review, a wide range of technologies were evaluated for toxic constituent removal. A listing of the technologies is as follows:

- Chemically enhanced primary treatment (CEPT): this physical and chemical technology is based on the addition of a metal salt to precipitate particles prior to primary treatment, followed by sedimentation of particles in the primary clarifiers. This technology has been shown to effectively remove arsenic but there is little data supporting the claims. As a result, the chemical facilities are listed as optional.

- Activated sludge treatment (with a short SRT of approximately 8 days or less): this biological technology is commonly referred to as secondary treatment. It relies on converting dissolved organics into solids using biomass. Having a short SRT is effective at removing degradable organics referred to as BOD compounds for meeting existing discharge limits. Dissolved constituents with a high affinity to adsorb to biomass (e.g., metals, high molecular weight organics, and others) will be better removed compared to smaller molecular weight organics and recalcitrant compounds which will have minimal removal at a short SRT.
- Enhanced activated sludge treatment (with a long SRT of approximately 8 days or more): this technology builds on secondary treatment by providing a longer SRT, which enhances sorption and biodegradation. The improved performance is based on having more biomass coupled with a more diverse biomass community, especially nitrifiers, which have been shown to assist in removal of some of the more recalcitrant constituents not removed with a shorter SRT (e.g., lower molecular weight PAHs). There is little or no data available on the effectiveness of this treatment for removing BAP.

  Additional benefits associated with having a longer SRT are as follows:

  - Lower BOD/TSS discharge load to receiving water
  - Improved water quality and benefit to downstream users
  - Lower effluent nutrient concentrations which reduce algal growth potential in receiving waters
  - Reduced receiving water dissolved oxygen demand due to ammonia removal
  - Reduced ammonia discharge, which is toxic to aquatic species
  - Improved water quality for habitat, especially as it relates to biodiversity and eutrophication
  - Secondary clarifier effluent more conditioned for filtration and disinfection
  - Greater process stability from the anaerobic/anoxic zones serving as biological selectors
- Coagulation/Flocculation and Filtration: this two-stage chemical and physical process relies on the addition of a metal salt to precipitate particles in the first stage, followed by the physical removal of particles in filtration. This technology lends itself to constituents prone to precipitation (e.g., arsenic).
- Lime Softening: this chemical process relies on increasing the pH as a means to either volatilize dissolved constituents or inactivate pathogens. Given that none of the constituents being studied are expected to volatilize, this technology was not carried forward.
- Adsorptive Media: this physical and chemical process adsorbs constituents to a combination of media and/or biomass/chemicals on the media. There are several types of media, with the most proven and common being GAC. GAC can also serve as a coarse roughing filter.
- Ion Exchange: this chemical technology exchanges targeted constituents with a resin. This technology is common with water softeners where the hard divalent cations are

exchanged for monovalent cations to soften the water. Recently, resins that target arsenic and mercury removal include activated alumina and granular ferric hydroxides have been developed. The resin needs to be cleaned and regenerated, which produces a waste slurry that requires subsequent treatment and disposal. As a result, ion exchange was not considered for further.

- Membrane Filtration: This physical treatment relies on the removal of particles larger than the membranes pore size. There are several different membrane pore sizes as categorized below.
    - Microfiltration (MF): nominal pore size range of typically between 0.1 to 1 micron. This pore size targets particles, both inert and biological, and bacteria. If placed in series with coagulation/flocculation upstream, dissolved constituents precipitated out of solution and bacteria can be removed by the MF membrane.
    - Ultrafiltration (UF): nominal pore size range of typically between 0.01 to 0.1 micron. This pore size targets those solids removed with MF (particles and bacteria) plus viruses and some colloidal material. If placed in series with coagulation/flocculation upstream, dissolved constituents precipitated out of solution can be removed by the UF membrane.
    - Nanofiltration (NF): nominal pore size range of typically between 0.001 to 0.010 micron. This pore size targets those removed with UF (particles, bacteria, viruses) plus colloidal material. If placed in series with coagulation/flocculation upstream, dissolved constituents precipitated out of solution can be removed by the NF membrane.
- MBR (with a long SRT): this technology builds on secondary treatment whereby the membrane (microfiltration) replaces the secondary clarifier for solids separation. As a result, the footprint is smaller, the mixed liquor suspended solids concentration can be increased to about 5,000 – 10,000 mg/L, and the physical space required for the facility reduced when compared to conventional activated sludge. As with the activated sludge option operated at a longer SRT, the sorption and biodegradation of organic compounds are enhanced in the MBR process. The improved performance is based on having more biomass coupled with a more diverse biomass community, especially nitrifiers which have been shown to assist in removal of persistent dissolved compounds (e.g., some PAHs). There is little or no data available on effectiveness at removing BAP. Although a proven technology, MBRs were not carried further in this technology review since they are less likely to be selected as a retrofit for an existing activated sludge (with a short SRT) secondary treatment facility. The MBR was considered to represent a treatment process approach more likely to be selected for a new, greenfield treatment facility. Retrofits to existing secondary treatment facilities can accomplish similar process enhancement by extending the SRT in the activated sludge process followed by the addition of tertiary membrane filtration units.
- RO: This physical treatment method relies on the use of sufficient pressure to osmotically displace water across the membrane surface while simultaneously rejecting most salts. RO is very effective at removing material smaller than the size ranges for the membrane filtration list above, as well as salts and other organic compounds. As a result, it is expected to be more effective than filtration and MBR methods described above at removing dissolved constituents. Although effective, RO produces a brine reject water that must be managed and disposed.

- Advanced Oxidation Processes (AOPs): this broad term considers all chemical and physical technologies that create strong hydroxyl-radicals. Examples of AOPs include Fenton's oxidation, ozonation, ultraviolet/hydrogen peroxide (UV-H2O2), and others. The radicals produced are rapid and highly reactive at breaking down recalcitrant compounds. Although effective at removing many complex compounds such as those evaluated in this study, AOPs does not typically have as many installations as membranes and activated carbon technologies. As a result, AOPs were not carried forward.

Based on the technical literature review discussed above, a summary of estimated contaminant removal rated by unit treatment process is presented in Table 4.

Table 4. Contaminants Removal Breakdown by Unit Process

Unit Process	Arsenic	BAP	Mercury	Polychlorinated Biphenyls
Activated Sludge Short SRT	No removal	Partial Removal by partitioning		80% removal; effluent <0.88 ng/L
Activated Sludge Long SRT	No removal	Partial removal by partitioning and/or partially biodegradation; MBR could potentially remove most of BAP		>90% removal with a membrane bioreactor, <0.04 ng/L (includes membrane filtration)
Membrane Filtration (MF)	More than 90 % removal (rejection of bound arsenic)	No removal	<1.3 ng/L	>90% removal with a membrane bioreactor, <0.04 ng/L (includes membrane filtration)
Reverse Osmosis (RO)	More than 90% removal (rejection of bound arsenic and removal of soluble arsenic)	More than 98% removal		
Granular Activated Carbon (GAC)	No removal, removal only when carbon is impregnated with iron	90 % removal	<300 ng/L (precipitation and carbon adsorption) <51 ng/L (GAC)	<800 ng/L Likely requires upstream filtration
Disinfection	--	--	--	--

4.4 Unit Processes Selected

The key conclusion from the literature review was that there is limited, to no evidence, that existing treatment technologies are capable of simultaneously meeting all four of the revised discharge limits for the toxics under consideration. Advanced treatment using RO or GAC is expected to provide the best overall removal of the constituents of concern. It is unclear whether these advanced technologies are able to meet revised effluent limits, however these processes may achieve the best effluent quality of the technologies reviewed. This limitation in the findings is based on a lack of an extensive dataset on treatment removal effectiveness in the technical literature for the constituents of interest at the low levels relevant to the proposed criteria, which approach the limits of reliable removal performance for the technologies. As Table 4 highlights, certain unit processes are capable of removing a portion, or all, of the removal requirements for each technology. The removal performance for each constituent will vary from facility to facility and require a site-specific, detailed evaluation because the proposed criteria are such low concentrations. In some cases, a facility may only have elevated concentrations of a single constituent of concern identified in this study. In other cases, a discharger may have elevated concentrations of the four constituents identified in this study, as well as others not identified in this study but subject to revised water quality criteria. This effort is intended to describe a planning level concept of what treatment processes are required to comply with discharge limits for all four constituents. Based on the literature review of unit processes above, two different treatment trains were developed for the analysis that are compared against a baseline of secondary treatment as follows:

- Baseline: represents conventional secondary treatment that is most commonly employed nationwide at wastewater treatment plants. A distinguishing feature for this treatment is the short solids residence time (SRT) (<8 days) is intended for removal of BOD with minimal removal for the toxic constituents of concern.
- Advanced Treatment – MF/RO: builds on baseline with the implementation of a longer SRT (>8 days) and the addition of MF and RO. The longer SRT not only removes BOD, but it also has the capacity to remove nutrients and a portion of the constituents of concern. This alternative requires a RO brine management strategy which will be discussed in sub-sections below.
- Advanced Treatment – MF/GAC: this alternative provides a different approach to advanced treatment with MF/RO by using GAC and avoiding the RO reject brine water management concern. Similar to the MF/RO process, this alternative has the longer SRT (>8 days) with the capacity to remove BOD, nutrients, and a portion of the toxic constituents of concern. As a result, the decision was made to develop costs for both advanced treatment options.

A description of each alternative is provided in Table 5. The process flowsheets for each alternative are presented in Figure 3 to Figure 5.

4.4.1 Baseline Treatment Process

A flowsheet of the baseline treatment process is provided in Figure 3. The baseline treatment process assumes the current method of treatment commonly employed by dischargers. For this process, water enters the headworks and undergoes primary treatment, followed by conventional activated sludge (short SRT) and disinfection. The solids wasted in the activated sludge process are thickened, followed by mixing with primary solids prior to entering the anaerobic digestion process for solids stabilization. The digested biosolids are dewatered to produce a cake and hauled off-site. Since the exact process for each interested facility in Washington is unique, this baseline treatment process was used to establish the baseline capital and O&M costs. The baseline costs will be compared against the advanced treatment alternatives to illustrate the magnitude of the increased costs and environmental impacts.

Table 5. Unit Processes Description for Each Alternative

Unit Process	Baseline	Advanced Treatment – MF/RO	Advanced Treatment - GAC
Influent Flow	5 mgd	5 mgd	5 mgd
Chemically Enhanced Primary Treatment (CEPT); Optional	--	• Metal salt addition (alum) upstream of primaries	• Metal salt addition (alum) upstream of primaries
Activated Sludge	• Hydraulic Residence Time (HRT): 6 hrs • Short Solids Residence Time (SRT): <8 days	• Hydraulic Residence Time (HRT): 12 hrs (Requires more tankage than the Baseline) • Long Solids Residence Time (SRT): >8 days (Requires more tankage than the Baseline)	• Hydraulic Residence Time (HRT): 12 hrs (Requires more tankage than the Baseline) • Long Solids Residence Time (SRT): >8 days (Requires more tankage than the Baseline)
Secondary Clarifiers	Hydraulically Limited	Solids Loading Limited (Larger clarifiers than Baseline)	Solids Loading Limited (Larger clarifiers than Baseline)
Microfiltration (MF)	--	Membrane Filtration to Remove Particles and Bacteria	Membrane Filtration to Remove Particles and Bacteria
Reverse Osmosis (RO)	--	Treat 50% of the Flow by RO to Remove Metals and Dissolved Constituents. Sending a portion of flow through the RO and blending it with the balance of plant flows ensures a stable non-corrosive, non-toxic discharge.	--
Reverse Osmosis Brine Reject Mgmt	--	Several Options (All Energy or Land Intensive)	--
Granular Activated Carbon (GAC)	--	--	Removes Dissolved Constituents
Disinfection	Not shown to remove any of the constituents	Not shown to remove any of the constituents	Not shown to remove any of the constituents

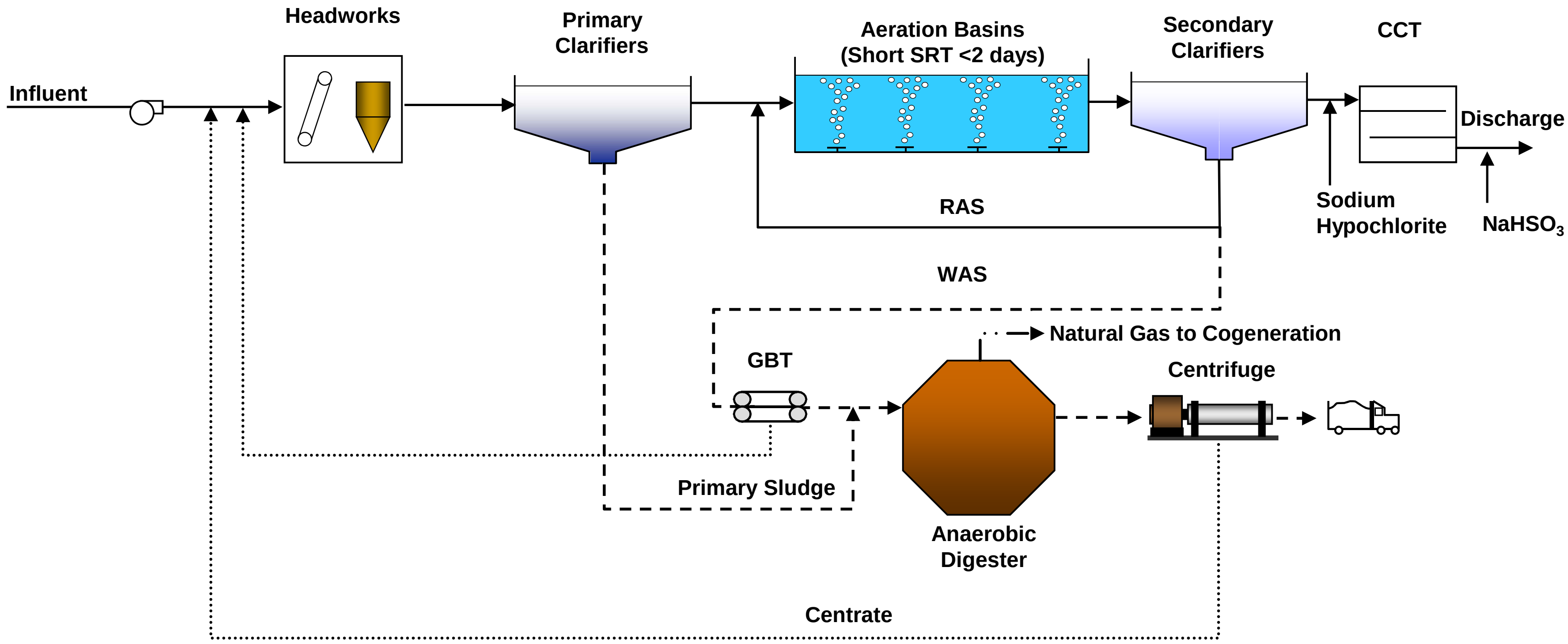

Figure 3. Baseline Flowsheet – Conventional Secondary Treatment

4.4.2 Advanced Treatment – MF/RO Alternative

A flowsheet of the advanced treatment – MF/RO alternative is provided in Figure 4. This alternative builds on the baseline secondary treatment facility, whereby the SRT is increased in the activated sludge process, and MF and RO are added prior to disinfection. The solids treatment train does not change with respect to the baseline. Additionally, a brine management strategy must be considered.

The RO process concentrates contaminants into a smaller volume reject stream. Disposing of the RO reject stream can be a problem because of the potentially large volume of water involved and the concentration of contaminants contained in the brine. For reference, a 5 mgd process wastewater flow might result in 1 mgd of brine reject requiring further management. The primary treatment/handling options for RO reject are as follows:

- Zero liquid discharge
- Surface water discharge
- Ocean discharge
- Haul and discharge to coastal location for ocean discharge
- Sewer discharge
- Deep well injection
- Evaporate in a pond
- Solar pond concentrator

Many of the RO brine reject management options above result in returning the dissolved solids to a "water of the state" such as surface water, groundwater, or marine waters. Past rulings in Washington State have indicated that once pollutants are removed from during treatment they are not to be re-introduced to a water of the state. As a result, technologies with this means for disposal were not considered viable options for management of RO reject water in Washington.

Zero Liquid Discharge

Zero liquid discharge (ZLD) is a treatment process that produces a little or no liquid brine discharge but rather a dried residual salt material. This process improves the water recovery of the RO system by reducing the volume of brine that must be treated and disposed of in some manner. ZLD options include intermediate treatment, thermal-based technologies, pressure driven membrane technologies, electric potential driven membrane technologies, and other alternative technologies.

Summary

There are many techniques which can be used to manage reject brine water associated with RO treatment. The appropriate alternative is primarily governed by geographic and local constraints. A comparison of the various brine management methods and potential costs are provided in Table 6.

Of the listed options, ZLD was considered for this analysis as the most viable approach to RO reject water management. An evaporation pond was used following ZLD. The strength in this combination is ZLD reduces the brine reject volume to treat, which in turn reduces the required evaporation pond footprint. The disadvantage is that evaporation ponds require a substantial amount of physical space which may not be available at existing treatment plant sites. It is also important to recognize that the greenhouse gas (GHG) emissions vary widely for the eight brine management options listed above based on energy and chemical intensity.

Table 6. Brine Disposal Method Relative Cost Comparison

Disposal Method	Description	Relative Capital Cost	Relative O&M Cost	Comments
Zero Liquid Discharge (ZLD)	Further concentrates brine reject for further downstream processing	High	High	This option is preferred as an intermediate step. This rationale is based on the reduction in volume to handle following ZLD. For example, RO reject stream volume is reduced on the order of 50-90%.
Surface Water Discharge	Brine discharge directly to surface water. Requires an NPDES permit.	Lowest	Lowest	Both capital and O&M costs heavily dependent on the distance from brine generation point to discharge. Not an option for nutrient removal.
Ocean Discharge	Discharge through a deep ocean outfall.	Medium	Low	Capital cost depends on location and availability of existing deep water outfall.
Sewer Discharge	Discharge to an existing sewer pipeline for treatment at a wastewater treatment plant.	Low	Low	Both capital and O&M costs heavily dependent on the brine generation point to discharge distance. Higher cost than surface water discharge due to ongoing sewer connection charge. Not an option for wastewater treatment.
Deep Well Injection	Brine is pumped underground to an area that is isolated from drinking water aquifers.	Medium	Medium	Technically sophisticated discharge and monitoring wells required. O&M cost highly variable based on injection pumping energy.
Evaporation Ponds	Large, lined ponds are filled with brine. The water evaporates and a concentrated salt remains.	Low – High	Low	Capital cost highly dependent on the amount and cost of land.
Salinity Gradient Solar Ponds (SGSP)	SGSPs harness solar power from pond to power an evaporative unit.	Low – High	Lowest	Same as evaporation ponds plus added cost of heat exchanger and pumps. Lower O&M cost due to electricity production.
Advanced Thermal Evaporation	Requires a two-step process consisting of a brine concentrator followed by crystallizer	High	Highest	Extremely small footprint, but the energy from H_2O removal is by far the most energy intensive unless waste heat is used.

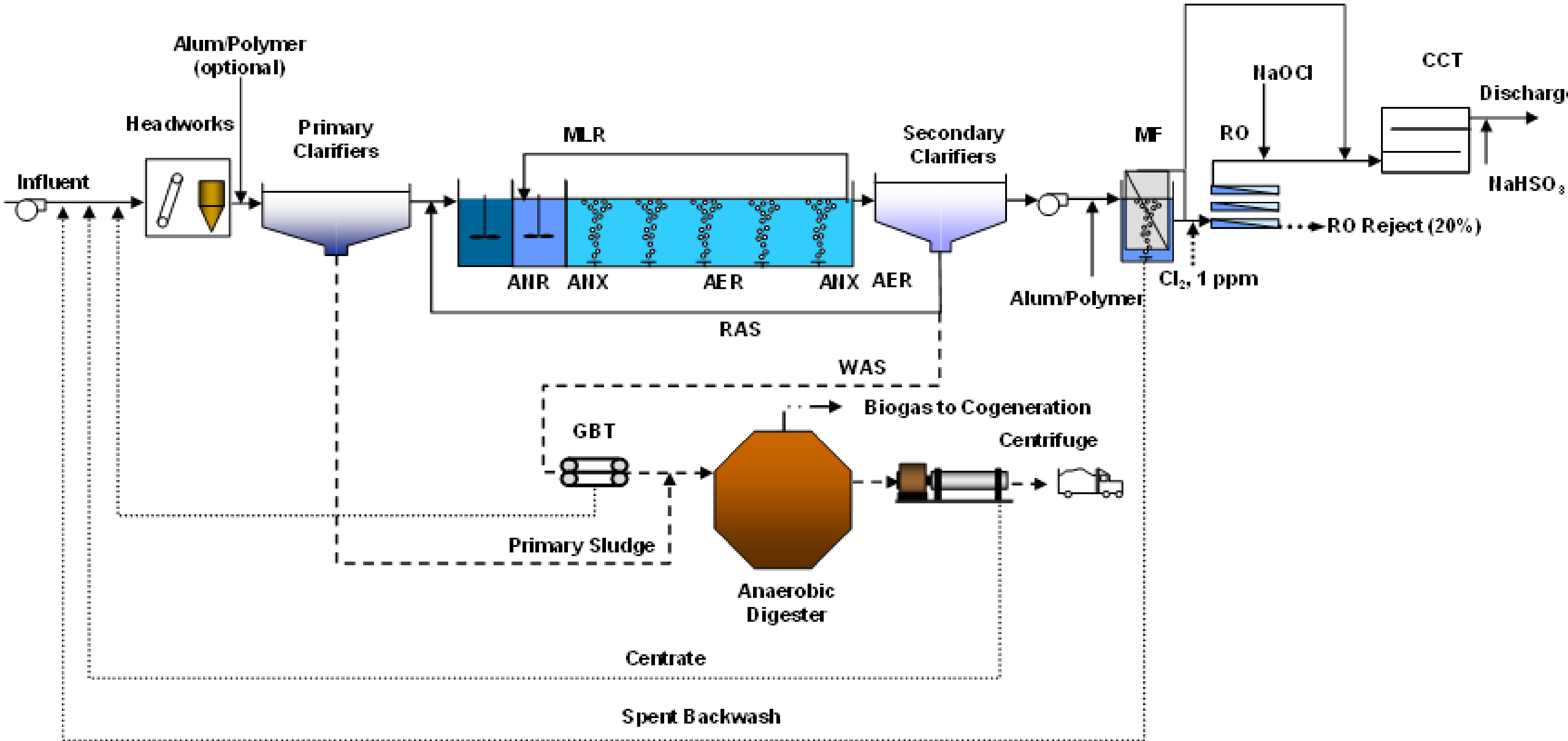

Figure 4. Advanced Treatment Flowsheet – Tertiary Microfiltration and Reverse Osmosis

4.4.3 Advanced Treatment – MF/GAC Alternative

A flowsheet of the advanced treatment – MF/GAC alternative is provided in Figure 5. Following the MF technology, a GAC contactor and media are required.

This alternative was developed as an option that does not require a brine management technology (e.g., ZLD) for comparison to the MF/RO advanced treatment alternative. However, this treatment alternative does require that the GAC be regenerated. A baseline secondary treatment facility can be retrofitted for MF/GAC. If an existing treatment facility has an extended aeration lagoon, the secondary effluent can be fed to the MF/GAC. The longer SRT in the extended aeration lagoon provides all the benefits associated with the long SRT in an activated sludge plant as previously stated:

- Lower BOD/TSS discharge load
- Higher removal of recalcitrant constituents and heavy metals
- Improved water quality and benefit to downstream users
- Less downstream algal growth
- Reduced receiving water dissolved oxygen demand due to ammonia removal
- Reduced ammonia discharge loads, which is toxic to several aquatic species
- Improved water quality for habitat, especially as it relates to biodiversity and eutrophication
- Secondary clarifier effluent more conditioned for filtration and disinfection
- Greater process stability from the anaerobic/anoxic zones serving as a selector

If an existing treatment facility employs a high rate activated sludge process (short SRT) similar to the baseline, it is recommended that the activated sludge process SRT be increased prior to the MF/GAC unit processes. The longer SRT upstream of the MF is preferred to enhance the membrane flux rate, reduce membrane biofouling, increase membrane life, and reduce the chemicals needed for membrane cleaning.

The key technical and operational challenges associated with the tertiary add-on membrane filtration units are as follows:

- The membrane filtration technology is a proven and reliable technology. With over 30 years of experience, it has made the transition in recent years from an emerging technology to a proven and reliable technology.
- Membrane durability dependent on feed water quality. The water quality is individual facility specific.
- Membranes are sensitive to particles, so upstream screening is critical. The newer generations of membranes have technical specifications that require a particular screen size.
- Membrane area requirements based on peak flows as water must pass through the membrane pores. Additionally, membranes struggle with variable hydraulic loading. Flow equalization upstream can greatly reduce the required membrane surface area and provide uniform membrane loading.

- Membrane tanks can exacerbate any foam related issues from the upstream biological process. Foam entrapment in the membrane tank from the upstream process can reduce membrane filtration capacity and in turn result in a plant-wide foam problem.
- Reliable access to the membrane modules is key to operation and maintenance. Once PLC is functionary properly, overall maintenance requirements for sustained operation of the system are relatively modest.
- The membranes go through frequent membrane relaxing or back pulse and a periodic deep chemical clean in place (CIP) process.
- Sizing of membrane filtration facilities governed by hydraulic flux. Municipal wastewaters have flux values that range from about 20 to 40 gallons per square foot per day (gfd) under average annual conditions. The flux associated with industrial applications is wastewater specific.

Following the MF is the activated carbon facilities. There are two kinds of activated carbon used in treating water: powdered activated carbon (PAC) and GAC. PAC is finely-ground, loose carbon that is added to water, mixed for a short period of time, and removed. GAC is larger than PAC, is generally used in beds or tanks that permit higher adsorption and easier process control than PAC allows, and is replaced periodically. PAC is not selective, and therefore, will adsorb all active organic substances making it an impractical solution for a wastewater treatment plant. As a result, GAC was considered for this analysis. The type of GAC (e.g., bituminous and subbituminous coal, wood, walnut shells, lignite or peat), gradation, and adsorption capacity are determined by the size of the largest molecule/ contaminant that is being filtered (AWWA, 1990).

As water flows through the carbon bed, contaminants are captured by the surfaces of the pores until the carbon is no longer able to adsorb new molecules. The concentration of the contaminant in the treated effluent starts to increase. Once the contaminant concentration in the treated water reaches an unacceptable level (called the breakthrough concentration), the carbon is considered "spent" and must be replaced by virgin or reactivated GAC.

The capacity of spent GAC can be restored by thermal reactivation. Some systems have the ability to regenerate GAC on-site, but in general, small systems haul away the spent GAC for off-site regeneration (EPA 1993). For this study, off-site regeneration was assumed.

The basic facilities and their potential unit processes included in this chapter are as follows:

- GAC supply and delivery
- Influent pumping
  - Low head feed pumping
  - High head feed pumping (assumed for this study as we have low limits so require high beds)
- Contactors and backwash facilities
  - Custom gravity GAC contactor
  - Pre-engineered pressure GAC contactor (Used for this study)
  - Backwash pumping
- GAC transport facilities
  - Slurry pumps
  - Eductors (Used for this study)

- Storage facilities
    - Steel tanks
    - Concrete tanks (Used for this study; larger plants would typically select concrete tanks)
- Spent carbon regeneration
    - On-site GAC regeneration
    - Off-Site GAC regeneration

Following the MF is the GAC facility. The GAC contactor provides about a 12-min hydraulic residence time for average annual conditions. The GAC media must be regenerated about twice per year in a furnace. The constituents sorbed to the GAC media are removed during the regeneration process. A typical design has full redundancy and additional storage tankage for spent and virgin GAC. Facilities that use GAC need to decide whether they will regenerate GAC on-site or off-site. Due to challenges associated with receiving air emission permits for new furnaces, it was assumed that off-site regeneration would be evaluated.

The key technical and operational challenges associated with the tertiary add-on GAC units are as follows:

- Nearest vendor to acquire virgin GAC – How frequently can they deliver virgin GAC and what are the hauling costs?
- Contactor selection is typically based on unit cost and flow variation. The concrete contactor is typically more cost effective at higher flows so it was used for this evaluation. The pre-engineered pressure contactor can handle a wider range of flows than a concrete contactor. Additionally, a pressure system requires little maintenance as they are essentially automated
- Periodical contactor backwashing is critical for maintaining the desired hydraulics and control biological growth
- Eductors are preferred over slurry pumps because they have fewer mechanical components. Additionally, the pump with eductors is not in contact with the carbon, which reduces wear.
- Off-site GAC regeneration seems more likely due to the challenges with obtaining an air emissions permit.

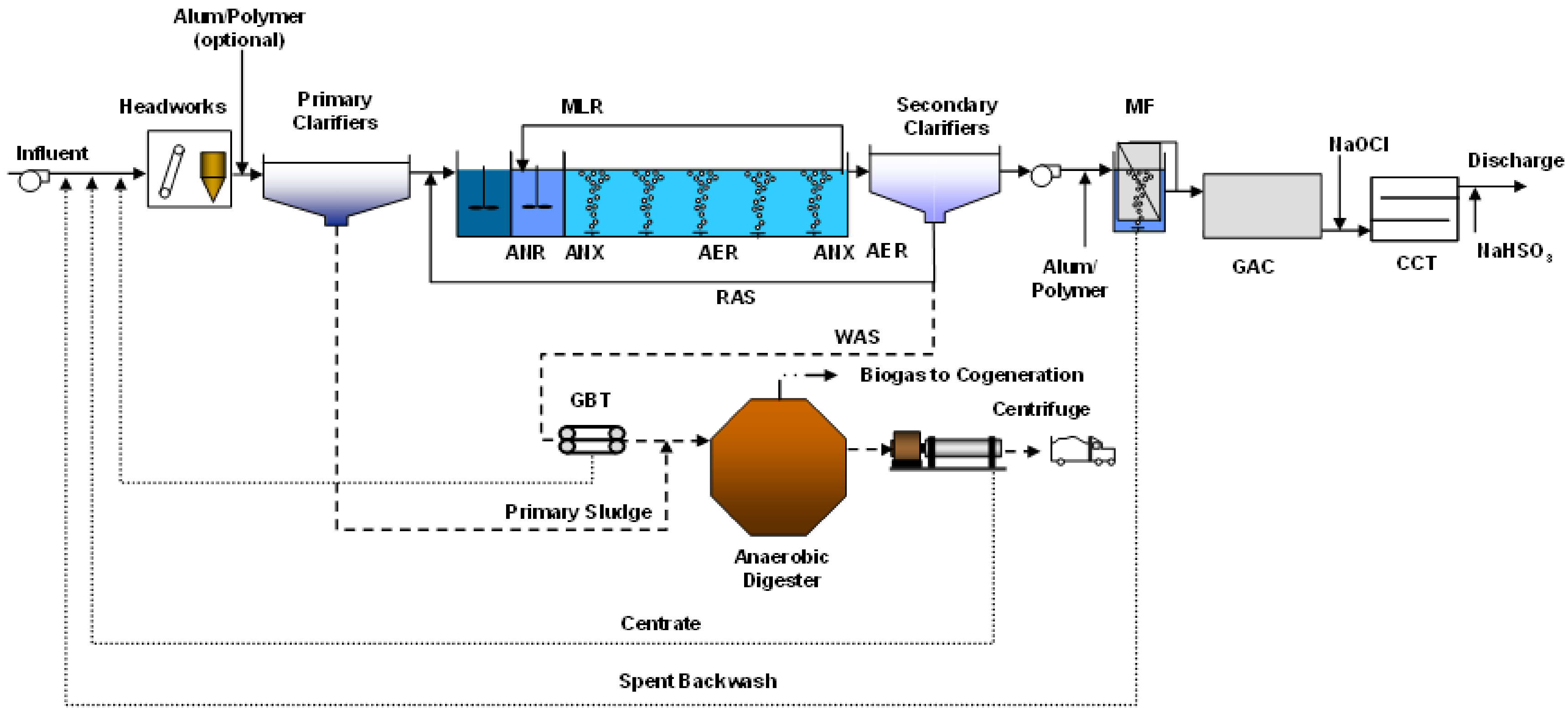

Figure 5. Advanced Treatment Flowsheet – Tertiary Microfiltration and Granular Activated Carbon

4.5 Steady-State Mass Balance

HDR used its steady-state mass balance program to calculate the flows and loads within the candidate advanced treatment processes as a means to size facilities. The design of wastewater treatment facilities are generally governed by steady-state mass balances. For a steady-state mass balance, the conservation of mass is calculated throughout the entire wastewater treatment facility for defined inputs. Dynamic mass balance programs exist for designing wastewater facilities, but for a planning level study such as this, a steady state mass balance program is adequate. A dynamic program is generally used for detailed design and is site-specific with associated requirements for more detailed wastewater characterization.

The set of model equations used to perform a steady-state mass balance are referred to as the model. The model equations provide a mathematical description of various wastewater treatment processes, such as an activated sludge process, that can be used to predict unit performance. The program relies on equations for each unit process to determine the flow, load, and concentration entering and leaving each unit process.

An example of how the model calculates the flow, load, and concentration for primary clarifiers is provided below. The steady-state mass balance equation for primary clarifiers has a single input and two outputs as shown in the simplified Figure 6. The primary clarifier feed can exit the primary clarifiers as either effluent or sludge. Solids not removed across the primaries leave as primary effluent, whereas solids captured leave as primary sludge. Scum is not accounted for.

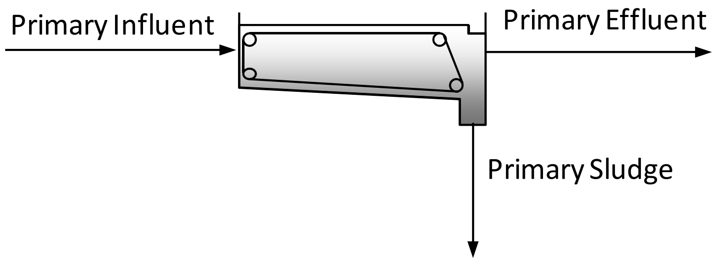

Figure 6. Primary Clarifier Inputs/Outputs

The mass balance calculation requires the following input:

- Solids removal percentage across the primaries (based on average industry accepted performance)
- Primary solids thickness (i.e., percent solids) (based on average industry accepted performance)

The steady-state mass balance program provides a reasonable first estimate for the process performance, and an accurate measure of the flows and mass balances at various points throughout the plant. The mass balance results were used for sizing the facility needs for each alternative. A listing of the unit process sizing criterion for each unit process is provided in Appendix A. By listing the unit process sizing criteria, a third-party user could redo the analysis and end up with comparable results. The key sizing criteria that differ between the baseline and treatment alternatives are as follows:

- Aeration basin mixed liquor is greater for the advanced treatment alternatives which in turn requires a larger volume
- The secondary clarifiers are sized based on hydraulic loading for the baseline versus solids loading for the advanced treatment alternatives

- The MF/GAC and MF/RO sizing is only required for the respective advanced treatment alternatives.

4.6 Adverse Environmental Impacts Associated with Advanced Treatment Technologies

The transition from the baseline (conventional secondary treatment) to either advanced treatment alternatives has some environmental impacts that merit consideration, including the following:

- Land area for additional system components (which for constrained facility sites, may necessitate land acquisition and encroachment into neighboring properties with associated issues and challenges, etc.).
- Increased energy use and atmospheric emissions of greenhouse gases and criteria air contaminants associated with power generation to meet new pumping requirements across the membrane filter systems (MF and RO) and GAC.
- Increased chemical demand associated with membrane filters (MF and RO).
- Energy and atmospheric emissions associated with granulated charcoal regeneration.
- RO brine reject disposal. The zero liquid discharge systems are energy intensive energy and increase atmospheric emissions as a consequence of the electrical power generation required for removing water content from brine reject.
- Increase in sludge generation while transitioning from the baseline to the advanced treatment alternatives. There will be additional sludge captured with the chemical addition to the primaries and membrane filters (MF and RO). Additionally, the GAC units will capture more solids.
- Benefits to receiving water quality by transitioning from a short SRT (<2 days) in the baseline to a long SRT (>8 days) for the advanced treatment alternatives (as previously stated):
    - Lower BOD/TSS discharge load
    - Higher removal of recalcitrant constituents and heavy metals
    - Improved water quality and benefit to downstream users
    - Reduced nutrient loadings to receiving waters and lower algal growth potential
    - Reduced receiving water dissolved oxygen demand due to ammonia removal
    - Reduced ammonia discharge loads, which is toxic to aquatic species
    - Improved water quality for habitat, especially as it relates to biodiversity and eutrophication
    - Secondary clarifier effluent better conditioned for subsequent filtration and disinfection
    - Greater process stability from the anaerobic/anoxic zones serving as a biological selectors

HDR calculated GHG emissions for the baseline and advanced treatment alternatives. The use of GHG emissions is a tool to normalize the role of energy, chemicals, biosolids hauling, and fugitive emissions (e.g., methane) in a single unit. The mass balance results were used to quantify energy demand and the corresponding GHG emissions for each alterative. Energy demand was estimated from preliminary process calculations. A listing of the energy demand for each process stream, the daily energy demand, and the unit energy demand is provided in Table 7. The advanced treatment options range from 2.3 to 4.1 times greater than the baseline. This large increase in energy demand is attributed to the energy required to pass water through the membrane barriers and/or the granular activated carbon. Additionally, there is energy required to handle the constituents removed as either regenerating the GAC or handling the RO brine reject water. This additional energy required to treat the removed constituents is presented in Table 7.

Table 7. Energy Breakdown for Each Alternative (5 mgd design flow)

Parameter	Units	Baseline	Advanced Treatment – MF/GAC	Advanced Treatment – MF/RO
Daily Liquid Stream Energy Demand	MWh/d	11.6	23.8	40.8
Daily Solids Stream Energy Demand	MWh/d	-1.6	-1.1	-1.1
Daily Energy Demand	MWh/d	10.0	22.7	39.7
Unit Energy Demand	kWh/MG Treated	2,000	4,500	7,900

MWh/d = megawatt hours per day
kWh/MG = kilowatt hours per million gallons

Details on the assumptions used to convert between energy demand, chemical demand and production, as well as biologically-mediated gases (i.e., CH4 and N2O) and GHG emissions are provided in Appendix B.

A plot of the GHG emissions for each alternative is shown in Figure 7. The GHG emissions increase from the baseline to the two advanced treatment alternatives. The GHG emissions increase about 50 percent with respect to baseline when MF/GAC is used and the GHG emissions increase over 100 percent with respect to baseline with the MF/RO advanced treatment alternative.

The MF/GAC energy demand would be larger if GAC regeneration was performed on-site. The GHG emissions do not include the energy or air emissions that result from off-site GAC regeneration. Only the hauling associated with moving spent GAC is included. The energy associated with operating the furnace would exceed the GHG emissions from hauling spent GAC.

The zero liquid discharge in the MF/RO alternative alone is comparable to the Baseline. This contribution to increased GHG emissions by zero liquid discharge brine system highlights the importance of the challenges associated with managing brine reject.

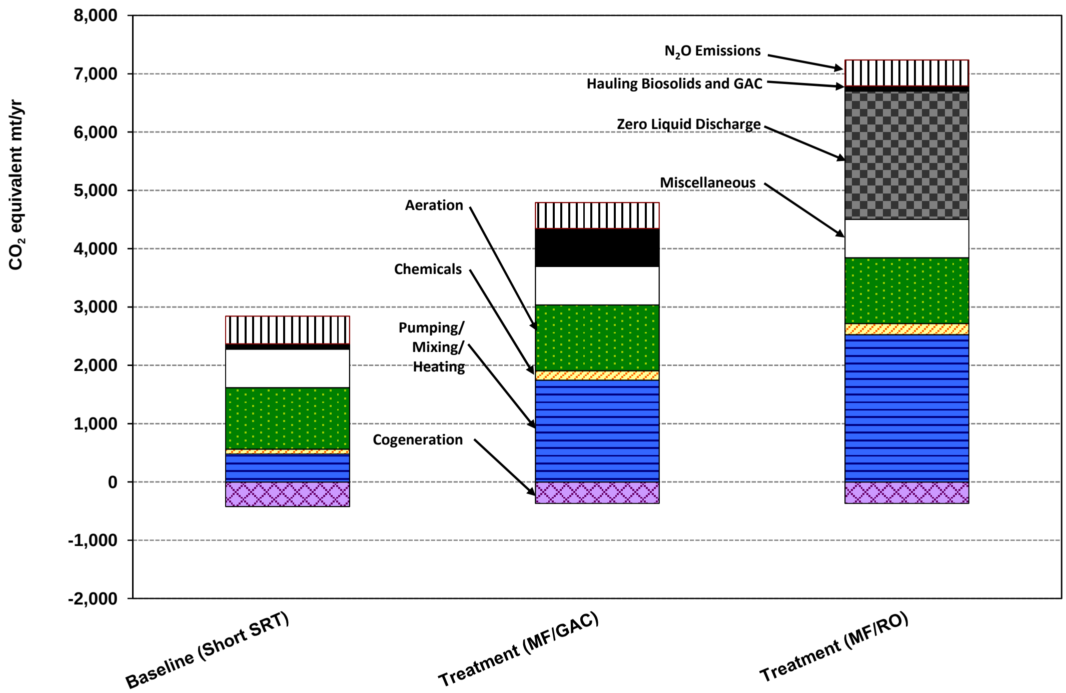

Figure 7. Greenhouse Gas Emissions for Each Alternative

The use of GHG emissions as a measure of sustainability does not constitute a complete comparison between the baseline and advanced treatment alternatives. Rather, it is one metric that captures the impacts of energy, chemical demand and production, as well as biologically-mediated gases (i.e., CH_4 and N_2O). The other environmental impacts of advanced treatment summarized in the list above should also be considered in decision making beyond cost analysis.

4.7 Costs

Total project costs along with the operations and maintenance costs were developed for each advanced treatment alternative for a comparison with baseline secondary treatment.

4.7.1 Approach

The cost estimates presented in this report are planning level opinions of probable construction costs for a nominal 5 mgd treatment plant design flow representing a typical facility without site specific details about local wastewater characteristics, physical site constraints, existing infrastructure, etc. The cost estimates are based on wastewater industry cost references, technical studies, actual project cost histories, and professional experience. The costs presented in this report are considered planning level estimates. A more detailed development of the advanced treatment process alternatives and site specific information would be required to further refine the cost estimates. Commonly this is accomplished in the preliminary design phase of project development for specific facilities following planning.

The cost opinion includes a range of costs associated with the level of detail used in this analysis. Cost opinions based on preliminary engineering can be expected to follow the Association for the Advancement of Cost Engineering (AACE International) Recommended Practice No. 17R-97 Cost Estimate Classification System estimate Class 4. A Class 4 estimate is based upon a 5 to 10 percent project definition and has an expected accuracy range of -30 to +50 percent and typical end usage of budget authorization and cost control. It is considered an "order-of-magnitude estimate." The life-cycle costs were prepared using the net present value (NPV) method.

The cost associated for each new unit process is based on a unit variable, such as required footprint, volume, demand (e.g., lb O_2/hr), and others. This approach is consistent with the approach developed for the EPA document titled "Estimating Water Treatment Costs: Volume 2-Cost Curves Applicable to 1 to 200 mgd Treatment Plants" dated August 1979. The approach has been updated since 1979 to account for inflation and competition, but the philosophy for estimating costs for unit processes has not changed. For example, the aeration system sizing/cost is governed by the maximum month airflow demand. Additionally, the cost associated constructing an aeration basin is based on the volume. The cost considers economies of scale.

The O&M cost estimates were calculated from preliminary process calculations. The operations cost includes energy and chemical demand. For example, a chemical dose was assumed based on industry accepted dosing rates and the corresponding annual chemical cost for that particular chemical was accounted for. The maintenance values only considered replacement equipment, specifically membrane replacement for the Advanced Treatment Alternatives.

4.7.2 Unit Cost Values

The life-cycle cost evaluation was based on using the economic assumptions shown in Table 8. The chemical costs were based on actual values from other projects. To perform detailed cost evaluations per industry, each selected technology would need to be laid out on their respective site plan based on the location of the existing piping, channels, and other necessary facilities.

Table 8. Economic Evaluation Variables

Item	Value
Nominal Discount Rate	5%
Inflation Rate:	
General	3.5%
Labor	3.5%
Energy	3.5%
Chemical	3.5%
Base Year	2013
Project Life	25 years
Energy	$0.06/kWh
Natural Gas	$0.60/therm
Chemicals:	
Alum	$1.1/gal
Polymer	$1.5/gal
Hypochlorite	$1.5/gal
Salt	$0.125/lb
Antiscalant	$12.5/lb
Acid	$0.35/lb
Deionized Water	$3.75/1,000 gal
Hauling:	

Table 8. Economic Evaluation Variables

Item	Value
Biosolids Hauling Distance	100 miles (one way)
Biosolids Truck Volume	6,000 gal/truck
Biosolids Truck Hauling	$250/truck trip
GAC Regeneration Hauling Distance	250 miles (round trip)
GAC Regeneration Truck Volume	$20,000 lb GAC/truck
GAC Regeneration Truck Hauling	Included in cost of Virgin GAC

kWh= kilowatt hours; lbs=pounds; GAC=granulated activated carbon; gal=gallon

4.7.3 Net Present Value of Total Project Costs and Operations and Maintenance Cost in 2013 Dollars

An estimate of the net present value for the baseline treatment process and the incremental cost to implement the advanced treatment alternatives is shown in Table 9. The cost for the existing baseline treatment process was estimated based on new construction for the entire conventional secondary treatment process (Figure 3). The incremental cost to expand from existing baseline secondary treatment to advanced treatment was calculated by taking the difference between the baseline and the advanced treatment alternatives. These values serve as a benchmark for understanding the prospective cost for constructing advanced treatment at the planning level of process development.

Table 9. Treatment Technology Total Project Costs in 2013 Dollars for a 5 mgd Facility

Alternative	Total Construction Cost, 2013 dollars ($ Million)	O&M Net Present Value, 2013 dollars ($ Million)*	Total Net Present Value, 2013 dollars ($ Million)	NPV Unit Cost, 2013 dollars ($/gpd)
Baseline (Conventional Secondary Treatment)*	59 - 127	5 - 11	65 – 138	13 - 28
Advanced Treatment – MF/RO**	108 - 231	31 - 67	139 - 298	28 - 60
Advanced Treatment – MF/GAC	131 - 280	50 - 108	181 - 388	36 - 78
Incremental Increase to Advanced Treatment MF/RO	48 - 104	26 - 56	75 - 160	15 - 32
Incremental Increase to Advanced Treatment MF/GAC	71 - 153	45 - 97	117 - 250	23 - 50

* The additional cost to increase the SRT to upwards of 30-days is about $12 - 20 million additional dollars in total project cost for a 5 mgd design flow
** Assumes zero liquid discharge for RO brine management, followed by evaporation ponds. Other options are available as listed in Section 4.4.2.
O&M=operations and maintenance; MF/RO=membrane filtration/reverse osmosis; MF/GAC=membrane filtration/granulated activated carbon; gpd=gallons per day

4.7.4 Unit Cost Assessment

Costs presented above are based on a treatment capacity of 5.0 mgd, however, existing treatment facilities range dramatically across Washington in size and flow treated. Table 9 indicates that the unit capital cost for baseline conventional secondary treatment for 5.0 mgd ranges between $13 to 28 per gallon per day of treatment capacity. The unit cost for the advanced treatment alternatives increases the range from the low $20s to upper $70s on a per-gallon per-day of capacity. The increase in cost for the advanced treatment alternatives is discussed in the sub-sections below.

Advanced Treatment MF/RO

The advanced treatment MF/RO alternative has a total present worth unit cost range of $28 to $60 million in per gallon per day of capacity. This translates to an incremental cost increase with respect to the baseline of $15 to $32 million dollars in per gallon per day treatment capacity. The key differences in cost between the baseline and the advanced treatment MF/RO are as follows:

- Larger aeration basins than the baseline to account for the longer SRT (<8 days versus >8 days).
- Additional pumping stations to pass water through the membrane facilities (MF and RO). These are based on peak flows.
- Membrane facilities (MF and RO; equipment, tanks chemical feed facilities, pumping, etc.) and replacement membrane equipment.
- Additional energy and chemical demand to operate the membrane facilities (MF and RO) and GAC.
- Zero liquid discharge facilities to further concentrate the brine reject.
- Zero liquid discharge facilities are energy/chemically intensive and they require membrane replacement every few years due to the brine reject water quality.
- An evaporation pond to handle the brine reject that has undergone further concentration by zero liquid discharge.

The advanced treatment MF/RO assumes that 100 percent of the flow is treated by MF, followed by 50 percent of the flow treated with RO. Sending a portion of flow through the RO and blending it with the balance of plant flows ensures a stable water to discharge. The RO brine reject (about 1.0 mgd) undergoes ZLD pre-treatment that further concentrates the brine reject to about 0.1-0.5 mgd. The recovery for both RO and ZLD processes is highly dependent on water quality (e.g., silicate levels).

ZLD technologies are effective at concentrating brine reject, but it comes at a substantial cost ($17.5 per gallon per day of ZLD treatment capacity of brine reject). The zero liquid discharge estimate was similar in approach to the demonstration study by Burbano and Brandhuber (2012) for La Junta, Colorado. The ability to further concentrate brine reject was critical from a management standpoint. Although 8 different options were presented for managing brine reject in Section 4.4.2, none of them is an attractive approach for handling brine reject. ZLD provides a viable pre-treatment step that requires subsequent downstream treatment. Evaporation ponds following ZLD were used for this study. Without ZLD, the footprint would be 3-5 times greater.

Roughly 30 acres of evaporation ponds, or more, may be required to handle the ZLD concentrate, depending upon concentrator effectiveness, local climate conditions, residuals accumulation, residual removal, etc. Precipitation throughout Washington is highly variable which can greatly influence evaporation pond footprint. The approach for costing the evaporation pond was in accordance with Mickley et al. (2006) and the cost was about $2.6 million.

Recent discussions with an industry installing evaporation ponds revealed that they will use mechanical evaporators to enhance evaporation rates. The use of mechanical evaporators was not included in this study, but merits consideration if a facility is performing a preliminary design that involves evaporation ponds. The mechanical evaporators have both a capital costs and annual energy costs.

Advanced Treatment MF/GAC

The advanced treatment MF/GAC alternative has a total present worth unit cost range of $36 to $78 million in per gallon per day capacity. This translates to an incremental cost increase with respect to the baseline of $23 to $50 million dollars on a per gallon per day of treatment capacity basis. The key differences in cost between the baseline and the advanced treatment MF/GAC are as follows:

- Larger aeration basins than the baseline to account for the longer SRT (<8 days versus >8 days).
- Additional pumping stations to pass water through the MF membrane and GAC facilities. These are based on peak flows.
- GAC facilities (equipment, contact tanks, pumping, GAC media, etc.)
- Additional energy to feed and backwash the GAC facilities.
- GAC media replacement was the largest contributor of any of the costs.
- Additional hauling and fees to regenerate GAC off-site.

The advanced treatment MF/GAC assumes that 100 percent of the flow is treated by MF, followed by 100 percent of the flow treated with GAC. The GAC technology is an established technology. The costing approach was in accordance with EPA guidelines developed in 1998.

The critical issue while costing the GAC technology is whether a GAC vendor/regeneration facility is located within the region. On-site regeneration is an established technology with a furnace.

However, there are several concerns as listed in Section 4.4.3:

- Ability to obtain an air emissions permit
- Additional equipment to operate and maintain
- Energy and air emissions to operate a furnace on-site
- Operational planning to ensure that furnace is operating 90-95 percent of the time. Otherwise, operations is constantly starting/stopping the furnace which is energy intensive and deleterious to equipment
- If not operated properly, the facility has the potential to create hazardous/toxic waste to be disposed

If located within a couple hundred miles, off-site regeneration is preferred. For this study, off-site regeneration was assumed with a 250-mile (one-way) distance to the nearest vendor that can provide virgin GAC and a regeneration facility.

Incremental Treatment Cost

The difference in costs between the baseline and the advanced treatment alternatives is listed in Table 10. The incremental cost to retrofit the baseline facility to the advanced treatment was calculated by taking the difference between the two alternatives. These values should serve as a planning level benchmark for understanding the potential cost for retrofitting a particular facility. The incremental cost is unique to a particular facility. Several reasons for the wide range in cost in retrofitting a baseline facility to advanced treatment are summarized as follows:

- Physical plant site constraints. A particular treatment technology may or may not fit within the constrained particular plant site. A more expensive technology solution that is more compact may be required. Alternately, land acquisition may be necessary to enlarge a plant site to allow the addition of advanced treatment facilities. An example of the former is stacking treatment processes vertically to account for footprint constraints. This is an additional financial burden that would not be captured in the incremental costs presented in Table 10.
- Yard piping. Site specific conditions may prevent the most efficient layout and piping arrangement for an individual facility. This could lead to additional piping and pumping to convey the wastewater through the plant. This is an additional financial burden that would not be captured in the incremental costs presented in Table 10.
- Pumping stations. Each facility has unique hydraulic challenges that might require additional pumping stations not captured in this planning level analysis. This is an additional financial burden that would not be captured in the incremental costs presented in Table 10.

A cursory unit cost assessment was completed to evaluate how costs would compare for facilities with lower (0.5 mgd) and higher capacity (25 mgd), as presented in Table 10. Capital costs were also evaluated for a 0.5 mgd and 25 mgd facility using non-linear scaling equations with scaling exponents. The unit capital cost for baseline conventional secondary treatment for 0.5 mgd and 25 mgd is approximately $44 and $10 per gallon per day of treatment capacity, respectively. The incremental unit costs to implement an advanced treatment retrofit for 0.5 mgd would range between $30 to $96 per gallon per day of treatment capacity and would be site and discharger specific. The incremental unit costs to implement an advanced treatment retrofit for 25 mgd would range between $10 to 35 per gallon per day of treatment capacity and would be site and discharger specific. The larger flow, 25 mgd, is not as expensive on a per gallon per day of treatment capacity. This discrepancy for the 0.5 and 25 mgd cost per gallon per day of treatment capacity is attributed to economies of scale. Cost curve comparisons (potential total construction cost and total net present value) for the baseline and the two tertiary treatment options (MF/RO and MF/GAC) are shown in Figure 8 and Figure 9 between the flows of 0.5 and 25 mgd. It is important to note that while the economies of scale suggest lower incremental costs for the larger size facilities, some aspects of the advanced treatment processes may become infeasible at larger capacities due to factors such as physical space limitations and the large size requirements for components such as RO reject brine management.

Table 10. Treatment Technology Total Project Costs in 2013 Dollars for a 0.5 mgd Facility and a 25 mgd Facility

Alternative	Total Construction Cost, 2013 dollars ($ Million)	O&M Net Present Value, 2013 dollars ($ Million)*	Total Net Present Value, 2013 dollars ($ Million)	NPV Unit Cost, 2013 dollars ($/gpd)
0.5 mgd:				
Baseline (Conventional Secondary Treatment)	15 - 32	0.5 - 1.1	15 - 33	31 - 66
Advanced Treatment – MF/RO**	27 - 58	3.2 - 6.8	30 - 65	60 - 130
Advanced Treatment – MF/GAC	33 - 70	5 - 10.8	38 - 81	76 - 162
Incremental Increase to Advanced Treatment MF/RO	12 - 26	2.7 - 5.7	15 - 32	30 - 64
Incremental Increase to Advanced Treatment MF/GAC	18 - 38	4.6 - 9.8	22 - 48	45 - 96
25 mgd:				
Baseline (Conventional Secondary Treatment)	156 - 335	25 - 54	182 - 389	7 - 16
Advanced Treatment – MF/RO**	283 - 606	157 - 336	440 - 942	18 - 38
Advanced Treatment – MF/GAC	343 - 735	252 - 541	595 - 1276	24 - 51
Incremental Increase to Advanced Treatment MF/RO	127 - 272	131 - 281	258 - 553	10 - 22
Incremental Increase to Advanced Treatment MF/GAC	187 - 401	226.9 - 486	414 - 887	17 - 35

* Does not include the cost for labor.
** Assumes zero liquid discharge for RO brine management, followed by evaporation ponds. Other options are available as listed in Section 4.4.2.
MF/RO=membrane filtration/reverse osmosis
MF/GAC=membrane filtration/granulated activated carbon
O&M=operations and maintenance
gpd=gallons per day

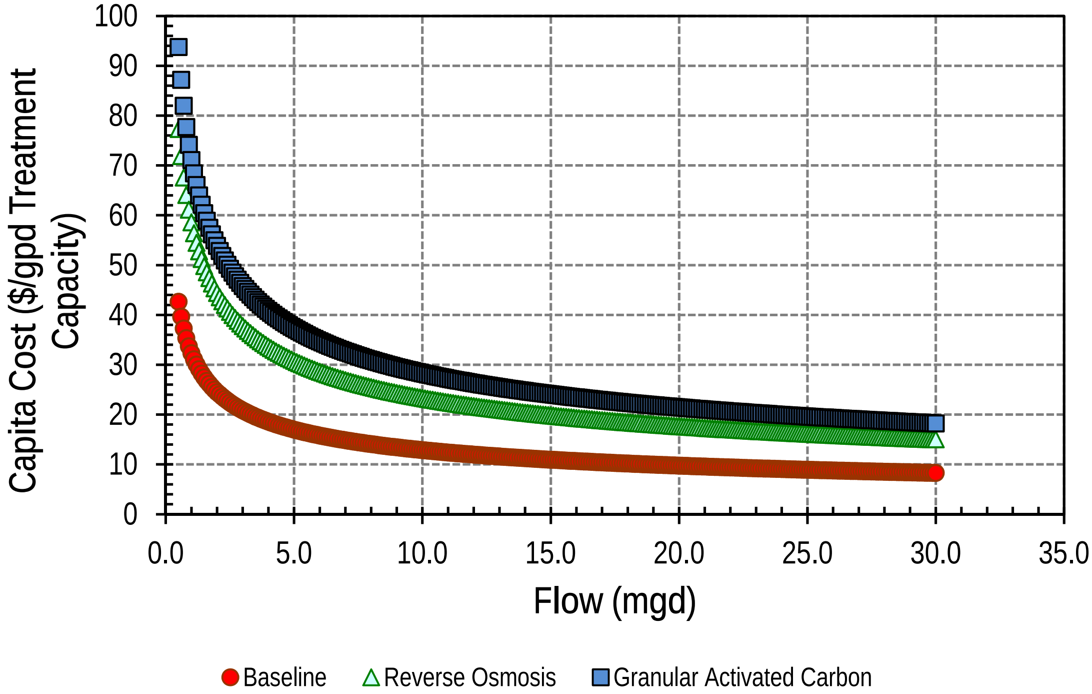

Figure 8: Capital Cost Curve Comparison for Baseline Treatment, MF/RO, and MF/GAC

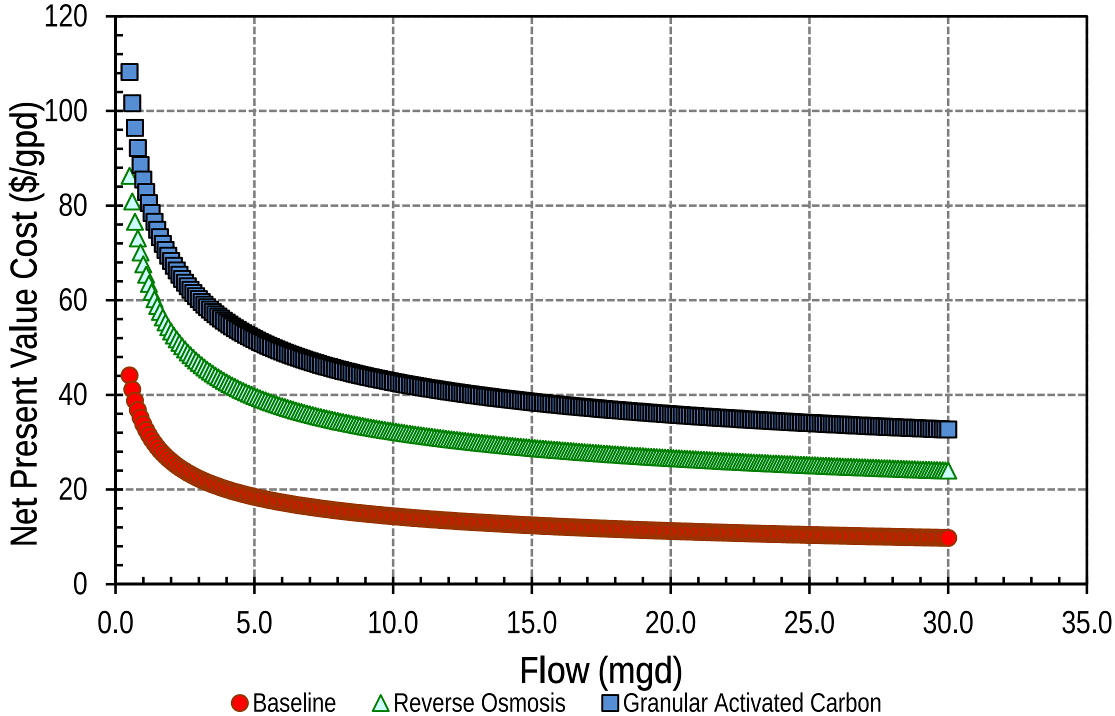

Figure 9: NPV Cost Curve Comparison for Baseline Treatment, MF/RO, and MF/GAC

4.8 Pollutant Mass Removal

An estimate of the projected load removal for the four constituents of concern was developed and is presented in Table 11. The current secondary effluent and advanced treatment effluent data is based on the only available data to HDR and is from municipal treatment plant facilities. Data is not available for advanced treatment facilities such as MF/RO or MF/GAC. Due to this lack of data, advanced treatment using MF/RO or MF/GAC was assumed to remove an additional zero to 90 percent of the constituents presented resulting in the range presented in Table 11. It is critical to note these estimates are based on limited data and are presented here simply for calculating mass removals. Current secondary effluent for industrial facilities would likely be greater than the data presented here and as a result, the projected effluent quality for industrial facilities would likely be higher as well. Based on the limited actual data from municipal treatment facilities, Table 11 indicates that mercury and BAP effluent limits may potentially be met using advanced treatment at facilities with similar existing secondary effluent quality.

Table 11. Pollutant Mass Removal by Contaminant for a 5 mgd Facility

Component	PCBs	Mercury	Arsenic	BAP
Required HHWQC based Effluent Quality (µg/L)	0.0000064	0.005	0.018	0.0013
Current Secondary Effluent Concentration (µg/L)*	0.0015	0.025	7.5	0.00031
Projected Effluent Quality (µg/L) from Advanced Treatment (MF/RO or MF/GAC)*	0.000041 – 0.00041	0.00012 – 0.0012	0.38 – 3.8	0.000029 - 0.00029
Mass Removed (mg/d)**	21 - 28	451 - 471	71,000 – 135,000	0.4 – 5.0
Mass Removed (lb/d)**	0.000045 – 0.000061	0.00099 – 0.0010	0.16 – 0.30	0.0000010 – 0.0000012

* Based on or estimated for actual treatment plant data from municipal facilities. Data sets are limited and current secondary effluent for industrial facilities would likely be greater than the data presented here.
** 1 lb = 454,000 mg
HHWQC=human health-based water quality criteria
MF/RO=membrane filtration/reverse osmosis
MF/GAC=membrane filtration/granulated activated carbon
µg/L=micrograms per liter
mg/d=milligrams per day
lb/d=pounds per day

Unit costs were developed based on required mass removal from a 5 mgd facility for each of the four constituents of concern to reduce discharges from current secondary effluent quality to the assumed required effluent quality (HHWQC). It important to note that this study concludes it is unclear if existing technology can meet the required effluent quality, however, the information presented in Table 12 assumes HHWQC would be met for developing unit costs. The unit costs are expressed as dollars in NPV (over a 25 year period) per pound of constituent removed over the same 25 year period using advanced treatment with MF/RO. The current secondary effluent quality data presented are based on typical secondary effluent quality expected for a municipal/industrial discharger. Table 12 suggests unit costs are most significant in meeting the PCB, mercury, and PAH required effluent quality.

Table 12. Unit Cost by Contaminant for a 5 mgd Facility Implementing Advanced Treatment using MF/RO

Component	PCBs	Mercury	Arsenic	PAHs
Required HHWQC based Effluent Quality (µg/L)	0.0000064	0.005	0.018	0.0013
Current Secondary Effluent Concentration (µg/L)*	0.002	0.025	7.5	0.006
Total Mass Removed (lbs) over 25-year Period	0.76	7.6	2,800	1.8
Unit Cost (NPV per total mass removed in pounds over 25 years)	$290,000,000	$29,000,000	$77,000	$120,000,000

*Derived from data presented in Table 3.
**Based on assumed 25-year NPV of $219,000,000 (average of the range presented in Table 10) and advanced treatment using MF/RO.
NPV=net present value
HHWQC=human health-based water quality criteria
µg/l=micrograms per liter

4.9 Sensitivity Analysis

The ability of dischargers to meet a HHWQC one order of magnitude less stringent (than HHWQC presented in Table 3 and used in this report) was considered. The same advanced treatment technologies using MF/RO or MF/GAC would still be applied to meet revised effluent quality one order-of-magnitude less stringent despite still not being able to meet less stringent effluent limits. As a result, this less stringent effluent quality would not impact costs. Based on available data, it appears the mercury and BAP limits would be met at a less stringent HHWQC. PCB effluent quality could potentially be met if advanced treatment with RO or GAC performed at the upper range of their projected treatment efficiency. It does not appear the less stringent arsenic HHWQC would be met with advanced treatment. It is important to note that a discharger's ability to meet these less stringent limits depends on existing secondary effluent characteristics and is facility specific. Facilities with higher secondary effluent constituent concentrations will have greater difficulty meeting HHWQC.

5.0 Summary and Conclusions

This study evaluated treatment technologies potentially capable of meeting revised effluent discharge limits associated with revised HHWQC. HDR completed a literature review of potential technologies and engineering review of their capabilities to evaluate and screen treatment methods for meeting revised effluent limits for four constituents of concern: arsenic, BAP, mercury, and PCBs. HDR selected two alternatives to compare against a baseline, including enhanced secondary treatment, enhanced secondary treatment with MF/RO, and enhanced secondary treatment with MF/GAC. HDR developed capital costs, operating costs, and a NPV for each alternative, including the incremental cost to implement from an existing secondary treatment facility.

The following conclusions can be made from this study.

- Revised HHWQC based on state of Oregon HHWQC (2001) and EPA "National Recommended Water Quality Criteria" will result in very low water quality criteria for toxic constituents.
- There are limited "proven" technologies available for dischargers to meet required effluent quality limits that would be derived from revised HHWQC.
    - Current secondary wastewater treatment facilities provide high degrees of removal for toxic constituents; however, they will not be capable of compliance with water quality-based NPDES permit effluent limits derived from revised HHWQC.
    - Advanced treatment technologies have been investigated and candidate process trains have been conceptualized for toxics removal.
        - Advanced wastewater treatment technologies may enhance toxics removal rates, however they will not be capable of compliance with HHWQC based effluent limits for PCBs. The lowest levels achieved based on the literature review were between <0.00001 and 0.00004 µg/L, as compared to a HHWQC of 0.0000064 µg/L.
        - Based on very limited performance data for arsenic and mercury from advanced treatment information available in the technical literature, compliance with revised criteria may or may not be possible, depending upon site specific circumstances.
            - Compliance with a HHWQC for arsenic of 0.018 µg/L appears unlikely. Most treatment technology performance information available in the literature is based on drinking water treatment applications targeting a much higher SDWA MCL of 10 µg/L.
            - Compliance with a HHWQC for mercury of 0.005 µg/L appears to be potentially attainable on an average basis but perhaps not if effluent limits are structured on a maximum monthly, weekly or daily basis. Some secondary treatment facilities attain average effluent mercury levels of 0.009 to 0.066 µg/L. Some treatment facilities with effluent filters attain average effluent mercury levels of 0.002 to 0.010 µg/L. Additional advanced treatment processes are expected to enhance these removal rates, but little mercury performance data is available for a definitive assessment.
        - Little information is available to assess the potential for advanced technologies to comply with revised benzo(a)pyrene criteria. A municipal wastewater treatment plant study reported both influent and effluent BAP concentrations less than the HHWQC of 0.0013 ug/L (Ecology, 2010).

- Some technologies may be effective at treating identified constituents of concern to meet revised limits while others may not. It is therefore even more challenging to identify a technology that can meet all constituent limits simultaneously.
- A HHWQC that is one order-of-magnitude less stringent could likely be met for mercury and PAHs however it appears PCB and arsenic limits would not be met.

- Advanced treatment processes incur significant capital and operating costs.
  - Advanced treatment process to remove additional arsenic, benzo(a)pyrene, mercury, and PCBs would combine enhancements to secondary treatment with microfiltration membranes, reverse osmosis, and granular activated carbon and increase the estimated capital cost of treatment from $17 to $29 in dollars per gallon per day of capacity (based on a 5.0 mgd facility).
  - The annual operation and maintenance costs for the advanced treatment process train will be substantially higher (approximately $5 million - $15 million increase for a 5.0 mgd capacity facility) than the current secondary treatment level.
- Implementation of additional treatment will result in additional collateral impacts.
  - High energy consumption.
  - Increased greenhouse gas emissions.
  - Increase in solids production from chemical addition to the primaries. Additionally, the membrane and GAC facilities will capture more solids that require handling.
  - Increased physical space requirements at treatment plant sites for advanced treatment facilities and residuals management including reverse osmosis reject brine processing.
- It appears advanced treatment technology alone cannot meet all revised water quality limits and implementation tools are necessary for discharger compliance.
  - Implementation flexibility will be necessary to reconcile the difference between the capabilities of treatment processes and the potential for HHWQC driven water quality based effluent limits to be lower than attainable with technology

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7.0 Appendices

- Appendix A - Unit Process Sizing Criteria
- Appendix B - Greenhouse Gas Emissions Calculation Assumptions

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APPENDIX A - UNIT PROCESS SIZING CRITERIA

Table A-1. Unit Processes Sizing Criteria for Each Alternative

Unit Process	Units	Baseline Treatment	Advanced Treatment	Comment
Influent Pumping Station	unitless	3 Times Ave Flow	3 Times Ave Flow	This is peaking factor used to size the pumps (peak flow:average flow)
Alum Dose for CEPT (optional)	mg/L	20	20	This is the metal salt upstream of the primaries
Primary Clarifiers	gpd/sf	1000	1000	This is for average annual flows
Primary Solids Pumping Station	unitless	1.25 Times Ave Flow	1.25 Times Ave Flow	This is peaking factor used to size the pumps (maximum month flow:average flow)
Aeration System Oxygen Uptake Rate (OUR)	mg/L/hr	25	25	Average annual OUR is used in tandem with mixed liquor to determine the required aeration basin volume (the limiting parameter governs the activated sludge basin volume)
Aeration Basin Mixed Liquor	mg/L	1250	2500	Average annual mixed liquor is used in tandem with OUR (see next row) to determine the required aeration basin volume (the limiting parameter governs the activated sludge basin volume)
Secondary Clarifiers Hydraulic Loading	gpd/sf	650	--	Only use for Baseline as clarifiers governed hydraulically with short SRT (<2 days)
Secondary Clarifiers Solids Loading	lb/d/sf	--	24	Only use for Advanced Treatment as clarifiers governed by solids with long SRT (>8 days)
Return Activated Sludge (RAS) Pumping Station	unitless	1.25 Times Ave Flow	1.25 Times Ave Flow	RAS must have capacity to meet 100% influent max month Flow. The influent flow is multiplied by this peaking factor to determine RAS pumping station capacity.
Waste Activated Sludge (WAS) Pumping Station	gpm	1.25 Times Ave Flow	1.25 Times Ave Flow	WAS must have capacity to meet max month WAS flows. The average annual WAS flow is multiplied by this peaking factor to determine WAS pumping station capacity.
Microfiltration (MF) Flux	gfd	--	25	Based on average annual pilot experience in Coeur D'Alene, ID
MF Backwash Storage Tank	unitless	--	1.25	Storage tanks must have capacity to meet maximum month MF backwash flows. The average annual MF backwash volume is multiplied by this peaking factor to determine required volume.

Table A-1. Unit Processes Sizing Criteria for Each Alternative

Unit Process	Units	Baseline Treatment	Advanced Treatment	Comment
MF Backwash Pumps	unitless	--	1.25	Backwash pumps must have capacity to meet maximum month MF backwash flows. The average annual MF backwash flow is multiplied by this peaking factor to determine required flows.
Reverse Osmosis (RO)	gallon per square foot per day (gfd)	--	10	
RO Reject	%	--	20	This represents the percentage of feed flow that is rejected as brine
Chlorination Dose	mg/L	15	15	
Chlorination Storage Capacity	days	14	14	
Chlorine Contact Tank	min	30	30	This is for average annual conditions.
Dechlorination Dose	mg/L	15	15	
Dechlorination Storage Capacity	days	14	14	
Gravity Belt Thickener	gpm/m	200	200	This is for maximum month conditions using the 1.25 peaking factor from average annual to maximum month
Anaerobic Digestion	Hydraulic residence time (HRT)	18	18	This is for average annual conditions
Dewatering Centrifuge	gpm	120	120	This is for maximum month conditions using the 1.25 peaking factor from average annual to maximum month

gpd=gallons per day; sf=square feet; gpm=gallons per minute

Appendix B – Greenhouse Gas Emissions Calculation Assumptions

The steady state mass balance results were used to calculate GHG emissions. The assumptions used to convert between energy demand, chemical demand and production, as well as biologically-mediated gases (i.e., CH4 and N2O) and GHG emissions are provided in Table B-1. The assumptions are based on EPA (2007) values for energy production, an adaptation of the database provided in Ahn et al. (2010) for N2O emissions contribution, Intergovernmental Panel on Climate Change (IPCC) (2006) for fugitive CH4 emissions, and various resources for chemical production and hauling from production to the wastewater treatment plant (WWTP). Additionally, the biogas produced during anaerobic digestion that is used as a fuel source is converted to energy with MOP8 (2009) recommended waste-to-energy values.

Table B-1. Greenhouse Gas Emissions Assumptions

Parameters	Units	Value	Source
N_2O to CO_2 Conversion	lb CO_2/lb N_2O	296	IPCC, 2006
CH_4 to CO_2 Conversion	lb CO_2/lb CH_4	23	IPCC, 2006
Energy Production			
CO_2	lb CO_2/MWh	1,329	USEPA (2007)
N_2O	lb N_2O/GWh	20.6	USEPA (2007)
CH_4	lb CO_2/GWh	27.3	USEPA (2007)
Sum Energy Production	lb CO_2/MWh	1336	USEPA (2007)
GHGs per BTU Natural Gas			
CO_2	lb CO_2/MMBTU Natural Gas	52.9	CA Climate Action Registry Reporting Tool
N_2O	lb N_2O/MMBTU Natural Gas	0.0001	CA Climate Action Registry Reporting Tool
CH_4	lb CO_2/MMBTU Natural Gas	0.0059	CA Climate Action Registry Reporting Tool
Sum Natural Gas		53.1	CA Climate Action Registry Reporting Tool
Non-BNR N_2O Emissions	g N_2O/PE/yr	32	Ahn et al. (2010)
BNR N_2O Emissions	g N_2O/PE/yr	30	Ahn et al. (2010)
Biogas Purity	% Methane	65	WEF, 2009
Biogas to Energy	BTU/cf CH4	550	WEF, 2009
Digester Gas to Electrical Energy Transfer Efficiency	%	32	HDR Data

Table B-1. Greenhouse Gas Emissions Assumptions

Parameters	Units	Value	Source
Chemical Production			
Alum	lb CO_2/lb Alum	0.28	SimaPro 6.0 - BUWAL250, Eco-indicator 95
Polymer	lb CO_2/lb Polymer	1.18	Owen (1982)
Sodium Hypochlorite	lb CO_2/lb Sodium Hypochlorite	1.07	Owen (1982)
Building Energy Efficiency	kBTU/sf/yr	60	Calif. Commercial End-Use Survey (2006)
Hauling Distance		-	
Local	miles	100	-
Hauling Emissions			
Fuel Efficiency	miles per gallon	8	
CO_2	kg CO_2/gal diesel	10.2	CA Climate Action Registry Reporting Tool
N_2O	kg N_2O/gal diesel	0.0001	CA Climate Action Registry Reporting Tool
CH_4	kg CH_4/gal diesel	0.003	CA Climate Action Registry Reporting Tool
Sum Hauling Fuel	kg CO_2/gal diesel	10.2	CA Climate Action Registry Reporting Tool

GWh = Giga Watt Hours
MWh = Mega Watt Hours
MMBTU = Million British Thermal Units
BTU = British Thermal Unit
PE = Population Equivalents
kBTU/sf/yr = 1,000 British Thermal Units per Square Foot per Year
cf = cubic feet
lb = pound
kg = kilogram
gal = gallon

City of Tacoma
Environmental Services Department

August 16, 2021

Eleanor Ott, PSNGP Permit Writer
Department of Ecology, Water Quality Program
PO Box 47600
Olympia, WA 98504-7600

Dear Ms. Ott:

City of Tacoma, Environmental Services Department (Environmental Services) appreciates the opportunity to comment on the Department of Ecology's (Ecology) draft Puget Sound Nutrient General Permit (Permit) and draft Fact Sheet. Environmental Services operates two wastewater treatment facilities: the North End Treatment Plant No. 3, a 7.2 MGD, facility, and the Central Treatment Plant, a 60 MGD facility. Both facilities discharge secondary effluent to Commencement Bay.

The City of Tacoma is an advocate for clean water and Environmental Services is committed to the protection of Puget Sound and making meaningful progress towards water quality goals. This commitment has been demonstrated through our voluntary acceptance of our responsibility to clean up the Thea Foss waterway and the over 50 million dollars the City has put towards this effort. Environmental Services recognizes that it is important to address the growing challenge of nutrient over-enrichment in Puget Sound to ensure that science-based and effective controls are put in place to address all sources of pollution. Environmental Services has demonstrated its support of a scientific approach to protecting Puget Sound by, among other things, providing the funding for the establishment of the Salish Sea Modeling Center. Environmental Services is also a founding member of the Puget Sound Clean Water Alliance; an organization dedicated to analyzing peer-reviewed, scientific, environmental, and economic data and using it to develop regional strategies aimed at both protecting and enhancing Puget Sound.

Environmental Services provides the following comments and questions regarding the draft Permit and Fact Sheet:

COMMENT NO. 1: THE GENERAL PERMIT IS NOT THE RIGHT TOOL

Ecology's process of developing the Permit has revealed several facts that do not support issuance of nutrient controls in a general permit.

A general permit is available as an alternative to an individual permit when Ecology determines that the dischargers are more appropriately controlled under a general permit. This determination must be made in accordance with the governing regulations. As discussed more fully below, a general permit is appropriate only when a defined category of dischargers have the same or substantially similar types of operations, wastes, effluent limits or operating conditions, and require similar monitoring. The Fact Sheet states, "A general permit is designed to provide coverage for a group of related facilities or operations of a specific industry type or group of industries.

It is appropriate when the discharge characteristics are sufficiently similar, and a standard set of permit requirements can effectively provide environmental protection and comply with ***water quality standards*** for discharges." See Fact Sheet, Page 12. Likewise, the NPDES Permit Writers' Manual explains that, "a facility that otherwise qualifies for a general permit may opt to apply for an individual permit." NPDES Permit Writers' Manual, Section 4.4, at 4-12. Ecology has not explained when and how it made the determination that a general permit was appropriate, what process it followed, what criteria, facts and information were taken into consideration when it made this determination and how each of the criteria were met.

Ecology's NPDES permit regulations provide in pertinent part as follows:

> (2) The director may issue general permits to cover categories of dischargers for geographic areas as described under subsection (3) of this section. The area shall correspond to existing geographic or political boundaries . .....
> (3) General permits may be written to cover the following within a described area:
> (a) Stormwater sources; or
> (b) Categories of dischargers that meet all of the following requirements:
> (i) Involve the same or substantially similar types of operations;
> (ii) Discharge the same or substantially similar types of wastes;
> (iii) Require the same or substantially similar effluent limitations or operating conditions, and require similar monitoring; and
> (iv) In the opinion of the director are more appropriately controlled under a general permit than under individual permits.

WAC 173-226-050(2) & (3); See also, 40 C.F.R. § 122.28(a)(1). Requirements (b)(i) – (iv) are written in the conjunctive, meaning that each requirement must be met for the category of dischargers subject to the Permit. The NPDES Permit Writers' Manual explains that,

> In deciding whether to develop a general permit, permitting authorities consider whether
>
> - A large number of facilities will be covered.
> - The facilities have similar production processes or activities.
> - The facilities generate similar pollutants.
> - Whether uniform WQBELs (where necessary) will appropriately implement water quality standards.

The above requirements appropriately limit the use of a general permit to those circumstances in which the selected category of dischargers are engaged in substantially similar operations and types of discharges. As noted in the NPDES Permit Writers' Manual, ". . . using a general permit ensures consistent permit conditions for comparable facilities." See, NPDES Permit Writers' Manual, Section 3.1.2, Page 3-2. Clearly, as explained below and as acknowledged by Ecology, the facilities are not comparable and the Permit conditions are not consistent.

First, several of the dischargers proposed to be covered under this Permit are not marine dischargers. The Permit itself recognizes this. Ecology has not explained how or why it is appropriate to include some non-marine dischargers in the Permit.

Second, a category of dischargers governed by a general permit must be within a designated geographical area. See, WAC 173-226-020(13).[1] The federal regulations (made applicable to Ecology pursuant to 40 C.F.R § 123.25 and 122.1(a)(2)) provide further clarification regarding what should be considered a geographic area for coverage,

> (a) Coverage. The Director may issue a general permit in accordance with the following:
>
> (1) . . . The area should correspond to existing geographic or political boundaries such as:
>
> (i) Designated planning areas under sections 208 and 303 of CWA;
>
> (ii) Sewer districts or sewer authorities;
>
> (iii) City, county, or State political boundaries;
>
> (iv) State highway systems;
>
> (v) Standard metropolitan statistical areas as defined by the Office of Management and Budget;
>
> (vi) Urbanized areas as designated by the Bureau of the Census according to criteria in 30 FR 15202 (May 1, 1974); or
>
> (vii) Any other appropriate division or combination of boundaries.

40 CFR §§ 122.28(a)(1) & 123.25.

The included non-marine discharges are not located in the same geographic area as the marine dischargers. Ecology has not explained why or how the geographic area for the non-marine dischargers is rationally or appropriately included in the same geographic area as the marine dischargers.

Third, because the dischargers do not have similar production processes or activities, the requirements of the Permit are not uniform in application. The Permit has been constructed to recognize that larger facilities have a different impact than smaller facilities and therefore are subject to different requirements. For example, larger facilities are required to update their planning documents annually, monitor more frequently and implement "optimization", while smaller facilities are only required to create optimization plans. Additionally, the Total Inorganic Nitrogen (TIN) Action Levels are effluent limits individualized for each plant. As noted in the NPDES Permit Writers' Manual, the general permit is not intended to be applied where "*uniform"* water quality based effluent limitations (WQBELs) will not appropriately implement water quality standards. See, NPDES Permit Writers' Manual, Section 3.1.2, Page 3-2.

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[1] (13) "General permit" means a permit that covers multiple dischargers of a point source category within a designated geographical area, in lieu of individual permits being issued to each discharger.

Likewise, the planning requirements in the Permit recognize that each facility is unique in its process and its discharge and cannot be subject to the same general requirements. There is no one size fits all solution and each plant must create their own planning and engineering documents to address the operating conditions of that plant. The wastewater treatment plants (WWTPs) have different technologies and processes for treatment that should be addressed under individual permits, not a general permit. A general permit is not a suitable or appropriate regulatory control when the dischargers, as they are here, are substantively dissimilar.

The Fact Sheet likewise recognizes the lack of similarity among the dischargers in its description of Ecology's "evolving" all known available and reasonable treatment technology (AKART) concept. The Fact Sheet states:

> The prevalence of 303(d) listings related to depleted dissolved oxygen levels from increased levels of nitrogen and phosphorus requires Ecology to reconsider the basis of AKART for domestic WWTPs. It is apparent that the agency must start to consider refining what constitutes AKART for this treatment category. The AKART provision needs evaluation on a case-by-case basis given its direct ties to economic impact. What constitutes AKART at one facility may be different at the next. This is especially true when considering the size differences between WWTPs, available space for expansion at the existing location, costs of additional treatment processes, the rate payer base and any identified hardship that may exist due to the median household income in the community.

See Fact Sheet, at 18. Ecology thus acknowledges that each facility is unique and requires an individualized evaluation to determine the appropriate nutrient controls. It stands to reason that these controls should be in individual permits. Indeed, in recognition of the lack of similarity among the plants included in the Permit, Ecology exempts one facility from the substantive requirements of the Permit. Ecology does not explain how or why inclusion of dischargers that are not the same or substantively the same satisfies the requirements of Ecology's own regulations and the federal regulations applicable to general permits.

Fourth, for the WWTP operators the major advantage of a general permit is that it might better facilitate a collaborative approach to nutrient management through effluent trading. However, Ecology's statement in the Fact Sheet that an effluent trading program would require waste load allocations for each individual facility negates any benefit that a general permit might provide in establishing such a program since there are no waste load allocations or final WQBELs in the Permit. Ecology does not explain how an effluent trading program would be feasible without waste load allocations of a final WQBEL in the Permit.

Finally, the prevalence of 303(d) listings related to depleted dissolved oxygen levels from increased levels of nitrogen and phosphorus requires Ecology to reconsider the basis of AKART for domestic WWTPs. It is apparent that the agency must start to consider refining what constitutes AKART for this treatment category. The AKART provision needs evaluation on a case-by-case basis given its direct ties to economic impact to each of the operators.

Recently, the Court of Appeals reiterated that the term 'reasonable' in the AKART standard limits Ecology to require a treatment system that is both technically and economically feasible.

Nw. Envtl. Advocates v Dep't of Ecology, 2021 Wash. App. LEXIS 1558, 2021 WL 2556573; citing to, *Puget Soundkeeper All. v Dep't of Ecology*, 102 Wn. App. 783, 793 (2000). What constitutes AKART at one facility will necessarily be different at the next. This is especially true when considering the size differences between WWTPs, available space for expansion at the existing location, costs of additional treatment processes, the rate payer base and any identified hardship that may exist due to the median household income in the community. Ecology has not explained how use of the general permit to regulate nutrients rather than the use of individual permits will ensure compliance with AKART.

COMMENT NO. 2: THE GENERAL PERMIT IS AN UNAUTHORIZED SECOND PERMIT FOR A SINGLE DISCHARGE

Ecology is proposing two mandatory permits, an individual permit and a general permit, to regulate a single discharge. The general permit coverage requirement proposed by Ecology conflicts with state and federal law regarding concurrency of a general and individual permits and constitutes an unlawful modification of the Tacoma's expired but administratively continued individual permits.

Ecology states that the Permit "supersedes effluent requirements related to total inorganic nitrogen in the individual NPDES permits with the exception of ammonia effluent limitations developed for control of ammonia toxicity." Fact Sheet, at 13. Ecology also states that the "permit supplements the individual NDPES permits held by the dischargers proposed for coverage." Fact Sheet, at 34.

These statements indicate that Nitrogen limits in individual permits still apply but are superseded by the Permit except under certain circumstances and that the Permit adds conditions not contained in the individual permits. This is not only confusing but in direct conflict with the Clean Water Act (CWA) which does not allow more than one permit for a single discharge, does not allow an individual permit to be amended through a general permit, and does not allow enforcement actions to be taken under the CWA when an operator is in compliance with an individual permit. Additionally, for dischargers operating under an administratively extended individual permit like Tacoma, coverage under the Permit will, by operation of law, extinguish the individual permit.

State NPDES permit programs authorized under the CWA are required to conform to the provisions of 33 USC § 1342 and guidelines for establishing state NPDES programs. 33 USC § 1342(c)(2). All state programs must be administered in accordance with the program requirements enumerated at 40 CFR § 123.25. 40 CFR §§ 122.1(a)(2) & 123.5. The program requirements made applicable to state programs include EPA regulations for general permits under 40 CFR § 122.28. Finally, the 2018 Memorandum of Agreement between the EPA and Ecology (2018 MOA) provides that Ecology will issue and administer general permits in accordance with State regulations and requirements consistent with 40 CFR § 122.28 (hereafter referred to as the "General Permit Regulations"). Ecology's' decision to require dischargers identified in the Permit to apply for coverage under the Permit conflicts with the provisions of 40 CFR § 122.28, the 2018 MOA and the CWA.

The EPA general permit regulations provide that general permits shall be written to cover one or more categories or subcategories of discharges or facilities not covered by individual permits. See, 40 CFR §122.28(a)(1). This provision does not contemplate or allow a general permit to operate concurrently with an individual permit. This is made clear in the same regulations which provide that, if a discharger is excluded from coverage under a general permit because the discharger already has an individual permit, the discharger may request that the individual permit be revoked in order to be covered under the general permit. 40 CFR § 122.28(a)(3)(G)(4)(v). Thus, to be covered by a general permit, the individual permit must be revoked.

Likewise, the application requirements for individual permits provide that any person discharging pollutants is required to apply for an individual permit unless that discharger is covered by a general permit. 40 CFR 122.21(a). And, if an individual NPDES permit is issued to a discharger already covered by a general permit, the general permit will be automatically terminated on the effective date of the individual permit. 40 CFR § 122.28(a)(3)(G)(4)(iv). The applicable EPA regulations do not provide for or allow concurrent coverage under both a general and individual permit. The same is true for Ecology's regulations.

Ecology's general permit program, at chapter 173-226 WAC, defines the term general permit as a permit that covers multiple dischargers of a point source category within a designated geographic area, in lieu of individual permits being issued to each discharger. WAC 173-226-020. Like the EPA regulations that Ecology's program must conform to, a general permit is an alternative to coverage under an individual permit. Ecology's regulations mirror the EPA regulations by providing that when an individual permit is issued to a discharger, the applicability of the general permit to that discharger is automatically terminated. In other words, there cannot be concurrent coverage. Further, a precondition to issuance of a general permit is a finding by Ecology that the category of dischargers to be covered are more appropriately controlled under a general permit than under individual permits. WAC 173-226-050(3)(b)(iv).[2] Again, the regulations establish that coverage must be under a general permit or an individual permit, but not both. Ecology has not explained its authority to require the operators to be subject to the Permit to be contemporaneously subject to the conditions of their individual permits and the Permit. Nor has Ecology explained why the individual permits for those operators subject to administratively extended permits will not terminate by operation of law upon coverage under the Permit, or why the Permit will not terminate by operation of law for those operators covered under an individual permit.

The Permit coverage requirement is also unenforceable. The permit shield contained in the CWA, 33 U.S.C. § 1342(k)) provides that compliance with the terms and conditions of a permit is deemed to be compliance with the CWA. The permit shield is also embodied in the Federal NPDES regulations.

> . . . [C]ompliance with a permit during its term constitutes compliance, for purposes of enforcement, with sections 301,302,306,307, 318, 403 and 405 (a)-(b) of CWA.

40 CFR § 122.5.

Accordingly, compliance with the terms of an individual permit is deemed to be compliance with the CWA. Ecology has not identified a provision in the CWA and its implementing regulations, or the State Water Pollution Control Act and its implementing regulations, that authorize Ecology to require coverage under a general permit for a discharger already covered by an individual

[2] See also WAC 173-226-070(2)(a)(i) providing that where water quality-based effluent limitations shall be incorporated into a general permit if, among other things, Ecology determines that the use of a general permit rather than individual permits is appropriate.

permit. In the absence of such authority, Ecology cannot require any of the covered dischargers to apply for coverage under the Permit or take enforcement action if they fail to do so.

The Permit will also operate to modify the conditions of the individual permit in violation of the procedures set forth in the CWA and its implementing regulations for a permit modification. As noted above, Ecology has stated that the Permit will supersede effluent requirements related to TIN in the individual NPDES permits and that the Permit will supplement the individual NPDES permits. Fact Sheet, at 13, 34. In effect, the Permit will operate as a modification of the individual permit because it purports to modify the discharger's obligations under the individual permit. In other words, certain actions which were deemed to be compliance with the CWA under the terms and conditions of the individual permit, will no longer be deemed compliance with the CWA under the Permit. Ecology has not explained its authority to modify the terms and conditions of an individual permit through coverage under a concurrent general permit and has not explained its authority to impose conditions through a general permit that would vitiate the permit shield of the individual permit.

Modifications of permits are governed by 40 CFR §§ 122.62 & 124.5, made applicable to Ecology pursuant to 40 CFR § 123.25. A permit modification requires that Ecology find that cause exists for a modification. 40 CFR § 122.62. Assuming cause exists, permit modifications (other than minor modifications) must conform to the process set forth at 40 CFR § 124. 40 CFR § 122.63. Ecology has not followed this process for modification of Tacoma's obligations under its individual NPDES permits. Accordingly, issuance of the Permit cannot operate to modify any of the terms and conditions of the individual permits issued to Tacoma. Nor can issuance of the Permit alter the provisions under the CWA, and implementing regulations, establishing that compliance by Tacoma with the terms and conditions of its existing permits constitutes compliance with the CWA.

Finally, even if Ecology has such authority, issuance of the Permit would by operation of law result in termination of the Tacoma individual permits pursuant to WAC 173-226-200(5) and for some jurisdictions, would result in immediate termination of the general permit pursuant to WAC 173-226-080(3); WAC 173-226-200(7). Termination of the individual permit as required under WAC 173-226-200(5), would violate the anti-backsliding provisions of 33 USC 1342(0) and 40 CFR 122.44(l) because the effluent limits in the individual permits would not be included in the Permit. The absence of those limits would constitute permit conditions and effluent limits that are less stringent than the terminated individual permits. Ecology's action to require coverage under the Permit would therefore violate the state NPDES permit program, the CWA and the 2018 MOA. Ecology has not explained how or why these provisions would be inoperative with respect to the Permit.

Questions:

- In response to comments, can Ecology explain how EPA and Ecology regulations precluding coverage under an individual and a general permit for the same discharge do not apply to the proposed permit?

- In response to comments, can Ecology also explain for individual permits that are currently under administrative extension, whether the administrative extension will expire as provided in WAC 173-226-300(5) ("…continuation of an expired individual permit, pursuant to WAC 173-220-180(5), shall terminate upon coverage by the general permit.")?

- In response to comments, can Ecology explain whether coverage under the general permit will be mandatory or voluntary?

COMMENT NO. 3: THE SSM DOES NOT HAVE THE PRECISION TO PREDICT WATER QUALITY (DO) IMPAIRMENTS

Ecology is misusing the Salish Sea Model (SSM) to drive an ineffective general permit. Using models to calculate wasteload allocations is entirely different from using models to predict the impact of nitrogen discharges on dissolved oxygen (DO) levels. Ecology's own guidance on water quality assessments requires the use of actual data to establish a water quality impairment for DO. Water Quality Policy 1-11 Chapter 1, at 50 (Ecology 2020)(Pub. No. 18-10-035). The SSM would be extremely useful in designing strategies for reducing impacts for various sources of Nitrogen. It is completely inappropriate for assessing water quality. Models have been used to predict DO in a waterbody and even to help calculate wasteload allocations. In these cases they have been compared against water quality samples not as Ecology has done here, by simply comparing the results of two hypothetical model runs. No model, not the SSM or the Chesapeake Bay or the San Francisco Bay model, has the precision to estimate 0.2 mg/L difference between two model runs. Indeed, the 2019 bounding scenarios report includes an assessment of the Mean Square Error (MSE) of the SSM. The MSE indicates that DO levels can be predicted within an error of 0.8 mg/L, an error rate that is nearly an order of magnitude greater than 0.2mg/L standard. Thus the SSM cannot determine if the water quality standard is being met. Ecology has presented no evidence of near field, or localized, impacts. If Ecology believes the model is capable of predicting far field impacts, that information should be used in constructing individual permits.

The Fact Sheet, at 31, states that following review, "Ecology will use the draft Puget Sound Nutrient Reduction Plan (NRP) to assign the applicable allocations, possibly at the basin level." If the ultimate outcome of the SSM is to derive waste load allocations, Ecology should use the TMDL process, not a general permit to regulate individual permit strategies. Ecology incorrectly claims that the "benefits of this alternative restoration plan approach include achieving cleaner water more quickly than a traditional TMDL and improved opportunities for stakeholder input throughout the document development." *Id.* This is clearly not the case. Assuming there is an impairment, Ecology's process does nothing to address the problem for at least five years when WQBELs are supposed to be established. A TMDL approach would more precisely (and probably more accurately) identify where the impairments are so that a more targeted strategy including effluent limits and non-point source reductions could be employed sooner.

The proposed process takes a sledge hammer approach that will have a minor, if any, effect everywhere and a major impact nowhere.

Ecology cites the 2019 Bounding Scenarios Report to support a conclusion that Puget Sound is impaired due to low DO. Ecology has not explained its reasoning or process for how it determined that there is a reasonable potential to exceed water quality standards. EPA guidance refers to the model selection decision tool (MSDT) available in the Nutrient Management Toolbox (NMT), a process which requires the permit writer to go through a series of steps to determine which modeling approach is best to use in a reasonable potential analysis. Neither the Fact Sheet nor the Permit give any indication that Ecology has gone through the proper steps to select the correct model and used the correct procedures to perform a reasonable potential analysis. A conclusion of reasonable potential to exceed a water quality (nutrient) standard requires Ecology to link nutrient loads to ecological response indicators for purposes of developing nutrient criteria or setting allowable load based response. This requires Ecology to identify the dominant habitat and ecological responder. Ecology has not done this and in fact has used a blanket approach that evaluates all of Puget Sound including shallow embayments and depths greater than 30 meters and lumps them together. Ecology has failed to identify the ecological responder as wells as the dominant habitat of the ecological responder.

COMMENT NO. 4: ECOLOGY HAS NOT PROVIDED ADEQUATE INFORMATION FOR A MEANINGFUL COMMENT ON THE REASONABLE POTENTIAL ANALYSIS THAT FORMS THE BASIS FOR THE GENERAL PERMIT

EPA and Ecology regulations require sufficient information to evaluate and comment on the basis for a NPDES permit. This information must be set forth in a draft Fact Sheet that is available for public review at the time a draft NPDES permit is issued for public comment. In the case of the Permit, Ecology has relied entirely on the 2019 Bounding Scenarios Report and the SSM model runs described therein. The Fact Sheet and report lack sufficient information for Tacoma to comment on the reasonable potential determination.

Tacoma made several requests to Ecology to obtain documentation on the assumptions and values that were used in the Bounding Scenarios Report SSM. Despite receiving thousands of pages of documents there is no documentation by Ecology of the values that were inputted to the SSM. Tacoma cannot determine, for example, how the inputs assigned its plants or any other plants were calculated. There is no document that can be identified that explains this information. Likewise, and again despite repeated requests, there is no documentation of how the model results were processed. The Bounding Scenarios Report provides a single set of figures that depict models cells that apparently fall below the applicable DO standard. It is impossible to determine from this generalized information what exact cells fall into this category, which layers of the cell were deemed impaired, and the duration of such impairment.

It appears from Ecology presentations that many, if not most, of the cells that Ecology deems to be impaired in the Bounding Scenarios Report and for the purposes of the reasonable potential analysis for the Permit were from modeled results in the deepest of ten layers for each cell in the SSM. This is contrary to the DO water quality standard under WAC 173-201A-210(d)(iii) where the standard must be applied to the "dominant aquatic habitat." Since the standards are based on salmon habitat, there is no basis for finding an impairment or interpreting the model results from deep layers in the model cells to make a reasonable potential determination.

Likewise, Ecology's WQP 1-11 is clear that data, or in this case model results, should not be used "if a water column meets the criterion except at depths close to the sediment interface." WQP 1-11, Ch. 1, Page 50. Ecology's own policy states that it is not appropriate to attribute a criterion exceedance to the data since "DO levels near the sediment interface are naturally depleted in certain waters." WQP 1-11, Ch. 1, Page 51.

Tacoma has been attempting to reverse engineer the SSM runs done by Ecology for the bounding scenarios report. This effort is compounded by the fact that Ecology did the modelling internally, with no documentation, and without any external peer review. Tacoma cannot provide meaningful comments on the reasonable potential analysis forming the basis for the Permit without completing this work.

Questions:

- In response to comments, can Ecology disclose how it processed it the results from the SSM modeling to make impairment determinations used in its reasonable potential analysis?

- In response to comments, can Ecology explain the extent of cells deemed out of compliance with DO standards based solely on model results in the deepest layer of a cell?

- In response to comments, can Ecology explain if WQP 1-11 represents the current interpretation and application of the marine DO water quality standard?

- In response to comments, can Ecology explain if it has adopted a new DO standard in the manner in which it has processed and applied the results from the SSM described in the Bounding Scenario Report?

COMMENT NO. 5: A TMDL WOULD BE THE MORE EFFECTIVE APPROACH TO MAINTAINING AND IMPROVING WATER QUALITY

Assuming there is an impairment, Ecology's proposed process does nothing to address the problem for at least five years when WQBELs may be established. A TMDL approach would more precisely and probably more accurately identify where the impairments are so that a targeted strategy including WQBELs and non-point source reductions could be employed. In addition a TMDL approach would more likely result in waste load allocations that would provide reasonable assurance that water quality standards will be achieved. The proposed process takes a sledge hammer approach that will have a minor, if any, effect everywhere and a major effect nowhere.

COMMENT NO. 6: THE DRAFT NARRATIVE WATER QUALITY-BASED EFFLUENT LIMITS (WQBELS) DO NOT CONTROL DISCHARGES AS NECESSARY TO MEET APPLICABLE WATER QUALITY STANDARDS FOR DO

As Ecology admits it does not have the data to determine if this Permit will control discharges in a manner that will result in meeting water quality standards. Ecology has further determined that current levels of TIN in WWTP effluent are causing or contributing to violations of the DO standards in Puget Sound. See Fact Sheet, Page 30. Ecology has not proposed a monitoring program that adequately measures DO in the “impaired” water bodies. Without this data there is no way to tell whether the proposed actions in the Permit have any impact on DO.

Questions:

- In response to comments, can Ecology explain whether discharges from a facility at or below the total inorganic nitrogen action levels in Condition S4.B will cause or contribute to a violation of water quality standards?

- In response to comments, can Ecology explain how the proposed permit narrative effluent limits will meet water quality standards for DO?

- In response to comments, can Ecology explain whether a facility in full compliance with the permit and discharging total inorganic nitrogen at or below

action levels in Condition S4.B will be meeting water quality standards for dissolved oxygen? Can Ecology explain the basis for its answer to this question?

COMMENT NO. 7: THE ACTION LEVEL CALCULATION DATA SET IS TOO SMALL

Ecology recognizes that most facilities did not have adequate data sets to represent the Nitrogen discharge from the facilities covered under the Permit. Ecology developed a calculation tool for ALo that uses a nonparametric method called "bootstrapping" to calculate the annual load from facility data.

Bootstrapping disregards the underlying problem that Ecology does not have a data set that accurately represents nitrogen discharges from the covered operators. In addition, some operators had only quarterly data which Ecology extrapolated in an illogical attempt to represent the variability. Using extrapolated data in the bootstrapping calculation destroys what little statistical validity existed in the bootstrapping analysis. The action level that Ecology is using is an annual total load of TIN. The bootstrapping analysis is based on monthly averages. The confidence interval calculated, that is the basis for the action levels, is based on the estimated monthly mean not the annual load. This greatly exaggerates the precision of this estimate and could result in a high probability of immediate exceedances of the action level. Tacoma estimates that it has a one in five chance of exceeding the action level in the first year of the Permit.

There is no way that meaningful confidence intervals for annual loads can be calculated from monthly data, particularly if the extrapolation and bootstrapping have been used to artificially increase the sample size. Ecology should design and require a sampling program for each plant to more precisely estimate current nitrogen discharges before setting effluent limits or action levels. Ecology should defer setting action levels until more data is collected.

Additionally, Ecology's reference for Bootstrapping in the bibliography is not reliable.

Bootstrapping (statistics). (2021, May 7). In *Wikipedia.*
https://en.wikipedia.org/w/index.php?title=Bootstrapping_(statistics)&oldid=1021858475) [11]

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COMMENT NO. 8: ALTERNATIVE RATE STRUCTURES ARE NOT LEGAL UNDER STATE LAW OR THE WASHINGTON STATE CONSTITUTION

Ecology has recognized that the financial impact of the costs of treatment can create an unreasonable burden upon communities served by wastewater treatment plants. See, *Northwest Environmental Advocates v State*, 2021 Wash. App. LEXIS 1558 (2021). Overburdened communities will bear a significant and disproportionate burden of the cost of compliance with the Permit.

While the City appreciates Ecology's effort to address environmental justice by requiring an affordability assessment, the assessment will do nothing to address the disparate impact of the cost burden of the Permit upon communities of color, Tribes, indigenous communities, and low income populations. State law does not allow dischargers to create rate classifications based upon ability to pay, except as authorized pursuant to RCW 74.38.070 for low-income citizens. See, RCW Chapters 35.67 and 35.92. Tacoma already has a program for rate reductions under this statute. All other rate classifications must be based upon the cost of service and must be allocated equitably based upon service received. See generally, *King County Water Dist. No. 75 v Seattle*, 89 Wn. 2d 890, 903 (1978). A utility has a duty to fix rates that are just and reasonable and not unduly discriminatory. *Faxe v Grandview*, 48 Wn. 2d 342, 347 (1956).

Rates must comply with Article 1 § 12 of the State Constitution which requires that rates be non-discriminatory, meaning that rates apply alike to all persons within a class, and that there must be a reasonable ground for creation of different rate classifications. *Faxe*, 89 Wn. 2d at 348. Rate classifications under state law are based upon such factors as cost of service, the character of the service furnished, or the quantity or amount received. *Faxe*, 89 Wn. 2d at 349-350. State law sets for the criteria in Chapter 35.67 and 35.92 RCW. Neither state law nor the state constitution allow rate classifications based upon an affordability assessment with the exception of low income rate reductions authorized under state law and which are already being implemented. Accordingly, the concept of a study and proposal for rate alternatives only serves to create false hope that the enormous impact of funding the cost of treatment can be more equitably distributed. Further, it will not address the reasonableness of the overall costs of compliance to be borne by all of the rate payers.

Question:

- In response to comments, can Ecology explain what assessment Ecology has made to address environmental justice impacts from the proposed permit?

- **In response to comments, can Ecology explain how the requested report will be used to regulate NPDES permits for publically owned WWTPs?**

COMMENT NO. 9: ADAPTIVE MANAGEMENT

Tacoma supports an adaptive management approach, however the Permit does not include the basic tenet of adaptive management. Adaptive management is based off of the Deming Cycle of plan, do, study, act.

Determine Management Objectives:

Ecology's stated management objective for the first Permit is to "prevent the dissolved oxygen problem in Puget Sound from getting any worse." To that end, Ecology's key desired outcome would be to prevent DO levels from declining throughout Puget Sound. The key performance indicator would be DO.

The problem is that there is no provision in the Permit that requires DO to be measured or to use that data in determining the success or failure of any actions taken. The performance provisions in the Permit are limited to the total nitrogen loading from the WWTPs. Presumably this data will be used to do additional model runs that will tell us that DO conditions have improved. But without actual measurements of DO all we will know is that we have successfully manipulated the model. A robust monitoring program designed to detect improvements in DO levels is absolutely essential to a successful adaptive management program.

The ultimate management objective of the Permit is to improve DO conditions in Puget Sound. Assuming that limiting TIN loads from marine dischargers will actually have a meaningful impact on DO impairment, Ecology should use the first Permit cycle to collect the data necessary to inform the strategies for accomplishing the ultimate objective. Rather than write plans that may never be implemented or implement strategies that will, at best, maintain the status quo, Ecology should use the first Permit cycle to develop strategies and actions that most efficiently and effectively achieve target DO levels.

Implement Strategies and Actions to Achieve Objectives:

Ecology's timeframes for implementation are far too short. Once a strategy has been selected and appropriate metrics determined, baseline data must be collected to determine the nominal state before implementation of the strategy. If we don't know where we began, how will we know how far we have travelled or if there has been any meaningful benefit from reduction of nutrient loads from marine dischargers? Measurement of the effectiveness of a strategy is the basis of adaptive management. Collecting baseline data can take months. Actually implementing the strategy can take months to years depending on the amount of construction involved and the difficulty in optimizing the process change. Finally the action must proceed for a long enough period of time that any differences can be reliably measured.

Evaluate Management Effectiveness:

The time required for data collection, strategy development and implementation suggest long term objectives rather than short term, first Permit cycle, objectives should be the focus of adaptive management.

COMMENT NO. 10: CONDITION S3 – COMPLIANCE WITH STANDARDS

The Permit provides as follows:

> A. Discharges must not cause or contribute to a violation of surface water quality standards (Chapter 173-201A WAC), sediment management standards (Chapter 173-204 WAC), and human health-based criteria in the Federal water quality criteria applicable to Washington (40 CFR Part 135.45). This Permit does not authorize discharge in violation of water quality standards.

Permit, Condition S3.A

Ecology has determined that WWTPs discharges are causing or contributing to violations of the DO standards in Puget Sound. Fact Sheet, at 30. Indeed Ecology has determined that excess nutrients discharged from WWTPs in one location cumulatively contribute to DO impairments in other locations due to the water exchange that occurs between basins. *Id.* Based on these determinations compliance with the conditions of Permit will not result in meeting water quality standards putting dischargers in immediate violation of Condition S3.A of the Permit. Accordingly, the Permit will not meet the requirements of the CWA because compliance with the permit will not result in meeting water quality standards.

Questions:

- In response to comments, can Ecology explain the scope of the prohibition in Condition S3 in the permit? Does the prohibition only apply to TIN?

- In response to comments, can Ecology explain the basis for its presumption that compliance with permit conditions will result in compliance with water quality standards?

- In response to comments, can Ecology explain whether discharges from a facility at or below the total inorganic nitrogen action levels in Condition S4.B will cause or contribute to a violation of water quality standards?

- In response to comments, can Ecology explain the basis for its presumption in Condition S3 that compliance with permit conditions will result in compliance with water quality standards?

- In response to comments, can Ecology explain whether discharges from a facility at or below the total inorganic nitrogen action levels in Condition S4.B will cause or contribute to a violation of water quality standards?

- In response to comments, can Ecology explain whether the reasonable potential determination in the Draft Fact Sheet, at 30, constitutes site specific information for each facility covered under the permit that the facility has a discharge that is causing or contributing to a violation of water quality standards?

COMMENT NO. 11: S4.A APPLICABILITY OF NARRATIVE EFFLUENT LIMITS

Condition S4 does not meet the requirements under 40 CFR §§ 122.44(d) and (k) for establishing narrative effluent limits. Effluent limits means any restriction, prohibition, or specification established by the Ecology in a permit on:

> . . . (a) Quantities, rates, percent removals, and/or concentrations of physical, chemical, or biological characteristics of wastes which are discharged into waters of the state; and (b) Management practices relevant to the prevention or control of such waste discharges.

WAC 173-221-030.

When Ecology has determined that there exists a reasonable potential for a discharger to cause, or contribute to an excursion above any water quality standard for a particular pollutant, the Permit must contain effluent limits for that pollutant. See, 40 CFR § 112.4(d). Best management practices may be used in lieu of a numeric effluent limit when numeric effluent limitations are infeasible. 40 CFR § 122.44(k)(3). Best management practices (BMPs) means,

> . . . schedules of activities, prohibitions of practices, maintenance procedures, and other management practices to prevent or reduce the pollution of ''waters of the United States.'' BMPs also include treatment requirements, operating procedures, and practices to control plant site runoff, spillage or leaks, sludge or waste disposal, or drainage from raw material storage.

See, 40 CFR § 122.2

Ecology acknowledges in the Fact Sheet that under 40 CFR § 122.44 the Permit must contain effluent limits to control pollutants which have the reasonable potential to cause an excursion above water qualities standards. Fact Sheet, at 33. As noted above, Ecology has stated in the Fact Sheet that it has determined that domestic wastewater discharges may cause or contribute to a violation of water quality standards for DO. See, Fact Sheet, at 34. If Ecology stands by this determination, numeric WQBELs are required to be included in the Permit. See, 40 CFR § 122.44(d). The Permit does not meet the requirements of 40 CFR § 122.44(d) for the following reasons.

As noted above, narrative effluent limits may be used in lieu of a numeric effluent limit when numeric effluent limits are infeasible. 40 CFR § 122.4(k)(3). However, Ecology has acknowledged that not only is it feasible to establish numeric water quality limits, it plans to do so in the second iteration of the Permit. Fact Sheet, at 33.[3] The fact that it will take more time to perform additional model runs to establish numeric effluent limits does not mean that it is infeasible to do so. Accordingly, the Permit does not meet the requirements of 40 CFR § 122.44(k)(3). The Permit also fails to comply with NPDES permit regulations because it does not require actions that will result in meeting water quality standards. 40 § CFR 122.44(k)(4). At best the Permit will require compliance with actions levels that Ecology has determined are causing violations of the DO water quality standard throughout Puget Sound.

Table 4 (Condition S4) sets forth what are labeled "Narrative Effluent Limitations for Dominant TIN Loaders" that include three items: (1) monitoring and reporting, (2) nitrogen optimization plan, and (3) a nutrient reduction evaluation. The Permit and Fact Sheet do not explain how these narrative effluent limitations will result in compliance with water quality standards as required under EPA and Ecology regulations.

In *Washington Dairy Federation v. Department of Ecology*, 2021 WL 2660024, *13, __ Wn. App. ____ (Div. II June 29, 2021) (citing WAC 173-226-100(1)(j)(ii)), the court ruled that with NPDES Ecology must "issue a fact sheet that includes an explanation of how the permits meet groundwater and surface water quality standards."

<u>Questions:</u>

- In response to comments, can Ecology explain how these narrative effluent limitations will result in compliance with DO water quality standards?

- In response to comments, can Ecology explain whether a facility in full compliance with the permit and discharging total inorganic nitrogen at or below action levels in Condition S4.B will be meeting water quality standards for dissolved oxygen? Can Ecology explain the basis for its answer to this question?

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[3] "Ecology continues to review model results from the first year of optimization scenarios and scope future model runs through the Puget Sound Nutrient Forum. Additional model runs will be defined in 2021 to further quantify far and near field effects of wastewater discharges to marine waters along with the anthropogenic nutrient loads from Puget Sound watershed. Once Ecology can establish a nutrient loading capacity that meets DO criteria in the marine waters of Puget Sound, allocations that will lead to numeric WQBELs can be established. The NRP will include draft allocations for point sources and watershed inflows. After internal and external review, the allocations will be finalized and numeric WQBELs will no longer be infeasible. It is anticipated that for the second iteration of this permit the approach will shift to working towards compliance with those numeric limits." Fact Sheet, at 33.

COMMENT NO. 12: TIN ACTION LEVELS

Table 5 in the Permit includes "action levels" for TIN applicable to some WWTPs.

Questions:

- In response to comments, can Ecology explain how the actions levels were calculated?

- In response to comments, can Ecology explain the basis and information that were used to derive the action levels?

- In response to comments, can Ecology explain if the actions levels were calculated at a level to achieve compliance with DO water quality standards?

COMMENT NO. 13: CONDITION S4.A NITROGEN OPTMIZATION PLAN AND REPORT

Condition S4.A requires a permittee to develop and implement a Nitrogen Optimization Plan and apply an adaptive management approach at the WWTP. Ecology has not adequately defined what optimization means and how an operator can determine if it has optimized or how Ecology or a third party will determine if the operator has optimized. The Permit defines "optimization" as a BMP resulting in the refinement of WWTP operations that lead to improved effluent water quality and/or treatment efficiencies. By Ecology's own admission, optimization does not have a large impact on the perceived DO impairment. A more effective measure would be to put effort into determining WQBELs and begin planning design and construction of facilities that would actually have a significant impact on DO impairment, assuming there is an impairment.

Nitrogen Optimization Plan and Report. If a plant initially optimizes for maximum Nitrogen removal and then exceeds the Action Level, the Permit does not explain what adaptive management strategies are available since the WWTPs have presumably already optimized for maximum nitrogen removal.

Ecology's requirement that optimization strategies be planned and implemented in under a year is unrealistic. The facility must select a strategy, define metrics, measure the baseline data, and implement the strategy and then using the selected metrics determine if the strategy works. It is not feasible to complete this work within one year.

Question:

- In response to comments, can Ecology explain if a plant initially optimizes for maximum nitrogen removal but exceeds the action level, then what adaptive management strategies are left since they have presumably already optimized for maximum nitrogen removal?

COMMENT NO. 14: CONDITION S4.C NITROGEN OPTIMIZATION PLAN AND REPORT

Condition S4.C.1.b requires that the nitrogen optimization plan determine the optimization goal(s) for the WWTP. It is not clear from this language what goal or goals should be considered other than maximizing nitrogen removal. In the same section of the Permit Ecology allows the plan to exclude any strategy that would exceed a one year timeframe. There are no strategies for optimizing nitrogen removal at Tacoma facilities that can be developed, tested, modelled, and implemented in under a year.

In Condition S4.C.2.a.iv requires documentation of any impacts to the overall treatment performance as a result of process changes. Ecology does not explain how a facility, or how Ecology, will address potential negative impacts from optimization to overall treatment performance. It is not clear if a facility may violate its individual permit if negative impacts result from implementing optimization efforts, or whether negative impacts from optimization will be addressed in modified or reissued individual permits. It is not clear if optimization strategies that will have negative impacts to overall treatment performance must be considered.

Condition A4.C.2.b.i requires a load evaluation by March 31 each year to determine the facility's annual average TIN concentration and load from the reporting period. Since there will only be one year of data in year two of the Permit, it is impossible to calculate an annual loading average.

Condition S4.C.3.b requires identification of strategies for reducing TIN from new multi-family/dense residential developments and commercial buildings. The Fact Sheet does not explain or provide any guidance on what strategies should be considered under this condition of the Permit.

Condition S4.D.1.c requires, when a facility exceeds its action level, it must include in its next Annual Report a proposed approach to reduce the annual effluent nitrogen level by 10 percent. The Permit does not explain how a facility can be capable of obtaining an additional 10 percent reduction in loading if it has already reduced nitrogen loading to the maximum extent under the Permit.

The Fact Sheet, at 44, cites two EPA Case Studies on Implementing Low-Cost Modifications to Improve Nutrient Reduction at Wastewater Treatment Plants (2015) as a resource for evaluating alternatives for optimizing nitrogen reductions at activated sludge plants. The EPA study concluded that most opportunities for optimization were only found in facilities with existing BNR capabilities. The EPA document does not apply to the Tacoma facilities and Ecology has cited no other guidance for optimization alternatives.

The Fact Sheet, at 47, suggests that facilities evaluate strategies for reducing nitrogen loading including increasing production volumes of reclaimed water (if applicable to the facility), implementing side stream treatment for a portion of return flows from solids treatment, reducing influent nitrogen loads, alternative effluent disposal options and any other intermediate treatment alternative which results in decreased nitrogen loads into Puget Sound prior to major facility upgrades. All of these alternatives require substantial capital investment or growth moratoria. This is contrary to the previous statement that substantial capital investment would not be part of the optimization program.

Questions:

- In response to comments, can Ecology explain how a facility can document the exclusion of optimization strategies under this section?

- In response to comments, can Ecology explain whether Condition S4.C.1.b applies to consideration of an additional 10 percent reduction – namely, that a

facility does not need to consider optimization strategies that exceed a reasonable implementation cost or timeframe that exceeds one year?

- In response to comments, can Ecology explain the consequence to a facility if there are no optimization strategies that can reasonably be implemented to reduce nitrogen loading by an additional 10 percent within five years?

- In response to comments, can Ecology explain whether a facility will be in violation of the permit where there are no reasonably available optimization strategies to achieve a 10 percent reduction in annual nitrogen loading?

COMMENT NO. 15: CONDITION S4.E NUTRIENT REDUCTION EVALUATION

Condition S4.E.2 states that a facility must submit an "approvable" nutrient reduction evaluation report. There is no regulatory standard for nutrient reduction evaluation report and no basis for a permittee to know what might constitute an approvable or unapprovable evaluation. The Permit states that the nutrient reduction evaluation must include an AKART analysis. Since Ecology has determined, and the state courts have affirmed, that BNR and other tertiary treatment technology are not AKART for Puget Sound WWTPs, it is assumed that these technologies do not have to be considered in the evaluation. The Permit and Fact Sheet do not provide any explanation or basis for considering these types of treatment technologies as AKART.

Condition S4.E.3 of the Permit requires consideration of treatment technologies to achieve an effluent concentration of 3 mg/L. The Permit and fact sheet do not explain the basis for this requirement and how this requirement applies in the context of the Condition S4.E.2 AKART evaluation. It is assumed that a facility does not need to include an evaluation of any technology that would not constitute AKART.

Question:

- In response to comments, can Ecology explain what specifically constitutes an "approvable" Nutrient Reduction Evaluation?

- In response to comments, can Ecology explain the basis for inclusion of a requirement to evaluate treatment technologies to achieve TIN effluent concentrations of 3 mg/L?

COMMENT NO. 16: CONDITION S4.E.5.C IS VAGUE

Condition S4.E.5.c requires an environmental justice review and affordability assessment for what "overburdened communities" can afford to pay for the wastewater utility. There is no explanation as to what constitutes an overburdened community or how to determine what a member of an overburdened community can afford to pay for the wastewater utility. It is not clear the basis on which Ecology is asking for this information. There are no regulatory standards under Ecology regulations for the assessment and there is no basis for a facility under the state constitution or state statutes to vary the utility rates of its customers based on environmental justice. This is an assessment that Ecology should undertake on its own initiative prior to issuance of the Permit.

COMMENT NO. 17: CONDITION G25 BYPASS PROHIBITED

General Condition G25 imposes a bypass prohibition that directly modifies the administratively extended individual permits for the Tacoma facilities. This is a clear violation of federal and state regulations and case law that prohibit the modification of expired and administratively extended permits. This condition cannot lawfully be included in a general permit applicable to the Tacoma facilities.

COMMENT NO. 18: SEPA COMPLIANCE

Ecology should withdraw its SEPA determination for the Permit and prepare an environmental impact statement. Ecology acknowledges that a "modification of permit coverage for physical alterations, modifications, or additions to the wastewater treatment process that are substantially different from the original design and/or expands the existing treatment footprint requires State Environmental Policy Act (SEPA) compliance." Ecology is incorrect, however, in concluding that optimization does not require additional SEPA review. The draft Fact Sheet, at 47, suggests that facilities evaluate strategies for reducing nitrogen loading including increasing production volumes of reclaimed water, if applicable to the facility, implementing side stream treatment for a portion of return flows from solids treatment, reducing influent nitrogen loads, alternative effluent disposal options and any other intermediate treatment alternative which results in decreased nitrogen loads into Puget Sound prior to major facility upgrades." All of these alternatives will require substantial capital investment or some sort of growth moratoria by Tacoma.

The Tacoma facilities were not designed for de-nitrification and the optimization alternatives proposed by Ecology will require modifications that subject the Permit to SEPA review under an environmental impact statement.

Additionally, condition S4.C.3.b requires identification of strategies for reducing TIN from new multi-family/dense residential developments and commercial buildings. This condition requires Tacoma to propose development regulations that would trigger SEPA review. See, WAC 365-196-620 (Adoption of comprehensive plans and development regulations are "actions" as defined under SEPA. Counties and cities must comply with SEPA when adopting new or amended comprehensive plans and development regulations.)

Regardless of the applicability of any SEPA exemption, Ecology is also required to assess the potential climate impacts from the optimization requirements and the evaluation of treatment technologies, particularly treatment technologies that can achieve an effluent concentration of TIN at 3 mg/L. These alternatives will have a profound impact on energy consumption at the Tacoma facilities. *See Washington Dairy Federation v. Department of Ecology,* 2021 WL 2660024, *23 ___ Wn. App. ____ (Div. II June 29, 2021) (Ecology must consider climate change impacts in issuing a NPDES permit).

COMMENT NO. 19: PERMIT LIMITS BASED ON CURRENT TIN LOADING CONFLICT WITH TACOMA'S OBLIGATION TO PROVIDE WASTEWATER SERVICES WITH THE SERVICE AREAS OF ITS FACILITIES

Ecology has improperly based numeric effluent action levels on calculated levels of TIN loading from flow data and nitrogen concentration data in recent years. Tacoma is obligated under the Growth Management Act to accept and facilitate growth within the applicable urban growth boundaries. Associated with this obligation is the parallel requirement under its NPDES permits to maintain sufficient capacity to provide wastewater treatment within the service areas of its two facilities. This is a permit condition in both of the individual NPDES permits issued by Ecology and a requirement that is reflected in the general facility plans and engineering documents generated by Tacoma under WAC 173-240-050 and WAC 173-240-060. By adopting an effluent limit based on current loading and concentrations Ecology will be denying Tacoma any ability to provide for anticipated growth or leave the City in violation of its individual permits. Moreover, Ecology is locking in effluent limitations that fail to consider the permitted design flows for its facilities and that may be irrevocable under state and federal water quality anti-backsliding regulations. This is a critical issue that should compel Ecology to abandon the Permit until it has completed a DO TMDL for Puget Sound and is able to address nitrogen issues in individual NPDES permits.

Questions:

- In response to comments, can Ecology explain why it has not considered design flows and the need to maintain treatment capacity in setting effluent limitations in the permit?

- In response to comments, can Ecology explain whether the general permit will supersede and modify the obligations in the individual Tacoma permits to maintain treatment capacity within the service areas of the facilities?

- In response to comments, can Ecology explain whether, based on the general permit, the department will now consider void those portions of Tacoma's general sewer plan and engineering reports that are based on providing and maintaining wastewater treatment capacity within the respective service areas of its two facilities?

- In response to comments, can Ecology explain how it has evaluated the likelihood that Tacoma will have to put building moratoria in place to meet the proposed effluent limitations?

- In response to comments, can Ecology explain how it has evaluated the impact of the effluent limitations on the ability to develop low and moderate income housing?

- In response to comments, can Ecology explain how it has evaluated the potential environmental justice concerns that will result from reduced access to affordable housing?

- In response to comments, can Ecology explain how it has evaluated the applicability of anti-backsliding regulations to the proposed effluent limitations?

Thank you for this opportunity to comment on the Puget Sound Nutrient General Permit. We trust our comments are useful. If you have any questions or would like additional information please contact Daniel C. Thompson, Ph.D at 253 502-2191 dthompso@cityoftacoma.org.

Sincerely

Michael P. Slevin III, P.E.

Michael P. Slevin III, P.E.
Environmental Services Director

POLLUTION CONTROL HEARINGS BOARD
STATE OF WASHINGTON

KING COUNTY, Appellant, v. WASHINGTON STATE DEPARTMENT OF ECOLOGY, Respondent.	Case No. 21-083 **DECLARATION OF CHRISTIE TRUE**

1. My name is Christie True. I make this Declaration in support of the County's Motion to Stay.

2. I am over the age of eighteen (18) and declare the following facts are true to the best of my recollection, and that I have personal knowledge of the same.

3. I am the Director of King County's Department of Natural Resources and Parks. In that capacity, I oversee, and am responsible for the County's operation of its wastewater treatment plants ("WWTPs" or "Plants"), including King County's Brightwater Plant, its South Plant, its Vashon Plant, and its West Point Plant. The WWTPs and their operations, including the costs of compliance with regulatory requirements and permit, are funded by fees that the County charges to users of the WWTPs.

4. Each of these Plants is currently regulated by an individual National Pollutant Discharge Elimination System ("NPDES") permit issued by the Department of Ecology

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("Ecology") as follows: Brightwater is covered by #WA0032247, which expires on February 28, 2023; South is covered by #WA00295810, which expired on July 31, 2020 but which has been administratively extended; West Point is covered by #WA00029181, which expired on January 31, 2020 but which has been administratively extended; and Vashon is covered by #WA022527, which expires on February 28, 2022 but which I anticipate will be administratively extended. Copies of these individual permits are attached to the County's Motion to Stay.

5. Ecology issued the Puget Sound Nutrient General Permit ("PSNGP" or "Permit") on December 1, 2021, which becomes effective on January 1, 2022. Although the County's four WWTPs are already covered by existing individual NPDES permits, the PSNGP requires the County to apply for coverage for these four WWTPs under the PSNGP by March 1, 2022. The PSNGP applies to discharges of nutrients from the WWTPs and will simultaneously regulate the WWTPs along with their existing individual NPDES permits. King County has appealed the PSNGP and now moves to stay its effectiveness as to the County's four WWTPs.

6. The PSNGP requires the County to immediately begin complying with a number of onerous requirements, including (i) additional sampling, monitoring, and reporting requirements for each of the County's WWTP's dischargers, including monitoring for Total Inorganic Nitrogen ("TIN"); (ii) developing and implementing for each of the WWTPs a Nitrogen Optimization Plan to maximize nitrogen removal; (iii) compliance with assigned TIN discharge "action levels" established under Condition S4.D of the Permit for each of the County's individual WWTPs, or alternatively, compliance with the cumulative or "bubbled" action level assigned to the County's three Plants classified by the Permit as "dominant dischargers"; and (iv) compliance with the PSNGP's generic prohibitions on causing or contributing to a violation of surface water quality standards, sediment management standards, and human health-based water quality criteria. These immediate obligations will require a significant amount of staff and outside consultant time and effort and will cost the County *tens of*

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millions of dollars in the next two years, in addition to continuing to comply with all the requirements of the WWTPs' individual NPDES permits, which will remain fully in effect.

7. More specifically, the PSNGP now requires the County to begin enhanced monitoring of the influent and effluent at each of its four WWTPs as well as monthly permit required DMR reporting. Conditions S7.A, S7.C. That will involve additional sampling and sample transport, analytical testing and associated lab practices, documentation and reporting, and the need to purchase additional equipment. This will also require the County to hire two new staffers. The total cost of this additional sampling, monitoring, and recording will be about $350,000 annually.

8. In addition to the enhanced monitoring, reporting and record keeping required under Conditions S7.A and S7.C described in ¶ 7 of this declaration, the PSNGP immediately requires the County to begin developing, preparing, and implementing a "Nitrogen Optimization Plan and Report" for each of the WWTPs pursuant to Conditions S4.C. and S6.B of the Permit. Because domestic wastewater treatment plants are not currently designed to remove nitrogen, the purposes of these optimization requirements are to "maximiz[e] nitrogen removal from the existing treatment plant[s] to stay below the calculated action level[s] "applicable to the three "dominant" WWTPs (South Plant, Brightwater, and West Point) and to "maximiz[e] nitrogen removal from" the "small" WWTP (Vashon). Conditions S4.C, S6.B. The Permit emphasizes that **"the Permittee must begin the actions described in this section immediately upon permit coverage."** *Id.* (emphasis in original). Condition S4.C.1.c requires the County to identify viable optimization strategies for each "dominant" WWTP owned and operated by the County, and to select **by July 1, 2022** at least one optimization strategy for implementation. Condition S6.B.1.b requires the County to identify the optimization strategy selected for implementation at the "small" WWTP by **December 31, 2022.**

9. To comply with Conditions S4.C. and S6.B the County must 1) select optimization strategies by July 1, 2022, and December 31, 2022, respectively, and 2) implement

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the selected optimization strategies and submit annual reports beginning in March 2023. The County will have to dedicate 7 of its current staff to this effort on a full-time basis. To backfill these staff, the County will have to hire new employees. The labor costs associated with this requirement alone are estimated to be $700,000 for the first two years for optimization planning and $1,200,000 for optimization implementation in the same two years. The County will also have to hire outside consultants to assist with these optimization planning efforts at an expense of approximately $500,000 for the first two years. The County will have increased operating and maintenance costs associated with optimization, which are estimated to be $950,000 annually. The capital cost to implement the selected optimization strategies (e.g., install new equipment) is estimated at $5,000,000 a year per plant. Because the WWTPs and their operations are funded by fees charged to the users of the WWTPs, the County's ratepayers will ultimately bear the costs of complying with the PSNGP.

10. The County is also required to immediately *implement* the selected optimization strategy identified under Condition S4.C.1. and then document the implementation of the selected optimization strategy for each Plant by March 3, 2023. Condition S4.C.2. The immediate implementation of the PSNGP optimization requirement will adversely affect the ability of the County to complete other major capital project upgrades currently scheduled. More specifically, the immediate optimization requirements imposed by the PSNGP will have a cascading negative effect across the County's capital program resulting in the reassignment of project managers, engineers, operations staff, and construction managers. It will result in the delay of capital projects are needed to increase system reliability, maintain system capacity, reduce overflows, and maintain permit compliance. As an example of a critically impacted program, King County's West Point Capital Improvement Program ("the Program") has over $600,000,000 of active and planned projects to improve the reliability of the West Point Treatment Plant. Staff currently assigned to the Program will now need to be reassigned to comply with the PSNGP. This will result in the deferral of projects that are badly needed at

West Point to improve reliability. This increases the risk of equipment failures and may result in an increase in plant bypasses, secondary treatment bypasses, increased risks to worker safety, and ultimately, to harm to the environment.

11. Additionally, immediate implementation of nitrogen optimization strategies at each WWTP has the real potential to create externalities that are not intended, including causing the Plant to violate a provision of its individual NPDES permit. For example, South Plant operates under NPDES Waste Discharge Permit No. WA0029581 which includes a pH limit and a prohibition on the bypass of sewage around the secondary treatment process. Operating South Plant to biologically remove nitrogen will likely result in a violation of both these requirements due to reduced flow capacity and the existing configuration of the treatment plant. Condition S1.A of the NPDES Waste Discharge Permit No. WA0029581.

12. If, as a result of compliance with Condition S4.C, the County determines that the Plant's annual TIN load exceeds its assigned action load (or, if applicable, the County's cumulative or "bubbled" load for all three dominant discharging Plants), then the County must proceed to take the corrective actions identified in Condition S4.D. Based on the County's data -- used by Ecology for development of the PSNGP-- the current discharge of total inorganic nitrogen (TIN) in effluent from any of the three dominant County dischargers demonstrate that the action levels, or bubbled action level, are likely to be exceeded within the first permit cycle.

13. Condition S4.D requires the County, if it exceeds its action level, to document why that happened and to identify what corrective actions will be needed to get the Plants below the action level. It must also, with the next annual report, submit a strategy to reduce the annual effluent load by *at least 10% below the action level* assigned to the individual plants or the bubbled action level for the three "dominant" plants. Condition S4.D.2. This "strategy" must be in the form of an engineering report that includes a summary of treatment alternatives considered, basic design information and influent characterization, a description of the proposed treatment approach and anticipated results from implementing that approach and have the

signature and certification of a licensed professional engineer. An engineering report sufficient to comply with the permit is estimated to cost $5,000,000 for each plant. As indicated in paragraph 10 of this Declaration, this will result in a cascading effect, delaying critical capital improvements already in the planning phase.

14. The County's election of the type of coverage must be made in the Notice of Application (NOI) process by or before March 1, 2022, before any substantive planning information can be developed to assist making an informed decision on the optimal path to Permit compliance. If the County elects Permit coverage under individual action levels for the three WWTPs, it estimates that it likely will trigger the S4.D.2. corrective action obligation to develop an abbreviated engineering report to document the actions necessary to reduce nitrogen by 10% of the action level. This Condition of the Permit is expected to be triggered on or before July 1, 2022 at its West Point Plant (even if that Plant discharges at or below its assigned action level), because the County currently knows of no "viable optimization strategies" for that Plant. *See* Condition S4.C.1.b. This could result in an extensive and stranded planning and design effort.

15. If the County exceeds an action level two years in a row, or for a third year during the permit term, the County must implement the strategy proposed in the abbreviated engineering report under a schedule negotiated with Ecology. Condition S4.D.2.a. If the County elects Permit coverage with the bubbled action level, the relatively lower optimization capacity at the West Point WWTP described above would contribute to a probability of exceeding the bubbled action level. Consequently, the County would need to identify a strategy to reduce nitrogen to 10% below the total bubbled action level which would likely require actions be implemented at two or three of the County's regional WWTPs. Should that happen, whether at any of the County's individual WWTPs, or to the 3 County WWTPs classified as "dominant dischargers" cumulatively (if the County choses to approach compliance on the basis of the "bubbled action level"), the County will be forced to prepare a combined engineering report at a cost of

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$9,000,000, and spend up to $88,000,000 for an individual treatment plant or $176,000,000 for the bubbled action level in implementing capital improvements to meet the draconian corrective action required by Condition S4.D.2.a. As explained more fully in ¶ 17 below, the investments in corrective actions could result in extensive stranded assets.

16. The County must immediately begin implementation of Condition S4.C.3 that includes, but is not limited to, "…investigate opportunities to reduce influent TIN loads from septage handling practices, commercial, dense residential and industrial sources and submit documentation with the annual report." While the County has limited institutional control over these matters, it accepts septage at the South Plant facility, has delegated authority for industrial waste pretreatment permits for all three regional plant customers, and has some land-use regulation role for unincorporated areas of the service area. Thus, the County must devote resources to work with stakeholders with direct roles in these matters, and develop and ensure compliance with the condition, including, but not limited to, 34 local sewer agencies, community engagement, local limit development, and permit writing. The County estimates that it will cost it a minimum of approximately $600,000 annually to provide the staffg needed to meet this requirement of the PSNGP.

17. The County will be irreparably harmed if the PSNGP is not stayed because the efforts outlined above that are required of the County to comply with the PSNGP will be for naught. Although Ecology is requiring the County to spend tens of millions of dollars to immediately evaluate, optimize, and modify its existing treatment systems, it is also requiring permittees to determine how each of their WWTPs will comply with a 3 mg/l TIN discharge limit as part of the required "Nutrient Reduction Evaluation" required under Condition S4.E.3. Through this requirement, Ecology is signaling that it intends to impose a 3 mg/L TIN discharge limit in the future, or perhaps an even more stringent limit, once it determines what constitutes all known and reasonable methods of treatment technology ("AKART") for domestic wastewater treatment plants that discharge nutrients to the Salish Sea, and once it determines what numeric

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water quality-based effluent limits are necessary for the County's four WWTPs to meet applicable dissolved oxygen water quality standards.

18. To meet TIN discharge limits as low as 3 mg/L at the County's four WWTPs, the County will have to employ tertiary treatment processes. For that to happen, the County will have to build new WWTPs because its existing plants were not built to remove TIN and cannot be retrofitted to accommodate tertiary treatment.

19. This means that if the PSNGP is not stayed, the County will be forced to take all the measures described in ¶¶ 6-16 herein and spend tens of millions of ratepayer dollars in the process, only to have that significant expenditure wasted when the County is forced to build new WWTPs that employ aggressive tertiary treatment methods.

20. In addition to the above, the County runs the risk of having to face an Ecology enforcement action or citizen suit filed under section 505 of the Clean Water Act ("CWA") and potential liability as a result of internally inconsistent provisions under Condition S3 of the PSNGP that render the County susceptible to being charged with discharging amounts of TIN that violate the CWA. On the one hand, Condition S3.A prohibits permittees from violating water quality standards ("WQS"), including the dissolved oxygen ("DO") standard at issue in this Appeal. On the other hand, Condition S3.B presumes that the very discharges that Ecology has authorized elsewhere in the PSNGP comply with the DO WQS. The inconsistencies between these two provisions put the County's four WWTPs at risk of immediate legal jeopardy.

21. More specifically, the Permit presumes that permittees are in compliance with the Permit and with applicable WQS so long as the permittee strictly complies with the Permit. The PSNGP establishes "TIN action levels" (Condition S3.B) for each dominant WWTP discharger that Ecology claims were established at current discharge levels. As described above, the PSNGP requires the dominant dischargers to discharge at or below those TIN action levels. *See generally*, Conditions S3, S4, and if those action levels are exceeded, to take appropriate corrective action.

22. Yet, at the same time, Ecology decided to issue the PSNGP and to make it immediately applicable to the County's four WWTPs, because Ecology has concluded that the current TIN discharges from the 58 covered WWTPs are causing or contributing to potential violations of the DO WQS. *See* Fact Sheet at 32-33 (explaining that modeling demonstrates that TIN collectively discharged from domestic wastewater treatment plants contributes to low dissolved oxygen concentrations in Puget Sound that do not meet water quality criteria). In other words, Ecology has concluded that "all wastewater discharges to the greater Puget Sound area containing nitrogen cumulatively contribute to existing DO impairments meeting the threshold for reasonable potential under 40 C.F.R. 122.44(d)(1)(iii)" Fact Sheet at 32.

23. In short, under Condition S3, Ecology has both authorized and prohibited the same discharge, rendering the County, and for that matter, all dischargers covered under the Permit, susceptible to potential liability for discharging nitrogen in amounts that the County has concluded violate the DO WQS.

24. Although the County firmly disagrees with and has appealed Ecology's conclusion that each of its four Plants are currently causing or contributing to a violation of the DO WQS (*see* Notice of Appeal at section I), Ecology's foundational premise for issuing the PSNGP and the inconsistent provisions of Condition S3 expose the County to the *immediate* prospect of potential liability under the Permit. Not only do Ecology's "reasonable potential" findings conflict with Condition S3.B and raise concerns that the Permit does not ensure compliance with WQS, they also expose the County to potential citizen suits under the CWA, 33 U.S.C. § 1365. This includes potential penalties up to $56,460 per day for allegedly discharging nutrients in a manner that violates WQS, even if the County strictly complies with the optimization planning requirements and its assigned action levels.

25. For all these reasons, together with those explained more fully in the County's stay motion, the County is being irreparably harmed by having to immediately comply with the

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PSNGP. The Board should stay the Permit's effect while it considers—and until it resolves—the County's Appeal.

I declare under penalty of perjury that the foregoing is true and correct.

12/27/2021

Executed on December __, 2021 in Seattle, Washington

DocuSigned by:
1BD15B1B73AE4A0...

Christie True
Director, King County Dept. of Natural Resources

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<u>CERTIFICATE OF SERVICE</u>

I, Lynn A. Stevens, certify and declare:

I am over the age of 18 years, make this Declaration based upon personal knowledge, and am competent to testify regarding the facts contained herein.

On December 28, 2021, I served true and correct copies of the document to which this certificate is attached on the following persons in the manner listed below:

The Department of Ecology
Appeals Coordinator
300 Desmond Drive SE
Lacey, WA 98503
[ ] Via Facsimile
[■] Via U.S. Mail
[■] Via Legal Messenger
[ ] Via Federal Express

Bob Ferguson
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I certify under penalty of perjury pursuant to the laws of the State of Washington that the foregoing is true and correct.

SIGNED on December 28, 2021 at Seattle, Washington.

Lynn A. Stevens

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POLLUTION CONTROL HEARINGS BOARD
STATE OF WASHINGTON

KING COUNTY, Appellant, v. WASHINGTON STATE DEPARTMENT OF ECOLOGY, Respondent.	Case No. 21-083 **KING COUNTY'S MOTION FOR STAY**

I. INTRODUCTION

King County ("County") moves the Pollution Control Hearings Board ("Board") for a stay of the effect of the Department of Ecology's ("Ecology") issuance of the Puget Sound Nutrient General Permit ("PSNGP" or "Permit") as it applies to the County. The Permit regulates the discharge of nutrients, including total inorganic nitrogen ("TIN"), from publicly owned domestic wastewater treatment plants ("WWTPs") to the Washington waters of the Salish Sea. Fact Sheet for the Puget Sound Nutrient General Permit ("Fact Sheet") at 2. The PSNGP requires the County, by March 1, 2022, to apply for coverage under the PSNGP for its four WWTPs that discharge to Puget Sound: the Brightwater, South, Vashon, and West Point WWTPs.

The Board should grant the stay because the County is likely to succeed on the merits of the appeal and because the PSNGP will cause the County irreparable harm if the stay is not granted. The County is likely to succeed on the merits for the reasons set forth in the County's

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Notice of Appeal. These reasons include but are not limited to the PSNGP's inconsistency with the federal Clean Water Act ("CWA"), 33 U.S.C. §§ 1251-1387, and state law by requiring the County to apply for and obtain coverage under the PSNGP when the County's WWTP discharges are already authorized and regulated under individual National Pollutant Discharge Elimination System ("NPDES") permits; by simultaneously regulating these discharges under both the PSNGP and the WWTPs' individual permits; and by effectively modifying the County's four individual NPDES permits without complying with permit modification procedures and requirements.

In addition, the County is likely to succeed on the merits of its challenge to PSNGP Condition S3, which is arbitrary, internally inconsistent, and contrary to the CWA. PSNGP Condition S3.A prohibits permittees from causing or contributing to violations of water quality standards, and Ecology has concluded that the current nutrient discharges from all 58 WWTPs that are subject to the PSNGP are contributing to violations of the water quality standards for dissolved oxygen in Puget Sound. Fact Sheet at 32-33. Condition S3.B, however, authorizes permittees to continue discharging at their current levels as long as they comply with the other provisions of the PSNGP. Obviously, the permittees' current nutrient discharges cannot be both compliant and non-compliant with the PSNGP at the same time. Moreover, there is no legal basis for this internally inconsistent provision because it is neither an effluent limit nor any other NPDES permit condition authorized by the CWA or state law. The only effect of Condition S3 is to immediately subject the County and other PSNGP permittees to potential liability, including CWA penalties as high as $56,460 per day per violation. *See* 33 U.S.C. § 1319(d); 40 C.F.R. § 19.4.

The County will also suffer irreparable harm if the Board does not stay the PSNGP. The PSNGP requires the County to immediately devote thousands of hours of employee time, vast amounts of County resources, and tens of millions of ratepayers' dollars to immediately begin complying with the PSNGP's treatment system "optimization" and other requirements.

Compliance with these requirements will also cause the County to forgo or delay upgrades to existing WWTPs that are needed to maintain system reliability, prevent wastewater from bypassing treatment systems, and improve treatment performance. In addition, the treatment system optimization measures required by the PSNGP are likely to cause the County to violate the conditions of its WWTPs' individual NPDES permit conditions.

Furthermore, the requirements of the PSNGP are likely to be for naught. PSNGP Condition S4.E requires all WWTPs designated as "dominant," including three of the four County WWTPs, to prepare an evaluation report to demonstrate how the County will achieve a seasonal TIN effluent limit of 3 milligrams per liter ("mg/L"), based on Ecology's belief that dischargers subject to the PSNGP will ultimately need to meet that or an even more stringent TIN effluent limit. To achieve a limit that low, the County will be required to employ tertiary treatment, which none of its existing WWTPs can be retrofitted to employ. This means that the County would have to build new WWTPs, thereby wasting the tens of millions of dollars that the PSNGP will require it to invest in "optimizing" its current WWTPs.

This Motion is supported by the accompanying Declaration of Christie True, King County's Director of Natural Resources. A copy of the PSNGP and its accompanying Fact Sheet were filed in support of the County's Notice of Appeal, which has been filed contemporaneously with this Motion.

II. FACTS

A. The PSNGP

Ecology issued the PSNGP on December 1, 2021. The Permit becomes effective on January 1, 2022, and expires on December 31, 2026. The Permit, which is a general NPDES permit issued pursuant to the CWA and RCW 90.48, applies to discharges of nutrients from the 58 WWTPs identified in the Permit that discharge directly to the Washington waters of the Salish Sea, including Puget Sound. *See* PSNGP Cover Page, Condition S1.A.

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The Permit *requires* the County to apply for coverage under the Permit by March 1, 2022, for each of its four WWTPs that discharge to Puget Sound. Condition S2.A. But each of these WWTPs is already fully authorized to discharge treated wastewater to Puget Sound, including the nutrients contained in the wastewater, by individual NPDES permits issued by Ecology. Specifically, the County's Brightwater WWTP is authorized to discharge "treated domestic wastewater to Puget Sound" by individual NPDES permit number WA0032247 (attached as Ex. A), its South WWTP is authorized to discharge "treated municipal wastewater to the Puget Sound" by individual NPDES permit number WA0029581 (attached as Ex. B), its West Point WWTP is authorized to discharge "treated municipal wastewater" to Puget Sound by individual NPDES permit number WA0029181 (attached as Ex. C), and its Vashon WWTP is authorized to discharge "treated domestic wastewater to the Puget Sound" by individual NPDES permit number WA022527 (attached as Ex. D).[1]

Because the County cannot "opt out" of coverage under the PSNGP, discharges from each of the four County WWTPs will be simultaneously regulated by both the PSNGP and the WWTP's individual NPDES permit.

B. PSNGP Requirements

The PSNGP requires the County to immediately begin complying with a number of onerous requirements, including but not limited to the following: Conditions S7 and S9 require additional sampling, monitoring, and reporting requirements for each of the County's WWTPs, including monitoring for TIN. Conditions S4.C and S6.B require developing and implementing for each of the WWTPs a Nitrogen Optimization Plan to maximize nitrogen removal. Condition S4.B establishes annual TIN discharge "action levels" for the three County WWTPs

[1] The individual NPDES permit for the Brightwater WWTP expires on February 28, 2023. The individual NPDES permits for the South WWTP and West Point WWTP expired on July 31, 2020, and January 31, 2020, respectively, but they remain in effect pending Ecology's final action on the County's timely and pending permit renewal applications. *See* WAC 173-220-180(5). The individual NPDES permit for the Vashon WWTP expires on February 28, 2022, but will remain in effect thereafter until Ecology takes final action on the County's timely and pending permit renewal application. *See id.*

designated by the PSNGP as "dominant" TIN dischargers, which Ecology asserts are based on their current TIN discharge levels. Condition S4.D requires the County to take various corrective actions if these action levels are not met. Condition S4.E requires a Nutrient Reduction Evaluation for the County's three dominant WWTPs to identify treatment technologies that provide "all known, available, and reasonable methods of prevention, control, and treatment" ("AKART") for nitrogen on an annual basis and to achieve a TIN discharge concentration of 3 mg/L on a seasonal (April through October) basis. Condition S6.C requires an AKART analysis for nitrogen removal for the County's Vashon WWTP. In addition, Condition S3.A prohibits causing or contributing to a violation of surface water quality standards.

C. Effects on the County

As detailed in the accompanying Declaration of Christie True, the PSNGP imposes immediate and substantial obligations on the County. Satisfying these obligations will require a significant amount of staff and outside consultant time and effort and will cost the County *tens of millions of dollars in the next two years*, in addition to continuing to comply with all the requirements of its WWTPs' individual NPDES permits, which will remain fully in effect. True Decl. ¶ 6.

Compliance with the PSNGP's enhanced monitoring and reporting requirements will immediately require the County to hire two new staffers and incur other costs of about $350,000 annually. True Decl. ¶ 7.

Compliance with the PSNGP's Nitrogen Optimization Plan requirements will require the County to immediately begin developing, preparing, and implementing the plans for each of its WWTPs. PSNGP Condition S4.C.1.c requires the County to identify and select viable optimization strategies for each of its three "dominant" WWTPs by July 1, 2022, and Condition S6.B.1.b requires the County to identify the optimization strategy selected for its Vashon WWTP by December 31, 2022. True Decl. ¶ 8. The County estimates that developing and implementing

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these plans will result in labor and outside consulting costs totaling $2.4 million for the first two years. *See* True Decl. ¶ 9. In addition, the County will have increased operating and maintenance costs associated with optimization, which are estimated to be $950,000 annually, and it estimates that the capital cost to implement the selected optimization strategies (*e.g.,* installing new equipment) to be $5 million a year per plant. *Id.*

The immediate implementation of the PSNGP optimization requirement will adversely affect the ability of the County to complete other major capital project upgrades currently scheduled. True Decl. ¶ 10. This will have a cascading negative effect across the County's capital program, including the reassignment of project managers, engineers, operations staff, and construction managers, which will delay ongoing capital projects that are needed to increase system reliability, maintain system capacity, reduce overflows, and maintain compliance with the County's individual NPDES permits. *Id.* This increases the risk of equipment failures and may result in an increase in plant bypasses, secondary treatment bypasses, increased risks to worker safety, and, ultimately, harm to the environment. *Id.* Furthermore, the immediate implementation of nitrogen optimization strategies at each WWTP has the potential to cause other changes in the quality of the wastewater discharged from the WWTPs, and violations of the discharge limits in the WWTPs individual NPDES permits. True Decl. ¶ 11.

These efforts and expenses are ultimately also likely to be for naught. PSNGP Condition S4.E requires the County to determine how each of the three dominant WWTPs will achieve a seasonal TIN discharge concentration of 3 mg/l because Ecology expects that future iterations of the PSNGP will include equally or even more stringent TIN discharge limits. True Decl. ¶ 17. Achieving TIN discharge limits as low as 3 mg/L will require tertiary treatment processes. True Decl. ¶ 18. For that to happen, the County will have to build new WWTPs because its existing plants were not built to remove TIN and cannot be retrofitted to accommodate tertiary treatment. *Id.* This means that if the PSNGP is not stayed, the County will be forced to take all the measures described above, and spend tens of millions of ratepayers'

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dollars in the process, only to have that significant expenditure wasted when the County is forced to build new WWTPs that employ aggressive tertiary treatment methods. True Decl. ¶ 19.

III. ARGUMENT

A. Standard for Stay

Pursuant to WAC 371-08-415, the Board may stay the effect of the PSNGP. The County makes a *prima facie* case for a stay if it "demonstrates *either* a likelihood of success on the merits of the appeal *or* irreparable harm." WAC 371-08-415(4) (emphasis added). Upon such a demonstration, the Board must grant the stay unless Ecology demonstrates either (i) "[a] substantial probability of success on the merits" or (ii) a "[l]ikelihood of success and an overriding public interest which justifies denial of the stay." WAC 371-08-415(4)(a)-(b). Likelihood of success on the merits "does not require the moving party to demonstrate that it will conclusively win on the merits, but only that there are questions 'so serious … as to make them fair ground for litigation and thus for more deliberative investigation.'" *Airport Communities Coal. v. Ecology*, PCHB No. 01-160 (Order Granting Motion to Stay Effectiveness of Section 401 Certification) (Dec. 17, 2001) (ellipsis in original; citation omitted). "The evaluation of the likely outcome on the merits is based on a sliding scale that balances the comparative injuries that the parties and non-parties may suffer if a stay is granted or denied." *Id.* The moving party's showing of likelihood of success on the merits need not be as strong where the non-moving party would suffer little or no harm. *Id.* The Board, after granting or denying a stay request, shall "expedite the hearing and decision on the merits," unless otherwise stipulated by the parties. WAC 371-08-415(5).

B. The County Has a Likelihood of Success on the Merits

The Board reviews the terms of an NPDES permit to determine if it is "invalid in any respect," and whether it is consistent with applicable legal requirements. WAC 371-08-540(2); *Puget Soundkeeper All. v. Ecology*, PCHB No. 15-050 (Order Granting Respondents' Motion for Summary Judgment, Jan. 6, 2016).

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As described in detail below, the PSNGP is invalid in multiple respects and is not consistent with either state or federal regulations. Accordingly, the County is likely to succeed on the merits, and the PSNGP must be stayed.

1. *Federal and State NPDES Permit Regulations Prohibit Ecology from Requiring Coverage Under a General NPDES Permit*

Each of the County's four WWTPs have coverage under individual NPDES permits. Exhibit A-D. Yet, PSNGP Condition S2 *requires* the County to apply for and obtain coverage under the PSNGP for each of its four WWTPs. For the 58 WWTPs listed in the PSNGP, including the County's four WWTPs, coverage under the PSNGP is *mandatory*. This *mandatory* general permit coverage is contrary to both the federal regulations implementing the CWA and Ecology's own regulations.

The federal regulations explicitly prohibit Ecology from developing general permits that cover the same discharges that are authorized by individual permits. 40 C.F.R. § 122.28(a)(1) ("The general permit shall be written to cover one or more categories or subcategories of discharges … *except those covered by individual permits*…." (emphasis added)). If Ecology assigns general NPDES permit coverage to a discharger that does not have permit coverage, the discharger must be allowed to request an individual permit. *See id.* § 122.28(b)(2)(vi). And even a discharger that has obtained coverage under a general permit may request to be excluded from coverage under the general permit by applying for and obtaining an individual NPDES permit. *Id.* § 122.28(b)(3)(iii) ("Any owner or operator authorized by a general permit may request to be excluded from the coverage of the general permit by applying for an individual permit."); *id.* § 122.28(b)(3)(iv).

The federal regulations are permissive in that they allow, but do not require, a discharger covered by an individual permit to apply for coverage under a general permit. *Id.* § 122.28(b)(3)(v) ("A source excluded from a general permit solely because it already has an individual permit *may* request that the individual permit be revoked, and that it be covered by the general permit." (emphasis added)). But the regulations do not allow Ecology to mandate coverage under a general permit. Instead, as the U.S. Environmental Protection Agency ("EPA") explained in the final rule promulgating the general permit regulations, "individual permittees can request to be covered by [a] general permit, and vice versa." Final Rule, National Pollutant Discharge Elimination System; Revision of Regulations, 44 Fed. Reg. 32,854, 32,874 (June 7, 1979).

Ecology's own regulations allow dischargers to choose to be regulated under a general permit. WAC 173-226-200(1) ("[A]ll dischargers *who desire to be covered* under the general permit shall notify the department of that fact…." (emphasis added)). Where a discharger has chosen to be covered under a general permit, the regulations specifically allow that discharger to subsequently "request to be excluded from coverage under the general permit by applying for and being issued an individual permit." WAC 173-226-080(3). If the discharger requests to be excluded from the general permit, "[t]he director *shall* either issue an individual permit or deny the request with a statement explaining the reason for denial." *Id.* (emphasis added); *see also* WAC 173-226-240(4) (same). "When an individual permit is issued to a discharger otherwise subject to a general permit, the applicability of the general permit to that permittee is automatically terminated on the effective date of the individual permit." WAC 173-226-080(4).

In direct contravention of the regulations, which allow dischargers discretion whether to apply for coverage under a general permit or apply for individual permit coverage, and which expressly prohibit requiring coverage under a general permit for a discharger already covered by an individual permit, the PSNGP *mandates* that the 58 listed WWTPs apply for and obtain coverage under the PSNGP for the same discharges that are already covered by their individual NPDES permits. Condition S2.A; Fact Sheet at 13 (listing "[d]ischargers that must apply for coverage under this … general permit"). Each of the four County WWTPs has an individual NPDES permit that authorizes discharges of treated wastewater subject to the conditions of those permits, including discharges of the nutrients that would be authorized by the PSNGP. Because

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the PSNGP violates these regulations, it is invalid insofar as it requires the listed facilities, including the County's four WWTPs, to apply for and obtain coverage under it.

2. *Federal and State NPDES Permit Regulations Prohibit Ecology from Regulating the Same Discharge Under Both a General and an Individual NPDES Permit*

The PSNGP is similarly unlawful because the nutrient discharges that it would authorize and regulate would simultaneously be authorized and regulated by the 58 facilities' individual NPDES permits, including those for the four County WWTPs. Ecology's Fact Sheet explains that

> Ecology currently issues individual NPDES permits to municipal wastewater treatment plants. The PSNGP addresses the discharge of nutrient pollution from POTWs that hold an existing, individual NPDES permit.

Fact Sheet at 2. The individual NPDES permits for the County's four WWTPs comprehensively regulate the discharge of effluent from the County's WWTPs by setting effluent limitations along with requirements related to monitoring, recordkeeping, reporting, design, operations, and maintenance, among others. The PSNGP imposes additional monitoring, recordkeeping, and reporting requirements on the County while purporting to authorize discharges of nutrients—something that is *already authorized* by the individual permit for each of the County's WWTPs. Yet, the PSNGP does not fully authorize discharges from the County's WWTPs; it only purports to authorize nutrient discharges, so the County cannot terminate the individual NPDES permits upon obtaining coverage under the PSNGP, as required by the regulations. Instead, the County must maintain its individual NPDES permits even after obtaining coverage under the PSNGP. This mandatory dual permit coverage is contrary to both EPA's and Ecology's regulations.

Both EPA and Ecology's regulations prescribe a binary system where discharges are covered either by an individual permit or by a general permit. WAC 173-226-020 ("No pollutants shall be discharged to waters of the state from any point source, except as authorized by an individual permit … *or* as authorized through coverage under a general permit…."

(emphasis added)). The federal regulations explicitly prohibit writing a general permit for dischargers covered by an individual permit. 40 C.F.R. § 122.28(a)(1) ("The general permit shall be written to cover one or more categories of discharges … except those covered by individual permits….").

The regulations provide that "[w]hen an individual NPDES permit is issued to an owner or operator otherwise subject to a general NPDES permit, the applicability of the general permit to the individual NPDES permittee *is automatically terminated* on the effective date of the individual permit." 40 C.F.R. § 122.28(b)(3)(iv) (emphasis added); *see also* WAC 173-226-080(4) (same), -200(7) (same). The federal regulations further specify that "[a] source excluded from a general permit solely because it already has an individual permit may request that the individual permit be revoked, and that it be covered by the general permit." 40 C.F.R. § 122.28(b)(3)(v). These regulations specifically prevent a discharger from obtaining coverage under both a general and individual permit for the same discharge at the same time. Instead, the regulation requires that coverage under a general permit automatically terminates when a general permit is issued. Likewise, general permit coverage may only be obtained when an individual permit is fully revoked.

Ecology's own regulations recognize this distinction by defining "General Permit" as "a permit that covers multiple dischargers of a point source category within a designated geographical area, *in lieu of individual permits being issued to each discharger*." WAC 173-226-030(13) (emphasis added). Yet, the PSNGP is not in lieu of individual permits, but is in addition to individual permits contrary to both EPA's and Ecology's regulations.

Because discharges from the four County WWTPs that are required to obtain coverage under the PSNGP are already fully authorized by their individual NPDES permits, Ecology cannot require coverage for and regulate the same discharges under the PSNGP. The PSNGP is therefore unlawful and invalid as it applies to the County's WWTPs and all other WWTPs whose discharges are fully authorized by individual NPDES permits.

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3. *The PSNGP Impermissibly Modifies the County's Individual NPDES Permits*

The individual NPDES permits for the four County WWTPs that are subject to the PSNGP authorize discharges to Puget Sound of treated wastewater, which includes nutrients, subject only to the conditions of those permits. The PSNGP imposes substantial additional requirements on these authorized discharges. This impermissibly modifies the requirements of the individual permits without adhering to the NPDES permit modification procedures mandated by the applicable federal and state NPDES permitting regulations.

As the Board explained in *Citizens Against SeaTac Expansion v. Ecology*, "an entity that already has an effective permit does not need to apply for an NPDES permit" when the entity, Ecology, or an interested person seeks a modification of the permit. PCHB No. 01-090 (Order Denying Stay, Aug. 29, 2001) (internal quotation marks omitted) (citing 40 C.F.R. § 122.21(a)(1)). Rather, if an entity, Ecology, or an interested person wishes to modify an existing permit, they must comply with 40 C.F.R. § 124.5, applicable to modification, revocation, reissuance, and termination of an existing NPDES permit. *Citizens Against SeaTac Expansion v. Ecology*, PCHB No. 01-090 (Order Granting Summary Judgment, Jan. 4, 2002). Permits may only be modified for the reasons specified in 40 C.F.R. § 122.62, unless they are minor modifications. *Id.*

The PSNGP purports to authorize permittees who obtain coverage under the PSNGP to "discharge nutrients." But the County's WWTPs are already fully authorized to discharge wastewater, which necessarily contains nutrients, as the PSNGP recognizes. *See* Fact Sheet at 12. Functionally, the PSNGP does not authorize the discharge of anything. The only legal effect of the PSNGP is to modify the effluent limits, monitoring requirements, reporting requirements, and other conditions of the individual NPDES permits that the County already holds.

Individual permits can only be modified for one of the 18 enumerated causes specified in 40 C.F.R. § 122.62. *Puget Soundkeeper All. v. Ecology*, PCHB No. 15-050 (Order Granting Respondents' Motion for Summary Judgment, Jan. 6, 2016); *see also* WAC 173-220-

150(1)(d), -190(1). Ecology has not identified any of the causes listed in 40 C.F.R. § 122.62 as a facility-specific reason for modifying the individual NPDES permits for the County's four WWTPs. Moreover, the individual NPDES permits for two of the WWTPs, South and West Point, have expired and therefore cannot be modified, only renewed. *See* 40 C.F.R. § 122.46(b); 49 Fed. Reg. 37,998, 38,045 (Sept. 26, 1984) ("Permits which have 'expired' cannot be modified. While expired permits may be continued in effect beyond the permit terms [pending final action on a permit renewal application], ... these permits may only be changed by reissuance.").

Even if Ecology had cause to modify the individual NPDES permits and the ability to do so, the regulations required Ecology to prepare draft permits addressing the individual permit modifications and to provide public notice and an opportunity for comment on each of the individual proposed permit modifications for the County's four WWTPs. *See* 40 C.F.R. §§ 124.5(c)(1), 124.6(d), 124.10(a)(1)(ii), (b)(1), (d)(1); WAC 173-220-190(3). Ecology did not do so.

The PSNGP modifies the requirements of the individual NPDES permits for the 58 facilities subject to the PSNGP, including the County's four WWTPs, by imposing additional NPDES permit requirements on the discharges from those facilities. Ecology has not identified a facility-specific cause for modifying the individual permits, and does not have the legal authority to modify the permits for two of the County's WWTPs. Even if Ecology did have cause and authority to modify the individual NPDES permits, it failed to comply with the permit modification procedures established by EPA's and Ecology's NPDES permit regulations. Therefore, the PSNGP is invalid as to the County's WWTPs and the other WWTPs subject to the Permit. Ecology cannot evade permit modification requirements and procedures by imposing a general permit on individually authorized discharges.

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4. *PSNGP Condition S3 Is Unreasonable and Unlawful Because It Has No Legal Basis and Is Inconsistent with Other PSNGP Provisions*

Condition S3.A prohibits discharges that cause or contribute to violations of water quality standards. The animating factor that led Ecology to issue the PSNGP and require the 58 dischargers subject to the Permit to obtain coverage under it is Ecology's determination that each of those individual WWTPs is causing or contributing to violations of the dissolved oxygen water quality standards by discharging TIN *at its current levels*. More specifically, the Fact Sheet states that

> nutrients, particularly inorganic nitrogen, discharged from domestic wastewater treatment plants contribute to low dissolved oxygen concentrations in Puget Sound that do not meet state water quality criteria.... The [modeled] circulation patterns showed how discharges in one basin can affect the water quality in other basins. Thus, all wastewater discharges to the greater Puget Sound area containing nitrogen currently contribute to existing DO [dissolved oxygen] impairments meeting the threshold for reasonable potential under 40 C.F.R. 122.44(d)(1)(iii).

Fact Sheet at 32-33.

Notwithstanding this assertion, the PSNGP authorizes each discharger subject to the PSNGP to continue discharging at what the PSNGP purports to be its current levels of TIN, subject to future evaluations that may result in unspecified reductions in TIN discharges. For example, Condition S4.B sets forth TIN action levels for each of the WWTPs classified by Ecology as "dominant dischargers" based on Ecology's calculation of the WWTP's *current* TIN discharges.[2] Similarly, although small WWTPs are not subject to action levels, Condition S6 allows them to continue discharging at their current TIN levels.

Furthermore, Condition S3.B includes a presumption that compliance with the monitoring, evaluation, optimization, corrective action, and other PSNGP requirements will result in compliance with water quality standards:

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[2] Ecology has concluded that a facility subject to these action levels has a one percent chance of exceeding the action level, based on its current operations, in any given year.

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> Ecology presumes that a Permittee complies with water quality standards unless discharge monitoring data or other site-specific information demonstrates that a discharge causes or contributes to a violation of water quality standards, when the Permittee complies with the following conditions. The Permittee must fully comply with all permit conditions, including planning, optimization, corrective actions (as necessary), sampling, monitoring, reporting, waste management, and recordkeeping conditions.

Id. This means that, so long as an individual WWTP does not exceed its TIN action level (or if it does exceed that level, it undertakes the measures required in Condition S4.D), that individual WWTP is presumed by Ecology to be in compliance with the PSNGP. This is so even though Ecology has determined that each WWTP's current discharge is causing or contributing to a water quality standards violation, and even though Condition S3.A explicitly prohibits discharges that cause water quality standards violations.

Thus, the PSNGP is unreasonable and internally inconsistent. It purports to allow discharges in Conditions S4.B, S5.B, and S6 that Ecology believes contribute to water quality standard violations and that are expressly disallowed in Condition S3.A. In other words, the PSNGP presumes compliance with water quality standards only if the permittee complies with water quality standards.

In addition to being unreasonable and internally inconsistent, Condition S3 is unlawful because it has no legal basis. Having determined that discharges of nutrients from the WWTPs have a reasonable potential to cause or contribute to a water quality standards violation, Ecology is required to establish permit effluent limits for nutrients. *See* 40 C.F.R. § 122.44(d)(1)(i); *Nat. Res. Def. Council v. U.S. Env't Prot. Agency* ("*NRDC*"), 808 F.3d 556, 577 (2d Cir. 2015). If numeric effluent limits for nutrients are "infeasible," "[b]est management practices" may be used instead. 40 C.F.R. § 122.44(k)(3); *see NRDC*, 808 F.3d at 577. But Condition S3.A is neither a numeric effluent limit nor a best management practice.

The condition is not a numeric effluent limit because it does not tell the permittee, Ecology, or the public what discharge quality the WWTP must achieve. The court in *NRDC*

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rejected a general NPDES permit condition nearly identical to Condition S3.A for precisely that reason.

> This narrative standard is insufficient to give ... [the permittee] guidance as to what is expected or to allow any permitting authority to determine whether ... [the permittee] is violating water quality standards. By requiring ... [permittees] to control discharges "as necessary to meet applicable water quality standards" without giving specific guidance on the discharge limits, EPA fails to fulfill its duty to "regulat[e] in fact, not only in principle." ... [This condition], although found by EPA to be required ... in fact add[s] nothing.

808 F.3d at 578 (fourth brackets in original; citation omitted).

Condition S3.A is also not a "best management practice" that may be used in lieu of a numeric effluent limit. "Best management practices" are "schedules of *activities*, prohibitions of *practices*, maintenance *procedures*, and other *management practices* to prevent or reduce the pollution of 'waters of the United States.'" 40 C.F.R. § 122.2 (emphasis added). Condition S3.A, however, does not require or prohibit any activities, practices, or procedures. Therefore, it cannot serve as a narrative substitute for numeric effluent limits, even if numeric limits are "infeasible." *See NRDC*, 808 F.3d at 579 (holding that a general NPDES permit nearly identical to Condition S3 did not qualify as a best management practice); *see also Wash. State Dairy Fed'n v. State*, 18 Wn. App. 2d 259, 297, 490 P.3d 290 (2021) (holding that a general permit prohibition on violating water quality standards is "not an adequate effluent limitation").

Condition S3.A cannot be justified as a numeric or narrative effluent limit, nor does it have any other legal basis. Rather, the condition simply exposes each of the permittees to liability, including penalties of up to $56,460 per day per violation, *see* 33 U.S.C. § 1319(d); 40 C.F.R. § 19.4, if an after-the-fact determination is made that the permittee's discharges caused or contributed to a violation of water quality standards. Determinations of the discharge levels needed to meet water quality standards, however, must be made before the permit is issued and used to establish effluent limits so that the permittee can take the steps needed to comply with standards. *See NRDC*, 808 F.3d at 579-80 (rejecting argument that a permit condition requiring

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compliance with water quality standards is a sufficient water quality-based effluent limit because it allows standards to be met through enforcement or other corrective actions).

Because Condition S3 is unreasonable, inconsistent with other PSNGP conditions, and without any legal basis, it is unlawful and invalid.

C. The County Will Be Irreparably Harmed in the Absence of a Stay

In addition to the County's likelihood of success on the merits, a stay is warranted because the County and its ratepayers will be irreparably harmed by the PSNGP. Compliance with the PSNGP will require the County to immediately begin spending millions of dollars on monitoring, evaluation, and treatment system optimization. These efforts will divert funds and personnel from ongoing capital projects and other measures to ensure compliance with existing NPDES permits, improve reliability, and increase system capacity. In addition, the treatment system optimization measures required by the PSNGP could result in violations of the County's individual NPDES permit, and those potential violations and PSNGP Condition S3.A's immediate prohibition on contributing to violations of water quality standards could expose the County to substantial liability from an agency enforcement action or CWA citizen suit. And, ultimately, the measures required by the PSNGP may be for naught because they will not enable the County to achieve the 3 mg/L or less TIN discharge limit that Ecology expects to impose in future iterations of the PSNGP.[3]

The County must immediately begin to implement Condition S4.C.3, which requires the County to investigate ways to reduce TIN loads in its influent. The County has limited control

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[3] As detailed in the True Declaration, the County will be required to spend at least $350,000 annually to comply with the enhanced influent and effluent monitoring requirements, $700,000 in the first two years to develop a Nitrogen Optimization Plan and Report for each of its WWTPs and $1.2 million to begin optimization implementation, $500,000 for outside consultants to assist with the optimization planning efforts in the first two years, and $950,000 annually in increased operation and maintenance costs. True Decl. ¶ 7. The County will have to divert at least seven staff members, and then eventually backfill their positions. *Id.* The County is also required to *immediately* implement the selected optimization strategy identified under Condition S4.C.1 and then document the implementation of the selected optimization strategy for each plant by March 2023, which will cost $5 million a year per plant. *Id.* ¶ 10.

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over the TIN load in its influent stream and will need to conduct extensive stakeholder engagement to even determine what options are feasible. True Decl. ¶ 16. The County estimates this will cost a minimum of $600,000 annually, simply to satisfy the staffing required for this effort. *Id.*

The County recognizes that expenditure of funds alone does not constitute irreparable harm under the stay regulations. *Martig Eng'g & Seashore Villa Mobile Home Park v. Ecology*, PCHB No. 03-013 (Order Denying Stay, Mar. 28, 2003). While these are significant costs that will directly impact King County ratepayers and citizens, the irreparable harm also arises from the enormous diversion of resources that will be required to immediately begin complying with the PSNGP. The immediate optimization requirements imposed by the PSNGP will have a cascading negative effect across the County's capital program, resulting in the reassignment of project managers, engineers, operations staff, and construction managers. True Decl. ¶ 10. It will result in the delay of capital projects that are needed to increase system reliability, maintain system capacity, reduce overflows, and maintain permit compliance. *Id.* As an example of a critically impacted program, the County's West Point Capital Improvement Program ("Program") has over $600 million of active and planned projects to improve the reliability of the West Point Treatment Plant. Staff currently assigned to the Program will now need to be reassigned to comply with the PSNGP. *Id.* This will result in the deferral of projects that are badly needed at West Point to improve reliability. *Id.* This increases the risk of equipment failures and may result in an increase in plant bypasses, secondary treatment bypasses, increased risks to worker safety, and, ultimately, harm to the environment.

Additionally, immediate implementation of nitrogen optimization strategies at each WWTP has the real potential to cause violations of individual NPDES permits. True Decl. ¶ 11. For example, the South Plant operates under NPDES Waste Discharge Permit No. WA0029581, which includes a pH limit and a prohibition on the bypass of sewage around the secondary treatment process. *Id.* Operating South Plant to biologically remove nitrogen will likely result in

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a violation of both these requirements due to reduced flow capacity and the existing configuration of the treatment plant. Condition S1.A of the NPDES Waste Discharge Permit No. WA0029581.

Further, if the County determines that a plant's annual TIN load exceeds its assigned action load (or, if applicable, the County's cumulative or "bubbled" load for all three dominant discharging plants), then the County must proceed to take the corrective actions identified in Condition S4.D. Based on the County's data, the current discharge of TIN in effluent from any of the three dominant County dischargers demonstrates that the action levels, or bubbled action level, are expected to be exceeded within the first permit cycle. True Decl. ¶ 12. When the County exceeds the action level, Condition S4.D requires the County to prepare a strategy, in the form of an engineering report, that identifies treatment options and design alternatives to reduce the annual effluent load by at least 10% below the action level. An engineering report sufficient to comply with the permit is estimated to cost $5 million for each plant. True Decl. ¶ 13. This will add to the cascading effect, further delaying critical capital improvements already in the planning phase.

Yet this enormous outlay of resources will likely be for naught. Although Ecology is requiring the County to spend tens of millions of dollars to immediately evaluate, optimize, and modify its existing treatment systems, it is simultaneously requiring permittees to determine how each of their WWTPs will comply with a 3 mg/l TIN discharge limit as part of the required "Nutrient Reduction Evaluation" required under Condition S4.E.3. Accordingly, Ecology is signaling that compliance with a 3 mg/L, or stricter, limit is what the agency is going to require in the future once it actually establishes AKART for domestic WWTPs that discharge nutrients to the Salish Sea, and once it determines what numeric water quality-based effluent limits are necessary for the County's four WWTPs to meet applicable dissolved oxygen water quality standards.

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To meet TIN discharge limits as low as 3 mg/L at the County's four WWTPs, the County will have to employ tertiary treatment processes. To achieve tertiary treatment, the County will have to build new WWTPs because its existing plants were not built to remove TIN and cannot be retrofitted to accommodate tertiary treatment. True Decl. ¶ 18.

This means that if the PSNGP is not stayed, the County will be forced to (1) immediately plan for and begin to optimize its four treatment plants; (ii) take the onerous corrective action dictated under the PSNGP (which may cause it to violate its individual permits); (iii) forgo or delay necessary improvements that it was otherwise planning at its four WWTPs; and (iv) spend tens of millions of ratepayer dollars in the process, only to have that expenditure wasted when the County is forced to employ tertiary treatment to meet aggressive treatment goals that will require the County to build new WWTPs altogether. True Decl. ¶ 19.

The Board has repeatedly held that, when an activity authorized or required under a permit is certain to have an irreparable impact, the appellant can demonstrate irreparable injury, even when the exact contours of the impact are not certain. *See Raymond A. Clough, Jr., v. Ecology*, PCHB No. 12-064 (Order Granting Partial Stay, Aug. 31, 2014) (finding irreparable harm to wetland from construction activities even though boundaries of wetland had not been delineated and actual harm was uncertain); *Carl & Dana Strode v. Ecology*, PCHB Nos. 11-085, 11-086, 11-089 (Order on Stay, Aug. 4, 2011) (finding irreparable harm from aquatic herbicide application even though exact location of herbicide application was not known).

Here, the County has demonstrated certain irreparable harm from the massive diversion of resources required to comply with the PSNGP when those compliance measures are likely to prove to have been wasted. This massive waste of resources will irreparably harm the County and its ratepayers.

The County will also be irreparably harmed because the internally inconsistent provisions of the PSNGP—on the one hand finding that the County's current TIN discharges are violating water quality standards, while on the other hand explicitly permitting the County to discharge

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TIN at current levels—will place the County at an immediate risk of an Ecology enforcement action or citizen suit under section 505 of the CWA and liability for violating the Act.

More specifically, the Permit presumes that permittees are in compliance with applicable water quality standards so long as the permittee strictly complies with the Permit. The PSNGP establishes "TIN action levels" (Condition S4.B) for each dominant WWTP discharger that Ecology asserts were established at current discharge levels. The PSNGP requires the dominant dischargers to discharge at or below those TIN action levels, and, if those action levels are exceeded, to take appropriate corrective action. *See generally* Condition S4.

Yet, at the same time, Ecology decided to issue the PSNGP and to make it immediately applicable to the County's four WWTPs, because Ecology has concluded that the current TIN discharges from the 58 covered WWTPs are causing or contributing to violations of the DO water quality standards. *See* Fact Sheet at 32-33 (explaining that modeling demonstrates that TIN collectively discharged from domestic wastewater treatment plants contributes to low dissolved oxygen concentrations in Puget Sound that do not meet water quality criteria).

In short, under Condition S3, Ecology has both authorized and prohibited the same discharge, rendering the County, and for that matter all dischargers covered under the Permit, susceptible to liability for discharging nutrients in amounts that Ecology has concluded violate the DO water quality standards. The inconsistent provisions of the Permit irreparably harm the County by subjecting it to legal liability as soon as the PSNGP takes effect.

Accordingly, the Board must stay the permit to preserve the status quo and prevent the irreparable loss of rights and waste of resources that will occur if the PSNGP is allowed to take effect before the Board is able to determine if the PSNGP is valid. *Raymond A. Clough, Jr. v. Ecology*, PCHB No. 12-064 (Order Granting Partial Stay, Aug. 31, 2012).

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DATED: December 28, 2021

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Attorneys for Appellant King County

CERTIFICATE OF SERVICE

I, Lynn A. Stevens, certify and declare:

I am over the age of 18 years, make this Declaration based upon personal knowledge, and am competent to testify regarding the facts contained herein.

On December 28, 2021, I served true and correct copies of the document to which this certificate is attached on the following persons in the manner listed below:

The Department of Ecology
Appeals Coordinator/Processing Desk
300 Desmond Drive SE
Lacey, WA 98503
[ ] Via Facsimile
[■] Via U.S. Mail
[■] Via Legal Messenger
[ ] Via Federal Express

Bob Ferguson
Washington State Attorney General
Office of the Attorney General
Ecology Division
1125 Washington Street, SE
Olympia, WA 98501
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[■] Via Legal Messenger
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The Pollution Control Hearings Board
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Tumwater, WA 98501
eluho@eluho.wa.gov
[ ] Via Facsimile
[■] Via U.S. Mail
[■] Via Email
[ ] Via Federal Express

I certify under penalty of perjury pursuant to the laws of the State of Washington that the foregoing is true and correct.

SIGNED on December 28, 2021, at Seattle, Washington.

Lynn A. Stevens

EXHIBIT A

Issuance Date: February 26, 2018
Effective Date: March 01, 2018
Expiration Date: February 28, 2023

National Pollutant Discharge Elimination System
Waste Discharge Permit No. WA0032247

State of Washington
DEPARTMENT OF ECOLOGY
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

In compliance with the provisions of
The State of Washington Water Pollution Control Law
Chapter 90.48 Revised Code of Washington
and
The Federal Water Pollution Control Act
(The Clean Water Act)
Title 33 United States Code, Section 1342 et seq.

King County Department of Natural Resources and Parks,
Wastewater Treatment Division
King Street Center, KSC-NR-700
201 South Jackson Street
Seattle, Washington 98104-3855

is authorized to discharge in accordance with the Special and General Conditions that follow.

Plant Name: Brightwater Wastewater Treatment Plant (WWTP)	Receiving Water: Puget Sound
Plant Location: 22505 SR 9 SE, Woodinville, WA 98072	Discharge Locations: Outfall 001
Plant Type: Activated Sludge with Hollow Fiber Membranes; Chemically Enhanced Primary Treatment for Peak Wet Weather Flows	*Diffuser 1* Latitude: 47.777138360 Longitude: -122.416948716 *Diffuser 2* Latitude: 47.776987265 Longitude: -122.417957020

Rachel McCrea
Water Quality Section Manager
Northwest Regional Office
Washington State Department of Ecology

Exhibit A

Table of Contents

Summary of Permit Report Submittals

This list is intended as a summary of submittal requirements in the permit and may not include all submittals required by the permit. The Permittee must refer to the Special and General Conditions of this permit for additional submittal requirements and submit reports according to their instructions.

Permit Section	Submittal	Frequency	First Submittal Date
S3.A	Discharge Monitoring Report (DMR)	Monthly	04/15/2018
S3.A	Discharge Monitoring Report (DMR)	Quarterly	07/15/2018
S3.A	Discharge Monitoring Report (DMR)	Semiannual	01/15/2019
S3.A	Discharge Monitoring Report (DMR)	Annual	03/15/2019
S4.E	Wasteload Assessment	1/permit cycle	12/31/2022
S5.G.a.1	Operations and Maintenance Manual	1/permit cycle	07/31/2018
S5.G.a.3	Operations and Maintenance Manual Updates	1/permit cycle	09/01/2022
S6.A.4	Pretreatment Report	1/year	04/30/2018
S9.B	Wet Weather Bypass Annual Report	1/year	07/01/2018
S9.C	Utility Analysis Report	1/permit cycle	09/01/2022
S9.E	MBR Pilot Testing Report	1/permit cycle	07/31/2018
S10	Outfall Evaluation	1/permit cycle	12/01/2021
S11.A	Acute Toxicity Effluent Test Results for Permit Renewal	2/permit cycle	See condition for specific due dates
S12.A	Chronic Toxicity Effluent Test Results for Permit Renewal	2/permit cycle	See condition for specific due dates
S13	Application for Permit Renewal	1/permit cycle	09/01/2022

Special Conditions

S1. Discharge limits

S1.A. Effluent limits

All discharges and activities authorized by this permit must comply with the terms and conditions of this permit. The discharge of any of the following pollutants more frequently than, or at a level in excess of, that identified and authorized by this permit violates the terms and conditions of this permit.

Beginning on the effective date of this permit, the Permittee may discharge treated domestic wastewater to Puget Sound at the permitted location subject to compliance with the following limits:

Effluent Limits: Outfall 001 See discharge coordinates on cover sheet		
Parameter	**Average Monthly [a]**	**Average Weekly [b]**
Biochemical Oxygen Demand (5-day) (BOD_5)	30 milligrams/liter (mg/L) 10,233 pounds/day (lbs/day) 85% removal of influent BOD_5	45 mg/L 15,350 lbs/day
Total Suspended Solids (TSS)	30 mg/L 10,233 lbs/day 85% removal of influent TSS	45 mg/L 15,350 lbs/day
Total Residual Chlorine	0.5 mg/L	0.75mg/L
Parameter	**Minimum**	**Maximum**
pH	6.0 standard units	9.0 standard units
Parameter	**Monthly Geometric Mean**	**Weekly Geometric Mean**
Fecal Coliform Bacteria [c]	200/100 milliliter (mL)	400/100 mL

a	Average monthly effluent limit means the highest allowable average of daily discharges over a calendar month. To calculate the discharge value to compare to the limit, you add the value of each daily discharge measured during a calendar month and divide this sum by the total number of daily discharges measured. See footnote c for fecal coliform calculations.
b	Average weekly discharge limit means the highest allowable average of daily discharges over a calendar week, calculated as the sum of all daily discharges measured during a calendar week divided by the number of daily discharges' measured during that week. See footnote c for fecal coliform calculations.
c	Ecology provides directions to calculate the monthly and the weekly geometric mean in publication No. 04-10-020, Information Manual for Treatment Plant Operators.

S1.B. Mixing zone authorization

Mixing zone for Outfall 001

The following paragraphs define the maximum boundaries of the mixing zones:

Chronic mixing zone

The mixing zone is a series of overlapping circles with radius of 794 feet measured from the center of each discharge port. The aggregate region of the mixing zone encompasses an oblong circular area measuring 2,088 feet long and 1,588 feet wide, centered around the 500-foot long diffuser. The mixing zone extends from the bottom to the top of the water column. The concentration of pollutants at the edge of the chronic zone must meet chronic aquatic life criteria and human health criteria.

Acute mixing zone

The acute mixing zone is a series of overlapping circles with radius of 79.4 feet measured from the center of each discharge port. The aggregate region of the mixing zone encompasses an oblong circular area measuring 658 feet long and 158.8 feet wide, centered around the 500-foot long diffuser. The mixing zone extends from the bottom to the top of the water column. The concentration of pollutants at the edge of the acute zone must meet acute aquatic life criteria.

Available Dilution (dilution factor)	
Acute Aquatic Life Criteria	115
Chronic Aquatic Life Criteria	238
Human Health Criteria - Carcinogen	511
Human Health Criteria - Non-carcinogen	415

S2. Monitoring requirements

S2.A. Monitoring schedule

The Permittee must monitor in accordance with the following schedule and the requirements specified in Appendix A.

Parameter	Units & Speciation	Minimum Sampling Frequency	Sample Type
(1) Wastewater influent, monitored at Headworks			
Wastewater Influent means the raw sewage flow from the collection system into the treatment facility. Sample the wastewater entering the headworks of the treatment plant excluding any side-stream returns from inside the plant.			
Flow	MGD	Continuous [a]	Metered/Recorded
BOD_5	mg/L	5/week	24-hr Composite [b]
BOD_5	lbs/day	5/week	Calculation [c]
TSS	mg/L	5/week	24-hr Composite
TSS	lbs/day	5/week	Calculation

Parameter	Units & Speciation	Minimum Sampling Frequency	Sample Type
(2) Final wastewater effluent, monitored at the Influent Pump Station (IPS)			
Final Wastewater Effluent means wastewater exiting the last treatment process or operation. Typically, this is after or at the exit from the chlorine contact chamber or other disinfection process. The Permittee may take effluent samples for the BOD_5 analysis before or after the disinfection process. If taken after, the Permittee must dechlorinate and reseed the sample.			
Flow	MGD	Continuous	Metered/recorded
BOD_5	mg/L	5/week	24-hr Composite
BOD_5	lbs/day	5/week	Calculation
BOD_5	% removal	1/month	Calculation [d]
TSS	mg/L	5/week	24-hr Composite
TSS	lbs/day	5/week	Calculation
TSS	% removal	1/month	Calculation [d]
Total Residual Chlorine	mg/L	Continuous	Metered/recorded [e]
pH [f]	Standard Units	Continuous	Metered/recorded
Fecal Coliform [g]	# /100 ml	5/week	Grab
Total Phosphorus	mg/L as P	1/Month	24-hr Composite
Soluble Reactive Phosphorus	mg/L as P	1/Month	24-hr Composite
Total Ammonia	mg/L as N	1/Month	24-hr Composite
Nitrate plus Nitrite Nitrogen	mg/L as N	1/Month	24-hr Composite
Total Kjeldahl Nitrogen (TKN)	mg/L as N	1/Month	24-hr Composite
(3) Wet weather bypass, monitored at the Chemically-Enhanced Primary Clarifier Effluent Channel			
The Permittee must monitor and report the following parameters for each split stream flow event in which the Permittee diverts a portion of the plant's influent to chemically enhanced primary treatment and bypasses the MBR treatment system. All parameters are monitored at the effluent channel of the active chemically enhanced primary clarifier(s), unless otherwise noted. See Special Condition S9 for additional requirements for wet weather bypasses.			
Calculated Membrane Flow Capacity	MGD	1/day [h]	Calculation [i]
Maximum Membrane TMP [j]	Pounds per square inch (psi)	1/day [h]	Measurement
Headworks Flow Rate [k]	MGD	1/day [h]	Measurement
Total Volume	Million Gallons (MG)	1/day [h]	Calculation
Total Duration of Bypass	Hours	1/day [h]	Measurement
Total Storm Duration [L]	Hours	1/day [h]	Measurement
Total Precipitation [m]	Inches	1/day [h]	Measurement or Calculation
BOD_5	mg/L	1/day [h]	Composite [n]
BOD_5	% removal	1/day [h]	Calculation [d]
TSS	mg/L	1/day [h]	Composite [n]
TSS	% removal	1/day [h]	Calculation [d]
pH	Standard Units	1/day [h]	Measurement
Priority Pollutants (PP) – Total Metals	µg/L; nanograms(ng/L) for mercury	2/year [o]	Composite [n] Grab for mercury [p]

Parameter	Units & Speciation	Minimum Sampling Frequency	Sample Type
(4) Priority pollutant testing, monitored in influent at Headworks, effluent at IPS, and in biosolids			
The Permittee must monitor the following parameters in the influent at the headworks, and biosolids in accordance with the Pretreatment requirements in Special Condition S6.B. The Permittee must also monitor effluent at the IPS in accordance with the Pretreatment requirements in Special Conditions S6.B and as required by the NPDES permit application. The schedule for pH below applies only to influent and biosolids since the effluent monitoring schedule above requires more frequent effluent monitoring for that parameter. Oil and grease monitoring applies only to influent and effluent.			
pH (influent and biosolids)	Standard units	1/quarter	Grab
Oil and Grease (influent and effluent)	mg/L	1/quarter	Grab
Cyanide	micrograms/liter (µg/L)	1/quarter	Grab
Total Phenolic Compounds	µg/L	1/quarter	Grab
PP – Total Metals	µg/L; nanograms (ng/L) for mercury	1/quarter	24-Hour composite Grab for mercury [p]
PP – Volatile Organic Compounds	µg/L	1/year	Manual Composite [q]
PP – Acid-extractable Compounds	µg/L	1/year	24-Hour composite
PP – Base-neutral Compounds	µg/L	1/year	24-Hour composite
PP – Pesticides/PCB Compounds	µg/L	1/year	24-Hour composite
(5) Permit renewal application requirements – final effluent monitored at IPS			
This section includes parameters required by the application that are not otherwise required by routine monitoring. The Permittee must report results with quarterly monitoring listed above			
Temperature	Degrees Celsius	1/quarter	Grab
Dissolved Oxygen	mg/L	1/quarter	Grab
Total Dissolved Solids	mg/L	1/quarter	Grab
Total Hardness	mg/L	1/quarter	Grab
(6) Whole effluent toxicity testing – final wastewater effluent			
Acute Toxicity Testing	See condition S11 for testing requirements	2/permit cycle during months specified in condition S11	24-hr composite
Chronic Toxicity Testing	See condition S12 for testing requirements	2/permit cycle during months specified in condition S12	24-hr composite

Monitoring schedule notes	
a	Continuous means uninterrupted except for brief lengths of time for calibration, power failure, or unanticipated equipment repair or maintenance. The Permittee must sample every 6 hours when continuous monitoring is not possible.
b	24-hour composite means a series of individual samples collected over a 24-hour period into a single container, and analyzed as one sample.
c	Calculate mass concurrently with the respective concentration of a sample, using the following formula: Concentration (in mg/L) X Flow (in MGD) X Conversion Factor (8.34) = lbs/day

d	Calculate the monthly average percent removal using the following formula: $$\% \text{ removal} = \frac{\text{Influent concentration (mg/L)} - \text{Effluent concentration (mg/L)}}{\text{Influent concentration (mg/L)}} \times 100$$ where influent and effluent concentrations are the monthly average concentrations of BOD_5 and TSS.
e	The Permittee must continuously record effluent total residual chlorine concentration using inline analyzers. Report the highest concentration from instantaneous data averaged over a maximum interval of 10 minutes as the daily maximum concentration.
f	The Permittee must continuously record effluent pH using inline analyzers. Report the daily maximum and minimum pH values from instantaneous data averaged over a maximum interval of 5 minutes. Do not report daily average pH values.
g	Report a numerical value for fecal coliforms following the procedures in Ecology's *Information Manual for Wastewater Treatment Plant Operators*, Publication Number 04-10-020. Do not report a result as too numerous to count (TNTC).
h	The Permittee must monitor and report all parameters in section 3 of this monitoring schedule, except metals, each day in which wet weather bypassing occurs. Report individual sample results on the monthly DMR in which bypassing occurred and summarize the results in the annual bypass report (S9.B). Report "No Discharge" for the CEPC monitoring point on the monthly DMR when no bypassing occurs during the month.
i	Membrane Flow Capacity to be calculated based on daily peak flow tests conducted on the day of a wet weather bypass event.
j	The maximum membrane TMP is the highest measured transmembrane pressure recorded at the initiation of a wet weather bypass event.
k	The Permittee must record and report the influent flow rate to the WWTP at the time of initiating a wet weather bypass. The Permittee must also calculate and report the average flow rate to the WWTP over the duration of the wet weather bypass event.
L	Storm duration is the amount of total time when precipitation that contributed to a wet weather bypass event occurred.
m	The Permittee must report precipitation for each storm event that led to a wet weather bypass. It may report precipitation using a single rain gauge that most represents precipitation over the drainage area tributary to the treatment plant or it may report precipitation based on an aggregate of multiple rain gauges in the drainage basin.
n	The Permittee must limit composite sampling of CEPC effluent to the duration of each wet weather bypass event. It may use automated composite sampling equipment or manually composite a series of grab samples over the duration of the bypass.
o	The Permittee must monitor metals in the CEPC effluent during a wet weather bypass event. Report individual results on the semiannual DMR corresponding to the months in which metals testing occurred. The semiannual monitoring periods are January through June and July through December.
p	Mercury monitoring requires clean sampling using EPA Method 1669 and low-level analysis using EPA Method 1631E. The Permittee will report mercury results with all other priority pollutant metals testing.
q	Manual composite refers to the collection of multiple discrete grab samples that are mixed and analyzed as a single sample. See Special Condition S6.B.1 for further details.

S2.B. Sampling and analytical procedures

Samples and measurements taken to meet the requirements of this permit must represent the volume and nature of the monitored parameters. The Permittee must conduct representative sampling of any unusual discharge or discharge condition, including bypasses, upsets, and maintenance-related conditions that may affect effluent quality.

Sampling and analytical methods used to meet the monitoring requirements specified in this permit must conform to the latest revision of the *Guidelines Establishing Test Procedures for the Analysis of Pollutants* contained in 40 CFR Part 136 (or as applicable in 40 CFR subchapters N [Parts 400–471] or O [Parts 501-503]) unless otherwise specified in this permit . Ecology may only specify alternative methods for parameters without permit limits and for those parameters without an EPA approved test method in 40 CFR Part 136.

S2.C. Flow measurement and continuous monitoring devices

The Permittee must:

1. Select and use appropriate flow measurement and continuous monitoring devices and methods consistent with accepted scientific practices.
2. Install, calibrate, and maintain these devices to ensure the accuracy of the measurements is consistent with the accepted industry standard, the manufacturer's recommendation, and approved O&M manual procedures for the device and the wastestream.
3. Calibrate continuous monitoring instruments weekly unless it can demonstrate a longer period is sufficient based on monitoring records. The Permittee:
    a. May calibrate apparatus for continuous monitoring of dissolved oxygen by air calibration.
    b. Must calibrate continuous pH measurement instruments using a grab sample analyzed in the lab with a pH meter calibrated with standard buffers and analyzed within 15 minutes of sampling.
    c. Must calibrate continuous chlorine measurement instruments using a grab sample analyzed in the laboratory within 15 minutes of sampling.
4. Calibrate flow-monitoring devices at a minimum frequency of at least one calibration per year.
5. Maintain calibration records for at least three years.

S2.D. Laboratory accreditation

The Permittee must ensure that all monitoring data required by Ecology for permit specified parameters is prepared by a laboratory registered or accredited under the provisions of chapter 173-50 WAC, *Accreditation of Environmental Laboratories*. Flow, temperature, settleable solids, conductivity, pH, and internal process control parameters are exempt from this requirement. The Permittee must obtain accreditation for conductivity and pH if it must receive accreditation or registration for other parameters.

S3. Reporting and recording requirements

The Permittee must monitor and report in accordance with the following conditions. Falsification of information submitted to Ecology is a violation of the terms and conditions of this permit.

S3.A. Discharge monitoring reports

The first monitoring period begins on the effective date of the permit (unless otherwise specified). The Permittee must:

1. Summarize, report, and submit monitoring data obtained during each monitoring period on the electronic discharge monitoring report (DMR) form provided by Ecology within the Water Quality Permitting Portal. Include data for each of the parameters tabulated in Special Condition S2 and as required by the form. Report a value for each day sampling occurred (unless specifically exempted in the permit) and for the summary values (when applicable) included on the electronic form.
2. Ensure that DMRs are electronically submitted no later than the dates specified below, unless otherwise specified in this permit.
3. The Permittee must also submit an electronic copy of the laboratory report as an attachment using WQWebDMR. The contract laboratory reports must also include information on the chain of custody, QA/QC results, and documentation of accreditation for the parameter.
4. Submit DMRs for parameters with the monitoring frequencies specified in S2 (monthly, quarterly, annual, etc.) at the reporting schedule identified below. The Permittee must:
   a. Submit **monthly** DMRs by the 15th day of the following month.
   b. Submit **quarterly DMRs**, unless otherwise specified in the permit, by the 15th day of the month following the monitoring period. Quarterly sampling periods are January through March, April through June, July through September, and October through December. The Permittee must submit the first quarterly DMR on July 15, 2018 for the quarter beginning on April 1, 2018.
   c. Submit **semiannual DMRs** to report metals testing of the CEPC effluent by July 15 and January 15 of each year. Semiannual sampling periods are January through June, and July through December. The first sampling period begins July 1, 2018 and the first DMR is due January 15, 2019. If there are no qualifying wet weather bypass events during a semiannual monitoring period, the Permittee must report “No Discharge” on the DMR for that period.

d. Submit **annual DMRs** by March 15th of each year for monitoring completed the previous year. The first monitoring period begins on the effective date of the permit and lasts 12 calendar months. The first annual DMR is due March 15, 2019.

e. Submit permit renewal application monitoring data in WQWebDMR on quarterly DMRs as required by S3.A.4.b.

5. Enter the "No Discharge" reporting code for an entire DMR, for a specific monitoring point, or for a specific parameter as appropriate, if the Permittee did not discharge wastewater or a specific pollutant during a given monitoring period.

6. Report single analytical values below detection as "less than the detection level (DL)" by entering < followed by the numeric value of the detection level (e.g. < 2.0) on the DMR. If the method used did not meet the minimum DL and quantitation level (QL) identified in the permit, report the actual QL and DL in the comments or in the location provided.

7. Report single analytical values between the detection level (DL) and the quantitation level (QL) by entering the estimated value, the code for estimated value/below quantitation limit (j) and any additional information in the comments. Submit a copy of the laboratory report as an attachment using WQWebDMR.

8. **Not** report zero for bacteria monitoring. Report as required by the laboratory method.

9. Calculate and report an arithmetic average value for each day for bacteria if multiple samples were taken in one day.

10. Calculate the geometric mean values for bacteria (unless otherwise specified in the permit) using:

    a. The reported numeric value for all bacteria samples measured above the detection value except when it took multiple samples in one day. If the Permittee takes multiple samples in one day it must use the arithmetic average for the day in the geometric mean calculation.

    b. The detection value for those samples measured below detection.

11. Report the test method used for analysis in the comments if the laboratory used an alternative method not specified in the permit and as allowed in Appendix A.

12. Calculate average values and calculated total values (unless otherwise specified in the permit) using:

    a. The reported numeric value for all parameters measured between the detection value and the quantitation value for the sample analysis.

    b. One-half the detection value (for values reported below detection) if the lab detected the parameter in another sample from the same monitoring point for the reporting period.

c. Zero (for values reported below detection) if the lab did not detect the parameter in another sample for the reporting period.

13. Report single-sample grouped parameters (for example: priority pollutants, PAHs, pulp and paper chlorophenolics, TTOs) on the WQWebDMR form and include: sample date, concentration detected, detection limit (DL) (as necessary), and laboratory quantitation level (QL) (as necessary).

S3.B. Permit submittals and schedules

The Permittee must use the Water Quality Permitting Portal – Permit Submittals application (unless otherwise specified in the permit) to submit all other written permit-required reports by the date specified in the permit.

When another permit condition requires submittal of a paper (hard-copy) report, the Permittee must ensure that it is postmarked or received by Ecology no later than the dates specified by this permit. Send these paper reports to Ecology at:

Water Quality Permit Coordinator
Department of Ecology
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

S3.C. Records retention

The Permittee must retain records of all monitoring information for a minimum of three (3) years. Such information must include all calibration and maintenance records and all original recordings for continuous monitoring instrumentation, copies of all reports required by this permit, and records of all data used to complete the application for this permit. The Permittee must extend this period of retention during the course of any unresolved litigation regarding the discharge of pollutants by the Permittee or when requested by Ecology.

S3.D. Recording of results

For each measurement or sample taken, the Permittee must record the following information:

1. The date, exact place, method, and time of sampling or measurement.
2. The individual who performed the sampling or measurement.
3. The dates the analyses were performed.
4. The individual who performed the analyses.
5. The analytical techniques or methods used.
6. The results of all analyses.

S3.E. Additional monitoring by the Permittee

If the Permittee monitors any pollutant more frequently than required by Special Condition S2 of this permit, then the Permittee must include the results of such monitoring in the calculation and reporting of the data submitted in the Permittee's DMR unless otherwise specified by Special Condition S2.

S3.F. Reporting permit violations

The Permittee must take the following actions when it violates or is unable to comply with any permit condition:

1. Immediately take action to stop, contain, and cleanup unauthorized discharges or otherwise stop the noncompliance and correct the problem.
2. If applicable, immediately repeat sampling and analysis. Submit the results of any repeat sampling to Ecology within thirty (30) days of sampling.

a. Immediate reporting

The Permittee must immediately report to Ecology and the Snohomish County Health District or Public Health of Seattle-King County (depending on location impacted by the incident) at the numbers listed below all:

- Failures of the disinfection system.
- Collection system overflows.
- Plant bypasses discharging to marine surface waters.
- Any other failures of the sewage system (pipe breaks, etc.)

Northwest Regional Office	425-649-7000
Snohomish County Health District	425-339-5200
Public Health of Seattle-King County	(206) 477-8050

If the reportable incident impacts marine waters, the Permittee must also contact the Department of Health, Shellfish Program:

Department of Health,	360-236-3330 (business hours)
Shellfish Program	360-789-8962 (after business hours)

Additionally, for any sanitary sewer overflow (SSO) that discharges to a municipal separate storm sewer system (MS4), the Permittee must notify the appropriate MS4 owner or operator.

b. Twenty-four-hour reporting

The Permittee must report the following occurrences of noncompliance by telephone, to Ecology at the telephone numbers listed above, within 24 hours from the time the Permittee becomes aware of any of the following circumstances:

1. Any noncompliance that may endanger health or the environment, unless previously reported under immediate reporting requirements.

2. Any unanticipated bypass that causes an exceedance of an effluent limit in the permit (See Part S5.F, “Bypass Procedures”).
3. Any upset that causes an exceedance of an effluent limit in the permit (See G.15, “Upset”).
4. Any violation of a maximum daily or instantaneous maximum discharge limit for any of the pollutants in Section S1.A of this permit.
5. Any overflow prior to the treatment works, whether or not such overflow endangers health or the environment or exceeds any effluent limit in the permit.

c. Report within five days

The Permittee must also submit a written report within five business days of the time that the Permittee becomes aware of any reportable event under S3.F.2.a or S3.F.2.b, above. Submit the written report electronically using the *Water Quality Permitting Portal – Permit Submittals* application under the “As Needed, 5-day Written Follow-up” submittal schedule. Include the ERTS number in the name of the file uploaded for this submittal. If the letter covers multiple ERTS reports, include the incident date in the file name (example file names: “ERTS XXXXXX follow-up” or “follow-up-MMDDYYYY incidents”). The report must contain:

1. A description of the noncompliance and its cause.
2. The period of noncompliance, including exact dates and times.
3. The estimated time the Permittee expects the noncompliance to continue if not yet corrected.
4. Steps taken or planned to reduce, eliminate, and prevent recurrence of the noncompliance.
5. If the noncompliance involves an overflow prior to the treatment works, an estimate of the quantity (in gallons) of untreated overflow.

d. Waiver of written reports

Ecology may waive the written report required in subpart c, above, on a case-by-case basis upon request if the Permittee has submitted a timely oral report.

e. All other permit violation reporting

The Permittee must report all permit violations, which do not require immediate or within 24 hours reporting, when it submits monitoring reports for S3.A ("Reporting"). The reports must contain the information listed in subpart c, above. Compliance with these requirements does not relieve the Permittee from responsibility to maintain continuous compliance with the terms and conditions of this permit or the resulting liability for failure to comply.

S3.G. Other reporting

a. Spills of oil or hazardous materials

The Permittee must report a spill of oil or hazardous materials in accordance with the requirements of RCW 90.56.280 and chapter 173-303-145. You can obtain further instructions at the following website: https://ecology.wa.gov/About-us/Get-involved/Report-an-environmental-issue/Report-a-spill.

b. Failure to submit relevant or correct facts

Where the Permittee becomes aware that it failed to submit any relevant facts in a permit application, or submitted incorrect information in a permit application, or in any report to Ecology, it must submit such facts or information promptly.

S3.H. Maintaining a copy of this permit

The Permittee must keep a copy of this permit at the facility and make it available upon request to Ecology inspectors.

S4. Facility loading

S4.A. Design criteria

The flows or waste loads for the permitted facility must not exceed the following design criteria:

Maximum Month Design Flow (MMDF)	40.9 MGD
BOD_5 Influent Loading for Maximum Month	66,063 lbs/day
TSS Influent Loading for Maximum Month	61,400 lbs/day

S4.B. Plans for maintaining adequate capacity

a. Conditions triggering plan submittal

The Permittee must submit a plan and a schedule for continuing to maintain capacity to Ecology when:

1. The actual flow or waste load reaches 85 percent of any one of the design criteria in S4.A for three consecutive months.
2. The projected plant flow or loading would reach design capacity within five years.

b. Plan and schedule content

The plan and schedule must identify the actions necessary to maintain adequate capacity for the expected population growth and to meet the limits and requirements of the permit. The Permittee must consider the following topics and actions in its plan.

1. Analysis of the present design and proposed process modifications.

2. Reduction or elimination of excessive infiltration and inflow of uncontaminated ground and surface water into the sewer system.
3. Limits on future sewer extensions or connections or additional waste loads.
4. Modification or expansion of facilities.
5. Reduction of industrial or commercial flows or waste loads.

Engineering documents associated with the plan must meet the requirements of WAC 173-240-060, "Engineering Report," and be approved by Ecology prior to any construction.

S4.C. Duty to mitigate

The Permittee must take all reasonable steps to minimize or prevent any discharge or sludge use or disposal in violation of this permit that has a reasonable likelihood of adversely affecting human health or the environment.

S4.D. Notification of new or altered sources

1. The Permittee must submit written notice to Ecology whenever any new discharge or a substantial change in volume or character of an existing discharge into the wastewater treatment plant is proposed which:
   a. Would interfere with the operation of, or exceed the design capacity of, any portion of the wastewater treatment plant.
   b. Is not part of an approved general sewer plan or approved plans and specifications.
   c. Is subject to pretreatment standards under 40 CFR Part 403 and Section 307(b) of the Clean Water Act.
2. This notice must include an evaluation of the wastewater treatment plant's ability to adequately transport and treat the added flow and/or waste load, the quality and volume of effluent to be discharged to the treatment plant, and the anticipated impact on the Permittee's effluent [40 CFR 122.42(b)].

S4.E. Wasteload assessment

The Permittee must conduct an assessment of its influent flow and waste load and submit a report to Ecology by December 31, 2022. The report must contain:

1. A description of compliance or noncompliance with the permit effluent limits.
2. A comparison between the existing and design:
   a. Monthly average dry weather and wet weather flows.
   b. Maximum month flows.
   c. Peak flows.
   d. BOD_5 loadings.
   e. Total suspended solids loadings.
3. The percent change in the above parameters since the previous report.

4. The present and design population or population equivalent.
5. The projected population growth rate.
6. The estimated date upon which the Permittee expects the wastewater treatment plant to reach design capacity, according to the most restrictive of the parameters above.
7. An Infiltration and Inflow (I/I) update that describes:
    a. For the collection system owned and operated by the County:
        i. The results of recent I/I monitoring
        ii. A summary of recent I/I improvement projects.
        iii. Projects planned to improve I/I.
    b. For the collection systems owned and operated by component agencies:
        i. Measures taken to encourage component agencies to control I/I.
        ii. Any known I/I concerns.
        iii. Steps planned to further encourage I/I reduction projects.

S5. Operation and maintenance

The Permittee must at all times properly operate and maintain all facilities and systems of treatment and control (and related appurtenances), which are installed to achieve compliance with the terms and conditions of this permit. Proper operation and maintenance also includes keeping a daily operation logbook (paper or electronic), adequate laboratory controls, and appropriate quality assurance procedures. This provision of the permit requires the Permittee to operate backup or auxiliary facilities or similar systems only when the operation is necessary to achieve compliance with the conditions of this permit.

S5.A. Certified operator

This permitted facility must be operated by an operator certified by the state of Washington for at least a Class IV plant. This operator must be in responsible charge of the day-to-day operation of the wastewater treatment plant. An operator certified for at least a Class III plant must be in charge during all regularly scheduled shifts.

S5.B. Operation and maintenance program

The Permittee must:

1. Institute an adequate operation and maintenance program for the entire sewage system.
2. Keep maintenance records on all major electrical and mechanical components of the treatment plant, as well as the sewage system and pumping stations. Such records must clearly specify the frequency and type of maintenance recommended by the manufacturer and must show the frequency and type of maintenance performed.
3. Make maintenance records available for inspection at all times.

S5.C. Short-term reduction

The Permittee must schedule any facility maintenance, which might require interruption of wastewater treatment and degrade effluent quality, during non-critical water quality periods and carry this maintenance out according to the approved O&M manual or as otherwise approved by Ecology.

If a Permittee contemplates a reduction in the level of treatment that would cause a violation of permit discharge limits on a short-term basis for any reason, and such reduction cannot be avoided, the Permittee must:

1. Give written notification to Ecology, if possible, thirty (30) days prior to such activities.
2. Detail the reasons for, length of time of, and the potential effects of the reduced level of treatment.

This notification does not relieve the Permittee of its obligations under this permit.

S5.D. Electrical power failure

The Permittee must ensure that adequate safeguards prevent the discharge of untreated wastes or wastes not treated in accordance with the requirements of this permit during electrical power failure at the treatment plant and/or sewage lift stations. Adequate safeguards include, but are not limited to, alternate power sources, standby generator(s), or retention of inadequately treated wastes.

The Permittee must maintain Reliability Class II (EPA 430-99-74-001) at the wastewater treatment plant. Reliability Class II requires a backup power source sufficient to operate all vital components and critical lighting and ventilation during peak wastewater flow conditions. Vital components used to support the secondary processes (i.e., mechanical aerators or aeration basin air compressors) need not be operable to full levels of treatment, but must be sufficient to maintain the biota.

S5.E. Prevent connection of inflow

The Permittee must strictly enforce its sewer ordinances and not allow the connection of inflow (roof drains, foundation drains, etc.) to the sanitary sewer system.

S5.F. Bypass procedures

A bypass is the intentional diversion of waste streams from any portion of a treatment facility. This permit prohibits all bypasses except when the bypass is for essential maintenance, as authorized in special condition S5.F.1, or is approved by Ecology as an anticipated bypass following the procedures in S5.F.2. Special Condition S9 authorizes anticipated wet weather bypasses of the MBR treatment system under specific conditions and limits.

1. Bypass for essential maintenance without the potential to cause violation of permit limits or conditions.

   This permit allows bypasses for essential maintenance of the treatment system when necessary to ensure efficient operation of the system. The Permittee may bypass the treatment system for essential maintenance only if doing so does not cause violations of effluent limits. The Permittee is not required to notify Ecology when bypassing for essential maintenance. However the Permittee must comply with the monitoring requirements specified in special condition S2.B.

2. Anticipated bypasses for non-essential maintenance

   Ecology may approve an anticipated bypass under the conditions listed below. This permit prohibits any anticipated bypass that is not approved through the following process.

   a. If a bypass is for non-essential maintenance, the Permittee must notify Ecology, if possible, at least ten (10) days before the planned date of bypass. The notice must contain:

      - A description of the bypass and the reason the bypass is necessary.
      - An analysis of all known alternatives which would eliminate, reduce, or mitigate the potential impacts from the proposed bypass.
      - A cost-effectiveness analysis of alternatives.
      - The minimum and maximum duration of bypass under each alternative.
      - A recommendation as to the preferred alternative for conducting the bypass.
      - The projected date of bypass initiation.
      - A statement of compliance with SEPA.
      - A request for modification of water quality standards as provided for in WAC 173-201A-410, if an exceedance of any water quality standard is anticipated.
      - Details of the steps taken or planned to reduce, eliminate, and prevent recurrence of the bypass.

   b. For probable construction bypasses, the Permittee must notify Ecology of the need to bypass as early in the planning process as possible. The Permittee must consider the analysis required above during the project planning and design process. The project-specific engineering report as well as the plans and specifications must include details of probable construction bypasses to the extent practical. In cases where the Permittee determines the probable need to bypass early, the Permittee must continue to analyze conditions up to and including the construction period in an effort to minimize or eliminate the bypass.

c. Ecology will determine if the Permittee has met the conditions of special condition S5.F.2 a and b and consider the following prior to issuing a determination letter, an administrative order, or a permit modification as appropriate for an anticipated bypass:

- If the Permittee planned and scheduled the bypass to minimize adverse effects on the public and the environment.
- If the bypass is unavoidable to prevent loss of life, personal injury, or severe property damage. “Severe property damage” means substantial physical damage to property, damage to the treatment facilities which would cause them to become inoperable, or substantial and permanent loss of natural resources which can reasonably be expected to occur in the absence of a bypass.
- If feasible alternatives to the bypass exist, such as:
  - The use of auxiliary treatment facilities.
  - Retention of untreated wastes.
  - Stopping production.
  - Maintenance during normal periods of equipment downtime, but not if the Permittee should have installed adequate backup equipment in the exercise of reasonable engineering judgment to prevent a bypass which occurred during normal periods of equipment downtime or preventative maintenance.
  - Transport of untreated wastes to another treatment facility.

S5.G. Operations and maintenance (O&M) manual

a. O&M manual submittal and requirements

The Permittee must:

1. Submit an electronic copy of the current Operations and Maintenance (O&M) Manual for the permitted facility that meets the requirements of 173-240-080 WAC by July 31, 2018. Due to the large size and complexity of the manual, the Permittee must submit the electronic files on a portable digital storage device, (flash drive, DVD or CD); do not submit files through the Water Quality Permitting Portal – Permit Submittals application.
2. Review the O&M Manual at least annually.
3. Submit to Ecology for review all substantial changes or updates to the O&M Manual whenever it incorporates them into the manual. Submit electronic copies of all updated sections by September 1, 2022.
4. Keep the approved O&M Manual at the permitted facility.
5. Follow the instructions and procedures of this manual.

b. O&M manual components

In addition to the requirements of WAC 173-240-080(1) through (5), the O&M Manual must be consistent with the guidance in Table G1-3 in the *Criteria for Sewage Works Design* (Orange Book), 2008. The O&M Manual must include:

1. Emergency procedures for cleanup in the event of wastewater system upset or failure.
2. A review of system components which if failed could pollute surface water or could impact human health. Provide a procedure for a routine schedule of checking the function of these components.
3. Wastewater system maintenance procedures that contribute to the generation of process wastewater.
4. Reporting protocols for submitting reports to Ecology to comply with the reporting requirements in the discharge permit.
5. Any directions to maintenance staff when cleaning or maintaining other equipment or performing other tasks which are necessary to protect the operation of the wastewater system (for example, defining maximum allowable discharge rate for draining a tank, blocking all floor drains before beginning the overhaul of a stationary engine).
6. The treatment plant process control monitoring schedule.
7. Minimum staffing adequate to operate and maintain the treatment processes and carry out compliance monitoring required by the permit.

S6. Pretreatment

S6.A. General requirements

1. The Permittee must implement the Industrial Pretreatment Program in accordance with King County Code 28.84.060 as amended by King County Ordinance No. 11963 on January 1, 1996, legal authorities, policies, procedures, and financial provisions described in the Permittee's approved pretreatment program submittal entitled "Industrial Pretreatment Program" and dated April 27, 1981; any approved revisions thereto; and the General Pretreatment Regulations (40 CFR Part 403). At a minimum, the Permittee must undertake the following pretreatment implementation activities:

   a. Enforce categorical pretreatment standards under Section 307(b) and (c) of the Federal Clean Water Act (hereinafter, the Act), prohibited discharge standards as set forth in 40 CFR 403.5, local limits, or state standards, which ever are most stringent or apply at the time of issuance or modification of a local industrial waste discharge permit. Locally derived limits are defined as pretreatment standards under Section 307(d) of the Act and are not limited to categorical industrial facilities.

b. Issue industrial waste discharge permits to all significant industrial users [SIUs, as defined in 40 CFR 403.3(v)(i)(ii)] contributing to the treatment system, including those from other jurisdictions. Industrial waste discharge permits must contain as a minimum, all the requirements of 40 CFR 403.8 (f)(l)(iii). The Permittee must coordinate the permitting process with Ecology regarding any industrial facility which may possess a state waste discharge permit issued by Ecology.

c. Maintain and update, as necessary, records identifying the nature, character, and volume of pollutants contributed by industrial users to the treatment works. The Permittee must maintain records for at least a three-year period.

d. Perform inspections, surveillance, and monitoring activities on industrial users to determine or confirm compliance with pretreatment standards and requirements. The Permittee must conduct a thorough inspection of SIUs annually, except Middle-Tier Categorical Industrial Users, as defined by 40 CFR 403.8(f)(2)(v)(B)&(C), need only be inspected once every two years. The Permittee must conduct regular local monitoring of SIU wastewaters commensurate with the character and volume of the wastewater but not less than once per year except for Middle-Tier Categorical Industrial Users which may be sampled once every two years. The Permittee must collect and analyze samples in accordance with 40 CFR Part 403.12(b)(5)(ii)-(v) and 40 CFR Part 136.

e. Enforce and obtain remedies for non-compliance by any industrial users with applicable pretreatment standards and requirements. Once violations have been identified, the Permittee must take timely and appropriate enforcement action to address the non-compliance. The Permittee's action must follow its enforcement response procedures and any amendments, thereof.

f. Publish, at least annually in a newspaper of general circulation within the Permittee's service area, a list of all non-domestic users which, at any time in the previous 12 months, were in significant non-compliance as defined in 40 CFR 403.8(f)(2)(vii).

g. If the Permittee elects to conduct sampling of an SIU's discharge in lieu of requiring user self-monitoring, it must satisfy all requirements of 40 CFR Part 403.12. This includes monitoring and record keeping requirements of sections 403.12(g) and (o). For SIU's subject to categorical standards (i.e., CIUs), the Permittee may either complete baseline and initial compliance reports for the CIU (when required by 403.12(b) and (d)) or require these of the CIU. The Permittee must ensure SIUs are provided the results of sampling in a timely manner, inform SIUs of their right to sample, their obligations to report any sampling they do, to respond to non-compliance, and to submit other notifications. These include a slug load report (403.12(f)), notice of changed discharge (403.12(j)), and hazardous waste notifications (403.12(p)). If sampling for the SIU, the Permittee must not sample less than once in every six month period unless the Permittee's approved program includes procedures for reduction of monitoring for Middle-Tier or Non-Significant Categorical Users per 403.12(e)(2) and (3) and those procedures have been followed.

h. Develop and maintain a data management system designed to track the status of the Permittee's industrial user inventory, industrial user discharge characteristics, and compliance status.

i. Maintain adequate staff, funds, and equipment to implement its pretreatment program.

j. Establish, where necessary, contracts or legally binding agreements with contributing jurisdictions to ensure compliance with applicable pretreatment requirements by commercial or industrial users within these jurisdictions. These contracts or agreements must identify the agency responsible for the various implementation and enforcement activities to be performed in the contributing jurisdiction.

2. Per 40 CFR 403.8(f)(2)(vii), the Permittee must evaluate each Significant Industrial User to determine if a Slug Control Plan is needed to prevent slug discharges which may cause interference, pass-through, or in any other way result in violations of the Permittee's regulations, local limits or permit conditions. The Slug Control Plan evaluation shall occur within one year of a user's designation as a SIU. In accordance with 40 CFR 403.8(f)(1)(iii)(B)(6) the Permittee shall include slug discharge control requirements in an SIU's permit if the Permittee determines that they are necessary.

3. Whenever Ecology determines that any waste source contributes pollutants to the Permittee's treatment works in violation of Subsection (b), (c), or (d) of Section 307 of the Act, and the Permittee has not taken adequate corrective action, Ecology will notify the Permittee of this determination. If the Permittee fails to take appropriate enforcement action within 30 days of this notification, Ecology may take appropriate enforcement action against the source or the Permittee.

4. Pretreatment Report

The Permittee must submit the annual report according to the instructions in Special Condition S3.B, Permit Submittals and Schedules. Submit one electronic copy of the annual report using the Water Quality Permitting Portal – Permit Submittals application by April 30th of each year.

The report must include the following information:

a. An updated listing of non-domestic industrial dischargers.

b. Summarized Results of wastewater sampling at the treatment plant as specified in Subsection S6.B below. The Permittee must submit complete results of each sampling event on the appropriate quarterly or annual DMR through Ecology's WQWebDMR system, as described in Special Condition S3.A. The Permittee must calculate removal rates for each pollutant and evaluate the adequacy of the existing local limits in prevention of treatment plant interference, pass through of pollutants that could affect receiving water quality and biosolids contamination.

c. Status of program implementation, including:

- Any substantial modifications to the pretreatment program as originally approved by Ecology, including staffing and funding levels.
- Any interferences, upsets, or permit violations experienced at the WWTP that are directly attributable to wastes from industrial users.
- Listing of industrial users inspected and/or monitored, and a summary of the results.
- Listing of industrial users scheduled for inspection and/or monitoring for the next year, and expected frequencies.
- Listing of industrial users notified of promulgated pretreatment standards and/or local standards as required in 40 CFR 403.8(f)(2)(iii). The list must indicate which industrial users are on compliance schedules and the final date of compliance for each.
- Listing of industrial users issued industrial waste discharge permits.
- Planned changes in the pretreatment program implementation plan.

d. Status of compliance activities, including:

- Listing of industrial users that failed to submit baseline monitoring reports or any other reports required under 40 CFR 403.12 and in the Permittee's pretreatment program, dated April 27, 1981.
- Listing of industrial users that were at any time during the reporting period not complying with federal, state, or local pretreatment standards or with applicable compliance schedules for achieving those standards, and the duration of such non-compliance.
- Summary of enforcement activities and other corrective actions taken or planned against non-complying industrial users. The Permittee must supply to Ecology a copy of the public notice of facilities that were in significant non-compliance.

5. The Permittee must request and obtain approval from Ecology before making any significant changes to the approved local pretreatment program. The Permittee must follow the procedure in 40 CFR 403.18 (b) and (c).

S6.B. Monitoring requirements

The Permittee must monitor its influent, effluent, and biosolids at the Brightwater WWTP for the priority pollutants identified in Tables II and III of Appendix D of 40 CFR Part 122 as amended, any compounds identified as a result of Condition S6.B.4, and any other pollutants expected from nondomestic sources using U.S. EPA-approved procedures for collection, preservation, storage, and analysis. The Permittee must test influent, effluent, and biosolids samples for the priority pollutant metals (Table III, 40 CFR 122, Appendix D) on a quarterly basis throughout the term of this permit. The Permittee must test influent, effluent, and biosolids samples for the organic priority pollutants (Table II, 40 CFR 122, Appendix D) on an annual basis.

1. The Permittee must sample Brightwater WWTP influent and effluent on a day when industrial discharges are occurring at normal to maximum levels. The Permittee must obtain 24-hour composite samples for the analysis of acid and base/neutral extractable compounds and metals. The Permittee must collect samples for the analysis of volatile organic compounds and samples must be collected using grab sampling techniques at equal intervals for a total of four grab samples per day.

   The laboratory may run a single analysis for volatile pollutants (using GC/MS procedures approved by 40 CFR 136) for each monitoring day by compositing equal volumes of each grab sample directly in the GC purge and trap apparatus in the laboratory, with no less than 1 ml of each grab included in the composite.

   Unless otherwise indicated, all reported test data for metals must represent the total amount of the constituent present in all phases, whether solid, suspended, or dissolved, elemental or combined including all oxidation states.

   The Permittee must handle, prepare, and analyze all wastewater samples taken for GC/MS analysis using procedures approved by 40 CFR 136.

2. The Permittee must collect a biosolids sample concurrently with a wastewater sample as a single grab sample of residual biosolids. Sampling and analysis must be performed using procedures approved by 40 CFR 136 unless the Permittee requests an alternate method and Ecology has approved.

3. The Permittee must take cyanide, phenols, and oils as grab samples. Oils must be hexane soluble or equivalent, and should be measured in the influent and effluent only.

4. In addition to quantifying pH, oil and grease, and all priority pollutants, the Permittee must make a reasonable attempt to identify all other substances and quantify all pollutants shown to be present by gas chromatograph/mass spectrometer (GC/MS) analysis using procedures approved by 40 CFR 136. The Permittee should attempt to make determinations of pollutants for each fraction, which produces identifiable spectra on total ion plots (reconstructed gas chromatograms). The Permittee should attempt to make determinations from all peaks with responses 5% or greater than the nearest internal standard. The 5% value is based on internal standard concentrations of 30 μg/l, and must be adjusted downward if higher internal standard concentrations are used or adjusted upward if lower internal standard concentrations are used. The Permittee may express results for non-substituted aliphatic compounds as total hydrocarbon content. The Permittee must use a laboratory whose computer data processing programs are capable of comparing sample mass spectra to a computerized library of mass spectra, with visual confirmation by an

experienced analyst. For all detected substances which are determined to be pollutants, the Permittee must conduct additional sampling and appropriate testing to determine concentration and variability, and to evaluate trends.

S6.C. Reporting of monitoring results

The Permittee must submit data from each sampling event electronically on quarterly and annual DMRs through the WQWebDMR system, as outlined in Special Condition S3.A. The Permittee must also include a summary of monitoring results in the Annual Pretreatment Report.

S6.D. Local limit development

As sufficient data become available, the Permittee must, in consultation with Ecology, reevaluate their local limits in order to prevent pass through or interference. If Ecology determines that any pollutant present causes pass through or interference, or exceeds established biosolids standards, the Permittee must establish new local limits or revise existing local limits as required by 40 CFR 403.5. Ecology may also require the Permittee to revise or establish local limits for any pollutant discharged from the treatment works that has a reasonable potential to exceed the water quality standards, sediment standards, or established effluent limits, or causes whole effluent toxicity. Ecology makes this determination in the form of an Administrative Order.

Ecology may modify this permit to incorporate additional requirements relating to the establishment and enforcement of local limits for pollutants of concern. Any permit modification is subject to formal due process procedures under state and federal law and regulation.

S7. Solid wastes

S7.A. Solid waste handling

The Permittee must handle and dispose of all solid waste material in such a manner as to prevent its entry into state ground or surface water.

S7.B. Leachate

The Permittee must not allow leachate from its solid waste material to enter state waters without providing all known, available, and reasonable methods of treatment, nor allow such leachate to cause violations of the State Surface Water Quality Standards, Chapter 173-201A WAC, or the State Ground Water Quality Standards, Chapter 173-200 WAC. The Permittee must apply for a permit or permit modification as may be required for such discharges to state ground or surface waters.

S8. Spill control plan

S8.A Spill control plan submittals and requirements

The Permittee must:

1. Review the existing spill control plan for the permitted facility at least annually and update the plan as needed.

2. Send changes to the plan to Ecology.
3. Follow the plan and any supplements throughout the term of the permit.

S.B. Spill control plan components

The spill control plan must include the following:

1. A list of all oil and petroleum products and other materials used and/or stored on-site, which when spilled, or otherwise released into the environment, designate as dangerous waste (DW) or extremely hazardous waste (EHW) by the procedures set forth in WAC 173-303-070. Include other materials used and/or stored on-site which may become pollutants or cause pollution upon reaching state's waters.
2. A description of preventive measures and facilities (including an overall facility plot showing drainage patterns) which prevent, contain, or treat spills of these materials.
3. A description of the reporting system the Permittee will use to alert responsible managers and legal authorities in the event of a spill.
4. A description of operator training to implement the plan.

The Permittee may submit plans and manuals required by 40 CFR Part 112, contingency plans required by Chapter 173-303 WAC, or other plans required by other agencies, which meet the intent of this section.

S9. Wet weather operations

S9.A. Flow blending approval

The Permittee may initiate a bypass of the membrane bioreactor (MBR) treatment components at the permitted facility when the flows entering the facility are within 10% of exceeding the calculated available daily Membrane Flow Capacity. The following conditions apply to each wet weather bypass event.

1. The membrane control system must be operating in “TMP Control Mode”.
2. The Permittee must determine available Membrane Flow Capacity using an automated peak flow test performed simultaneously on two MBR trains for a one-hour period each day. The available Membrane Flow Capacity for the facility is the average individual train flow rate measured during the two-train peak flow test multiplied by the maximum number of installed MBR trains.
3. The Permittee must minimize the release of pollutants to the environment by taking the following actions:
    - Maximize flow through the MBR treatment system,
    - Maximize the use of storage capacity in the influent system, and
    - Divert flow to the West Point and/or South WWTPs, if conveyance and treatment capacity for those facilities is available.

4. When bypassing the MBR treatment components, the Permittee must ensure all bypass flows receive treatment through screening, grit removal, chemically enhanced primary clarification, and disinfection. The final discharge must meet the effluent limits listed in special condition S1.
5. The bypass event must result from increased flows caused by wet weather. The Permittee must document the duration and amount of rainfall for each storm event that causes a wet weather bypass.

Bypasses that do meet the above conditions are subject to the bypass provisions of special condition S5.F.

S9.B. Records and reporting

The Permittee must maintain records of all bypasses at the treatment plant. These records must document the date, duration, and volume of each bypass event, and the magnitude of the associated precipitation event. The records must also indicate the influent flow rate at the time when bypassing is initiated and the average influent flow rate during the split flow event.

The Permittee must report on the facility's monthly DMR all data from bypass monitoring listed in table S2A(3) of this permit. In addition, the Permittee must submit an annual bypass report by July 1st each year that summarizes all bypass occurrences for the previous year.

The annual report must document that each bypass complied with the authorizing conditions in part A above. It must also include a net environmental benefit (NEB) analysis. The NEB section must calculate the actual mass of BOD_5 and TSS discharged through the marine outfall on a monthly and annual basis and compare the results to a theoretical mass loading for a conventional, non-blending plant with the following assumed effluent quality:

Annual Average BOD_5 and TSS Concentrations: 15 mg/L

Maximum Monthly BOD_5 and TSS Concentrations: 25 mg/L

S9.C. Utility analysis report

The Permittee must submit an updated Utility Analysis Report by September 1, 2022.

S9.D. Net environmental benefit (NEB) performance standard

A performance standard applies to the Net Environmental Benefit achieved by the Brightwater WWTP. Achievement of the NEB is required in accordance with the standards in the table below which were approved by Ecology as part of the facility plan approval. If the Brightwater WWTP does not meet the required NEB, the Permittee must submit an explanation in the annual report(s) explaining the cause of non-compliance of the NEB and measures that will be taken to ensure achievement of the NEB.

Net Environmental Benefit Required[1]

Parameter	Net Environmental Benefit (percent reduction in BOD/TSS) [a, b]
Phase 1 – Revised (2012-2030) [c]	
BOD_5	
Maximum year [d]	51 percent
Maximum month [d]	16 percent
TSS	
Maximum year [d]	66 percent
Maximum month [d]	47 percent

a	Net environmental benefit is the reduction in a pollutant from the actual discharge compared to the theoretical discharge from a Conventional Activated Sludge (CAS) process.
b	Assumes CAS = 15 mg/L BOD_5/TSS for yearly conditions and 25 mg/L BOD_5/TSS for maximum-month condition.
c	Based on flow projections for 2030 and utilization of 0.8 million gallons of inline storage upstream of Hollywood Pump Station
d	20-year maximum flow based on 60 years of simulation.

S9.E. MBR pilot testing report

The Permittee must submit by July 31, 2018, a report that presents the findings of MBR pilot testing conducted at the Brightwater WWTP beginning in December 2014. The report must identify the variables testing revealed as potential causes of seasonal decreases in membrane performance. The report must also describe operational changes the Permittee may make to improve seasonal performance.

S10. Outfall evaluation

The Permittee must inspect the submerged portion of the outfall line and diffuser to document its integrity and continued function. If conditions allow for a photographic verification, the Permittee must include such verification in the report. By December 1, 2021, the Permittee must submit the inspection report to Ecology through the Water Quality Permitting Portal – Permit Submittals application. The Permittee must submit hard-copies of any video files to Ecology as required by Permit Condition S3.B. The Portal does not support submittal of video files.

[1] King County Wastewater Treatment Division, Brightwater Regional Wastewater Treatment System, Facilities Plan, May 2005, p 4-35 and King County Wastewater Treatment Division, Brightwater Regional Wastewater Treatment System, Facilities Plan Amendment No. 3, October 2016, p 15-17.

The inspector must at a minimum:

- Assess the physical condition of the outfall pipe, diffuser, and associated couplings and pipe anchors.
- Evaluate whether alignment issues reported in the 2012 Brightwater Marine Outfall Inspection and Commissioning report have worsened. Issues included the suspension of pipeline sections over depressions in the seabed and a slight rotation of one pipe as it sank into place during construction.
- Determine the extent of sediment accumulation in the vicinity of the diffuser.
- Ensure diffuser ports are free of obstructions and are allowing uniform flow.
- Confirm physical location (latitude/longitude) and depth (at MLLW) of the diffuser section of the outfall.

S11. Acute toxicity

S11.A. Testing when there is no permit limit for acute toxicity

The Permittee must:

1. Conduct acute toxicity testing on final effluent during the year prior to applying for permit renewal. Testing must occur once during the third quarter of 2021, no later than September 30, 2021, and once during the first quarter of 2022, no later than March 31, 2022.
2. Conduct acute toxicity testing on a series of at least five concentrations of effluent, including 100% effluent and a control.
3. Use each of the following species and protocols for each acute toxicity test:

Acute Toxicity Tests	Species	Method
Fathead minnow 96-hour static-renewal test	*Pimephales promelas*	EPA-821-R-02-012
Daphnid 48-hour static test	*Ceriodaphnia dubia, Daphnia pulex,* or *Daphnia magna*	EPA-821-R-02-012

4. Submit the results to Ecology electronically through the Water Quality Permitting Portal – Permit Submittals application by November 15, 2021 (for third quarter 2021 testing) and May 15, 2022 (for first quarter 2022 testing). The Permittee must also summarize the results in the next application for permit renewal.

S11.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain toxicity data, bench sheets, and reference toxicant results for test methods. In addition, the Permittee must submit toxicity test data in electronic format (CETIS export file preferred) for entry into Ecology's database.

2. The Permittee must collect 24-hour composite samples of effluent at the IPS for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.
3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.
4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Subsection C and the Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.
5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Section A or pristine natural water of sufficient quality for good control performance.
6. The Permittee must conduct whole effluent toxicity tests on an unmodified sample of final effluent.
7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the acute critical effluent concentration (ACEC). The ACEC equals 0.87% effluent.
8. All whole effluent toxicity tests, effluent screening tests, and rapid screening tests that involve hypothesis testing must comply with the acute statistical power standard of 29% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S12. Chronic toxicity

S12.A. Testing when there is no permit limit for chronic toxicity

The Permittee must:

1. Conduct chronic toxicity testing on final effluent during the year prior to applying for permit renewal. Testing must occur once during the fourth quarter of 2021, no later than December 31, 2021, and once during the second quarter of 2022, no later than June 30, 2022.
2. Conduct chronic toxicity testing on a series of at least five concentrations of effluent and a control. This series of dilutions must include the acute critical effluent concentration (ACEC). The ACEC equals 0.87% effluent. The series of dilutions should also contain the CCEC of 0.42% effluent.

3. Compare the ACEC to the control using hypothesis testing at the 0.05 level of significance as described in Appendix H, EPA/600/4-89/001.

4. Submit the results to Ecology electronically through the Water Quality Permitting Portal – Permit Submittals application by February 15, 2022 (for fourth quarter 2021 testing) and August 15, 2022 (for second quarter 2022 testing). The Permittee must also summarize the results in the next application for permit renewal.

5. Perform chronic toxicity tests with all of the following species and the most recent version of the following protocols:

Saltwater Chronic Test	Species	Method
Topsmelt survival and growth	*Atherinops affinis*	EPA/600/R-95/136
Mysid shrimp survival and growth	*Americamysis bahia* (formerly *Mysidopsis bahia*)	EPA-821-R-02-014

S12.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain toxicity data, bench sheets, and reference toxicant results for test methods. In addition, the Permittee must submit toxicity test data in electronic format (CETIS export file preferred) for entry into Ecology's database.

2. The Permittee must collect 24-hour composite samples of effluent at the IPS for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.

3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.

4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Section C and the Ecology Publication no. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.

5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Subsection C or pristine natural water of sufficient quality for good control performance.

6. The Permittee must conduct whole effluent toxicity tests on an unmodified sample of final effluent.

7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the CCEC and the ACEC. The CCEC and the ACEC may either substitute for the effluent concentrations that are closest to them in the dilution series or be extra effluent concentrations. The CCEC equals 0.42% effluent. The ACEC equals 0.87% effluent.
8. All whole effluent toxicity tests that involve hypothesis testing must comply with the chronic statistical power standard of 39% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S13. Application for permit renewal or modification for facility changes

The Permittee must submit an application for renewal of this permit by September 1, 2022.

The Permittee must also submit a new application or addendum at least one hundred eighty (180) days prior to commencement of discharges, resulting from the activities listed below, which may result in permit violations. These activities include any facility expansions, production increases, or other planned changes, such as process modifications, in the permitted facility.

General Conditions

G1. Signatory requirements

1. All applications submitted to Ecology must be signed and certified.
   a. In the case of corporations, by a responsible corporate officer. For the purpose of this section, a responsible corporate officer means:
      - A president, secretary, treasurer, or vice-president of the corporation in charge of a principal business function, or any other person who performs similar policy or decision making functions for the corporation, or
      - The manager of one or more manufacturing, production, or operating facilities, provided, the manager is authorized to make management decisions which govern the operation of the regulated facility including having the explicit or implicit duty of making major capital investment recommendations, and initiating and directing other comprehensive measures to assure long-term environmental compliance with environmental laws and regulations; the manager can ensure that the necessary systems are established or actions taken to gather complete and accurate information for permit application requirements; and where authority to sign documents has been assigned or delegated to the manager in accordance with corporate procedures.

   b. In the case of a partnership, by a general partner.
   c. In the case of sole proprietorship, by the proprietor.
   d. In the case of a municipal, state, or other public facility, by either a principal executive officer or ranking elected official.

   Applications for permits for domestic wastewater facilities that are either owned or operated by, or under contract to, a public entity shall be submitted by the public entity.

2. All reports required by this permit and other information requested by Ecology must be signed by a person described above or by a duly authorized representative of that person. A person is a duly authorized representative only if:
   a. The authorization is made in writing by a person described above and submitted to Ecology.
   b. The authorization specifies either an individual or a position having responsibility for the overall operation of the regulated facility, such as the position of plant manager, superintendent, position of equivalent responsibility, or an individual or position having overall responsibility for environmental matters. (A duly authorized representative may thus be either a named individual or any individual occupying a named position.)

3. Changes to authorization. If an authorization under paragraph G1.2, above, is no longer accurate because a different individual or position has responsibility for the overall operation of the facility, a new authorization satisfying the requirements of paragraph G1.2, above, must be submitted to Ecology prior to or together with any reports, information, or applications to be signed by an authorized representative.

4. Certification. Any person signing a document under this section must make the following certification:

   "I certify under penalty of law, that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gathered and evaluated the information submitted. Based on my inquiry of the person or persons who manage the system or those persons directly responsible for gathering information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations."

G2. Right of inspection and entry

The Permittee must allow an authorized representative of Ecology, upon the presentation of credentials and such other documents as may be required by law:

1. To enter upon the premises where a discharge is located or where any records must be kept under the terms and conditions of this permit.
2. To have access to and copy, at reasonable times and at reasonable cost, any records required to be kept under the terms and conditions of this permit.
3. To inspect, at reasonable times, any facilities, equipment (including monitoring and control equipment), practices, methods, or operations regulated or required under this permit.
4. To sample or monitor, at reasonable times, any substances or parameters at any location for purposes of assuring permit compliance or as otherwise authorized by the Clean Water Act.

G3. Permit actions

This permit may be modified, revoked and reissued, or terminated either at the request of any interested person (including the Permittee) or upon Ecology's initiative. However, the permit may only be modified, revoked and reissued, or terminated for the reasons specified in 40 CFR 122.62, 40 CFR 122.64 or WAC 173-220-150 according to the procedures of 40 CFR 124.5.

1. The following are causes for terminating this permit during its term, or for denying a permit renewal application:
   a. Violation of any permit term or condition.
   b. Obtaining a permit by misrepresentation or failure to disclose all relevant facts.
   c. A material change in quantity or type of waste disposal.
   d. A determination that the permitted activity endangers human health or the environment, or contributes to water quality standards violations and can only be regulated to acceptable levels by permit modification or termination.

e. A change in any condition that requires either a temporary or permanent reduction, or elimination of any discharge or sludge use or disposal practice controlled by the permit.

f. Nonpayment of fees assessed pursuant to RCW 90.48.465.

g. Failure or refusal of the Permittee to allow entry as required in RCW 90.48.090.

2. The following are causes for modification but not revocation and reissuance except when the Permittee requests or agrees:

   a. A material change in the condition of the waters of the state.

   b. New information not available at the time of permit issuance that would have justified the application of different permit conditions.

   c. Material and substantial alterations or additions to the permitted facility or activities which occurred after this permit issuance.

   d. Promulgation of new or amended standards or regulations having a direct bearing upon permit conditions, or requiring permit revision.

   e. The Permittee has requested a modification based on other rationale meeting the criteria of 40 CFR Part 122.62.

   f. Ecology has determined that good cause exists for modification of a compliance schedule, and the modification will not violate statutory deadlines.

   g. Incorporation of an approved local pretreatment program into a municipality’s permit.

3. The following are causes for modification or alternatively revocation and reissuance:

   a. When cause exists for termination for reasons listed in 1.a through 1.g of this section, and Ecology determines that modification or revocation and reissuance is appropriate.

   b. When Ecology has received notification of a proposed transfer of the permit. A permit may also be modified to reflect a transfer after the effective date of an automatic transfer (General Condition G7) but will not be revoked and reissued after the effective date of the transfer except upon the request of the new Permittee.

G4. Reporting planned changes

The Permittee must, as soon as possible, but no later than one hundred eighty (180) days prior to the proposed changes, give notice to Ecology of planned physical alterations or additions to the permitted facility, production increases, or process modification which will result in:

1. The permitted facility being determined to be a new source pursuant to 40 CFR 122.29(b).

2. A significant change in the nature or an increase in quantity of pollutants discharged.

3. A significant change in the Permittee's sludge use or disposal practices. Following such notice, and the submittal of a new application or supplement to the existing application, along with required engineering plans and reports, this permit may be modified, or revoked and reissued pursuant to 40 CFR 122.62(a) to specify and limit any pollutants not previously limited. Until such modification is effective, any new or increased discharge in excess of permit limits or not specifically authorized by this permit constitutes a violation.

G5. Plan review required

Prior to constructing or modifying any wastewater control facilities, an engineering report and detailed plans and specifications must be submitted to Ecology for approval in accordance with chapter 173-240 WAC. Engineering reports, plans, and specifications must be submitted at least one hundred eighty (180) days prior to the planned start of construction unless a shorter time is approved by Ecology. Facilities must be constructed and operated in accordance with the approved plans.

G6. Compliance with other laws and statutes

Nothing in this permit excuses the Permittee from compliance with any applicable federal, state, or local statutes, ordinances, or regulations.

G7. Transfer of this permit

In the event of any change in control or ownership of facilities from which the authorized discharge emanate, the Permittee must notify the succeeding owner or controller of the existence of this permit by letter, a copy of which must be forwarded to Ecology.

1. Transfers by Modification

   Except as provided in paragraph (2) below, this permit may be transferred by the Permittee to a new owner or operator only if this permit has been modified or revoked and reissued under 40 CFR 122.62(b)(2), or a minor modification made under 40 CFR 122.63(d), to identify the new Permittee and incorporate such other requirements as may be necessary under the Clean Water Act.

2. Automatic Transfers

   This permit may be automatically transferred to a new Permittee if:

   a. The Permittee notifies Ecology at least thirty (30) days in advance of the proposed transfer date.

   b. The notice includes a written agreement between the existing and new Permittees containing a specific date transfer of permit responsibility, coverage, and liability between them.

   c. Ecology does not notify the existing Permittee and the proposed new Permittee of its intent to modify or revoke and reissue this permit. A modification under this subparagraph may also be minor modification under 40 CFR 122.63. If this notice is not received, the transfer is effective on the date specified in the written agreement.

G8. Reduced production for compliance

The Permittee, in order to maintain compliance with its permit, must control production and/or all discharges upon reduction, loss, failure, or bypass of the treatment facility until the facility is restored or an alternative method of treatment is provided. This requirement applies in the situation where, among other things, the primary source of power of the treatment facility is reduced, lost, or fails.

G9. Removed substances

Collected screenings, grit, solids, sludges, filter backwash, or other pollutants removed in the course of treatment or control of wastewaters must not be resuspended or reintroduced to the final effluent stream for discharge to state waters.

G10. Duty to provide information

The Permittee must submit to Ecology, within a reasonable time, all information which Ecology may request to determine whether cause exists for modifying, revoking and reissuing, or terminating this permit or to determine compliance with this permit. The Permittee must also submit to Ecology upon request, copies of records required to be kept by this permit.

G11. Other requirements of 40 CFR

All other requirements of 40 CFR 122.41 and 122.42 are incorporated in this permit by reference.

G12. Additional monitoring

Ecology may establish specific monitoring requirements in addition to those contained in this permit by administrative order or permit modification.

G13. Payment of fees

The Permittee must submit payment of fees associated with this permit as assessed by Ecology.

G14. Penalties for violating permit conditions

Any person who is found guilty of willfully violating the terms and conditions of this permit is deemed guilty of a crime, and upon conviction thereof shall be punished by a fine of up to ten thousand dollars ($10,000) and costs of prosecution, or by imprisonment in the discretion of the court. Each day upon which a willful violation occurs may be deemed a separate and additional violation.

Any person who violates the terms and conditions of a waste discharge permit may incur, in addition to any other penalty as provided by law, a civil penalty in the amount of up to ten thousand dollars ($10,000) for every such violation. Each and every such violation is a separate and distinct offense, and in case of a continuing violation, every day's continuance is deemed to be a separate and distinct violation.

G15. Upset

Definition – "Upset" means an exceptional incident in which there is unintentional and temporary noncompliance with technology-based permit effluent limits because of factors beyond the reasonable control of the Permittee. An upset does not include noncompliance to the extent caused by operational error, improperly designed treatment facilities, inadequate treatment facilities, lack of preventive maintenance, or careless or improper operation.

An upset constitutes an affirmative defense to an action brought for noncompliance with such technology-based permit effluent limits if the requirements of the following paragraph are met.

A Permittee who wishes to establish the affirmative defense of upset must demonstrate, through properly signed, contemporaneous operating logs, or other relevant evidence that:

1. An upset occurred and that the Permittee can identify the cause(s) of the upset.
2. The permitted facility was being properly operated at the time of the upset.
3. The Permittee submitted notice of the upset as required in Special Condition S3.F.
4. The Permittee complied with any remedial measures required under S3.F of this permit.

In any enforcement action the Permittee seeking to establish the occurrence of an upset has the burden of proof.

G16. Property rights

This permit does not convey any property rights of any sort, or any exclusive privilege.

G17. Duty to comply

The Permittee must comply with all conditions of this permit. Any permit noncompliance constitutes a violation of the Clean Water Act and is grounds for enforcement action; for permit termination, revocation and reissuance, or modification; or denial of a permit renewal application.

G18. Toxic pollutants

The Permittee must comply with effluent standards or prohibitions established under Section 307(a) of the Clean Water Act for toxic pollutants within the time provided in the regulations that establish those standards or prohibitions, even if this permit has not yet been modified to incorporate the requirement.

G19. Penalties for tampering

The Clean Water Act provides that any person who falsifies, tampers with, or knowingly renders inaccurate any monitoring device or method required to be maintained under this permit shall, upon conviction, be punished by a fine of not more than $10,000 per violation, or by imprisonment for not more than two (2) years per violation, or by both. If a conviction of a person is for a violation committed after a first conviction of such person under this condition, punishment shall be a fine of not more than $20,000 per day of violation, or by imprisonment of not more than four (4) years, or by both.

G20. Compliance schedules

Reports of compliance or noncompliance with, or any progress reports on, interim and final requirements contained in any compliance schedule of this permit must be submitted no later than fourteen (14) days following each schedule date.

G21. Service agreement review

The Permittee must submit to Ecology any proposed service agreements and proposed revisions or updates to existing agreements for the operation of any wastewater treatment facility covered by this permit. The review is to ensure consistency with chapters 90.46 and 90.48 RCW as required by RCW 70.150.040(9). In the event that Ecology does not comment within a thirty-day (30) period, the Permittee may assume consistency and proceed with the service agreement or the revised/updated service agreement.

Appendix A

LIST OF POLLUTANTS WITH ANALYTICAL METHODS, DETECTION LIMITS AND QUANTITATION LEVELS

The Permittee must use the specified analytical methods, detection limits (DLs) and quantitation levels (QLs) in the following table for permit and application required monitoring unless:

- Another permit condition specifies other methods, detection levels, or quantitation levels.
- The method used produces measurable results in the sample and EPA has listed it as an EPA-approved method in 40 CFR Part 136.

If the Permittee uses an alternative method, not specified in the permit and as allowed above, it must report the test method, DL, and QL on the discharge monitoring report or in the required report.

If the Permittee is unable to obtain the required DL and QL in its effluent due to matrix effects, the Permittee must submit a matrix-specific detection limit (MDL) and a quantitation limit (QL) to Ecology with appropriate laboratory documentation.

When the permit requires the Permittee to measure the base neutral compounds in the list of priority pollutants, it must measure all of the base neutral pollutants listed in the table below. The list includes EPA required base neutral priority pollutants and several additional polynuclear aromatic hydrocarbons (PAHs). The Water Quality Program added several PAHs to the list of base neutrals below from Ecology's Persistent Bioaccumulative Toxics (PBT) List. It only added those PBT parameters of interest to Appendix A that did not increase the overall cost of analysis unreasonably.

Ecology added this appendix to the permit in order to reduce the number of analytical "non-detects" in permit-required monitoring and to measure effluent concentrations near or below criteria values where possible at a reasonable cost.

The lists below include conventional pollutants (as defined in CWA section 502(6) and 40 CFR Part 122.), toxic or priority pollutants as defined in CWA section 307(a)(1) and listed in 40 CFR Part 122 Appendix D, 40 CFR Part 401.15 and 40 CFR Part 423 Appendix A), and nonconventionals. 40 CFR Part 122 Appendix D (Table V) also identifies toxic pollutants and hazardous substances which are required to be reported by dischargers if expected to be present. This permit Appendix A list does not include those parameters.

CONVENTIONAL POLLUTANTS

Pollutant	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] *µg/L unless specified*	Quantitation Level (QL)[2] *µg/L unless specified*
Biochemical Oxygen Demand		SM5210-B		2 mg/L
Biochemical Oxygen Demand, Soluble		SM5210-B [3]		2 mg/L
Fecal Coliform		SM 9221E,9222	N/A	Specified in method - sample aliquot dependent
Oil and Grease (HEM) (Hexane Extractable Material)		1664 A or B	1,400	5,000
pH		SM4500-H^+ B	N/A	N/A
Total Suspended Solids		SM2540-D		5 mg/L

NONCONVENTIONAL POLLUTANTS

Pollutant & CAS No. (if available)	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] µg/L unless specified	Quantitation Level (QL)[2] µg/L unless specified
Alkalinity, Total		SM2320-B		5 mg/L as CaCO3
Aluminum, Total	7429-90-5	200.8	2.0	10
Ammonia, Total (as N)		SM4500-NH3-B and C/D/E/G/H		20
Barium Total	7440-39-3	200.8	0.5	2.0
BTEX (benzene +toluene + ethylbenzene + m,o,p xylenes)		EPA SW 846 8021/8260	1	2
Boron, Total	7440-42-8	200.8	2.0	10.0
Chemical Oxygen Demand		SM5220-D		10 mg/L
Chloride		SM4500-Cl B/C/D/E and SM4110 B		Sample and limit dependent
Chlorine, Total Residual		SM4500 Cl G		50.0
Cobalt, Total	7440-48-4	200.8	0.05	0.25
Color		SM2120 B/C/E		10 color units
Dissolved oxygen		SM4500-OC/OG		0.2 mg/L
Flow		Calibrated device		
Fluoride	16984-48-8	SM4500-F E	25	100
Hardness, Total		SM2340B		200 as CaCO3
Iron, Total	7439-89-6	200.7	12.5	50
Magnesium, Total	7439-95-4	200.7	10	50
Manganese, Total	7439-96-5	200.8	0.1	0.5
Molybdenum, Total	7439-98-7	200.8	0.1	0.5
Nitrate + Nitrite Nitrogen (as N)		SM4500-NO3- E/F/H		100
Nitrogen, Total Kjeldahl (as N)		SM4500-N_{org}B/C and SM4500NH_3-B/C/D/EF/G/H		300
NWTPH Dx [4]		Ecology NWTPH Dx	250	250
NWTPH Gx [5]		Ecology NWTPH Gx	250	250
Phosphorus, Total (as P)		SM 4500 PB followed by SM4500-PE/PF	3	10
Salinity		SM2520-B		3 practical salinity units or scale (PSU or PSS)

Exhibit A

NONCONVENTIONAL POLLUTANTS

Pollutant & CAS No. (if available)	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] µg/L unless specified	Quantitation Level (QL)[2] µg/L unless specified
Settleable Solids		SM2540 -F		Sample and limit dependent
Soluble Reactive Phosphorus (as P)		SM4500-P E/F/G	3	10
Sulfate (as mg/L SO_4)		SM4110-B		0.2 mg/L
Sulfide (as mg/L S)		SM4500-S^2F/D/E/G		0.2 mg/L
Sulfite (as mg/L SO_3)		SM4500-SO3B		2 mg/L
Temperature (max. 7-day avg.)		Analog recorder or use micro-recording devices known as thermistors		0.2º C
Tin, Total	7440-31-5	200.8	0.3	1.5
Titanium, Total	7440-32-6	200.8	0.5	2.5
Total Coliform		SM 9221B, 9222B, 9223B	N/A	Specified in method - sample aliquot dependent
Total Organic Carbon		SM5310-B/C/D		1 mg/L
Total dissolved solids		SM2540 C		20 mg/L

PRIORITY POLLUTANTS	PP #	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] ***µg/L unless specified***	Quantitation Level (QL)[2] ***µg/L unless specified***
METALS, CYANIDE & TOTAL PHENOLS					
Antimony, Total	114	7440-36-0	200.8	0.3	1.0
Arsenic, Total	115	7440-38-2	200.8	0.1	0.5
Beryllium, Total	117	7440-41-7	200.8	0.1	0.5
Cadmium, Total	118	7440-43-9	200.8	0.05	0.25
Chromium (hex) dissolved	119	18540-29-9	SM3500-Cr C	0.3	1.2
Chromium, Total	119	7440-47-3	200.8	0.2	1.0
Copper, Total	120	7440-50-8	200.8	0.4	2.0
Lead, Total	122	7439-92-1	200.8	0.1	0.5
Mercury, Total	123	7439-97-6	1631E	0.0002	0.0005
Nickel, Total	124	7440-02-0	200.8	0.1	0.5
Selenium, Total	125	7782-49-2	200.8	1.0	1.0
Silver, Total	126	7440-22-4	200.8	0.04	0.2
Thallium, Total	127	7440-28-0	200.8	0.09	0.36
Zinc, Total	128	7440-66-6	200.8	0.5	2.5
Cyanide, Total	121	57-12-5	335.4	5	10
Cyanide, Weak Acid Dissociable	121		SM4500-CN I	5	10
Cyanide, Free Amenable to Chlorination (Available Cyanide)	121		SM4500-CN G	5	10
Phenols, Total	65		EPA 420.1		50

PRIORITY POLLUTANTS	**PP #**	**CAS Number (if available)**	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL)[2] *µg/L unless specified***
ACID COMPOUNDS					
2-Chlorophenol	24	95-57-8	625.1	3.3	9.9
2,4-Dichlorophenol	31	120-83-2	625.1	2.7	8.1
2,4-Dimethylphenol	34	105-67-9	625.1	2.7	8.1
4,6-dinitro-o-cresol (2-methyl-4,6,-dinitrophenol)	60	534-52-1	625.1/1625B	24	72
2,4 dinitrophenol	59	51-28-5	625.1	42	126
2-Nitrophenol	57	88-75-5	625.1	3.6	10.8
4-Nitrophenol	58	100-02-7	625.1	2.4	7.2
Parachlorometa cresol (4-chloro-3-methylphenol)	22	59-50-7	625.1	3.0	9.0
Pentachlorophenol	64	87-86-5	625.1	3.6	10.8
Phenol	65	108-95-2	625.1	1.5	4.5
2,4,6-Trichlorophenol	21	88-06-2	625.1	2.7	8.1

PRIORITY POLLUTANTS	**PP #**	**CAS Number (if available)**	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL)[2] *µg/L unless specified***
VOLATILE COMPOUNDS					
Acrolein	2	107-02-8	624.1	5	10
Acrylonitrile	3	107-13-1	624.1	1.0	2.0
Benzene	4	71-43-2	624.1	4.4	13.2
Bromoform	47	75-25-2	624.1	4.7	14.1
Carbon tetrachloride	6	56-23-5	624.1/601 or SM6230B	2.8	8.4
Chlorobenzene	7	108-90-7	624.1	6.0	18.0
Chloroethane	16	75-00-3	624.1 or 601	1.0	2.0
2-Chloroethylvinyl Ether	19	110-75-8	624.1	1.0	2.0
Chloroform	23	67-66-3	624.1 or SM6210B	1.6	4.8
Dibromochloromethane (chlordibromomethane)	51	124-48-1	624.1	3.1	9.3
1,2-Dichlorobenzene	25	95-50-1	624.1	1.9	7.6
1,3-Dichlorobenzene	26	541-73-1	624.1	1.9	7.6
1,4-Dichlorobenzene	27	106-46-7	624.1	4.4	17.6
Dichlorobromomethane	48	75-27-4	624.1	2.2	6.6
1,1-Dichloroethane	13	75-34-3	624.1	4.7	14.1
1,2-Dichloroethane	10	107-06-2	624.1	2.8	8.4
1,1-Dichloroethylene	29	75-35-4	624.1	2.8	8.4
1,2-Dichloropropane	32	78-87-5	624.1	6.0	18.0
1,3-dichloropropene (mixed isomers) (1,2-dichloropropylene) [6]	33	542-75-6	624.1	5.0	15.0
Ethylbenzene	38	100-41-4	624.1	7.2	21.6
Methyl bromide (Bromomethane)	46	74-83-9	624.1 or 601	5.0	10.0
Methyl chloride (Chloromethane)	45	74-87-3	624.1	1.0	2.0
Methylene chloride	44	75-09-2	624.1	2.8	8.4
1,1,2,2-Tetrachloroethane	15	79-34-5	624.1	6.9	20.7
Tetrachloroethylene	85	127-18-4	624.1	4.1	12.3
Toluene	86	108-88-3	624.1	6.0	18.0
1,2-Trans-Dichloroethylene (Ethylene dichloride)	30	156-60-5	624.1	1.6	4.8
1,1,1-Trichloroethane	11	71-55-6	624.1	3.8	11.4

PRIORITY POLLUTANTS	**PP #**	**CAS Number (if available)**	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL) [2] *µg/L unless specified***
VOLATILE COMPOUNDS					
1,1,2-Trichloroethane	14	79-00-5	624.1	5.0	15.0
Trichloroethylene	87	79-01-6	624.1	1.9	5.7
Vinyl chloride	88	75-01-4	624.1 or SM6200B	1.0	2.0

PRIORITY POLLUTANTS	**PP #**	**CAS Number (if available)**	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL) [2] *µg/L unless specified***
BASE/NEUTRAL COMPOUNDS (compounds in bold are Ecology PBTs)					
Acenaphthene	1	83-32-9	625.1	1.9	5.7
Acenaphthylene	77	208-96-8	625.1	3.5	10.5
Anthracene	78	120-12-7	625.1	1.9	5.7
Benzidine	5	92-87-5	625.1	44	132
Benzyl butyl phthalate	67	85-68-7	625.1	2.5	7.5
Benzo(*a*)anthracene	72	56-55-3	625.1	7.8	23.4
Benzo(b)fluoranthene (3,4-benzofluoranthene) [7]	74	205-99-2	610/625.1	4.8	14.4
Benzo(j)fluoranthene [7]		**205-82-3**	625.1	0.5	1.0
Benzo(k)fluoranthene (11,12-benzofluoranthene) [7]	75	207-08-9	610/625.1	2.5	7.5
Benzo(b,j,k)fluoranthene (combined according to footnote 7) [7]			625.1	7.8	22.9
Benzo(r,s,t)pentaphene		**189-55-9**	625.1	1.3	5.0
Benzo(*a*)pyrene	73	50-32-8	610/625.1	2.5	7.5
Benzo(*ghi*)Perylene	79	191-24-2	610/625.1	4.1	12.3
Bis(*2-chloroethoxy)*methane	43	111-91-1	625.1	5.3	15.9
Bis(*2-chloroethyl*)ether	18	111-44-4	611/625.1	5.7	17.1
Bis(*2-chloroisopropyl*)ether	42	39638-32-9	625.1	0.5	1.0
Bis(*2-ethylhexyl*)phthalate	66	117-81-7	625.1	2.5	7.5
4-Bromophenyl phenyl ether	41	101-55-3	625.1	1.9	5.7
2-Chloronaphthalene	20	91-58-7	625.1	1.9	5.7
4-Chlorophenyl phenyl ether	40	7005-72-3	625.1	4.2	12.6
Chrysene	76	218-01-9	610/625.1	2.5	7.5
Dibenzo (a,h)acridine		**226-36-8**	610M/625M	2.5	10.0
Dibenzo (a,j)acridine		**224-42-0**	610M/625M	2.5	10.0
Dibenzo(a-*h*)anthracene (1,2,5,6-dibenzanthracene)	82	53-70-3	625.1	2.5	7.5
Dibenzo(a,e)pyrene		192-65-4	610M/625M	2.5	10.0
Dibenzo(a,h)pyrene		189-64-0	625M	2.5	10.0
3,3-Dichlorobenzidine	28	91-94-1	605/625.1	16.5	49.5
Diethyl phthalate	70	84-66-2	625.1	1.9	5.7
Dimethyl phthalate	71	131-11-3	625.1	1.6	4.8
Di-n-butyl phthalate	68	84-74-2	625.1	2.5	7.5
2,4-dinitrotoluene	35	121-14-2	609/625.1	5.7	17.1
2,6-dinitrotoluene	36	606-20-2	609/625.1	1.9	5.7
Di-n-octyl phthalate	69	117-84-0	625.1	2.5	7.5
1,2-Diphenylhydrazine (*as Azobenzene*)	37	122-66-7	1625B	5.0	20
Fluoranthene	39	206-44-0	625.1	2.2	6.6
Fluorene	80	86-73-7	625.1	1.9	5.7
Hexachlorobenzene	9	118-74-1	612/625.1	1.9	5.7
Hexachlorobutadiene	52	87-68-3	625.1	0.9	2.7

PRIORITY POLLUTANTS	**PP #**	**CAS Number (if available)**	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL) [2] *µg/L unless specified***
BASE/NEUTRAL COMPOUNDS (compounds in bold are Ecology PBTs)					
Hexachlorocyclopentadiene	53	77-47-4	1625B/625	2.0	4.0
Hexachloroethane	12	67-72-1	625.1	1.6	4.8
Indeno(*1,2,3-cd*)Pyrene	83	193-39-5	610/625.1	3.7	11.1
Isophorone	54	78-59-1	625.1	2.2	6.6
3-Methyl cholanthrene		**56-49-5**	625.1	2.0	8.0
Naphthalene	55	91-20-3	625.1	1.6	4.8
Nitrobenzene	56	98-95-3	625.1	1.9	5.7
N-Nitrosodimethylamine	61	62-75-9	607/625.1	2.0	4.0
N-Nitrosodi-n-propylamine	63	621-64-7	607/625.1	0.5	1.0
N-Nitrosodiphenylamine	62	86-30-6	625.1	1.0	2.0
Perylene		**198-55-0**	625.1	1.9	7.6
Phenanthrene	81	85-01-8	625.1	5.4	16.2
Pyrene	84	129-00-0	625.1	1.9	5.7
1,2,4-Trichlorobenzene	8	120-82-1	625.1	1.9	5.7

PRIORITY POLLUTANT	**PP #**	**CAS Number (if available)**	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL) [2] *µg/L unless specified***
DIOXIN					
2,3,7,8-Tetra-Chlorodibenzo-P-Dioxin (2,3,7,8 TCDD)	129	1746-01-6	1613B	1.3 pg/L	5 pg/L

PRIORITY POLLUTANTS	**PP #**	**CAS Number (if available)**	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL) [2] *µg/L unless specified***
PESTICIDES/PCBs					
Aldrin	89	309-00-2	608.3	4.0 ng/L	12 ng/L
alpha-BHC	102	319-84-6	608.3	3.0 ng/L	9.0 ng/L
beta-BHC	103	319-85-7	608.3	6.0 ng/L	18 ng/L
gamma-BHC (Lindane)	104	58-89-9	608.3	4.0 ng/L	12 ng/L
delta-BHC	105	319-86-8	608.3	9.0 ng/L	27 ng/L
Chlordane [8]	91	57-74-9	608.3	14 ng/L	42 ng/L
4,4'-DDT	92	50-29-3	608.3	12 ng/L	36 ng/L
4,4'-DDE	93	72-55-9	608.3	4.0 ng/L	12 ng/L
4,4' DDD	94	72-54-8	608.3	11ng/L	33 ng/L
Dieldrin	90	60-57-1	608.3	2.0 ng/L	6.0 ng/L
alpha-Endosulfan	95	959-98-8	608.3	14 ng/L	42 ng/L
beta-Endosulfan	96	33213-65-9	608.3	4.0 ng/L	12 ng/L
Endosulfan Sulfate	97	1031-07-8	608.3	66 ng/L	198 ng/L
Endrin	98	72-20-8	608.3	6.0 ng/L	18 ng/L
Endrin Aldehyde	99	7421-93-4	608.3	23 ng/L	70 ng/L
Heptachlor	100	76-44-8	608.3	3.0 ng/L	9.0 ng/L
Heptachlor Epoxide	101	1024-57-3	608.3	83 ng/L	249 ng/L
PCB-1242 [9]	106	53469-21-9	608.3	0.065	0.095
PCB-1254	107	11097-69-1	608.3	0.065	0.095
PCB-1221	108	11104-28-2	608.3	0.065	0.095
PCB-1232	109	11141-16-5	608.3	0.065	0.095
PCB-1248	110	12672-29-6	608.3	0.065	0.095
PCB-1260	111	11096-82-5	608.3	0.065	0.095
PCB-1016 [9]	112	12674-11-2	608.3	0.065	0.095
Toxaphene	113	8001-35-2	608.3	240 ng/L	720 ng/L

1. Detection level (DL) or detection limit means the minimum concentration of an analyte (substance) that can be measured and reported with a 99% confidence that the analyte concentration is greater than zero as determined by the procedure given in 40 CFR part 136, Appendix B.

2. Quantitation Level (QL) also known as Minimum Level of Quantitation (ML) – The lowest level at which the entire analytical system must give a recognizable signal and acceptable calibration point for the analyte. It is equivalent to the concentration of the lowest calibration standard or a multiple of the method detection limit. The Permittee must ensure that the analytical lab derives QLs for each analyte according to the procedures documented in the specific analytical method used by the lab.
ALSO GIVEN AS:
The smallest detectable concentration of analyte greater than the Detection Limit (DL) where the accuracy (precision & bias) achieves the objectives of the intended purpose. (Report of the Federal Advisory Committee on Detection and Quantitation Approaches and Uses in Clean Water Act Programs Submitted to the US Environmental Protection Agency, December 2007).

3. Soluble Biochemical Oxygen Demand method note: First, filter the sample through a Millipore Nylon filter (or equivalent) - pore size of 0.45-0.50 um (prep all filters by filtering 250 ml of laboratory grade deionized water through the filter and discard). Then, analyze sample as per method 5210-B.

4. NWTPH Dx - Northwest Total Petroleum Hydrocarbons Diesel Extended Range – see http://www.ecy.wa.gov/biblio/97602.html

5. NWTPH Gx - Northwest Total Petroleum Hydrocarbons Gasoline Extended Range – see http://www.ecy.wa.gov/biblio/97602.html

6. 1, 3-dichloroproylene (mixed isomers) - You may report this parameter as two separate parameters: cis-1, 3-dichlorpropropene (10061-01-5) and trans-1, 3-dichloropropene (10061-02-6).

7. Total Benzofluoranthenes - Because Benzo(b)fluoranthene, Benzo(j)fluoranthene and Benzo(k)fluoranthene co-elute you may report these three isomers as total benzofluoranthenes.

8. Chlordane – You may report alpha-chlordane (5103-71-9) and gamma-chlordane (5103-74-2) in place of chlordane (57-74-9). If you report alpha and gamma-chlordane, the DL/PQLs that apply are 14/42 ng/L.

9. PCB 1016 & PCB 1242 – You may report these two PCB compounds as one parameter called PCB 1016/1242.

EXHIBIT B

Issuance Date:	July 1, 2015
Effective Date:	August 1,2015
Expiration Date:	July 31, 2020

National Pollutant Discharge Elimination System
Waste Discharge Permit No. WA0029581

State of Washington
DEPARTMENT OF ECOLOGY
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

In compliance with the provisions of
The State of Washington Water Pollution Control Law
Chapter 90.48 Revised Code of Washington
and
The Federal Water Pollution Control Act
(The Clean Water Act)
Title 33 United States Code, Section 1342 et seq.

King County Wastewater Treatment Division
King Street Center, KSC-NR-0512
Seattle, Washington 98104-3855

is authorized to discharge in accordance with the Special and General Conditions that follow.

Plant Location:	Receiving Water:
King County South Wastewater Treatment Plant 1200 Monster Road SW Renton, WA 98057	Puget Sound – Central
Treatment Type: Activated Sludge with chlorine disinfection	

Kevin C. Fitzpatrick
Water Quality Section Manager
Northwest Regional Office
Washington State Department of Ecology

Exhibit B

Table of Contents

Summary of Permit Report Submittals

Refer to the Special and General Conditions of this permit for additional submittal requirements.

Permit Section	Submittal	Frequency	First Submittal Date
S3.A	Discharge Monitoring Report (DMR)	Monthly	September 15, 2015
S3.A	Permit application and priority pollutant data in WQWebDMR	Annually	July 31, 2016
S3.F	Reporting Permit Violations	As necessary	
S4.B	Plans for Maintaining Adequate Capacity	As necessary	
S4.D	Notification of New or Altered Sources	As necessary	
S4.E	Wasteload Assessment	1/permit cycle	October 31, 2018
S5.F	Bypass Notification	As necessary	
S5.G	Operations and Maintenance Manual Update	As necessary	
S6.A.4	Pretreatment Report	1/year	April 30, 2016
S8	Spill Control Plan Update	As necessary	
S9.A	Sediment Sampling and Analysis Plan	1/permit cycle	December 1, 2016
S9.B	Sediment Data Report	1/permit cycle	December 1, 2018
S10.A	Acute Toxicity Effluent Test Results - Submit with Permit Renewal Application	2 tests/permit cycle, 1 submittal/permit cycle	Tests: 2018, 1st and 3rd quarters. Submittal: July 31, 2019
S11.A	Chronic Toxicity Effluent Test Results with Permit Renewal Application	2 tests/permit cycle, 1 submittal/permit cycle	Tests: 2018, 2nd and 4th quarters. Submittal: July 31, 2019
S13	Application for Permit Renewal	1/permit cycle	July 31, 2019
G4	Reporting Planned Changes	As necessary	
G5	Engineering Report for Construction or Modification Activities	As necessary	

Exhibit B

Special Conditions

S1. Discharge limits

S1.A. Effluent limits

Puget Sound (Marine) Outfall No. 001

All discharges and activities authorized by this permit must comply with the terms and conditions of this permit. The discharge of any of the following pollutants more frequently than, or at a level in excess of, that identified and authorized by this permit violates the terms and conditions of this permit.

Beginning on the effective date of this permit, the Permittee may discharge treated municipal wastewater to the Puget Sound at the permitted locations subject to compliance with the following limits:

Effluent Limits: Outfall 001 (Puget Sound) *North Diffuser Lat/Long:* 47.602778˚, -122.429000˚ *South Diffuser Lat/Long:* 47.599722˚, -122.429028˚		
Parameter	**Average Monthly** [a]	**Average Weekly** [b]
Carbonaceous Biochemical Oxygen Demand (5-day) ($CBOD_5$)	25 milligrams/liter (mg/L) 30,000 pounds/day (lbs/day) 85% removal of influent $CBOD_5$	40 mg/L 48,000 lbs/day
Total Suspended Solids (TSS)	30 mg/L 36,000 lbs/day 85% removal of influent TSS	45 mg/L 54,000 lbs/day
	Average Monthly	**Maximum Daily** [c]
Total Residual Chlorine	500 µg/L	750 µg/L
	Instantaneous Minimum	**Instantaneous Maximum**
pH [d]	6.0 standard units	9.0 standard units
	Monthly Geometric Mean	**Weekly Geometric Mean**
Fecal Coliform Bacteria [e]	200/100 milliliter (mL)	400/100 mL

[a] Average monthly effluent limit is the highest allowable average of daily discharges over a calendar month, calculated as the sum of all daily discharges measured during a calendar month divided by the number of daily discharges measured during that month.

[b] Average weekly discharge limit is the highest allowable average of daily discharges over a calendar week, calculated as the sum of all daily discharges measured during a calendar week divided by the number of daily discharges measured during that week.

[c] Maximum daily effluent limit is the highest allowable daily discharge. The daily discharge is the average discharge of a pollutant measured during a calendar day. This does not apply to pH.

[d] Report the instantaneous maximum and minimum pH monthly. Do not average pH values.

[e] Ecology provides directions to calculate the monthly and the weekly geometric mean in publication No. 04-10-020, *Information Manual for Treatment Plant Operators* available at: http://www.ecy.wa.gov/pubs/0410020.pdf

Green River (Freshwater) - Outfall No. 002

Beginning on the effective date of this permit and lasting through the expiration date, the Permittee is authorized to discharge treated municipal wastewater at the Green River outfall for maintenance purposes only under the following conditions:

1. The Permittee must obtain approval from Ecology at least five (5) working days in advance of the discharging to the Green River for maintenance purposes.
2. The duration of the discharge must not exceed four (4) hours.
3. The discharge must comply with the limits specified below.

Effluent Limits: Outfall 002A (Green River) *Lat/Long:* 47.467500˚, -122.244167˚	
Parameter	**Maximum Daily** [1]
Effluent Flow, MGD [2]	Must be less than or equal to: 0.25 * Green River Flow (MGD) / 5
$CBOD_5$	20 mg/L
Total Suspended Solids	20 mg/L
Total Residual Chlorine	95 µg/L
pH	Shall not be outside the range 6.0 to 9.0
	Maximum Geometric Mean
Fecal Coliform	200/100 mL

[1] Maximum daily effluent limit is the highest allowable daily discharge. In this case, the daily discharge is the average measurement over the discharge duration.

[2] Effluent flow limit is based on a dilution factor of 5, which is required to assure compliance with water quality criteria.

4. The Permittee may only discharge when the Green River flow is greater than 500 cfs.
5. The Permittee must treat any maintenance discharges to the Green River using secondary treatment, disinfection, and dechlorination.
6. The Permittee must monitor the discharge as required in S2.A to ensure that effluent limits are met.
7. The Permittee must sample receiving water turbidity as detailed in S2.A.
8. Any discharge from the treatment plant that results in water quality violations or contributes significantly to a fish kill is a violation of this permit.
9. The Permittee may only discharge, as a result of maintenance activities, during the out-going tide (after a high tide and before the subsequent low tide).
10. The Permittee should consider fish migration patterns when scheduling maintenance discharges.

S1.B. Mixing zone authorization

Outfall 001 – Puget Sound (marine)

The following paragraphs define the maximum boundaries of the mixing zones:

Chronic mixing zone

The chronic mixing zone consists of circles surrounding each discharge port with radii of 825 feet measured from the center of each port. The mixing zone extends from the bottom to the top of the water column. The concentration of pollutants at the edge of the chronic zone must meet chronic aquatic life criteria and human health criteria.

Acute mixing zone

The extended acute mixing zone consists of circles surrounding each discharge port with radii of 82 feet measured from the center of each port. The mixing zone extends from the bottom to the top of the water column. The concentration of pollutants at the edge of the acute zone must meet acute aquatic life criteria.

Outfall 001 - Available Dilution (dilution factor)	
Acute Aquatic Life Criteria	186
Chronic Aquatic Life Criteria	225
Human Health Criteria - Carcinogen	428
Human Health Criteria - Non-carcinogen	428

Outfall 002 – Green River (freshwater)

The Green River outfall is used as an emergency/backup outfall and is permitted for maintenance purposes only; emergency discharges from this outfall are permitted under S5.F. No chronic mixing zone is granted because maintenance discharges are permitted for durations of 4 hours or less.

Acute mixing zone

The acute mixing zone encompasses 25% of the river flow in accordance with WAC 173-201A-400(12). The resulting dilution factor is 5.0. The mixing zone extends 100 feet upstream, 300 feet downstream, and from the bottom to the top of the water column. The concentration of pollutants at the edge of the acute zone must meet acute aquatic life criteria.

Outfall 002 - Available Dilution (dilution factor)	
Chronic Dilution Ratio*	Not Applicable
Acute Dilution Ratio	5.0:1

* Maintenance discharges are permitted for durations of 4 hours or less and therefore a chronic dilution factor is not applicable.

S2. Monitoring requirements

S2.A. Monitoring schedules

The Permittee must monitor in accordance with the following schedules and must use the laboratory method, detection level (DL), and quantitation level (QL) specified in Appendix A or corresponding Sampling Analysis Plan/Quality Assurance Project Plan (SAP/QAPP) documents. Alternative methods from 40 CFR Part 136 are acceptable for those parameters without limits, and if the DL and QL are equivalent to those specified in Appendix A, corresponding SAP/QAPP documents, or sufficient to produce a measurable quantity.

Monitoring Requirements for Outfall 001 – Puget Sound

Parameter	Units	Minimum Sampling Frequency	Sample Type
(1) Wastewater influent (raw sewage from the collection system into the treatment facility)			
BOD_5	mg/L	1/week	24-hour composite [a]
	lbs/day [b]	1/week	Calculation
$CBOD_5$	mg/L	4/week	24-hour composite
	lbs/day [b]	4/week	Calculation
TSS	mg/L	4/week	24-hour composite
	lbs/day [b]	4/week	Calculation
(2) Final wastewater effluent (wastewater exiting the last treatment process or operation)			
Flow	MGD	Continuous [c]	Metered/recorded
$CBOD_5$ [d]	mg/L	4/week	24-hour composite
	lbs/day [b]	4/week	Calculation
	% removal [e]	Monthly	Calculation
TSS	mg/L	4/week	24-hour composite
	lbs/day [b]	4/week	Calculation
	% removal [e]	Monthly	Calculation
Chlorine (Total Residual)	µg/L	Continuous	Metered/recorded
Fecal Coliform [f]	# /100 ml	5/week	Grab [g]
pH [h]	Standard Units	Continuous	Metered/recorded
Total Ammonia	mg/L as N	Monthly	24-hour composite
	lbs/day [b]	Monthly	Calculation
Nitrate plus Nitrite Nitrogen	mg/L as N	Monthly	24-hour composite
Total Kjeldahl Nitrogen (TKN)	mg/L as N	Monthly	24-hour composite
Total Phosphorus	mg/L as P	Monthly	24-hour composite
Soluble Reactive Phosphorus	mg/L as P	Monthly	24-hour composite
Cyanide	micrograms/liter (µg/L)	2/year: Aug & Jan	Grab

Parameter	Units	Minimum Sampling Frequency	Sample Type
Total Phenolic Compounds	µg/L	2/year: Aug & Jan	Grab
Priority Pollutants (PP) – Total Metals [i]	µg/L ng/L for mercury	2/year: Aug & Jan	24-hour composite Grab for mercury
PP – Volatile Organic Compounds [i]	µg/L	2/year: Aug & Jan	Grab
PP – Acid-extractable Compounds [i]	µg/L	2/year: Aug & Jan	24-hour composite
PP – Base-neutral Compounds [i]	µg/L	2/year: Aug & Jan	24-hour composite
PP – PCBs [i]	µg/L	2/year: Aug & Jan	24-hour composite
(3) Whole effluent toxicity testing – As specified in Permit Conditions S10 & S11			
Acute Toxicity Testing		2/permit cycle	24-hour composite
Chronic Toxicity Testing		2/permit cycle	24-hour composite
(4) Pretreatment - As specified in Permit Condition S6			
(5) Permit Application Requirements – Final Wastewater Effluent			
Dissolved Oxygen	mg/L	1/year in Aug	Grab
Oil and Grease (HEM)	mg/L	1/year in Aug	Grab
Total Dissolved Solids	mg/L	1/year in Aug	24-hour composite
Total Hardness	mg/L	1/year in Aug	24-hour composite
Alkalinity	mg/L as CaCO3	1/year in Aug	Grab
Temperature	˚C	1/year in Aug	Grab
(6) Sediment - As specified in Permit Condition S9			

[a] 24-hour composite means a series of individual samples collected over a 24-hour period into a single container, and analyzed as one sample.

[b] lbs/day = Concentration (in mg/L) x Flow (in MGD) x Conversion Factor (8.34). Calculate using the average flow measured during the sample collection period.

[c] "Continuous" means uninterrupted except for brief lengths of time for calibration, power failure, or unanticipated equipment repair or maintenance. The time interval for the associated data logger must be no greater than 30 minutes. The Permittee must sample every six hours when continuous monitoring is not possible.

[d] Effluent samples for $CBOD_5$ analysis may be taken before or after the disinfection process. If taken after, dechlorinate and reseed the sample.

[e] % removal = $\frac{\text{Influent monthly average conc. (mg/L) – Effluent monthly average conc. (mg/L)}}{\text{Influent monthly average concentration (mg/L)}} \times 100$

[f] Report a numerical value for fecal coliforms following the procedures in Ecology's *Information Manual for Wastewater Treatment Plant Operators*, Publication Number 04-10-020 available at: http://www.ecy.wa.gov/programs/wq/permits/guidance.html. Do not report a result as too numerous to count (TNTC).

[g] Grab means an individual sample collected over a fifteen (15) minute, or less, period.

[h] Report the instantaneous maximum and minimum pH daily. Do not average pH values.

[i] Record and report the effluent flow discharged on the day of the priority pollutant samples.
See Appendix A or corresponding SAP/QAPP for the required detection (DL) or quantitation (QL) levels.
Report single analytical values below detection as "less than (detection level)" where (detection level) is the numeric value specified in Appendix A.
Report single analytical values between the detection and quantitation levels with qualifier code of 'j' following the value. If unable to obtain the required DL and QL due to matrix effects, the Permittee must submit a matrix specific MDL and a QL with appropriate laboratory documentation.

Monitoring Requirements for Outfall 002A – Green River

Parameter	Units	Minimum Sampling Frequency	Sample Type
(1) Wastewater Final Effluent (wastewater exiting the last treatment process or operation)			
Effluent Flow - maximum	MGD	Continuous	Metered/recorded
Duration	Hours	Once per event	Measurement
$CBOD_5$	mg/L	Once per event	Composite of equal volume grab samples during event
TSS	mg/L	Once per event	Composite of equal volume grab samples during event
pH	s.u.	Continuous	Metered/recorded
Fecal Coliform	# /100 ml	Once per event	Grab
Total Residual Chlorine	µg/L	Continuous	Metered/recorded
Dilution Factor *	None	Once per event	Calculated
(2) Downstream of Discharge - 300 feet			
River Flow	cfs	Once per event	Measurement
Turbidity	NTU	Once per event	Grab
(3) Upstream of Discharge			
Turbidity	NTU	Once per event	Grab

* Dilution Factor = [0.25 * River Flow, MGD] / [Effluent Flow, MGD], report as comment on DMR

S2.B. Sampling and analytical procedures

Samples and measurements taken to meet the requirements of this permit must represent the volume and nature of the monitored parameters. The Permittee must conduct representative sampling of any unusual discharge or discharge condition, including bypasses, upsets, and maintenance-related conditions that may affect effluent quality.

Sampling and analytical methods used to meet the monitoring requirements specified in this permit must conform to the latest revision of the *Guidelines Establishing Test Procedures for the Analysis of Pollutants* contained in 40 CFR Part 136 (or as applicable in 40 CFR subchapters N [Parts 400–471] or O [Parts 501-503]) unless otherwise specified in this permit . Ecology may only specify alternative methods for parameters without permit limits and for those parameters without an EPA approved test method in 40 CFR Part 136.

S2.C. Flow measurement and continuous monitoring devices

The Permittee must:

1. Select and use appropriate flow measurement and continuous monitoring devices and methods consistent with accepted scientific practices.

2. Install, calibrate, and maintain these devices to ensure the accuracy of the measurements is consistent with the accepted industry standard, the manufacturer's recommendation, and approved O&M manual procedures for the device and the wastestream.
3. Calibrate continuous monitoring instruments consistent with the manufacturer's recommendation.
4. Maintain calibration records for at least three years.

S2.D. Laboratory accreditation

The Permittee must ensure that all monitoring data required by Ecology for permit specified parameters is prepared by a laboratory registered or accredited under the provisions of chapter 173-50 WAC, *Accreditation of Environmental Laboratories*. Flow and internal process control parameters are exempt from this requirement.

S3. Reporting and recording requirements

The Permittee must monitor and report in accordance with the following conditions. Falsification of information submitted to Ecology is a violation of the terms and conditions of this permit.

S3.A. Discharge monitoring reports

The first monitoring period begins on the effective date of the permit. Permittee must:

1. Summarize, report, and submit monitoring data obtained during each monitoring period on the electronic discharge monitoring report (DMR) form provided by Ecology within the Water Quality Permitting Portal. Include data for each of the parameters tabulated in Special Condition S2 and as required by the form. Report a value for each day sampling occurred and for the summary values (when applicable) included on the electronic form.

   To find out more information and to sign up for the Water Quality Permitting Portal go to: http://www.ecy.wa.gov/programs/wq/permits/paris/webdmr.html
2. Enter the "No Discharge" reporting code for an entire DMR, for a specific monitoring point, or for a specific parameter as appropriate, if the Permittee did not discharge wastewater or a specific pollutant during a given monitoring period.
3. Report single analytical values below detection as "less than the detection level (DL)" by entering < followed by the numeric value of the detection level (e.g. < 2.0) on the DMR. If the method used did not meet the minimum DL and quantitation level (QL) identified in the permit, report the actual QL and DL in the comments or in the location provided.
4. **Not** report zero for bacteria monitoring. Report as required by the laboratory method.
5. Calculate the geometric mean values for bacteria using:

   a. The reported numeric value for all bacteria samples measured above the detection value except when it took multiple samples in one day. If the Permittee takes multiple samples in one day it must use the arithmetic average for that day in the geometric mean calculation.
   b. The detection value for those samples measured below detection.

6. Report the test method used for analysis in the comments if the laboratory used an alternative method not specified in the permit and as allowed in Appendix A.
7. Calculate average values and total values (unless otherwise specified in the permit) using:
   a. The reported numeric value for all parameters measured between the agency-required detection value and the agency-required quantitation value.
   b. One-half the detection value (for values reported below detection) if the lab detected the parameter in another sample from the same monitoring point for the reporting period.
   c. Zero (for values reported below detection) if the lab did not detect the parameter in another sample for the reporting period.
8. Report single-sample grouped parameters (for example: priority pollutants) on the WQWebDMR form and include sample date, concentration detected, detection limit (DL) (as necessary), laboratory quantitation level (QL) (as necessary), and CAS number. The Permittee must also submit an electronic copy of the laboratory report as an attachment using WQWebDMR. The contract laboratory reports must also include information on the chain of custody, QA/QC results, and documentation of accreditation for the parameter.
9. Ensure that DMRs are electronically submitted no later than the dates specified below, unless otherwise specified in this permit.
10. Submit DMRs in WQWebDMR for parameters with the monitoring frequencies specified in S2 (monthly, annually, etc.) at the reporting schedule identified below. The Permittee must:
    a. Submit **monthly** DMRs by the 15th day of the following month.
    b. Submit **annual** DMRs by July 31st for the previous calendar year. These submittals must include the permit renewal application monitoring data, priority pollutant, cyanide, and phenolic compound data as required in Special Condition S2.A. The annual sampling period is the calendar year.

S3.B. Permit submittals and schedules

The Permittee must use the *Water Quality Permitting Portal – Permit Submittals* application to submit all other written permit-required reports by the date specified in the permit.

When another permit condition requires submittal of a paper (hard-copy) report, the Permittee must ensure that it is postmarked or received by Ecology no later than the dates specified by this permit. Send these paper reports to Ecology at:

Water Quality Permit Coordinator
Department of Ecology
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

S3.C. Records retention

The Permittee must retain records of all monitoring information for a minimum of three (3) years. Such information must include all calibration and maintenance records and all original recordings for continuous monitoring instrumentation, copies of all reports required by this permit, and records of all data used to complete the application for this permit. The Permittee must extend this period of retention during the course of any unresolved litigation regarding the discharge of pollutants by the Permittee or when requested by Ecology.

S3.D. Recording of results

For each measurement or sample taken, the Permittee must record the following information:

1. The date, exact place, method, and time of sampling or measurement.
2. The individual who performed the sampling or measurement.
3. The dates the analyses were performed.
4. The individual who performed the analyses.
5. The analytical techniques or methods used.
6. The results of all analyses.

S3.E. Additional monitoring by the Permittee

If the Permittee monitors any pollutant more frequently than required by Special Condition S2 of this permit, then the Permittee must include the results of such monitoring in the calculation and reporting of the data submitted in the Permittee's DMR unless otherwise specified by Special Condition S2.

S3.F. Reporting permit violations

The Permittee must take the following actions when it violates or is unable to comply with any permit condition:

1. Immediately take action to stop, contain, and cleanup unauthorized discharges or otherwise stop the noncompliance and correct the problem.
2. If applicable, immediately repeat sampling and analysis. Submit the results of any repeat sampling to Ecology within thirty (30) days of sampling.

a. *Immediate reporting*

The Permittee must **immediately** report to Ecology and the Department of Health, Shellfish Program, and Public Health of Seattle-King County (phone numbers listed below), all:

- Failures of the disinfection system
- Collection system overflows
- Plant bypasses discharging to marine surface waters
- Any other failures of the sewage system (pipe breaks, etc.)

The Permittee must also *immediately* report any collection system overflows discharging to a waterbody used as a source of drinking water to Ecology, the Department of Health Drinking Water Program, and Public Health of Seattle-King County.

Ecology - Northwest Regional Office	425-649-7000
Department of Health - Shellfish Program	360-236-3330 (business hours) 360-789-8962 (after business hours)
Public Health of Seattle-King County	206-477-8177
Department of Health, Drinking Water Program	800-521-0323 (business hours) 877-481-4901 (after business hours)

Additionally, for any sanitary sewer overflow (SSO) that discharges to a municipal separate storm sewer system (MS4), the Permittee must notify the appropriate MS4 owner or operator.

b. *Twenty-four-hour reporting*

The Permittee must report the following occurrences of noncompliance by telephone, to Ecology at the telephone number listed above, within 24 hours from the time the Permittee becomes aware of any of the following circumstances:

i. Any noncompliance that may endanger health or the environment, unless previously reported under immediate reporting requirements.

ii. Any unanticipated bypass that causes an exceedance of an effluent limit in the permit (See Part S5.F, “Bypass Procedures”).

iii. Any upset that causes an exceedance of an effluent limit in the permit (see G15, “Upset”).

iv. Any violation of a maximum daily or instantaneous maximum discharge limit for any of the pollutants in Section S1.A of this permit.

v. Any overflow prior to the treatment works, whether or not such overflow endangers health or the environment or exceeds any effluent limit in the permit.

c. *Report within five days*

The Permittee must also submit a written report within five business days of the time that the Permittee becomes aware of any reportable event under subparts a or b, above. The report must contain:

i. A description of the noncompliance and its cause.

ii. The period of noncompliance, including exact dates and times.

iii. The estimated time the Permittee expects the noncompliance to continue if not yet corrected.

iv. Steps taken or planned to reduce, eliminate, and prevent recurrence of the noncompliance.

v. If the noncompliance involves an overflow prior to the treatment works, an estimate of the quantity (in gallons) of untreated overflow.

d. *Waiver of written reports*

Ecology may waive the written report required in subpart c, above, on a case-by-case basis upon request if the Permittee has submitted a timely oral report.

e. *All other permit violation reporting*

The Permittee must report all permit violations, which do not require immediate or within 24 hours reporting, when it submits monitoring reports for S3.A ("Reporting"). The reports must contain the information listed in subpart c, above. Compliance with these requirements does not relieve the Permittee from responsibility to maintain continuous compliance with the terms and conditions of this permit or the resulting liability for failure to comply.

S3.G. Other reporting

1. Spills of oil or hazardous materials

The Permittee must report a spill of oil or hazardous materials in accordance with the requirements of RCW 90.56.280 and chapter 173-303-145. You can obtain further instructions at the following website: http://www.ecy.wa.gov/programs/spills/other/reportaspill.htm .

2. Failure to submit relevant or correct facts

Where the Permittee becomes aware that it failed to submit any relevant facts in a permit application, or submitted incorrect information in a permit application, or in any report to Ecology, it must submit such facts or information promptly.

S3.H. Maintaining a copy of this permit

The Permittee must keep a copy of this permit at the facility and make it available upon request to Ecology inspectors.

S4. Facility loading

S4.A. Design criteria

The flows or waste loads for the permitted facility must not exceed the following design criteria:

Maximum Month Design Flow (MMDF)	144 MGD
BOD_5 Influent Loading for Maximum Month	251,000 lbs/day
TSS Influent Loading for Maximum Month	235,000 lbs/day

S4.B. Plans for maintaining adequate capacity

1. Conditions triggering plan submittal

   The Permittee must submit a plan and a schedule for continuing to maintain capacity to Ecology when:

   a. The actual flow or waste load reaches 85 percent of any one of the design criteria in S4.A for three consecutive months.

   b. The projected plant flow or loading would reach design capacity within five years.

2. Plan and schedule content

   The plan and schedule must identify the actions necessary to maintain adequate capacity for the expected population growth and to meet the limits and requirements of the permit. The Permittee must consider the following topics and actions in its plan.

   a. Analysis of the present design and proposed process modifications.

   b. Reduction or elimination of excessive infiltration and inflow of uncontaminated ground and surface water into the sewer system.

   c. Limits on future sewer extensions or connections or additional waste loads.

   d. Modification or expansion of facilities.

   e. Reduction of industrial or commercial flows or waste loads

   Engineering documents associated with the plan must meet the requirements of WAC 173-240-060, "Engineering Report," and be approved by Ecology prior to any construction.

S4.C. Duty to mitigate

The Permittee must take all reasonable steps to minimize or prevent any discharge or biosolids use or disposal in violation of this permit that has a reasonable likelihood of adversely affecting human health or the environment.

S4.D. Notification of new or altered sources

1. The Permittee must submit written notice to Ecology whenever any new discharge or a substantial change in volume or character of an existing discharge into the wastewater treatment plant is proposed which:
   a. Would interfere with the operation of, or exceed the design capacity of, any portion of the wastewater treatment plant.
   b. Is not part of an approved general sewer plan or approved plans and specifications.
   c. Is subject to pretreatment standards under 40 CFR Part 403 and Section 307(b) of the Clean Water Act.
2. This notice must include an evaluation of the wastewater treatment plant's ability to adequately transport and treat the added flow and/or waste load, the quality and volume of effluent to be discharged to the treatment plant, and the anticipated impact on the Permittee's effluent [40 CFR 122.42(b)].

S4.E. Wasteload assessment

The Permittee must conduct an assessment of its influent flow and waste load and submit a report to Ecology by October 31, 2018. The report must contain:

1. A description of compliance or noncompliance with the permit effluent limits.
2. A comparison between the existing and design:
   a. Monthly average dry weather and wet weather flows.
   b. Maximum month flows.
   c. Peak flows.
   d. BOD_5 loadings.
   e. Total suspended solids loadings.
3. The percent change in the above parameters since the previous report.
4. The present and design population or population equivalent.
5. The projected population growth rate.
6. The estimated date upon which the Permittee expects the wastewater treatment plant to reach design capacity, according to the most restrictive of the parameters above.
7. An Infiltration and Inflow (I/I) update that describes:
   a. For the collection system owned and operated by the County:
      i. The results of recent I/I monitoring
      ii. A summary of recent I/I improvement projects.
      iii. Projects planned to improve I/I.

b. For the collection systems owned and operated by component agencies:

   i. Measures taken to encourage component agencies to control I/I.

   ii. Any known I/I concerns.

   iii. Steps planned to further encourage I/I reduction projects.

S5. Operation and maintenance

The Permittee must at all times properly operate and maintain all facilities and systems of treatment and control (and related appurtenances), which are installed to achieve compliance with the terms and conditions of this permit. Proper operation and maintenance also includes keeping a daily operation logbook (paper or electronic), adequate laboratory controls, and appropriate quality assurance procedures. This provision of the permit requires the Permittee to operate backup or auxiliary facilities or similar systems only when the operation is necessary to achieve compliance with the conditions of this permit.

S5.A. Certified operator

This permitted facility must be operated by an operator certified by the state of Washington for at least a Class IV plant. This operator must be in responsible charge of the day-to-day operation of the wastewater treatment plant. An operator certified for at least a Class III plant must be in charge during all regularly scheduled shifts.

S5.B. Operation and maintenance program

The Permittee must:

1. Institute an adequate operation and maintenance program for the entire sewage system.
2. Keep maintenance records on all major electrical and mechanical components of the treatment plant, as well as the sewage system and pumping stations. Such records must clearly specify the frequency and type of maintenance recommended by the manufacturer and must show the frequency and type of maintenance performed.
3. Make maintenance records available for inspection at all times.

S5.C. Short-term reduction

The Permittee must schedule any facility maintenance, which might require interruption of wastewater treatment and degrade effluent quality, during non-critical water quality periods and carry this maintenance out according to the approved O&M manual or as otherwise approved by Ecology.

If a Permittee contemplates a reduction in the level of treatment that would cause a violation of permit discharge limits on a short-term basis for any reason, and such reduction cannot be avoided, the Permittee must:

1. Give written notification to Ecology, if possible, thirty (30) days prior to such activities.
2. Detail the reasons for, length of time of, and the potential effects of the reduced level of treatment.

This notification does not relieve the Permittee of its obligations under this permit.

S5.D. Electrical power failure

The Permittee must ensure that adequate safeguards prevent the discharge of untreated wastes or wastes not treated in accordance with the requirements of this permit during electrical power failure at the treatment plant and/or sewage lift stations. Adequate safeguards include, but are not limited to, alternate power sources, standby generator(s), or retention of inadequately treated wastes.

The Permittee must maintain Reliability Class II (EPA 430-99-74-001) at the wastewater treatment plant. Reliability Class II requires a backup power source sufficient to operate all vital components and critical lighting and ventilation during peak wastewater flow conditions. Vital components used to support the secondary processes (i.e., mechanical aerators or aeration basin air compressors) need not be operable to full levels of treatment, but must be sufficient to maintain the biota.

S5.E. Prevent connection of inflow

The Permittee must strictly enforce its sewer ordinances and not allow the connection of inflow (roof drains, foundation drains, etc.) to the sanitary sewer system within King County control.

S5.F. Bypass procedures

This permit prohibits a bypass, which is the intentional diversion of waste streams from any portion of a treatment facility. Ecology may take enforcement action against a Permittee for a bypass unless one of the following circumstances (1, 2, or 3) applies.

1. Bypass for essential maintenance without the potential to cause violation of permit limits or conditions.

   This permit authorizes a bypass if it allows for essential maintenance and does not have the potential to cause violations of limits or other conditions of this permit, or adversely impact public health as determined by Ecology prior to the bypass. The Permittee must submit prior notice, if possible, at least ten (10) days before the date of the bypass.

2. Bypass which is unavoidable, unanticipated, and results in noncompliance of this permit.

   This permit authorizes such a bypass only if:

a. Bypass is unavoidable to prevent loss of life, personal injury, or severe property damage. "Severe property damage" means substantial physical damage to property, damage to the treatment facilities which would cause them to become inoperable, or substantial and permanent loss of natural resources which can reasonably be expected to occur in the absence of a bypass.

b. No feasible alternatives to the bypass exist, such as:

- The use of auxiliary treatment facilities.
- Retention of untreated wastes.
- Maintenance during normal periods of equipment downtime, but not if the Permittee should have installed adequate backup equipment in the exercise of reasonable engineering judgment to prevent a bypass.
- Transport of untreated wastes to another treatment facility.

c. Ecology is properly notified of the bypass as required in Special Condition S3.F of this permit.

3. If bypass is anticipated and has the potential to result in noncompliance of this permit.

a. The Permittee must notify Ecology at least thirty (30) days before the planned date of bypass. The notice must contain:

- A description of the bypass and its cause.
- An analysis of all known alternatives which would eliminate, reduce, or mitigate the need for bypassing.
- A cost-effectiveness analysis of alternatives including comparative resource damage assessment.
- The minimum and maximum duration of bypass under each alternative.
- A recommendation as to the preferred alternative for conducting the bypass.
- The projected date of bypass initiation.
- A statement of compliance with SEPA.
- A request for modification of water quality standards as provided for in WAC 173-201A-410, if an exceedance of any water quality standard is anticipated.
- Details of the steps taken or planned to reduce, eliminate, and prevent reoccurrence of the bypass.

b. For probable construction bypasses, the Permittee must notify Ecology of the need to bypass as early in the planning process as possible. The Permittee must consider the analysis required above during the project planning and design process. The project-specific engineering report or facilities plan as well as the plans and specifications must include details of probable construction bypasses to the extent practical. In cases where the Permittee determines the probable need to bypass early, the Permittee must continue to analyze conditions up to and including the construction period in an effort to minimize or eliminate the bypass.

c. Ecology will consider the following prior to issuing an administrative order for this type of bypass:

   - If the bypass is necessary to perform construction or maintenance-related activities essential to meet the requirements of this permit.
   - If feasible alternatives to bypass exist, such as the use of auxiliary treatment facilities, retention of untreated wastes, stopping production, maintenance during normal periods of equipment down time, or transport of untreated wastes to another treatment facility.
   - If the Permittee planned and scheduled the bypass to minimize adverse effects on the public and the environment.

After consideration of the above and the adverse effects of the proposed bypass and any other relevant factors, Ecology will approve or deny the request. Ecology will give the public an opportunity to comment on bypass incidents of significant duration, to the extent feasible. Ecology will approve a request to bypass by issuing an administrative order under RCW 90.48.120.

S5.G. Operations and maintenance (O&M) manuals

1. O&M manual submittal and requirements

   The Permittee must:

   a. Review the O&M Manuals at least annually.

   b. Submit to Ecology for review and approval substantial changes or updates to the O&M Manuals.

   c. Keep the approved O&M Manuals at the permitted facility.

   d. Follow the instructions and procedures of the manuals.

2. O&M manual components

   In addition to the requirements of WAC 173-240-080 (1) through (5), the O&M manuals must include:

   a. Emergency procedures for cleanup in the event of wastewater system upset or failure.

   b. A review of system components which if failed could pollute surface water or could impact human health. Provide a procedure for a routine schedule of checking the function of these components.

   c. Wastewater system maintenance procedures that contribute to the generation of process wastewater.

d. Reporting protocols for submitting reports to Ecology to comply with the reporting requirements in the discharge permit.

e. Any directions to maintenance staff when cleaning or maintaining other equipment or performing other tasks which are necessary to protect the operation of the wastewater system (for example, defining maximum allowable discharge rate for draining a tank, blocking all floor drains before beginning the overhaul of a stationary engine).

f. The treatment plant process control monitoring schedule.

S6. Pretreatment

S6.A. General requirements

1. The Permittee must implement the Industrial Pretreatment Program in accordance with King County Code 28.84.060 as amended by King County Ordinance No. 11963 on January 1, 1996, legal authorities, policies, procedures, and financial provisions described in the Permittee's approved pretreatment program submittal entitled "Industrial Pretreatment Program" and dated April 27, 1981; any approved revisions thereto; and the General Pretreatment Regulations (40 CFR Part 403). At a minimum, the Permittee must undertake the following pretreatment implementation activities:

   a. Enforce categorical pretreatment standards under Section 307(b) and (c) of the Federal Clean Water Act (hereinafter, the Act), prohibited discharge standards as set forth in 40 CFR 403.5, local limits, or state standards, which ever are most stringent or apply at the time of issuance or modification of a local industrial waste discharge permit. Locally derived limits are defined as pretreatment standards under Section 307(d) of the Act and are not limited to categorical industrial facilities.

   b. Issue industrial waste discharge permits to all significant industrial users [SIUs, as defined in 40 CFR 403.3(v)(i)(ii)] contributing to the treatment system, including those from other jurisdictions. Industrial waste discharge permits must contain as a minimum, all the requirements of 40 CFR 403.8 (f)(l)(iii). The Permittee must coordinate the permitting process with Ecology regarding any industrial facility which may possess a state waste discharge permit issued by Ecology.

   c. Maintain and update, as necessary, records identifying the nature, character, and volume of pollutants contributed by industrial users to the treatment works. The Permittee must maintain records for at least a three-year period.

   d. Perform inspections, surveillance, and monitoring activities on industrial users to determine or confirm compliance with pretreatment standards and requirements. The Permittee must conduct a thorough inspection of SIUs annually, except Middle-Tier Categorical Industrial Users, as defined by 40 CFR 403.8(f)(2)(v)(B)&(C), need only be inspected once every two years. The Permittee must conduct regular local monitoring of SIU wastewaters commensurate with the character and volume of the wastewater but not less than once per year except for Middle-Tier Categorical Industrial Users which may be sampled once every two years. The Permittee must collect and analyze samples in accordance with 40 CFR Part 403.12(b)(5)(ii)-(v) and 40 CFR Part 136.

e. Enforce and obtain remedies for non-compliance by any industrial users with applicable pretreatment standards and requirements. Once violations have been identified, the Permittee must take timely and appropriate enforcement action to address the non-compliance. The Permittee's action must follow its enforcement response procedures and any amendments, thereof.

f. Publish, at least annually in a newspaper of general circulation within the Permittee's service area, a list of all non-domestic users which, at any time in the previous 12 months, were in significant non-compliance as defined in 40 CFR 403.8(f)(2)(vii).

g. If the Permittee elects to conduct sampling of an SIU's discharge in lieu of requiring user self-monitoring, it must satisfy all requirements of 40 CFR Part 403.12. This includes monitoring and record keeping requirements of sections 403.12(g) and (o). For SIU's subject to categorical standards (i.e., CIUs), the Permittee may either complete baseline and initial compliance reports for the CIU (when required by 403.12(b) and (d)) or require these of the CIU. The Permittee must ensure SIUs are provided the results of sampling in a timely manner, inform SIUs of their right to sample, their obligations to report any sampling they do, to respond to non-compliance, and to submit other notifications. These include a slug load report (403.12(f)), notice of changed discharge (403.12(j)), and hazardous waste notifications (403.12(p)). If sampling for the SIU, the Permittee must not sample less than once in every six month period unless the Permittee's approved program includes procedures for reduction of monitoring for Middle-Tier or Non-Significant Categorical Users per 403.12(e)(2) and (3) and those procedures have been followed.

h. Develop and maintain a data management system designed to track the status of the Permittee's industrial user inventory, industrial user discharge characteristics, and compliance status.

i. Maintain adequate staff, funds, and equipment to implement its pretreatment program.

j. Establish, where necessary, contracts or legally binding agreements with contributing jurisdictions to ensure compliance with applicable pretreatment requirements by commercial or industrial users within these jurisdictions. These contracts or agreements must identify the agency responsible for the various implementation and enforcement activities to be performed in the contributing jurisdiction.

2. Per 40 CFR 403.8(f)(2)(vii), the Permittee must evaluate each Significant Industrial User to determine if a Slug Control Plan is needed to prevent slug discharges which may cause interference, pass-through, or in any other way result in violations of the Permittee's regulations, local limits or permit conditions. The Slug Control Plan evaluation shall occur within one year of a user's designation as a SIU. In accordance with 40 CFR 403.8(f)(1)(iii)(B)(6) the Permittee shall include slug discharge control requirements in an SIU's permit if the Permittee determines that they are necessary.

3. Whenever Ecology determines that any waste source contributes pollutants to the Permittee's treatment works in violation of Subsection (b), (c), or (d) of Section 307 of the Act, and the Permittee has not taken adequate corrective action, Ecology will notify the Permittee of this determination. If the Permittee fails to take appropriate enforcement action within 30 days of this notification, Ecology may take appropriate enforcement action against the source or the Permittee.

4. Pretreatment Report

   The Permittee must provide to Ecology an annual report that briefly describes its program activities during the previous calendar year. By April 30th, the Permittee must send the annual report to Ecology at:

   Water Quality Permit Coordinator
   Department of Ecology
   Northwest Regional Office
   3190 160th Avenue SE
   Bellevue, WA 98008-5452

   The report must include the following information:

   a. An updated listing of non-domestic industrial dischargers.

   b. Results of wastewater sampling at the treatment plant as specified in Subsection S6.B below. The Permittee must calculate removal rates for each pollutant and evaluate the adequacy of the existing local limits in prevention of treatment plant interference, pass through of pollutants that could affect receiving water quality and biosolids contamination.

   c. Status of program implementation, including:

      i. Any substantial modifications to the pretreatment program as originally approved by Ecology, including staffing and funding levels.

      ii. Any interferences, upsets, or permit violations experienced at the WWTP that are directly attributable to wastes from industrial users.

      iii. Listing of industrial users inspected and/or monitored, and a summary of the results.

      iv. Listing of industrial users scheduled for inspection and/or monitoring for the next year, and expected frequencies.

v. Listing of industrial users notified of promulgated pretreatment standards and/or local standards as required in 40 CFR 403.8(f)(2)(iii). The list must indicate which industrial users are on compliance schedules and the final date of compliance for each.

vi. Listing of industrial users issued industrial waste discharge permits.

vii. Planned changes in the pretreatment program implementation plan.

d. Status of compliance activities, including:

i. Listing of industrial users that failed to submit baseline monitoring reports or any other reports required under 40 CFR 403.12 and in the Permittee's pretreatment program, dated April 27, 1981.

ii. Listing of industrial users that were at any time during the reporting period not complying with federal, state, or local pretreatment standards or with applicable compliance schedules for achieving those standards, and the duration of such non-compliance.

iii. Summary of enforcement activities and other corrective actions taken or planned against non-complying industrial users. The Permittee must supply to Ecology a copy of the public notice of facilities that were in significant non-compliance.

5. The Permittee must request and obtain approval from Ecology before making any significant changes to the approved local pretreatment program. The Permittee must follow the procedure in 40 CFR 403.18 (b) and (c).

S6.B. Monitoring requirements

The Permittee must monitor its influent, effluent, and biosolids at the South Plant WWTP for the priority pollutants identified in Tables II and III of Appendix D of 40 CFR Part 122 as amended, any compounds identified as a result of Condition S6.B.4, and any other pollutants expected from nondomestic sources using U.S. EPA-approved procedures for collection, preservation, storage, and analysis. The Permittee must test influent, effluent, and biosolids samples for the priority pollutant metals (Table III, 40 CFR 122, Appendix D) on a quarterly basis throughout the term of this permit. The Permittee must test influent, effluent, and biosolids samples for the organic priority pollutants (Table II, 40 CFR 122, Appendix D) on an annual basis.

1. The Permittee must sample South Plant WWTP influent and effluent on a day when industrial discharges are occurring at normal to maximum levels. The Permittee must obtain 24-hour composite samples for the analysis of acid and base/neutral extractable compounds and metals. The Permittee must collect samples for the analysis of volatile organic compounds and samples must be collected using grab sampling techniques at equal intervals for a total of four grab samples per day.

   The laboratory may run a single analysis for volatile pollutants (using GC/MS procedures approved by 40 CFR 136) for each monitoring day by compositing equal volumes of each grab sample directly in the GC purge and trap apparatus in the laboratory, with no less than 1 ml of each grab included in the composite.

Unless otherwise indicated, all reported test data for metals must represent the total amount of the constituent present in all phases, whether solid, suspended, or dissolved, elemental or combined including all oxidation states.

The Permittee must handle, prepare, and analyze all wastewater samples taken for GC/MS analysis using procedures approved by 40 CFR 136.

2. The Permittee must collect a biosolids sample concurrently with a wastewater sample as a single grab sample of residual biosolids. Sampling and analysis must be performed using procedures approved by 40 CFR 136 unless the Permittee requests an alternate method and Ecology has approved.
3. The Permittee must take cyanide, phenols, and oils as grab samples. Oils must be hexane soluble or equivalent, and should be measured in the influent and effluent only.
4. In addition to quantifying pH, oil and grease, and all priority pollutants, the Permittee must make a reasonable attempt to identify all other substances and quantify all pollutants shown to be present by gas chromatograph/mass spectrometer (GC/MS) analysis using procedures approved by 40 CFR 136. The Permittee should attempt to make determinations of pollutants for each fraction, which produces identifiable spectra on total ion plots (reconstructed gas chromatograms). The Permittee should attempt to make determinations from all peaks with responses 5% or greater than the nearest internal standard. The 5% value is based on internal standard concentrations of 30 μg/l, and must be adjusted downward if higher internal standard concentrations are used or adjusted upward if lower internal standard concentrations are used. The Permittee may express results for non-substituted aliphatic compounds as total hydrocarbon content. The Permittee must use a laboratory whose computer data processing programs are capable of comparing sample mass spectra to a computerized library of mass spectra, with visual confirmation by an experienced analyst. For all detected substances which are determined to be pollutants, the Permittee must conduct additional sampling and appropriate testing to determine concentration and variability, and to evaluate trends.

S6.C. Reporting of monitoring results

The Permittee must include a summary of monitoring results in the Annual Pretreatment Report.

S6.D. Local limit development

As sufficient data become available, the Permittee must, in consultation with Ecology, reevaluate their local limits in order to prevent pass through or interference. If Ecology determines that any pollutant present causes pass through or interference, or exceeds established biosolids standards, the Permittee must establish new local limits or revise existing local limits as required by 40 CFR 403.5. Ecology may also require the Permittee to revise or establish local limits for any pollutant discharged from the treatment works that has a reasonable potential to exceed the water quality standards, sediment standards, or established effluent limits, or causes whole effluent toxicity. Ecology makes this determination in the form of an Administrative Order.

Ecology may modify this permit to incorporate additional requirements relating to the establishment and enforcement of local limits for pollutants of concern. Any permit modification is subject to formal due process procedures under state and federal law and regulation.

S7. Solid wastes

S7.A. Solid waste handling

The Permittee must handle and dispose of all solid waste material in such a manner as to prevent its entry into state ground or surface water.

S7.B. Leachate

The Permittee must not allow leachate from its solid waste material to enter state waters without providing all known, available, and reasonable methods of treatment, nor allow such leachate to cause violations of the State Surface Water Quality Standards, Chapter 173-201A WAC, or the State Ground Water Quality Standards, Chapter 173-200 WAC. The Permittee must apply for a permit or permit modification as may be required for such discharges to state ground or surface waters.

S8. Spill control plan

S8.A Spill control plan submittals and requirements

The Permittee must:

1. Review the existing spill plan at least annually and update the spill plan as needed.
2. Send significant changes to the plan to Ecology.
3. Follow the plan and any supplements throughout the term of the permit.

S8.B. Spill control plan components

The spill control plan must include the following:

1. A list of all oil and petroleum products and other materials used and/or stored on-site, which when spilled, or otherwise released into the environment, designate as dangerous waste (DW) or extremely hazardous waste (EHW) by the procedures set forth in WAC 173-303-070. Include other materials used and/or stored on-site which may become pollutants or cause pollution upon reaching state's waters.

2. A description of preventive measures and facilities (including an overall facility plot showing drainage patterns) which prevent, contain, or treat spills of these materials.
3. A description of the reporting system the Permittee will use to alert responsible managers and legal authorities in the event of a spill.
4. A description of operator training to implement the plan.

The Permittee may submit plans and manuals required by 40 CFR Part 112, contingency plans required by Chapter 173-303 WAC, or other plans required by other agencies, which meet the intent of this section.

S9. Sediment monitoring

S9.A. Sediment sampling and analysis plan

The Permittee must submit to Ecology for review and approval a sediment sampling and analysis plan for sediment monitoring by December 1, 2016. The purpose of the plan is to recharacterize sediment (the nature and extent of chemical contamination and biological toxicity) quality in the vicinity of the Permittee's discharge locations. The Permittee must sample the top 10 cm of sediment at the same eight stations sampled during the previous permit term, and the sediments must be analyzed for the 47 chemicals with SMS numeric criteria as well as conventional analytes. The Permittee must follow the guidance provided in the current version of the *Sediment Source Control Standards User Manual, Appendix B: sediment sampling and analysis plan.*

S9.B. Sediment data report

Following Ecology approval of the sediment sampling and analysis plan, the Permittee must collect sediments between August 15th and September 30th of 2017. The Permittee must submit to Ecology a sediment data report containing the results of the sediment sampling and analysis no later than December 1, 2018. The sediment data report must conform to the approved sediment sampling and analysis plan. The report must document when the data was successfully loaded into EIM as required below.

In addition to a sediment data report, submit the sediment chemical and any biological data to Ecology's EIM database (http://www.ecy.wa.gov/eim/). Data must be submitted to EIM according to the instructions on the EIM website. The data submittal portion of the EIM website (http://www.ecy.wa.gov/eim/submitdata.htm) provides information and help on formats and requirements for submitting tabular data.

S10. Acute toxicity

S10.A. Testing when there is no permit limit for acute toxicity

The Permittee must:

1. Conduct acute toxicity testing on final effluent once in the first quarter of 2018 and once in the third quarter of 2018.
2. Conduct acute toxicity testing on a series of at least five concentrations of effluent, including 100% effluent and a control.
3. Use each of the following species and protocols for each acute toxicity test:

Acute Toxicity Tests	Species	Method
Fathead minnow 96-hour static-renewal test	*Pimephales promelas*	EPA-821-R-02-012
Daphnid 48-hour static test	*Ceriodaphnia dubia, Daphnia pulex,* or *Daphnia magna*	EPA-821-R-02-012

4. Submit the results to Ecology with the permit renewal application.

S10.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain toxicity data, bench sheets, and reference toxicant results for test methods. In addition, the Permittee must submit toxicity test data in electronic format (CETIS export file preferred) for entry into Ecology's database.
2. The Permittee must collect 24-hour composite effluent samples for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.
3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.
4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Subsection C and the Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.
5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Section A or pristine natural water of sufficient quality for good control performance.

6. The Permittee must collect effluent samples for whole effluent toxicity testing just prior to the chlorination step in the treatment process.
7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the acute critical effluent concentration (ACEC). The ACEC equals 0.54% effluent.
8. All whole effluent toxicity tests, effluent screening tests, and rapid screening tests that involve hypothesis testing must comply with the acute statistical power standard of 29% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S11. Chronic toxicity

S11.A. Testing when there is no permit limit for chronic toxicity

The Permittee must:

1. Conduct chronic toxicity testing on final effluent once in the second quarter of 2018 and once in the fourth quarter of 2018.
2. Conduct chronic toxicity testing on a series of at least five concentrations of effluent and a control. This series of dilutions must include the acute critical effluent concentration (ACEC). The ACEC equals 0.54% effluent. The series of dilutions should also contain the CCEC of 0.44% effluent.
3. Compare the ACEC to the control using hypothesis testing at the 0.05 level of significance as described in Appendix H, EPA/600/4-89/001.
4. Submit the results to Ecology with the next permit renewal application.
5. Perform chronic toxicity tests with all of the following species and the most recent version of the following protocols:

Saltwater Chronic Test	Species	Method
Topsmelt survival and growth	*Atherinops affinis*	EPA/600/R-95/136
Mysid shrimp survival and growth	*Americamysis bahia* (formerly *Mysidopsis bahia*)	EPA-821-R-02-014

S11.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain toxicity data, bench sheets, and reference toxicant results for test methods. In addition, the Permittee must submit toxicity test data in electronic format (CETIS export file preferred) for entry into Ecology’s database.

2. The Permittee must collect 24-hour composite effluent samples for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.
3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.
4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Section C and the Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.
5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Subsection C or pristine natural water of sufficient quality for good control performance.
6. The Permittee must collect effluent samples for whole effluent toxicity testing just prior to the chlorination step in the treatment process.
7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the CCEC and the ACEC. The CCEC and the ACEC may either substitute for the effluent concentrations that are closest to them in the dilution series or be extra effluent concentrations. The CCEC equals 0.44% effluent. The ACEC equals 0.54% effluent.
8. All whole effluent toxicity tests that involve hypothesis testing must comply with the chronic statistical power standard of 39% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S12. Use of effluent from effluent transfer system

The Permittee may distribute effluent from the effluent transfer system (ETS) for use and return to the ETS for discharge via Outfall #001 of this permit – without modification of this permit – under the following conditions:

1. The distributed ETS effluent must meet all treatment and disinfection requirements of Condition S1 of this permit.
2. The effluent is used at the Boeing facility in the approved, closed loop, noncontact chiller project.

3. The Permittee may distribute ETS effluent to a similar closed-loop, noncontact system only after it requests and receives specific written approval from both the Departments of Ecology and Health.
4. The effluent returned to the ETS system for discharge via Outfall #001 must meet all permit requirements for that discharge.
5. The Permittee obtains, files, and enforces a signed user contract assuring compliance with all requirements of the approved project. All new contracts must be approved by the Departments of Ecology and Health and signed by all parties prior to any distribution of the effluent.
6. The Permittee immediately notifies all users during instances of noncompliance.

No other uses of ETS effluent are authorized under this permit.

S13. Application for permit renewal or modification for facility changes

The Permittee must submit an application for renewal of this permit by July 31, 2019.

The Permittee must also submit a new application or supplement at least one hundred eighty (180) days prior to commencement of discharges, resulting from the activities listed below, which may result in permit violations. These activities include any facility expansions, production increases, or other planned changes, such as process modifications, in the permitted facility.

General Conditions

G1. Signatory requirements

1. All applications, reports, or information submitted to Ecology must be signed and certified.
   a. In the case of corporations, by a responsible corporate officer. For the purpose of this section, a responsible corporate officer means:
      - A president, secretary, treasurer, or vice-president of the corporation in charge of a principal business function, or any other person who performs similar policy or decision making functions for the corporation, or
      - The manager of one or more manufacturing, production, or operating facilities, provided, the manager is authorized to make management decisions which govern the operation of the regulated facility including having the explicit or implicit duty of making major capital investment recommendations, and initiating and directing other comprehensive measures to assure long-term environmental compliance with environmental laws and regulations; the manager can ensure that the necessary systems are established or actions taken to gather complete and accurate information for permit application requirements; and where authority to sign documents has been assigned or delegated to the manager in accordance with corporate procedures.

   b. In the case of a partnership, by a general partner.
   c. In the case of sole proprietorship, by the proprietor.
   d. In the case of a municipal, state, or other public facility, by either a principal executive officer or ranking elected official.

   Applications for permits for domestic wastewater facilities that are either owned or operated by, or under contract to, a public entity shall be submitted by the public entity.
2. All reports required by this permit and other information requested by Ecology must be signed by a person described above or by a duly authorized representative of that person. A person is a duly authorized representative only if:
   a. The authorization is made in writing by a person described above and submitted to Ecology.
   b. The authorization specifies either an individual or a position having responsibility for the overall operation of the regulated facility, such as the position of plant manager, superintendent, position of equivalent responsibility, or an individual or position having overall responsibility for environmental matters. (A duly authorized representative may thus be either a named individual or any individual occupying a named position.)
3. Changes to authorization. If an authorization under paragraph G1.2, above, is no longer accurate because a different individual or position has responsibility for the overall operation of the facility, a new authorization satisfying the requirements of paragraph G1.2, above, must be submitted to Ecology prior to or together with any reports, information, or applications to be signed by an authorized representative.

4. Certification. Any person signing a document under this section must make the following certification:

   "I certify under penalty of law, that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gathered and evaluated the information submitted. Based on my inquiry of the person or persons who manage the system or those persons directly responsible for gathering information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations."

G2. Right of inspection and entry

The Permittee must allow an authorized representative of Ecology, upon the presentation of credentials and such other documents as may be required by law:

1. To enter upon the premises where a discharge is located or where any records must be kept under the terms and conditions of this permit.
2. To have access to and copy, at reasonable times and at reasonable cost, any records required to be kept under the terms and conditions of this permit.
3. To inspect, at reasonable times, any facilities, equipment (including monitoring and control equipment), practices, methods, or operations regulated or required under this permit.
4. To sample or monitor, at reasonable times, any substances or parameters at any location for purposes of assuring permit compliance or as otherwise authorized by the Clean Water Act.

G3. Permit actions

This permit may be modified, revoked and reissued, or terminated either at the request of any interested person (including the Permittee) or upon Ecology's initiative. However, the permit may only be modified, revoked and reissued, or terminated for the reasons specified in 40 CFR 122.62, 40 CFR 122.64 or WAC 173-220-150 according to the procedures of 40 CFR 124.5.

1. The following are causes for terminating this permit during its term, or for denying a permit renewal application:
   a. Violation of any permit term or condition.
   b. Obtaining a permit by misrepresentation or failure to disclose all relevant facts.
   c. A material change in quantity or type of waste disposal.
   d. A determination that the permitted activity endangers human health or the environment, or contributes to water quality standards violations and can only be regulated to acceptable levels by permit modification or termination.

   e. A change in any condition that requires either a temporary or permanent reduction, or elimination of any discharge or biosolids use or disposal practice controlled by the permit.

   f. Nonpayment of fees assessed pursuant to RCW 90.48.465.

   g. Failure or refusal of the Permittee to allow entry as required in RCW 90.48.090.

2. The following are causes for modification but not revocation and reissuance except when the Permittee requests or agrees:

   a. A material change in the condition of the waters of the state.

   b. New information not available at the time of permit issuance that would have justified the application of different permit conditions.

   c. Material and substantial alterations or additions to the permitted facility or activities which occurred after this permit issuance.

   d. Promulgation of new or amended standards or regulations having a direct bearing upon permit conditions, or requiring permit revision.

   e. The Permittee has requested a modification based on other rationale meeting the criteria of 40 CFR Part 122.62.

   f. Ecology has determined that good cause exists for modification of a compliance schedule, and the modification will not violate statutory deadlines.

   g. Incorporation of an approved local pretreatment program into a municipality's permit.

3. The following are causes for modification or alternatively revocation and reissuance:

   a. When cause exists for termination for reasons listed in 1.a through 1.g of this section, and Ecology determines that modification or revocation and reissuance is appropriate.

   b. When Ecology has received notification of a proposed transfer of the permit. A permit may also be modified to reflect a transfer after the effective date of an automatic transfer (General Condition G7) but will not be revoked and reissued after the effective date of the transfer except upon the request of the new Permittee.

G4. Reporting planned changes

The Permittee must, as soon as possible, but no later than one hundred eighty (180) days prior to the proposed changes, give notice to Ecology of planned physical alterations or additions to the permitted facility, production increases, or process modification which will result in:

1. The permitted facility being determined to be a new source pursuant to 40 CFR 122.29(b).

2. A significant change in the nature or an increase in quantity of pollutants discharged.

3. A significant change in the Permittee's biosolids use or disposal practices. Following such notice, and the submittal of a new application or supplement to the existing application, along with required engineering plans and reports, this permit may be modified, or revoked and reissued pursuant to 40 CFR 122.62(a) to specify and limit any pollutants not previously limited. Until such modification is effective, any new or increased discharge in excess of permit limits or not specifically authorized by this permit constitutes a violation.

G5. Plan review required

Prior to constructing or modifying any wastewater control facilities, an engineering report and detailed plans and specifications must be submitted to Ecology for approval in accordance with chapter 173-240 WAC. Engineering reports, plans, and specifications must be submitted at least one hundred eighty (180) days prior to the planned start of construction unless a shorter time is approved by Ecology. Facilities must be constructed and operated in accordance with the approved plans.

G6. Compliance with other laws and statutes

Nothing in this permit excuses the Permittee from compliance with any applicable federal, state, or local statutes, ordinances, or regulations.

G7. Transfer of this permit

In the event of any change in control or ownership of facilities from which the authorized discharge emanate, the Permittee must notify the succeeding owner or controller of the existence of this permit by letter, a copy of which must be forwarded to Ecology.

1. Transfers by Modification

   Except as provided in paragraph (2) below, this permit may be transferred by the Permittee to a new owner or operator only if this permit has been modified or revoked and reissued under 40 CFR 122.62(b)(2), or a minor modification made under 40 CFR 122.63(d), to identify the new Permittee and incorporate such other requirements as may be necessary under the Clean Water Act.

2. Automatic Transfers

   This permit may be automatically transferred to a new Permittee if:

   a. The Permittee notifies Ecology at least thirty (30) days in advance of the proposed transfer date.

   b. The notice includes a written agreement between the existing and new Permittees containing a specific date transfer of permit responsibility, coverage, and liability between them.

   c. Ecology does not notify the existing Permittee and the proposed new Permittee of its intent to modify or revoke and reissue this permit. A modification under this subparagraph may also be minor modification under 40 CFR 122.63. If this notice is not received, the transfer is effective on the date specified in the written agreement.

G8. Reduced production for compliance

The Permittee, in order to maintain compliance with its permit, must control production and/or all discharges upon reduction, loss, failure, or bypass of the treatment facility until the facility is restored or an alternative method of treatment is provided. This requirement applies in the situation where, among other things, the primary source of power of the treatment facility is reduced, lost, or fails.

G9. Removed substances

Collected screenings, grit, solids, sludges, filter backwash, or other pollutants removed in the course of treatment or control of wastewaters must not be resuspended or reintroduced to the final effluent stream for discharge to state waters.

G10. Duty to provide information

The Permittee must submit to Ecology, within a reasonable time, all information which Ecology may request to determine whether cause exists for modifying, revoking and reissuing, or terminating this permit or to determine compliance with this permit. The Permittee must also submit to Ecology upon request, copies of records required to be kept by this permit.

G11. Other requirements of 40 CFR

All other requirements of 40 CFR 122.41 and 122.42 are incorporated in this permit by reference.

G12. Additional monitoring

Ecology may establish specific monitoring requirements in addition to those contained in this permit by administrative order or permit modification.

G13. Payment of fees

The Permittee must submit payment of fees associated with this permit as assessed by Ecology.

G14. Penalties for violating permit conditions

Any person who is found guilty of willfully violating the terms and conditions of this permit is deemed guilty of a crime, and upon conviction thereof shall be punished by a fine of up to ten thousand dollars ($10,000) and costs of prosecution, or by imprisonment in the discretion of the court. Each day upon which a willful violation occurs may be deemed a separate and additional violation.

Any person who violates the terms and conditions of a waste discharge permit may incur, in addition to any other penalty as provided by law, a civil penalty in the amount of up to ten thousand dollars ($10,000) for every such violation. Each and every such violation is a separate and distinct offense, and in case of a continuing violation, every day's continuance is deemed to be a separate and distinct violation.

G15. Upset

Definition – "Upset" means an exceptional incident in which there is unintentional and temporary noncompliance with technology-based permit effluent limits because of factors beyond the reasonable control of the Permittee. An upset does not include noncompliance to the extent caused by operational error, improperly designed treatment facilities, inadequate treatment facilities, lack of preventive maintenance, or careless or improper operation.

An upset constitutes an affirmative defense to an action brought for noncompliance with such technology-based permit effluent limits if the requirements of the following paragraph are met.

A Permittee who wishes to establish the affirmative defense of upset must demonstrate, through properly signed, contemporaneous operating logs, or other relevant evidence that:

1. An upset occurred and that the Permittee can identify the cause(s) of the upset.
2. The permitted facility was being properly operated at the time of the upset.
3. The Permittee submitted notice of the upset as required in Special Condition S3.E.
4. The Permittee complied with any remedial measures required under S3.E of this permit.

In any enforcement action the Permittee seeking to establish the occurrence of an upset has the burden of proof.

G16. Property rights

This permit does not convey any property rights of any sort, or any exclusive privilege.

G17. Duty to comply

The Permittee must comply with all conditions of this permit. Any permit noncompliance constitutes a violation of the Clean Water Act and is grounds for enforcement action; for permit termination, revocation and reissuance, or modification; or denial of a permit renewal application.

G18. Toxic pollutants

The Permittee must comply with effluent standards or prohibitions established under Section 307(a) of the Clean Water Act for toxic pollutants within the time provided in the regulations that establish those standards or prohibitions, even if this permit has not yet been modified to incorporate the requirement.

G19. Penalties for tampering

The Clean Water Act provides that any person who falsifies, tampers with, or knowingly renders inaccurate any monitoring device or method required to be maintained under this permit shall, upon conviction, be punished by a fine of not more than $10,000 per violation, or by imprisonment for not more than two (2) years per violation, or by both. If a conviction of a person is for a violation committed after a first conviction of such person under this condition, punishment shall be a fine of not more than $20,000 per day of violation, or by imprisonment of not more than four (4) years, or by both.

G20. Compliance schedules

Reports of compliance or noncompliance with, or any progress reports on, interim and final requirements contained in any compliance schedule of this permit must be submitted no later than fourteen (14) days following each schedule date.

G21. Service agreement review

The Permittee must submit to Ecology any proposed service agreements and proposed revisions or updates to existing agreements for the operation of any wastewater treatment facility covered by this permit. The review is to ensure consistency with chapters 90.46 and 90.48 RCW as required by RCW 70.150.040(9). In the event that Ecology does not comment within a thirty-day (30) period, the Permittee may assume consistency and proceed with the service agreement or the revised/updated service agreement.

Appendix A

LIST OF POLLUTANTS WITH ANALYTICAL METHODS, DETECTION LIMITS AND QUANTITATION LEVELS

The Permittee must use the specified analytical methods, detection limits (DLs) and quantitation levels (QLs) in the following table for permit and application required monitoring unless:

- Another permit condition specifies other methods, detection levels, or quantitation levels.
- The method used produces measurable results in the sample and EPA has listed it as an EPA-approved method in 40 CFR Part 136, or EPA has granted the laboratory written permission to use the method.
- The Permittee knows that an alternate, less sensitive method (higher DL and QL) from those listed below is sufficient to produce measurable results in their effluent.
- If the Permittee is unable to obtain the required DL and QL due to matrix effects (such as for treatment plant influent or CSO effluent), the Permittee must strive to achieve to lowest possible DL and QL and report the DL and QL in the required report.

If the Permittee uses an alternative method, not specified in the permit and as allowed above, it must report the test method, DL, and QL on the discharge monitoring report or in the required report.

All pollutants that have numeric limits in Section S1 of this permit must be analyzed with the methods specified below. When the permit requires the Permittee to measure the base neutral compounds in the list of priority pollutants, it must measure all of the base neutral pollutants listed in the table below. The list includes EPA required base neutral priority pollutants and several additional polynuclear aromatic hydrocarbons (PAHs). The Water Quality Program added several PAHs to the list of base neutrals below from Ecology's Persistent Bioaccumulative Toxics (PBT) List. It only added those PBT parameters of interest to Appendix A that did not increase the overall cost of analysis unreasonably.

Ecology added this appendix to the permit in order to reduce the number of analytical "non-detects" in permit-required monitoring and to measure effluent concentrations near or below criteria values where possible at a reasonable cost.

CONVENTIONAL PARAMETERS

Pollutant & CAS No. *(if available)*	Recommended Analytical Protocol	Detection (DL)[1], µg/L unless specified	Quantitation Level (QL)[2], µg/L unless specified
Biochemical Oxygen Demand	SM5210-B		2 mg/L
Total Suspended Solids	SM2540-D		5 mg/L
Total Ammonia (as N)	SM4500-NH3-B and C/D/E/G/H Kerouel & Aminot 1997		0.3 mg/L
Dissolved oxygen	SM4500-OC/OG		0.2 mg/L
Temperature (max. 7-day avg.)	Analog recorder or use micro-recording devices known as thermistors		0.2º C
pH	SM4500-H^+ B	N/A	N/A

NONCONVENTIONAL PARAMETERS

Pollutant & CAS No. (if available)	Recommended Analytical Protocol	Detection (DL)[1], µg/L unless specified	Quantitation Level (QL)[2], µg/L unless specified
Total Alkalinity	SM2320-B		5.0 mg/L as CaCO3
Chlorine, Total Residual	SM4500 Cl G 4500 Cl D/E, Hach 8370		50.0
Fecal Coliform	SM 9221E,9222 B, D	N/A	Specified in method - sample aliquot dependent
Total Coliform	SM 9221B, 9222B,9223B	N/A	Specified in method - sample aliquot dependent
Nitrate + Nitrite Nitrogen (as N)	SM4500-NO3- E/F/H		200
Nitrogen, Total Kjeldahl (as N)	SM4500-N_{org}B/C and SM4500NH_3-B/C/D/EF/G/H EPA 351.2		500
Nitrogen, Total (as N)	SM4500-N-C	50	100
Soluble Reactive Phosphorus (as P)	SM4500- PE/PF	100	100
Phosphorus, Total (as P)	SM 4500 PB followed by SM4500-PE/PF	100	300

Exhibit B

Pollutant & CAS No. (if available)	Recommended Analytical Protocol	Detection (DL)[1], µg/L unless specified	Quantitation Level (QL)[2], µg/L unless specified
Oil and Grease (HEM)	1664 A or B	1,400	5,000
Salinity	SM2520-B		3 practical salinity units or scale (PSU or PSS)
Settleable Solids	SM2540 -F		Sample and limit dependent
Sulfate (as mg/L SO_4)	SM4110-B, 4500-SO4 E		7.1 mg/L
Sulfide (as mg/L S)	SM4500-S^2F/D/E/G		200
Sulfite (as mg/L SO_3)	SM4500-SO3B		2000
Total dissolved solids	SM2540 C		98 mg/L
Total Hardness	SM2340B C, 200.7, 200.8		200 as $CaCO_3$
Aluminum, Total (7429-90-5)	200.8	2.0	10
Barium Total (7440-39-3)	200.8	0.5	2.0
BTEX (benzene +toluene + ethylbenzene + m,o,p xylenes)	EPA SW 846 8021/8260	1	2
Boron Total (7440-42-8)	200.8	2.0	10.0
Cobalt, Total (7440-48-4)	200.8	0.05	0.25
Iron, Total (7439-89-6)	200.7, 200.8	12.5	50
Magnesium, Total (7439-95-4)	200.7, 200.8	10	50
Molybdenum, Total (7439-98-7)	200.8	0.1	0.5
Manganese, Total (7439-96-5)	200.8	0.1	0.5
NWTPH Dx [4]	Ecology NWTPH Dx	250	250
NWTPH Gx [5]	Ecology NWTPH Gx	250	250
Tin, Total (7440-31-5)	200.8	0.3	1.5
Titanium, Total (7440-32-6)	200.8	0.5	2.5

Pollutant & CAS No. (if available)	Recommended Analytical Protocol	Detection (DL)[1], µg/L unless specified	Quantitation Level (QL)[2], µg/L unless specified
METALS, CYANIDE & TOTAL PHENOLS			
Antimony, Total (7440-36-0)	200.8	0.3	1.0
Arsenic, Total (7440-38-2)	200.8	0.1	0.5
Beryllium, Total (7440-41-7)	200.8	0.1	0.5
Cadmium, Total (7440-43-9)	200.8	0.05	0.25
Chromium (hex) dissolved (18540-29-9)	SM3500-Cr B	5	10
Chromium, Total (7440-47-3)	200.8	0.2	1.0
Copper, Total (7440-50-8)	200.8	0.4	2.0
Lead, Total (7439-92-1)	200.8	0.1	0.5
Mercury, Total (7439-97-6)	1631E	0.0002	0.0005
Nickel, Total (7440-02-0)	200.8	0.1	0.5
Selenium, Total (7782-49-2)	200.8	1.0	1.0
Silver, Total (7440-22-4)	200.8	0.04	0.2
Thallium, Total (7440-28-0)	200.8	0.09	0.36
Zinc, Total (7440-66-6)	200.8	0.5	2.5
Cyanide, Total (57-12-5)	335.4, SM4500-CN-C,E	5	10
Cyanide, Weak Acid Dissociable	SM4500-CN I	5	10
Cyanide, Free Amenable to Chlorination (Available Cyanide)	SM4500-CN G	5	10
Phenols, Total	EPA 420.1		50
ACID COMPOUNDS			
2-Chlorophenol (95-57-8)	625	1.0	2.0
2,4-Dichlorophenol (120-83-2)	625	0.5	1.0
2,4-Dimethylphenol (105-67-9)	625	0.5	1.0
4,6-dinitro-o-cresol (534-52-1) (2-methyl-4,6,-dinitrophenol)	625/1625B	2.0	4.0
2,4 dinitrophenol (51-28-5)	625	1.5	3.0
2-Nitrophenol (88-75-5)	625	0.5	1.0
4-nitrophenol (100-02-7)	625	1.0	2.0
Parachlorometa cresol (59-50-7) (4-chloro-3-methylphenol)	625	1.0	2.0
Pentachlorophenol (87-86-5)	625	0.5	1.0

Pollutant & CAS No. (if available)	Recommended Analytical Protocol	Detection (DL)[1], µg/L unless specified	Quantitation Level (QL)[2], µg/L unless specified
Phenol (108-95-2)	625	2.0	4.0
2,4,6-Trichlorophenol (88-06-2)	625	2.0	4.0
VOLATILE COMPOUNDS			
Acrolein (107-02-8)	624	5	10
Acrylonitrile (107-13-1)	624	1.0	2.0
Benzene (71-43-2)	624	1.0	2.0
Bromoform (75-25-2)	624	1.0	2.0
Carbon tetrachloride (56-23-5)	624/601 or SM6230B	1.0	2.0
Chlorobenzene (108-90-7)	624	1.0	2.0
Chloroethane (75-00-3)	624/601	1.0	2.0
2-Chloroethylvinyl Ether (110-75-8)	624	1.0	2.0
Chloroform (67-66-3)	624 or SM6210B	1.0	2.0
Dibromochloromethane (124-48-1)	624	1.0	2.0
1,2-Dichlorobenzene (95-50-1)	624	1.9	7.6
1,3-Dichlorobenzene (541-73-1)	624	1.9	7.6
1,4-Dichlorobenzene (106-46-7)	624	4.4	17.6
Dichlorobromomethane (75-27-4)	624	1.0	2.0
1,1-Dichloroethane (75-34-3)	624	1.0	2.0
1,2-Dichloroethane (107-06-2)	624	1.0	2.0
1,1-Dichloroethylene (75-35-4)	624	1.0	2.0
1,2-Dichloropropane (78-87-5)	624	1.0	2.0
1,3-dichloropropene (mixed isomers) (1,2-dichloropropylene) (542-75-6) [6]	624	1.0	2.0
Ethylbenzene (100-41-4)	624	1.0	2.0
Methyl bromide (74-83-9) (Bromomethane)	624/601	5.0	10.0
Methyl chloride (74-87-3) (Chloromethane)	624	1.0	2.0
Methylene chloride (75-09-2)	624	5.0	10.0
1,1,2,2-Tetrachloroethane (79-34-5)	624	1.9	2.0
Tetrachloroethylene (127-18-4)	624	1.0	2.0
Toluene (108-88-3)	624	1.0	2.0
1,2-Trans-Dichloroethylene (156-60-5) (Ethylene dichloride)	624	1.0	2.0
1,1,1-Trichloroethane (71-55-6)	624	1.0	2.0
1,1,2-Trichloroethane (79-00-5)	624	1.0	2.0
Trichloroethylene (79-01-6)	624	1.0	2.0
Vinyl chloride (75-01-4)	624/SM6200B	1.0	2.0
BASE/NEUTRAL COMPOUNDS (compounds in bold are Ecology PBTs)			
Acenaphthene (83-32-9)	625	0.2	0.4
Acenaphthylene (208-96-8)	625	0.3	0.6
Anthracene (120-12-7)	625	0.3	0.6
Benzidine (92-87-5)	625	20	40
Benzyl butyl phthalate (85-68-7)	625	0.3	0.6
Benzo(*a*)anthracene (56-55-3)	625	0.3	0.6
Benzo(b)fluoranthene (3,4-benzofluoranthene) (205-99-2) [7]	610/625	0.8	1.6
Benzo(j)fluoranthene (205-82-3) [7]	625	0.5	1.0
Benzo(k)fluoranthene (11,12-benzofluoranthene) (207-08-9) [7]	610/625	0.8	1.6
Benzo(r,s,t)pentaphene (189-55-9)	625	1.3	5.0
Benzo(*a*)pyrene (50-32-8)	610/625	0.5	1.0
Benzo(*ghi*)Perylene (191-24-2)	610/625	0.5	1.0
Bis(*2-chloroethoxy)*methane (111-91-1)	625	5.3	21.2
Bis(*2-chloroethyl*)ether (111-44-4)	611/625	0.3	1.0
Bis(*2-chloroisopropyl*)ether (39638-32-9)	625	0.5	1.0
Bis(*2-ethylhexyl*)phthalate (117-81-7)	625	0.3	1.0
4-Bromophenyl phenyl ether (101-55-3)	625	0.3	0.5
2-Chloronaphthalene (91-58-7)	625	0.3	0.6
4-Chlorophenyl phenyl ether (7005-72-3)	625	0.3	0.5

Pollutant & CAS No. (if available)	Recommended Analytical Protocol	Detection (DL)[1], µg/L unless specified	Quantitation Level (QL)[2], µg/L unless specified
Chrysene (218-01-9)	610/625	0.3	0.6
Dibenzo (a,h)acridine (226-36-8)	610M/625M	2.5	10.0
Dibenzo (a,j)acridine (224-42-0)	610M/625M	2.5	10.0
Dibenzo(a-*h*)anthracene (53-70-3)(1,2,5,6-dibenzanthracene)	625	0.8	1.6
Dibenzo(a,e)pyrene (192-65-4)	610M/625M	2.5	10.0
Dibenzo(a,h)pyrene (189-64-0)	625M	2.5	10.0
3,3-Dichlorobenzidine (91-94-1)	605/625	2.0	4.0
Diethyl phthalate (84-66-2)	625	1.9	7.6
Dimethyl phthalate (131-11-3)	625	1.6	6.4
Di-n-butyl phthalate (84-74-2)	625	0.5	1.0
2,4-dinitrotoluene (121-14-2)	609/625	1.0	2.0
2,6-dinitrotoluene (606-20-2)	609/625	1.0	2.0
Di-n-octyl phthalate (117-84-0)	625	0.3	0.6
1,2-Diphenylhydrazine (*as Azobenzene*) (122-66-7)	1625B, 625	5.0	20
Fluoranthene (206-44-0)	625	0.3	0.6
Fluorene (86-73-7)	625	0.3	0.6
Hexachlorobenzene (118-74-1)	612/625	0.3	0.6
Hexachlorobutadiene (87-68-3)	625	0.5	1.0
Hexachlorocyclopentadiene (77-47-4)	1625B/625	2.0	4.0
Hexachloroethane (67-72-1)	625	0.5	1.0
Indeno(*1,2,3-cd*)Pyrene (193-39-5)	610/625	0.5	1.0
Isophorone (78-59-1)	625	0.5	1.0
3-Methyl cholanthrene (56-49-5)	625	2.0	8.0
Naphthalene (91-20-3)	625	0.4	0.75
Nitrobenzene (98-95-3)	625	0.5	1.0
N-Nitrosodimethylamine (62-75-9)	607/625	2.0	4.0
N-Nitrosodi-n-propylamine (621-64-7)	607/625	0.5	1.0
N-Nitrosodiphenylamine (86-30-6)	625	1.0	2.0
Perylene (198-55-0)	625	1.9	7.6
Phenanthrene (85-01-8)	625	0.3	0.6
Pyrene (129-00-0)	625	0.3	0.6
1,2,4-Trichlorobenzene (120-82-1)	625	0.3	0.6
PCBs			
PCB-1242 [8]	608	0.25	0.5
PCB-1254	608	0.25	0.5
PCB-1221	608	0.25	0.5
PCB-1232	608	0.25	0.5
PCB-1248	608	0.25	0.5
PCB-1260	608	0.13	0.5
PCB-1016 [8]	608	0.13	0.5

1. Detection level (DL) or detection limit means the minimum concentration of an analyte (substance) that can be measured and reported with a 99% confidence that the analyte concentration is greater than zero as determined by the procedure given in 40 CFR part 136, Appendix B.
2. Quantitation Level (QL) also known as Minimum Level of Quantitation (ML) – TThe smallest detectable concentration of analyte greater than the Detection Limit (DL) where the accuracy (precision & bias) achieves the objectives of the intended purpose. (Report of the Federal Advisory Committee on Detection and Quantitation Approaches and Uses in Clean Water Act Programs Submitted to the US Environmental Protection Agency December 2007).
3. Soluble Biochemical Oxygen Demand method note: First, filter the sample through a Millipore Nylon filter (or equivalent) - pore size of 0.45-0.50 um (prep all filters by filtering 250 ml of laboratory grade deionized water through the filter and discard). Then, analyze sample as per method 5210-B.
4. NWTPH Dx Northwest Total Petroleum Hydrocarbons Diesel Extended Range – see http://www.ecy.wa.gov/biblio/97602.html
5. NWTPH Gx - Northwest Total Petroleum Hydrocarbons Gasoline Extended Range – see http://www.ecy.wa.gov/biblio/97602.html
6. 1, 3-dichloroproylene (mixed isomers) You may report this parameter as two separate parameters: cis-1, 3-dichlorpropropene (10061-01-5) and trans-1, 3-dichloropropene (10061-02-6).
7. Total Benzofluoranthenes – Because Benzo(b)fluoranthene, Benzo(j)fluoranthene and Benzo(k)fluoranthene co-elute you may report these three isomers as total benzofluoranthenes.
8. PCB 1016 & PCB 1242 – You may report these two PCB compounds as one parameter called PCB 1016/1242.

EXHIBIT C

Issuance Date: December 19, 2014
Effective Date: February 1, 2015
Expiration Date: January 31, 2020

National Pollutant Discharge Elimination System
Waste Discharge Permit No. WA0029181

State of Washington
DEPARTMENT OF ECOLOGY
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

In compliance with the provisions of
The State of Washington Water Pollution Control Law
Chapter 90.48 Revised Code of Washington
and
The Federal Water Pollution Control Act
(The Clean Water Act)
Title 33 United States Code, Section 1342 et seq.

KING COUNTY WASTEWATER TREATMENT DIVISION – WEST POINT WASTEWATER TREATMENT PLANT & COMBINED SEWER OVERFLOW SYSTEM

King Street Center, KSC-NR-0512
201 South Jackson Street
Seattle, WA 98104-3855

is authorized to discharge in accordance with the Special and General Conditions that follow.

Facility Name	West Point Wastewater Treatment Plant (serves combined sewer area)	Alki Storage and CSO Treatment Plant	Carkeek Storage and CSO Treatment Plant	Denny/Elliott West Storage and CSO Treatment Plant	Henderson/MLK Storage and CSO Treatment Plant
Plant Address	1400 Discovery Park Blvd Seattle, WA 98199	3380 Beach Drive SW Seattle, WA 98116-2616	1201 NW Carkeek Park Rd, Seattle, WA 98177-4640	545 Elliott Ave W Seattle, WA 98119	Outlet Regulator 9829 42nd Ave S Seattle, WA 98118
Receiving Water	Puget Sound	Puget Sound	Puget Sound	Elliott Bay	Duwamish Waterway
Plant Type	Secondary, Activated Sludge, Chlorine Disinfection	Satellite CSO Storage and Treatment Plant	Satellite CSO Storage and Treatment Plant	Satellite CSO Storage and Treatment Plant	Satellite CSO Storage and Treatment Plant
Discharge Location:	Lat: 47.661111˚ Long: -122.446389˚	Lat: 47.57025˚ Long: -122.4225˚	Lat: 47.71264˚ Long: -122.38789˚	Lat: 47.61755˚ Long: -122.36186˚	Lat: 47.51194˚ Long: -122.29736˚

Kevin C. Fitzpatrick
Water Quality Section Manager
Northwest Regional Office
Washington State Department of Ecology

Exhibit C

Table of Contents

Summary of Permit Report Submittals

Section	Submittal	Frequency	First Submittal Date
S3.A	Discharge Monitoring Report	Monthly Annually	March 15, 2015 July 31, 2015
S3.F	Reporting Permit Violations	As necessary	
S4.B	Plans for Maintaining Adequate Capacity	As necessary	
S4.D	Notification of New or Altered Sources	As necessary	
S4.E	Wasteload Assessment	1/permit cycle	With permit application
S5.F	Bypass Notification	As necessary	
S5.G	Operations and Maintenance Update	As necessary	
S6.A	Pretreatment Report	1/year	March 31, 2015
S8	Acute Toxicity Effluent Tests (testing in 1st and 3rd quarters of 2017)	2 tests/permit cycle, 1 submittal/permit cycle	With permit application
S9	Chronic Toxicity Effluent Tests (testing in 2nd and 4th quarters of 2017)	2 tests/permit cycle, 1 submittal/permit cycle	With permit application
S10	Wet Weather Operation Reports	As necessary with monthly DMR submittal	
S11.C	CSO Monthly Report	Monthly with monthly DMR submittal	
S11.C	CSO Annual Report	Annually	July 31, 2015
S11.D	CSO Reduction Plan Amendment	1/permit cycle	With permit application
S11.F.d	CSO Post Construction Monitoring Data Report	1/permit cycle	December 1, 2019
S12	Spill Control Plan Update	As necessary	
S13.A	Sediment Sampling & Analysis Plan- West Pt Sediment Data Report - West Pt	1/permit cycle	December 1, 2016 December 1, 2018
S13.B	Sediment Sampling & Analysis Plan- CSO Outfalls Sediment Data Report - CSO Outfalls	1/permit cycle	December 1, 2016 December 1, 2018
S13.C	Sediment Quality at CSO Outfalls Summary Report	1/permit cycle	December 1, 2018
S14	Outfall Evaluation Reports – West Point and CSO TPs	1/permit cycle	With permit application
S15	Elliott West Copper Reduction Assessment	1/permit cycle	November 1, 2018
S16	Elliott West Settleable Solids Removal Assessment	1/permit cycle	November 1, 2018
S17	Application for Permit Renewal	1/permit cycle	January 31, 2019
G1	Notice of Change in Authorization	As necessary	
G4	Reporting Planned Changes	As necessary	
G5	Engineering Report for Construction or Modification Activities	As necessary	
G13	Payment of Fees	As assessed	

Exhibit C

Special Conditions

S1. Discharge limits

All discharges and activities authorized by this permit must comply with the terms and conditions of this permit. The discharge of any of the following pollutants more frequently than, or at a level in excess of, that identified and authorized by this permit violates the terms and conditions of this permit.

S1.A. Effluent limits for Outfall 001 - West Point wastewater treatment plant

Beginning on the effective date of this permit and lasting through the expiration date, the Permittee may discharge treated municipal wastewater at the permitted locations subject to compliance with the following limits:

Effluent Limits: Outfall #001 - West Point WWTP Latitude: 47.661111˚ Longitude: -122.446389˚		
Parameter	**Average Monthly** [a]	**Average Weekly** [b]
Carbonaceous Biochemical Oxygen Demand (5-day)	25 milligrams/liter (mg/L) 44,800 pounds/day (lbs/day) May–Oct: 85% removal of influent $CBOD_5$ Nov–April: 80% removal of influent $CBOD_5$	40 mg/L 71,700 lbs/day
Total Suspended Solids	30 mg/L, 53,800 lbs/day May–Oct: 85% removal of influent TSS Nov–April: 80% removal of influent TSS	45 mg/L 80,700 lbs/day
	Monthly Geometric Mean	**Weekly Geometric Mean**
Fecal Coliform Bacteria [c]	200/100 mL	400/100 mL
	Instantaneous Minimum	**Instantaneous Maximum**
pH [d]	6.0	9.0
	Average Monthly [a]	**Maximum Daily** [e]
Total Residual Chlorine	139 µg/L	364 µg/L

[a] Average monthly effluent limit means the highest allowable average of daily discharges over a calendar month, calculated as the sum of all daily discharges measured during a calendar month divided by the number of daily discharges measured during that month.

[b] Average weekly discharge limit means the highest allowable average of daily discharges over a calendar week, calculated as the sum of all daily discharges measured during a calendar week divided by the number of daily discharges measured during that week.

[c] Ecology provides directions to calculate this value in publication No. 04-10-020, *Information Manual for Treatment Plant Operators,* available at: http://www.ecy.wa.gov/pubs/0410020.pdf.

[d] Report the instantaneous maximum and minimum pH monthly. Do not average pH values.

[e] Maximum daily effluent limit means the highest allowable daily discharge. The daily discharge is the average measurement of the pollutant over the day.

S1.B. Effluent limits for the CSO treatment plants

Beginning on the effective date of this permit and lasting through the expiration date, the Permittee may discharge treated combined sewer overflows at the following permitted locations subject to compliance with the following limits. Discharges from these outfalls are prohibited except as a result of precipitation events.

Effluent Limits: Outfall #051 - Alki CSO TP Latitude: 47.57025˚ Longitude: -122.4225˚		
Parameter	**Average Monthly**	**Annual Average [a]**
Total Suspended Solids Removal Efficiency [b]	Report	Equal to or greater than 50% removal of influent TSS
	Monthly Geometric Mean	
Fecal Coliform Bacteria	400/100 mL [c]	
		Annual Average [a]
Settleable Solids		0.3 mL/L/hr
	Instantaneous Minimum	**Instantaneous Maximum**
pH [d]	6.0	9.0
	Maximum Daily [e]	
Total Residual Chlorine	234 µg/L	
	Long-Term Average [f]	
Number of Discharge Events	29 events/year	
Discharge Volume	108 million gallons/year	

[a] Calculate annual averages as the average of all 'event' averages. Do not omit one event per year from calculation. Data must be collected and reported on a calendar year basis via WQWebDMR and in the Annual CSO Report.

[b] Calculate the TSS total removal efficiency on a mass balance basis as the percent of solids captured at the CSO treatment facility and then permanently removed at the West Point WWTP. The reported daily average TSS % removal efficiency at the West Point WWTP, corresponding to the event, must be used for calculating the total removal efficiency for the CSO facility. Note: While % TSS removal is reported on a monthly basis, compliance is based on the annual average as reported via WQWebDMR and in the annual CSO report as required in S11.

[c] For the monthly geometric mean, calculate the geometric mean of all samples collected during the month; use a value of 1 for the geomean calc when fecal coliform results are 0. Do not include non-discharge days in the calculation. Ecology provides directions to calculate this value in publication No. 04-10-020, *Information Manual for Treatment Plant Operators,* available at: http://www.ecy.wa.gov/pubs/0410020.pdf.

[d] Report the instantaneous maximum and minimum pH monthly. Do not average pH values.

[e] Maximum daily effluent limit means the highest allowable daily discharge. The daily discharge is the average measurement of the pollutant measured over a calendar day while discharging.

[f] Long-term average will be assessed using data collected over the full permit cycle. Data must be collected and reported for the period of the permit cycle prior to permit renewal, as required in S4.E.

Effluent Limits: Outfall #046 - Carkeek CSO TP Latitude: 47.71264˚ Longitude: -122.38789˚		
Parameter	**Average Monthly**	**Annual Average [a]**
Total Suspended Solids Removal Efficiency [b]	Report	Equal to or greater than 50% removal of influent TSS
	Monthly Geometric Mean	
Fecal Coliform Bacteria [c]	400/100 mL	
		Annual Average [a]
Settleable Solids		0.3 mL/L/hr
	Instantaneous Minimum	**Instantaneous Maximum**
pH [d]	6.0	9.0
	Maximum Daily [e]	
Total Residual Chlorine	490 µg/L	
	Long-Term Average [f]	
Number of Discharge Events	10 events/year	
Discharge Volume	46 million gallons/year	

[a] Calculate annual averages as the average of all 'event' averages. Do not omit one event per year from calculation. Data must be collected and reported on a calendar year basis via WQWebDMR and in the Annual CSO Report.

[b] Calculate the TSS total removal efficiency on a mass balance basis as the percent of solids captured at the CSO treatment facility and then permanently removed at the West Point WWTP. The reported daily average TSS % removal efficiency at the West Point WWTP, corresponding to the event, must be used for calculating the total removal efficiency for the CSO facility. Note: While % TSS removal is reported on a monthly basis, compliance is based on the annual average as reported via WQWebDMR and in the annual CSO report as required in S11.

[c] For the monthly geometric mean, calculate the geometric mean of all samples collected during the month; use a value of 1 for the geomean calc when fecal coliform results are 0. Do not include non-discharge days in the calculation. Ecology provides directions to calculate this value in publication No. 04-10-020, *Information Manual for Treatment Plant Operators,* available at: http://www.ecy.wa.gov/pubs/0410020.pdf.

[d] Report the instantaneous maximum and minimum pH monthly. Do not average pH values.

[e] Maximum daily effluent limit means the highest allowable daily discharge. The daily discharge is the average measurement of the pollutant measured over a calendar day while discharging.

[f] Long-term average will be assessed using data collected over the full permit cycle. Data must be collected and reported for the period of the permit cycle prior to permit renewal, as required in S4.E.

Effluent Limits: Outfall #027B - Elliott West CSO TP Latitude: 47.61755˚ Longitude: -122.361856˚		
Parameter	**Average Monthly**	**Annual Average [a]**
Total Suspended Solids Removal Efficiency [b]	Report	Equal to or greater than 50% removal of influent TSS
	Monthly Geometric Mean	
Fecal Coliform Bacteria [c]	400/100 mL	
		Annual Average [a]
Settleable Solids		0.3 mL/L/hr
	Instantaneous Minimum	**Instantaneous Maximum**
pH [d]	6.0	9.0
	Maximum Daily [e]	
Total Residual Chlorine	109 µg/L	

[a] Calculate annual averages as the average of all ‘event’ averages. Do not omit one event per year from calculation. Data must be collected and reported on a calendar year basis via WQWebDMR and in the Annual CSO Report.

[b] Calculate the TSS total removal efficiency on a mass balance basis as the percent of solids captured at the CSO treatment facility and then permanently removed at the West Point WWTP. The reported daily average TSS % removal efficiency at the West Point WWTP, corresponding to the event, must be used for calculating the total removal efficiency for the CSO facility. Note: While % TSS removal is reported on a monthly basis, compliance is based on the annual average as reported via WQWebDMR and in the annual CSO report as required in S11.

[c] For the monthly geometric mean, calculate the geometric mean of all samples collected during the month; use a value of 1 for the geomean calc when fecal coliform results are 0. Do not include non-discharge days in the calculation. Ecology provides directions to calculate this value in publication No. 04-10-020, *Information Manual for Treatment Plant Operators,* available at: http://www.ecy.wa.gov/pubs/0410020.pdf.

[d] Report the instantaneous maximum and minimum pH monthly. Do not average pH values.

[e] Maximum daily effluent limit means the highest allowable daily discharge. The daily discharge is the average measurement of the pollutant measured over a calendar day while discharging.

Effluent Limits: Outfall #044 - Henderson/MLK CSO TP Latitude: 47.51194˚ Longitude: -122.29736˚		
Parameter	**Average Monthly**	**Annual Average [a]**
Total Suspended Solids Removal Efficiency [b]	Report	Equal to or greater than 50% removal of influent TSS
	Monthly Geometric Mean	
Fecal Coliform Bacteria [c]	400/100 mL	
		Annual Average [a]
Settleable Solids		0.3 mL/L/hr
	Instantaneous Minimum	**Instantaneous Maximum**
pH [d]	6.0	9.0
	Maximum Daily [e]	
Total Residual Chlorine	39 µg/L	

[a] Calculate annual averages as the average of all 'event' averages. Do not omit one event per year from calculation. Data must be collected and reported on a calendar year basis via WQWebDMR and in the Annual CSO Report.

[b] Calculate the TSS total removal efficiency on a mass balance basis as the percent of solids captured at the CSO treatment facility and then permanently removed at the West Point WWTP. The reported daily average TSS % removal efficiency at the West Point WWTP, corresponding to the event, must be used for calculating the total removal efficiency for the CSO facility. Note: While % TSS removal is reported on a monthly basis, compliance is based on the annual average as reported via WQWebDMR and in the annual CSO report as required in S11.

[c] For the monthly geometric mean, calculate the geometric mean of all samples collected during the month; use a value of 1 for the geomean calc when fecal coliform results are 0. Do not include non-discharge days in the calculation. Ecology provides directions to calculate this value in publication No. 04-10-020, *Information Manual for Treatment Plant Operators,* available at: http://www.ecy.wa.gov/pubs/0410020.pdf.

[d] Report the instantaneous maximum and minimum pH monthly. Do not average pH values.

[e] Maximum daily effluent limit means the highest allowable daily discharge. The daily discharge is the average measurement of the pollutant measured over a calendar day while discharging.

S1.C. Mixing zone authorizations

Table 1 summarizes the mixing boundaries and dilution factors for the West Point WWTP and CSO treatment plant outfalls.

Table 1. Dilution zone sizes and dilution factors for permitted outfalls

Outfall	Mixing Zone Radius (feet) [a]		Dilution Factors			
	Chronic	**Acute**	**Aquatic Life Chronic**	**Aquatic Life Acute**	**Human Health: Carcinogen**	**Human Health: Non-Carcinogen**
West Point WWTP	430	43	188	28	324	324
Alki CSO [b]	343	34	99	20		
Carkeek CSO [b]	395	39.5	104	75		
Elliott West CSO [b]	260	26	9.7	8.4		
Henderson/MLK CSO [b]	312 [c]	31.2 [c]	10.3	1.9		

[a] As measured from each port.

[b] Mixing zone dilution modeling is more accurate for continuous discharges. The resultant dilution factor that is achieved in the mixing zone of an intermittent discharge such as this is an approximation that is based on reasonable assumptions about the flow characteristics of the discharge and conditions of the receiving water.

[c] Since this is a river discharge, these dimensions represent distance downstream of outfall instead of radius.

S2. Monitoring requirements

S2.A. Monitoring schedules

The Permittee must monitor in accordance with the schedules in the following tables and the requirements specified in Appendix A or any corresponding *Sampling Analysis Plan/Quality Assurance Project Plan (SAP/QAPP)* documents. Alternative methods from 40 CFR Part 136 are acceptable only for those parameters without limits and if the DL and QL are equivalent to those specified in Appendix A, any corresponding SAP/QAPP documents, or sufficient to produce a measurable quantity.

Table 2. Monitoring Schedule – West Point WWTP (001)

Parameter	Units	Minimum Frequency	Sample Type
(1) Wastewater Influent [a]			
BOD_5	mg/L	1/week	24-hr Composite [b]
	lbs/day [c]	1/week	Calculation
$CBOD_5$	mg/L	1/day	24-hr Composite
	lbs/day [c]	1/day	Calculation
TSS	mg/L	1/day	24-hr Composite
	lbs/day	1/day	Calculation
(2) Final Wastewater Effluent [d]			
Flow	MGD	Continuous [e]	Meter
$CBOD_5$ [f]	mg/L	1/day	24-hr Composite
	lbs/day [c]	1/day	Calculation
	% removal [g]	1/month	Calculation
TSS	mg/L	1/day	24-hr Composite
	lbs/day [c]	1/day	Calculation
	% removal [g]	1/month	Calculation
Chlorine (after dechlorination)	µg/L	Continuous [e]	Meter
Fecal Coliform	# /100 ml	1/day	Grab [h]
pH	Standard Units	Continuous [e]	Meter
(3) Effluent Characterization – Final Wastewater Effluent			
Total Ammonia	mg/L N	1/month	24-hr Composite
	lbs/day	1/month	Calculation
Nitrate + Nitrite Nitrogen	mg/L N	1/month	24-hr Composite
Total Kjeldahl Nitrogen	mg/L N	1/month	24-hr Composite
Total Phosphorus	mg/L P	1/month	24-hr Composite
Soluble Reactive Phosphorus	mg/L P	1/month	24-hr Composite
(4) Whole Effluent Toxicity Testing – Final Wastewater Effluent - As specified in Permit Conditions S8 & S9.			
Acute Toxicity Testing		2/permit cycle	24-hr Composite
Chronic Toxicity Testing		2/permit cycle	24-hr Composite
(5) Pretreatment - As specified in Permit Condition S6.			
(6) CSO Monitoring - As specified in Permit Condition S11.			
(7) Permit Application Requirements – Final Wastewater Effluent [j]			
Dissolved Oxygen	mg/L	1/year in Aug	Grab
Oil and Grease (HEM)	mg/L	1/year in Aug	Grab
Total Dissolved Solids	mg/L	1/year in Aug	24-hr Composite
Total Hardness	mg/L	1/year in Aug	24-hr Composite
Alkalinity	mg/L as $CaCO_3$	1/year in Aug	Grab

Table 2. Monitoring Schedule – West Point WWTP (001)

Parameter	Units	Minimum Frequency	Sample Type
Temperature	˚C	1/year in Aug	Grab
Cyanide	µg/L	2/year [i, j]	Grab
Total Phenolic Compounds	µg/L	2/year [i, j]	Grab
Priority Pollutants (PP) – Total Metals	µg/L (ng for mercury)	2/year [i, j]	24-hr Composite; Grab for mercury
PP – Volatile Organic Compounds	µg/L	2/year [i, j]	Grab
PP – Acid-extractable Compounds	µg/L	2/year [i, j]	24-hr Composite
PP – Base-neutral Compounds	µg/L	2/year [i, j]	24-hr Composite
(8) Sediment Study - As specified in Permit Condition S13.A.			

[a] Wastewater Influent means the raw sewage flow from the collection system into the treatment facility. Sample the wastewater entering the headworks of the plant excluding any side-stream returns from inside the plant.

[b] 24-hour composite means a series of individual samples collected over a 24-hour period in a single container and analyzed as one sample.

[c] lbs/day = Concentration (in mg/L) x Flow (in MGD) x Conversion Factor (8.34) = lbs/day. Calculate using the average flow measured during the sample collection period.

[d] Final Wastewater Effluent means wastewater which is exiting, or has exited, the last treatment process or operation.

[e] "Continuous" means uninterrupted except for brief lengths of time for calibration, power failure, or unanticipated equipment repair or maintenance. The Permittee must sample every six hours when continuous monitoring is not possible.

[f] Effluent samples for $CBOD_5$ analysis may be taken before or after the disinfection process. If taken after, dechlorinate and reseed the sample.

[g] $$\text{\% removal} = \frac{\text{Influent monthly average concentration (mg/L)} - \text{Effluent monthly average concentration (mg/L)}}{\text{Influent monthly average concentration (mg/L)}} \times 100$$

[h] "Grab" means an individual sample collected over a 15-minute, or less, period.

[i] One of the two annual sampling events must occur when flows are being diverted around the secondary process (i.e. instantaneous effluent flow rate is greater than 300 MGD) or when the average daily precipitation is equal to or greater than 0.25 inches.

[j] The Permittee must record and report the wastewater treatment plant flow discharged on the day it collects the sample for Appendix A pollutant testing with the discharge monitoring report.

See Appendix A or corresponding SAP/QAPP for the required detection (DL) or quantitation (QL) levels.

Report single analytical values below detection as "less than (detection level)" where (detection level) is the numeric value specified in Appendix A.

Report single analytical values between the detection and quantitation levels with qualifier code of 'j' following the value. If unable to obtain the required DL and QL due to matrix effects, the Permittee must submit a matrix specific MDL and a QL with appropriate laboratory documentation.

Table 3. Monitoring Schedule for all CSO TPs: Alki-051, Carkeek-046, Elliott West-027, Henderson/MLK-044

Parameter	Units	Minimum Frequency	Sample Type
(1) Influent [a]			
Volume	MG	Per Event [b]	Meter/Calculation [c]
BOD_5	mg/L	Per Event	Flow Proportional Composite [d]
TSS	mg/L	Per Event	Flow Proportional Composite
(2) Final Effluent [e]			
Volume	MG	Per Event	Meter/Calculation
BOD_5	mg/L	Per Event	Flow Proportional Composite
TSS	mg/L	Per Event	Flow Proportional Composite
	% removal [f]	1/month	Calculation
Settleable Solids	mL/L/hr	Per Event	Flow Proportional Composite
Total Residual Chlorine	ug/L	Continuous during events [g]	Meter
Fecal Coliform	# /100 ml	Per Event	Grab [h, i]
pH	Std Units	Continuous during events	Meter
Copper, total recoverable [j]	µg/L	Elliott West and Henderson/MLK: Per Event All others: 1/year	Flow Proportional Composite
Cyanide	µg/L	Elliott West: 4/yr	Grab
Dissolved Oxygen	mg/L	Elliott West: Per Event starting in Nov 2016 All others: 1/year	Meter or Grab
Discharge Duration	Hours	Per Event	Meter/Calculation
Storm Duration [k]	Hours	Per Event	Meter/Calculation
Precipitation	Inches	Per Event	Meter/Calculation
(3) Effluent Characterization – Final Effluent			
Total Ammonia	mg/L N	Henderson/MLK: 1st 4 discharge events, then 1/year All others: 1/year	Flow Proportional Composite
Nitrate-Nitrite Nitrogen	mg/L N		Flow Proportional Composite
Total Kjeldahl Nitrogen	mg/L N		Flow Proportional Composite
Total Phosphorus	mg/L P		Flow Proportional Composite
Soluble Reactive Phosphorus	mg/L P		Flow Proportional Composite
Total Alkalinity	mg $CaCO_3$/L		Flow Proportional Composite or Grab
Temperature	°C		Grab
Priority Pollutants (PP)–Total Metals	µg/L		Flow Proportional Composite; Grab for mercury
PP – Volatile Organic Compounds	µg/L		Grab
PP – Acid-extractable Compounds	µg/L		Flow Proportional Composite
PP – Base-neutral Compounds	µg/L		Flow Proportional Composite
Cyanide	µg/L		Grab
Total Phenols	µg/L		Grab
PP – Total PCBs [l]	µg/L	Henderson/MLK only: 1/year	Flow Proportional Composite
(4) Permit Application Requirements – Final Effluent [m]			
Oil and Grease	mg/L	1/year	Grab
Total Dissolved Solids	mg/L	1/year	Flow Proportional Composite

Table 3. Monitoring Schedule for all CSO TPs: Alki-051, Carkeek-046, Elliott West-027, Henderson/MLK-044

Parameter	Units	Minimum Frequency	Sample Type
Total Hardness	mg/L	1/year	Flow Proportional Composite

[a] Influent means the combined raw sewage and stormwater flows from the collection system into the treatment facility. Sample the wastewater entering the treatment plant.

[b] "Per Event" means a unique flow event as defined in the *Permit Writer's Manual*, p. V-30. Ecology defines the minimum inter-event period as 24 hours. A CSO event is considered to have ended only after at least 24 hours has elapsed since the last measured occurrence of an overflow.

[c] "Meter/Calculation" means the total volume of the discharge or amount of precipitation event as estimated by direct measurement or indirectly by calculation (i.e. flow weirs, pressure transducers, tipping bucket). Precipitation must be measured by the nearest precipitation-measuring device as owned and operated by King County and actively monitored during the period of interest.

[d] "Flow proportional composite" means a series of individual samples collected over a flow period in a single container, and analyzed as one sample. The composite sample should represent the entire discharge event.

[e] "Final Effluent" means treated CSO effluent which is discharged to the receiving water, sampled after the dechlorination process. The Permittee may take effluent samples for the BOD_5 analysis before or after the disinfection process. If taken after, dechlorinate and reseed the sample.

[f] The total removal efficiency for TSS is to be calculated on a mass balance basis as the percent of solids captured at the CSO Treatment Plant and then permanently removed at the West Point Treatment Plant based on the estimated removal efficiency at West Point.

[g] "Continuous" means uninterrupted except for brief lengths of time for calibration, power failure, or unanticipated equipment repair or maintenance. The Permittee must sample every hour when continuous monitoring is not possible.

[h] "Grab" means an individual sample collected over a 15-minute, or less, period.

[i] Fecal grab samples must be taken at specific time intervals after the discharge begins to the receiving water as follows:

1. 1 sample within first 3 hours.
2. 1 sample between 3-8 hours.
3. 1 sample between 20-24 hours.
4. If discharge extends beyond 24 hours, at a minimum take 1 sample each day until the discharge ends.

If more than 1 sample is collected within the time intervals listed above, report the average of the fecal values for that time interval. Report one fecal value for each interval (as appropriate for the discharge duration) and calculate the monthly geomean using all of the reported fecal values for the month.
Chlorine and pH analyzer readings must be logged when fecal coliform samples are taken. Each individual fecal coliform sample should be dechlorinated.

[j] Copper sampling must be performed with laboratory-verified sampling procedures.

[k] Storm duration is the total amount of time precipitation occurred that contributed to a discharge event; it is determined on a case-by-case basis.

[l] PCB monitoring only required for the Henderson/MLK CSO treatment plant. Total PCBs must be analyzed using method 1668 with a detection limit of 0.0001 µg/L or lower.

[m] The Permittee must record and report the wastewater treatment plant flow discharged on the day it collects the sample for Appendix A pollutant testing with the discharge monitoring report.

See Appendix A or corresponding SAP/QAPP for the required detection (DL) or quantitation (QL) levels.

Report single analytical values below detection as "less than [detection level]" where [detection level] is the numeric value specified in Appendix A.

Report single analytical values between the detection and quantitation levels with qualifier code of 'j' following the value.

Untreated CSO Outfalls

The Permittee must monitor all discharges from the CSO outfalls listed in Special Condition S11, not including any CSO treatment plants, using the following monitoring schedule. The Permittee must use automatic flow monitoring equipment to collect the information required below, and must calibrate flow monitoring equipment according to requirements in Condition S2.C. A CSO discharge is defined as any untreated CSO which will exit or has exited the CSO outfall.

Table 4. Monitoring Schedule – Untreated CSO Outfalls

Parameter	Units	Minimum Sampling Frequency	Sample Type
Volume Discharged	MG	Per Event [a]	Meter/Calculation [b]
Discharge Duration	Hours	Per Event	Meter/Calculation
Storm Duration [c]	Hours	Per Event	Meter/Calculation
Precipitation	Inches	Per Event	Meter/Calculation
Sediments – As specified in Permit Condition S13.C.			

[a] "Per Event" means a unique flow event as defined in the *Permit Writer's Manual*, p. V-30. Ecology defines the minimum inter-event period as 24 hours. A CSO event is considered to have ended only after at least 24 hours has elapsed since the last measured occurrence of an overflow.

[b] "Meter/Calculation" means the total volume of the discharge or amount of precipitation event as estimated by direct measurement or indirectly by calculation (i.e. flow weirs, pressure transducers, tipping bucket). Precipitation must be measured by the nearest possible precipitation-measuring device and actively monitored during the period of interest.

[c] Storm duration is the total amount of time precipitation occurred that contributed to a discharge event; it is determined on a case-by-case basis.

S2.B. Sampling and analytical procedures

Samples and measurements taken to meet the requirements of this permit must represent the volume and nature of the monitored parameters. The Permittee must conduct representative sampling of any unusual discharge or discharge condition, including bypasses, upsets, and maintenance-related conditions that may affect effluent quality.

Sampling and analytical methods used to meet the monitoring requirements specified in this permit must conform to the latest revision of the *Guidelines Establishing Test Procedures for the Analysis of Pollutants* contained in 40 CFR Part 136 (or as applicable in 40 CFR subchapters N [Parts 400–471] or O [Parts 501-503]) unless otherwise specified in this permit. Ecology may only specify alternative methods for parameters without permit limits and for those parameters without an EPA approved test method in 40 CFR Part 136.

S2.C. Flow measurement, field measurement, and continuous monitoring devices

The Permittee must:

1. Select and use appropriate flow measurement, field measurement, and continuous monitoring devices and methods consistent with accepted scientific practices.

2. Install and maintain these devices to ensure the accuracy of the measurements is consistent with the accepted industry standard and the manufacturer's recommendation for that type of device.
3. Calibrate continuous monitoring instruments consistent with the manufacturer's recommendation.
4. Maintain calibration records for at least three years.

S2.D. Laboratory accreditation

The Permittee must ensure that all monitoring data required by Ecology for permit specified parameters is prepared by a laboratory registered or accredited under the provisions of chapter 173-50 WAC, *Accreditation of Environmental Laboratories*. Flow, temperature, settleable solids, and internal process control parameters are exempt from this requirement. .

S3. Reporting and recording requirements

The Permittee must monitor and report in accordance with the following conditions. Falsification of information submitted to Ecology is a violation of the terms and conditions of this permit.

S3.A. Reporting

The first monitoring period begins on the effective date of the permit. The Permittee must:

1. Summarize, report, and submit monitoring data obtained during each monitoring period on the electronic Discharge Monitoring Report (DMR) form provided by Ecology within the Water Quality Permitting Portal. Include data for each of the parameters tabulated in Special Condition S2 and as required by the form. Report a value for each day sampling occurred (unless specifically exempted in the permit) and for the summary values (when applicable) included on the electronic form.

   To find out more information and to sign up for the Water Quality Permitting Portal go to: http://www.ecy.wa.gov/programs/wq/permits/paris/webdmr.html.
2. Enter the "no discharge" reporting code for an entire DMR, for a specific monitoring point, or for a specific parameter as appropriate, if the Permittee did not discharge wastewater or a specific pollutant during a given monitoring period.
3. Report single analytical values below detection as "less than the detection level (DL)" by entering < followed by the numeric value of the detection level (e.g. < 2.0) on the DMR. If the method used did not meet the minimum DL and quantitation level (QL) identified in the permit, report the actual QL and DL in the comments or in the location provided.
4. Report the test method used for analysis in the comments if the laboratory used an alternative method not specified in the permit and as allowed in Appendix A.

5. Calculate average values and calculated total values (unless otherwise specified in the permit) using:

   a. The reported numeric value for all parameters measured between the agency-required detection value and the agency-required quantitation value.

   b. One-half the detection value (for values reported below detection) if the lab detected the parameter in another sample for the reporting period.

   c. Zero (for values reported below detection) if the lab did not detect the parameter in another sample for the reporting period.

6. Report priority pollutant data on the WQWebDMR form and include sample date, concentration detected, detection limit (DL) (as necessary), laboratory quantitation level (QL) (as necessary), and CAS number. The Permittee must also submit an electronic PDF copy of the laboratory report as an attachment using WQWebDMR. The laboratory report must provide the following information: date sampled, sample location, date of analysis, parameter name, CAS number, analytical method/number, detection limit (DL), laboratory quantitation level (QL), reporting units, and concentration detected. The laboratory report must also include information on the chain of custody, QA/QC results, and documentation of accreditation for the parameter.

7. Submit DMRs for parameters with the monitoring frequencies specified in S2 (monthly, quarterly, annual, etc.) at the reporting schedule identified below. The Permittee must:

   a. Submit **monthly** DMRs by the 15th day of the following month.

   b. Submit **annual** DMRs by July 31st for the previous calendar year. The annual sampling period is the calendar year.

S3.B. Permit submittals and schedules

The Permittee must use the *Water Quality Permitting Portal – Permit Submittals* application to submit all other written permit-required reports by the date specified in the permit.

When another permit condition requires submittal of a report/file that cannot be accepted by the Water Quality Permitting Portal (i.e. video file for outfall inspection), the Permittee must ensure that the report/file is postmarked or received by Ecology no later than the dates specified by this permit. Send these reports/files to Ecology at:

Water Quality Permit Coordinator
Department of Ecology
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

S3.C. Records retention

The Permittee must retain records of all monitoring information for a minimum of three (3) years. Such information must include all calibration and maintenance records and all original recordings for continuous monitoring instrumentation, copies of all reports required by this permit, and records of all data used to complete the application for this permit. The Permittee must extend this period of retention during the course of any unresolved litigation regarding the discharge of pollutants by the Permittee or when requested by Ecology.

S3.D. Recording of results

For each measurement or sample taken, the Permittee must record the following information:

1. The date, exact place, method, and time of sampling or measurement.
2. The individual who performed the sampling or measurement.
3. The dates the analyses were performed.
4. The individual who performed the analyses.
5. The analytical techniques or methods used and the relevant detection limits.
6. The results of all analyses.

S3.E. Additional monitoring by the Permittee

If the Permittee monitors any pollutant more frequently than required by Special Condition S2 of this permit, then the Permittee must include the results of such monitoring in the calculation and reporting of the data submitted in the Permittee's DMR or annual CSO report, as appropriate. If the Permittee monitors sediment or untreated CSO discharges more frequently than required by this permit, then the Permittee must enter the results of such monitoring into Ecology’s EIM database or include the results in the annual CSO report, as appropriate.

S3.F. Reporting permit violations

The Permittee must take the following actions when it violates or is unable to comply with any permit condition:

1. Immediately take action to stop, contain, and cleanup unauthorized discharges or otherwise stop the non-compliance and correct the problem.
2. If applicable, immediately repeat sampling and analysis. Submit the results of any repeat sampling to Ecology within thirty (30) days of sampling.

a. Immediate reporting

The Permittee must *immediately* report to Ecology and the Department of Health, Shellfish Program, and King County Public Health (at the numbers listed below), all:

- Failures of the disinfection systems.
- Collection system overflows other than permitted CSO discharges.

- Plant bypasses discharging to marine surface waters, other than as described in Section S10.
- Any other failures of the sewage system (pipe breaks, etc.)

Additionally, for any sanitary sewer overflow (SSO) that discharges to a municipal separate storm sewer system (MS4), the Permittee must notify the appropriate MS4 owner or operator.

Northwest Regional Office	425-649-7000
Department of Health, Shellfish Program	360-236-3330 (business hours) 360-789-8962 (after business hours)
Public Health of Seattle-King County	206-296-4932

b. *Twenty-four-hour reporting*

The Permittee must report the following occurrences of non-compliance by telephone, to Ecology at the telephone numbers listed above, within 24 hours from the time the Permittee becomes aware of any of the following circumstances:

1. Any non-compliance that may endanger health or the environment, unless previously reported under immediate reporting requirements.
2. Any unanticipated bypass that causes an exceedance of an effluent limit in the permit (See Section S5.F, “Bypass Procedures”).
3. Any upset that causes an exceedance of an effluent limit in the permit (See G15, “Upset”).
4. Any violation of a maximum daily or instantaneous maximum discharge limit for any of the pollutants in Section S1 of this permit for the West Point outfall 001.
5. Any overflow prior to the treatment works, whether or not such overflow endangers health or the environment or exceeds any effluent limit in the permit.

c. *Report within five days*

The Permittee must also submit a written report within five business days of the time that the Permittee becomes aware of any reportable event under subparts a or b, above. The report must contain:

1. A description of the non-compliance and its cause.
2. The period of non-compliance, including exact dates and times.
3. The estimated time the Permittee expects the non-compliance to continue if not yet corrected.
4. Steps taken or planned to reduce, eliminate, and prevent recurrence of the non-compliance.

5. If the non-compliance involves an overflow prior to the treatment works, an estimate of the quantity (in gallons) of untreated overflow.

d. *Waiver of written reports*

Ecology may waive the written report required in subpart c, above, on a case-by-case basis upon request if the Permittee has submitted a timely oral report.

e. *All other permit violation reporting*

The Permittee must report all permit violations, which do not require immediate or within 24 hours reporting, when it submits monitoring reports for S3.A ("Reporting"). The reports must contain the information listed in subpart c, above. Compliance with these requirements does not relieve the Permittee from responsibility to maintain continuous compliance with the terms and conditions of this permit or the resulting liability for failure to comply.

f. *Report submittal*

The Permittee must submit reports to the address listed in S3.B.

S3.G. Other reporting

a. *Spills of oil or hazardous materials*

The Permittee must report a spill of oil or hazardous materials in accordance with the requirements of RCW 90.56.280 and chapter 173-303-145. You can obtain further instructions at the following website: http://www.ecy.wa.gov/programs/spills/other/reportaspill.htm .

b. *Failure to submit relevant or correct facts*

Where the Permittee becomes aware that it failed to submit any relevant facts in a permit application, or submitted incorrect information in a permit application, or in any report to Ecology, it must submit such facts or information promptly.

S3.H. Maintaining a copy of this permit

The Permittee must keep a copy of this permit at all treatment facilities and make it available upon request to Ecology inspectors.

S4. Facility loading (West Point WWTP)

S4.A. Design criteria

The flows or waste loads for the permitted West Point WWTP must not exceed the following design criteria:

Maximum Month Design Flow (MMDF)	215 MGD
BOD_5 Influent Loading for Maximum Month	201,000 lbs/day
TSS Influent Loading for Maximum Month	218,000 lbs/day

S4.B. Plans for maintaining adequate capacity

a. Conditions triggering plan submittal

The Permittee must submit a plan and a schedule for continuing to maintain capacity to Ecology when:

1. The actual flow or waste load reaches 85 percent of any one of the design criteria in S4.A for three consecutive months, or
2. The projected plant flow or loading would reach design capacity within five years.

b. Plan and schedule content

The plan and schedule must identify the actions necessary to maintain adequate capacity for the expected population growth and to meet the limits and requirements of the permit. The Permittee must consider the following topics and actions in its plan.

1. Analysis of the present design and proposed process modifications.
2. Reduction or elimination of excessive infiltration and inflow of uncontaminated ground and surface water into the sewer system.
3. Limits on future sewer extensions or connections or additional waste loads.
4. Modification or expansion of facilities.
5. Reduction of industrial or commercial flows or waste loads.

Engineering documents associated with the plan must meet the requirements of WAC 173-240-060, "Engineering Report," and be approved by Ecology prior to any construction.

S4.C. Duty to mitigate

The Permittee must take all reasonable steps to minimize or prevent any discharge, use, or disposal of sludge or biosolids in violation of this permit that has a reasonable likelihood of adversely affecting human health or the environment.

S4.D. Notification of new or altered sources

1. The Permittee must submit written notice to Ecology whenever any new discharge or a substantial change in volume or character of an existing discharge into the wastewater treatment plant is proposed which:
   a. Would interfere with the operation of, or exceed the design capacity of, any portion of the wastewater treatment plant.
   b. Is not part of an approved general sewer plan or approved plans and specifications.
   c. Is subject to pretreatment standards under 40 CFR Part 403 and Section 307(b) of the Clean Water Act.

2. This notice must include an evaluation of the wastewater treatment plant's ability to adequately transport and treat the added flow and/or waste load, the quality and volume of effluent to be discharged to the treatment plant, and the anticipated impact on the Permittee's effluent [40 CFR 122.42(b)].

S4.E. Wasteload assessment

The Permittee must conduct wasteload assessments of the West Point WWTP and each CSO treatment plant and submit a report to Ecology with the next permit application. The Permittee must also submit the report electronically. The report must contain:

1. A description of compliance or non-compliance with the permit effluent limits.
2. A comparison between the existing and design:
   a. Monthly average dry weather and wet weather flows.
   b. Peak flows.
   c. $CBOD_5$ and TSS loadings (West Point only).
   d. 5-year average of annual discharge events and annual discharge volume for the Alki and Carkeek CSO treatment plants.
3. The percent change in the above parameters since the previous report.
4. The present and design population or population equivalent.
5. The projected population growth rate.
6. The estimated date upon which the Permittee expects the wastewater treatment plant to reach design capacity, according to the most restrictive of the parameters above.

S5. Operation and maintenance

The Permittee must at all times properly operate and maintain all facilities and systems of treatment and control (and related appurtenances), which are installed to achieve compliance with the terms and conditions of this permit. Proper operation and maintenance also includes keeping a daily operation logbook (paper or electronic), adequate laboratory controls, and appropriate quality assurance procedures. This provision of the permit requires the Permittee to operate backup or auxiliary facilities or similar systems only when the operation is necessary to achieve compliance with the conditions of this permit.

S5.A. Certified operator

These permitted facilities must be operated by an operator certified by the state of Washington for at least a Class IV plant. This operator must be in responsible charge of the day-to-day operation of the wastewater treatment facilities. An operator certified for at least a Class III plant must be in charge during all regularly scheduled shifts.

S5.B. Operation and maintenance program

The Permittee must:

1. Maintain the operation and maintenance program for the entire sewage system under the ownership and control of KC.
2. Keep maintenance records on all major electrical and mechanical components of the treatment plant, as well as the sewage system and pumping stations. Such records must clearly specify the frequency and type of maintenance recommended by the manufacturer and must show the frequency and type of maintenance performed.
3. Make maintenance records available for inspection at all times.

S5.C. Short-term reduction

The Permittee must schedule any facility maintenance, which might require interruption of wastewater treatment and degrade effluent quality, during non-critical water quality periods and carry this maintenance out in a manner approved by Ecology.

If a Permittee contemplates a reduction in the level of treatment that would cause a violation of permit discharge limits on a short-term basis for any reason, and such reduction cannot be avoided, the Permittee must:

1. Give written notification to Ecology, if possible, thirty (30) days prior to such activities.
2. Detail the reasons for, length of time of, and the potential effects of the reduced level of treatment.

This notification does not relieve the Permittee of its obligations under this permit.

S5.D. Electrical power failure

The Permittee must ensure that adequate safeguards prevent the discharge of untreated wastes or wastes not treated in accordance with the requirements of this permit during electrical power failure at the treatment plant and/or sewage lift stations. Adequate safeguards include, but are not limited to, alternate power sources, standby generator(s), or retention of inadequately treated wastes.

The Permittee must maintain Reliability Class II (EPA 430-99-74-001) at the wastewater treatment plant. Reliability Class II requires a backup power source sufficient to operate all vital components and critical lighting and ventilation during peak wastewater flow conditions. Vital components used to support the secondary processes (i.e., mechanical aerators or aeration basin air compressors) need not be operable to full levels of treatment, but must be sufficient to maintain the biota.

S5.E. Prevent connection of inflow

The Permittee must strictly enforce its sewer ordinances and not allow the connection of inflow (roof drains, foundation drains, etc.) to the sanitary sewer system where under ownership and control of King County.

S5.F. Bypass procedures

This permit prohibits a bypass, which is the intentional diversion of waste streams from any portion of a treatment facility. Ecology may take enforcement action against a Permittee for a bypass unless one of the following circumstances (1, 2, or 3) applies.

1. Bypass for essential maintenance without the potential to cause violation of permit limits or conditions.

   This permit authorizes a bypass if it allows for essential maintenance and does not have the potential to cause violations of limits or other conditions of this permit, or adversely impact public health as determined by Ecology prior to the bypass. The Permittee must submit prior notice, if possible, at least ten (10) days before the date of the bypass.

2. Bypass which is unavoidable, unanticipated, and results in non-compliance of this permit.

   This permit authorizes such a bypass only if:

   a. Bypass is unavoidable to prevent loss of life, personal injury, or severe property damage. "Severe property damage" means substantial physical damage to property, damage to the treatment facilities which would cause them to become inoperable, or substantial and permanent loss of natural resources which can reasonably be expected to occur in the absence of a bypass.

   b. No feasible alternatives to the bypass exist, such as:

      - The use of auxiliary treatment facilities.
      - Retention of untreated wastes.
      - Maintenance during normal periods of equipment downtime, but not if the Permittee should have installed adequate backup equipment in the exercise of reasonable engineering judgment to prevent a bypass.
      - Transport of untreated wastes to another treatment facility or preventative maintenance.

   c. Ecology is properly notified of the bypass as required in Special Condition S3.E of this permit.

3. If bypass is anticipated and has the potential to result in non-compliance of this permit.

   a. The Permittee must notify Ecology at least thirty (30) days before the planned date of bypass. The notice must contain:

      - A description of the bypass and its cause.
      - An analysis of all known alternatives which would eliminate, reduce, or mitigate the need for bypassing.
      - A cost-effectiveness analysis of alternatives including comparative resource damage assessment.

- The minimum and maximum duration of bypass under each alternative.
- A recommendation as to the preferred alternative for conducting the bypass.
- The projected date of bypass initiation.
- A statement of compliance with SEPA.
- A request for modification of water quality standards as provided for in WAC 173-201A-410, if an exceedance of any water quality standard is anticipated.
- Details of the steps taken or planned to reduce, eliminate, and prevent reoccurrence of the bypass.

b. For probable construction bypasses, the Permittee must notify Ecology of the need to bypass as early in the planning process as possible. The Permittee must consider the analysis required above during preparation of the engineering report or facilities plan and plans and specifications and must include these to the extent practical. In cases where the Permittee determines the probable need to bypass early, the Permittee must continue to analyze conditions up to and including the construction period in an effort to minimize or eliminate the bypass.

c. Ecology will consider the following prior to issuing an administrative order for this type of bypass:

- If the bypass is necessary to perform construction or maintenance-related activities essential to meet the requirements of this permit.
- If feasible alternatives to bypass exist, such as the use of auxiliary treatment facilities, retention of untreated wastes, stopping production, maintenance during normal periods of equipment down time, or transport of untreated wastes to another treatment facility.
- If the Permittee planned and scheduled the bypass to minimize adverse effects on the public and the environment.

After consideration of the above and the adverse effects of the proposed bypass and any other relevant factors, Ecology will approve or deny the request. Ecology will give the public an opportunity to comment on bypass incidents of significant duration, to the extent feasible. Ecology will approve a request to bypass by issuing an administrative order under RCW 90.48.120.

S5.G. Operations and maintenance (O&M) manual

a. O&M manual submittal and requirements

The Permittee must:

1. Review the O&M manuals at least annually.

2. Submit to Ecology for review and approval substantial changes or updates to the O&M manuals whenever it incorporates them into the manual. The Permittee must submit an electronic copy (preferably as a PDF).
3. Keep the approved O&M manuals at the permitted facility.
4. Follow the instructions and procedures of these manuals.

b. O&M manual components

In addition to the requirements of WAC 173-240-080 (1) through (5), the O&M manuals must include:

- Emergency procedures for cleanup in the event of wastewater system upset or failure.
- A review of system components which if failed could pollute surface water or could impact human health. Provide a procedure for a routine schedule of checking the function of these components.
- Wastewater system maintenance procedures that contribute to the generation of process wastewater.
- Reporting protocols for submitting reports to Ecology to comply with the reporting requirements in the discharge permit.
- Any directions to maintenance staff when cleaning or maintaining other equipment or performing other tasks which are necessary to protect the operation of the wastewater system (for example, defining maximum allowable discharge rate for draining a tank, blocking all floor drains before beginning the overhaul of a stationary engine).
- Treatment plant process control monitoring schedules.

S6. Pretreatment

S6.A. General requirements

1. The Permittee must implement the Industrial Pretreatment Program in accordance with King County Code 28.84.060 as amended by King County Ordinance No. 11963 on January 1, 1996, legal authorities, policies, procedures, and financial provisions described in the Permittee's approved pretreatment program submittal entitled "Industrial Pretreatment Program" and dated April 27, 1981; any approved revisions thereto; and the General Pretreatment Regulations (40 CFR Part 403). At a minimum, the Permittee must undertake the following pretreatment implementation activities:

   a. Enforce categorical pretreatment standards under Section 307(b) and (c) of the Federal Clean Water Act (hereinafter, the Act), prohibited discharge standards as set forth in 40 CFR 403.5, local limits, or state standards, which ever are most stringent or apply at the time of issuance or modification of a local industrial waste discharge permit. Locally derived limits are defined as pretreatment standards under Section 307(d) of the Act and are not limited to categorical industrial facilities.

b. Issue industrial waste discharge permits to all significant industrial users [SIUs, as defined in 40 CFR 403.3(v)(i)(ii)] contributing to the treatment system, including those from other jurisdictions. Industrial waste discharge permits must contain as a minimum, all the requirements of 40 CFR 403.8 (f)(l)(iii). The Permittee must coordinate the permitting process with Ecology regarding any industrial facility which may possess a state waste discharge permit issued by Ecology.

c. Maintain and update, as necessary, records identifying the nature, character, and volume of pollutants contributed by industrial users to the treatment works. The Permittee must maintain records for at least a three-year period.

d. Perform inspections, surveillance, and monitoring activities on industrial users to determine or confirm compliance with pretreatment standards and requirements. The Permittee must conduct a thorough inspection of SIUs annually, except Middle-Tier Categorical Industrial Users, as defined by 40 CFR 403.8(f)(2)(v)(B)&(C), need only be inspected once every two years, unless they discharge to a CSO outfall (controlled and uncontrolled) located within the Lower Duwamish Waterway cleanup site boundary, in which case they must be inspected annually. The Permittee must conduct regular local monitoring of SIU wastewaters commensurate with the character and volume of the wastewater but not less than once per year except for Middle-Tier Categorical Industrial Users which may be sampled once every two years. The Permittee must collect and analyze samples in accordance with 40 CFR Part 403.12(b)(5)(ii)-(v) and 40 CFR Part 136.

e. Enforce and obtain remedies for non-compliance by any industrial users with applicable pretreatment standards and requirements. Once violations have been identified, the Permittee must take timely and appropriate enforcement action to address the non-compliance. The Permittee's action must follow its enforcement response procedures and any amendments, thereof.

f. Publish, at least annually in a newspaper of general circulation within the Permittee's service area, a list of all non-domestic users which, at any time in the previous 12 months, were in significant non-compliance as defined in 40 CFR 403.8(f)(2)(vii).

g. If the Permittee elects to conduct sampling of an SIU's discharge in lieu of requiring user self-monitoring, it must satisfy all requirements of 40 CFR Part 403.12. This includes monitoring and record keeping requirements of sections 403.12(g) and (o). For SIU's subject to categorical standards (i.e., CIUs), the Permittee may either complete baseline and initial compliance reports for the CIU (when required by 403.12(b) and (d)) or require these of the CIU. The Permittee must ensure SIUs are provided the results of sampling in a timely manner, inform SIUs of their right to sample, their obligations to report any sampling they do, to respond to non-compliance, and to submit other notifications.

These include a slug load report (403.12(f)), notice of changed discharge (403.12(j)), and hazardous waste notifications (403.12(p)). If sampling for the SIU, the Permittee must not sample less than once in every six month period unless the Permittee's approved program includes procedures for reduction of monitoring for Middle-Tier or Non-Significant Categorical Users per 403.12(e)(2) and (3) and those procedures have been followed.

h. Develop and maintain a data management system designed to track the status of the Permittee's industrial user inventory, industrial user discharge characteristics, and compliance status.

i. Maintain adequate staff, funds, and equipment to implement its pretreatment program.

j. Establish, where necessary, contracts or legally binding agreements with contributing jurisdictions to ensure compliance with applicable pretreatment requirements by commercial or industrial users within these jurisdictions. These contracts or agreements must identify the agency responsible for the various implementation and enforcement activities to be performed in the contributing jurisdiction.

2. Per 40 CFR 403.8(f)(2)(vii), the Permittee must evaluate each Significant Industrial User to determine if a Slug Control Plan is needed to prevent slug discharges which may cause interference, pass-through, or in any other way result in violations of the Permittee's regulations, local limits or permit conditions. The Slug Control Plan evaluation shall occur within one year of a user's designation as a SIU. In accordance with 40 CFR 403.8(f)(1)(iii)(B)(6) the Permittee shall include slug discharge control requirements in an SIU's permit if the Permittee determines that they are necessary.

3. Whenever Ecology determines that any waste source contributes pollutants to the Permittee's treatment works in violation of Subsection (b), (c), or (d) of Section 307 of the Act, and the Permittee has not taken adequate corrective action, Ecology will notify the Permittee of this determination. If the Permittee fails to take appropriate enforcement action within 30 days of this notification, Ecology may take appropriate enforcement action against the source or the Permittee.

4. *Pretreatment Report*

The Permittee must provide to Ecology an annual report that briefly describes its program activities during the previous calendar year. By March 31st, the Permittee must send the annual report to Ecology at:

Water Quality Permit Coordinator
Department of Ecology
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

The report must include the following information:

a. An updated listing of non-domestic industrial dischargers. Starting with the report submitted in 2016, the list must identify, for each discharger with a King County discharge authorization (minor or major) or discharge permit, the downstream CSO outfall(s) to which the discharger contributes, where applicable.

b. Results of wastewater sampling at the treatment plant as specified in Subsection S6.B below. The Permittee must calculate removal rates for each pollutant and evaluate the adequacy of the existing local limits in prevention of treatment plant interference, pass through of pollutants that could affect receiving water quality and biosolids contamination.

c. Status of program implementation, including:

   i. Any substantial modifications to the pretreatment program as originally approved by Ecology, including staffing and funding levels.

   ii. Any interferences, upsets, or permit violations experienced at the WWTP that are directly attributable to wastes from industrial users.

   iii. Listing of industrial users inspected and/or monitored, and a summary of the results.

   iv. Listing of industrial users scheduled for inspection and/or monitoring for the next year, and expected frequencies.

   v. Listing of industrial users notified of promulgated pretreatment standards and/or local standards as required in 40 CFR 403.8(f)(2)(iii). The list must indicate which industrial users are on compliance schedules and the final date of compliance for each.

   vi. Listing of industrial users issued industrial waste discharge permits.

   vii. Planned changes in the pretreatment program implementation plan.

d. Status of compliance activities, including:

   i. Listing of industrial users that failed to submit baseline monitoring reports or any other reports required under 40 CFR 403.12 and in the Permittee's pretreatment program, dated April 27, 1981.

   ii. Listing of industrial users that were at any time during the reporting period not complying with federal, state, or local pretreatment standards or with applicable compliance schedules for achieving those standards, and the duration of such non-compliance.

   iii. Summary of enforcement activities and other corrective actions taken or planned against non-complying industrial users. The Permittee must supply to Ecology a copy of the public notice of facilities that were in significant non-compliance.

5. The Permittee must request and obtain approval from Ecology before making any significant changes to the approved local pretreatment program. The Permittee must follow the procedure in 40 CFR 403.18 (b) and (c).

S6.B. Monitoring requirements

The Permittee must monitor its influent, effluent, and biosolids at the West Point WWTP for the priority pollutants identified in Tables II and III of Appendix D of 40 CFR Part 122 as amended, any compounds identified as a result of Condition S6.B.4, and any other pollutants expected from nondomestic sources using U.S. EPA-approved procedures for collection, preservation, storage, and analysis. The Permittee must test influent, effluent, and biosolids samples for the priority pollutant metals (Table III, 40 CFR 122, Appendix D) on a quarterly basis throughout the term of this permit. The Permittee must test influent, effluent, and biosolids samples for the organic priority pollutants (Table II, 40 CFR 122, Appendix D) on an annual basis.

1. The Permittee must sample West Point WWTP influent and effluent on a day when industrial discharges are occurring at normal to maximum levels. The Permittee must obtain 24-hour composite samples for the analysis of acid and base/neutral extractable compounds and metals. The Permittee must collect samples for the analysis of volatile organic compounds and samples must be collected using grab sampling techniques at equal intervals for a total of four grab samples per day.

   The laboratory may run a single analysis for volatile pollutants (using GC/MS procedures approved by 40 CFR 136) for each monitoring day by compositing equal volumes of each grab sample directly in the GC purge and trap apparatus in the laboratory, with no less than 1 ml of each grab included in the composite.

   Unless otherwise indicated, all reported test data for metals must represent the total amount of the constituent present in all phases, whether solid, suspended, or dissolved, elemental or combined including all oxidation states.

   The Permittee must handle, prepare, and analyze all wastewater samples taken for GC/MS analysis using procedures approved by 40 CFR 136.

2. The Permittee must collect a biosolids sample concurrently with a wastewater sample as a single grab sample of residual biosolids. Sampling and analysis must be performed using procedures approved by 40 CFR 136 unless the Permittee requests an alternate method and Ecology has approved.

3. The Permittee must take cyanide, phenols, and oils as grab samples. Oils must be hexane soluble or equivalent, and should be measured in the influent and effluent only.

4. In addition to quantifying pH, oil and grease, and all priority pollutants, the Permittee must make a reasonable attempt to identify all other substances and quantify all pollutants shown to be present by gas chromatograph/mass spectrometer (GC/MS) analysis using procedures approved by 40 CFR 136. The Permittee should attempt to make determinations of pollutants for each

fraction, which produces identifiable spectra on total ion plots (reconstructed gas chromatograms). The Permittee should attempt to make determinations from all peaks with responses 5% or greater than the nearest internal standard. The 5% value is based on internal standard concentrations of 30 μg/l, and must be adjusted downward if higher internal standard concentrations are used or adjusted upward if lower internal standard concentrations are used. The Permittee may express results for non-substituted aliphatic compounds as total hydrocarbon content. The Permittee must use a laboratory whose computer data processing programs are capable of comparing sample mass spectra to a computerized library of mass spectra, with visual confirmation by an experienced analyst. For all detected substances which are determined to be pollutants, the Permittee must conduct additional sampling and appropriate testing to determine concentration and variability, and to evaluate trends.

S6.C. Reporting of monitoring results

The Permittee must include a summary of monitoring results in the Annual Pretreatment Report.

S6.D. Local limit development

As sufficient data become available, the Permittee must, in consultation with Ecology, reevaluate their local limits in order to prevent pass through or interference. On a case-by-case basis, as applicable, the Permittee should consider the impacts of CSO discharges on the receiving waterbody when establishing limits for individual permittees. If Ecology determines that any pollutant present causes pass through or interference, or exceeds established biosolids standards, the Permittee must establish new local limits or revise existing local limits as required by 40 CFR 403.5. Ecology may also require the Permittee to revise or establish local limits for any pollutant discharged from the treatment works that has a reasonable potential to exceed the water quality standards, sediment standards, or established effluent limits, or causes whole effluent toxicity. Ecology makes this determination in the form of an Administrative Order.

Ecology may modify this permit to incorporate additional requirements relating to the establishment and enforcement of local limits for pollutants of concern. Any permit modification is subject to formal due process procedures under state and federal law and regulation.

S7. Solid wastes

S7.A. Solid waste handling

The Permittee must handle and dispose of all solid waste material in such a manner as to prevent its entry into state ground or surface water.

S7.B. Leachate

The Permittee must not allow leachate from its solid waste material to enter state waters without providing all known, available, and reasonable methods of treatment, nor allow such leachate to cause violations of the State Surface Water Quality Standards, Chapter 173-201A WAC, or the State Ground Water Quality

Standards, Chapter 173-200 WAC. The Permittee must apply for a permit or permit modification as may be required for such discharges to state ground or surface waters.

S8. Acute toxicity

S8.A. Acute testing

The Permittee must:

1. Conduct acute toxicity testing on final West Point WWTP effluent during the first and third quarters of 2017.
2. Submit the results to Ecology with the permit renewal application.
3. Conduct acute toxicity testing on a series of at least five concentrations of effluent, including 100% effluent and a control.
4. Use each of the following species and protocols for each acute toxicity test:

Acute Toxicity Tests	Species	Method
Fathead minnow 96-hour static-renewal test	*Pimephales promelas*	EPA-821-R-02-012
Daphnid 48-hour static test	*Ceriodaphnia dubia, Daphnia pulex,* or *Daphnia magna*	EPA-821-R-02-012

S8.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain bench sheets and reference toxicant results for test methods. If the lab provides the toxicity test data in electronic format for entry into Ecology's database, then the Permittee must send the data to Ecology along with the test report, bench sheets, and reference toxicant results.
2. The Permittee must collect 24-hour composite effluent samples for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.
3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.
4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Subsection C and the Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.

5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Section A or pristine natural water of sufficient quality for good control performance.
6. The Permittee must collect effluent samples for whole effluent toxicity testing just prior to the chlorination step in the treatment process.
7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the acute critical effluent concentration (ACEC). The ACEC equals 3.6 % effluent.
8. All whole effluent toxicity tests that involve hypothesis testing must comply with the acute statistical power standard of 29% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S9. Chronic toxicity

S9.A. Chronic testing

The Permittee must:

1. Conduct chronic toxicity testing on final West Point WWTP effluent during the second and fourth quarters of 2017.
2. Submit the results to Ecology with the permit renewal application.
3. Conduct chronic toxicity testing on a series of at least five concentrations of effluent and a control. This series of dilutions must include the acute critical effluent concentration (ACEC). The ACEC equals 3.6% effluent. The series of dilutions should also contain the CCEC of 0.53 % effluent.
4. Compare the ACEC to the control using hypothesis testing at the 0.05 level of significance as described in Appendix H, EPA/600/4-89/001.
5. Perform chronic toxicity tests with all of the following species and the most recent version of the following protocols:

Saltwater Chronic Test	Species	Method
Topsmelt survival and growth	*Atherinops affinis*	EPA/600/R-95/136
Mysid shrimp survival and growth	*Americamysis bahia* (formerly *Mysidopsis bahia*)	EPA-821-R-02-014

S9.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain bench sheets and reference toxicant results for test methods. If the lab

provides the toxicity test data in electronic format for entry into Ecology's database, then the Permittee must send the data to Ecology along with the test report, bench sheets, and reference toxicant results.

2. The Permittee must collect 24-hour composite effluent samples for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.
3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.
4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Section C and the Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.
5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Subsection C or pristine natural water of sufficient quality for good control performance.
6. The Permittee must collect effluent samples for whole effluent toxicity testing just prior to the chlorination step in the treatment process.
7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the CCEC and the ACEC. The CCEC and the ACEC may either substitute for the effluent concentrations that are closest to them in the dilution series or be extra effluent concentrations. The CCEC equals 0.53% effluent. The ACEC equals 3.6% effluent.
8. All whole effluent toxicity tests that involve hypothesis testing must comply with the chronic statistical power standard of 39% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S10. Wet weather operation

CSO-related bypass of the secondary treatment portion of the West Point WWTP is authorized when the instantaneous flow rate to the WWTP exceeds 300 MGD as a result of precipitation events. Bypasses that occur when the instantaneous flow rate is less than 300 MGD are not authorized under this condition and are subject to the bypass provisions as stated in S5.F of the permit. In the event of a CSO-related bypass authorized under this condition, the Permittee must minimize the discharge of pollutants to the environment. At a minimum, CSO-related bypass flows must receive solids and floatables removal, primary clarification, and disinfection. The final discharge must at all times meet the effluent limits of this permit as listed in S1.

The Permittee must maintain records of all CSO-related bypasses at the treatment plant. These records must document the date, duration, and volume of each bypass event, and the magnitude of the precipitation event. The records must also indicate the effluent flow rate at the time when bypassing is initiated. The Permittee must report all occurrences of bypassing on a monthly and annual basis. The monthly report must include the above information and must be included in narrative form with the discharge monitoring report. The annual report must include all of the above information in summary format and should be reported in the annual CSO report per S11.C.

S11. Combined sewer overflows

S11.A. Authorized CSO discharge locations

Beginning on the effective date of this permit, the Permittee may discharge combined wastewater and stormwater from the 38 combined sewer overflow (CSO) outfalls listed in

Table 5. These point source discharges occur intermittently when rain events overload the combined sewer system. The permit prohibits discharges from the CSO outfall sites except as a result of precipitation. This permit does not authorize discharges from CSO outfalls that threaten characteristic uses of the receiving water as identified in the water quality standards, Chapter 173-201A WAC, or that result in an exceedance of the Sediment Management Standards, Chapter 173-204 WAC.

Table 5. Permitted CSO outfalls (38)

Outfall No.	Facility Name	Receiving Water	Latitude	Longitude
003	Ballard Siphon Reg.via Seattle storm drain	Lake Washington Ship Canal	47.663916°	-122.382333°
004	11th Ave NW (AKA East Ballard)	Lake Washington Ship Canal	47.659491°	-122.370774°
006	Magnolia Overflow	Elliott Bay/Puget Sound	47.630184°	-122.399021°
007	Canal Street Overflow	Lake Washington Ship Canal	47.651856°	-122.358113°
008	3rd Ave W and Ewing St.	Lake Washington Ship Canal	47.652084°	-122.360052°
009	Dexter Ave Regulator	Lake Union	47.632273°	-122.339235°
011	E Pine St. PS Emergency Overflow	Lake Washington	47.614926°	-122.280304°
012	Belvoir Pump Station Emergency Overflow	Lake Washington	47.656698°	-122.287589°
013	MLK Trunkline Overflow - via storm drain	Lake Washington	47.523285°	-122.262950°
014	Montlake Overflow	Lake Washington Ship Canal	47.647110°	-122.304861°
015	University Regulator	Lake Washington Ship Canal	47.648929°	-122.311296°
018	Matthews Park PS Emergency Overflows	Lake Washington	47.697458°	-122.272650°
027a	Denny Way Regulator	Elliott Bay	47.618139°	-122.361888°
028	King Street Regulator	Elliott Bay	47.599003°	-122.337425°
029	Kingdome	Elliott Bay	47.592532°	-122.342106°
030	Lander St. Regulator	Elliott Bay	47.581476°	-122.342997°

Outfall No.	Facility Name	Receiving Water	Latitude	Longitude
031a, b, c	Hanford #1 Overflow - Via Diagonal Storm Drain	Duwamish River	47.563108˚	-122.345315˚
032	Hanford #2 Regulator	Duwamish - East Waterway	47.577223˚	-122.34278˚
033	Rainier Ave Pump Station	Lake Washington	47.571374˚	-122.27553˚
034	E. Duwamish Pump Station	Duwamish River	47.562985˚	-122.345272˚
035	W. Duwamish Pump Station	Duwamish River	47.563224˚	-122.348256˚
036	Chelan Ave Regulator	Duwamish - West Waterway	47.573667˚	-122.357779˚
037	Harbor Avenue Regulator	Duwamish to Elliott Bay	47.573706˚	-122.361159˚
038	Terminal 115 Overflow	Duwamish River	47.54826˚	-122.340503˚
039	Michigan S. Regulator	Duwamish River	47.54353˚	-122.334967˚
040	8th Ave South Reg. (W. Marginal Way PS)	Duwamish River	47.533648˚	-122.322639˚
041	Brandon Street Regulator	Duwamish River	47.554661˚	-122.340832˚
042	Michigan W. Regulator	Duwamish River	47.541561˚	-122.334994˚
043	East Marginal Pump Station	Duwamish River	47.537048˚	-122.31849˚
044a	Norfolk Outfall	Duwamish River	47.511941˚	-122.297356˚
045	Henderson Pump Station	Lake Washington	47.523285˚	-122.26295˚
048a,b	North Beach Pump Station: a.) wet well, b) inlet structure	Puget Sound	47.704007˚ 47.702142˚	-122.392337˚ -122.392564˚
049	30th Avenue NE Pump Station	Lake Washington	47.656698˚	-122.287589˚
052	53rd Avenue SW Pump Station	Puget Sound	47.584799˚	-122.402552˚
054	63rd Avenue SW Pump Station	Puget Sound	47.570016˚	-122.416301˚
055	SW Alaska Street Overflow	Puget Sound	47.559442˚	-122.406947˚
056	Murray Street Pump Station	Puget Sound	47.540275˚	-122.400003˚
057	Barton Street Pump Station	Puget Sound	47.523886˚	-122.396393˚

S11.B. Nine minimum controls

In accordance with chapter 173-245 WAC and US EPA CSO control policy (59 FR 18688), the Permittee must implement and document the following nine minimum controls (NMC) for CSOs. The Permittee must document compliance with the NMCs in the annual CSO report as required in Special Condition S11.C.

The NMCs are considered technology-based requirements for CSO systems. In order to comply with these requirements, the Permittee must:

1. Implement proper operation and maintenance programs for the sewer system and all CSO outfalls to reduce the magnitude, frequency, and duration of CSOs. The program must consider regular sewer inspections; sewer, catch basin, and regulator cleaning; equipment and sewer collection system repair or replacement, where necessary; and disconnection of illegal connections.
2. Implement procedures that will maximize use of the collection system for wastewater storage that can be accommodated by the storage capacity of the collection system in order to reduce the magnitude, frequency, and duration of CSOs.

3. Review and modify, as appropriate, its existing pretreatment program to minimize CSO impacts from the discharges from non-domestic users. Starting with its annual Pretreatment Report submitted in 2016, the County must include in the report, for each discharger with a King County discharge authorization (major or minor) or discharge permit, the downstream CSO outfall(s) to which the discharger contributes, where applicable.
4. Operate the wastewater treatment plant at maximum treatable flow during all wet weather flow conditions to reduce the magnitude, frequency, and duration of CSOs. The Permittee must deliver all flows to the treatment plant within the constraints of the treatment capacity of the treatment works.
5. Not discharge overflows from CSO outfalls except as a result of precipitation events; dry weather overflows from CSO outfalls are prohibited. The Permittee must report each dry weather overflow to the permitting authority immediately per Special Condition S3.E. When it detects a dry weather overflow, the Permittee must begin corrective action immediately and inspect the dry weather overflow each subsequent day until it has eliminated the overflow.
6. Implement measures to control solid and floatable materials in CSOs.
7. Implement a pollution prevention program focused on reducing the impact of CSOs on receiving waters. Best management practices (BMPs) to control pollutant sources in stormwater in CSO basins must be an element of the pollution prevention program. Ecology's *Stormwater Management Manual for Western Washington* (2012) contains appropriate BMPs for reference.

   Starting with the Annual CSO Report submitted in 2017, the Permittee must include a detailed description of the pollution prevention program, appropriate BMPs, and the legal authority and administrative procedures that will be used to ensure the program is being implemented. If the legal authority and/or administrative procedures are not in place, the Annual CSO Report must include a detailed description of the steps needed to establish such a program and the timeline for getting the program in place.
8. Continue to implement the public notification process that informs citizens of when and where CSOs occur. The process must continue to include (a) a mechanism to alert citizens of CSO occurrences and (b) a system to determine the nature and duration of conditions that are potentially harmful for users of receiving waters due to CSOs.
9. Monitor CSO outfalls to characterize CSO impacts and the efficacy of CSO controls. This must include collection of data to document existing baseline conditions and to evaluate the efficacy of the technology-based controls. This data must include:
   a. Characteristics of the combined sewer system, including the population served by the combined portion of the system and locations of all CSO outfalls.

b. Total number of CSO events, and the frequency and duration of CSOs for all events.

c. Locations and designated uses of receiving water bodies.

d. Water quality data for receiving water bodies.

e. Water quality impacts directly related to CSO (e.g., beach closing, floatables, wash-up episodes, fish kills).

S11.C. Combined sewer overflow reporting

1. *Monthly CSO Report*

   The Permittee must submit a monthly report by the 15th of each month that includes:

   a. Discharge monitoring reports (DMRs) and narrative summaries for each CSO treatment plant (Alki, Carkeek, Elliott West, and Henderson), and

   b. An event-based summary that includes discharge volume, duration, and precipitation for all CSO discharge events that occur during the reporting period.

2. *Annual CSO Report*

   The Permittee must submit a CSO Annual Report to Ecology for review by July 31st of each year. The CSO Annual Report must cover the previous calendar year. The report must comply with the requirements of WAC 173-245-090(1) and must include documentation of compliance with the Nine Minimum Controls for CSOs described in Special Condition S11.B. The Permittee must submit paper and electronic copies of the report, and Excel spreadsheet copies of significant spreadsheets. The CSO Annual Report must include the following information:

   a. A summary of the number and volume of untreated discharge events per outfall for that year.

   b. A summary of the 20-year moving average number of untreated discharge events per outfall, calculated once annually.

   c. An event-based reporting form (provided by Ecology) for all CSO discharges for the reporting period, summarizing all data collected according to the monitoring schedule in Special Condition S11.B.9.

   d. An explanation of the previous year's CSO reduction accomplishments.

   e. A list of CSO reduction projects planned for the next year.

   f. A list of which permitted CSO outfalls can be categorized as meeting the one untreated discharge per year on a 20-year moving average performance standard. This annual assessment may be based on historical long-term discharge data, modeling, or other reasonable methods as approved by Ecology.

S11.D. Combined sewer overflow reduction plan amendment

The Permittee must submit an amendment of its *2012 Long Term Control Plan Amendment* (also referred to as a CSO Reduction Plan) to Ecology for review and approval with the application for permit renewal. The amendment must comply with the requirements of WAC 173-245-090(2).

S11.E. Engineering reports and plans and specifications for CSO reduction projects

The Permittee must submit to Ecology an engineering report for each specific CSO reduction construction project. Engineering documents associated with each CSO reduction project must meet the requirements of WAC 173-240-060, *Engineering Report*, and be approved by Ecology prior to construction. The report must:

1. Specify any contracts, ordinances, methods of financing, or any other arrangements necessary to achieve this objective.
2. Describe how each project will achieve the performance standard of *greatest reasonable control* and explicitly state the expected frequency of overflow events per year per associated outfall after the CSO reduction construction project has been completed.
3. Identify the potential hydraulic impacts of the project on downstream conveyance and treatment facilities.

For each specific CSO reduction construction project, the Permittee must prepare and submit approvable plans and specifications consistent with chapter 173-240-070 WAC to Ecology for review and approval. Ecology must approve plans and specifications prior to construction.

Prior to the start of construction, the Permittee must submit to Ecology a construction quality assurance plan as required by chapter 173-240-075 WAC.

S11.F. Requirements for controlled combined sewer overflows

a. CSOs identified as controlled

Based on monitoring data presented in King County's *2012 Annual CSO Report* and King County's *2012 Long Term Control Plan Amendment*, the 16 CSO outfalls listed in Table 6 meet the requirement of "greatest reasonable reduction" as defined in chapter WAC 173-245-020(22). Frequency of overflow events at these CSO outfalls, as a result of precipitation events, must continue to meet the performance standard.

Table 6. Controlled CSO outfalls (16)

CSO Outfall No	Location/Name	Receiving Water	Latitude	Longitude
007	Canal Street Overflow	Lake Washington Ship Canal	47.651856˚	-122.358113˚
011	E Pine St. PS Emergency Overflow	Lake Washington	47.614926˚	-122.280304˚
012	Belvoir PS Emergency Overflow	Lake Washington	47.656698˚	-122.287589˚
013	MLK Trunkline Overflow - via storm drain	Lake Washington	47.523285˚	-122.26295˚
018	Matthews Park PS Emergency Overflows	Lake Washington	47.697458˚	-122.27265˚
033	Rainier Ave Pump Station	Lake Washington	47.571374˚	-122.27553˚
034	E. Duwamish Pump Station	Duwamish River	47.563224˚	-122.348256˚
035	W. Duwamish Pump Station	Duwamish River	47.562986˚	-122.345272˚
040	8th Ave South Reg. (W Marginal Way PS)	Duwamish River	47.533648˚	-122.322639˚
043	East Marginal Pump Station	Duwamish River	47.537048˚	-122.31849˚
044a	Norfolk Outfall	Duwamish River	47.511941˚	-122.297356˚
045	Henderson Pump Station	Lake Washington	47.523285˚	-122.26295˚
049	30th Avenue NE Pump Station	Lake Washington	47.656698˚	-122.287589˚
052	53rd Avenue SW Pump Station	Puget Sound	47.584799˚	-122.402552˚
054	63rd Avenue SW Pump Station	Puget Sound	47.570016˚	-122.416301˚
055	SW Alaska Street Overflow	Puget Sound	47.559442˚	-122.406947˚

b. *Performance standards for controlled CSO outfalls*

The performance standard for each controlled CSO outfall is not more than one discharge event per outfall per year on average, due to precipitation. Ecology evaluates compliance with the performance standard annually based on a 20 year moving average. The Permittee must report the running 20-year average number of overflow events per year during this permit term from these CSO outfalls in the *CSO Annual Report* required in Section S11.C.

c. *CSO post construction monitoring*

The Permittee must continue to implement a post construction compliance monitoring program to verify the effectiveness of CSO controls and to demonstrate compliance with water quality standards and protection of designated uses. The Permittee must follow the approved *King County 2012 Post Construction Monitoring Plan* and submit to Ecology for review and approval any proposed changes to this plan.

d. *CSO post construction monitoring data report*

The Permittee must submit to Ecology, by December 1, 2019, a post-construction monitoring summary report that demonstrates how each CSO outfall listed as controlled in Table 6, as well as those brought under control during the permit term, achieves performance requirements and complies with state water and sediment quality standards. The report must conform to the approved *CSO Post Construction Monitoring Plan*. For outfalls with SMS exceedances associated with CSO discharges, the report must describe clean-up activities in the vicinity including clean-up actions planned or that have been performed, targeted chemicals, any available pre- and post-cleanup monitoring results, clean-up project schedule, post-project monitoring schedule, and a list of parties involved.

The outfalls scheduled to be controlled during this permit term and to be discussed in the CSO post construction monitoring data report include: Dexter Avenue Regulator (DSN 009), Denny Way Regulator (DSN 027a), Harbor Avenue Regulator (DSN 037), Ballard Siphon Regulator (DSN 003), Barton (DSN 057), Murray (DSN 056), South Magnolia (DSN 006), and North Beach (DSN 048).

S12. Spill control plan

The Permittee must:

1. Review the West Point WWTP Spill Plan at least annually and update as needed.
2. Send updated plans to Ecology when significant changes are made.
3. Follow the plan and any supplements throughout the term of the permit.

The spill control plan must include the following:

1. A list of all oil and petroleum products and other materials used and/or stored on site, which when spilled, or otherwise released into the environment, designate as dangerous waste (DW) or extremely hazardous waste (EHW) by the procedures set forth in WAC 173-303-070. Include other materials used and/or stored on site which may become pollutants or cause pollution upon reaching state's waters.
2. A description of preventive measures and facilities (including an overall facility plot showing drainage patterns) which prevent, contain, or treat spills of these materials.
3. A description of the reporting system the Permittee will use to alert responsible managers and legal authorities in the event of a spill.
4. A description of operator training to implement the plan.

S13. Sediment monitoring

S13.A. Sediment sampling – West Point WWTP

a. *Sediment sampling and analysis plan*

The Permittee must submit to Ecology for review and approval a sediment sampling and analysis plan for sediment monitoring for the West Point WWTP outfall. The Permittee must submit one paper copy and an electronic copy (preferably as a PDF) by December 1, 2016. The purpose of the plan is to re-characterize sediment quality in the vicinity of the discharge location.

The Permittee must:

- Follow the guidance provided in the *Sediment Source Control Standards User Manual, Appendix B: sediment sampling and analysis plan* (Ecology, 2008). Method detection limits must be listed in the plan.
- Collect enough sediment in the top 10 cm at each station to allow for conventional parameter testing (percent solids, total organic carbon, particle size), chemistry testing, and if necessary, bioassay testing. Chemistry tests must be performed before bioassay tests and if there are Sediment Quality Standard (SQS) exceedances, then bioassay tests must be performed.
- Chemistry: Analyze conventional parameters and the full suite of 47 Sediment Management Standards (SMS) marine chemicals at all stations.
- Bioassay: Perform bioassay tests at all stations with SQS exceedances. Run parallel larval echinoderm tests, using standard protocols and screen tube manipulation, in order to see if a physical influence from turbidity in the overlying test water continues to lead to failed bioassays.
- Stations: Collect samples at the same stations as the previous sampling events. Identify the predominant current direction in the vicinity of the outfall on all figures.

b. Sediment data report

Following Ecology approval of the Sediment Sampling and Analysis Plan, the Permittee must collect sediments between August 15th and September 15th. The Permittee must submit to Ecology a Sediment Data Report containing the results of the sediment sampling and analysis no later than December 1, 2018. The Permittee must submit two paper copies and an electronic copy (preferably as a PDF). The sediment data report must conform to the approved sediment sampling and analysis plan.

In addition to a Sediment Data Report, the sediment chemical and biological data must be submitted to Ecology's EIM database (http://www.ecy.wa.gov/eim/), and Ecology's MyEIM tools must be used to confirm the accuracy of the submitted data (http://www.ecy.wa.gov/eim/MyEIM.htm).

S13.B. Sediment sampling – CSO outfalls

The Permittee must model and/or collect sediment samples in the vicinities of controlled CSO outfalls: E. Pine Street Pump Station Emergency Overflow (011), Belvoir (012)/30th Ave NE Pump Station (049), Martin Luther King (013)/Henderson Pump Station (045), Matthews Park Pump Station Emergency Overflow (018), and Rainier Avenue Pump Station Emergency Overflow (033). A sediment sampling and analysis plan (SAP) must be submitted by December 1, 2016 in accordance with (a) below. Following Ecology approval of the sediment SAP, the Permittee must collect sediments according to the SAP. The Permittee must submit to Ecology a sediment data report, in accordance with (b) below, that contains the sediment sampling and analysis results no later than December 1, 2018.

In addition, the Permittee must model and/or sample sediments in accordance with their approved *2012 Post Construction Monitoring Plan* or any subsequent approved plan revisions. Post construction monitoring of sediments is required with the completion of CSO projects once the CSO has been deemed controlled unless sufficient recent data exists that shows there are no SMS exceedances. An exception is made if an area-wide cleanup project is planned with sediment sampling scheduled at cleanup project completion.

For each CSO outfall site that requires sediment monitoring, the Permittee must submit a sediment sampling and analysis plan and data report in accordance with the following.

a. *Sediment sampling and analysis plan*

The Permittee must submit to Ecology for review and approval a sediment sampling and analysis plan (SSAP) for sediment monitoring at least eight months prior to sediment testing. The Permittee must submit one paper copy and an electronic copy (preferably as a PDF). The purpose of the plan is to characterize sediment (the nature and extent of chemical contamination and biological toxicity) quality in the vicinity of the discharge locations. The SSAP must be consistent with the *CSO Sediment Quality Characterization Sampling and Analysis Plan* in Appendix H of the County's approved *Post-Construction Monitoring Plan.* The Permittee must list method detection limits in the plan.

b. *Sediment data report*

Following Ecology approval of the Sediment Sampling and Analysis Plan, the Permittee must collect sediments according to the plan. The Permittee must submit to Ecology a Sediment Data Report containing the results of the sediment sampling and analysis no later than ten months after the data was collected. The Permittee must submit two paper copies and an electronic copy (preferably as a PDF). The sediment data report must conform to the approved sediment sampling and analysis plan.

In addition to a Sediment Data Report, the sediment chemical and biological data must be submitted to Ecology's EIM database (http://www.ecy.wa.gov/eim/), and Ecology's MyEIM tools must be used to confirm the accuracy of the submitted data (http://www.ecy.wa.gov/eim/MyEIM.htm).

S13.C. Sediment quality summary at CSO outfalls

The Permittee must submit to Ecology an update to the *2009 Comprehensive Sediment Quality Summary Report* no later than December 1, 2018. The 2009 report summarizes sediment data collected at all CSO outfalls including CSO treatment plants. The purpose of this update is to keep CSO sediment monitoring history information consolidated to help King County and Ecology assess the potential for sediment impacts from CSO discharges.

This update report must provide any new site-specific information including quantity and quality of the discharges, receiving water characteristics, and new knowledge about sediment quality near the CSO outfalls. The report must also include a status of sediment cleanup sites and monitoring plans.

Data not previously submitted and not yet formatted and future data must be formatted in the EIM format.

S14. Outfall evaluation

The Permittee must inspect, once during the permit term, the submerged portions of the West Point WWTP and CSO treatment plant outfall lines and diffusers to document their integrity and continued function. If conditions allow for a photographic verification, the Permittee must include such verification in the reports. The Permittee must submit the inspection reports to Ecology with the NPDES Permit renewal application. The inspector must at minimum:

- Assess the physical condition of the outfall pipes, diffusers, and associated couplings.
- Determine the extent of sediment accumulation in the vicinity of the diffusers.
- Ensure diffuser ports are free of obstructions and are allowing uniform flow.
- Confirm physical location (latitude/longitude) and depth (at MLLW) of the diffuser sections of the outfalls.
- Assess physical condition of anchors used to secure the submarine lines.
- For the West Point WWTP, follow-up on the findings from the 2011 inspection by inspecting gaps and checking for leaks at station 30.

S15. Elliott West CSO treatment plant – copper reduction assessment

The Permittee must assess copper discharges from the Elliott West CSO treatment plant and submit a *Copper Reduction Assessment Report* to Ecology by November 1, 2018. As part of the assessment, the Permittee must:

1. Evaluate sample reliability/accuracy of copper measurements, including potential sample interferences, from the Elliott West facility.
2. Assess copper discharge patterns such as first flush or seasonal (wet season vs. dry season) impacts, land use patterns, etc.
3. Conduct a copper source inventory and provide a list of significant copper sources.
4. Provide a description of copper source control options.
5. Examine opportunities for outfall mixing enhancements.
6. Recommend a preferred strategy with corresponding schedule to address copper discharges from the Elliott West CSO treatment plant.

S16. Elliott West CSO treatment plant – settleable solids removal assessment

The Permittee must assess settleable solids discharges from the Elliott West CSO treatment plant and submit a *Settleable Solids Reduction Assessment Report* to Ecology by November 1, 2018. As part of the assessment, the Permittee must:

1. Assess settleable solids discharge patterns such as seasonal or first flush impacts, stormwater vs. domestic wastewater concentrations, etc.

2. Recommend a preferred strategy with corresponding schedule to address settleable solids discharges from the Elliott West CSO treatment plant in order to meet the annual average settleable solids limit.

S17. Application for permit renewal or facility modifications

The Permittee must submit an application for renewal of this permit one year prior to its expiration date, or by January 31, 2019. The Permittee must submit a paper copy and an electronic copy (preferably as a PDF).

The Permittee must also submit a new application or application supplement at least one hundred eighty (180) days prior to commencement of discharges, resulting from the activities listed below, which may result in permit violations. These activities include any facility expansions, production increases, or other planned changes, such as process modifications, in the permitted facility.

General Conditions

G1. Signatory requirements

1. All applications, reports, or information submitted to Ecology must be signed and certified.

   a. In the case of corporations, by a responsible corporate officer. For the purpose of this section, a responsible corporate officer means:

      - A president, secretary, treasurer, or vice-president of the corporation in charge of a principal business function, or any other person who performs similar policy or decision making functions for the corporation, or
      - The manager of one or more manufacturing, production, or operating facilities, provided, the manager is authorized to make management decisions which govern the operation of the regulated facility including having the explicit or implicit duty of making major capital investment recommendations, and initiating and directing other comprehensive measures to assure long-term environmental compliance with environmental laws and regulations; the manager can ensure that the necessary systems are established or actions taken to gather complete and accurate information for permit application requirements; and where authority to sign documents has been assigned or delegated to the manager in accordance with corporate procedures.

   b. In the case of a partnership, by a general partner.

   c. In the case of sole proprietorship, by the proprietor.

   d. In the case of a municipal, state, or other public facility, by either a principal executive officer or ranking elected official.

   Applications for permits for domestic wastewater facilities that are either owned or operated by, or under contract to, a public entity shall be submitted by the public entity.

2. All reports required by this permit and other information requested by Ecology must be signed by a person described above or by a duly authorized representative of that person. A person is a duly authorized representative only if:

   a. The authorization is made in writing by a person described above and submitted to Ecology.

   b. The authorization specifies either an individual or a position having responsibility for the overall operation of the regulated facility, such as the position of plant manager, superintendent, position of equivalent responsibility, or an individual or position having overall responsibility for environmental matters. (A duly authorized representative may thus be either a named individual or any individual occupying a named position.)

3. Changes to authorization. If an authorization under paragraph G1.2, above, is no longer accurate because a different individual or position has responsibility for the overall operation of the facility, a new authorization satisfying the requirements of

paragraph G1.2, above, must be submitted to Ecology prior to or together with any reports, information, or applications to be signed by an authorized representative.

4. Certification. Any person signing a document under this section must make the following certification:

   I certify under penalty of law, that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gathered and evaluated the information submitted. Based on my inquiry of the person or persons who manage the system or those persons directly responsible for gathering information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

G2. Right of inspection and entry

The Permittee must allow an authorized representative of Ecology, upon the presentation of credentials and such other documents as may be required by law:

1. To enter upon the premises where a discharge is located or where any records must be kept under the terms and conditions of this permit.
2. To have access to and copy, at reasonable times and at reasonable cost, any records required to be kept under the terms and conditions of this permit.
3. To inspect, at reasonable times, any facilities, equipment (including monitoring and control equipment), practices, methods, or operations regulated or required under this permit.
4. To sample or monitor, at reasonable times, any substances or parameters at any location for purposes of assuring permit compliance or as otherwise authorized by the Clean Water Act.

G3. Permit actions

This permit may be modified, revoked and reissued, or terminated either at the request of any interested person (including the Permittee) or upon Ecology's initiative. However, the permit may only be modified, revoked and reissued, or terminated for the reasons specified in 40 CFR 122.62, 40 CFR 122.64 or WAC 173-220-150 according to the procedures of 40 CFR 124.5.

1. The following are causes for terminating this permit during its term, or for denying a permit renewal application:
   a. Violation of any permit term or condition.
   b. Obtaining a permit by misrepresentation or failure to disclose all relevant facts.
   c. A material change in quantity or type of waste disposal.
   d. A determination that the permitted activity endangers human health or the environment, or contributes to water quality standards violations and can only be regulated to acceptable levels by permit modification or termination.

e. A change in any condition that requires either a temporary or permanent reduction, or elimination of any discharge or biosolids use or disposal practice controlled by the permit.

f. Nonpayment of fees assessed pursuant to RCW 90.48.465.

g. Failure or refusal of the Permittee to allow entry as required in RCW 90.48.090.

2. The following are causes for modification but not revocation and reissuance except when the Permittee requests or agrees:

   a. A material change in the condition of the waters of the state.

   b. New information not available at the time of permit issuance that would have justified the application of different permit conditions.

   c. Material and substantial alterations or additions to the permitted facility or activities which occurred after this permit issuance.

   d. Promulgation of new or amended standards or regulations having a direct bearing upon permit conditions, or requiring permit revision.

   e. The Permittee has requested a modification based on other rationale meeting the criteria of 40 CFR Part 122.62.

   f. Ecology has determined that good cause exists for modification of a compliance schedule, and the modification will not violate statutory deadlines.

   g. Incorporation of an approved local pretreatment program into a municipality's permit.

3. The following are causes for modification or alternatively revocation and reissuance:

   a. When cause exists for termination for reasons listed in 1.a through 1.g of this section, and Ecology determines that modification or revocation and reissuance is appropriate.

   b. When Ecology has received notification of a proposed transfer of the permit. A permit may also be modified to reflect a transfer after the effective date of an automatic transfer (General Condition G7) but will not be revoked and reissued after the effective date of the transfer except upon the request of the new Permittee.

G4. Reporting planned changes

The Permittee must, as soon as possible, but no later than one hundred eighty (180) days prior to the proposed changes, give notice to Ecology of planned physical alterations or additions to the permitted facility, production increases, or process modification which will result in:

1. The permitted facility being determined to be a new source pursuant to 40 CFR 122.29(b)

2. A significant change in the nature or an increase in quantity of pollutants discharged.

3. A significant change in the Permittee's biosolids use or disposal practices. Following such notice, and the submittal of a new application or supplement to the existing

application, along with required engineering plans and reports, this permit may be modified, or revoked and reissued pursuant to 40 CFR 122.62(a) to specify and limit any pollutants not previously limited. Until such modification is effective, any new or increased discharge in excess of permit limits or not specifically authorized by this permit constitutes a violation.

G5. Plan review required

Prior to constructing or modifying any wastewater control facilities, an engineering report and detailed plans and specifications must be submitted to Ecology for approval in accordance with chapter 173-240 WAC. Engineering reports, plans, and specifications must be submitted at least one hundred eighty (180) days prior to the planned start of construction unless a shorter time is approved by Ecology. Facilities must be constructed and operated in accordance with the approved plans.

G6. Compliance with other laws and statutes

Nothing in this permit excuses the Permittee from compliance with any applicable federal, state, or local statutes, ordinances, or regulations.

G7. Transfer of this permit

In the event of any change in control or ownership of facilities from which the authorized discharge emanate, the Permittee must notify the succeeding owner or controller of the existence of this permit by letter, a copy of which must be forwarded to Ecology.

1. Transfers by Modification

   Except as provided in paragraph (2) below, this permit may be transferred by the Permittee to a new owner or operator only if this permit has been modified or revoked and reissued under 40 CFR 122.62(b)(2), or a minor modification made under 40 CFR 122.63(d), to identify the new Permittee and incorporate such other requirements as may be necessary under the Clean Water Act.

2. Automatic Transfers

   This permit may be automatically transferred to a new Permittee if:

   a. The Permittee notifies Ecology at least thirty (30) days in advance of the proposed transfer date.

   b. The notice includes a written agreement between the existing and new Permittees containing a specific date transfer of permit responsibility, coverage, and liability between them.

   c. Ecology does not notify the existing Permittee and the proposed new Permittee of its intent to modify or revoke and reissue this permit. A modification under this subparagraph may also be minor modification under 40 CFR 122.63. If this notice is not received, the transfer is effective on the date specified in the written agreement.

G8. Reduced production for compliance

The Permittee, in order to maintain compliance with its permit, must control production and/or all discharges upon reduction, loss, failure, or bypass of the treatment facility until the facility is restored or an alternative method of treatment is provided. This requirement applies in the situation where, among other things, the primary source of power of the treatment facility is reduced, lost, or fails.

G9. Removed substances

Collected screenings, grit, solids, sludges, filter backwash, or other pollutants removed in the course of treatment or control of wastewaters must not be resuspended or reintroduced to the final effluent stream for discharge to state waters.

G10. Duty to provide information

The Permittee must submit to Ecology, within a reasonable time, all information which Ecology may request to determine whether cause exists for modifying, revoking and reissuing, or terminating this permit or to determine compliance with this permit. The Permittee must also submit to Ecology upon request, copies of records required to be kept by this permit.

G11. Other requirements of 40 CFR

All other requirements of 40 CFR 122.41 and 122.42 are incorporated in this permit by reference.

G12. Additional monitoring

Ecology may establish specific monitoring requirements in addition to those contained in this permit by administrative order or permit modification.

G13. Payment of fees

The Permittee must submit payment of fees associated with this permit as assessed by Ecology.

G14. Penalties for violating permit conditions

Any person who is found guilty of willfully violating the terms and conditions of this permit is deemed guilty of a crime, and upon conviction thereof shall be punished by a fine of up to ten thousand dollars ($10,000) and costs of prosecution, or by imprisonment in the discretion of the court. Each day upon which a willful violation occurs may be deemed a separate and additional violation.

Any person who violates the terms and conditions of a waste discharge permit may incur, in addition to any other penalty as provided by law, a civil penalty in the amount of up to ten thousand dollars ($10,000) for every such violation. Each and every such violation is a separate and distinct offense, and in case of a continuing violation, every day's continuance is deemed to be a separate and distinct violation.

G15. Upset

Definition – "Upset" means an exceptional incident in which there is unintentional and temporary non-compliance with technology-based permit effluent limits because of factors beyond the reasonable control of the Permittee. An upset does not include non-compliance to the extent caused by operational error, improperly designed treatment facilities, inadequate treatment facilities, lack of preventive maintenance, or careless or improper operation.

An upset constitutes an affirmative defense to an action brought for non-compliance with such technology-based permit effluent limits if the requirements of the following paragraph are met.

A Permittee who wishes to establish the affirmative defense of upset must demonstrate, through properly signed, contemporaneous operating logs, or other relevant evidence that:

1. An upset occurred and that the Permittee can identify the cause(s) of the upset.
2. The permitted facility was being properly operated at the time of the upset.
3. The Permittee submitted notice of the upset as required in Special Condition S3.F.
4. The Permittee complied with any remedial measures required under S3.F of this permit.

In any enforcement action the Permittee seeking to establish the occurrence of an upset has the burden of proof.

G16. Property rights

This permit does not convey any property rights of any sort, or any exclusive privilege.

G17. Duty to comply

The Permittee must comply with all conditions of this permit. Any permit non-compliance constitutes a violation of the Clean Water Act and is grounds for enforcement action; for permit termination, revocation and reissuance, or modification; or denial of a permit renewal application.

G18. Toxic pollutants

The Permittee must comply with effluent standards or prohibitions established under Section 307(a) of the Clean Water Act for toxic pollutants within the time provided in the regulations that establish those standards or prohibitions, even if this permit has not yet been modified to incorporate the requirement.

G19. Penalties for tampering

The Clean Water Act provides that any person who falsifies, tampers with, or knowingly renders inaccurate any monitoring device or method required to be maintained under this permit shall, upon conviction, be punished by a fine of not more than $10,000 per violation, or by imprisonment for not more than two (2) years per violation, or by both. If a conviction of a person is for a violation committed after a first conviction of such person under this condition, punishment shall be a fine of not more than $20,000 per day of violation, or by imprisonment of not more than four (4) years, or by both.

G20. Compliance schedules

Reports of compliance or non-compliance with, or any progress reports on, interim and final requirements contained in any compliance schedule of this permit must be submitted no later than fourteen (14) days following each schedule date.

G21. Service agreement review

The Permittee must submit to Ecology any proposed service agreements and proposed revisions or updates to existing agreements for the operation of any wastewater treatment facility covered by this permit. The review is to ensure consistency with chapters 90.46 and 90.48 RCW as required by RCW 70.150.040(9). In the event that Ecology does not comment within a thirty-day (30) period, the Permittee may assume consistency and proceed with the service agreement or the revised/updated service agreement.

Appendix A

LIST OF POLLUTANTS WITH ANALYTICAL METHODS, DETECTION LIMITS AND QUANTITATION LEVELS

The Permittee must use the specified analytical methods, detection limits (DLs) and quantitation levels (QLs) in the following table for permit and application required monitoring unless:

- Another permit condition specifies other methods, detection levels, or quantitation levels.
- The method used produces measurable results in the sample and EPA has listed it as an EPA-approved method in 40 CFR Part 136, or EPA has granted the laboratory written permission to use the method.
- The Permittee knows that an alternate, less sensitive method (higher DL and QL) from those listed below is sufficient to produce measurable results in their effluent.
- If the Permittee is unable to obtain the required DL and QL due to matrix effects (such as for treatment plant influent or CSO effluent), the Permittee must strive to achieve to lowest possible DL and QL and report the DL and QL in the required report.

If the Permittee uses an alternative method, not specified in the permit and as allowed above, it must report the test method, DL, and QL on the discharge monitoring report or in the required report.

All pollutants that have numeric limits in Section S1 of this permit must be analyzed with the methods specified below. When the permit requires the Permittee to measure the base neutral compounds in the list of priority pollutants, it must measure all of the base neutral pollutants listed in the table below. The list includes EPA required base neutral priority pollutants and several additional polynuclear aromatic hydrocarbons (PAHs). The Water Quality Program added several PAHs to the list of base neutrals below from Ecology's Persistent Bioaccumulative Toxics (PBT) List. It only added those PBT parameters of interest to Appendix A that did not increase the overall cost of analysis unreasonably.

Ecology added this appendix to the permit in order to reduce the number of analytical "non-detects" in permit-required monitoring and to measure effluent concentrations near or below criteria values where possible at a reasonable cost.

CONVENTIONAL PARAMETERS

Pollutant & CAS No. *(if available)*	**Recommended Analytical Protocol**	**Detection (DL)[1] *µg/L unless specified***	**Quantitation Level (QL)[2] *µg/L unless specified***
Biochemical Oxygen Demand	SM5210-B		2 mg/L
Total Suspended Solids	SM2540-D		5 mg/L
Total Ammonia (as N)	SM4500-NH3-B and C/D/E/G/H Kerouel & Aminot 1997		0.3 mg/L
Dissolved oxygen	SM4500-OC/OG		0.2 mg/L
Temperature (max. 7-day avg.)	Analog recorder or use micro-recording devices known as thermistors		0.2º C
pH	SM4500-H^+ B	N/A	N/A

NONCONVENTIONAL PARAMETERS

Pollutant & CAS No. (if available)	**Recommended Analytical Protocol**	**Detection (DL)[1] µg/L unless specified**	**Quantitation Level (QL)[2] µg/L unless specified**
Total Alkalinity	SM2320-B		1.3 mg/L as CaCO3
Chlorine, Total Residual	SM4500 Cl G 4500 Cl D/E, Hach 8370		50.0
Fecal Coliform	SM 9221E,9222	N/A	Specified in method - sample aliquot dependent
Nitrate + Nitrite Nitrogen (as N)	SM4500-NO3- E/F/H		200
Nitrogen, Total Kjeldahl (as N)	SM4500-N_{org}B/C and SM4500NH_3-B/C/D/EF/G/H EPA 351.2		500

Exhibit C

Pollutant & CAS No. (if available)	Recommended Analytical Protocol	Detection (DL)[1] µg/L unless specified	Quantitation Level (QL)[2] µg/L unless specified
Nitrogen, Total (as N)	SM4500-N-C	50	100
Soluble Reactive Phosphorus (as P)	SM4500- PE/PF	100	100
Phosphorus, Total (as P)	SM 4500 PB followed by SM4500-PE/PF	100	300
Oil and Grease (HEM)	1664 A or B	1,400	5,000
Salinity	SM2520-B		3 practical salinity units or scale (PSU or PSS)
Settleable Solids	SM2540 -F		Sample and limit dependent
Sulfate (as mg/L SO_4)	SM4110-B, 4500-SO4 E		7.1 mg/L
Sulfide (as mg/L S)	SM4500-S^2F/D/E/G		200
Sulfite (as mg/L SO_3)	SM4500-SO3B		2000
Total dissolved solids	SM2540 C		20 mg/L
Total Hardness	SM2340B C, 200.7, 200.8		200 as $CaCO_3$
Aluminum, Total (7429-90-5)	200.8	2.0	10
Barium Total (7440-39-3)	200.8	0.5	2.0
BTEX (benzene +toluene + ethylbenzene + m,o,p xylenes)	EPA SW 846 8021/8260	1	2
Boron Total (7440-42-8)	200.8	2.0	10.0
Cobalt, Total (7440-48-4)	200.8	0.05	0.25
Iron, Total (7439-89-6)	200.7, 200.8	12.5	50
Magnesium, Total (7439-95-4)	200.7, 200.8	10	50
Molybdenum, Total (7439-98-7)	200.8	0.1	0.5
Manganese, Total (7439-96-5)	200.8	0.1	0.5
NWTPH Dx [4]	Ecology NWTPH Dx	250	250
NWTPH Gx [5]	Ecology NWTPH Gx	250	250
Tin, Total (7440-31-5)	200.8	0.3	1.5
Titanium, Total (7440-32-6)	200.8	0.5	2.5

METALS, CYANIDE & TOTAL PHENOLS			
Antimony, Total (7440-36-0)	200.8	0.3	1.0
Arsenic, Total (7440-38-2)	200.8	0.1	0.5
Beryllium, Total (7440-41-7)	200.8	0.1	0.5
Cadmium, Total (7440-43-9)	200.8	0.05	0.25
Chromium (hex) dissolved (18540-29-9)	SM3500-Cr B	5	10
Chromium, Total (7440-47-3)	200.8	0.2	1.0
Copper, Total (7440-50-8)	200.8	0.4	2.0
Lead, Total (7439-92-1)	200.8	0.1	0.5
Mercury, Total (7439-97-6)	1631E	0.0002	0.0005
Nickel, Total (7440-02-0)	200.8	0.1	0.5
Selenium, Total (7782-49-2)	200.8	1.0	1.0
Silver, Total (7440-22-4)	200.8	0.04	0.2
Thallium, Total (7440-28-0)	200.8	0.09	0.36
Zinc, Total (7440-66-6)	200.8	0.5	2.5
Cyanide, Total (57-12-5)	335.4, SM4500-CN-C,E	5	10
Cyanide, Weak Acid Dissociable	SM4500-CN I	5	10
Cyanide, Free Amenable to Chlorination (Available Cyanide)	SM4500-CN G	5	10
Phenols, Total	EPA 420.1		50
ACID COMPOUNDS			
2-Chlorophenol (95-57-8)	625	1.0	2.0
2,4-Dichlorophenol (120-83-2)	625	0.5	1.0

2,4-Dimethylphenol (105-67-9)	625	0.5	1.0
4,6-dinitro-o-cresol (534-52-1) (2-methyl-4,6,-dinitrophenol)	625/1625B	2.0	4.0
2,4 dinitrophenol (51-28-5)	625	1.5	3.0
2-Nitrophenol (88-75-5)	625	0.5	1.0
4-nitrophenol (100-02-7)	625	1.0	2.0
Parachlorometa cresol (59-50-7) (4-chloro-3-methylphenol)	625	1.0	2.0
Pentachlorophenol (87-86-5)	625	0.5	1.0
Phenol (108-95-2)	625	2.0	4.0
2,4,6-Trichlorophenol (88-06-2)	625	2.0	4.0
VOLATILE COMPOUNDS			
Acrolein (107-02-8)	624	5	10
Acrylonitrile (107-13-1)	624	1.0	2.0
Benzene (71-43-2)	624	1.0	2.0
Bromoform (75-25-2)	624	1.0	2.0
Carbon tetrachloride (56-23-5)	624/601 or SM6230B	1.0	2.0
Chlorobenzene (108-90-7)	624	1.0	2.0
Chloroethane (75-00-3)	624/601	1.0	2.0
2-Chloroethylvinyl Ether (110-75-8)	624	1.0	2.0
Chloroform (67-66-3)	624 or SM6210B	1.0	2.0
Dibromochloromethane (124-48-1)	624	1.0	2.0
1,2-Dichlorobenzene (95-50-1)	624	1.9	7.6
1,3-Dichlorobenzene (541-73-1)	624	1.9	7.6
1,4-Dichlorobenzene (106-46-7)	624	4.4	17.6
Dichlorobromomethane (75-27-4)	624	1.0	2.0
1,1-Dichloroethane (75-34-3)	624	1.0	2.0
1,2-Dichloroethane (107-06-2)	624	1.0	2.0
1,1-Dichloroethylene (75-35-4)	624	1.0	2.0
1,2-Dichloropropane (78-87-5)	624	1.0	2.0
1,3-dichloropropene (mixed isomers) (1,2-dichloropropylene) (542-75-6) [6]	624	1.0	2.0
Ethylbenzene (100-41-4)	624	1.0	2.0
Methyl bromide (74-83-9) (Bromomethane)	624/601	5.0	10.0
Methyl chloride (74-87-3) (Chloromethane)	624	1.0	2.0
Methylene chloride (75-09-2)	624	5.0	10.0
1,1,2,2-Tetrachloroethane (79-34-5)	624	1.9	2.0
Tetrachloroethylene (127-18-4)	624	1.0	2.0
Toluene (108-88-3)	624	1.0	2.0
1,2-Trans-Dichloroethylene (156-60-5) (Ethylene dichloride)	624	1.0	2.0
1,1,1-Trichloroethane (71-55-6)	624	1.0	2.0
1,1,2-Trichloroethane (79-00-5)	624	1.0	2.0
Trichloroethylene (79-01-6)	624	1.0	2.0
Vinyl chloride (75-01-4)	624/SM6200B	1.0	2.0
BASE/NEUTRAL COMPOUNDS (compounds in bold are Ecology PBTs)			
Acenaphthene (83-32-9)	625	0.2	0.4
Acenaphthylene (208-96-8)	625	0.3	0.6
Anthracene (120-12-7)	625	0.3	0.6
Benzidine (92-87-5)	625	20	40
Benzyl butyl phthalate (85-68-7)	625	0.3	0.6
Benzo(*a*)anthracene (56-55-3)	625	0.3	0.6
Benzo(b)fluoranthene (3,4-benzofluoranthene) (205-99-2) [7]	610/625	0.8	1.6
Benzo(j)fluoranthene (205-82-3) [7]	625	0.5	1.0
Benzo(k)fluoranthene (11,12-benzofluoranthene) (207-08-9) [7]	610/625	0.8	1.6
Benzo(r,s,t)pentaphene (189-55-9)	625	1.3	5.0
Benzo(*a*)pyrene (50-32-8)	610/625	0.5	1.0

Benzo(*ghi*)Perylene (191-24-2)	610/625	0.5	1.0
Bis(*2-chloroethoxy)*methane (111-91-1)	625	5.3	21.2
Bis(*2-chloroethyl*)ether (111-44-4)	611/625	0.3	1.0
Bis(*2-chloroisopropyl*)ether (39638-32-9)	625	0.5	1.0
Bis(*2-ethylhexyl*)phthalate (117-81-7)	625	0.3	1.0
4-Bromophenyl phenyl ether (101-55-3)	625	0.3	0.5
2-Chloronaphthalene (91-58-7)	625	0.3	0.6
4-Chlorophenyl phenyl ether (7005-72-3)	625	0.3	0.5
Chrysene (218-01-9)	610/625	0.3	0.6
Dibenzo (a,h)acridine (226-36-8)	610M/625M	2.5	10.0
Dibenzo (a,j)acridine (224-42-0)	610M/625M	2.5	10.0
Dibenzo(a-*h*)anthracene (53-70-3)(1,2,5,6-dibenzanthracene)	625	0.8	1.6
Dibenzo(a,e)pyrene (192-65-4)	610M/625M	2.5	10.0
Dibenzo(a,h)pyrene (189-64-0)	625M	2.5	10.0
3,3-Dichlorobenzidine (91-94-1)	605/625	2.0	4.0
Diethyl phthalate (84-66-2)	625	1.9	7.6
Dimethyl phthalate (131-11-3)	625	1.6	6.4
Di-n-butyl phthalate (84-74-2)	625	0.5	1.0
2,4-dinitrotoluene (121-14-2)	609/625	1.0	2.0
2,6-dinitrotoluene (606-20-2)	609/625	1.0	2.0
Di-n-octyl phthalate (117-84-0)	625	0.3	0.6
1,2-Diphenylhydrazine (*as Azobenzene*)(122-66-7)	1625B, 625	5.0	20
Fluoranthene (206-44-0)	625	0.3	0.6
Fluorene (86-73-7)	625	0.3	0.6
Hexachlorobenzene (118-74-1)	612/625	0.3	0.6
Hexachlorobutadiene (87-68-3)	625	0.5	1.0
Hexachlorocyclopentadiene (77-47-4)	1625B/625	2.0	4.0
Hexachloroethane (67-72-1)	625	0.5	1.0
Indeno(*1,2,3-cd*)Pyrene (193-39-5)	610/625	0.5	1.0
Isophorone (78-59-1)	625	0.5	1.0
3-Methyl cholanthrene (56-49-5)	625	2.0	8.0
Naphthalene (91-20-3)	625	0.4	0.75
Nitrobenzene (98-95-3)	625	0.5	1.0
N-Nitrosodimethylamine (62-75-9)	607/625	2.0	4.0
N-Nitrosodi-n-propylamine (621-64-7)	607/625	0.5	1.0
N-Nitrosodiphenylamine (86-30-6)	625	1.0	2.0
Perylene (198-55-0)	625	1.9	7.6
Phenanthrene (85-01-8)	625	0.3	0.6
Pyrene (129-00-0)	625	0.3	0.6
1,2,4-Trichlorobenzene (120-82-1)	625	0.3	0.6
DIOXIN			
2,3,7,8-Tetra-Chlorodibenzo-P-Dioxin (176-40-16) (2,3,7,8 TCDD)	1613B	1.3 pg/L	5 pg/L

1. Detection level (DL) or detection limit means the minimum concentration of an analyte (substance) that can be measured and reported with a 99% confidence that the analyte concentration is greater than zero as determined by the procedure given in 40 CFR part 136, Appendix B.
2. Quantitation Level (QL) also known as Minimum Level of Quantitation (ML) – The smallest detectable concentration of analyte greater than the Detection Limit (DL) where the accuracy (precision & bias) achieves the objectives of the intended purpose. (Report of the Federal Advisory Committee on Detection and Quantitation Approaches and Uses in Clean Water Act Programs Submitted to the US Environmental Protection Agency, December 2007).
3. Soluble Biochemical Oxygen Demand method note: First, filter the sample through a Millipore Nylon filter (or equivalent) - pore size of 0.45-0.50 um (prep all filters by filtering 250 ml of laboratory grade deionized water through the filter and discard). Then, analyze sample as per method 5210-B.
4. NWTPH Dx - Northwest Total Petroleum Hydrocarbons Diesel Extended Range – see http://www.ecy.wa.gov/biblio/97602.html
5. NWTPH Gx - Northwest Total Petroleum Hydrocarbons Gasoline Extended Range – see http://www.ecy.wa.gov/biblio/97602.html
6. 1, 3-dichloroproylene (mixed isomers) - You may report this parameter as two separate parameters: cis-1, 3-dichlorpropropene (10061-01-5) and trans-1, 3-dichloropropene (10061-02-6).
7. Total Benzofluoranthenes - Because Benzo(b)fluoranthene, Benzo(j)fluoranthene and Benzo(k)fluoranthene co-elute you may report these three isomers as total benzofluoranthenes.

EXHIBIT D

Issuance Date: January 16, 2017
Effective Date: March 1, 2017
Expiration Date: February 28, 2022

National Pollutant Discharge Elimination System Waste Discharge Permit No. WA0022527

State of Washington
DEPARTMENT OF ECOLOGY
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

In compliance with the provisions of
The State of Washington Water Pollution Control Law
Chapter 90.48 Revised Code of Washington
and
The Federal Water Pollution Control Act
(The Clean Water Act)
Title 33 United States Code, Section 1342 et seq.

Vashon Wastewater Treatment Plant
King County Department of Natural Resources & Parks
Wastewater Treatment Division
201 S. Jackson St.
Seattle, WA 98104-3855

is authorized to discharge in accordance with the Special and General Conditions that follow.

Plant Location:	Receiving Water:
9621 SW 171 Street Vashon, WA 98070	Puget Sound
Treatment Type: Oxidation Ditch	

Mark Henley, P.E.
Water Quality Section Manager
Northwest Regional Office
Washington State Department of Ecology

Exhibit D

Table of Contents

Summary of Permit Report Submittals

Refer to the Special and General Conditions of this permit for additional submittal requirements.

Permit Section	Submittal	Frequency	First Submittal Date
S3.A	Discharge Monitoring Report (DMR)	Monthly	April 15, 2017
S3.A	Discharge Monitoring Report (DMR)	Quarterly	July 15, 2017
S3.F	Reporting Permit Violations	As necessary	
S4.B	Plans for Maintaining Adequate Capacity	As necessary	
S4.D	Notification of New or Altered Sources	As necessary	
S5.F	Bypass Notification	As necessary	
S6.A.3	Pretreatment Report	1/year	April 30, 2017
S8	Acute Toxicity Effluent Test Results with Permit Renewal Application	2/permit cycle July 2019 January 2020	July 31, 2021
S9	Chronic Toxicity Effluent Test Results with Permit Renewal Application	2/permit cycle October 2019 March 2020	July 31, 2021
S10	Application for Permit Renewal	1/permit cycle	July 31, 2021
G1	Notice of Change in Authorization	As necessary	
G4	Reporting Planned Changes	As necessary	
G5	Engineering Report for Construction or Modification Activities	As necessary	
G7	Notice of Permit Transfer	As necessary	
G10	Duty to Provide Information	As necessary	
G20	Compliance Schedules	As necessary	
G21	Contract Submittal	As necessary	

Special Conditions

S1. Discharge limits

S1.A. Effluent limits

All discharges and activities authorized by this permit must comply with the terms and conditions of this permit. The discharge of any of the following pollutants more frequently than, or at a level in excess of, that identified and authorized by this permit violates the terms and conditions of this permit.

Beginning on the effective date of this permit, the Permittee may discharge treated domestic wastewater to the Puget Sound at the permitted location subject to compliance with the following limits:

Effluent Limits: Outfall 001 Latitude: 47.452917 Longitude: -122.433333		
Parameter	**Average Monthly** [a]	**Average Weekly** [b]
Biochemical Oxygen Demand (5-day) (BOD_5)	30 milligrams/liter (mg/L) 130 pounds/day (lbs/day) 85% removal of influent BOD_5	45 mg/L 195 lbs/day
Total Suspended Solids (TSS)	30 mg/L 130 lbs/day 85% removal of influent TSS	45 mg/L 195 lbs/day
Parameter	**Minimum**	**Maximum**
pH	6.0 standard units	9.0 standard units
Parameter	**Monthly Geometric Mean**	**Weekly Geometric Mean**
Fecal Coliform Bacteria [c]	200/100 milliliter (mL)	400/100 mL
Parameter	**Maximum Daily** [d]	
Total Residual Chlorine [f]	0.75 mg/L	

a	Average monthly effluent limit means the highest allowable average of daily discharges over a calendar month. To calculate the discharge value to compare to the limit, you add the value of each daily discharge measured during a calendar month and divide this sum by the total number of daily discharges measured. See footnote c for fecal coliform calculations.
b	Average weekly discharge limit means the highest allowable average of daily discharges over a calendar week, calculated as the sum of all daily discharges measured during a calendar week divided by the number of daily discharges' measured during that week. See footnote c for fecal coliform calculations.
c	Ecology provides directions to calculate the monthly and the weekly geometric mean in publication No. 04-10-020, Information Manual for Treatment Plant Operators available at: http://www.ecy.wa.gov/pubs/0410020.pdf
d	Maximum daily effluent limit is the highest allowable daily discharge. The daily discharge is the average discharge of a pollutant measured during a calendar day. For pollutants with limits expressed in units of mass, calculate the daily discharge as the total mass of the pollutant discharged over the day. This does not apply to pH or temperature.
f	Chlorine limits apply only during periods when chlorine is used for partial or full disinfection of the effluent. When UV disinfection is the only disinfection method used, chlorine limits do not apply. When not using chlorine for disinfection during the monitoring period, enter qualifier code “M” into the WQWebDMR form.

S1.B. Mixing zone authorization

Mixing zone for Outfall 001

The following paragraphs define the maximum boundaries of the mixing zones:

Chronic mixing zone

The mixing zone is a circular region with radius of 400 feet measured from the center of the discharge port. The mixing zone extends from the bottom to the top of the water column. The concentration of pollutants at the edge of the chronic zone must meet chronic aquatic life criteria and human health criteria.

Acute mixing zone

The acute mixing zone is a circular region with radius of 40 feet measured from the center of the discharge port. The mixing zone extends from the bottom to the top of the water column. The concentration of pollutants at the edge of the acute zone must meet acute aquatic life criteria.

Available Dilution (dilution factor)	
Acute Aquatic Life Criteria	89
Chronic Aquatic Life Criteria	681
Human Health Criteria - Carcinogen	681
Human Health Criteria - Non-carcinogen	681

S2. Monitoring requirements

S2.A. Monitoring schedule

The Permittee must monitor in accordance with the following schedule and the requirements specified in Appendix A.

Parameter	Units & Speciation	Minimum Sampling Frequency	Sample Type
(1) Wastewater influent			
Wastewater Influent means the raw sewage flow from the collection system into the treatment facility. Sample the wastewater entering the headworks of the treatment plant excluding any side-stream returns from inside the plant.			
Flow	gpd	Continuous [a]	Metered/Recorded
BOD_5	mg/L	2/week [c]	24-hr Composite [b]
BOD_5	lbs/day	2/week	Calculation [d]
TSS	mg/L	2/week	24-hr Composite
TSS	lbs/day	2/week	Calculation [d]
(2) Final wastewater effluent			
Final Wastewater Effluent means wastewater exiting the last treatment process or operation. Typically, this is after or at the exit from the chlorine contact chamber or other disinfection process. The Permittee may take effluent samples for the BOD_5 analysis before or after the disinfection process. If taken after, the Permittee must dechlorinate and reseed the sample.			
BOD_5 [g]	mg/L	2/week	24-hr Composite
BOD_5	lbs/day	2/week	Calculation [d]
BOD_5	% removal	1/month	Calculation [e]
TSS	mg/L	2/week	24-hr Composite

Parameter	Units & Speciation	Minimum Sampling Frequency	Sample Type
TSS	lbs/day	2/week	Calculation
TSS	% removal	1/month	Calculation
Chlorine (Total Residual) [h]	mg/L	Daily, when used for disinfection	Grab [f]
Fecal Coliform [i]	CFUs /100 ml	2/week	Grab
pH [j]	Standard Units	Continuous	Metered/Recorded
(3) Effluent characterization – final wastewater effluent			
Acute Toxicity Testing	--	2/permit cycle	24-hr Composite
Chronic Toxicity Testing	--	2/permit cycle	24-hr Composite
Additional requirements specified in Permit Conditions S8 & S9.			
(4) Effluent characterization – final wastewater effluent			
Total Ammonia	mg/L as N	Quarterly [k]	24-hr Composite
Nitrate plus Nitrite Nitrogen	mg/L as N	Quarterly	24-hr Composite
Total Kjeldahl Nitrogen (TKN)	mg/L as N	Quarterly	24-hr Composite
(5) Permit renewal application requirements – final wastewater effluent			
The Permittee must record and report the wastewater treatment plant flow discharged on the day it collects the sample for priority pollutant testing with the discharge monitoring report.			
Temperature [l]	Degrees Celsius	Quarterly during 2020	Measurement
Dissolved Oxygen	mg/L	Quarterly during 2020	Grab
Oil and Grease	mg/L	Quarterly during 2020	Grab
Total Dissolved Solids	mg/L	Quarterly during 2020	24-hr Composite
Total Hardness	mg/L	Quarterly during 2020	24-hr Composite
Cyanide	micrograms/liter (µg/L)	Quarterly during 2020	Grab
Total Phosphorus	mg/L	Quarterly during 2020	24-hr Composite
Priority Pollutants (PP) – Total Metals	µg/L; nanograms(ng/L) for mercury	Quarterly during 2020	24-hr Composite Grab for mercury

a	Continuous means uninterrupted except for brief lengths of time for calibration, power failure, or unanticipated equipment repair or maintenance. The time interval for the associated data logger must be no greater than 30 minutes. The Permittee must sample every 4 hours when continuous monitoring is not possible.
b	24-hour composite means a series of individual samples collected over a 24-hour period into a single container, and analyzed as one sample.
c	2/week means two (2) times during each calendar week.
d	Calculated means figured concurrently with the respective sample, using the following formula: Concentration (in mg/L) X Flow (in MGD) X Conversion Factor (8.34) = lbs/day
e	% removal = $\frac{\text{Influent concentration (mg/L)} - \text{Effluent concentration (mg/L)}}{\text{Influent concentration (mg/L)}} \times 100$ Calculate the percent (%) removal of BOD_5 and TSS using the above equation.
f	Grab means an individual sample collected over a fifteen (15) minute, or less, period.
g	Take effluent samples for the BOD_5 analysis before or after the disinfection process. If taken after, and if sampling occurs during a period when chlorine is being used for disinfection, dechlorinate and reseed the sample.
h	Chlorine limits apply only during emergency periods when UV disinfection is not available and the Permittee uses chlorine to disinfect effluent. During normal operations with UV disinfection, chlorine limits do not apply. When not using chlorine during the monitoring period, enter qualifier code “M” into the WQWebDMR form to indicate that for chlorine was conditional and not required for the monitoring period.

Parameter		Units & Speciation	Minimum Sampling Frequency	Sample Type
i	Report a numerical value for fecal coliforms following the procedures in Ecology's *Information Manual for Wastewater Treatment Plant Operators*, Publication Number 04-10-020 available at: http://www.ecy.wa.gov/programs/wq/permits/guidance.html . Do not report a result as too numerous to count (TNTC).			
j	The Permittee must report the instantaneous maximum and minimum pH daily. Do not average pH values.			
k	Quarterly sampling periods are January through March, April through June, July through September, and October through December. See condition S3.A.10.b for additional details.			
l	Temperature grab sampling must occur when the effluent is at or near its daily maximum temperature, which usually occurs in the late afternoon.			

S2.B. Sampling and analytical procedures

Samples and measurements taken to meet the requirements of this permit must represent the volume and nature of the monitored parameters. The Permittee must conduct representative sampling of any unusual discharge or discharge condition, including bypasses, upsets, and maintenance-related conditions that may affect effluent quality.

Sampling and analytical methods used to meet the monitoring requirements specified in this permit must conform to the latest revision of the *Guidelines Establishing Test Procedures for the Analysis of Pollutants* contained in 40 CFR Part 136 (or as applicable in 40 CFR subchapters N [Parts 400–471] or O [Parts 501-503]) unless otherwise specified in this permit . Ecology may only specify alternative methods for parameters without permit limits and for those parameters without an EPA approved test method in 40 CFR Part 136.

S2.C. Flow measurement and continuous monitoring devices

The Permittee must:

1. Select and use appropriate flow measurement and continuous monitoring devices and methods consistent with accepted scientific practices.
2. Install, calibrate, and maintain these devices to ensure the accuracy of the measurements is consistent with the accepted industry standard, the manufacturer's recommendation, and approved O&M manual procedures for the device and the wastestream.
3. Calibrate continuous monitoring instruments weekly unless it can demonstrate a longer period is sufficient based on monitoring records. The Permittee:
   a. May calibrate apparatus for continuous monitoring of dissolved oxygen by air calibration.
   b. Must calibrate continuous pH measurement instruments using a grab sample analyzed in the lab with a pH meter calibrated with standard buffers and analyzed within 15 minutes of sampling.

4. Calibrate flow-monitoring devices at a minimum frequency of at least one calibration per year or according to manufacturer's recommendation for that type of device.
5. Maintain calibration records for at least three years.

S2.D. Laboratory accreditation

The Permittee must ensure that all monitoring data required by Ecology for permit specified parameters is prepared by a laboratory registered or accredited under the provisions of chapter 173-50 WAC, *Accreditation of Environmental Laboratories*. Flow, temperature, settleable solids, conductivity, pH, and internal process control parameters are exempt from this requirement. The Permittee must obtain accreditation for conductivity and pH if it must receive accreditation or registration for other parameters.

S2.E. Request for reduction in monitoring

The Permittee may request a reduction of the sampling frequency after twelve (12) months of monitoring. Ecology will review each request and at its discretion grant the request when it reissues the permit or by a permit modification.

The Permittee must:

1. Provide a written request.
2. Clearly state the parameters for which it is requesting reduced monitoring.
3. Clearly state the justification for the reduction.

S3. Reporting and recording requirements

The Permittee must monitor and report in accordance with the following conditions. Falsification of information submitted to Ecology is a violation of the terms and conditions of this permit.

S3.A. Discharge monitoring reports

The first monitoring period begins on the effective date of the permit (unless otherwise specified). The Permittee must:

1. Summarize, report, and submit monitoring data obtained during each monitoring period on the electronic discharge monitoring report (DMR) form provided by Ecology within the Water Quality Permitting Portal. Include data for each of the parameters tabulated in Special Condition S2 and as required by the form. Report a value for each day sampling occurred (unless specifically exempted in the permit) and for the summary values (when applicable) included on the electronic form.
2. Enter the "No Discharge" reporting code for an entire DMR, for a specific monitoring point, or for a specific parameter as appropriate, if the Permittee did not discharge wastewater or a specific pollutant during a given monitoring period.

3. Report single analytical values below detection as "less than the detection level (DL)" by entering < followed by the numeric value of the detection level (e.g. < 2.0) on the DMR. If the method used did not meet the minimum DL and quantitation level (QL) identified in the permit, report the actual QL and DL in the comments or in the location provided.

4. **Not** report zero for bacteria monitoring. Report as required by the laboratory method.

5. Calculate and report an arithmetic average value for each day for bacteria if multiple samples were taken in one day.

6. Calculate the geometric mean values for bacteria (unless otherwise specified in the permit) using:

   a. The reported numeric value for all bacteria samples measured above the detection value except when it took multiple samples in one day. If the Permittee takes multiple samples in one day it must use the arithmetic average for the day in the geometric mean calculation.

   b. The detection value for those samples measured below detection.

7. Report the test method used for analysis in the comments if the laboratory used an alternative method not specified in the permit and as allowed in Appendix A.

8. Calculate average values and calculated total values (unless otherwise specified in the permit) using:

   a. The reported numeric value for all parameters measured between the agency-required detection value and the agency-required quantitation value.

   b. One-half the detection value (for values reported below detection) if the lab detected the parameter in another sample from the same monitoring point for the reporting period.

   c. Zero (for values reported below detection) if the lab did not detect the parameter in another sample for the reporting period.

9. Report single-sample grouped parameters (for example: priority pollutants) on the WQWebDMR form and include: sample date, concentration detected, detection limit (DL) (as necessary), and laboratory quantitation level (QL) (as necessary).

   The Permittee must also submit an electronic copy of the laboratory report as an attachment using WQWebDMR. The contract laboratory reports must also include information on the chain of custody, QA/QC results, and documentation of accreditation for the parameter.

10. Ensure that DMRs are electronically submitted no later than the dates specified below, unless otherwise specified in this permit.

11. Submit DMRs for parameters with the monitoring frequencies specified in S2 (monthly, quarterly, annual, etc.) at the reporting schedule identified below.

The Permittee must:

a. Submit **monthly** DMRs by the 15th day of the following month.

b. Submit **quarterly DMRs**, unless otherwise specified in the permit, by the 15th day of the month following the monitoring period. Quarterly sampling periods are January through March, April through June, July through September, and October through December. The Permittee must submit the first quarterly DMR on July 15, 2017 for the quarter beginning on April 1, 2017.

S3.B. Permit submittals and schedules

The Permittee must use the Water Quality Permitting Portal – Permit Submittals application (unless otherwise specified in the permit) to submit all other written permit-required reports by the date specified in the permit.

When another permit condition requires submittal of a paper (hard-copy) report, the Permittee must ensure that it is postmarked or received by Ecology no later than the dates specified by this permit. Send these paper reports to Ecology at:

Water Quality Permit Coordinator
Department of Ecology
Northwest Regional Office
3190 160th Avenue SE
Bellevue, WA 98008-5452

S3.C. Records retention

The Permittee must retain records of all monitoring information for a minimum of three (3) years. Such information must include all calibration and maintenance records and all original recordings for continuous monitoring instrumentation, copies of all reports required by this permit, and records of all data used to complete the application for this permit. The Permittee must extend this period of retention during the course of any unresolved litigation regarding the discharge of pollutants by the Permittee or when requested by Ecology.

S3.D. Recording of results

For each measurement or sample taken, the Permittee must record the following information:

1. The date, exact place, method, and time of sampling or measurement.
2. The individual who performed the sampling or measurement.
3. The dates the analyses were performed.
4. The individual who performed the analyses.
5. The analytical techniques or methods used.
6. The results of all analyses.

S3.E. Additional monitoring by the Permittee

If the Permittee monitors any pollutant more frequently than required by Special Condition S2 of this permit, then the Permittee must include the results of such monitoring in the calculation and reporting of the data submitted in the Permittee's DMR unless otherwise specified by Special Condition S2.

S3.F. Reporting permit violations

The Permittee must take the following actions when it violates or is unable to comply with any permit condition:

1. Immediately take action to stop, contain, and cleanup unauthorized discharges or otherwise stop the noncompliance and correct the problem.
2. If applicable, immediately repeat sampling and analysis. Submit the results of any repeat sampling to Ecology within thirty (30) days of sampling.

a. Immediate reporting

The Permittee must **immediately** report to Ecology and the Department of Health, Shellfish Program, and the Local Health Jurisdiction (at the numbers listed below), all:

- Failures of the disinfection system.
- Collection system overflows.
- Plant bypasses discharging to marine surface waters.
- Any other failures of the sewage system (pipe breaks, etc.)

Northwest Regional Office	**425-649-7000**
Department of Health, Shellfish Program	**360-236-3330 (business hours)** **360-789-8962 (after business hours)**
Public Health Seattle-King County	**206-477-8050 (Mon-Fri 8 am to 4 pm)**

Additionally, for any sanitary sewer overflow (SSO) that discharges to a municipal separate storm sewer system (MS4), the Permittee must notify the appropriate MS4 owner or operator.

b. Twenty-four-hour reporting

The Permittee must report the following occurrences of noncompliance by telephone, to Ecology at the telephone numbers listed above, within 24 hours from the time the Permittee becomes aware of any of the following circumstances:

1. Any noncompliance that may endanger health or the environment, unless previously reported under immediate reporting requirements.
2. Any unanticipated bypass that causes an exceedance of an effluent limit in the permit (See Part S5.F, “Bypass Procedures”).
3. Any upset that causes an exceedance of an effluent limit in the permit (See G.15, “Upset”).
4. Any violation of a maximum daily or instantaneous maximum discharge limit for any of the pollutants in Section S1.A of this permit.
5. Any overflow prior to the treatment works, whether or not such overflow endangers health or the environment or exceeds any effluent limit in the permit.

c. Report within five days

The Permittee must also submit a written report within five days of the time that the Permittee becomes aware of any reportable event under subparts a or b, above. The report must contain:

1. A description of the noncompliance and its cause.
2. The period of noncompliance, including exact dates and times.
3. The estimated time the Permittee expects the noncompliance to continue if not yet corrected.
4. Steps taken or planned to reduce, eliminate, and prevent recurrence of the noncompliance.
5. If the noncompliance involves an overflow prior to the treatment works, an estimate of the quantity (in gallons) of untreated overflow.

d. Waiver of written reports

Ecology may waive the written report required in subpart c, above, on a case-by-case basis upon request if the Permittee has submitted a timely oral report.

e. All other permit violation reporting

The Permittee must report all permit violations, which do not require immediate or within 24 hours reporting, when it submits monitoring reports for S3.A ("Reporting"). The reports must contain the information listed in subpart c, above. Compliance with these requirements does not relieve the Permittee from responsibility to maintain continuous compliance with the terms and conditions of this permit or the resulting liability for failure to comply.

S3.G. Other reporting

a. Spills of oil or hazardous materials

The Permittee must report a spill of oil or hazardous materials in accordance with the requirements of RCW 90.56.280 and chapter 173-303-145. You can obtain further instructions at the following website: http://www.ecy.wa.gov/programs/spills/other/reportaspill.htm .

b. Failure to submit relevant or correct facts

Where the Permittee becomes aware that it failed to submit any relevant facts in a permit application, or submitted incorrect information in a permit application, or in any report to Ecology, it must submit such facts or information promptly.

S3.H. Maintaining a copy of this permit

The Permittee must keep a copy of this permit at the facility and make it available upon request to Ecology inspectors.

S4. Facility loading

S4.A. Design criteria

The flows or waste loads for the permitted facility must not exceed the following design criteria:

Maximum Month Design Flow (MMDF)	**0.52 MGD**
BOD_5 Influent Loading for Maximum Month	**671 lbs/day**
TSS Influent Loading for Maximum Month	**671 lbs/day**

S4.B. Plans for maintaining adequate capacity

a. Conditions triggering plan submittal

The Permittee must submit a plan and a schedule for continuing to maintain capacity to Ecology when:

1. The actual flow or waste load reaches 85 percent of any one of the design criteria in S4.A for three consecutive months.
2. The projected plant flow or loading would reach design capacity within five years.

b. Plan and schedule content

The plan and schedule must identify the actions necessary to maintain adequate capacity for the expected population growth and to meet the limits and requirements of the permit. The Permittee must consider the following topics and actions in its plan.

1. Analysis of the present design and proposed process modifications.
2. Reduction or elimination of excessive infiltration and inflow of uncontaminated ground and surface water into the sewer system.
3. Limits on future sewer extensions or connections or additional waste loads.
4. Modification or expansion of facilities.
5. Reduction of industrial or commercial flows or waste loads.

Engineering documents associated with the plan must meet the requirements of WAC 173-240-060, "Engineering Report," and be approved by Ecology prior to any construction.

S4.C. Duty to mitigate

The Permittee must take all reasonable steps to minimize or prevent any discharge or sludge use or disposal in violation of this permit that has a reasonable likelihood of adversely affecting human health or the environment.

S4.D. Notification of new or altered sources

1. The Permittee must submit written notice to Ecology whenever any new discharge or a substantial change in volume or character of an existing discharge into the wastewater treatment plant is proposed which:

a. Would interfere with the operation of, or exceed the design capacity of, any portion of the wastewater treatment plant.

b. Is not part of an approved general sewer plan or approved plans and specifications.

c. Is subject to pretreatment standards under 40 CFR Part 403 and Section 307(b) of the Clean Water Act.

2. This notice must include an evaluation of the wastewater treatment plant's ability to adequately transport and treat the added flow and/or waste load, the quality and volume of effluent to be discharged to the treatment plant, and the anticipated impact on the Permittee's effluent [40 CFR 122.42(b)].

S5. Operation and maintenance

The Permittee must at all times properly operate and maintain all facilities and systems of treatment and control (and related appurtenances), which are installed to achieve compliance with the terms and conditions of this permit. Proper operation and maintenance also includes keeping a daily operation logbook (paper or electronic), adequate laboratory controls, and appropriate quality assurance procedures. This provision of the permit requires the Permittee to operate backup or auxiliary facilities or similar systems only when the operation is necessary to achieve compliance with the conditions of this permit.

S5.A. Certified operator

This permitted facility must be operated by an operator certified by the state of Washington for at least a Class II plant. This operator must be in responsible charge of the day-to-day operation of the wastewater treatment plant. An operator certified for at least a Class I plant must be in charge during all regularly scheduled shifts. The Permittee must notify Ecology when the operator in charge at the facility changes. It must provide the new operator's name and certification level and provide the name of the operator leaving the facility.

S5.B. Operation and maintenance program

The Permittee must:

1. Institute an adequate operation and maintenance program for the entire sewage system.
2. Keep maintenance records on all major electrical and mechanical components of the treatment plant, as well as the sewage system and pumping stations. Such records must clearly specify the frequency and type of maintenance recommended by the manufacturer and must show the frequency and type of maintenance performed.
3. Make maintenance records available for inspection at all times.

S5.C. Short-term reduction

The Permittee must schedule any facility maintenance, which might require interruption of wastewater treatment and degrade effluent quality, during non-critical water quality periods and carry this maintenance out according to the approved O&M manual or as otherwise approved by Ecology.

If a Permittee contemplates a reduction in the level of treatment that would cause a violation of permit discharge limits on a short-term basis for any reason, and such reduction cannot be avoided, the Permittee must:

1. Give written notification to Ecology, if possible, thirty (30) days prior to such activities.
2. Detail the reasons for, length of time of, and the potential effects of the reduced level of treatment.

This notification does not relieve the Permittee of its obligations under this permit.

S5.D. Electrical power failure

The Permittee must ensure that adequate safeguards prevent the discharge of untreated wastes or wastes not treated in accordance with the requirements of this permit during electrical power failure at the treatment plant and/or sewage lift stations. Adequate safeguards include, but are not limited to, alternate power sources, standby generator(s), or retention of inadequately treated wastes.

The Permittee must maintain Reliability Class II (EPA 430-99-74-001) at the wastewater treatment plant. Reliability Class II requires a backup power source sufficient to operate all vital components and critical lighting and ventilation during peak wastewater flow conditions. Vital components used to support the secondary processes (i.e., mechanical aerators or aeration basin air compressors) need not be operable to full levels of treatment, but must be sufficient to maintain the biota.

S5.E. Prevent connection of inflow

The Permittee must strictly enforce its sewer ordinances and not allow the connection of inflow (roof drains, foundation drains, etc.) to the sanitary sewer system.

S5.F. Bypass procedures

A bypass is the intentional diversion of waste streams from any portion of a treatment facility. This permit prohibits all bypasses except when the bypass is for essential maintenance, as authorized in special condition S5.F.1, or is approved by Ecology as an anticipated bypass following the procedures in S5.F.2.

1. **Bypass for essential maintenance without the potential to cause violation of permit limits or conditions**

   This permit allows bypasses for essential maintenance of the treatment system when necessary to ensure efficient operation of the system. The Permittee may bypass the treatment system for essential maintenance only if doing so does not cause violations of effluent limits. The Permittee is not required to notify Ecology when bypassing for essential maintenance. However the Permittee must comply with the monitoring requirements specified in special condition S2.B.

2. **Anticipated bypasses for non-essential maintenance**

   Ecology may approve an anticipated bypass under the conditions listed below. This permit prohibits any anticipated bypass that is not approved through the following process.

   a. If a bypass is for non-essential maintenance, the Permittee must notify Ecology, if possible, at least ten (10) days before the planned date of bypass. The notice must contain:

      - A description of the bypass and the reason the bypass is necessary.
      - An analysis of all known alternatives which would eliminate, reduce, or mitigate the potential impacts from the proposed bypass.
      - A cost-effectiveness analysis of alternatives.
      - The minimum and maximum duration of bypass under each alternative.
      - A recommendation as to the preferred alternative for conducting the bypass.
      - The projected date of bypass initiation.
      - A statement of compliance with SEPA.
      - A request for modification of water quality standards as provided for in WAC 173-201A-410, if an exceedance of any water quality standard is anticipated.
      - Details of the steps taken or planned to reduce, eliminate, and prevent recurrence of the bypass.

   b. For probable construction bypasses, the Permittee must notify Ecology of the need to bypass as early in the planning process as possible. The Permittee must consider the analysis required above during the project planning and design process. The project-specific engineering report as well as the plans and specifications must include details of probable construction bypasses to the extent practical. In cases where the Permittee determines the probable need to bypass early, the Permittee must continue to analyze conditions up to and including the construction period in an effort to minimize or eliminate the bypass.

c. Ecology will determine if the Permittee has met the conditions of special condition S5.F.2 a and b and consider the following prior to issuing a determination letter, an administrative order, or a permit modification as appropriate for an anticipated bypass:

- If the Permittee planned and scheduled the bypass to minimize adverse effects on the public and the environment.
- If the bypass is unavoidable to prevent loss of life, personal injury, or severe property damage. "Severe property damage" means substantial physical damage to property, damage to the treatment facilities which would cause them to become inoperable, or substantial and permanent loss of natural resources which can reasonably be expected to occur in the absence of a bypass.
- If feasible alternatives to the bypass exist, such as:
  - The use of auxiliary treatment facilities.
  - Retention of untreated wastes.
  - Stopping production.
  - Maintenance during normal periods of equipment downtime, but not if the Permittee should have installed adequate backup equipment in the exercise of reasonable engineering judgment to prevent a bypass which occurred during normal periods of equipment downtime or preventative maintenance.
  - Transport of untreated wastes to another treatment facility.

S5.G. Operations and maintenance (O&M) manual

a. O&M manual submittal and requirements

The Permittee must:

1. Review the O&M Manual at least annually.
2. Submit to Ecology for review and approval substantial changes or updates to the O&M Manual whenever it incorporates them into the manual.
3. Keep the approved O&M Manual at the permitted facility.
4. Follow the instructions and procedures of this manual.

b. O&M manual components

In addition to the requirements of WAC 173-240-080(1) through (5), the O&M manual must be consistent with the guidance in Table G1-3 in the *Criteria for Sewage Works Design* (Orange Book), 2008. The O&M manual must include:

1. Emergency procedures for cleanup in the event of wastewater system upset or failure.

2. A review of system components which if failed could pollute surface water or could impact human health. Provide a procedure for a routine schedule of checking the function of these components.
3. Wastewater system maintenance procedures that contribute to the generation of process wastewater.
4. Reporting protocols for submitting reports to Ecology to comply with the reporting requirements in the discharge permit.
5. Any directions to maintenance staff when cleaning or maintaining other equipment or performing other tasks which are necessary to protect the operation of the wastewater system (for example, defining maximum allowable discharge rate for draining a tank, blocking all floor drains before beginning the overhaul of a stationary engine).
6. The treatment plant process control monitoring schedule.
7. Minimum staffing adequate to operate and maintain the treatment processes and carry out compliance monitoring required by the permit.

S6. Pretreatment

S6.A. General requirements

1. The Permittee must implement the Industrial Pretreatment Program in accordance with King County Code 28.84.060 and 28.82 as amended by King County Ordinance No. 11963 on January 1, 1996 and Ordinance No. 16929 on September 30, 2010; legal authorities, policies, procedures, and financial provisions described in the Permittee's approved pretreatment program submittal entitled "Industrial Pretreatment Program" and dated April 27, 1981; any approved revisions thereto; and the General Pretreatment Regulations (40 CFR Part 403), including any revisions to 40 CFR Part 403. At a minimum, the Permittee must undertake the following pretreatment implementation activities:

   a. Enforce categorical pretreatment standards under Section 307(b) and (c) of the Federal Clean Water Act (hereinafter, the Act), prohibited discharge standards as set forth in 40 CFR 403.5, local limits, or state standards, whichever are most stringent or apply at the time of issuance or modification of a local industrial waste discharge permit. Locally derived limits are defined as pretreatment standards under Section 307(d) of the Act and are not limited to categorical industrial facilities.

   b. Issue industrial waste discharge permits to all significant industrial users [SIUs, as defined in 40 CFR 403.3(v)(i)(ii)] contributing to the treatment system, including those from other jurisdictions. Industrial waste discharge permits must contain, as a minimum, all the requirements of 40 CFR 403.8 (f)(l)(iii). The Permittee must coordinate the permitting process with Ecology regarding any industrial facility that may possess a State Waste Discharge Permit issued by Ecology. Once issued, an industrial waste discharge permit takes precedence over a state-issued waste discharge permit.

c. Maintain and update, as necessary, records identifying the nature, character, and volume of pollutants contributed by industrial users to the POTW. The Permittee must maintain records for at least a three-year period.

d. Perform inspections, surveillance, and monitoring activities on industrial users to determine or confirm compliance with pretreatment standards and requirements. The Permittee must conduct a thorough inspection of SIUs annually. The Permittee must conduct regular local monitoring of SIU wastewaters commensurate with the character and volume of the wastewater but not less than once per year per SIU. If an SIU qualifies for reduced monitoring under 40 CFR 403.12(e)(3) (Middle Tier Categorical Industrial Users), inspection and monitoring must be conducted no less frequently than once every 2 years. The Permittee must collect and analyze samples in accordance with 40 CFR Part 403.12(b)(5)(ii)-(v) and 40 CFR Part 136.

e. Enforce and obtain remedies for noncompliance by any industrial users with applicable pretreatment standards and requirements. Once it identifies violations, the Permittee must take timely and appropriate enforcement action to address the noncompliance. The Permittee's action must follow its enforcement response procedures and any amendments, thereof.

f. Publish, at least annually in the largest daily newspaper in the Permittee's service area, a list of all non-domestic users which, at any time in the previous 12 months, were in significant noncompliance as defined in 40 CFR 403.8(f)(2)(vii).

g. If the Permittee elects to conduct sampling of an SIU's discharge in lieu of requiring user self-monitoring, it must satisfy all requirements of 40 CFR Part 403.12. This includes monitoring and record keeping requirements of Sections 403.12(g) and (o). For SIUs subject to categorical standards (CIUs), the Permittee may either complete baseline and initial compliance reports for the CIU (when required by 403.12(b) and (d)) or require these of the CIU. The Permittee must ensure that it provides SIUs the results of sampling in a timely manner, inform SIUs of their right to sample, their obligations to report any sampling they do, to respond to non-compliance, and to submit other notifications. These include a slug load report (403.12(f)), notice of changed discharge (403.12(j)), and hazardous waste notifications (403.12(p)). If sampling for the SIU, the Permittee must not sample less than once in every six-month period unless the Permittee's approved program includes procedures for reduction of monitoring for Middle-Tier or Non-Significant Categorical Users per 403.12(e)(2) and (3) and those procedures have been followed.

h. Develop and maintain a data management system designed to track the status of the Permittee's industrial user inventory, industrial user discharge characteristics, and compliance status.

i. Maintain adequate staff, funds, and equipment to implement its pretreatment program.

j. Establish, where necessary, contracts or legally binding agreements with contributing jurisdictions to ensure compliance with applicable pretreatment requirements by commercial or industrial users within these jurisdictions. These contracts or agreements must identify the agency responsible to perform the various implementation and enforcement activities in the contributing jurisdiction. To the extent that there are contributing jurisdictions in which the Permittee has legal authority which is inadequate with respect to the requirements of 40 CFR 403.8(f)(1), the Permittee must enter into a joint powers agreement that specifies the specific roles, responsibilities, and pretreatment requirements of each jurisdiction and enables the Permittee to enforce its pretreatment regulations within the contributing jurisdiction(s).

k. The Permittee must evaluate whether each new SIU needs a plan to control Slug Discharges within 1 year of designating the entity as a SIU. For purposes of this subsection, a Slug Discharge is any Discharge of a non-routine, episodic nature, including but not limited to an accidental spill or a non-customary batch Discharge, which has a reasonable potential to cause Interference or Pass Through, or in any other way violate the permittee’s regulations, local limits or permit conditions. The Permittee must make this evaluation available to Ecology upon request. The Permittee must required each SIU to immediately notify them of any changes at its facility affecting the potential for a Slug Discharge. If the Permittee decides that a slug control plan is needed, the plan shall contain, at a minimum, the following elements:

    i. Description of discharge practices, including non-routine batch Discharges;
    ii. Description of stored chemicals;
    iii. Procedures for immediately notifying the POTW of Slug Discharges, including any Discharge that would violate a prohibition under 40 CFR 403.5(b) with procedures for follow-up written notification within five days;

2. If necessary, procedures to prevent adverse impact from accidental spills, including inspection and maintenance of storage areas, handling and transfer of materials, loading and unloading operations, control of plant site run-off, worker training, building of containment structures or equipment, measures for containing toxic organic pollutants (including solvents), and/or measures and equipment for emergency response. Whenever Ecology determines that any waste source contributes pollutants to the Permittee's treatment works in violation of Section (b), (c), or (d) of Section 307 of the Act, and the Permittee has not taken adequate corrective action, Ecology will notify the Permittee of this determination. If the Permittee fails to take appropriate enforcement action within 30 days of this notification, Ecology may take appropriate enforcement action against the source or the Permittee.

3. Pretreatment Report

The Permittee must provide to Ecology an annual report that briefly describes its program activities during the previous calendar year.

The Permittee must submit the annual report to Ecology by April 30th of each year. The report must include the following information:

a. An updated non-domestic inventory.

b. Results of wastewater sampling at the treatment plant conducted to support local limit development, if completed during the reporting year. The Permittee must calculate removal rates for each pollutant and evaluate the adequacy of the existing local limits in prevention of treatment plant interference, pass through of pollutants that could affect receiving water quality, and sludge contamination.

c. Status of program implementation, including:

   i. Any substantial modifications to the pretreatment program as originally approved by Ecology, including staffing and funding levels.
   ii. Any interference, upset, or permit violations experienced at the POTW that are directly attributable to wastes from industrial users.
   iii. Listing of industrial users inspected and/or monitored, and a summary of the results.
   iv. Listing of industrial users scheduled for inspection and/or monitoring for the next year, and expected frequencies.
   v. Listing of industrial users notified of promulgated pretreatment standards and/or local standards as required in 40 CFR 403.8(f)(2)(iii). The list must indicate which industrial users are on compliance schedules and the final date of compliance for each.
   vi. Listing of industrial users issued industrial waste discharge permits.
   vii. Planned changes in the approved local pretreatment program. (See Subsection A.7. below)

d. Status of compliance activities, including:

   i. Listing of industrial users that failed to submit baseline monitoring reports or any other reports required under 40 CFR 403.12 and in the Permittee's pretreatment program, dated April 27, 1981.
   ii. Listing of industrial users that were at any time during the reporting period not complying with federal, state, or local pretreatment standards or with applicable compliance schedules for achieving those standards, and the duration of such noncompliance.
   iii. Summary of enforcement activities and other corrective actions taken or planned against non-complying industrial users. The Permittee must supply to Ecology a copy of the public notice of facilities that were in significant noncompliance.

4. The Permittee must request and obtain approval from Ecology before making any significant changes to the approved local pretreatment program. The Permittee must follow the procedure in 40 CFR 403.18 (b) and (c).

S6.B. Local limit development

As sufficient data become available, the Permittee, in consultation with Ecology, must reevaluate its local limits in order to prevent pass through or interference. If Ecology determines that any pollutant present causes pass through or interference, or exceeds established sludge standards, the Permittee must establish new local limits or revise existing local limits as required by 40 CFR 403.5. Ecology may also require the Permittee to revise or establish local limits for any pollutant discharged from the POTW that has a reasonable potential to exceed the Water Quality Standards, Sediment Standards, or established effluent limits, or causes whole effluent toxicity. Ecology makes this determination in the form of an Administrative Order.

Ecology may modify this permit to incorporate additional requirements relating to the establishment and enforcement of local limits for pollutants of concern. Any permit modification is subject to formal due process procedures under state and federal law and regulation.

S7. Solid wastes

S7.A. Solid waste handling

The Permittee must handle and dispose of all solid waste material in such a manner as to prevent its entry into state ground or surface water.

S7.B. Leachate

The Permittee must not allow leachate from its solid waste material to enter state waters without providing all known, available, and reasonable methods of treatment, nor allow such leachate to cause violations of the State Surface Water Quality Standards, Chapter 173-201A WAC, or the State Ground Water Quality Standards, Chapter 173-200 WAC. The Permittee must apply for a permit or permit modification as may be required for such discharges to state ground or surface waters.

S8. Acute toxicity

S8.A. Testing when there is no permit limit for acute toxicity

The Permittee must:

1. Conduct acute toxicity testing on final effluent during the third quarter of 2019 and the first quarter of 2020.
2. Conduct acute toxicity testing on a series of at least five concentrations of effluent, including 100% effluent and a control.
3. Submit the results to Ecology with the permit renewal application.
4. Use each of the following species and protocols for each acute toxicity test:

Acute Toxicity Tests	Species	Method
Fathead minnow 96-hour static-renewal test	*Pimephales promelas*	EPA-821-R-02-012
Daphnid 48-hour static test	*Ceriodaphnia dubia, Daphnia pulex,* or *Daphnia magna*	EPA-821-R-02-012

S8.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain toxicity data, bench sheets, and reference toxicant results for test methods. In addition, the Permittee must submit toxicity test data in electronic format (CETIS export file preferred) for entry into Ecology's database.
2. The Permittee must collect 24-hour composite effluent samples for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.
3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.
4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Subsection C and the Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.
5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Section A or pristine natural water of sufficient quality for good control performance.
6. The Permittee must conduct whole effluent toxicity tests on an unmodified sample of final effluent.
7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the acute critical effluent concentration (ACEC). The ACEC equals 1.12% effluent.
8. All whole effluent toxicity tests, effluent screening tests, and rapid screening tests that involve hypothesis testing must comply with the acute statistical power standard of 29% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S9. Chronic toxicity

S9.A. Testing when there is no permit limit for chronic toxicity

The Permittee must:

1. Conduct acute toxicity testing on final effluent during fourth quarter of 2019 and the second quarter of 2020.
2. Conduct chronic toxicity testing on a series of at least five concentrations of effluent and a control. This series of dilutions must include the acute critical effluent concentration (ACEC). The ACEC equals 1.12% effluent. The series of dilutions should also contain the CCEC of 0.15% effluent.
3. Compare the ACEC to the control using hypothesis testing at the 0.05 level of significance as described in Appendix H, EPA/600/4-89/001.
4. Submit the results to Ecology with the permit renewal application.
5. Perform chronic toxicity tests with all of the following species and the most recent version of the following protocols:

Saltwater Chronic Test	Species	Method
Topsmelt survival and growth	*Atherinops affinis*	EPA/600/R-95/136
Mysid shrimp survival and growth	*Americamysis bahia* (formerly *Mysidopsis bahia*)	EPA-821-R-02-014

S9.B. Sampling and reporting requirements

1. The Permittee must submit all reports for toxicity testing in accordance with the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. Reports must contain toxicity data, bench sheets, and reference toxicant results for test methods. In addition, the Permittee must submit toxicity test data in electronic format (CETIS export file preferred) for entry into Ecology's database.
2. The Permittee must collect 24-hour composite effluent samples for toxicity testing. The Permittee must cool the samples to 0 - 6 degrees Celsius during collection and send them to the lab immediately upon completion. The lab must begin the toxicity testing as soon as possible but no later than 36 hours after sampling was completed.
3. The laboratory must conduct water quality measurements on all samples and test solutions for toxicity testing, as specified in the most recent version of Ecology Publication No. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*.
4. All toxicity tests must meet quality assurance criteria and test conditions specified in the most recent versions of the EPA methods listed in Section C and the Ecology Publication no. WQ-R-95-80, *Laboratory Guidance and Whole Effluent Toxicity Test Review Criteria*. If Ecology determines any test results to be invalid or anomalous, the Permittee must repeat the testing with freshly collected effluent.

5. The laboratory must use control water and dilution water meeting the requirements of the EPA methods listed in Subsection C or pristine natural water of sufficient quality for good control performance.
6. The Permittee must conduct whole effluent toxicity tests on an unmodified sample of final effluent.
7. The Permittee may choose to conduct a full dilution series test during compliance testing in order to determine dose response. In this case, the series must have a minimum of five effluent concentrations and a control. The series of concentrations must include the CCEC and the ACEC. The CCEC and the ACEC may either substitute for the effluent concentrations that are closest to them in the dilution series or be extra effluent concentrations. The CCEC equals 0.15% effluent. The ACEC equals 1.12% effluent.
8. All whole effluent toxicity tests that involve hypothesis testing must comply with the chronic statistical power standard of 39% as defined in WAC 173-205-020. If the test does not meet the power standard, the Permittee must repeat the test on a fresh sample with an increased number of replicates to increase the power.

S10. Application for permit renewal or modification for facility changes

The Permittee must submit an application for renewal of this permit by July 31, 2021.

The Permittee must also submit a new application or addendum at least one hundred eighty (180) days prior to commencement of discharges, resulting from the activities listed below, which may result in permit violations. These activities include any facility expansions, production increases, or other planned changes, such as process modifications, in the permitted facility.

General Conditions

G1. Signatory requirements

1. All applications, reports, or information submitted to Ecology must be signed and certified.
   a. In the case of corporations, by a responsible corporate officer. For the purpose of this section, a responsible corporate officer means:
      - A president, secretary, treasurer, or vice-president of the corporation in charge of a principal business function, or any other person who performs similar policy or decision making functions for the corporation, or
      - The manager of one or more manufacturing, production, or operating facilities, provided, the manager is authorized to make management decisions which govern the operation of the regulated facility including having the explicit or implicit duty of making major capital investment recommendations, and initiating and directing other comprehensive measures to assure long-term environmental compliance with environmental laws and regulations; the manager can ensure that the necessary systems are established or actions taken to gather complete and accurate information for permit application requirements; and where authority to sign documents has been assigned or delegated to the manager in accordance with corporate procedures.

   b. In the case of a partnership, by a general partner.
   c. In the case of sole proprietorship, by the proprietor.
   d. In the case of a municipal, state, or other public facility, by either a principal executive officer or ranking elected official.

   Applications for permits for domestic wastewater facilities that are either owned or operated by, or under contract to, a public entity shall be submitted by the public entity.

2. All reports required by this permit and other information requested by Ecology must be signed by a person described above or by a duly authorized representative of that person. A person is a duly authorized representative only if:
   a. The authorization is made in writing by a person described above and submitted to Ecology.
   b. The authorization specifies either an individual or a position having responsibility for the overall operation of the regulated facility, such as the position of plant manager, superintendent, position of equivalent responsibility, or an individual or position having overall responsibility for environmental matters. (A duly authorized representative may thus be either a named individual or any individual occupying a named position.)

3. Changes to authorization. If an authorization under paragraph G1.2, above, is no longer accurate because a different individual or position has responsibility for the overall operation of the facility, a new authorization satisfying the requirements of paragraph G1.2, above, must be submitted to Ecology prior to or together with any reports, information, or applications to be signed by an authorized representative.

4. Certification. Any person signing a document under this section must make the following certification:

   "I certify under penalty of law, that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gathered and evaluated the information submitted. Based on my inquiry of the person or persons who manage the system or those persons directly responsible for gathering information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations."

G2. Right of inspection and entry

The Permittee must allow an authorized representative of Ecology, upon the presentation of credentials and such other documents as may be required by law:

1. To enter upon the premises where a discharge is located or where any records must be kept under the terms and conditions of this permit.
2. To have access to and copy, at reasonable times and at reasonable cost, any records required to be kept under the terms and conditions of this permit.
3. To inspect, at reasonable times, any facilities, equipment (including monitoring and control equipment), practices, methods, or operations regulated or required under this permit.
4. To sample or monitor, at reasonable times, any substances or parameters at any location for purposes of assuring permit compliance or as otherwise authorized by the Clean Water Act.

G3. Permit actions

This permit may be modified, revoked and reissued, or terminated either at the request of any interested person (including the Permittee) or upon Ecology's initiative. However, the permit may only be modified, revoked and reissued, or terminated for the reasons specified in 40 CFR 122.62, 40 CFR 122.64 or WAC 173-220-150 according to the procedures of 40 CFR 124.5.

1. The following are causes for terminating this permit during its term, or for denying a permit renewal application:
   a. Violation of any permit term or condition.
   b. Obtaining a permit by misrepresentation or failure to disclose all relevant facts.
   c. A material change in quantity or type of waste disposal.
   d. A determination that the permitted activity endangers human health or the environment, or contributes to water quality standards violations and can only be regulated to acceptable levels by permit modification or termination.

e. A change in any condition that requires either a temporary or permanent reduction, or elimination of any discharge or sludge use or disposal practice controlled by the permit.

f. Nonpayment of fees assessed pursuant to RCW 90.48.465.

g. Failure or refusal of the Permittee to allow entry as required in RCW 90.48.090.

2. The following are causes for modification but not revocation and reissuance except when the Permittee requests or agrees:

   a. A material change in the condition of the waters of the state.

   b. New information not available at the time of permit issuance that would have justified the application of different permit conditions.

   c. Material and substantial alterations or additions to the permitted facility or activities which occurred after this permit issuance.

   d. Promulgation of new or amended standards or regulations having a direct bearing upon permit conditions, or requiring permit revision.

   e. The Permittee has requested a modification based on other rationale meeting the criteria of 40 CFR Part 122.62.

   f. Ecology has determined that good cause exists for modification of a compliance schedule, and the modification will not violate statutory deadlines.

   g. Incorporation of an approved local pretreatment program into a municipality's permit.

3. The following are causes for modification or alternatively revocation and reissuance:

   a. When cause exists for termination for reasons listed in 1.a through 1.g of this section, and Ecology determines that modification or revocation and reissuance is appropriate.

   b. When Ecology has received notification of a proposed transfer of the permit. A permit may also be modified to reflect a transfer after the effective date of an automatic transfer (General Condition G7) but will not be revoked and reissued after the effective date of the transfer except upon the request of the new Permittee.

G4. Reporting planned changes

The Permittee must, as soon as possible, but no later than one hundred eighty (180) days prior to the proposed changes, give notice to Ecology of planned physical alterations or additions to the permitted facility, production increases, or process modification which will result in:

1. The permitted facility being determined to be a new source pursuant to 40 CFR 122.29(b).
2. A significant change in the nature or an increase in quantity of pollutants discharged.
3. A significant change in the Permittee's sludge use or disposal practices. Following such notice, and the submittal of a new application or supplement to the existing application, along with required engineering plans and reports, this permit may be modified, or revoked and reissued pursuant to 40 CFR 122.62(a) to specify and limit any pollutants not previously limited. Until such modification is effective, any new or increased discharge in excess of permit limits or not specifically authorized by this permit constitutes a violation.

G5. Plan review required

Prior to constructing or modifying any wastewater control facilities, an engineering report and detailed plans and specifications must be submitted to Ecology for approval in accordance with chapter 173-240 WAC. Engineering reports, plans, and specifications must be submitted at least one hundred eighty (180) days prior to the planned start of construction unless a shorter time is approved by Ecology. Facilities must be constructed and operated in accordance with the approved plans.

G6. Compliance with other laws and statutes

Nothing in this permit excuses the Permittee from compliance with any applicable federal, state, or local statutes, ordinances, or regulations.

G7. Transfer of this permit

In the event of any change in control or ownership of facilities from which the authorized discharge emanate, the Permittee must notify the succeeding owner or controller of the existence of this permit by letter, a copy of which must be forwarded to Ecology.

1. Transfers by Modification

   Except as provided in paragraph (2) below, this permit may be transferred by the Permittee to a new owner or operator only if this permit has been modified or revoked and reissued under 40 CFR 122.62(b)(2), or a minor modification made under 40 CFR 122.63(d), to identify the new Permittee and incorporate such other requirements as may be necessary under the Clean Water Act.

2. Automatic Transfers

   This permit may be automatically transferred to a new Permittee if:

   a. The Permittee notifies Ecology at least thirty (30) days in advance of the proposed transfer date.

   b. The notice includes a written agreement between the existing and new Permittees containing a specific date transfer of permit responsibility, coverage, and liability between them.

   c. Ecology does not notify the existing Permittee and the proposed new Permittee of its intent to modify or revoke and reissue this permit. A modification under this subparagraph may also be minor modification under 40 CFR 122.63. If this notice is not received, the transfer is effective on the date specified in the written agreement.

G8. Reduced production for compliance

The Permittee, in order to maintain compliance with its permit, must control production and/or all discharges upon reduction, loss, failure, or bypass of the treatment facility until the facility is restored or an alternative method of treatment is provided. This requirement applies in the situation where, among other things, the primary source of power of the treatment facility is reduced, lost, or fails.

G9. Removed substances

Collected screenings, grit, solids, sludges, filter backwash, or other pollutants removed in the course of treatment or control of wastewaters must not be resuspended or reintroduced to the final effluent stream for discharge to state waters.

G10. Duty to provide information

The Permittee must submit to Ecology, within a reasonable time, all information which Ecology may request to determine whether cause exists for modifying, revoking and reissuing, or terminating this permit or to determine compliance with this permit. The Permittee must also submit to Ecology upon request, copies of records required to be kept by this permit.

G11. Other requirements of 40 CFR

All other requirements of 40 CFR 122.41 and 122.42 are incorporated in this permit by reference.

G12. Additional monitoring

Ecology may establish specific monitoring requirements in addition to those contained in this permit by administrative order or permit modification.

G13. Payment of fees

The Permittee must submit payment of fees associated with this permit as assessed by Ecology.

G14. Penalties for violating permit conditions

Any person who is found guilty of willfully violating the terms and conditions of this permit is deemed guilty of a crime, and upon conviction thereof shall be punished by a fine of up to ten thousand dollars ($10,000) and costs of prosecution, or by imprisonment in the discretion of the court. Each day upon which a willful violation occurs may be deemed a separate and additional violation.

Any person who violates the terms and conditions of a waste discharge permit may incur, in addition to any other penalty as provided by law, a civil penalty in the amount of up to ten thousand dollars ($10,000) for every such violation. Each and every such violation is a separate and distinct offense, and in case of a continuing violation, every day's continuance is deemed to be a separate and distinct violation.

G15. Upset

Definition – “Upset” means an exceptional incident in which there is unintentional and temporary noncompliance with technology-based permit effluent limits because of factors beyond the reasonable control of the Permittee. An upset does not include noncompliance to the extent caused by operational error, improperly designed treatment facilities, inadequate treatment facilities, lack of preventive maintenance, or careless or improper operation.

An upset constitutes an affirmative defense to an action brought for noncompliance with such technology-based permit effluent limits if the requirements of the following paragraph are met.

A Permittee who wishes to establish the affirmative defense of upset must demonstrate, through properly signed, contemporaneous operating logs, or other relevant evidence that:

1. An upset occurred and that the Permittee can identify the cause(s) of the upset.
2. The permitted facility was being properly operated at the time of the upset.
3. The Permittee submitted notice of the upset as required in Special Condition S3.F.
4. The Permittee complied with any remedial measures required under S3.F of this permit.

In any enforcement action the Permittee seeking to establish the occurrence of an upset has the burden of proof.

G16. Property rights

This permit does not convey any property rights of any sort, or any exclusive privilege.

G17. Duty to comply

The Permittee must comply with all conditions of this permit. Any permit noncompliance constitutes a violation of the Clean Water Act and is grounds for enforcement action; for permit termination, revocation and reissuance, or modification; or denial of a permit renewal application.

G18. Toxic pollutants

The Permittee must comply with effluent standards or prohibitions established under Section 307(a) of the Clean Water Act for toxic pollutants within the time provided in the regulations that establish those standards or prohibitions, even if this permit has not yet been modified to incorporate the requirement.

G19. Penalties for tampering

The Clean Water Act provides that any person who falsifies, tampers with, or knowingly renders inaccurate any monitoring device or method required to be maintained under this permit shall, upon conviction, be punished by a fine of not more than $10,000 per violation, or by imprisonment for not more than two (2) years per violation, or by both. If a conviction of a person is for a violation committed after a first conviction of such person under this condition, punishment shall be a fine of not more than $20,000 per day of violation, or by imprisonment of not more than four (4) years, or by both.

G20. Compliance schedules

Reports of compliance or noncompliance with, or any progress reports on, interim and final requirements contained in any compliance schedule of this permit must be submitted no later than fourteen (14) days following each schedule date.

G21. Service agreement review

The Permittee must submit to Ecology any proposed service agreements and proposed revisions or updates to existing agreements for the operation of any wastewater treatment facility covered by this permit. The review is to ensure consistency with chapters 90.46 and 90.48 RCW as required by RCW 70.150.040(9). In the event that Ecology does not comment within a thirty-day (30) period, the Permittee may assume consistency and proceed with the service agreement or the revised/updated service agreement.

Appendix A

LIST OF POLLUTANTS WITH ANALYTICAL METHODS, DETECTION LIMITS AND QUANTITATION LEVELS

The Permittee must use the specified analytical methods, detection limits (DLs) and quantitation levels (QLs) in the following table for permit and application required monitoring unless:

- Another permit condition specifies other methods, detection levels, or quantitation levels.
- The method used produces measurable results in the sample and EPA has listed it as an EPA-approved method in 40 CFR Part 136.

If the Permittee uses an alternative method, not specified in the permit and as allowed above, it must report the test method, DL, and QL on the discharge monitoring report or in the required report.

If the Permittee is unable to obtain the required DL and QL in its effluent due to matrix effects, the Permittee must submit a matrix-specific detection limit (MDL) and a quantitation limit (QL) to Ecology with appropriate laboratory documentation.

Ecology added this appendix to the permit in order to reduce the number of analytical “non-detects” in permit-required monitoring and to measure effluent concentrations near or below criteria values where possible at a reasonable cost.

The lists below include conventional pollutants (as defined in CWA section 502(6) and 40 CFR Part 122.), some toxic or priority pollutants as defined in CWA section 307(a)(1) and listed in 40 CFR Part 122 Appendix D, 40 CFR Part 401.15 and 40 CFR Part 423 Appendix A), and nonconventionals. 40 CFR Part 122 Appendix D (Table V) identifies toxic pollutants and hazardous substances which are required to be reported by dischargers if expected to be present. This permit Appendix A list does not include those parameters.

CONVENTIONAL POLLUTANTS

Pollutant	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] *µg/L unless specified*	Quantitation Level (QL)[2] *µg/L unless specified*
Biochemical Oxygen Demand		SM5210-B		2 mg/L
Biochemical Oxygen Demand, Soluble		SM5210-B [3]		2 mg/L
Fecal Coliform		SM 9221E,9222	N/A	Specified in method - sample aliquot dependent
Oil and Grease (HEM) (Hexane Extractable Material)		1664 A or B	1,400	5,000
pH		SM4500-H^+ B	N/A	N/A
Total Suspended Solids		SM2540-D		5 mg/L

NONCONVENTIONAL POLLUTANTS

Pollutant & CAS No. (if available)	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] µg/L unless specified	Quantitation Level (QL)[2] µg/L unless specified
Alkalinity, Total		SM2320-B		5 mg/L as CaCO3
Aluminum, Total	7429-90-5	200.8	2.0	10
Ammonia, Total (as N)		SM4500-NH3-B and C/D/E/G/H		20
Barium Total	7440-39-3	200.8	0.5	2.0
BTEX (benzene +toluene + ethylbenzene + m,o,p xylenes)		EPA SW 846 8021/8260	1	2
Boron, Total	7440-42-8	200.8	2.0	10.0
Chemical Oxygen Demand		SM5220-D		10 mg/L

NONCONVENTIONAL POLLUTANTS

Pollutant & CAS No. (if available)	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] µg/L unless specified	Quantitation Level (QL)[2] µg/L unless specified
Chloride		SM4500-Cl B/C/D/E and SM4110 B		Sample and limit dependent
Chlorine, Total Residual		SM4500 Cl G		50.0
Cobalt, Total	7440-48-4	200.8	0.05	0.25
Color		SM2120 B/C/E		10 color units
Dissolved oxygen		SM4500-OC/OG		0.2 mg/L
Flow		Calibrated device		
Fluoride	16984-48-8	SM4500-F E	25	100
Hardness, Total		SM2340B		200 as CaCO3
Iron, Total	7439-89-6	200.7	12.5	50
Magnesium, Total	7439-95-4	200.7	10	50
Manganese, Total	7439-96-5	200.8	0.1	0.5
Molybdenum, Total	7439-98-7	200.8	0.1	0.5
Nitrate + Nitrite Nitrogen (as N)		SM4500-NO3- E/F/H		100
Nitrogen, Total Kjeldahl (as N)		SM4500-N_{org}B/C and SM4500NH_3-B/C/D/EF/G/H		300
NWTPH Dx [4]		Ecology NWTPH Dx	250	250
NWTPH Gx [5]		Ecology NWTPH Gx	250	250
Phosphorus, Total (as P)		SM 4500 PB followed by SM4500-PE/PF	3	10
Salinity		SM2520-B		3 practical salinity units or scale (PSU or PSS)
Settleable Solids		SM2540 -F		Sample and limit dependent
Soluble Reactive Phosphorus (as P)		SM4500-P E/F/G	3	10
Sulfate (as mg/L SO_4)		SM4110-B		0.2 mg/L
Sulfide (as mg/L S)		SM4500-S^2F/D/E/G		0.2 mg/L
Sulfite (as mg/L SO_3)		SM4500-SO3B		2 mg/L
Temperature (max. 7-day avg.)		Analog recorder or use micro-recording devices known as thermistors		0.2º C
Tin, Total	7440-31-5	200.8	0.3	1.5
Titanium, Total	7440-32-6	200.8	0.5	2.5
Total Coliform		SM 9221B, 9222B, 9223B	N/A	Specified in method - sample aliquot dependent
Total Organic Carbon		SM5310-B/C/D		1 mg/L
Total dissolved solids		SM2540 C		20 mg/L

PRIORITY POLLUTANTS	PP #	CAS Number (if available)	Recommended Analytical Protocol	Detection (DL)[1] *µg/L unless specified*	Quantitation Level (QL)[2] *µg/L unless specified*
METALS, CYANIDE & TOTAL PHENOLS					
Antimony, Total	114	7440-36-0	200.8	0.3	1.0
Arsenic, Total	115	7440-38-2	200.8	0.1	0.5
Beryllium, Total	117	7440-41-7	200.8	0.1	0.5
Cadmium, Total	118	7440-43-9	200.8	0.05	0.25
Chromium (hex) dissolved	119	18540-29-9	SM3500-Cr C	0.3	1.2
Chromium, Total	119	7440-47-3	200.8	0.2	1.0
Copper, Total	120	7440-50-8	200.8	0.4	2.0
Lead, Total	122	7439-92-1	200.8	0.1	0.5
Mercury, Total	123	7439-97-6	1631E	0.0002	0.0005
Nickel, Total	124	7440-02-0	200.8	0.1	0.5
Selenium, Total	125	7782-49-2	200.8	1.0	1.0
Silver, Total	126	7440-22-4	200.8	0.04	0.2
Thallium, Total	127	7440-28-0	200.8	0.09	0.36
Zinc, Total	128	7440-66-6	200.8	0.5	2.5
Cyanide, Total	121	57-12-5	335.4	5	10
Cyanide, Weak Acid Dissociable	121		SM4500-CN I	5	10
Cyanide, Free Amenable to Chlorination (Available Cyanide)	121		SM4500-CN G	5	10
Phenols, Total	65		EPA 420.1		50

1. Detection level (DL) or detection limit means the minimum concentration of an analyte (substance) that can be measured and reported with a 99% confidence that the analyte concentration is greater than zero as determined by the procedure given in 40 CFR part 136, Appendix B.
2. Quantitation Level (QL) also known as Minimum Level of Quantitation (ML) – The lowest level at which the entire analytical system must give a recognizable signal and acceptable calibration point for the analyte. It is equivalent to the concentration of the lowest calibration standard, assuming that the lab has used all method-specified sample weights, volumes, and cleanup procedures. The QL is calculated by multiplying the MDL by 3.18 and rounding the result to the number nearest to (1, 2, or 5) x 10^n, where n is an integer (64 FR 30417).
ALSO GIVEN AS:
The smallest detectable concentration of analyte greater than the Detection Limit (DL) where the accuracy (precision & bias) achieves the objectives of the intended purpose. (Report of the Federal Advisory Committee on Detection and Quantitation Approaches and Uses in Clean Water Act Programs Submitted to the US Environmental Protection Agency December 2007).
3. Soluble Biochemical Oxygen Demand method note: First, filter the sample through a Millipore Nylon filter (or equivalent) - pore size of 0.45-0.50 um (prep all filters by filtering 250 ml of laboratory grade deionized water through the filter and discard). Then, analyze sample as per method 5210-B.
4. NWTPH Dx - Northwest Total Petroleum Hydrocarbons Diesel Extended Range – see http://www.ecy.wa.gov/biblio/97602.html
5. NWTPH Gx - Northwest Total Petroleum Hydrocarbons Gasoline Extended Range – see http://www.ecy.wa.gov/biblio/97602.html

From: Brown, Chad (ECY) <CHBR461@ECY.WA.GOV>
Sent: Wednesday, December 07, 2022 2:21 PM EST
To: Gildersleeve, Melissa (ECY) <MGIL461@ECY.WA.GOV>
CC: Bugica, Kalman (ECY) <kbug461@ECY.WA.GOV>
Subject: Notes on EPA Ecology discussion of NC process / PS D.O.

Melissa,
Here are some key points from the outcome of this meeting---

- We explained our key points referenced below.
- After a lot of questions and discussion EPA agrees accepts our approach and accepts that we aren't going to be doing anything special for D.O. in Puget Sound.
- EPA latched on to one of our draft ideas that we could develop NC procedure documents for each parameter type and waterbody. For example. Performance-base process for each D.O.in marine; D.O. in freshwater; Temperature in freshwater; Temperature in Marine (not sure we need)…. And possibly pH in marine and fresh as well. They felt this gave them more approval options in the case the needed to move forward with just marine D.O. I pointed out that they would need a reason, not convenience for there process, to hold back others and move with just marine D.O.
- We identified two questions that Ecology needs to hear from EPA early in this process
    - Will a rule that considers only the NC of waters make it through ESA without any assessment of the species impacts? This is the basis of NC provisions – need to know this is not changing. (EPA R10 staff still seem to conflate NC with site-specific criteria development process in our standards which are based on biology.)
    - Will EPA support a Performance-based procedure that uses state boundary reference inputs? Example- is NC process now going to require that we model oceanic influence to pre-industrial conditions? Ben Cope has been supporting our take on this – he had use reference for incoming water from Canada on the Columbia R. TMDL.
- EPA R10 counsel attended but no legal staff from EPA HQ – Alex Fidis is tasked with bringing the 'decisions' from this meet to EPA counsel and the DOJ.

From: Brown, Chad (ECY)
Sent: Monday, November 21, 2022 5:26 PM
To: Lavigne, Ronald L (ATG) <ronald.lavigne@atg.wa.gov>
Cc: Bugica, Kalman (ECY) <kbug461@ECY.WA.GOV>; Koberstein, Marla (ECY) <mkob461@ECY.WA.GOV>; Gildersleeve, Melissa (ECY) <MGIL461@ECY.WA.GOV>
Subject: Follow-up information from today

Ron,

Thanks for the pre-meeting today. Here is a write-up regarding what we shared with you in the meeting.

Overview or the issue

EPA is asking that Ecology develop site-specific criteria for the Puget Sound within/ or concurrent to our current rulemaking for natural conditions provision. We believe that EPA's own policies and previous decisions work against a defensible rulemaking for Puget Sound D.O. until our current rulemaking is complete. We cannot add this element to the current rulemaking because it is beyond the scope of the CR-101 (attached to this email) which focuses on updating our NC provisions, not proposing any waterbody-specific criteria.

We also don't believe that these 2 rulemakings could be performed concurrently, because a PS D.O. criteria development that incorporates natural conditions would require us to rely on a process that has not yet been adopted into rule nor approved by EPA.

EPA's Current Policy

EPA's current national policy regarding natural conditions is found within *A Framework for Defining and Documenting Natural Conditions for Development of Site-Specific Natural Background Aquatic Life Criteria for Temperature, Dissolved Oxygen, and pH: Interim Document* (EPA 820-R-15-001; February 2015). Prior to announcing our rulemaking, we asked EPA is this guidance document stands as EPA's current methodology regarding natural condition. EPA confirmed this in a response letter to our inquiry. (response letter attached to this email.)

In this document, EPA states that their policy regarding establishing site-specific natural background criteria is that you establish site-specific numeric aquatic life criteria equal to the value of the natural background, where natural background is defined as due *only* to non-anthropogenic sources.

To do this, EPA says that States and authorized Tribes "should include the following [elements] in their water quality standards":

1. A definition of natural background
2. A provision that site-specific criteria may be set equal to natural background
3. A procedure for determining natural background or reference to another documenting describing the binding procedure that will be used.

These three elements are not novel to this document. In 1997, EPA released a memo entitled *Establishing Site Specific Aquatic Life Criteria Equal to Natural Background* (EPA Office of Water; November 1997). In that document, EPA notes that "in setting criteria equal to natural background the State or Tribe should, at a minimum, include in their water quality standards" the same three elements listed above.

Washington's Current WQS

For Washington's current water quality standards, I'd like to walk through each of these three elements:

1. **A definition of natural background.**

   At WAC 173-201A-020 *Definitions*, we define "natural conditions" or "natural background levels" as the surface water quality present before any human-caused pollution.

   Thus, in my perspective, our WQS contains this element.

2. **A provision that site-specific criteria may be set equal to natural background.**

   At WAC 173-201A-260(1) *Natural and irreversible human conditions*, we state that when a water body does not meet its assigned criteria due to "natural climatic or landscape attributes", the natural conditions are the criteria.

   Thus, our WQS contains this element. **However**, this section of our standards was disapproved by EPA in November 2021. Thus, this element is not applicable for Clean Water Act purposes.

   Additionally, we have this element at WAC 173-201A-310(3) in our Tier I protections. Note that this element was**not** disapproved by EPA in November 2021 but has the same identified "flaw" as -260(1) -- that it does not limit application to only aquatic life criteria.

3. **A procedure for determining natural background.**

   The WQS does not contain detailed language for how to determine natural background, as such.

   At 173-201A-430, we provide the steps that must be taken to develop site-specific criteria. This asserts that development of new criteria must be "scientifically justifiable", among other requirements.

   Thus, I am unsure if our WQS contains language that meets the requirements of this specific element.

Chelan UAA consideration

When we conducted the rulemaking for the Chelan UAA, we referred to the temperature criteria that resulted from the UAA as "site-specific criteria". During our preliminary review of the rule with EPA, they had us modify the technical support document to state that the SSC proposed in the Chelan UAA rule was not based on our SSC provision in part 430 of the standards. EPA asserted that we could not site this provision because part 430 must be based on a the biological needs of organisms in the waterbody and not on natural conditions of the waterbody.

When we reviewed our SSC provision, we agreed because it states that…

"The site-specific analyses for the development of a new water quality criterion must be conducted in a manner that is scientifically justifiable and consistent with the assumptions and rationale in "Guidelines for Deriving National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses," EPA 1985; and conducted in accordance with the procedures established in the "Water Quality Standards Handbook," EPA 1994, as revised." EPA, 1985 are procedures for developing biologically-based numeric criteria and do not consider natural conditions.

Therefore, based on EPA's comments and our review of Part 430, we placed the following note in the Chelan UAA rulemaking based on their comments – "Site-specific criteria [*established in this rule*] are used to describe water body specific criteria associated with the highest attainable use analysis and not the process described in CFR 131.11 or WAC 173-201A-430"

Conclusion

To conclude, from a federal perspective, we do not believe that our WQS contains all three elements necessary to establish site-specific criteria set equal to the natural background. While we clearly have a definition of natural conditions, we fail to have a specific procedure detailed on how we will determine natural background. However, even if one considers our site-specific criteria language to be sufficient, our SSC provision in WAC 173-201A-430 is not sufficient for basing an SSC on natural condition, as made clear in the language of the provision and as echoed in EPA's comments regarding the Chelan UAA rulemaking.

Chad Brown | Water Quality Management Unit Supervisor | Washington Department of Ecology
chad.brown@ecy.wa.gov | 360-522-6441 - mobile


Puget Sound Clean Water Alliance
February 28, 2023

Agenda

Time	Content	Speakers
9:00 – 9:10 AM	Introduction	Cassandra Moore Teresa Peterson
9:10 – 9:25	Context: PSCWA and Puget Sound Institute	Joel Baker
9:25 – 10:10 AM	Puget Sound Wastewater Service Affordability Analysis	Aimee Kinney Susan Burke
10:10 – 10:20 AM	Break	
10:20 – 11:15 AM	Overview of Modeling Results • Whidbey Region • Strait of Georgia & Northern Bays Region	Joel Baker
11:15 – 11:45 AM	Draft Modeling Workplan	Stefano Mazzilli
11:45 – 12:00 PM	Vision and Next Steps for PS CWA	Cassandra Moore Teresa Peterson

University of Washington Puget Sound Institute

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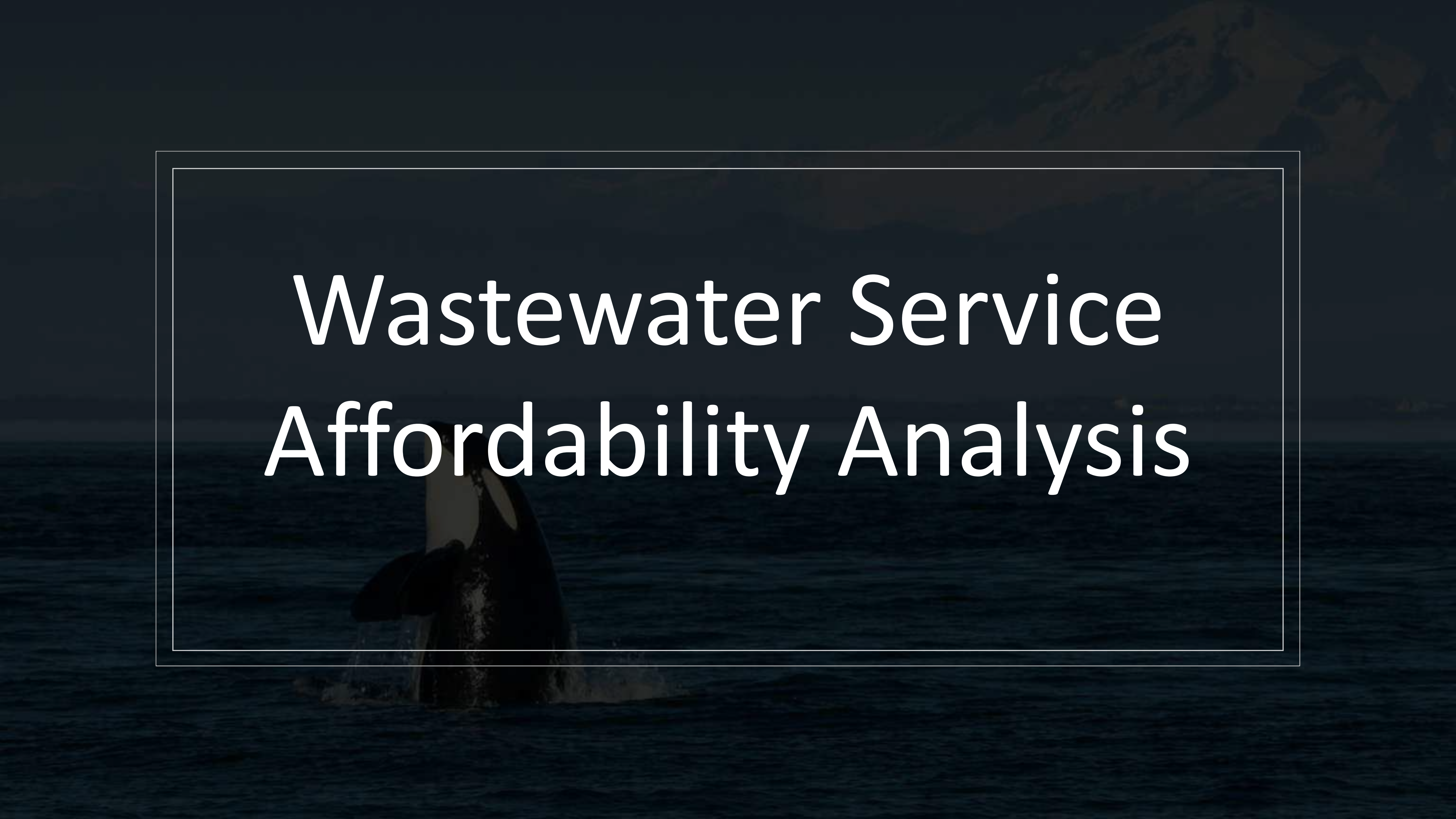
Ongoing Collaboration

PUGET SOUND INSTITUTE

Puget Sound clean water alliance

- Address emerging science needs in the context of utility-scale decision making
- Move beyond nitrogen to consider water quality holistically and proactively
- Collaborate to leverage limited resources
- Provide relevant, timely, and independent scientific analysis
- Connect to cutting-edge research at the University of Washington and globally
- Trusted, scientific journalism
- Coordinate with regulatory and incentive programs

Wastewater Service Affordability Analysis



Wastewater Service Affordability Analysis

Susan Burke, ECO Resource Group & WWU
Aimee Kinney, Puget Sound Institute
Audrey Barber, WWU student
Nate Jo, WWU student
Kevin Bogue, Puget Sound Institute
Sandra Davis, ECO Resource Group

ECO RESOURCE GROUP

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West Point Treatment Plant (Photo: King County)

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THE BELLINGHAM HERALD

HOMEPAGE

Bellingham sewer rates may quadruple. Here's why

BY ROBERT MITTENDORF

MAY 10, 2022 12:10 PM

Questions

1. How “affordable” are current sewer service costs in the Puget Sound region as measured by %MHI and %LQI?

2. How many sewer service providers would exceed a 2% “affordability” threshold if projected increases attributable to PSNGP-required upgrades are added to current service costs?

3. Is the regional distribution of clean water costs and benefits equitable?

    Are costs borne by ratepayers proportional across providers?
    Will all that benefit from clean water pay a “fair” share?

METHODS

Broad regional survey

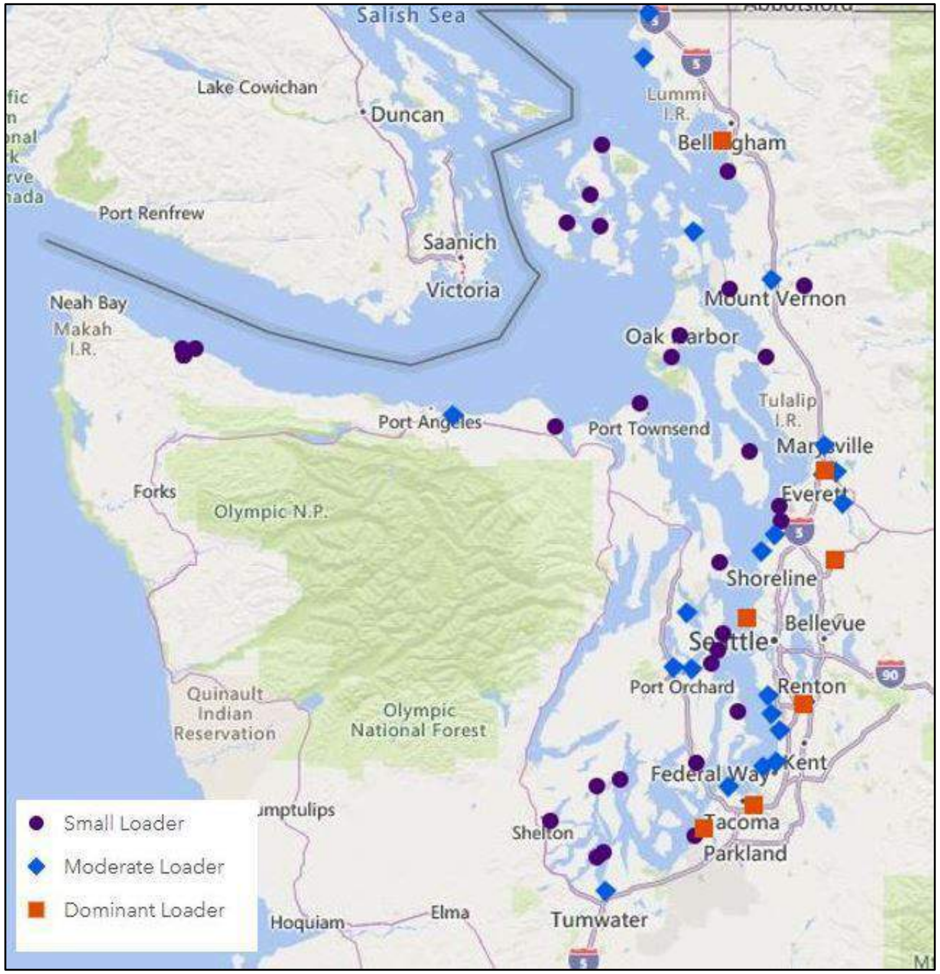
$\neq$

Statistically rigorous for EPA financial capability assessment

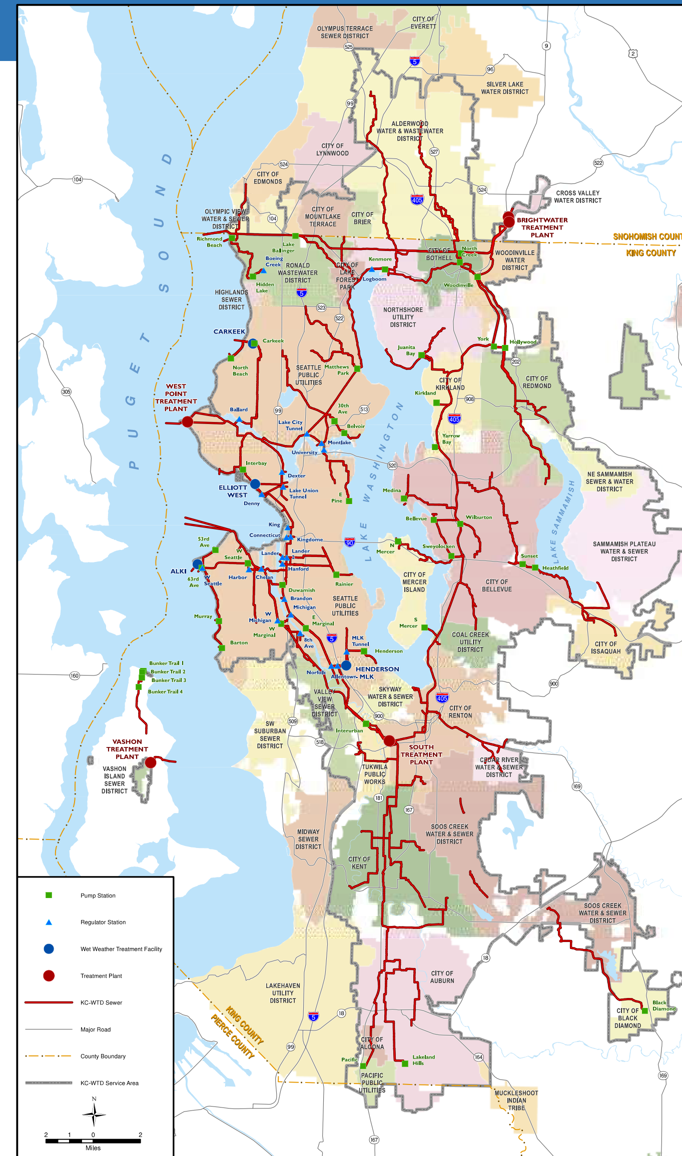
All datasets available open access

https://digital.lib.washington.edu/researchworks/

(1) Identified and obtained service area boundaries for local sewer service providers affected by the PSNGP



WWTPs (n=55)
Permittees (n=40)



Local sewer providers (n=89)

(2) Compiled rate data for local sewer providers and estimated monthly sewer service costs assuming standardized volume (5.5 ccf/household)

	A	B	C	Formula Bar	E	F	G	H	I	J
1	ORGDOHNum	Name/Webpage link	Flat Rate	Number of months in flat rate	Variable Rate	Unit of measure for variable rate (1 = CF, 2 = CCF, 3 = Gallons)	Estimated Monthly Use (based on units of variable rate)	Monthly Flat Rate	Monthly Variable Cost	Total Monthly Sewer Cost
2	01300E	Alderwood Water District	$144.38	2	$0.00	1	5.5	$72.19	$0.00	*$72.19*
3	95904U	Birch Bay Water and Sewer Distr	$22.20	1	$2.90	1	5.5	$22.20	$4.35	*$26.55*
4	418007	Cedar River Water and Sewer Dis	$152.58	2	$0.00	1	5.5	$76.29	$0.00	*$76.29*
5	01450V	City of Algona	$68.02	1	$0.00	1	5.5	$68.02	$0.00	*$68.02*
6	02200C	City of Anacortes	$43.14	1	$0.03	2	550	$43.14	$18.72	*$61.86*
7	03350V	City of Auburn	$75.26	1	$0.00	1	5.5	$75.26	$0.00	*$75.26*
8	97650T	City of Bainbridge Island	$43.54	1	$7.34	1	5.5	$43.54	$40.37	*$83.91*
9	05575B	City of Bellevue	$99.00	2	$5.15	1	5.5	$49.50	$28.33	*$77.83*
10	56003	City of Bellingham	$98.20	2	$0.00	1	5.5	$49.10	$0.00	*$49.10*
11	72207	City of Black Diamond	$72.37	1	$0.00	1	5.5	$72.37	$0.00	*$72.37*
12	07300U	City of Blaine	$115.07	1	$0.00	1	5.5	$115.07	$0.00	*$115.07*
13	07900L	City of Bothell	$139.78	2	$4.63	1	5.5	$69.89	$16.21	*$86.10*
14	08200R	City of Bremerton	$67.23	1	$5.00	1	5.5	$67.23	$27.50	*$94.73*
15	WW_11	City of Brier	$113.78	2	$0.00	1	5.5	$56.89	$0.00	*$56.89*
16	25050N	City of Fife	$90.56	1	$0.00	1	5.5	$90.56	$0.00	*$90.56*

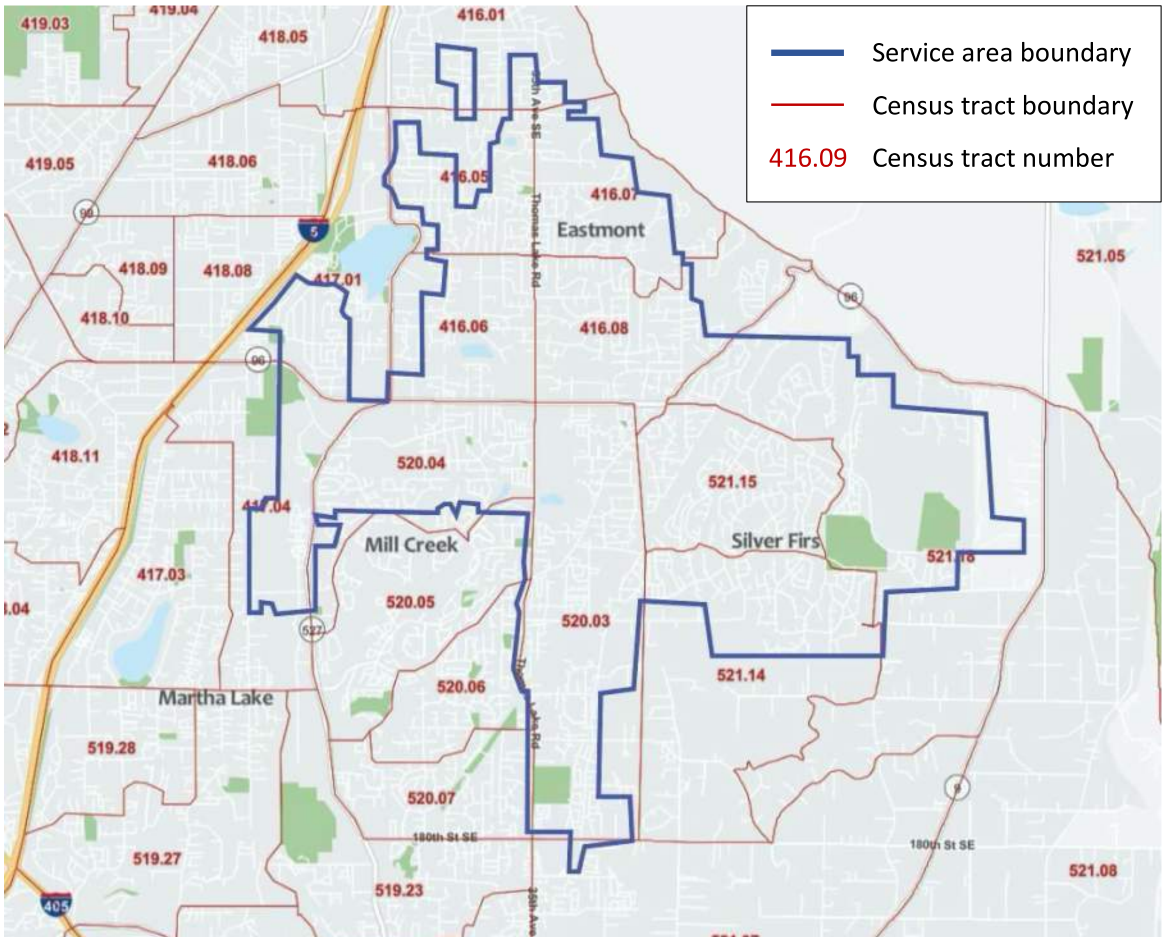
Sources of error:

- Multi-family buildings not included
- State and local utility taxes sometimes incorporated into rates, sometimes not
- Household size and seasonal variation not incorporated into our standardized volume assumption
- Several utilities contacted indicated their actual volumes are higher

(3) Compiled income and population data for 700+ Census tracts

(4) Conducted spatial analysis to correspond service area or city boundaries with Census tracts

(5) Calculated population-weighted MHI & LQI for each service area



Sources: https://www.slwsd.com/servicearea.html and https://data.census.gov/cedsci/table?q=United%20States

Sources of error:

- Service areas and Census tract boundaries differ
- Service area and city boundaries differ
- Households with septic systems within sewer service area not excluded

(6) Calculated annual SFR service cost for 80 local providers as a percentage of MHI and LQI

$$\%MHI = \frac{\text{Annual cost of sewer service}}{\text{Median Household Income}}$$

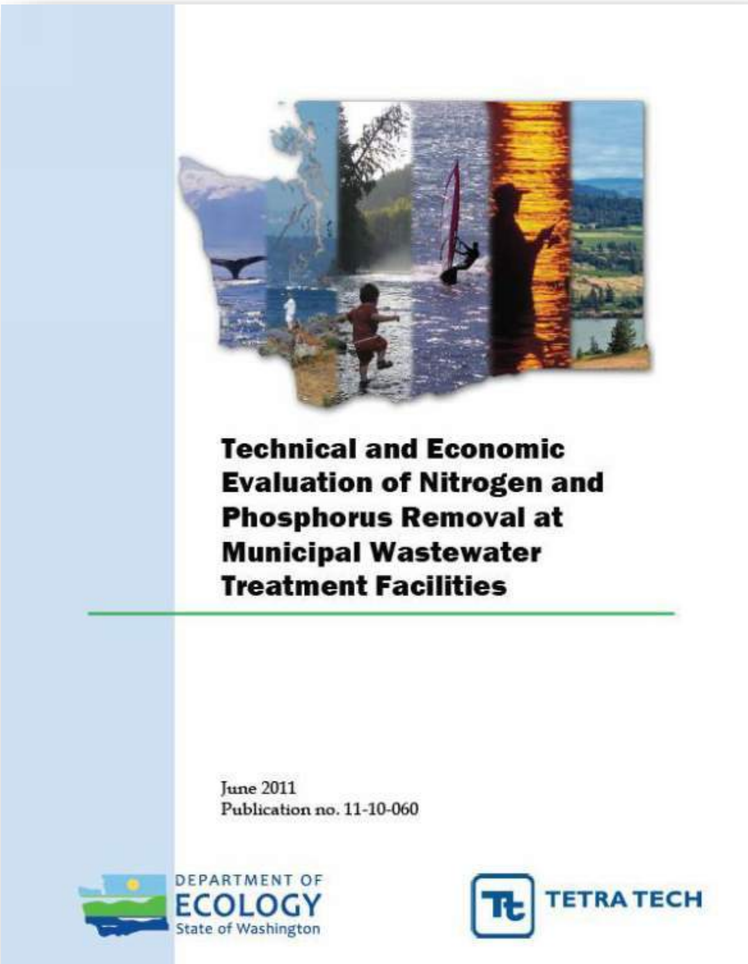
$$\%LQI = \frac{\text{Annual cost of sewer service}}{\text{Lowest Quintile Income}}$$

Sources of error:

- No universally accepted definition of "affordable"
- EPA guidance is in flux, but we elected to present our results relative to the commonly used 2% benchmark

(7) Added predicted monthly cost increase associated with 2 PSNGP upgrade scenarios to service costs estimated in Step 2

(8) Calculated PSNGP-adjusted cost as a percentage of MHI and LQI


Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities

June 2011
Publication no. 11-10-060

DEPARTMENT OF ECOLOGY State of Washington

TETRA TECH

	TIN <3 mg/L year-round	TIN <8 mg/L dry season
$ 2010 [a]	$ 19.48	$ 9.43
$ 2022 [b]	$ 35.36	$ 17.12

Sources:

(a) Table ES-3 of 2011 report

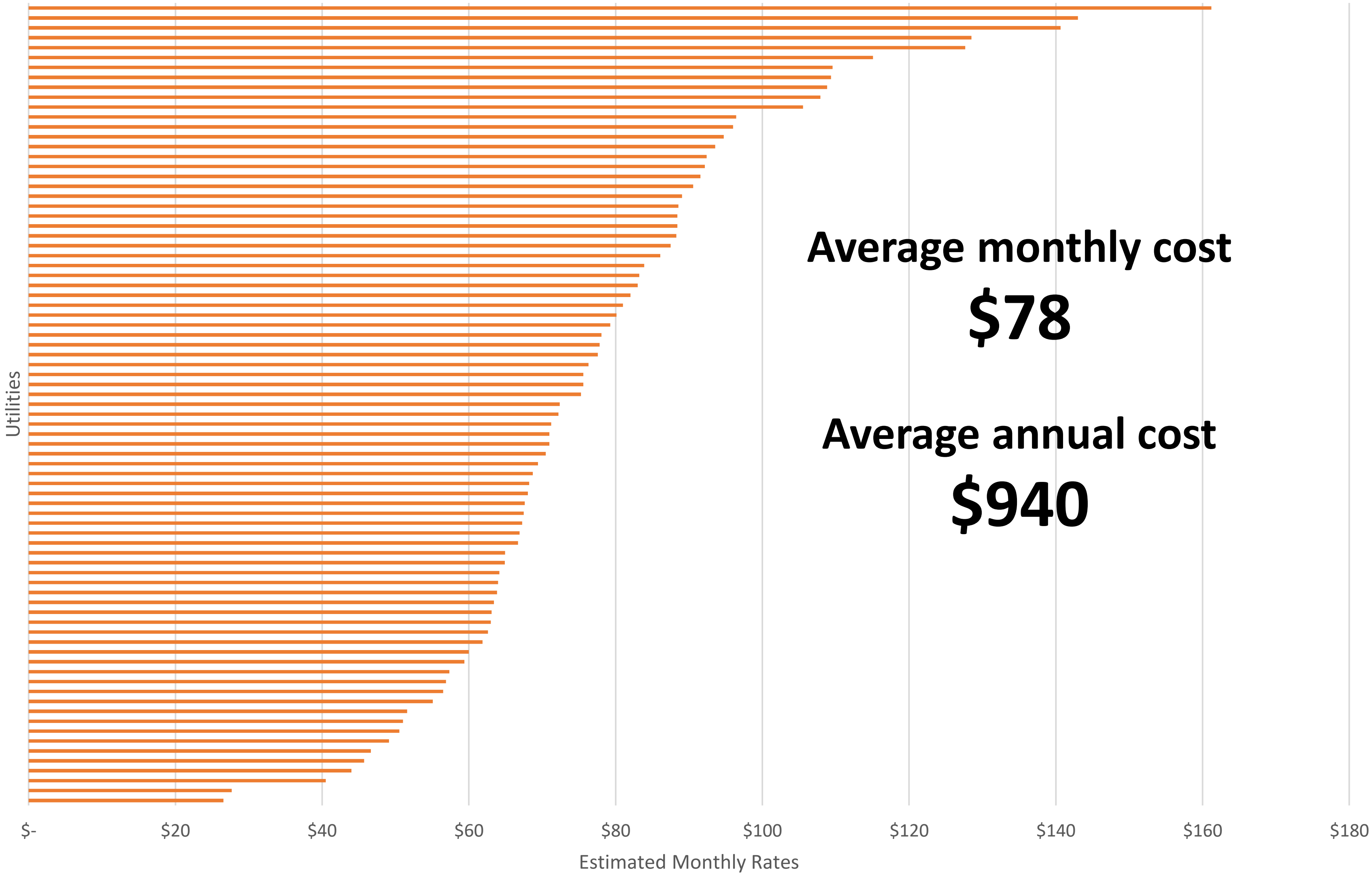
(b) Costs adjusted by inflation factor of 182% (PPI by Commodity: Special Indexes, Construction Materials)

Sources of error:

- Utility Caucus to PSNGP Advisory Committee noted costs will be higher than estimated in the 2011 report
- Projected PSNGP-adjusted cost doesn’t include already-scheduled rate increases needed to accommodate other needs

RESULTS

Monthly wastewater service cost



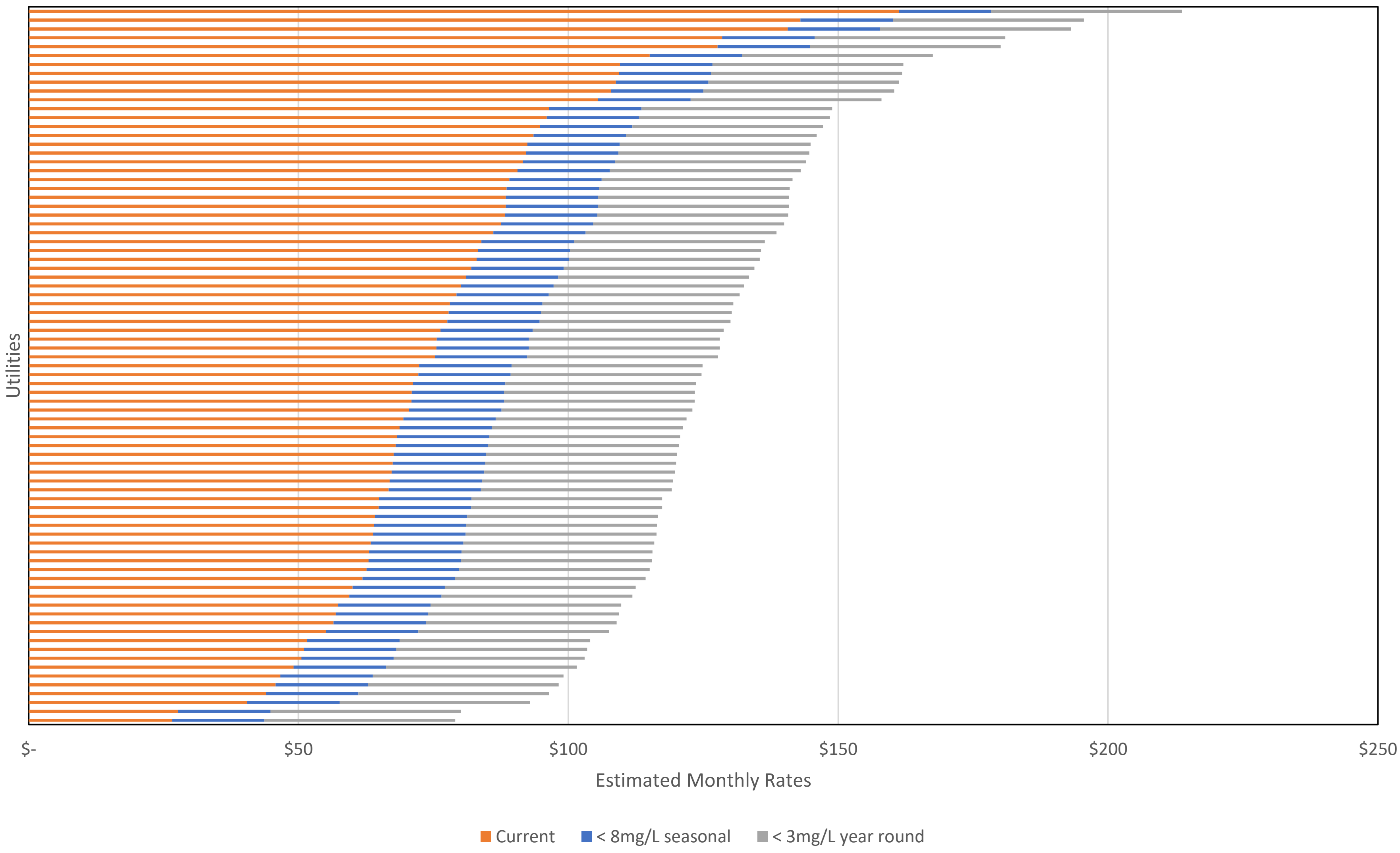
Average monthly cost

$78

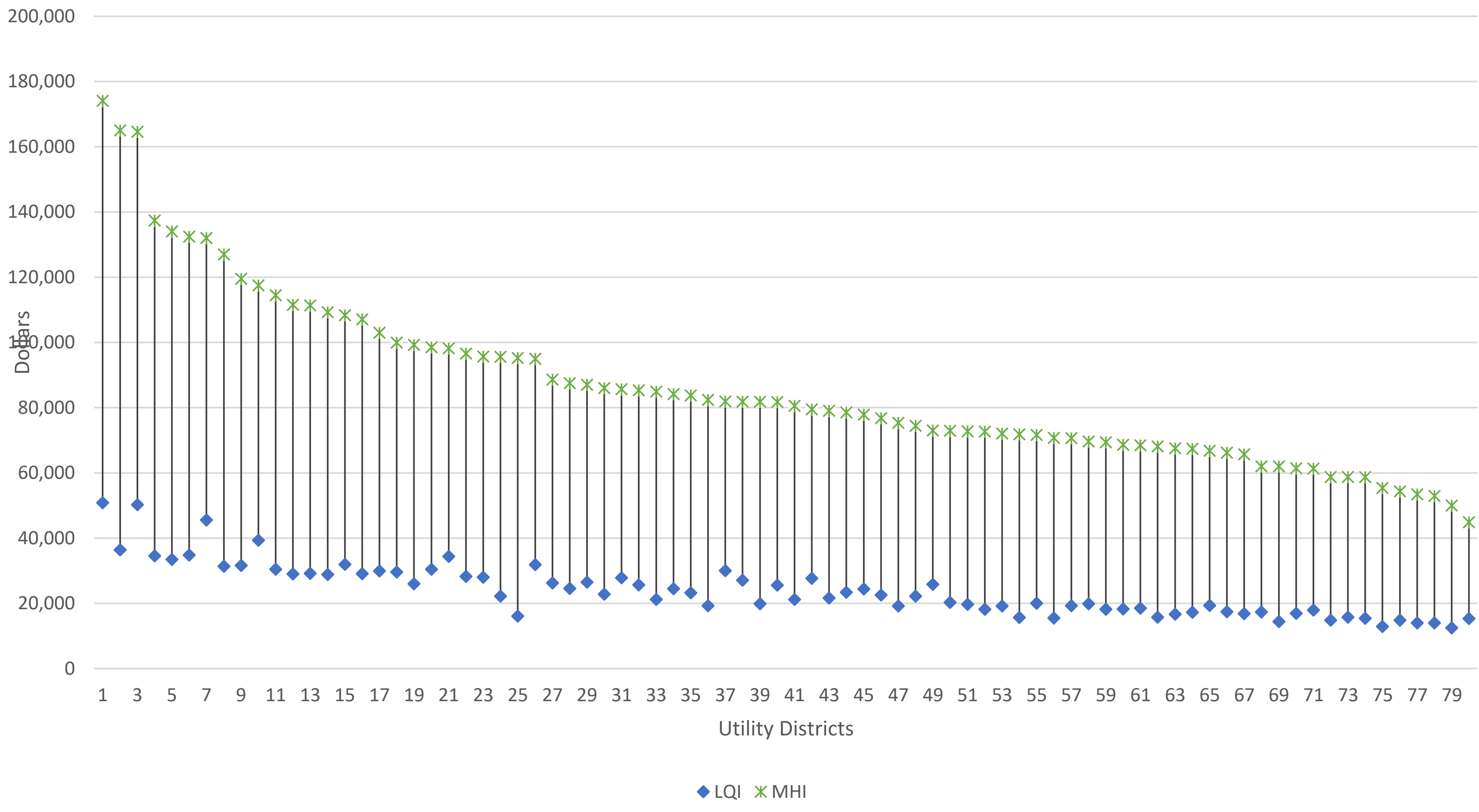
Average annual cost

$940

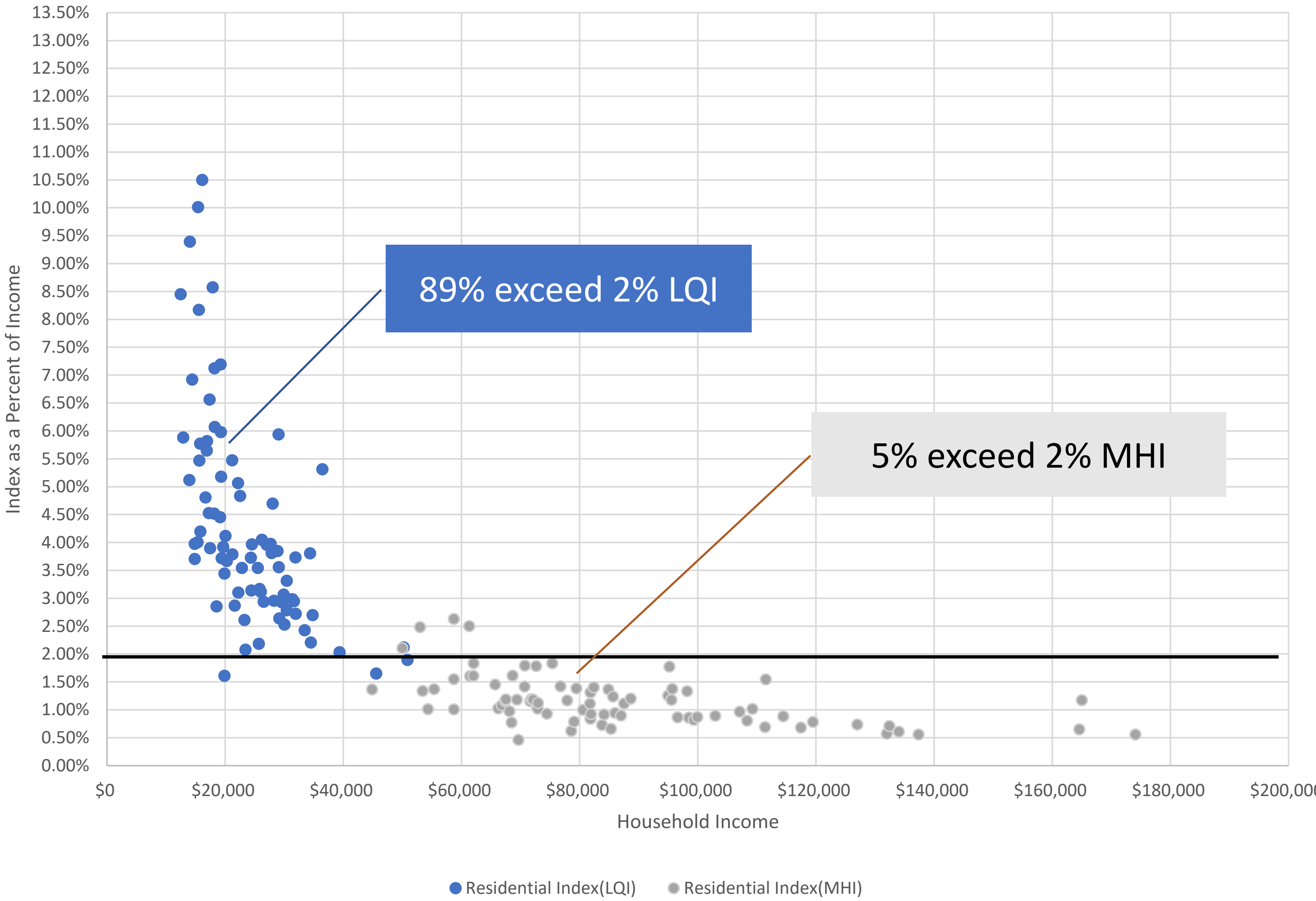
PSNGP-adjusted monthly cost



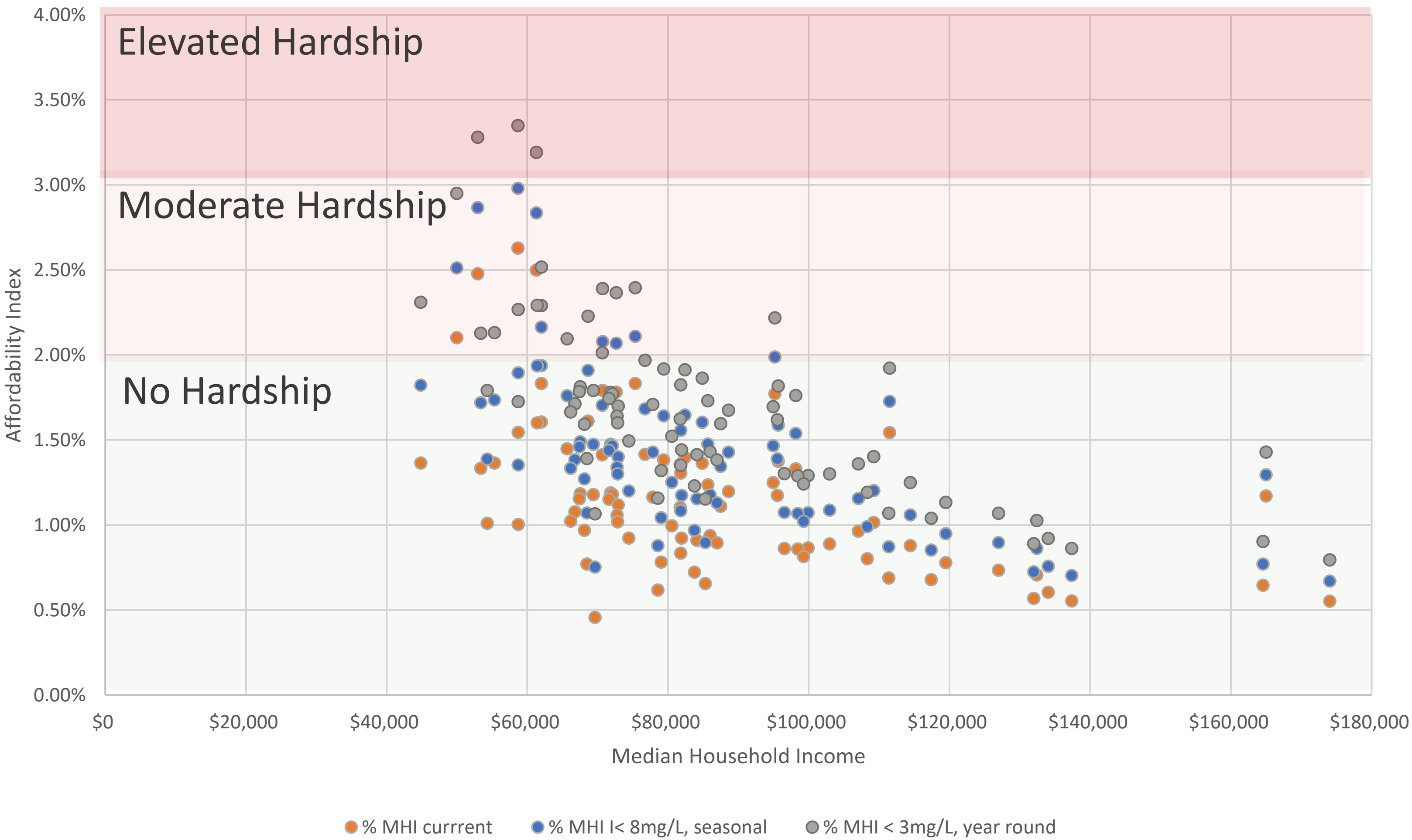
Household Income Ranges



Are current service costs affordable?



PSNGP-adjusted wastewater service costs as %MHI

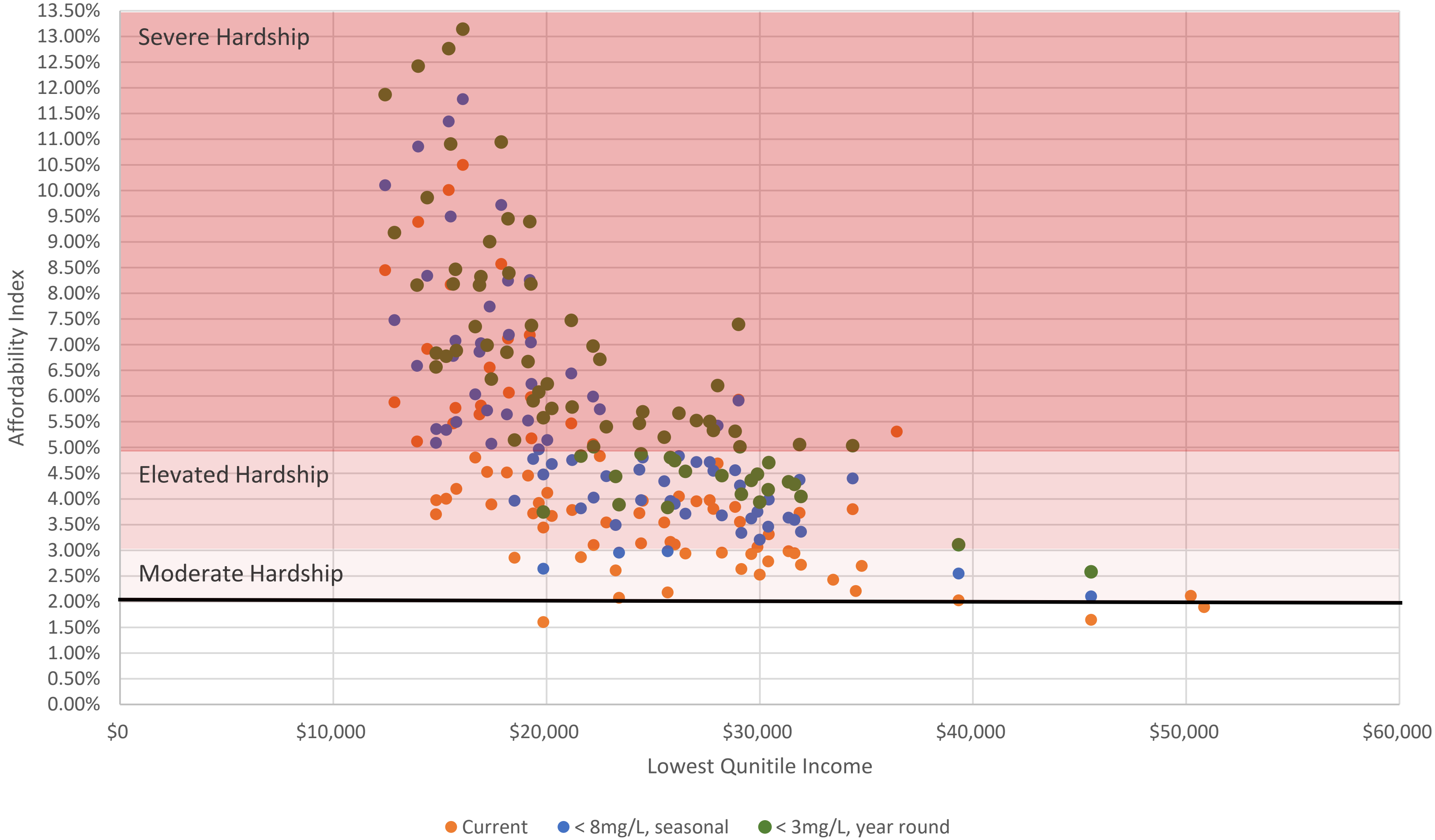


Current
4 hardship utilities (5%)

<8 mg/L seasonal
8 hardship utilities (10%)

<3 mg/L year round
18 hardship utilities (23%)

PSNGP-adjusted wastewater service costs as %LQI



Current
77 utilities >2% (96%)

<8 mg/L seasonal
80 utilities >2% (100%)

<3 mg/L year round
80 utilities >2% (100%)

Conclusion: The number of ratepayers at being billed >5% of their income for sewer service will increase with PSNGP requirements and potentially threaten the financial resiliency of wastewater service providers

Recommendation: Develop a state or region-wide low-income assistance program designed to reduce administrative burdens on and legal challenges to wastewater service providers. LIHWAP/ LIHEAP as model?

Recommendation: Consider a feasibility study on changing rate structures using a financial resilience model

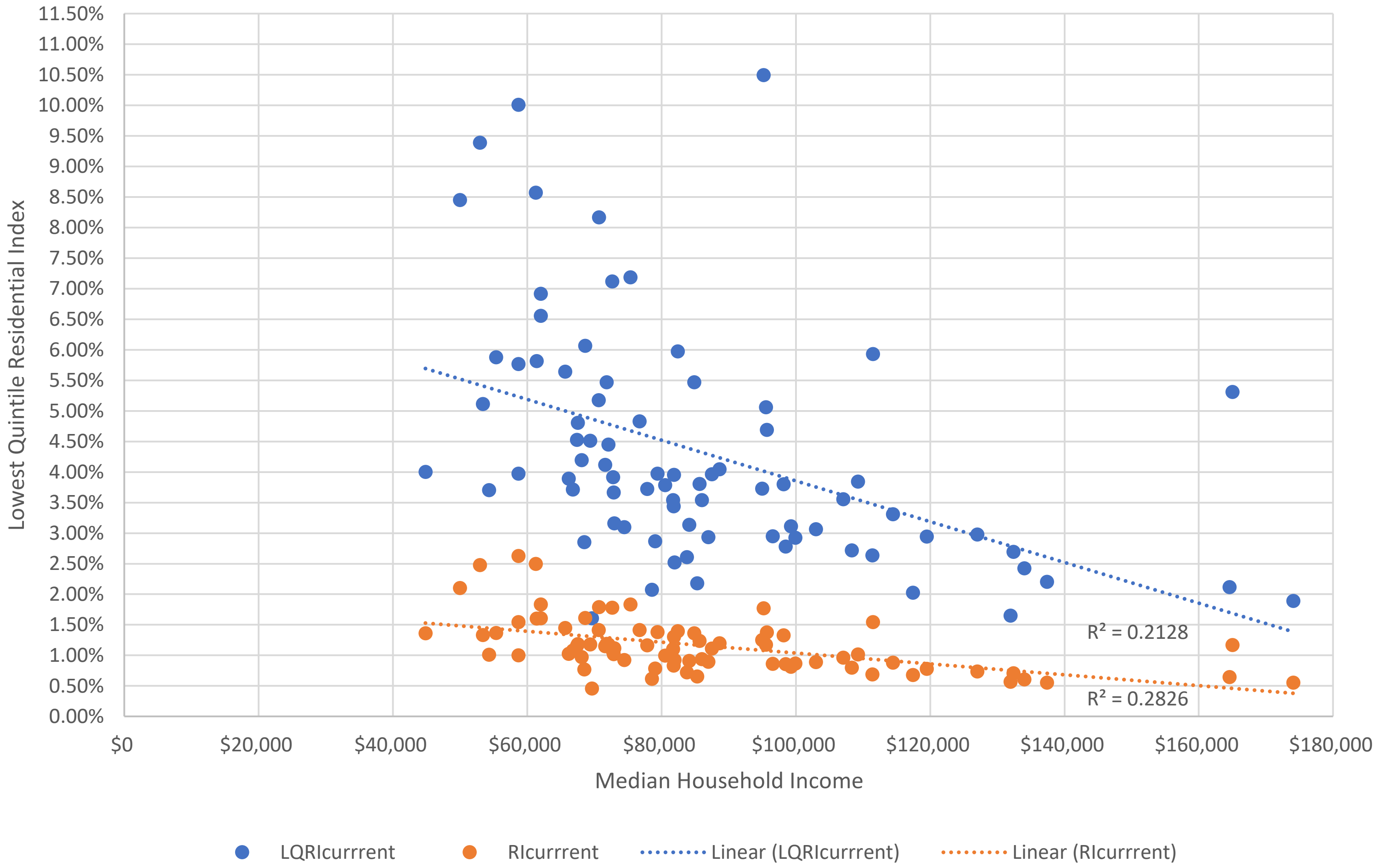

US Water Alliance

Recovering Stronger

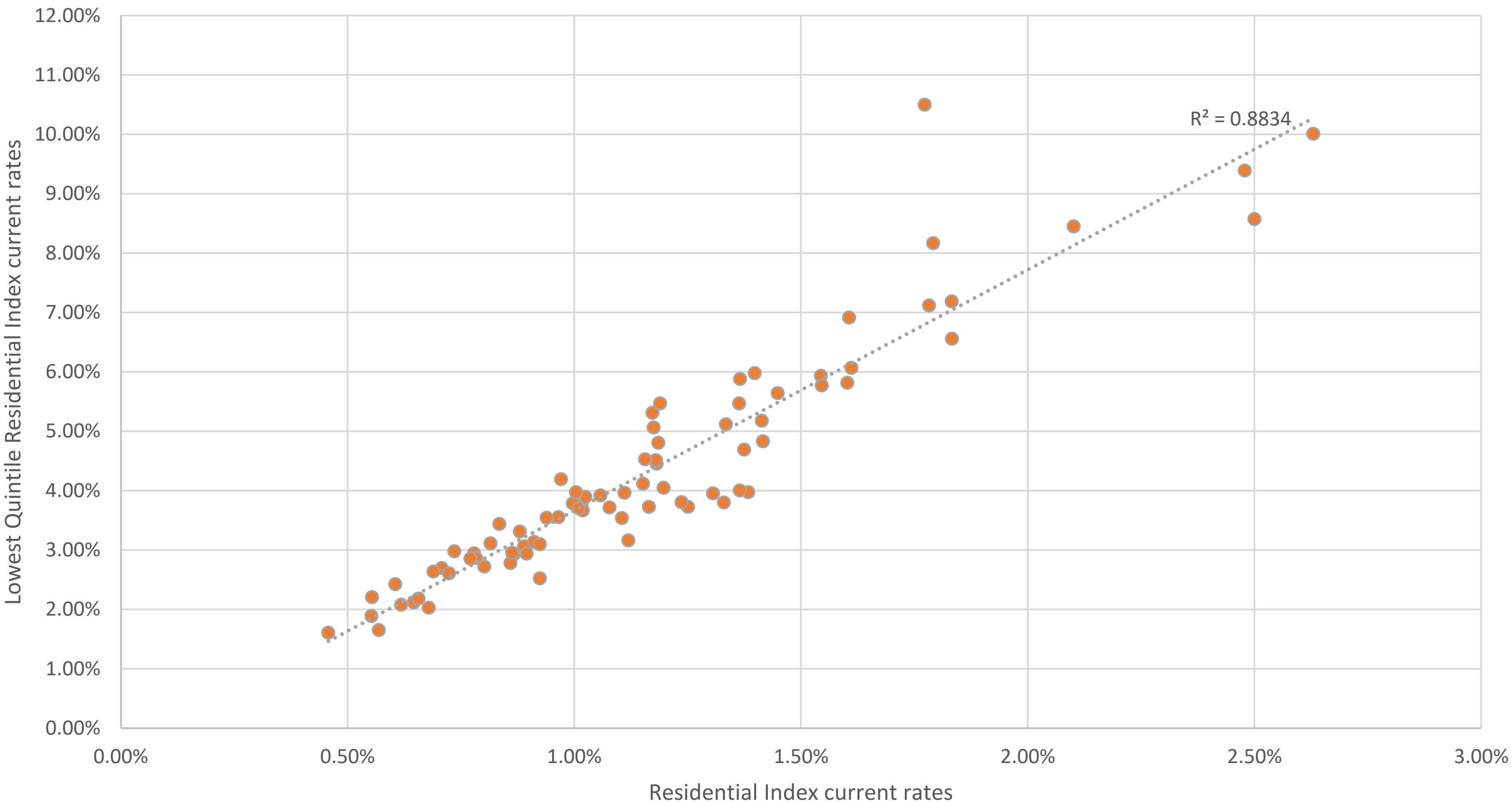
Pricing Water for Public Health and Financial Resilience: An Applied Modeling Pilot

Project Description

Is MHI good proxy for %MHI? NO



Is %MHI good proxy for %LQI?
YES



Conclusion: The criteria used by Ecology to make grant and hardship loan decisions don’t fully address current affordability issues in the region

Recommendation: Use %MHI instead of MHI to allocate Puget Sound Nutrient Grant Program funding among jurisdictions.

Recommendation: Incorporate %LQI as a component of eligibility determinations for CWSRF additional subsidization.

Possible Next Steps?

- Develop a spatial data layer with accurate service area boundaries for all wastewater utilities
- Improve Census tract – service area correspondence methodology
- Compile utility-provided data on number of housing units served residential usage, and current sewer service cost
  - Multi-family housing units
  - Cost of drinking water service (and stormwater fees)
- Compile utility-provided data on already-planned rate increases and those that would be required to cover PSNGP upgrades

Questions and discussion

burkes5@wwu.edu

aimeek@uw.edu

Q&A

Break

Overview of Modeling Results

DEPARTMENT OF
ECOLOGY
State of Washington

Nutrient modeling includes:

- Model scenarios to refine nutrient limits
- Refine watershed modeling for nutrients (SPARROW)

PUGET SOUND INSTITUTE

Advance Model Interpretation, Capacity, & Access

- Launched Salish Sea Modeling Center
- Expanded computational capacity
- Increased access to model outputs by region with:
- Daily results
  - Concentrations
  - Other parameters
- Developed a volume-based metric
- Increased access to model and scripts

Applied modeling to inform utility decisions

PUGET SOUND INSTITUTE

Develop Modeling Tools and Research

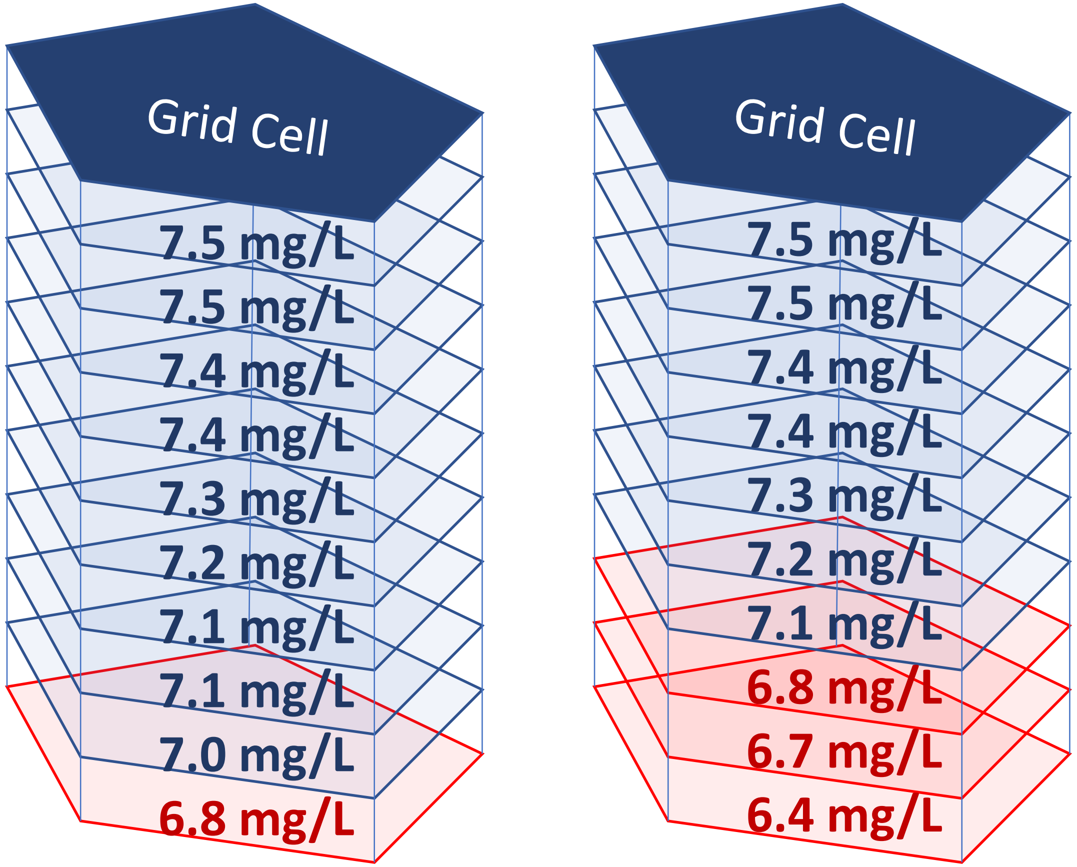
- Leading the Puget Sound Integrated Modeling Framework
- Developing a Toxics Fate and Transport Module
- Evaluating social-ecological outcomes using qualitative ecosystem models
- Coordinating the PSEMP Modeling Work Group
- Convening a Model Evaluation Group
- Facilitating workshops and communicating insights to inform decision making

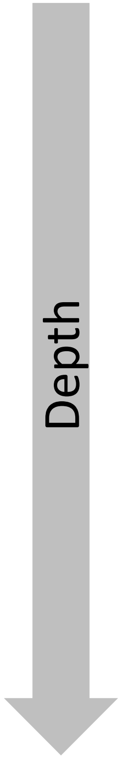
+ Puget Sound Institute's research allows for a more holistic and effective approach to water quality

Volume Days Refresher

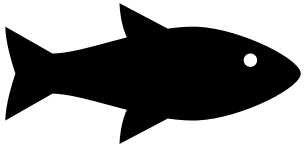
	Day A	Day B
Day	Non-Compliant	Non-Compliant
Area	10 km^2	10 km^2
Volume	1 km^3	3 km^3

- Non-compliant area and days are the same
- Volume is more nuanced and relevant to biological impacts





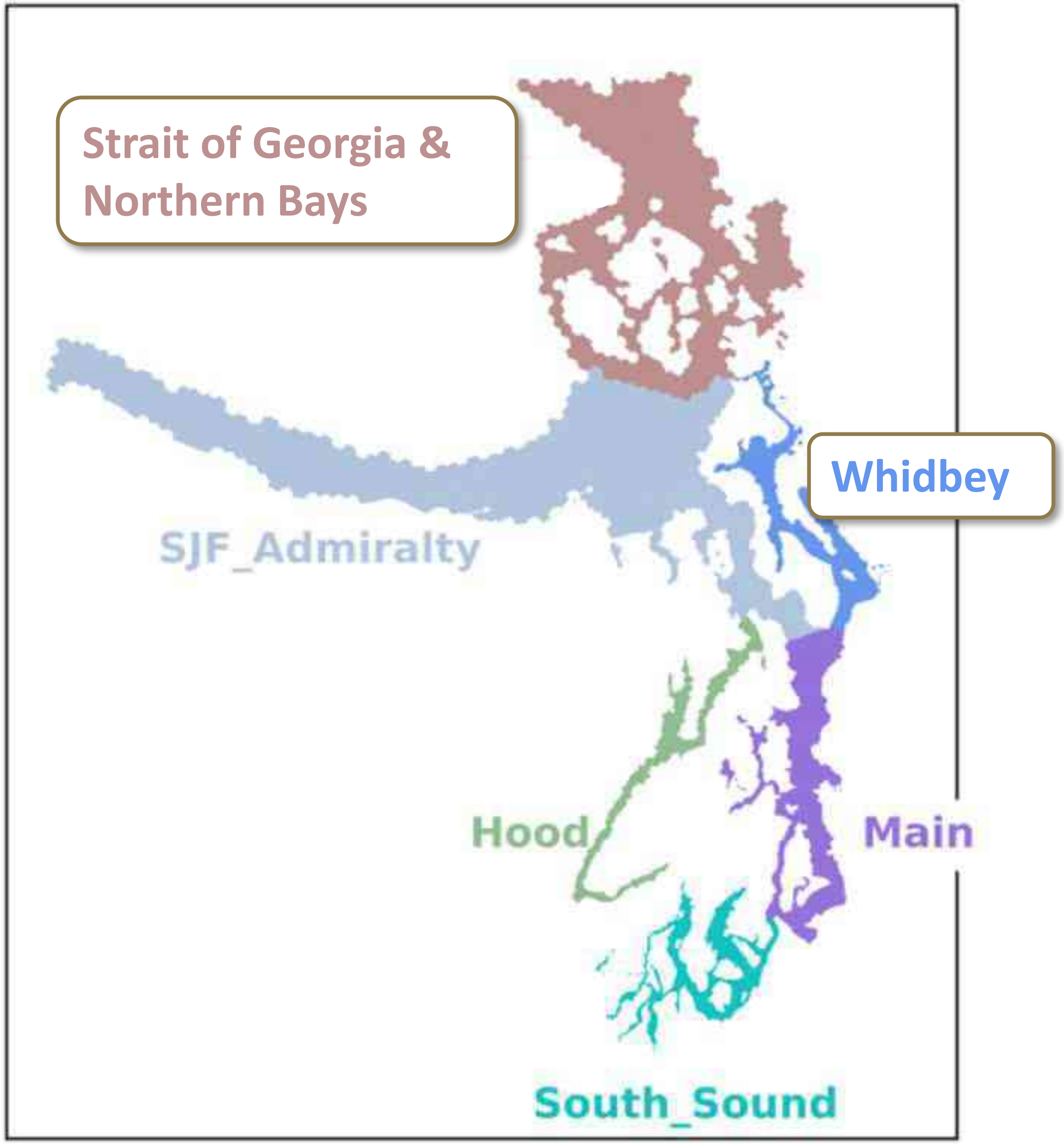
Standard: Excellent 7 mg/L



Red: Dissolved oxygen minimum does **not** meet the standard for any hour

Blue: Dissolved oxygen minimum meets the standard every hour

Regional Reports | Scenarios in 2014



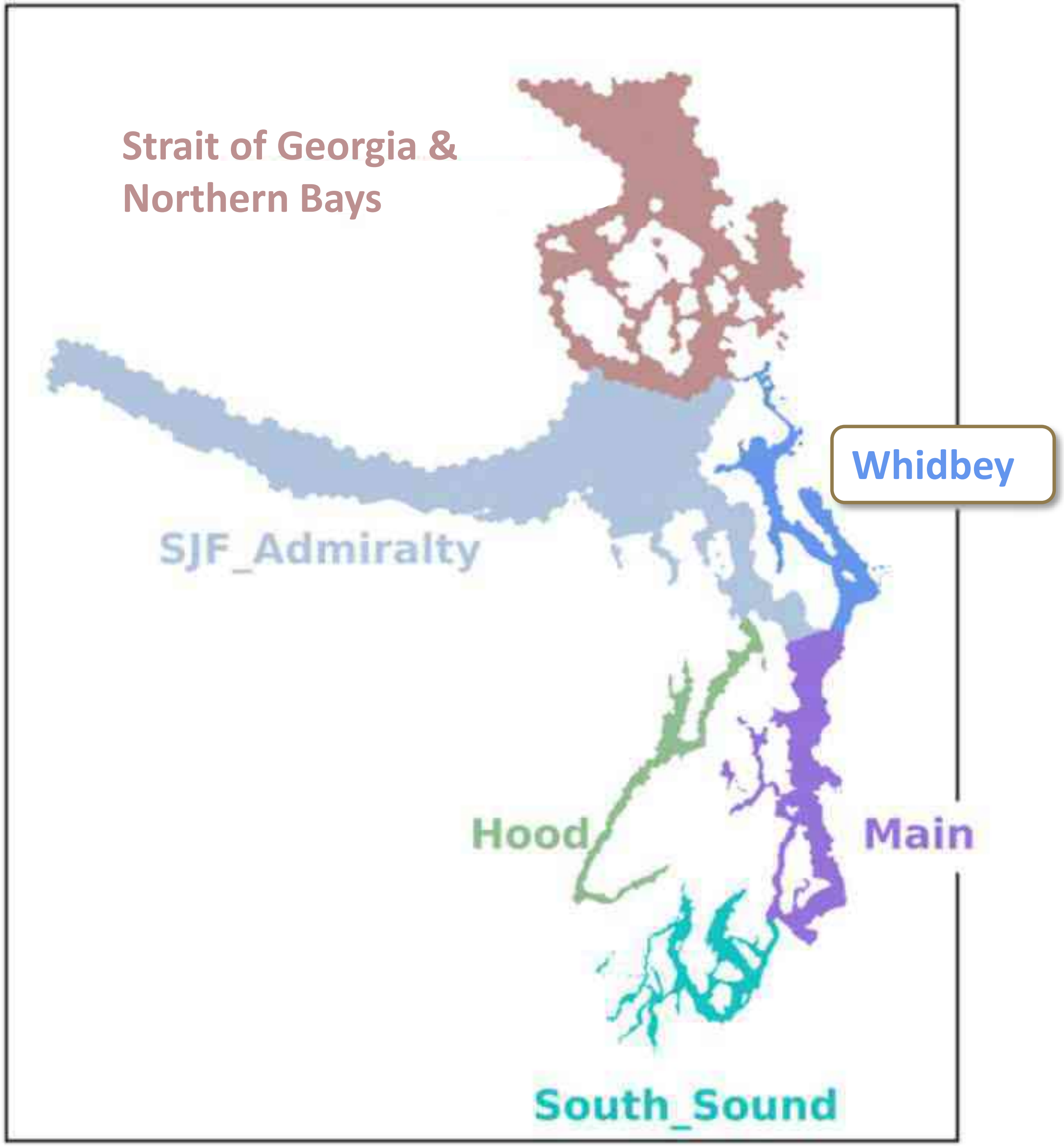
Alter nitrogen concentrations (both NO_2^-/NO_3^- and NH_4^+) for local wastewater treatment plants and rivers, but maintain flows

- Keep concentrations at 'current conditions' in other regions

Maintain other conditions (e.g., hydrodynamics, meteorology, biogeochemical kinetics, ocean exchange, etc.) at their 'current conditions'

Classify wastewater treatment plants as **small, moderate (medium), and dominant** in alignment with the State's permit documentation (issued 12/1/2021)

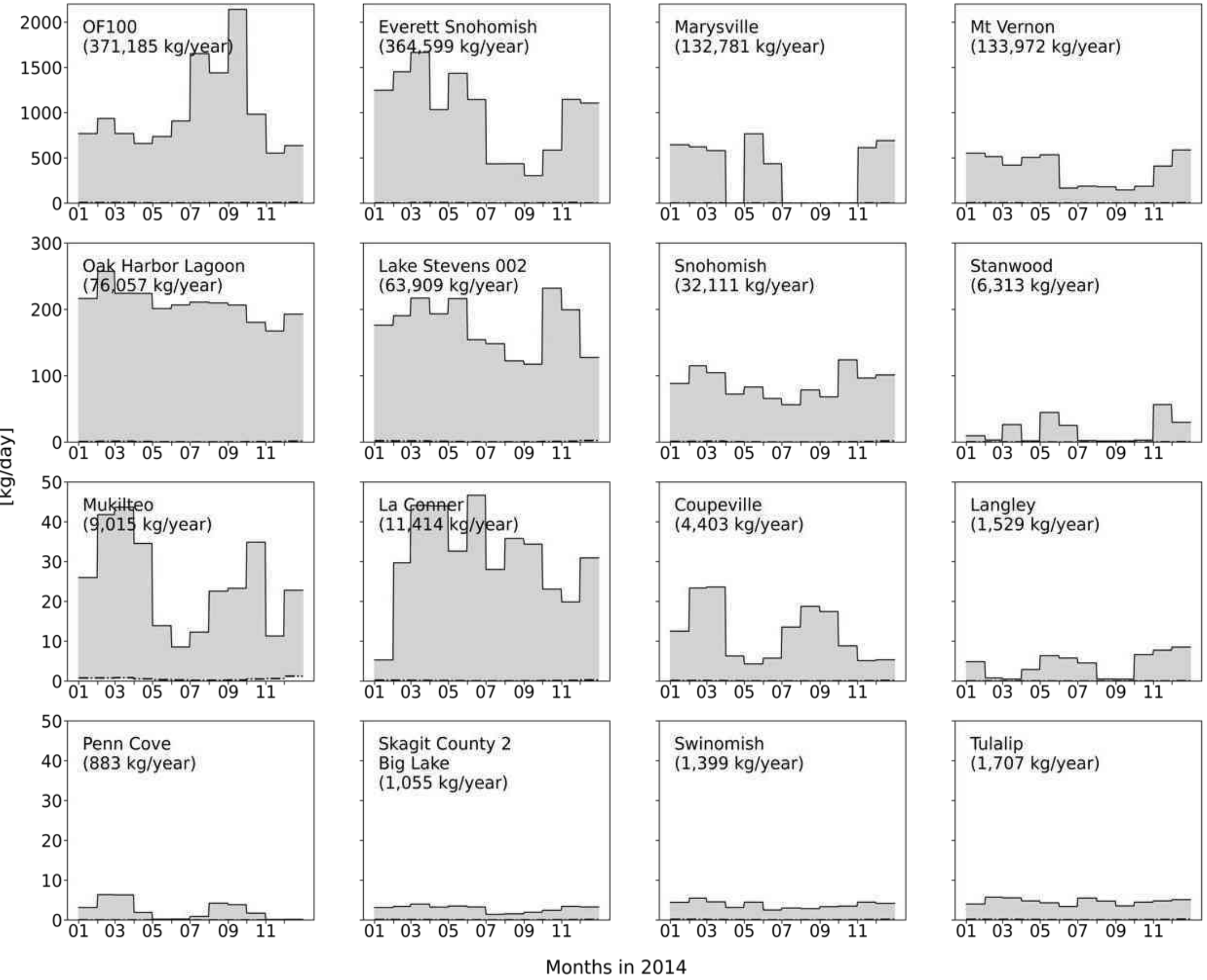
Whidbey Basin



Whidbey Basin| Local Nitrogen Loading in 2014

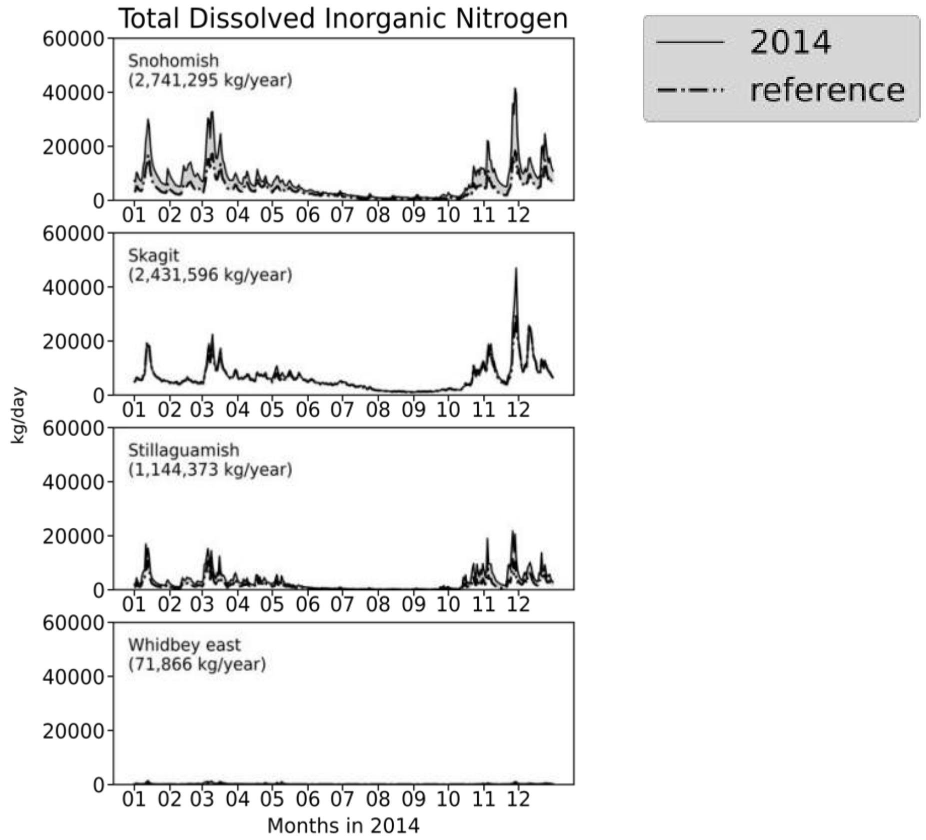
Wastewater Treatment Plants

Total Dissolved Inorganic Nitrogen



River Loading

Total Dissolved Inorganic Nitrogen



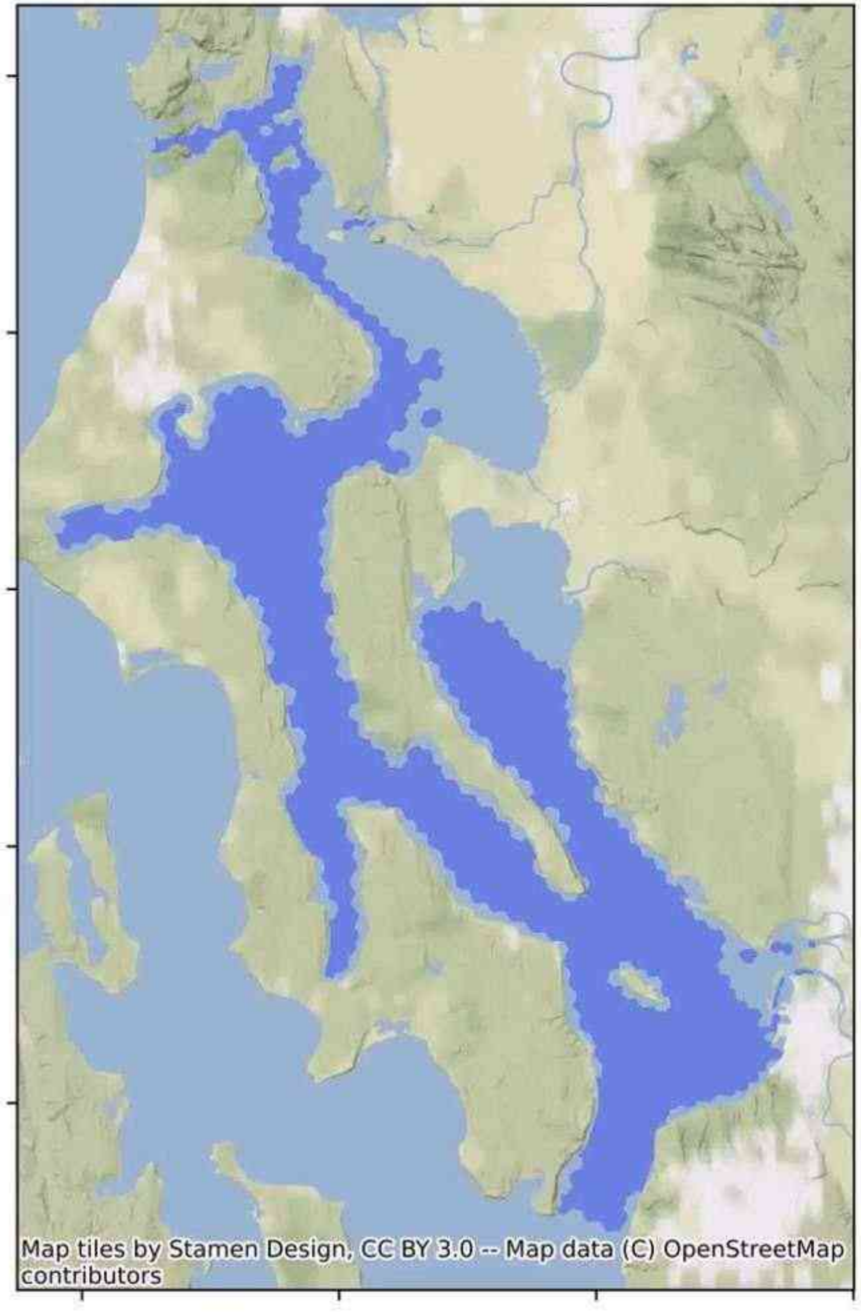
1.2 million kg/year wastewater
2.0 million kg/year rivers, human influence
4.4 million kg/year rivers, natural

Whidbey Basin | Current Conditions in 2014

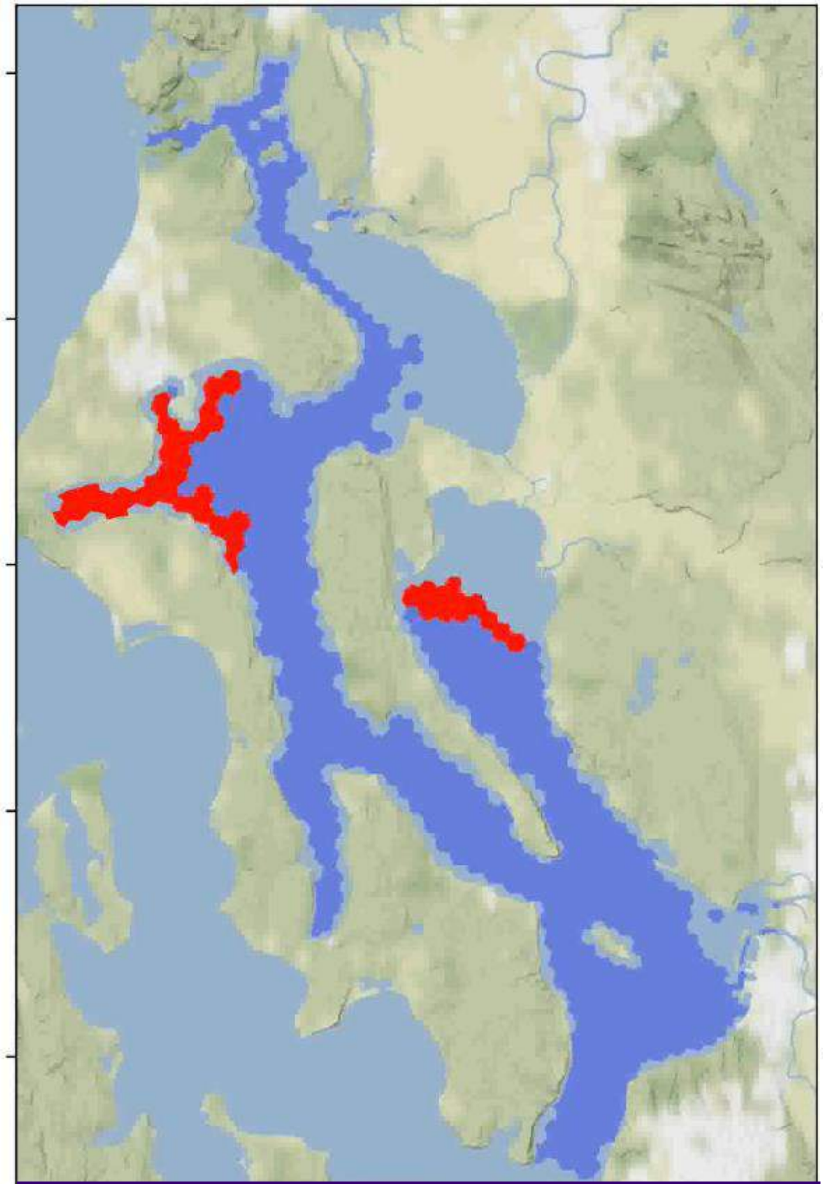
Within Whidbey Basin

- 174 days non-compliant
- Peak non-compliant volume is 3%
  - Non-compliant volume is sustained above 1% for 4 months, peaking in August and September

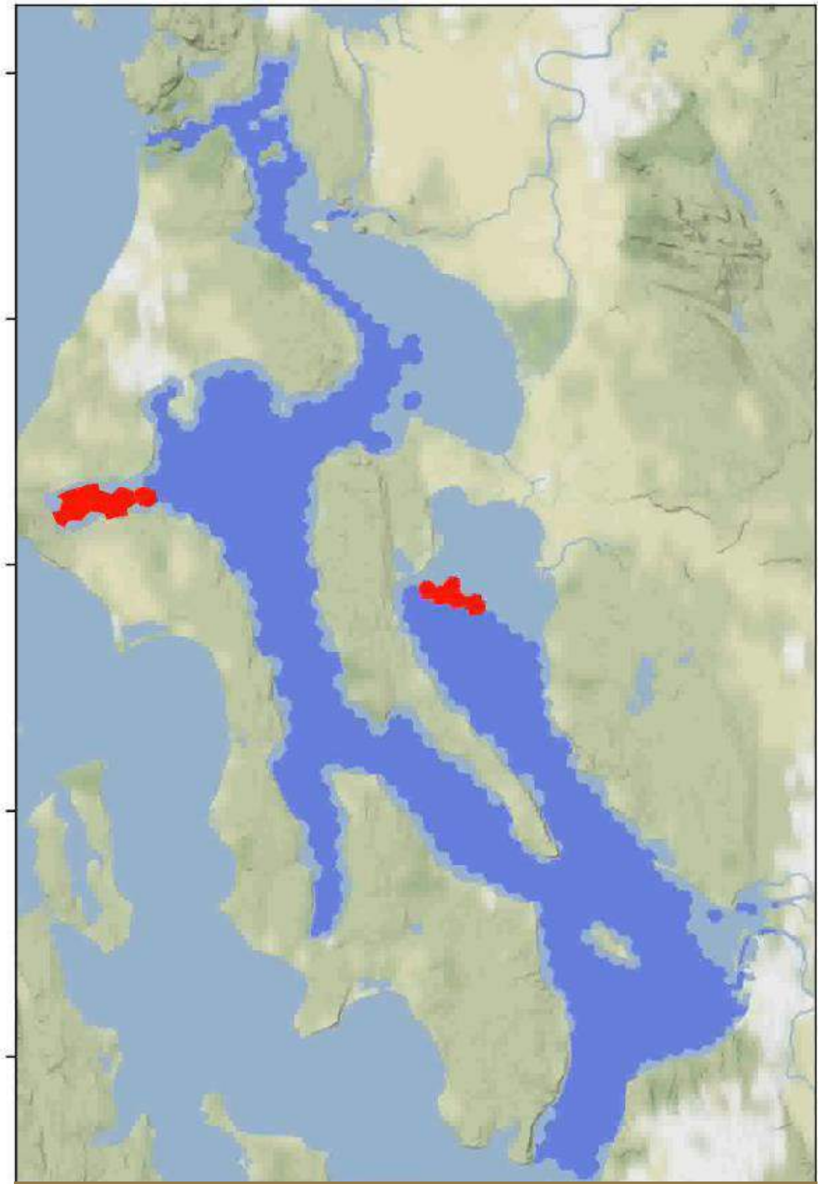
2014 conditions
non-compliant nodes for January 06, 2014



Whidbey Basin | Current vs. Reference



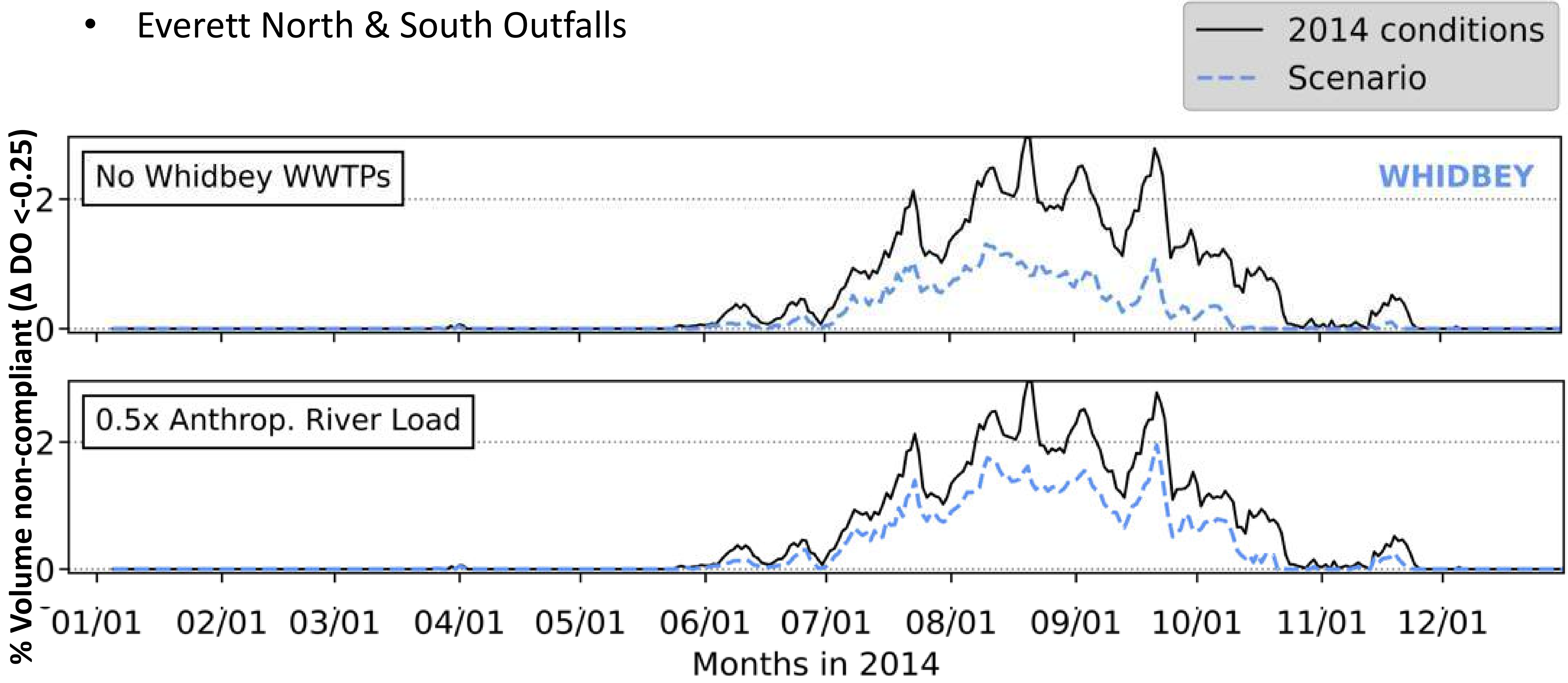
DO < 2 mg/L *Current Conditions*



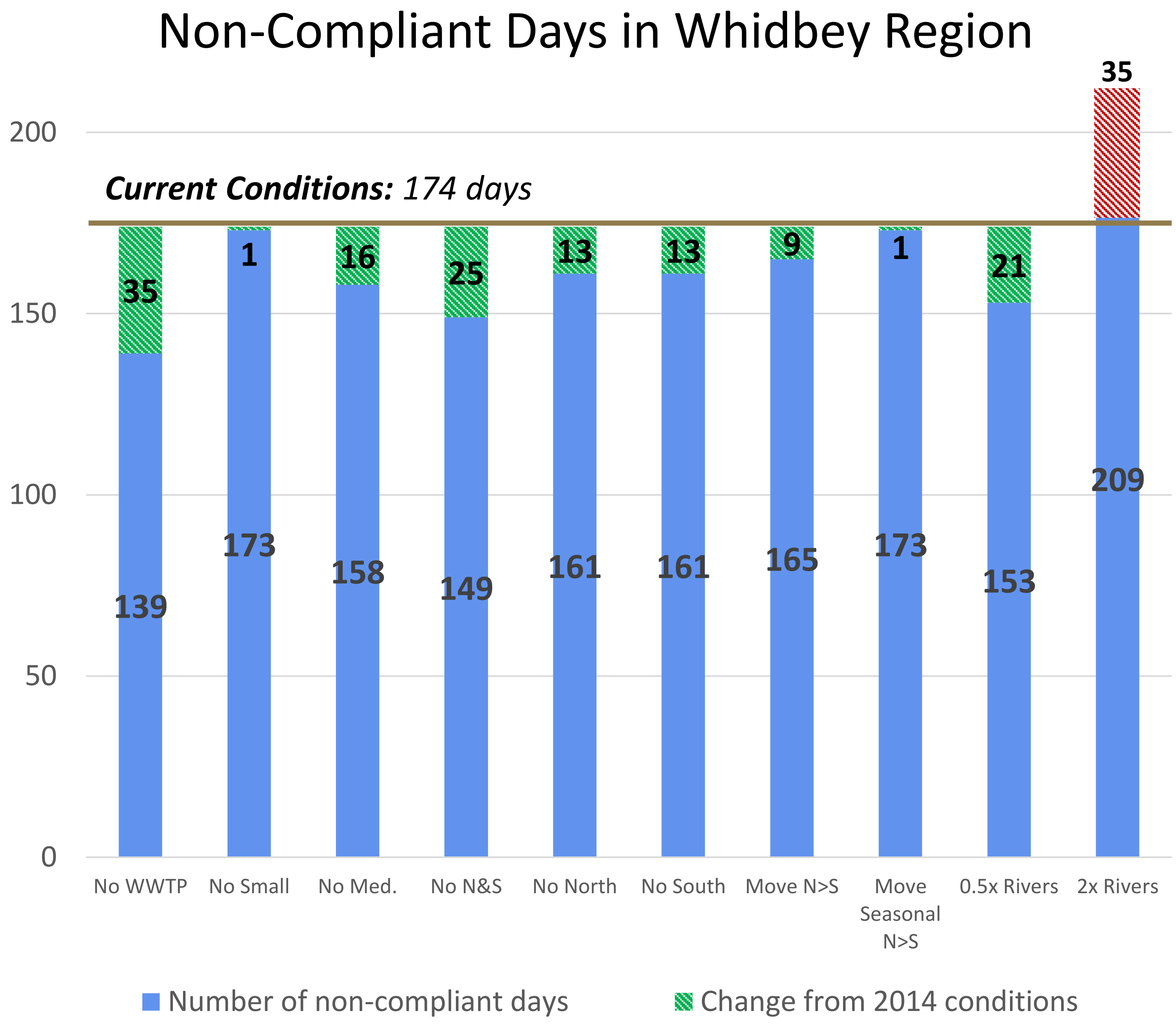
DO < 2 mg/L *Reference Conditions*

Whidbey Basin| Scenarios

- No small, medium, large, or any local wastewater treatment plants
- No local river loading, double river loading, and half the anthropogenic load
- Everett North & South Outfalls



Whidbey Basin| Within the Region



- Eliminating all **wastewater treatment plants:**
  - Reduces non-compliance from 174 to 139 days (↓ 35)
  - Decreases the max volume of non-compliant water from 3% to 1%
  - Shortens the duration of non-compliance by a few weeks
- No demonstrable impact from small plants
- Halving the human contribution to **river** loading:
  - Reduces non-compliance from 174 153 days (↓ 21)
  - Decreases the max volume of non-

Whidbey Basin| Everett North & South Outfalls

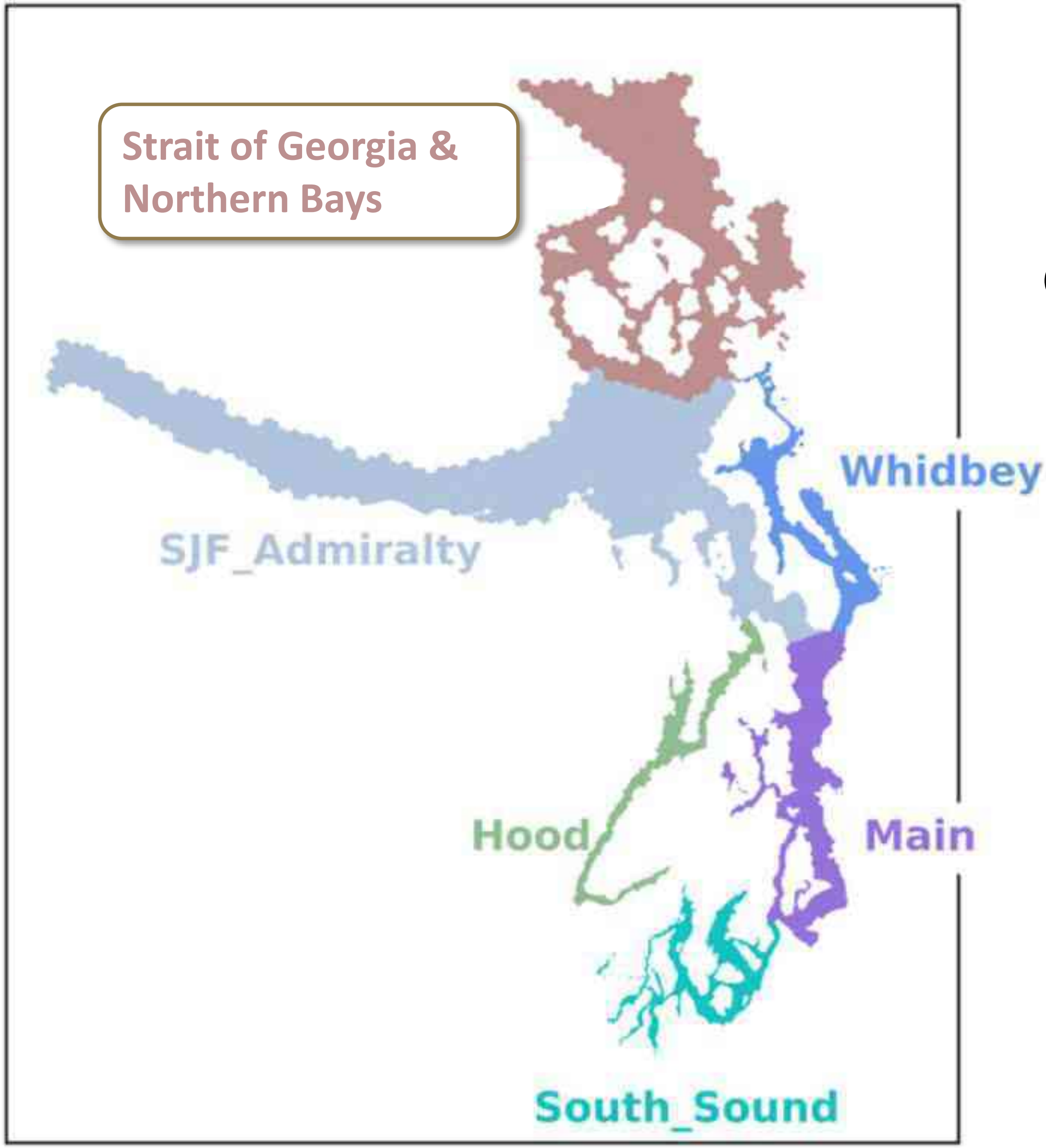
Number of Non-Compliant Days

	2014 Conditions	Wtp4 No N&S	Wtp5 No North	Wtp6 No South	Wtp7 Move N>S	Wtp8 Move Seas.N>S
Whidbey Basin	174	149	161	161	165	173
Hood Canal	146	134	135	142	138	145
Main Basin	162	153	156	160	160	162
Strait of Juan de Fuca & Admiralty	0	0	0	0	0	0
Strait of Georgia & Northern Bays	39	37	37	37	37	39
South Sound	176	176	176	176	176	176

- Everett North & South outfalls have a similar impact on Whidbey Basin
- Everett North & South outfalls, respectively, have a similar influence as all the medium plants collectively
- The North outfall may have a larger influence on Hood Canal and Main Basin despite having a similar load to the South outfall

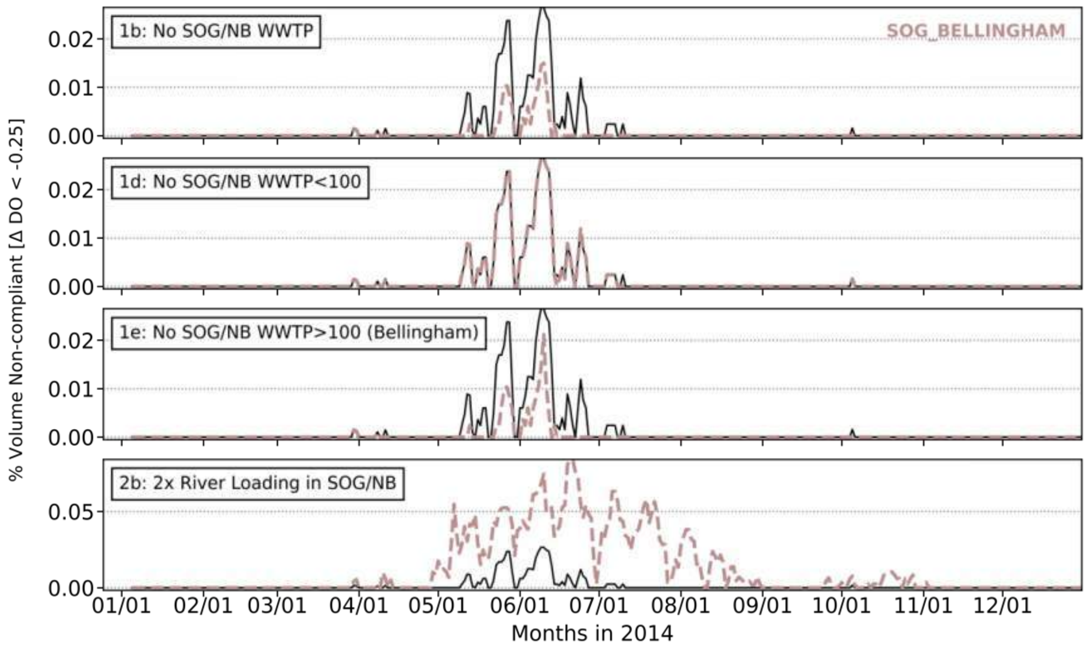
Whidbey Basin| Scenarios

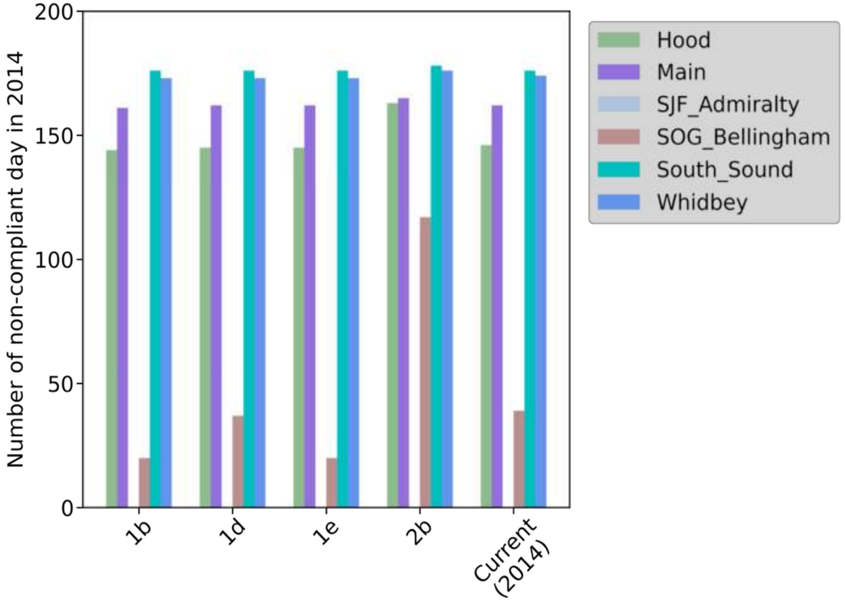
	2014 Conditions	Wtp1 No WWTP	Wtp2 No Small	Wtp3 No Med.	Wtp4 No N&S	Wtp5 No North	Wtp6 No South	Wtp7 Move N>S	Wtp8 Move Seas.N>S	Wr1 No Rivers	Wr2 0.5x Rivers	Wr3 2x Rivers
Days Non-Compliant												
Whidbey Basin	174	139	173	158	149	161	161	165	173	0	153	209
Hood Canal	146	130	145	137	134	135	142	138	145	41	133	207
Main Basin	162	147	162	158	153	156	160	160	162	38	153	185
Strait of Juan de Fuca & Admiralty	0	0	0	0	0	0	0	0	0	0	0	0
Strait of Georgia & Northern Bays	39	36	39	37	37	37	37	37	39	0	36	45
South Sound	176	175	176	176	176	176	176	176	176	103	176	183
ALL REGIONS	229	215	228	223	221	223	224	223	229	115	222	270
Percent Volume Days Non-Compliant												
Whidbey Basin	0.50	0.18	0.49	0.35	0.29	0.37	0.40	0.45	0.50	0.00	0.30	5.05
Hood Canal	0.05	0.04	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.01	0.04	0.25
Main Basin	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
Strait of Juan de Fuca & Admiralty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Strait of Georgia & Northern Bays	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Sound	1.15	1.02	1.14	1.10	1.06	1.09	1.12	1.11	1.14	0.05	1.06	1.79
ALL REGIONS	0.05	0.03	0.05	0.04	0.04	0.04	0.05	0.05	0.05	0.00	0.04	0.26



Strait of Georgia & Northern Bays

Strait of Georgia & Northern Bays | Recap





Within the Strait of Georgia & Northern Bays

- 0.5 million kg/year from local wastewater treatment plants and 2.4 million kg/year from local rivers
- Current conditions in 2014:
  - 52 days non-compliant
  - Peak non-compliant volume is 0.025%
  - Primarily in May & June
- Eliminating small wastewater treatment plant loads reduced the non-compliance from 39 to 37 days
- Eliminating the largest plant load, Bellingham, reduced non-compliance from 39 to 20 days
- Eliminating wastewater loads from the Strait of Georgia Northern Bays, did not substantially alter conditions in the other five regions (Δ ≤ 2 days)

Q&A

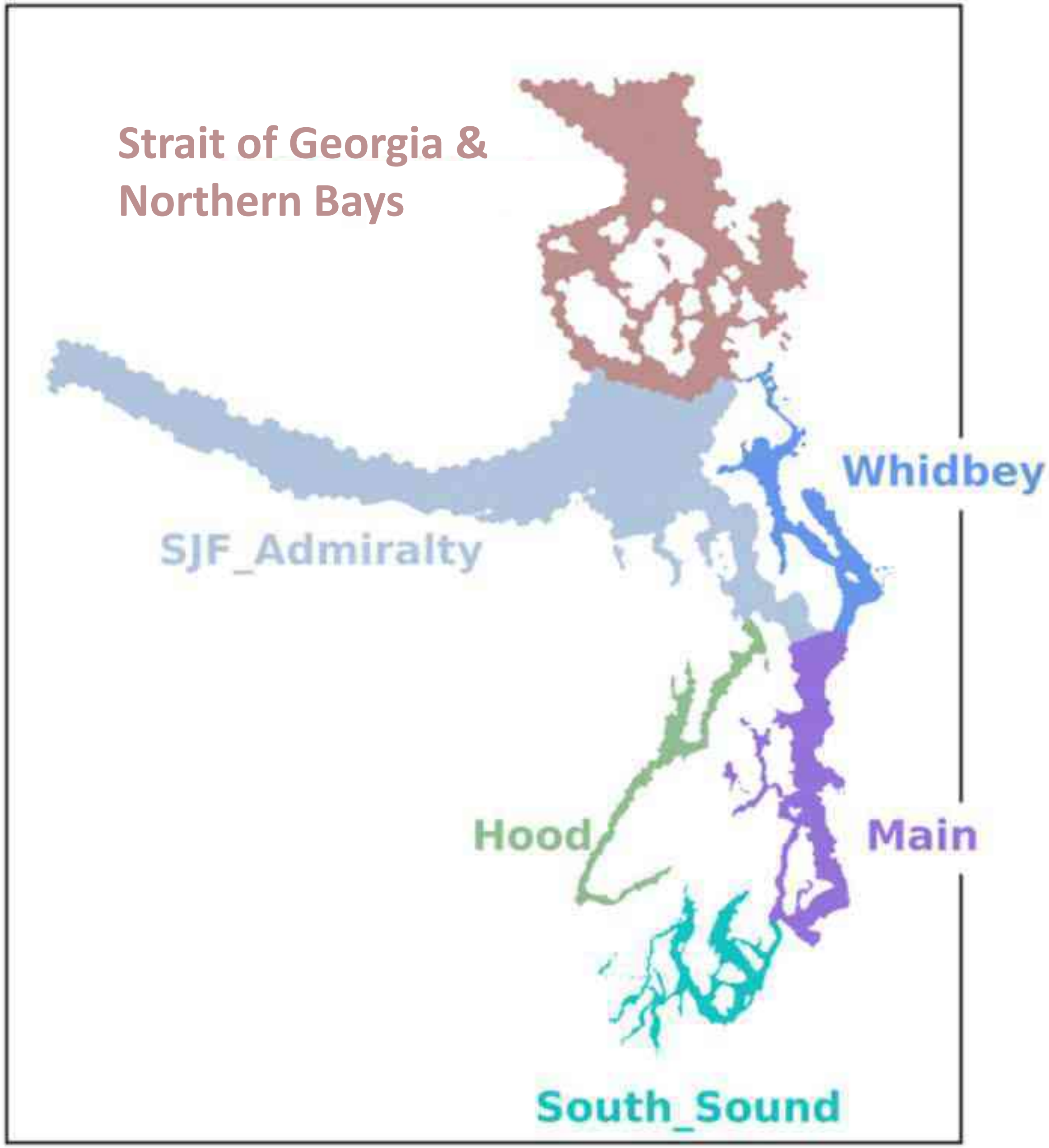
Draft Modeling Workplan

King County Scenarios

- West Point load reduced to 85%, South Plant and Brightwater TIN reduced to 3mg/l
- West Point, South Plant, Brightwater load reduced to 85%
- West Point load reduced to 50%
- West Point load reduced to 0%
- South Plant load reduced to 50%
- South Plant load reduced to 0%
- Brightwater load reduced to 50%
- Brightwater load reduced to 0%
- Green River 50% reduction in pre-anthropogenic loading
- *West Point, South Plant, Brightwater TIN reduced to 3mg/l (April – October only)*

Photo courtesy of King County

Draft Workplan | Regional Reports



- ❑ Main Basin (5 runs)
- ❑ South Sound (8 runs)
- ❑ Hood Canal (8 runs)
- ❑ Canadian treatment plants and river impact on Puget Sound (8 runs)
- ❑ ~~Strait of Juan de Fuca & Admiralty Inlet~~

Each Report Typically Includes

- Baseline (current conditions)
- Pre-anthropogenic (reference conditions)
- No small, medium, large, or any local wastewater treatment plants
- Half the anthropogenic load and double the current loads of local rivers
- + 2 customized scenarios

Draft Workplan | Scientific Engagement & Leadership

- Proactively address water quality issues in the Puget Sound (e.g., PFAS)
- This year, focus code development on dissolved oxygen available to organisms
  - Consider temperature and multiple stressors like climate change

[Presentation by Martha Sutula at The Science of Puget Sound Water Quality workshop on July 26, 2022](#)

STILLAGUAMISH
TRIBE OF INDIANS

stuləgʷábš : People of the River
t: (360) 652-7362 f: (360) 659-3113

May 26, 2023

WA Department of Ecology
P.O. Box 47600
Olympia, WA 98504-7600

US Environmental Protection Agency
U.S. EPA, Region 10
1200 Sixth Avenue, Suite 155
Seattle, WA 98101

RE: The Marine Dissolved Oxygen Water Quality Criteria of WA State

Dear Sirs and Madams,

It is the view of the Stillaguamish Tribe that the Marine Dissolved Oxygen Water Quality Criteria (MDOWQC: Table 210 WAC 173-201A-210 (1)(d)) of WA State are in need of thoughtful, science-based revision. They are outdated, simplistic, and fail to consider the geography and hydrology of Puget Sound. Neither are they based on or referenced with scientific research. The Sound is a fjord-like estuary complex comprised of multiple deep-water basins separated by shallow sills, and many basins terminate in shallow inlets that may also include shallow brackish river deltas. The current marine dissolved oxygen standards are neither reasonable nor realistic and in many locations the standards will never be achieved due to these physical factors.

The State should rewrite the MDOWQC to address the natural seasonal conditions of various waterbodies in the Sound as they relate to the biological requirements of organisms using those habitats. Each type of waterbody (deep basin water, open water, shallow bay water, shallow intertidal, shallow estuary) need standards that match its natural condition for each season. The criteria should include minimums for 7-day and 30-day means in addition to instantaneous values, to address seasonal averages and trends. These conditions can be defined using the results of local science and monitoring efforts.

The state has identified waters not meeting the MDOWQC, yet that determination does not demonstrate the waters are truly impaired. Once appropriate standards are established, it is likely many of so-called water quality exceedances will cease to exist. Currently marine waters with 5 mg/L dissolved oxygen in many deep-water basins are considered non-compliant, when in fact this oxygen level poses no threat to organisms that might be using it. Scientists in the region commonly acknowledge that the harm to a deep-water marine biological community does not occur until the water becomes hypoxic, that is, when oxygen levels drop below 2 mg/L.

Agencies are spending a great deal of focus, time, and money to determine nitrogen inputs and how they move around the Sound. Yet the models used to determine loading and circulation have inadequate inputs for important parameters such agricultural loading and shoreline septic systems. Even as Ecology plans to install nutrient monitoring devices in various watersheds, these devices will mostly be located upstream of agricultural lowlands and/or they will not be measuring total nitrogen. Shoreline residences of Puget Sound that are on septic systems are another potential source of nitrogen that is not measured. Some counties such as Snohomish do not even have regular required inspections and have inadequate inventories of their shoreline septic systems.

While nutrient loading in Puget Sound may be excessive and unhealthy in some locations, we feel that the amount of money, time, and resources spent on nutrients in the marine water are ignoring several other “elephants in the water” that harm wildlife and their habitat. The Tribe is concerned about preventing marine impacts from water quality issues that often lack required treatment and adequate source prevention: storm water, shoreline septics, persistent organic pollutants, and emerging contaminants.

The Stillaguamish Tribe urges the state and EPA to <u>conduct a complete, science-based revision</u> of the Washington Marine Dissolved Oxygen Water Quality Criteria. Because Marine Dissolved Oxygen Water Quality Criteria are driving the listing of impaired waters, these criteria must be based on scientifically defensible methods.

Sincerely,

Sara Thitipraserth, Director
Stillaguamish Tribe Natural Resources Department

Supreme Court No. 102479-7

SUPREME COURT OF THE STATE OF WASHINGTON

CITY OF TACOMA, BIRCH BAY WATER AND SEWER DISTRICT, KITSAP COUNTY, SOUTHWEST SUBURBAN SEWER DISTRICT, and ALDERWOOD WATER & WASTEWATER DISTRICT,

Respondents,

v.

STATE OF WASHINGTON, DEPARTMENT OF ECOLOGY,

Petitioner.

AMICUS CURIAE BRIEF BY BUILDING INDUSTRY ASSOCIATION OF WASHINGTON

BUILDING INDUSTRY ASSOCIATION OF WASHINGTON
Ashli Raye Tagoai, WSBA No. 58883
General Counsel
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Counsel for Amicus Curiae

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<u>CASES</u>

<u>STATUTES</u>

<u>OTHER AUTHORITIES</u>

I. INTRODUCTION

Affordable housing is a luxury in Washington, one which becomes more elusive to average citizens every day. Allowing the Washington State Department of Ecology ("Ecology") to require tertiary treatment at wastewater treatment plants ("WWTP") (or subject WWTP to total inorganic nitrogen ("TIN") load caps in the interim) without following the necessary procedures under the Administrative Procedure Act ("APA") will make owning and building homes in western Washington practically impossible.

The Building Industry Association of Washington ("BIAW" or the "Association") is the trade association for home builders and associated trades in Washington and has firsthand knowledge of the impact that additional wastewater and sewer bills will have upon Washingtonians. Without the Department following the requirements of the APA, and permitting the necessary stakeholders to meaningfully participate in discussions surrounding a requirement to add tertiary treatment, the following will happen: 1) Washington citizens, especially racial and social minorities, will be further unable to afford to purchase or rent homes in the communities where they currently live and work; 2) Washington citizens will not be permitted, nor will they be able to afford to build homes in western Washington counties; and 3) other private businesses and citizens will be detrimentally impacted when working with state agencies regarding rulemaking. For these reasons, this Court should affirm the decision of the lower court, and hold that the Department violated the APA when it issued its directive regarding the total inorganic nitrogen cap load.

II. FACTUAL AND PROCEDURAL BACKGROUND

In the interest of judicial economy, this brief defers to the thorough recitation of the facts and procedural background of this case as provided by the Court below, and the Respondent before this Court.

III. IDENTITY AND INTEREST OF AMICUS CURIAE

BIAW represents nearly 8,000 members of the Washington home-building industry. The Association is made up of fourteen affiliated local associations: the Central Washington Home Builders Association, the Building Industry Association of Clark County, the Jefferson County Home Builders Association, the Master Builders Association of King and Snohomish Counties, the Kitsap Building Association, the Lower Columbia Contractors Association, the North Peninsula Builders Association, the Olympia Master Builders, the Master Builders Association of Pierce County, the San Juan Building Association, the Skagit-Island Counties Builders Association, the Spokane Home Builders Association, the Home Builders Association of Tri-Cities, and the Building Industry Association of Whatcom County. BIAW is one of the largest home-building associations in America, championing the rights of its members and fighting for affordable home ownership at all levels of government. BIAW pursues these goals through several means including legal challenges, legislative and policy work, and through our research center, the Washington Center for Housing Studies ("WCHS"). Additionally, BIAW supports its members by providing awardwinning education, employee healthcare plans, and the state's largest, longest-operating Retro (Retrospective Rating) safety incentive program, ROII[1].

BIAW offers this brief to assist the Court in considering the harmful impacts of requiring tertiary treatment, and/or TIN load caps, at WWTP on homeowners in Washington, as well as the uncertainty created if government agencies are permitted to create rules outside of the APA process.

IV. ISSUES ADDRESSED

1. Whether requiring tertiary treatment, and/or TIN load caps, at WWTP will increase costs to homeowners and result in the denial of permits for affordable housing in Washington.

---

[1] Retro is a safety incentive program offered by the Washington State Department of Labor and Industries ("L&I"). In Retro a participating company can earn a partial refund of their workers' compensation premiums if the company can reduce workplace injuries and lower associated claim losses. *See* About Retrospective Rating (Retro), last viewed March 18, 2024, https://www.lni.wa.gov/insurance/rates-risk-classes/reducing-rates/about-retro.

2. Whether permitting Washington State agencies to create administrative rules and regulations outside of the APA process will create uncertainty in other regulatory agencies like the State Building Code Council ("SBCC") and L&I.

V. ARGUMENT

A. Requiring Tertiary Treatment Will Further Prevent Affordable Housing in Washington

If the Department of Ecology requires tertiary treatment at WWTP in Washington, then monthly housing-related bills will increase for homeowners and renters. Additionally, housing supply will inevitably decrease when this requirement, or a TIN load cap, leads to canceled development permits.[2]

---

[2] Canceled and delayed building permits are not speculative hypotheticals, rather they present a very real risk to affordable housing. A delay in permitting can cost home builders and owners thousands of dollars. Statewide, the average permit delay is six and a half months, costing on average $31,375 in total holding cost. "For every $1,000 added to the cost of constructing a new home, 2,200 families lose their ability to purchase a new home." Andrea Smith, *Cost of Permitting Delays*, Washington Center for Housing Studies – BIAW, https://www.biaw.com/research-center/cost-of-permitting-delays/ (internal quotations omitted). Immediately following Ecology's denial letter stating it would "set nutrient loading limits at current levels…", the City of Tacoma placed "caveats in

Washingtonians, cannot afford additional bills – especially not an additional $500 added on to their monthly sewer bill. Nor can Washingtonians continue to be priced out of opportunities for home ownership, and rentals.

Data shows that Washington State is one of the most expensive states to live in and that the demand for affordable homes to rent and own is significantly greater than the supply.[3]

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building permits allowing the City to 'rescind the permit' in the event Ecology limited the City's treatment capacity by capping nitrogen discharges. This put several major projects in limbo, including multifamily housing developments, a behavioral health hospital, and an expansion at Bates Technical College Medical School." *City of Tacoma v. Dep't of Ecology*, 28 Wn. App. 2d 221, 233-34 (2023) (internal citation omitted).

[3] The expense of home ownership is apparent when viewing the increase in typical home value. Between 2000 and 2023 the increase in Washington was 216 percent. The only seven states higher were Hawaii (309 percent), California (259 percent), Idaho (258 percent), D.C. (254 percent), Florida (248 percent), Maine (240 percent), and Vermont (219 percent). Matt Brannon, *Home Prices vs. Inflation: Why Americans Can't Afford a House in 2024*, Clever (March 11, 2024), https://listwithclever.com/research/housing-inflation-2024/. Further, Washington is now home to 18 cities where the typical home is worth $1 million or more, ranking seventh in the nation for having the most million-dollar cities. King 5 Staff, *Report: Washington now home to 18 cities where the typical home is*

BIAW's research center, WCHS, has been working tirelessly to help inform decision-makers and politicians about the ever-rising costs and barriers to homebuilding, homeownership, and the rental market in Washington. BIAW and the National Association of Home Builders ("NAHB") estimate that a change of less than $1,000 to monthly bills would result in home ownership and renting being entirely unaffordable to most Americans, resulting in increased debt and homelessness. *See* Na Zhao, *NAHB Priced-Out Estimates for 2023*, National Association of Home Builders (March 2023), https://www.nahb.org/-/media/NAHB/news-and-economics/docs/housing-economics-plus/special-studies/2023/special-study-nahb-priced-out-estimates-for-2023-march-2023.pdf.

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worth $1 million or more, King 5 News (April 4, 2024 at 1:21 pm), https://www.king5.com/article/money/washington-home-to-18-cities-typical-home-worth-1-million-or-more/281-3225a860-e9a5-461a-9ab4-982211caabfc.

1. Cost is the greatest barrier for homes to own or rent in Washington.

The population growth in Washington State outpaces and outmatches the available, affordable homes. The Washington State Department of Commerce ("Commerce"), as well as WCHS, have determined, after reviewing the available data, that home ownership is nearly unattainable for most people in Washington. *See*, *Washington state will need more than 1 million homes in next 20 years*, Washington State Department of Commerce (March 2, 2023), https://www.commerce.wa.gov/news/washington-state-will-need-more-than-1-million-homes-in-next-20-years/, *see also,* Andrea Smith, *Housing Affordability In Washington*, Washington Center for Housing Studies - BIAW (March 1, 2024), https://www.biaw.com/research-center/washington-states-housing-affordability-index/. Inflation, an aging workforce, supply chain issues, rising construction costs, regulatory costs, and an ever-increasing cost of living all contribute to the barriers to home ownership and the ability to rent in Washington. The impact, however, of unaffordable housing ultimately lands upon low- and middle-income households, disproportionately affecting minorities - especially Black, Indigenous, and people of color ("BIPOC"), immigrants, LGBTQ2+ individuals, individuals with disabilities, first-time home buyers, and those living outside the nuclear family.[4]

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[4] *See, e.g.,* "Home ownership in Washington has followed a disturbing pattern […] 69% of White families are homeowners compared to only 34% of Black families. Fifty years ago, in 1970, 50% of Black families owned homes." The Racial Restrictive Covenants Project, *Homeownership by race 1970-2022 – Washington State*, Civil Rights and Labor History Consortium University of Washington (last viewed March 18, 2024), https://depts.washington.edu/covenants/homeownership_washington.shtml; "[…] Black, Indigenous, and people of color (BIPOC) would need to buy more than 140,000 houses in the state to achieve parity with white homeownership on a percentage basis. The housing gap is even more significant today than in the 1960s, when housing discrimination and redlining were legal." *Report: Black, Indigenous, and people of color (BIPOC) would need to buy more than 140,000 houses in the state to achieve parity with white homeownership in Washington State*, Washington Department of Commerce (last viewed on March 18, 2024), https://www.commerce.wa.gov/news/report-black-indigenous-and-people-of-color-bipoc-would-need-to-buy-more-than-140000-houses-to-achieve-parity-with-white-homeownership-in-washington-state/ (emphasis added); "According to a 2021 Public Health – Seattle & King County

survey […] 35% of LGBTQ respondents reported earning less than $30,000 per year, which isn't enough to live anywhere, let alone [Capitol Hill]." Rich Smith, *Seattle's LGBTQ Communities Demand Rent Stabilization*, The Stranger (February 22, 2024, 9:00 am), https://www.thestranger.com/olympia/2024/02/21/79395600/seattles-lgbtq-communities-demand-rent-stabilization; "Only 16% of [transgender] people owned their homes, in contrast to 63% in the U.S. population." James, S.E., *et al.*, *The Report of the U.S. Transgender Survey*, Washington, DC: National Center for Transgender Equality (last viewed March 19, 2024), https://calculators.io/national-transgender-discrimination-survey/; "One of the greatest priorities of the Legislature is the work to mitigate the impacts of the housing affordability crisis. […] the crisis remains acute and the barriers to housing are unacceptably high. This is just as true for those with intellectual and developmental disabilities in Washington as it is for everyone else. A recent grant program in the Housing Trust Fund received twice as many applications for more housing in Supported Living as expected, confirming an unmet need for housing continues." Jamila Taylor, *People with disabilities are part of the WA housing crisis, too*, Seattle Times (February 13, 2024, 4:23 pm), https://www.seattletimes.com/opinion/people-with-disabilities-are-part-of-the-wa-housing-crisis-too/; "Small, independently rented residential units with shared kitchen and common spaces may soon be allowed in cities and counties across Washington […] Co-living housing units are similar to dorm rooms, with each sleeping quarters independently rented and other parts of the building shared. […] Housing advocates say co-living is one of the best ways to increase the amount of affordable housing in Washington." Laurel Demkovich, *WA House approves bill to expand dormitory-like housing*, Washington State Standard (February 7, 2024, 12:10 pm), BIAW's Housing Affordability Index, a Washington-based resource for understanding the extent to which county-level housing markets are providing a range of choices that are affordable and attainable to Washingtonians found that "[h]ome ownership is unaffordable for 84 percent of Washington families, based on the median-priced home of $586,100." *See Housing Affordability In Washington*, *supra*. In less than a year, home prices in Washington have increased by 36 percent, rising from an average of $430,000 in June 2023 to an average of $586,100 in March 2024. *Housing Affordability Index: Homes less affordable today*, BIAW (March 11, 2024), https://www.biaw.com/housing-less-affordable/. To afford the current median home prices, BIAW's WCHS has determined that Washington homeowners need to earn approximately $165,100 per year, however, the statewide median income is $90,325 –

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https://washingtonstatestandard.com/2024/02/07/wa-house-approves-bill-to-expand-dormitory-like-housing/.

almost $75,000 less per year than the necessary income to afford a median-priced home.

WCHS's research shows that should a Washingtonian, making the median income, have the necessary downpayment, and qualify for the purchase of the current median-priced home this purchase will result in an average monthly payment of $3,862 (or 51 percent of their monthly gross income) – eking out 49 percent of their income to spend on every other bill a household may maintain including necessities such as food, electricity, water, as well as student loans, and medical debt. Personal finance experts only recommend a household spend 30 percent of their income on housing.[5] Only 16.2 percent of households in Washington can afford median-priced homes with

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[5] The NAHB adopts for purposes of its yearly "Priced-Out" report that the sum of the mortgage payment for a household (which includes principal, loan interest, property tax, as well as homeowners' property and private mortgage insurance premiums) is no more than 28 percent of the monthly gross household income. *See* Zhao, *supra*.

a conventional mortgage, and 83.8 percent of Washingtonians are not able to afford homes with a conventional mortgage.

Inflation also greatly impacts the affordability of homes. In a new study from Clever Real Estate, based on Redfin data, the cost of a typical home in the U.S. is $412,778 - 24 times more expensive than the cost of a home in the 1960s, while inflation is only 10 times more expensive since the 1960s. Ana Teresa Solá, *Home prices rose 2.4 times faster than inflation since 1960s, study finds. What that means for homebuyers*, CNBC (March 19, 2024, 2:12 pm), https://www.cnbc.com/2024/03/19/why-home-prices-have-risen-faster-than-inflation-since-the-1960s.html. This same study found that home prices have risen 2.4 times faster than inflation, pointing out that if home prices had kept pace with inflation since the 1960s, homes would on average only cost $177,500, not nearly half a million dollars. Matt Brannon, *Home Prices vs. Inflation: Why Americans Can't Afford a House in 2024*, Clever (March 11, 2024), https://listwithclever.com/research/housing-inflation-2024/.

Further, the study found that in the 1980s, it took about three and a half years' worth of household income to purchase the typical home. Now, in 2024, it takes six years and four months' worth of household income to purchase the same home. *Id.*

Across Washington, the shortage of affordable homes to own and rent impacts extremely low-income households ("ELI"), whose incomes are at or below the poverty guideline, or 30 percent of their area's median income. Many of these households are spending more than half of their income on housing, and these individuals are more likely than others to sacrifice necessities such as food and healthcare to continue to pay their mortgage or rent, and face the risk of eviction or foreclosure at a greater rate.

2. <u>The Cost of Adding Tertiary Treatment at WWTP Will Prevent More Washingtonians from Affording A Home.</u>

Division III understood the main barrier to the implementation of tertiary treatment – cost. As discussed *supra*, several factors play into housing affordability, however, the cost of monthly, recurring bills such as a sewer or wastewater bill can place housing in jeopardy if increased. The Court below acknowledged the unintended consequences of an interim TIN load cap while a WWTP raises the funds necessary to implement tertiary treatment – halting development, creating a de facto moratorium. *See City of Tacoma*, 28 Wn. App. 2d at 234. A City, such as Tacoma, would have to place conditions on the sewer availability notices leading to impaired lending, and effectively halting most developments including affordable housing, shelters, and accessory dwelling units. *Id.* The answer to many issues in western Washington is <u>more</u> affordable housing, not less. Preventing affordable homes from being built due to sewer limits from the addition of tertiary treatment (or TIN load caps) <u>will</u> force ELI families from urban communities, and further place the fragile Washington housing supply into a "tailspin."

BIAW's WCHS is currently working on a report to be published later this year regarding the cost of Washington water and sewer connections, and the data demonstrates that the average cost of hookups to homes in communities <u>without</u>

tertiary treatment is already $5,601.86. This data is tied to new builds, but costs for sewage and other wastewater exist on a monthly and recurring basis, not including emergencies which are often the responsibility of the homeowner or renter. These costs can severely impact a household's ability to pay all its bills. Nearly all WWTP in Washington State do not currently have tertiary treatment available at their plant, and do not have the current infrastructure to add tertiary treatment without passing on significant costs to the customers they serve or the tax base as a whole.

One of the only WWTP in Washington to implement tertiary treatment, out of several hundred public WWTPs, is the Riverside Park Water Reclamation Facility ("Riverside") in Spokane. Riverside added tertiary treatment based on the Department of Ecology's requirement due to excess levels of phosphorus being released into the Spokane River. *The Riverside Park Water Reclamation Facility*, Spokane City (last viewed April 1, 2024), https://my.spokanecity.org/publicworks/wastewater/treatment-plant/. The addition of tertiary treatment to Riverside was estimated to cost $126 million for the construction alone. *Id.* This figure does not include additional maintenance, testing, and other costs associated with tertiary treatment. These costs must be borne by someone, and inevitably these costs will be borne by those with the least access to the funds necessary to cover these costs, resulting in increased homelessness, and individuals moving further from their work and communities to be able to afford to live.

The City of Tacoma estimates that the addition of tertiary treatment at its WWTPs connected to the Salish Sea will cost anywhere from $250 million to $750 million in construction costs alone. *See*, *City of Tacoma*, 28 Wn. App. 2d at 233, AR 620. The cost of constructing tertiary treatment for WWTPs in western Washington, without formal rule-making processes allowing stakeholders and the public to voice their concerns would render housing even more unaffordable to

Washingtonians. As mentioned *supra*, there are substantial costs to add tertiary treatment or to enforce TIN load caps, and the average Washingtonian cannot afford to cover that cost.

The APA provides the necessary procedures to prevent injustices in the administrative rule-making process – injustices such as allowing underprivileged individuals to bear the burden of cost for the decrease of nitrogen into the Salish Sea. There are alternative opportunities available to ensure the health of the environment while still providing affordable housing in Washington. However, without the salient opportunities for all necessary parties to raise their concerns, opinions, and solutions, there cannot be a world in which we can prioritize both of these goals.

B. Permitting Governmental Agencies to Create State Rules and Directives Without Engaging in Formal Rule Making Under the APA Harms the Citizens of Washington

The APA provides certainty and security to the citizens of Washington. The APA was enacted to "clarify the existing law of administrative procedure, to achieve greater consistency with other states and the federal government in administrative procedure, and to provide greater public and legislative access to administrative decision making. *See* RCW 34.05.001 (emphasis added).

The APA provides certainty to parties, and those participating in an agency's decision-making process, especially regarding the role the judiciary plays in reviewing decisions. For many, knowing that the Washington State Supreme Court sits in the same position as the superior court, applying the APA directly to the same record before the agency, provides great comfort by leveling the proverbial "playing field" for all parties and providing clear, administrable rules. *Dep't of Labor & Industries v. Rowley*, 185 Wn.2d 186, 200 (2016) (citing *Brown v. Dep't of Commerce*, 184 Wn.2d 509 (2015)). This Court has consistently stated that "[r]ules are invalid unless adopted in compliance with the APA." *Northwest Pulp & Paper Ass'n v. Dep't of Ecology*, 200 Wn.2d 666, 672 (2022) (citing *Hillis v. Dep't of Ecology*, 131 Wn.2d 373, 398 (1997)). This Court has acknowledged that "[r]ule making procedures under the APA involves providing the public with notice of the proposed rule and an opportunity to comment on the proposal. These procedures allow members of the public to meaningfully participate in the development of agency policies that affect them. *Id.* (internal citations omitted).

BIAW, and ROII, both participate closely with several State agencies including L&I and the SBCC. Should either of these agencies act similarly to Ecology and enact rules and directives without following the necessary steps under the APA, this decision would be detrimental to both BIAW and ROII's work. Trade associations play a major role in advising members on how laws, regulations, and administrative rules impact their day-to-day operations.

For example, in the building industry, BIAW takes on the task of updating its members on all the changes to the building code when a new code cycle goes into effect. This communication is necessary for several reasons: 1) our members are dedicated to providing the highest quality of products to their clients and need to be aware of the newest regulations; 2) our members are leaders in the building industry and want to be ahead of the curve when it comes to health and safety; and 3) our members are dedicated to building affordable homes for Washingtonians. BIAW staff participate in every SBCC meeting, attend work groups, advise on proposed directives and regulations, and, if necessary, file litigation to protect the rights of our members. BIAW can participate in the rulemaking process because the APA provides the necessary procedures to do so. Similarly, ROII participates in all aspects of L&I regarding home building – everything from safety at work to ensuring that injured employees are appropriately assisted to ensure the greatest recovery possible. ROII staff can participate in these processes with L&I staff because of the APA process. It allows the ROII staff to have certainty in the relationship with L&I, and the manner in which L&I will handle all of their rules.

Should Ecology be permitted to issue directives regarding WWTP without following the APA rulemaking process, this decision will remove the voice of numerous private businesses in Washington that work closely with State agencies.

VI. CONCLUSION

Washingtonians cannot afford houses in Washington as it currently stands, let alone if required to pay for the addition of tertiary treatment, or a TIN load cap in the interim, to WWTP. This Court should affirm Division III's decision, and confirm that the Department of Ecology cannot issue a directive requiring the addition of tertiary treatment without following APA rules.

This document contains 3,611 words, excluding the parts of the document exempted from the word count by RAP 18.17.

Respectfully submitted this 12th day of April, 2024.

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IN THE SUPREME COURT
OF THE STATE OF WASHINGTON

CITY OF TACOMA, BIRCH BAY WATER AND SEWER DISTRICT, KITSAP COUNTY, SOUTHWEST SUBURBAN SEWER DISTRICT, and ALDERWOOD WATER & WASTEWATER DISTRICT,

Respondents,

v.

STATE OF WASHINGTON, DEPARTMENT OF ECOLOGY,

Petitioner.

BRIEF OF AMICUS CURIAE KING COUNTY

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I. INTRODUCTION AND INTEREST OF AMICUS CURIAE

King County (the "County") is the largest wastewater utility in the Puget Sound (the "Sound"). Through operation of five municipal domestic wastewater treatment facilities ("WWTFs") – the Carnation, Brightwater, Vashon, South, and West Point facilities – the County provides wastewater treatment and disposal service to 18 cities, 15 sewer districts, and the Muckleshoot Tribe, serving approximately two million people in over a 424 square mile service area. Four of these facilities discharge treated wastewater pursuant to the Puget Sound Nutrient General Permit and an individual Clean Water Act National Pollutant Discharge Elimination System ("NPDES") permit issued by the Department of Ecology ("Ecology").

King County shares Ecology's goal of improving Puget Sound's water quality and is not opposed to the adoption of more stringent regulations to address low dissolved oxygen and any resulting harm to aquatic organisms. But those regulations must be science-based and adopted through a transparent rulemaking process that includes a cost-benefit analysis and a least cost alternative developed through a robust public comment period.

The County has committed to a robust set of actions to protect and restore water quality in Puget Sound. In 2020, the County projected it would invest $9.5 billion in the next decade, the vast majority of which will be directed to improving the quality of its wastewater discharges and combined sewer overflows. Additional investments will be used for stormwater management, toxic pollutant source control, legacy site-remediation and salmon restoration and recovery. Notably, the $9.5 billion projection does not reflect the significant additional expenditures the County must now earmark to comply with Ecology's nutrient regulation-- the subject of this appeal.

Every dollar spent is raised through rates paid by the public. For this reason, it is imperative that public investments of this magnitude, which include measures the County must take to comply with environmental rules, are informed by regulatory processes that fully consider the costs as well as the ecological outcomes and community impacts-- including effects on housing affordability-- of these investments.

In 2019, without satisfying the rulemaking requirements set out in RCW chapter 34.05, Ecology directed its permit writers to impose on *all* dischargers a nitrogen nutrient loading limit ("TIN Rule"). That limit effectively froze the amount of nitrogen discharged from each WWTF at then-current levels, without regard to the anticipated population growth or cost. In so doing, it purported to enact a new "rule" that required notice and comment. *City of Tacoma v. Dep't of Ecology* ("*Tacoma*"), 28 Wn.

App. 2d 221, 535 P.3d 462 (2023) (invalidating the rule). As a result of Ecology's violation of RCW chapter 34.05, the State Administrative Procedures Act ("APA"), in imposing the new TIN Rule, King County and the public were deprived of an opportunity to comment on this significant proposed change.

This is no small matter. To comply requires the County to spend between $25 and $50 million in the next five years, $100 to $200 million in the next 10 to 15 years, and between $9 billion and $14 billion on future nitrogen removal. This results in monthly sewer rate increases of between $20 and $130 per month *per household,* representing a 40% to 230% increase to residents' current monthly sewer rates. Rate increases of this staggering magnitude will impact housing affordability, especially for the communities least able to afford these increases.

Making matters worse, because Ecology failed to engage in the robust and deliberate rulemaking process required by RCW chapter 34.05, it blinded itself to the environmental and societal costs of imposing the one-size-fits-all TIN Rule.

Given that the County's WWTFs discharge 50% of all wastewater discharged to the Sound, the County is the local government that is most financially and operationally impacted by the illegally adopted rule that is the subject of this appeal. By submitting this amicus brief, the County seeks to assist the Court in appreciating the real-world impacts of Ecology's failure to conduct a rulemaking process that will yield robust information about the costs, benefits and real-world impacts of actions taken to address low dissolved oxygen that has a higher likelihood of leading to more impactful and less costly improvements for the Sound.

The Court of Appeals correctly ruled that Ecology was not free to dispense with notice and comment in imposing the new TIN Rule. *Tacoma*, Wn. App. 2d at 251. By *requiring* its permit writers to "[s]et nutrient loading limits at current levels from *all permitted dischargers* in Puget Sound," Ecology adopted a rule that must go through formal rulemaking. *Id*. at 232 (emphasis added) (a directive to staff to add new terms for reissuing a permit is a rule). Because the TIN Rule violated the APA, the decision below should be affirmed.

II. ARGUMENT

King County incorporates the Court of Appeals' statement of the case background. *Tacoma,* 28 Wn. App. 2d at 224-36. This brief will address the key issue of whether Ecology's TIN Rule is a "rule" under the APA, the Rule's likely effects on the regulated community, and why formal rulemaking is essential. *Id*. at 246 ("The precise issue presented in this appeal is whether a directive can be an internal directive, *e.g.,* a commitment by Ecology that its own staff will impose new requirements on permittees.").

A. The Court of Appeals Should Be Affirmed

The APA defines a "rule" broadly as

> ***any*** agency order, ***directive***, or regulation ***of general applicability*** (a) ***the violation of which subjects a person to a penalty or administrative sanction***; (b) which establishes, alters, or revokes any procedure, practice, or requirement relating to agency hearings; ***(c) which establishes, alters, or revokes any qualification or requirement relating to the enjoyment of benefits or privileges conferred by law***; (d) which establishes, alters, or revokes any qualifications or standards for the issuance, suspension, or revocation of licenses to pursue any commercial activity, trade, or profession; or (e) which establishes, alters, or revokes any mandatory standards for any product or material which must be met before distribution or sale.

RCW 34.05.010(16) (emphasis added); *see also* RCW 34.05.001 ("[T]he courts should interpret provisions of [the APA] consistently with decisions of other courts interpreting similar provisions of other states, the federal government, and model acts."); *Wells Fargo Bank, N.A. v. Dep't of Revenue*, 166 Wn. App. 342, 354, 271 P.3d 268 (2012) (interpretation of the state act consistent with federal APA).

The test is one of substance, not labels preferred by the agency. *McGee Guest Home., Inc v. Dep't of Soc. & Health Servs*., 142 Wn.2d 316, 322, 12 P.3d 144 (2000). It involves a two-step inquiry: first, the court determines whether the purported rule is an "'order, ***directive***, or regulation of general applicability'; [s]econd, the court determines whether [it] 'fall[s] into one of the five enumerated categories'" in RCW 34.05.010(16)(a) through (e). *Tacoma*, Wn. App. 2d at 237 (citations omitted).

A directive "impel[s] one to act." *Id*. at 238, 245-46. Further, a "directive" is of "general applicability" – and therefore a "rule" – where "'the challenge is to a policy applicable to all participants in a program, not its implementation under a single contract or assessment of individual benefits.'" *Id*. at 238 (quoting *Failor's Pharm. v. Dep't of Soc. Health & Health Servs.,* 125 Wn.2d 488, 886 P.2d 147 (1994)); *see also Simpson Tacoma Kraft Co. v. Dep't of Ecology*, 119 Wn.2d 640, 648, 835 P.2d 1030 (1992) (holding that "'the nature of a rule [is] that it [must] apply to individuals ***only as members of a class***,'" and ruling that the numeric standard was a directive of general applicability because it applied "***uniformly to the entire class*** of entities which discharges dioxin into the state's waters ..." (emphasis added; citation omitted)).

Contrary to statutory language, Ecology insists that for a directive to be a rule it must have "independent regulatory effect" directly binding the regulated community. Petitioner State of Washington, Department of Ecology's Supplemental Brief ("Ecology Supp. Br.") at 21, 23. But the APA explicitly defines agency actions that govern *internal agency procedures* as rules. RCW 34.05.010(16)(c) (action that alters requirements for privilege or benefit is rule), (d) (action that alters standards for issuance of license is rule).

In addition, RCW 34.05.413(3) requires formal rulemaking before agencies like Ecology can make any changes to the procedural form provided to aggrieved persons when seeking an adjudicative proceeding. Obviously, rules like this are not self-executing and have no independent regulatory or binding effect on the regulated community – until an applicant fills out the form and requests an adjudicative proceeding. Ecology's argument would render both RCW 34.05.413(3) and RCW 34.05.010(16)(c) and (d) meaningless. *See Hillis v. State, Dep't of Ecology*, 131 Wn. 2d 373, 399, 932 P.2d 139 (1997) (agency procedures for processing water rights applications were a rule).

Not only are Ecology's arguments contrary to the Washington APA, but they are also contrary to the federal APA and caselaw adjudicating this same issue. That caselaw is consistent with King County's interpretation and should be followed because the APA is modeled after the federal APA and because the permits that Ecology issues are part of a federally delegated program supervised by the Environmental Protection Agency ("EPA") under the CWA. RCW 34.05.010(16); 33 U.S.C. § 1342(b)-(d).

Under federal law, the key is whether the agency's action or statement binds private parties ***or the agency itself*** with the force of law.

See, e.g., CropLife Am. v. EPA, 329 F.3d 876, 881 (D.C. Cir. 2003) (EPA's statement that it would cease using third-party human study data in evaluating pesticide safety used "clear and unequivocal language, reflecting] an obvious change in established agency practice, creates a 'binding norm' that is 'finally determinative of the issues or rights to which it is addressed'" because the statement divested EPA staff of discretion, it was a binding rule that must go through notice and comment rulemaking (citation omitted)); *Nat. Res. Defense Counsel v. EPA*, 643 F.3d 311, 405 (D.C. Cir. 2011) (EPA's "guidance" purporting to interpret the Clean Air Act, was a rule that must go through notice and comment because it authorized EPA regional air division directors to accept alternative compliance plans for the regulation of particulate matter, where they previously did not have discretion to do so); *Gen. Elec. Co. v. EPA*, 290 F.3d 377, 384-85 (D.C. Cir. 2002) (EPA guidance addressing alternatives for evaluating risks from waste containing polychlorinated biphenyls was a rule because it "b[ou]nd the Agency to accept applications" using the identified toxicity factor and imposed "further obligation[] on EPA" to now categorically accept the use of the identified toxicity factor); *Am. Trucking Ass'ns v. Interstate Com. Comm'n,* 659 F.2d 452, 463-64 (5th Cir. 1981) (court looks to the language of the agency document to determine if it "'genuinely leaves the agency and its decision-makers free to exercise discretion'"; when "the specifics … are couched in terms of command" and the guidelines, while "decorated with words that appear to be carefully chosen to avert classification as rules … lead all applicants toward one course … these are not guidelines but normative rules, and must be evaluated as such." (citation omitted)).

In the case below, the Court of Appeals correctly applied a similar methodology. As in *Simpson* and the federal cases discussed above, internal agency guidance constitutes a rule that must go through notice and comment when "the agency's employees were directed to include a new standard in all renewed permits and, by doing so, the permittees were subject to punishment if they violated the new standard." *Tacoma*, 28 Wn. App. 2d at 247. "*Simpson* stands for the proposition that 'directive' includes an agency's ***internal directive to its staff*** for issuing permits." *Id.* (emphasis added); *see also Nat. Res. Defense Counsel,* 643 F.3d at 405.

Here, Ecology's rule took the form of a letter dated January 11, 2019 (the "NWEA denial letter"), denying a rulemaking petition filed by Northwest Environmental Advocates to require tertiary nitrogen treatment for all 79 Puget Sound WWTFs to satisfy the regulatory requirement[1] to employ "all known, available and reasonable treatment" ("AKART").

[1] WAC 173-201A-020.

Ecology issued the NWEA denial letter because AKART technologies must be economically feasible and cost-effective, and tertiary treatment was cost prohibitive. To satisfy its procedural obligation to identify an alternative action to address NWEA's concerns as required under the APA, RCW 34.05.330(1), Ecology committed to have its staff include nitrogen limits, based on current nitrogen loads, in ***all*** future individual permits:

> Ecology *will* through the individual permitting process:
>
> 1. Set nutrient loading limits at current levels from all permitted dischargers in Puget Sound and its key tributaries to prevent increases in loading that would continue to contribute to Puget Sound's impaired status.
>
> 2. Require permittees to initiate planning efforts to evaluate different effluent nutrient reduction targets.
>
> 3. For treatment plants that already use a nutrient removal process, require reissued discharge permits to reflect the treatment efficiency of the existing plant by implementing numeric effluent limits used as design parameters in facility specific engineering reports.

Nw. Env't Advocs. v. Dep't of Ecology ("*NWEA*"), 18 Wn. App. 2d 1005, 2021 WL 2556573, at *11 (2021) (unpublished). "The record indicates these requirements were nondiscretionary and were part and parcel of the commitments Ecology made to NWEA." *Tacoma*, 28 Wn. App. 2d at 248.

Ecology tries to distance itself from these commitments arguing that its staff "were not bound" by the alternative measures identified in the denial letter. Ecology Supp. Br. at 24. This is contrary to reality and Ecology cannot have it both ways. Having defended its rulemaking petition denial by relying on its commitment to employ the TIN Rule alternative, Ecology cannot disclaim that commitment here, especially because the Court of Appeals relied on that promise in upholding Ecology's petition denial. *NWEA,* 2021 WL 2556573*,* at *11-13 (finding that Ecology satisfied its procedural requirements in denying a rulemaking petition by listing the alternative measures it ***was taking*** to apply AKART to its individual treatment plant permitting process: "Ecology's denial letter … stated the alternative means by which it ***will*** address NWEA's concerns." (emphasis added)).

More to the point, Ecology should be judicially estopped from disclaiming that promise, given the Court of Appeals' reliance on those commitments. *New Hampshire v. Maine*, 532 U.S. 742, 749-50, 121 S.Ct. 1808 (2001) (judicial estoppel prevents a party from prevailing on an argument and then relying on a contradictory argument to prevail simply because the party's interests have changed). The doctrine is designed to prevent Ecology from doing what it is doing here – seeking an advantage by litigating on one theory and then pursuing a contrary theory to gain a litigation advantage.

Ecology's argument that it is simply using its "existing pollution control authority to regulate nutrient pollution" is equally deficient. Ecology Supp. Br. at 25. The TIN Rule does not allow permit writers to use their discretion to employ a facility-specific approach to address nutrients, as would be appropriate under existing regulations. Instead, the TIN Rule requires Ecology's permit writers to apply the same loading limit to *each* WWTF in the Puget Sound, regardless of "case-by-case" factors. The TIN Rule is directly binding on Ecology and imposes a new, substantive legal obligation not previously found in the statute or regulations for issuing discharge permits and was subject to notice and comment.

B. By Promulgating the TIN Rule Without Public Notice and Comment, the Agency Deprived Itself of Foundational Information That May Have Led to a More Cost-Effective and Environmentally Beneficial Alternative

The purpose of the rulemaking procedures established by the APA is "to ensure that members of the public can participate meaningfully in the development of agency policies which affect them." *Simpson*, 119 Wn.2d at 649. By promulgating the TIN Rule without public comment, Ecology not only violated the purpose and intent of the APA, it failed to account for the impacts of the TIN Rule or identify alternative, less burdensome means to achieve the same or similar result.

In 1995, the Legislature amended the APA to "ensure that the citizens and environment of this state receive the highest level of protection, *in an effective and efficient manner*, without stifling legitimate activities and responsible economic growth." H.B. 1010, Reg. Sess. § 1(2) (Wash. 1995) (emphasis added). The Regulatory Reform Act of 1995 added requirements for agencies to follow in promulgating significant legislative rules. *Id.* § 201; RCW 34.05.328. These additional requirements were designed to ensure that, when an agency adopted a substantive rule, it would do so "responsibly" so that the rule is "justified and reasonable" and "obligations imposed are truly in the public interest." H.B. 1010 § 1(2)(b).

The TIN Rule falls within the definition of "significant legislative rule," RCW 34.05.328(5)(c)(iii), yet Ecology undertook none of the analysis required to ensure that it was justified, cost-effective and reasonable, and that the obligations it imposed were in the public interest. Ecology's failure to follow APA rulemaking procedures has deprived County ratepayers and the public of the opportunity to meaningfully understand the impacts of, and provide comment on, the TIN Rule. More significantly, Ecology's procedural failings also deprived ***it*** of critical public input that may have led to a different decision that would ensure that ratepayers' funds were spent wisely given the inherent uncertainties in existing science concerning what is causing the dissolved oxygen impairments in the Sound.

Indeed, there is insufficient evidence that reducing nitrogen in wastewater effluent will be effective at increasing dissolved oxygen in impaired and sensitive areas of the Sound. As the Court of Appeals emphasized, it is currently unknown to what extent excess nitrogen in parts of the Sound is due to WWTF discharges. *Tacoma*, 28 Wn. App. 2d at 228. This is because, while nitrogen can be measured at the point of discharge, Ecology cannot determine where that nitrogen goes once it gets carried away with the currents and mixes with the rest of the Sound. *Id.* at 227. And, while the Salish Sea Model is an important tool for high-level water quality modeling, leading scientists at the University of Washington have criticized Ecology's heavy reliance on it for site-specific regulatory purposes, given its inability to isolate the water quality impacts of individual WWTFs. *Id.*

Given the gaps in the current scientific knowledge about the complex factors causing dissolved oxygen impairments in the shallow embayments of the Sound, coupled with the enormity of the costs associated with nitrogen removal, it was particularly important for Ecology to adhere to formal rulemaking requirements in promulgating the TIN Rule.

Had Ecology followed the process required by the APA, it would have 1) evaluated whether alternative methods were available for achieving the purpose of the TIN Rule; 2) conducted a cost-benefit analysis; 3) evaluated whether the TIN Rule was the least burdensome alternative for wastewater utilities in the Puget Sound; and 4) evaluated whether compliance with the TIN Rule would impede or prevent compliance with other competing NPDES permit obligations. RCW 34.05.328. Ecology would have also evaluated the environmental impacts of the TIN Rule and determined whether adoption of the Rule would have resulted in significant environmental impacts under the State Environmental Policy Act ("SEPA"). RCW 43.21C.030; WAC 197-11-960. Ecology's failure to comply with the APA and SEPA left the benefits and impacts of the TIN Rule unquantified and therefore unknown, even where, as here, EPA has cautioned that "careful consideration should be given to the benefits from lower nutrient levels compared to the potential environmental and economic costs associated with treatment processes used to achieve those levels."[2]

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[2] U.S. EPA, Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants ("Life Cycle") at iii (Aug. 2021), https://www.epa.gov/system/files/documents/2023-06/life-cycle-nutrient-removal.pdf.

1. The Lack of Cost-Benefit Analysis Hampered Ecology's Decision-Making

The APA requires that Ecology prepare a cost-benefit analysis that determines the probable benefits of the rule are greater than its probable costs. RCW 34.05.328(1)(c), (d). By failing to quantify either the costs or the benefits of the TIN Rule, Ecology shielded itself from receiving and developing foundational information that may well have resulted in a very different outcome that would have provided County ratepayers with a greater public, and water quality, benefit at a fraction of the cost.

This failure is particularly acute considering what Ecology already knows about the significant costs of reducing nutrient loading in effluent from WWTFs. Ecology denied NWEA's rulemaking petition because of the enormous costs associated with installing and operating tertiary treatment to reduce nutrient loading. *NWEA,* 2021 WL 2556573, at *15. Although Ecology chose a different path to reduce nutrient loading, it promulgated the TIN Rule requiring WWTFs to newly install nutrient treatment technology without considering the associated costs. Given the magnitude of nutrient treatment costs, and knowing that some plants, including the County's West Point Facility, have no additional land on which to expand or build additional treatment infrastructure,[3] it is nothing

[3] *Tacoma*, 28 Wn. App. 2d at 225-26.

short of remarkable that the agency decided to take the shortcut it took by forgoing the formal cost/benefit analysis.

Compounding this omission is the fact that the population of Puget Sound is rapidly growing and is projected to continue to grow into the future. This growth requires utility providers, such as King County, to plan for and provide additional wastewater treatment capacity. The County alone is on track to spend between $25 million to $50 million in the next five years to comply with the TIN Rule and hold nutrient discharges at current levels. Additional required nutrient removal projects will cost up to $200 million in the next 10 to 15 years.

As explained above, these additional costs will directly impact King County ratepayers, at a time when rates are already set to double over the next decade to meet non-TIN Rule obligations, capacity needs, and critical maintenance requirements. The City of Tacoma estimated that full-scale improvements required for it to meet the TIN Rule would cost between $250 million and over $750 million. *Tacoma*, 28 Wn. App. 2d at 234 (citing AR at 620). Tacoma and King County are but two examples of the significant costs the TIN Rule imposes on utilities, and more importantly, ratepayers, that were ignored by Ecology in issuing the rule.

Equally problematic, Ecology did not assess the potential benefits of the TIN Rule. As the Court of Appeals observed, the Salish Sea Model that Ecology used to develop the rule has been criticized as "not yet ready for prime time" and cannot "isolate the effect of individual WWT[Fs]" on water quality in the Puget Sound. *Id.* at 229. Accordingly, Ecology does not know what effect, if any, application of the TIN Rule will have on water quality in the Sound, and as Division III notes, the agency does not know to what extent the nitrogen discharged by WWTFs actually causes the Sound's dissolved oxygen impairment. *Id*. at 228. Without this information, it is not possible to reasonably regulate nitrogen discharges from WWTFs. *Id*.

2. Ecology Failed to Evaluate Alternative Methods of Reducing Nutrient Discharges and Failed to Determine if Less Burdensome Alternatives Were Available

In adopting the TIN Rule, Ecology did not use its underlying regulatory authority to develop facility-specific approaches that would have evaluated the technological feasibility of removing nutrients at meaningful levels. Nor did it analyze ratepayer impacts, and perhaps most importantly, effects to water quality from a facility-specific, data-driven and scientifically-tailored effluent limits. Instead, it took a shortcut by developing a one-size-fits-all rule and applied it irrespective of the impacts or alternatives.

By regulating nutrient loading through the TIN Rule as an unanalyzed stand-alone requirement, instead of an integrated suite of individual, facility-specific permit conditions, Ecology has prioritized nutrient load reduction at the potential expense of other CWA requirements. Had Ecology performed the least- burdensome alternatives analysis required by the APA, it might have found that a more flexible approach would allow utilities to experiment with phased treatment process changes over time to obtain more meaningful results.

Indeed, upgrading wastewater facilities that are as large as the County's is not unlike turning an aircraft carrier or stopping a train – it takes time. These are large, complex systems that have complicated processes that require multiple stages of careful planning and engineering, as well as technical and financial analyses before making significant upgrades. Changes to one aspect of the treatment or pollutant removal process often has rippling effects on other parts of the WWTF. Facilities as large as the County's cannot be re-engineered on a dime to address one factor without causing other externalities, which is why it often takes 10 to 15 years or more to implement significant capital improvements. For example, because the County's WWTFs were not designed for nitrogen removal, a more deliberate and flexible approach to managing TIN would have avoided the unintended consequences that occurred at the County's South Treatment Plant. Staff efforts to meet the TIN Rule resulted in changes to the pH level, another regulated parameter. This required the

County to incur significant labor costs in spending an additional $3 million to construct a chemical addition system to prevent pH violations of its individual NPDES permit.

Similarly, a more flexible approach might have also allowed utilities to conduct rigorous nutrient influent and effluent monitoring to better understand what the Court of Appeals found is currently missing from existing science – *i.e.,* the real-world water quality impacts of WWTFs' discharges. *Id.* at 228. While King County has developed a robust marine water quality science program and has spent millions of dollars collecting physical, chemical, and biological data in Puget Sound, including dissolved oxygen measurements, our collective understanding of how best to remedy the dissolved oxygen deficits impacting water quality is admittedly very limited. By failing to identify, let alone evaluate, alternatives to determine if there is a less burdensome approach than adoption of the TIN Rule, Ecology not only violated the APA, but more importantly blind-sighted itself to other alternatives that were much less expensive and much more environmentally beneficial to the Region.

3. Ecology Failed to Evaluate the Environmental Impacts of the TIN Rule

Ecology's SEPA regulations require all state agencies to consider the environmental impacts of a proposed rule.[4] *See* WAC 197-11-960. Yet, Ecology ignored its own regulations and failed to quantify the potential environmental impacts of the TIN Rule. This is particularly problematic considering that Ecology has previously recognized the potential environmental impacts of requiring WWTFs to adopt additional nutrient removal technology – including the likelihood that tertiary treatment will not only generate more effluent sludge that will require disposal but will also require two to three times the amount of electrical energy currently used in WWTFs. *NWEA,* 2021 WL 2556573, at *9. Ecology also ignored climate change impacts of its Rule, including the fact that nitrogen removal from wastewater converts some nitrogen in the wastewater to nitrous oxide, a greenhouse gas that is 300 times more potent than carbon dioxide.[5]

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[4] The County notes that, to the extent Ecology, or other *amici,* are concerned about the rate at which Ecology is addressing water quality concerns in the Puget Sound, the Superior Court held that Ecology was required to go through notice and comment rulemaking over two years ago. But instead of doing so, Ecology chose to appeal. In the time it has taken Ecology to arrive before this Court, it could have completed the rulemaking process and achieved a legally and scientifically defensible path to reducing nutrient loading to the Sound.

[5] *See* Life Cycle, *supra* note 2, at 4-7.

In addition to the above, the rule will lead to an increase in the cost of living for County residents. Affordability is not just an economic issue for our communities; it is an environmental issue. When rates and other expenses of living in urban areas increase, housing development sprawls to rural areas where urban sewer systems do not reach. On a per capita basis, rural septic is far more polluting and can result in untreated septic waste entering Puget Sound. *Tacoma*, 28 Wn. App. 2d at 234.

Finally, SEPA required Ecology to evaluate the impacts of the TIN Rule on low-income and environmental justice communities. Given the enormity of the costs associated with its implementation, Ecology ignored the TIN Rule's impact on housing affordability and increased utility rates for those who are least able to afford them.

III. CONCLUSION

Had Ecology gone through the rulemaking process, as required by the APA, King County would have actively participated to help identify workable and scientifically sound solutions. The County cares deeply about the health of Puget Sound and has worked for years to find scientifically sound ways to improve its water quality. The County, ratepayers, and public were denied the opportunity for meaningful public engagement and as a result, no one – not Ecology, the regulated community, this Court, nor the public – knows the true impacts of

Ecology's rule. For all these reasons and those set forth in Tacoma's Supplemental Brief, the Court of Appeals should be affirmed, and Ecology should be required to comply with the APA.

I certify that this document contains 4806 words, pursuant to RAP 18.17.

DATED: April 15, 2024.

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Supreme Court No. 1024797

**IN THE SUPREME COURT
OF THE STATE OF WASHINGTON**

CITY OF TACOMA, BIRCH BAY WATER AND SEWER DISTRICT, KITSAP COUNTY, SOUTHWEST SUBURBAN SEWER DISTRICT, and ALDERWOOD WATER & WASTEWATER DISTRICT,

Respondents,

v.

STATE OF WASHINGTON, DEPARTMENT OF ECOLOGY,

Petitioner.

WASHINGTON ASSOCIATION OF SEWER & WATER DISTRICTS' MOTION FOR LEAVE TO JOIN IN AMICUS BRIEF FILED BY KING COUNTY

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Attorneys for Washington Association of Sewer & Water Districts

Pursuant to Rules of Appellate Procedure 10.6, the Washington Association of Sewer & Water Districts ("WASWD") seeks this Court's permission to join in the *amicus curiae* brief filed by King County. [1]

I. IDENTITY AND INTEREST OF *AMICUS* PARTY

WASWD seeks to join King County's *amicus* brief since WASWD represents members that share substantially the same positions and concerns as those raised by King County due to the fact that approximately 26 of WASWD's members collect and/or discharge treated wastewater directly or indirectly into the waters of Puget Sound. In fact, 15 WASWD members

[1] The undersigned counsel has requested the parties' position relating to WASWD's motion. As of the filing of this motion, the City of Tacoma, Kitsap County and Southwest Suburban Sewer District have indicated that they do not oppose and support WASWD's motion. The Department of Ecology, Alderwood Water & Wastewater District and Birch Bay Water and Sewer District have not yet responded. Although, Alderwood and Birch Bay both support King County's motion for leave to file an amicus brief and are not expected to take a different position on WASWD's motion. Further, King County has responded that it supports WASWD's motion.

receive wastewater treatment and disposal services from King County under wastewater treatment contracts. The impacts described by King County in its a*micus* brief will similarly affect these WASWD members and their respective customers.

Allowing WASWD to join in King County's *amicus* brief serves the underlying purposes of RAP 10.6, including providing access to the appellate court by those persons or groups who will be significantly affected by the outcome of issues on review which will materially assist the Court in the decision-making processing. *See* 3 Washington Practice, Rules Practice, RAP 10.6 at 110 (Task Force Comment).

A. WASWD'S Mission and Membership.

WASWD has been providing education, advocacy and collaboration for sewer and water districts throughout the State of Washington since 1961. WASWD supports sewer and water districts in providing environmentally responsible wastewater collection and treatment and safe drinking water in an informed, efficient and effective manner. WASWD strives to ensure that its members providing sewer and water services throughout the State of Washington remain at the forefront of these ever-evolving industries, while ensuring effective operations, and appropriate regulatory and legislative representation.

There are approximately 180 sewer and water districts located throughout the State of Washington, each governed by locally elected officials. These districts provide cost-effective sewer and water services ranging from the state's largest population centers to the smallest rural communities. WASWD regularly works with these sewer and water districts to ensure the districts have a voice in regulatory matters that impact the delivery of sewer and water services.

B. WASWD's Interests Relating to this Appeal.

WASWD has 15 members that receive wastewater treatment and disposal services under contracts with King County which is the largest wastewater utility in the Puget Sound region. Four of King County's wastewater treatment facilities discharge treated wastewater into Puget Sound pursuant to the Puget Sound Nutrient General Permit ("PSNGP") and an individual Clean Water Act National Pollutant Discharge Elimination System ("NPDES") permit issued by the Department of Ecology ("Ecology") to King County. County Brief at 1. The impacts described by King County relating to the issues on appeal will also affect WASWD's 15 members and their respective customers who reside throughout the greater Puget Sound area. In addition, WASWD has 11 members operating wastewater treatment facilities that discharge treated wastewater directly or indirectly into Puget Sound under the PSNGP and separate NPDES permits issued by Ecology.

WASWD desires to participate in this appeal on behalf of its members to make sure the Court understands fully the real-world impacts of this Court's decision. These impacts will similarly extend to WASWD's members located in the greater Puget Sound region. More broadly, ensuring that state agencies follow proper rulemaking procedures affects and benefits all of

WASWD's members that provide sewer or water services throughout the state, especially since the sewer and water industries are heavily regulated. If Ecology is allowed to set binding regulatory rules through staff directives like occurred here, then Ecology could do it in other situations that will affect WASWD members throughout the state. Therefore, WASWD has a strong interest and desire to actively participate in this appeal to weigh in on these important issues.

C. WASWD'S Involvement in the PSNGP Process.

WASWD has been actively involved in the regulatory development process and review of the potential impacts of Ecology's PSNGP given the potential impacts of the proposed PSNGP. In fact, WASWD had a seat at the regulatory table through the appointment of a WASWD representative to serve as a member of the General Permit Advisory Committee which was formed and convened by Ecology in March of 2020. The WASWD representative's role was to provide input on behalf of small to medium sized wastewater treatment plants covering the entire Puget Sound region. The stated purpose of the Advisory Committee was to advise Ecology in drafting general permit requirements for domestic wastewater treatment plants discharging to Puget Sound.

The Advisory Committee met throughout 2020 to develop recommendations for general permit conditions. Final Recommendations relating to the development of the PSNGP were completed in October of 2020 and were released in November of 2020.[2] The Final Recommendations reflect significant areas of disagreement between members of the Advisory Committee with Ecology's position on various matters relating to the PSNGP.

WASWD was also an active participant on behalf of its members when Ecology issued the preliminary draft of the

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[2]The Final Recommendations of the Advisory Committee are available at the following link: https://www.ezview.wa.gov/Portals/_1962/Documents/nutrients/PSNGP%20AC%20final%20recommendations%202020_10_21_Final.pdf.

PSGNP in January of 2021 and the formal draft of the PSGNP in June of 2021 by providing comments on the draft PSGNP and raising and documenting its members' concerns about various portions of the draft PSGNP before it was adopted.

While WASWD was able to participate in the rulemaking process relating to the PSNGP before it was adopted, Ecology provided no opportunity to WASWD, the regulated community, or the public to provide comments or raise concerns relating to Ecology's 2019 directive to its permit writers to impose on all wastewater treatment facilities (WWTFs) discharging to Puget Sound a nitrogen nutrient limit ("total inorganic nitrogen" or "TIN Rule") that froze the amount of nitrogen that could be discharged at current levels, without regard to the anticipated population growth or cost. Had Ecology engaged in the required rulemaking procedures before adopting its TIN Rule, WASWD would have been an active participant in that rulemaking process on behalf of its members, just as it was during the process of Ecology adopting the PSGNP. Having been denied by Ecology of the opportunity to participate in the required rulemaking process that should have occurred prior to the adoption and implementation of the TIN Rule, WASWD is committed to being actively engaged in this important appeal because of the significant implications this case will have on WASWD's members.

D. Relationship to and Support of King County's Arguments and Positions.

As stated in King County's *amicus* brief, Ecology's decision to adopt the TIN Rule without complying with formal rulemaking procedures significantly impacts King County's ability to affordably serve its growing population and thus presents an issue of critical importance to King County and the 2 million people it serves. County Brief at 1-3. Importantly, WASWD's members that either receive wastewater treatment and disposal services from King County under contracts or otherwise discharge directly or indirectly treated wastewater into Puget Sound are similarly impacted by Ecology's unlawful rulemaking and stand in substantially the same position as King County.

In its *amicus* brief, King County advises the Court that in order to comply with Ecology's directive King County will need to spend between $25 and $50 million in the next five years, $100 to $200 million in the next 10 to 15 years, and between $9 billion and $14 billion on future nitrogen removal. County Brief at 3. King County states that these expenditures will result in monthly sewer rate increases of between $20 and $130 per month per household, representing a 40% - 230% increase to residents' current monthly sewer rates. *Id.* Importantly, the magnitude of these rate increases will have a negative impact on housing affordability, including those communities or areas that are least able to afford these increases. *Id.*

Based on a review of the State Legislature's Detailed Legislative Reports Topical Index[3] for the 2019-20, 2021-22 and 2023-24 biennia, more than 30 separate pieces of legislation to address affordable housing issues have been adopted by the Legislature and signed into law during the referenced time periods. Therefore, it is clear that affordable housing issues are now a focal point of the State Legislature and local governments seeking to address the affordable housing concerns and mandates. The sewer rate increases that will naturally flow from Ecology's unlawful rulemaking process relating to the TIN Rule will be borne by both King County and WASWD's members, and their respective customers, which will make the affordable housing issues even more challenging.

[3] The Topical Index can be found at the following location on the State Legislature website: https://app.leg.wa.gov/bi/topicalindex.

WASWD believes it is important for the Court to understand and appreciate that increases in costs to King County to comply with the TIN Rule will be paid by the County's customers and contract agencies, which includes 15 WASWD members that contract with King County for wastewater treatment services. In the utility industry, rates are established based on the cost of service. As King County's costs of complying with Ecology's directives increase, those costs will have to be recovered through higher rates charged to WASWD's 15 members. In turn, WASWD's members will then have to adopt higher rates which must be paid by their respective customers. In some cases, smaller districts with fewer customers end up being impacted more by increased regulatory costs because they have a smaller customer base over which to share the financial burden.

A representative sampling of the published sewer rates charged by 6 WASWD members that receive wastewater treatment services from King County reveals that their rates are already heavily influenced by treatment costs imposed on them by King County. For example, the published sewer rates for 6 of the 15 WASWD members that contract with King County for wastewater treatment services show that approximately 46.3% to 69.4% of the total sewer bills charged to the members' customers are directly attributable to the cost of wastewater treatment that gets paid to King County. The sewer rate schedules for these 6 WASWD members are publicly available on their official websites.[4] The rate schedules are offered to illustrate the point that these sewer districts lack the

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[4] Cedar River Water & Sewer District (https://www.crwsd.com/wp-content/uploads/2024/03/Rate-Fee-Schedule-Final-Rev.-03-2024.pdf); Coal Creek Utility District (https://www.ccud.org/uploads/1/0/3/0/10309811/2022_rate_sheet.pdf); Northeast Sammamish Sewer & Water District (https://www.nesswd.org/customer-rates-and-charges/); Sammamish Plateau Water & Sewer District (https://spwater.org/DocumentCenter/View/1718/12052023-Master-Fees-and-Charges-Schedule-PDF?bidId=); Skyway Water & Sewer District (https://www.skywayws.org/billing.php); Soos Creek Water & Sewer District (https://www.sooscreek.com/utility-rates-2024).

ability to control costs that are imposed on them by King County which make up approximately one-half or more of the cost of sewer service charged to their customers. Any increased costs incurred by King County to comply with the TIN Rule will get passed down to WASWD's members that contract with King County and will eventually get paid by their respective customers in the form of increased sewer rates. The increases in costs paid by these 15 WASWD members will put an additional financial strain on their funding capacity to address their other regulatory or facility repair and replacement requirements. As described by King County, these rate increases are going to be substantial given the projected costs of complying with the TIN Rule.

Given the nature of the current treatment technology utilized by most WWTFs, it is not an exaggeration to say that every resident within the greater Puget Sound region that is served by King County is going to experience substantial rate increases associated with the TIN Rule without Ecology ever having engaged in proper rulemaking. Such a result is contrary to the purposes of the Administrative Procedures Act (APA) which is "to provide greater public and legislative access to administrative decision making." RCW 34.05.001. The purpose of APA-required rulemaking procedures is to give notice to the public of the proposed rule and to allow it to comment on the proposal. *Hunter v. Univ. of Wash.*, 101 Wn. App. 283, 293, 2 P.3d 1022 (2000) (*citing Hillis v. Dep't of Ecology*, 131 Wn.2d 373, 399). Notice and comment rulemaking "ensure[s] that members of the public can participate meaningfully in the development of agency policies which affect them." *Hillis*, 131 Wn.2d at 399.

As stated by King County, Ecology failed to engage in the robust and deliberate rulemaking process required by chapter 34.05 RCW. By doing so, Ecology intentionally overlooked or ignored the environmental and societal costs and benefits of imposing the one-size-fits-all TIN Rule. Like King County, WASWD and its members care about the health of

Puget Sound and they acknowledge that further investment will have to be made in order to protect water quality, protect and restore habitat, and assist in salmon recovery. However, WASWD and its members have an interest in making sure that Ecology does not take short cuts when engaging in rulemaking, especially when the costs associated with a rule or directive are as substantial as those that will have to be incurred to comply with the TIN Rule.

II. WASWD'S FAMILIARITY WITH THE ISSUES

As discussed in Section I above, WASWD has been actively involved in Ecology's efforts to adopt the PSNGP since the beginning of the process. WASWD and many of its members that will be directly impacted by Ecology's unlawful rulemaking are very familiar with the issues involved in this appeal and WASWD has been closely monitoring this matter since the initial lawsuit challenging Ecology's TIN Rule was commenced in Superior Court. WASWD has regularly followed the legal proceedings because the outcome of this case could have a significant impact on many of WASWD's members.

Further, legal counsel for WASWD has reviewed the applicable pleadings and appellate briefs filed in this matter.

III. ISSUES ADDRESSED IN KING COUNTY'S *AMICUS* BRIEF WHICH WASWD SEEKS TO JOIN

As discussed above, WASWD's interests are closely aligned with King County's interests. Given the similarity of interests, WASWD seeks the Court's approval for WASWD to participate in this appeal by joining in King County's *amicus* brief which was well briefed and set forth compelling legal arguments which are fully endorsed and supported by WASWD. By joining in the legal arguments made by King County, WASWD believes it can achieve its goal of ensuring that the Court has the benefit of hearing from WASWD on the important issues affecting WASWD's members.

With respect to the merits of the appeal, King County addresses how Ecology's decision to impose a TIN cap on all

WWTFs discharging to Puget Sound was a significant legislative rule that required formal rulemaking pursuant to chapter 34.05 RCW. Specifically, King County presents two issues for the Court's consideration which are shared and supported by WASWD. First, King County responds to Ecology's argument that a directive is not a rule unless it has "independent regulatory effect" that directly binds the regulated community. County Brief at 6 (*citing* Ecology Supp. Br. at 21, 23). King County demonstrates that Ecology's argument is contrary to the plain text of the State Administrative Procedure Act, specifically rendering RCW 34.05.413(3) a nullity. King County further demonstrates that Ecology's argument is also contrary to the Federal Administrative Procedure Act and federal case law adjudicating this same issue. King County explains that this case law is particularly informative where, as here, the State APA was modeled after the federal APA, and where Ecology's permitting authority derives from authority the

Environmental Protection Agency granted it under a federally supervised program. County Brief at 7.

Second, King County demonstrates that formal commitments made by Ecology to satisfy Ecology's procedural obligations under RCW 34.05.330(1) in denying a petition for rulemaking filed by Northwest Environmental Advocates ("NWEA") were both promoted by Ecology in defending its denial and relied on by Division II in upholding Ecology's denial. Those commitments specifically included the TIN Rule (*i.e.*, capping TIN in WWTF discharges at current levels) which Ecology now attempts to disavows by insisting that its staff "were not bound" by the measures Ecology put forward as an alternative to the very costly "tertiary treatment" to remove TIN being advocated by NWEA. King County argues that Ecology should be judicially estopped from disclaiming that promise, given the Court of Appeals' reliance on those commitments in upholding Ecology's decision in *Nw. Env't Advocs. v. Dep't of Ecology*, 18 Wn. App. 2d 1005, 2021 WL 2556573, at *11

(2021). *See New Hampshire v. Maine*, 532 U.S. 742, 749-50 (2001) (judicial estoppel prevents a party from prevailing in one phase of a case on an argument and then relying on a contradictory argument to prevail in another phase simply because the party's interests have changed). County Brief at 10-11.

Beyond the merits, King County argues by promulgating the TIN Rule without public comment Ecology not only violated the purpose and intent of the APA, but Ecology also entirely failed to account for the impacts of the TIN Rule or to identify alternative, less burdensome means to achieve the same or similar result. County Brief at 12. King County demonstrates that Ecology's procedural failings also deprived Ecology of critical public input that may have led to a different decision that ensured that taxpayers' funds were spent wisely given the inherent uncertainties in existing science concerning what is causing the dissolved oxygen impairments in Puget Sound. King County argues that given the gaps in the current scientific knowledge about the complex factors causing dissolved oxygen impairments in the shallow embayments of Puget Sound, coupled with the enormity of the costs associated with nitrogen removal, it was particularly important for Ecology to adhere to formal rulemaking requirements in promulgating the TIN Rule. County Brief at 14.

By regulating nutrient loading through the TIN Rule as an unanalyzed stand-alone requirement, instead of an integrated suite of individual, facility-specific, permit conditions, King County shows that Ecology has prioritized nutrient load reduction at the potential expense of other Clean Water Act requirements. Had Ecology performed the "less burdensome analysis" required by the APA, Ecology might have found a more flexible approach that would allow utilities to experiment with phased treatment process changes over time to obtain more meaningful results. County Brief at 18.

King County also explains how upgrading wastewater facilities that are as large as King County's facilities is a complicated process which takes time. WWTFs are large complex systems that have complicated processes that require multiple stages of careful planning and engineering, as well as technical and financial analyses before making significant upgrades. Changes to one aspect of the treatment or pollutant removal process often has rippling effects on other parts of the WWTF. King County shows how facilities as large as the County's cannot be re-engineered on a dime to address one factor without causing other externalities which is why it often takes 10-15 years or more to implement significant capital improvements. County Brief at 19. These same issues apply to other wastewater treatment facilities owned or utilized by WASWD's members outside of areas served by King County.

Similarly, King County asserts that a more flexible approach might have allowed utilities to conduct rigorous nutrient influent and effluent monitoring to better understand what Division III found is currently missing from existing science - *i.e.*, the real-world water quality impacts of WWTFs' discharges. By failing to identify, let alone evaluate alternatives to determine if there is a less burdensome approach than adoption of the TIN Rule, Ecology not only violated the APA, but more importantly overlooked or ignored other alternatives that were both much less expensive and more environmentally beneficial to the greater Puget Sound region. County Brief at 19-20.

WASWD unequivocally supports and endorses all of the arguments made by King County. WASWD believes that these arguments will help the Court understand the real impact of Ecology's unlawful rulemaking when Ecology directed its staff to implement the TIN Rule.

IV. ADDITIONAL ARGUMENT IS NECESSARY TO INFORM THE COURT OF THE CONSEQUENCES OF THE TIN RULE

The additional arguments made by King County in its *amicus* brief which WASWD seeks to join are necessary to raise important arguments on the merits that have a different focus than were made by the named parties to the appeal.

Additional argument is also necessary to help educate the Court about the very real consequences of Ecology's decision to adopt the TIN Rule without adhering to formal rulemaking requirements.

Had Ecology gone through the rulemaking process, as required by the APA, WASWD would have actively participated in the rulemaking process to help identify workable and scientifically sound solutions. WASWD would have advocated on behalf of its members impacted by the TIN Rule for a more flexible approach that would require sewer utilities discharging treated wastewater directly or indirectly into Puget Sound to conduct rigorous nutrient influent and effluent monitoring to better understand the real-world water quality impacts of WWTFs' discharges.

Additional argument is also necessary to demonstrate the information that would have been gathered had Ecology followed the procedures mandated by the State Environmental Policy Act, including the environmental externalities that have and will continue to result from putting TIN removal above other water quality improvements and other impacts that have resulted from these actions. If Ecology had satisfied its SEPA mandate, that process would have also revealed the environmental justice ramifications of Ecology's decision to impose TIN caps across the board rather than on a case-by-case basis.

Like King County, WASWD's members desire to be good stewards of the environment and to protect the health of Puget Sound. However, WASWD and its members were denied the opportunity for meaningful public engagement regarding Ecology's TIN Rule directive. As a result, all interested parties have not had an opportunity to weigh in on the true impact of Ecology's TIN Rule.

V. CONCLUSION

For reasons discussed above, WASWD seeks permission from the Court to participate as an *amicus* party by joining in King County's *amicus* brief. WASWD and its members stand in a similar position as King County, but with a slightly different perspective. WASWD believes it is important for WASWD to participate in this appeal to advocate for its members since the TIN Rule will have significant ramifications to the districts providing wastewater collection and treatment services not only in the Puget Sound region, but throughout the state.

I certify that this document contains 3896 words, pursuant to RAP 18.17.

DATED: April 15, 2024

INSLEE, BEST, DOEZIE & RYDER, P.S.

s/ Eric C. Frimodt
ERIC C. FRIMODT, WSBA #21938

Attorneys for Washington Association of Sewer & Water Districts

DECLARATION OF SERVICE

I declare under penalty of perjury under the laws of the State of Washington that on this date I caused the foregoing document to be served on the following parties via the Appellate Court filing portal as indicated below:

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DATED this 15th day of April 2024 at Bellevue, Washington.

Katia R. Perez
Katia R. Perez, Legal Assistant

INSLEE BEST DOEZIE & RYDER, P.S.

April 15, 2024 - 2:18 PM

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Filed with Court:	Supreme Court
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Superior Court Case Number:	20-2-02539-6

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Peterson, Teresa

From: James A. Tupper
Sent: Tuesday, July 2, 2024 10:40 AM
To: Emma L. Lautanen
Subject: FW: Thoughts regarding natural conditions criteria

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Partner

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MARTEN LAW

From: Lincoln Loehr <lcloehr@yahoo.com>
Sent: Wednesday, April 17, 2024 4:07 PM
To: James A. Tupper <jtupper@martenlaw.com>
Subject: Fw: Thoughts regarding natural conditions criteria

Kalman's response

----- Forwarded Message -----
From: Bugica, Kalman (ECY) <kbug461@ecy.wa.gov>
To: Lincoln Loehr <lcloehr@yahoo.com>
Sent: Tuesday, April 16, 2024 at 06:42:37 PM PDT
Subject: Re: Thoughts regarding natural conditions criteria

Good afternoon Lincoln,

I appreciate your thoughts on natural conditions.

I'll talk more about our approach for this rulemaking next week to provide details, but in short, I'm not considering recommending changing the intent of WAC 173-201A-260(1)(a) regarding our approach to use of natural conditions. I.e., my recommendation is to keep our current approach, but tailor it to just aquatic life criteria.

Regarding DO criteria and those designated uses, I appreciate your thoughts. I would like to think that any DO criteria update may consider use updates as well, so perhaps there may be further distinctions between uses in the future.

Those changes might be necessary, as well, to avoid the scenario you identified below: where we would need to impair waters that aren't meeting 6 mg/l or 7 mg/L, but could still meet 5 mg/L.

Have a good afternoon, and I hope you plan on attending the preliminary decisions webinar for natural conditions next week.

Cheers,

Kalman

From: Lincoln Loehr <lcloehr@yahoo.com>
Sent: Friday, April 12, 2024 3:24 PM
To: Bugica, Kalman (ECY) <kbug461@ECY.WA.GOV>
Subject: Thoughts regarding natural conditions criteria

External Email

Kalman,

As you work on trying to satisfy EPA on a way to interpret natural conditions, I ask that the use of natural condition based approaches and the allowance for some human caused decrease should apply only when current numeric criteria are not met. (This is the current approach in our regulations.) The same allowance should also be available in the future when our marine DO criteria get a badly needed update to criteria similar to Chesapeake Bay's.

Given the explanation of our current numeric criteria, the natural condition trigger should only be when 5 mg/L (Good use) is not met. 5 mg/L is identified as protective *for most uses including, but not limited to, salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.*

True there are also criteria of 6 mg/L (Excellent use) and 7 mg/L (Extraordinary use), but the are identified as protecting all of the same uses that are protected by 5 mg/L (Good), and hence are unnecessary as triggers for natural condition considerations when not met. Granted, the Good use says "most uses" while the other uses have needless wording of "shall markedly and uniformly exceed the requirements for all uses including ...." and "shall meet or exceed the requirements for all uses including ...." When originally adopted in 1967, the list of uses included salmonid spawning for Excellent and Extraordinary, but did not include it for Good, hence the use of "most" in the list of uses protected by the Good classification. After 50 years, Ecology realized salmonids do not spawn in salt water, so that use was dropped, leaving three different classes (Extraordinary, Excellent, and Good) protecting all the same uses, without exceptions.

Given the common uses identified for 7, 6, and 5 mg/L, one cannot look to our criteria and assert there is impairment when DO is less than 7 or 6, but still meets 5 mg/L.

Please give these concerns consideration as you proceed with your rule-making task.

Lincoln Loehr

Preliminary Regulatory Analyses:

Including the:

- Preliminary Cost-Benefit Analysis
- Least-Burdensome Alternative Analysis
- Administrative Procedure Act Determinations
- Regulatory Fairness Act Compliance

Chapter 173-201A WAC

Water Quality Standards for Surface Waters of the State of Washington

By

Logan Blair, Ph.D.

Emma Diamond

For the

Water Quality Program

Washington State Department of Ecology

Olympia, Washington

May 2024, Publication 24-10-022

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Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
Headquarters	Across Washington	P.O. Box 46700 Olympia, WA 98504	360-407-6000

Preliminary Regulatory Analyses

Including the:

Preliminary Cost-Benefit Analysis

Least-Burdensome Alternative Analysis

Administrative Procedure Act Determinations

Regulatory Fairness Act Compliance

Chapter 173-201A WAC, Water Quality Standards for Surface Waters of the State of Washington

Water Quality Program
Washington State Department of Ecology

Olympia, WA

May 2024 | Publication 24-10-022

DEPARTMENT OF
ECOLOGY
State of Washington

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Tables

Abbreviations and Acronyms

APA	Administrative Procedure Act
CBA	Cost Benefit Analysis
CFR	Code of Federal Regulations
CWA	Clean Water Act
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
ESA	Endangered Species Act
GP	General Permit
IP	Individual Permit
LBA	Least Burdensome Alternative
MGD	Million Gallons per Day
O&M	Operations and Maintenance
PPM	Parts Per Million
pH	potential of Hydrogen
RCW	Revised Code of Washington
RFA	Regulatory Fairness Act
SU	Standard Units
TMDL	Total Maximum Daily Load
UAA	Use Attainability Analysis
ug/L	Micrograms Per Liter
USFWS	United States Fish and Wildlife Service
WAC	Washington Administrative Code
WLA	Waste Load Allocations
WQ	Water Quality
WQS	Water Quality Standards

Executive Summary

This report presents the determinations made by the Washington State Department of Ecology as required under Chapters 34.05 RCW and 19.85 RCW, for the proposed amendments to the Water Quality Standards for the Surface Waters of the State of Washington rule (Chapter 173-201A WAC; the "rule"). This includes the:

- Preliminary Cost-Benefit Analysis (CBA)
- Least-Burdensome Alternative Analysis (LBA)
- Administrative Procedure Act Determinations
- Regulatory Fairness Act Compliance

why hasn't this been updated for DO since 1967?

Washington's administrative code contains numeric water quality criteria for temperature, DO, and pH that are determined by designated use categories, as well as aquatic life toxics criteria such as copper, lead, and zinc. These numeric criteria are designed to protect designated uses and form the basis for water quality actions including permit limits.

However, numeric criteria do not always capture the unique chemical, physical, or biological characteristics that exist in any one system. Inconsistencies may be due to natural processes or seasonal conditions that vary across geography like water source, natural shading, and flow rate, among others. For example, a naturally low-flowing stream in a natural prairie without any human alteration may have seasonally higher temperatures than the numeric limit set to protect aquatic life. Here, a difficult situation may arise in which water bodies fail to meet water quality standards because of natural conditions, yet regulations require their improvement.

We are considering rule amendments to address EPA's 2021 disapproval of previously-approved natural condition provisions in our standards, including for fresh and marine dissolved oxygen (DO) and temperature (excluding lakes). Nearly all states have some provision of this kind. Washington needs natural conditions provisions to recognizing that conditions in some surface waters naturally do not always meet water quality criteria throughout the year, and to effectively implement our Clean Water Act programs.

The proposed rule amendments consist of:

how is this defined? It wasn't detailed in the natural condition.

Proposed revisions to existing criteria:

- Updates to the natural conditions provision to limit use to aquatic life criteria.
- Updating allowances for human impacts to fresh and marine waters for dissolved oxygen and temperature when the natural conditions constitute the water quality criteria.

- Updates to the site-specific criteria process for an allowance for natural conditions to be used as a basis for developing these criteria.

Other proposed changes:

- Adding definitions for the performance-based approach and local and regional sources of human-caused pollution.
- Adding a new section detailing the use of the performance-based approach and applicable aquatic life criteria.
- Adding a rule document referenced in the water quality standards that details the methodology of the performance-based approach.

Minor non-substantive edits:

- One update to reflect the latest and current revision for a referenced EPA document

Costs from the proposed rule amendments would originate from any actions taken by permittees to comply with procedures or conditions that generate new capital expenses (e.g. technology, engineering solutions or land acquisition), labor cost (e.g. source control and monitoring), or other miscellaneous activities (scientific studies) compared to costs experienced under baseline conditions.

see EPA comment on costs (previous approval)

Based on guidance and conversations with Ecology staff, we determined that the most likely action to occur because of the proposed rule amendments taken together, would be meeting waste load allocations based on natural conditions criteria developed through the total maximum daily load (TMDL) process compared to meeting numeric temperature, DO, and / or pH criterion.[2] After filtering future TMDL studies for these criteria, with potential for natural conditions, and prioritized in the next 20 years, we identified 3,671 associated permits.

EPA previous approval concern...

no stakeholder process?

We cannot quantify the costs of the proposed rulemaking to associated permits because future TMDL studies have not been performed yet. Qualitatively, the most likely actions taken because of the proposed rulemaking are not likely to impose new costs, but rather produce benefits in the form of avoided costs. Historical TMDLs reviewed by the study team and the general logic of natural conditions provisions suggest that criteria considering local factors and seasonal variation would be more easily met through fewer actions or investments—up to avoiding paradoxical situations in which permittees need to improve the quality of the water they discharged to beyond what is achievable without any human influence.[3]

[2] See other potential actions and baseline comparisons detailed in Section 3.

[3] We note that if it were determined that for one part of the year natural conditions criteria are more stringent than the biologically based criteria (e.g. lower temperatures in winter months), permittees might face new cost during this period compared to baseline under the proposed rule. However, other aspects of the proposed rule like the human allowance and limiting allowances to local and regional sources, could mitigate these to an unknown degree. The net impact on costs would depend on the relative size of new costs and cost-savings. Ultimately, data

based on what?

We cannot fully quantify the extent of potential benefits of the proposed rulemaking because future TMDL studies have not been performed yet. However, through a pair of illustrative examples, we applied a small and arbitrary temperature and DO criteria change to a selection of potentially impacted permits—akin to just one scenario when meeting natural conditions under the proposed rulemaking. We estimated a total 20-year present value benefit of $675 million through this exercise, but stress that this represents partial benefits and should be considered a conservative lower bound. Additional, but unquantified, benefits include the avoided costs of meeting numeric criteria for freshwater pH compared to a natural condition based criteria, and any avoided cost of independent science by permittees in support of Ecology performing site-specific criteria and UAA in the baseline.

The baseline conditions and proposed rulemaking (if adopted) would be considered protective of aquatic life and designated uses. Therefore, we do not expect new costs or benefits from a material change in related ecosystem services.

We conclude, based on a reasonable understanding of the quantified and qualitative costs and benefits likely to arise from the proposed rule amendments, as compared to the baseline, that the benefits of the proposed rule amendments are greater than the costs.

After considering alternatives, within the context of the goals and objectives of the authorizing statute, we determined that the proposed rule represents the least-burdensome alternative of possible rule requirements meeting the goals and objectives.

Based on this analysis, Ecology is exempt from performing additional analyses under the Regulatory Fairness Act, under RCW 19.85.025(4) which states that, “This chapter does not apply to the adoption of a rule if an agency is able to demonstrate that the proposed rule does not affect small businesses.” Moreover, by not imposing compliance costs, the proposed rule amendments do not meet the RFA applicability standard under RCW 19.85.030(1)(a).

limitations prevent us from quantifying a forecast of how often this might occur and the net cost of such a scenario.

Chapter 1: Background and Introduction

1.1 Introduction

This report presents the determinations made by the Washington State Department of Ecology, as required under Chapters 34.05 RCW and 19.85 RCW, for the proposed Water Quality Standards for the Surface Waters of the State of Washington rule (Chapter 173-201A WAC; the "rule"). This includes the:

- Preliminary Cost-Benefit Analysis (CBA)
- Least-Burdensome Alternative Analysis (LBA)
- Administrative Procedure Act Determinations
- Regulatory Fairness Act Compliance

The Washington Administrative Procedure Act (APA; RCW 34.05.328(1)(d)) requires Ecology to evaluate significant legislative rules to "determine that the probable benefits of the rule are greater than its probable costs, taking into account both the qualitative and quantitative benefits and costs and the specific directives of the law being implemented." Chapters 1 – 5 of this document describe that determination.

The APA also requires Ecology to "determine, after considering alternative versions of the rule…that the rule being adopted is the least burdensome alternative for those required to comply with it that will achieve the general goals and specific objectives" of the governing and authorizing statutes. Chapter 6 of this document describes that determination.

The APA also requires Ecology to make several other determinations (RCW 34.05.328(1)(a) – (c) and (f) – (h)) about the rule, including authorization, need, context, and coordination. Appendix A of this document provides the documentation for these determinations.

The Washington Regulatory Fairness Act (RFA; Chapter 19.85 RCW) requires Ecology to evaluate the relative impact of proposed rules that impose costs on businesses in an industry. It compares the relative compliance costs for small businesses to those of the largest businesses affected. Chapter 7 of this document documents that analysis, when applicable.

All determinations are based on the best available information at the time of publication. We encourage feedback (including specific data) that may improve the accuracy of this analysis.

1.1.1 Background

The distribution, health, and survival of many aquatic species in Washington directly or indirectly depend on the quality of the water in which they live. Changes in water temperature, for example, can materially impact the life of a salmonid given that cooler river water temperatures in the fall signal upstream migration. Human activities can directly contribute to thermal input to rivers, reduce groundwater that serves to moderate stream temperatures, or reduce the capacity of a river to absorb heat. Importantly, seasonal swings in temperature and variations in climatic conditions can also push temperatures outside the optimal range (USEPA, 2003).

DO, another important criterion, is the amount of oxygen that is present in water, which all aquatic animals need to breathe. Low levels of oxygen (hypoxia) or no oxygen levels (anoxia) can occur when excess organic materials, such as large algal blooms, are decomposed by microorganisms. As DO levels drop, some sensitive animals may move away, decline in health, or die (EPA, 2023). DO can be affected directly by local human actions such as contributing organic and inorganic materials that are metabolized by organisms (consuming available oxygen), and by actions that raise the temperature of waterbodies (thus reducing the solubility of oxygen). Like temperature, DO levels also fluctuate periodically, seasonally, and as part of the daily ecology of the aquatic resource (Ecology, 2018).

Variation in pH above (basic) or below (acidic) safe ranges may physiologically stress species and can result in decreased reproduction, decreased growth, disease, or death. While human activity can contribute to fluctuations in pH, pH levels vary naturally with the draining of wetlands or floodplains, substrate composition, and dissolved vegetative material or photosynthetic activity (EPA, 2024). Other toxic pollutants known to threaten aquatic life in a waterbody such as copper, lead, and zinc, may also come from human and natural contributors.

This rulemaking seeks to establish provisions that allow the use of natural conditions as a basis when setting aquatic life criteria through site-specific rulemaking or use attainability analysis (UAA). For temperature, DO and the potential of hydrogen ion concentration in freshwater (pH) specifically, this rulemaking provides a pathway for Ecology to set these criteria based on natural conditions without subsequent rulemaking through a performance-based approach. In waters where temperature and DO natural conditions apply, this rulemaking will limit human actions, or allowances. The rulemaking also includes definitions and methodological documentation supporting these proposed changes.

In this document, we predominantly focus our attention on describing and analyzing the proposed rule as it concerns temperature, DO and pH criteria given that establishing other criteria under this rulemaking will require additional rulemaking and regulatory analysis.

Numeric Criteria

Washington's administrative code contains numeric water quality criteria determined by designated use categories (see for example temperature in 173-201A-200(1)(c) WAC and 173-201A-210(1)(c) WAC, and DO in 173-201A-200(1)(d) WAC and 173-201A-210(1)(d) WAC), as well as a complete list of aquatic life toxics criteria in 173-201A-240 WAC.[4] Designated uses, sometimes called "beneficial uses," describe uses specified in Washington's water quality standards, and use designations are made for each surface water body or water body segment (see 173-201A-600 WAC and 173-201A-610 WAC).

Numeric criteria are designed to protect designated uses and form the basis for water quality actions including permit limits. There are six designated uses related to aquatic life for

[4] Note that 173-201A-610 WAC contain all site-specific criteria where applicable.

freshwater bodies including: char spawning and rearing; core summer salmonid habitat; and salmonoid spawning, rearing, and migration. There are four marine water designated uses related to aquatic life ranging from extraordinary to fair quality. Each designated use is associated with a biologically-based numeric criterion ("numeric criteria" hereafter) determined to be protective of aquatic life. In the fresh water temperate criteria, for example, the numeric criterion for freshwater segments designated char spawning and rearing is 12 degrees Celsius (53.6 degrees Fahrenheit).[5]

Natural Condition Provisions at Ecology

Numeric criteria do not always capture the unique chemical, physical, or biological characteristics that exist in any one system. Inconsistencies may be due to natural processes or seasonal conditions that vary across geography like water source, natural shading, and flow rate among others. For example, a naturally low-flowing stream in a natural prairie without any human alteration may have seasonally higher temperatures than the numeric limit set to protect aquatic life.

In the example above, a difficult situation may arise in which water bodies fail to meet water quality standards because of natural conditions, yet regulations require their improvement. Permitting and enforcement would be costly if not impossible in this regulatory environment. Not only would dischargers need to curb their impacts, but they would be required to bring water quality to a state that is potentially unachievable, even in their collective absence.

To overcome these and similar challenges, the US Environmental Protection Agency (EPA) recommends that generalized aquatic life criteria be further refined through adoption of local criteria to protect unique characteristics inherent to a specific water (USEPA, 2015).[6] In this way, Ecology's regulatory work has relied on "natural condition provisions" to reconcile numeric criteria and local conditions before human alteration.[7]

Natural conditions provisions were adopted into the first water quality standards for the state in 1967 which placed limits on non-natural increases for temperature and allowed limited modifications when natural water quality conditions dropped due to "unusual and not reasonably foreseeable" natural causes.

The 1973 updates to the Water Quality Standards (WQS) introduced a general natural conditions provision, stating that "[w]henever the natural conditions are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria." This was further refined in 2003 and migrated to WAC 173-201A-260:

> "It is recognized that portions of many water bodies cannot meet the assigned criteria due to the natural conditions of the water body. When a water body does not meet its assigned criteria due to natural climatic or landscape attributes, the natural conditions constitute the water quality criteria."

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[5] See tables 200(1)(c), 200(1)(d), 210(1)(c), and 210(1)(d) in 173-201A WAC for additional details.
[6] https://www.epa.gov/sites/default/files/2015-02/documents/natural-conditions-framework-2015.pdf
[7] See WAC 173-201A-260(1); 173-201A-200(1)(c)(i); -210(1)(c)(i)); 173-201A-200(1)(d)(i); -210(1)(d)(i)).

Human action values were subsequently adopted to limit temperature (WAC 173-201A-200(1)(c)(i), -210(1)(c)(i))) and DO (WAC 173-201A-200(1)(d)(i), -210(1)(d)(i))) increases caused by human activity. For example, with respect to freshwater temperature (WAC 173-201A-200(1)(c)(i)):

> "When a water body's temperature is warmer than the criteria in Table 200 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F)"

EPA Disapproval

On Nov. 19, 2021, the EPA reconsidered and disapproved some of Ecology's previously approved natural conditions provisions and criteria in Surface Water Quality Standards (USEPA, 2021)[8] EPA disapproved the following WQS:

- A general provision that allows a water body's natural conditions to serve as the water quality standard. [WAC 173-201A-260(1)(a)]
- A specific provision that sets the temperature requirement to how cool a water body would be without human alterations. This provision also limits temperature increases caused by human activity cumulatively to less than 0.3 degrees Celsius. [WAC 173-201A-200(1)(c)(i), -210(1)(c)(i))]
- A specific provision that sets the dissolved oxygen requirement to the highest concentration a water body can achieve without human alterations. This provision also states that human activity cannot cumulatively cause dissolved oxygen in a water body to decrease more than 0.2 mg/L. [WAC 173-201A-200(1)(d)(i), -210(1)(d)(i)]

EPA stated in its justification of disapproving WAC 173-201A-260(1)(a) that the provision is broadly drafted and does not specify the types of criteria or pollutants to which it applies. Therefore, such a provision could apply to a wide range of naturally occurring pollutants, including toxic pollutants, and even allow an exception from otherwise applicable numeric human health criteria. This is not consistent with EPA's interpretation of the relationship between natural conditions and protection of designated human health uses. Washington's adopted provision did not limit in scope the natural conditions provision to aquatic life uses or specific pollutants.

EPA noted that there are no changes necessary to address the disapproval. Washington's WQS currently include applicable numeric criteria that EPA has determined to be protective of designated uses. EPA did, however, provide discretionary recommendations. EPA noted that it continues to believe an "appropriately drafted natural condition provision can serve an

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[8] In February 2014, the Northwest Environmental Advocates (NWEA) filed a complaint with the United States District Court for the Western District of Washington (Case No. 2:14-cv-0196-RSM) over EPA's 2008 CWA Section 303(c) approval. In October 2018, the Court issued an Order Granting a Stay (Dkt. 95) pending EPA's reconsideration of its prior determinations and subsequently granted an extension (Dkt. 118) for EPA to complete its reconsideration of these natural condition provisions by November 19, 2021. See https://fortress.wa.gov/ecy/ezshare/wq/standards/EPA_ActionsNCC_Nov192021.pdf for EPA's decisions.

important role in state WQS by reflecting a naturally occurring spatial and temporal variability in water quality that is protective of uses" (Opalski, 2021). EPA notes that a new provision for natural conditions narrowly tailored to aquatic life uses could be adopted. Alternative, the adoption of a performance-based approach could be used to establish aquatic life criteria reflecting the natural condition for specific pollutants.

In their justification for disapproving human allowance provisions in WAC 173-201A-200 and -210, EPA noted that it had disapproved the general provision in WAC 173-201A-260(1)(a) (as discussed above). Without an approved WQS that allows for natural conditions to constitute the applicable water quality criteria, then the applicable criteria for temperature and DO are the numeric criteria. The natural condition provisions for allowable human contribution are not based on these biologically based numeric criteria, but on the natural condition of the waterbody. Further, these provisions do not authorize human actions to cause insignificant exceedances to the applicable numeric criteria. Thus, EPA disapproved these provisions because such impacts are not tied to approved criteria that are in effect for Clean Water Act (CWA) purposes.

EPA noted again that no changes were necessary to address the disapproval, but that Washington could adopt new natural conditions criteria specific to temperature or DO. For instance, a performance-based approach for establishing these criteria representative of the natural condition of a waterbody could be adopted into the WQS. Another option would be for Washington to adopt numeric temperature and dissolved oxygen criteria that account for natural conditions using the best available relevant data. This could include site-specific criteria. EPA notes that Washington could also choose to adopt a new WQS provision that allows for human actions to cause insignificant decreases in DO or increases to temperature.

1.2 Reasons for the proposed rule amendments

We are considering rule amendments to address EPA's 2021 disapproval of previously-approved natural condition provisions in our standards, including for fresh and marine dissolved oxygen and temperature (excluding lakes).

It is important that we have a provision in the WQS recognizing that conditions in some surface waters naturally do not meet water quality criteria at all times throughout the year. Nearly all states have some provision of this kind. Washington needs natural conditions provisions to effectively implement our Clean Water Act programs.

1.3 Summary of the proposed rule amendments

In this rulemaking, we are using information from previous ESA consultations, prior EPA biological evaluations, EPA memorandums, EPA guidance documents, exploration of how other states address natural conditions, and the latest scientific information to propose natural conditions criteria that will protect designated and existing uses in Washington; while recognizing that some waters in Washington do not meet applicable biologically based numeric criteria due to natural or seasonal factors (see *inter alia* USEPA 2003, 2005, 2007, 2009, 2015b, 2021, 2023; USFWS, 2008).

The proposed rule amendments consist of:

Proposed revisions to existing criteria:

- Updates to the natural conditions provision to limit use to aquatic life criteria.
- Updating allowances for human impacts to fresh and marine waters for dissolved oxygen and temperature when the natural conditions constitute the water quality criteria
- Updates to the site-specific criteria process for an allowance for natural conditions to be used as a basis for developing these criteria.

Other proposed changes:

- Adding definitions for the performance-based approach and local and regional sources of human-caused pollution.
- Adding a new section detailing the use of the performance-based approach and applicable aquatic life criteria.
- Adding a rule document referenced in the water quality standards that details the methodology of the performance-based approach.

Minor non-substantive edits:

- One update to reflect the latest and current revision for a referenced EPA document

1.4 Document organization

The chapters of this document are organized as follows:

- **Chapter 2 - Baseline and the proposed rule amendments:** Description and comparison of the baseline (what would occur in the absence of the proposed rule amendments) and the proposed rule requirements.
- **Chapter 3 - Likely costs of the proposed rule amendments:** Analysis of the types and sizes of costs we expect impacted entities to incur as a result of the proposed rule amendments.
- **Chapter 4 - Likely benefits of the proposed rule amendments:** Analysis of the types and sizes of benefits we expect to result from the proposed rule amendments.
- **Chapter 5 - Cost-benefit comparison and conclusions:** Discussion of the complete implications of the CBA.
- **Chapter 6 - Least-Burdensome Alternative Analysis:** Analysis of considered alternatives to the contents of the proposed rule amendments.

- **Chapter 7 - Regulatory Fairness Act Compliance:** When applicable. Comparison of compliance costs for small and large businesses; mitigation; impact on jobs.
- **Appendix A - APA Determinations:** RCW 34.05.328 determinations not discussed in chapters 5 and 6.
- **Appendix B - Additional Tables and Figures**

Chapter 2: Baseline and Proposed Rule Amendments

2.1 Introduction

We analyzed the impacts of the proposed rule amendments relative to the existing rule, within the context of all existing requirements (federal and state laws and rules). This context for comparison is called the baseline and reflects the most likely regulatory circumstances that entities would face if Ecology does not adopt the proposed rule.

2.2 Baseline

The baseline is what allows us to make a consistent comparison between the state of the world with and without the proposed rule amendments. Should Ecology not adopt the proposed rulemaking, administering water quality actions are determined by existing laws and rules discussed in further detail in the remainder of this chapter.[9] Specifically, the baseline for this rulemaking includes:

- Clean Water Act
- Water Pollution Control Act
- Impaired Waterbody Listing and Cleanup Plan
- State Surface Water Quality Standards
- Permitting Guidelines and Compliance

The reminder of this section discusses the baseline in greater detail.

2.2.1 Clean Water Act

Section 303(c)(2)(A) states, about surface water quality standards:

> "…Such standards shall be such as to protect the public health or welfare, enhance the quality of the water and serve the purposes of this Chapter. Such standards shall be established taking into consideration their use and value for public water supplies, propagation of fish and wildlife, recreational purposes and agricultural, industrial and other purposes and also taking into consideration their use and value for navigation."

On standards, Section 304(a) cites that states should:

[9] Note again that we focus our attention predominantly on water quality actions related to temperature, DO and pH. That is because the proposed rule provides an option for these criteria to consider natural conditions through a performance-based approach. For all others, a site-specific study or UAA is needed, which will require a separate rulemaking and regulatory analysis.

(1) Establish numeric criteria values based on: 304(a) Guidance; 304(a) Guidance modified to reflect site-specific conditions; or other scientifically defensible methods.[10]

(2) Establish narrative criteria or criteria based upon biomonitoring methods where numerical criteria cannot be established or to supplement numerical criteria.

2.2.2 Water Pollution Control Act

RCW 90.48.010 states, about water quality standards:

> It is declared to be the public policy of the state of Washington **to maintain the highest possible standards to insure the purity of all waters of the state consistent with public health and public enjoyment thereof, the propagation and protection of wild life, birds, game, fish and other aquatic life, and the industrial development of the state,** and to that end require the use of all known available and reasonable methods by industries and others to prevent and control the pollution of the waters of the state of Washington. Consistent with this policy, the state of Washington will exercise its powers, as fully and as effectively as possible, to retain and secure high quality for all waters of the state. The state of Washington in recognition of the federal government's interest in the quality of the navigable waters of the United States, of which certain portions thereof are within the jurisdictional limits of this state, proclaims a public policy of working cooperatively with the federal government in a joint effort to extinguish the sources of water quality degradation, while at the same time preserving and vigorously exercising state powers to insure that present and future standards of water quality within the state shall be determined by the citizenry, through and by the efforts of state government, of the state of Washington.

RCW 90.48.035 states, about rule-making authority:

> The department shall have the authority to, and shall promulgate, amend, or rescind such rules and regulations as it shall deem necessary to carry out the provisions of this Chapter, including but not limited to rules and regulations relating to standards of quality for waters of the state and for substances discharged therein in order to maintain the highest possible standards of all waters of the state in accordance with the public policy as declared in RCW 90.48.010.

2.2.3 Impaired Waterbody Listing and Cleanup Plan

The CWA section 303(d) establishes a process to identify and clean up polluted waters. Every two years, all states are required to perform a water quality assessment of surface waters in

[10] Where other scientifically defensible methods include setting site-specific criteria equal to natural conditions (See https://www.epa.gov/sites/default/files/2015-02/documents/natural-conditions-framework-2015.pdf)

the state, including all the rivers, lakes, and marine waters where data are available. Ecology compiles its own water quality data and federal data and invites other groups to submit water quality data they have collected. All data submitted must be collected using appropriate scientific methods and follow an approved Quality Assurance Project Plan.[11] The assessed waters are placed in categories that describe the status of water quality. Once the assessment is complete, the public is given a chance to review and provide comments. The final assessment is formally submitted to the EPA for approval.

Waters with beneficial uses – such as aquatic habitat– that are impaired by pollutants are placed in the polluted water category in the water quality assessment 303(d) list. These water bodies fall short of state surface water quality standards and are not expected to improve within the next two years. , Waters placed on the 303(d) list require the preparation of a water cleanup plan (TMDL) or other approved water quality improvement project.[12] The improvement plan identifies how much pollution needs to be reduced or eliminated to achieve clean water and allocates that amount of required pollution reduction among the existing sources.

Ecology's assessment of which waters to place on the 303(d) list is guided by federal laws, state water quality standards, and the Policy on the Washington State Water Quality Assessment (Ecology 2023b). This policy describes how the standards are applied, requirements for the data used, and how to prioritize TMDLs, among other issues.[13] In addition, even before a TMDL is completed, the inclusion of a water body on the 303(d) list can reduce the amount of pollutants allowed to be released under permits issued by Ecology.

2.2.4 State Surface Water Quality Standards

State surface water quality standards form the initial basis for federal 303(d) listings and TMDLs described in section 2.2.2. Relevant rules that determine standards without this rulemaking include the following.[14]

Biologically based numeric criteria

Fresh water aquatic life designated uses and criteria WAC 173-201A-200, and marine water designated uses and criteria WAC 173-201A-210, establish Washington's biologically based numeric criteria for freshwater temperature, marine temperature, freshwater DO, saltwater

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[11] See https://apps.ecology.wa.gov/publications/documents/2110032.pdf

[12] The term "TMDL" is often also applied to the process to determine a TMDL ("Ecology is doing a TMDL") and to the final documentation of the TMDL ("Ecology has submitted a TMDL").

[13] A TMDL is the sum of the Load Allocations and Wasteload Allocations, plus reserves for future growth and a margin of safety, which are equal to the Loading Capacity of the water body. This is a requirement of Section 303(d) of the federal Clean Water Act and is defined in 40 CFR 130.2(i). See https://ecology.wa.gov/Water-Shorelines/Water-quality/Water-improvement/Total-Maximum-Daily-Load-process for additional details on the TMDL process.

[14] Note that 90.48 RCW discussed above is the authorizing statute for opening WAC 173-201A discussed below.

DO, and freshwater pH—except for criteria applicable to specific waterbody segments found in Table 602 (173-201A-602).[15]

As discussed in Section 1.1.2, WAC 173-201A-260(1)(a), WAC 173-201A-200(1)(c)(i), -210(1)(c)(i)) and WAC 173-201A-200(1)(d)(i) -210(1)(d)(i) are not in effect for federal actions. This means that **without the proposed rulemaking, natural conditions cannot constitute water quality criteria for the purposes of federal actions, such as 303(d) listings and TMDLs.** Entities associated with water bodies that exceed numeric criteria in WAC 173-201A-200 & -210 for temperature, DO and pH will remain subject to numeric criteria.

Site-Specific Criteria and Use Attainability Analysis

Ecology can develop new site-specific criteria or change the designated use through a use attainability analysis (UAA). **Without the proposed rulemaking, natural conditions cannot form the basis for site-specific criteria, only biologically based numeric criteria determined from aquatic life species studies.[16]**

Currently, a private entity wishing to establish a site-specific criterion or to modify a use may evaluate, develop, and present the scientific support to Ecology for such an action. However, Ecology would carry out the full process of considering, proposing, and adoption through rulemaking.[17]

WAC 173-201A-430 states, about establishing site-specific criteria:

> (1) Where the attainable condition of existing and designated uses for the water body would be fully protected using an alternative criterion, site-specific criteria may be adopted. (a) The site-specific criterion must be consistent with the federal regulations on designating and protecting uses (currently 40 C.F.R. 131.10 and 131.11); and (b) The decision to approve a site-specific criterion must be subject to a public involvement and intergovernmental coordination process.
>
> (2) The site-specific analyses for the development of a new water quality criterion must be conducted in a manner that is scientifically justifiable and consistent with the assumptions and rationale in "Guidelines for Deriving National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses," EPA 1985; and conducted in accordance with the procedures established in the "Water Quality Standards Handbook," EPA 1994, as revised.
>
> (3) The decision to approve the site-specific criterion must be based on a demonstration that it will protect the existing and attainable uses of the water body.

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[15] Note that in addition to tables in 173-201A-200 and -210, 1 DADMax values and supplemental numeric spawning criteria described in subsequent subsections may also apply.

[16] Based on the scientific approach detailed in EPA (1985) guidelines.

[17] In this way, developing site-specific criteria or a UAA is a resource intensive process (Ecology, 2004). The need to balance resources with other water quality activities—such as permit management and TMDL work—means that site-specific criteria and UAA are taken on sparingly.

(4) Site-specific criteria are not in effect until they have been incorporated into this chapter and approved by the USEPA."

WAC 173-201A-440 states, about use attainability analysis:

(1) Removal of a designated use for a water body assigned in this chapter must be based on a use attainability analysis (UAA). A UAA is a structured scientific assessment of the factors affecting the attainment of the use which may include physical, chemical, biological, and economic factors. A use can only be removed through a UAA if it is not existing or attainable.

(2) A UAA proposing to remove a designated use on a water body must be submitted to the department in writing and include sufficient information to demonstrate that the use is neither existing nor attainable.

(3) A UAA must be consistent with the federal regulations on designating and protecting uses (currently 40 C.F.R. 131.10).

(4) Subcategories of use protection that reflect the lower physical potential of the water body for protecting designated uses must be based upon federal regulations (currently 40 C.F.R. 131.10(c)).

(5) Allowing for seasonal uses where doing so would not harm existing or designated uses occurring in that or another season must be based upon federal regulations (currently 40 C.F.R. 131.10(f)).

(6) After receiving a proposed UAA, the department will respond within sixty days of receipt with a decision on whether to proceed toward rule making.

(7) The decision to approve a UAA is subject to a public involvement and intergovernmental coordination process, including tribal consultation.

(8) The department will maintain a list of federally recognized tribes in the state of Washington. During all stages of development and review of UAA proposals, the department will provide notice and consult with representatives of the interested affected Indian tribes on a government-to-government basis, and carefully consider their recommendations.

(9) The results of a UAA are not in effect until they have been incorporated into this chapter and approved by the USEPA. Any designated uses established through the UAA process are included in WAC 173-201A-602 and 173-201A-612.

2.2.5 Permitting Guidelines and Compliance

Permitting guidelines help determine how permit writers approach different permit scenarios. They assist permit writers in how to think through meeting water quality criteria for protection of aquatic life to permittee-specific requirements. While not a legal requirement, guidance informs how aquatic life criteria might impact permittees who discharge effluent to water bodies. Therefore, in describing the baseline for this analysis of the rule amendments, it is necessary to consider the permitting guidelines in the baseline and amended scenarios, as they will contribute to the cost and benefit estimates and the discussed impacts.

Ecology uses the Water Quality Program Permit Writer's Manual (Ecology, 2018) for technical guidance when developing wastewater discharge permits.[18] With respect to temperature, pH, and DO limits, permit writers would first determine if an applicable TMDL has been approved, or is in development before determining whether effluent will cause, or have reasonable potential to cause or contribute to, violation of water quality standards. If an approved TMDL exists, waste load allocations (WLA) described in the TMDL are used to determine appropriate water quality-based effluent limits.

If no TMDL exists, permit writers determine whether effluent will cause, or have reasonable potential to cause or contribute to, a violation of water quality standards. If so, then effluent limits are established using methods described in the permit writer's manual to meet biologically based numeric criteria.

Occasionally, the permit writer will have information that the receiving water concentration at the point of discharge during critical condition does not meet the aquatic life criteria and that the receiving water body is not listed on the 303(d) list.[19] In these cases, where the excursion is documented with data that meets the criteria for 303(d) listing, the permit writer should develop interim effluent limits based on existing performance (no increase in loading) to be placed in the permit.[20] The periodic Water Quality Assessment will evaluate the data and subsequently categorize the water body. If the water body is impaired, it will be put in Category 5 on the 303(d) list and prioritized for a TMDL.

Past or existing compliance

The baseline includes past or existing compliance behavior in response to federal and state laws, rules, permits, guidance, and policies. These include currently implemented TMDLs that set WLAs and other necessary actions to protect the natural conditions of the water, site-specific criteria, and criteria set through previous UAAs.[21] This behavior might include, but is not limited to, existing treatment technologies, production processes, and effluent volumes.

Future compliance

The baseline includes future compliance behavior without the proposed rulemaking. This includes response to in-development and future TMDL activity and permit actions related to temperature, DO and pH. In the absence of this proposed rulemaking, meeting temperature, pH, and DO on an impaired waterbody would eventually subject permits to a TMDL based on statewide numeric criteria (WAC 173-201A), criteria established under a biologically based site-specific study, or criteria established following a UAA.

[18] https://apps.ecology.wa.gov/publications/documents/92109.pdf

[19] Critical condition refers to the time during which the combination of receiving water and waste discharge conditions have the highest potential for causing toxicity in the receiving water environment. This situation usually occurs when the flow within a water body is low, thus, its ability to dilute effluent is reduced.

[20] Where loading refers to the mass of a substance that passes particular point in a specified amount of time.

[21] Note that Washington has only performed one UAA, which is still with the EPA for review.

2.3 Proposed rule amendments

The proposed rule amendments consist of:

Proposed revisions to existing criteria:

- Updates to the natural conditions provision to limit use to aquatic life criteria.
- Updating allowances for human impacts to fresh and marine waters for dissolved oxygen and temperature when the natural conditions constitute the water quality criteria
- Updates to the site-specific criteria process for an allowance for natural conditions to be used as a basis for developing these criteria.

Other proposed changes:

- Adding definitions for the performance-based approach and local and regional sources of human-caused pollution.
- Adding a new section detailing the use of the performance-based approach and applicable aquatic life criteria.
- Adding a rule document referenced in the water quality standards that details the methodology of the performance-based approach.

Minor non-substantive edits:

- One update to reflect the latest and current revision for a referenced EPA document

2.4 Regulatory Impacts by Component

2.4.1 Updates to the natural conditions provision to limit use to aquatic life criteria

Baseline

State

On account of EPA's disapproval, there is no state baseline associated with natural conditions currently approved for federal actions (USEPA, 2021). Previous EPA-approved state regulations at WAC 173-201A-260(1)(a) states that:

"…portions of many water bodies cannot meet the assigned criteria due to the natural conditions of the water body. When a water body does not meet its assigned criteria due to natural climatic or landscape attributes, the natural conditions constitute the water quality criteria."

Federal

The EPA's interpretation of the Clean Water Act allows for site-specific criteria to be set to natural conditions (see 2015 guidance on site-specific conditions and EPA's Action on Revisions to the Washington State Department of Ecology's Surface Water Quality Standards for Natural Conditions Provisions).[22,23]

Proposed

The proposed rule would:

- Change "assigned criteria" to "assigned aquatic life criteria" in WAC 173-201A-260(1)(a) to clarify that natural conditions apply only to aquatic life.
- Add WAC 173-201A-260(1)(a)(i) to provide information to determine natural conditions criteria values, which reflect EPA's requirement that there is a binding procedure in a state's WQS to determine natural background (Davies, 1997).[24]

Expected impact

This proposed amendment, in combination with others in this rulemaking, is expected to restore Ecology's ability to establish site-specific criteria equal to the natural conditions of a water body, in water quality standards. In particular, the proposed amendments will allow future TMDL studies and those currently under development to consider the natural conditions of a water body in the context of aquatic life.

Site-specific aquatic life criteria based on natural conditions are typically pursued when a water body does not meet statewide numeric criteria and the natural conditions of the water body are suspected of contributing to the failure to meet the water quality standard. In this rulemaking, applying natural conditions provisions to water bodies with insignificant human allowances, would provide protection for aquatic life while recognizing the characteristics and seasonal attributes unique to a specific water body. This likely constitutes a **benefit** because criteria set through natural conditions provisions will typically be more achievable by permittees than those based on numeric criteria.

Without the proposed rulemaking, permittees discharging to water bodies that exceed numeric criteria, but suspect exceedance is in part due to natural conditions, will be subject to the applicable numeric criteria unless a site-specific criterion or a UAA is adopted through rule making. Site-specific criteria or a UAA are rarely pursued by Ecology, but private entities may evaluate, develop, and present the science support to Ecology for such an action (see section 2.2.4). Independently conducted science must be evaluated by Ecology and the EPA and does not guarantee agreement or adoption. In this way, the proposed rulemaking constitutes an additional **benefit** to the degree that it would lessen the need for privately conducted scientific support of site-specific criteria or designated use changes and associated cost.

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[22] https://www.epa.gov/sites/default/files/2015-02/documents/natural-conditions-framework-2015.pdf

[23] https://fortress.wa.gov/ecy/ezshare/wq/standards/EPA_ActionsNCC_Nov192021.pdf.

[24] Where natural background is defined as "background concentration due only to non-anthropogenic sources, i.e., non-manmade sources."

Note that the costs of TMDL studies and associated data collection, labor, and other resources are borne by Ecology. Therefore, amending the TMDL process through this rulemaking to include natural conditions provisions does not represent new costs to private entities.

Also note that biologically based numeric criteria, site-specific criteria, or criteria established based on natural conditions of a water body proposed in this rulemaking are fully protective of aquatic life. Thus, the proposed amendments are not expected to materially impact ecosystem services or cultural values otherwise associated with changes to aquatic life.

2.4.2 Updating allowances for human impacts to fresh and marine waters for dissolved oxygen and temperature when the natural conditions constitute the water quality criteria

Baseline

State

On account of EPA's disapproval, there is no state baseline associated with natural conditions currently approved for federal actions (EPA, 2021). The previously EPA-approved state laws regulating human impacts when the natural conditions constitute the water quality criteria are: WAC 173-201A-200(1)(c)(i), 173-201A-200(1)(d)(i), WAC 173-201A-210(1)(c)(i), WAC 173-201A-210(1)(d)(i) and for specific waterbody segments listed under 173-201A-602.

In the disapproved sections above, "human actions" considered cumulatively may not cause the DO of that water body to decrease [from natural conditions] more than 0.2 mg/L, or the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F) for both fresh waters and marine waters.

Federal

The EPA's interpretation of the Clean Water Act allows for site-specific criteria to be set equal to the natural conditions of a water body. EPA guidance further suggest adopting a provision that allows for human actions to cause insignificant decreases in DO or increases to temperature (see 2015 guidance on site-specific conditions, EPA's Action on Revisions to the Washington State Department of Ecology's Surface Water Quality Standards for Natural Conditions Provisions).[25,26]

Proposed

(1) Change "human actions" to "local and regional sources of human-caused pollution".[27]

(2) Add that DO allowances may not cause the DO of that water body to decrease more than 10% or 0.2 mg/L below natural conditions, whichever decrease is smaller.

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[25] https://www.epa.gov/sites/default/files/2015-02/documents/natural-conditions-framework-2015.pdf

[26] https://fortress.wa.gov/ecy/ezshare/wq/standards/EPA_ActionsNCC_Nov192021.pdf.

[27] See proposed definition of "local and regional sources of human-caused pollution" below

(3) Insert “below natural condition” referring to DO allowances and “above natural condition” for temperature allowance, to clarify they are given from the natural conditions criteria.

Expected impact

This proposed amendment, in combination with others in this rulemaking, is expected to restore Ecology’s ability to establish site-specific criteria equal to the natural conditions of a water body, as amended, in water quality standards. In particular, the proposed amendments will allow future TMDL studies and those currently under development to consider protecting aquatic life by requiring actions that would allow the water to meet site-specific criteria set equal to the natural conditions of a water body.

The proposed change (1) to the human action allowances will provide Ecology with the tools to regulate insignificant allowances when natural conditions criteria apply to a water body without the cumulative human action allowance being partially or fully allocated to impacts that are outside of Ecology’s regulatory authority (e.g., point source discharges in upstream Canadian waters, global climate change impacts). Amending DO allowance (2) provides additional protections in hypoxic waters, as otherwise a 0.2 mg/L decrease when waters are <2 mg/L DO may cause harm to aquatic life. Proposed language in (3) is purely for clarification.

If compared to EPA-disapproved state language, proposed amendments in (1) would allow for more achievable water quality by permittees while remaining protective of aquatic life, thus representing a benefit. Amendment (2) would be more stringent in some instances representing a cost to permittees and benefit to society by improving aquatic life. Amendment 3 has no impact.

Note that these proposed amendments are only impactful in the context of Ecology re-establishing the use of natural conditions provisions in water quality standards (i.e. WAC 173-201A-260(1)(a)). From the current baseline, the proposed amendments in this section will provide **benefits** as part of the broader collection of amendments establishing natural condition described in section 2.4.1.

2.4.3 Updates to the site-specific criteria process for an allowance for natural conditions to be used as a basis for developing criteria

Baseline

State

WAC 173-201A-430(2) says, of developing a new site-specific criteria, that it must be consistent with assumptions and rationale in “Guidelines for Deriving National Water Quality Criteria for the Protection of Aquatic Organisms and their Uses” (USEPA, 1985).

The 1985 guidelines from the EPA were incorporated by reference and provide a mechanism for developing protective biologically based criteria, but these guidelines rule out the possibility of developing protective natural conditions criteria.

Federal

The EPA's interpretation of the CWA allows for site-specific criteria to be set equal to the natural conditions of a water body. Communication with the EPA guided Ecology to adopt 40 CFR 131.11 for simplicity and to cite federal regulations rather than guidance documents. This allowed Ecology to incorporate the ability to use the natural conditions of a water body as the basis for developing site-specific aquatic life criteria.

Proposed

To replace the 1985 EPA guidance references in WAC 173-201A-430(2) with 40 CFR 131.11.

Expected impact

This proposed amendment, in combination with others in this rulemaking, will restore Ecology's ability to establish site-specific criteria equal to the natural conditions of a water body, in water quality standards. This proposed amendment specifically allows the use of natural conditions as justification for site-specific criteria development. Adopting 40 CFR 131.11 broadens what approaches can be used to scientifically support site-specific criteria development. Under the proposed rulemaking, site-specific criteria development would become particularly useful when data, parameter, or site constraints prevent use of the performance-based approaches described elsewhere in this proposed rulemaking. On the margin where other approaches are not pursued (e.g. performance-based), and private entities wish to develop scientific support for site-specific criteria, the additional options and flexibility afforded by the proposed amendment likely translates to a **benefit.**

As with other means of establishing WQ criteria, note that site-specific criteria pursued through this amendment are also expected to be fully protective of aquatic life and the designated uses of the water body. Thus, the proposed amendment is not expected to impact ecosystem services or cultural values associated with changes to aquatic life compared to the baseline.

2.4.4 Adding definitions for the performance-based approach and local and regional sources of human-caused pollution

Baseline

Proposed

Add the following definitions to WAC 173-201A-020:

"Performance-based Approach" means a water quality standard that is a transparent process (i.e., methodology) which is sufficiently detailed and has suitable safeguards that ensures predictable and repeatable outcomes, rather than a specific outcome (i.e., concentration limit for a pollutant), consistent with 40 C.F.R. 131.11 and 40 C.F.R. 131.13.

"Local and regional sources of human-caused pollution" means sources of pollution caused by human actions, and the pollution originates from: (1) within the boundaries of the State; or (2) within the boundaries of a U.S. jurisdiction abutting to the State that impacts surface waters of the State.

Expected impact

Definition. No direct impact outside of where the defined terms are used in the proposed rule, discussed above and below in this Section.

2.4.5 Adding a new section detailing the use of the performance-based approach and applicable aquatic life criteria

Baseline

Federal

The EPA's interpretation of the Clean Water Act allows for site-specific criteria to be set equal to the natural conditions of a water body. The EPA guidance has identified two general approaches states and authorized tribes can use when adopting site-specific water quality criteria: determining a specific outcome (i.e., concentration limit for a pollutant) through the development of an individual numeric criterion, and adopting a criteria derivation process through the performance-based approach (see USEPA, 2021, 2023).[28,29]

Proposed

Add a new section to the WAC (173-201A-470) detailing performance-based approach as a tool that Ecology can choose to use for implementing aquatic life criteria in its state and federal CWA actions. In this proposed rule, the performance-based approach applies to dissolved oxygen (fresh water and marine water), pH (fresh water), and temperature (fresh water and marine water) only. Ecology does not propose a requirement that the tool must be used.

Expected impact

This proposed amendment, in combination with others in this rulemaking, is expected to restore Ecology's ability to establish site-specific criteria equal to the natural conditions of a water body, as amended, in water quality standards. In particular, the proposed amendments will allow future TMDL studies and those currently under development to consider protecting aquatic life by requiring actions that would allow the water to meet site-specific criteria set equal to the natural conditions of a water body without additional rulemakings.

From the current baseline, the proposed amendment in this section is part of a broader natural condition provision that will **provide benefits** described above in section 2.4.1.

2.4.6 Adding a rule document referenced in the water quality standards that details the methodology of the performance-based approach

Baseline

Federal

[28] https://www.epa.gov/sites/default/files/2015-02/documents/natural-conditions-framework-2015.pdf
[29] https://fortress.wa.gov/ecy/ezshare/wq/standards/EPA_ActionsNCC_Nov192021.pdf.

The EPA's interpretation of the Clean Water Act allows for site-specific criteria to be set equal to the natural conditions of a water body The EPA guidance has identified two general approaches states and authorized tribes can use when adopting site-specific water quality criteria: determining a specific outcome (i.e., concentration limit for a pollutant) through the development of an individual numeric criterion, and adopting a criteria derivation process through the performance-based approach (see 2015 guidance on site-specific conditions and EPA's Action on Revisions to the Washington State Department of Ecology's Surface Water Quality Standards for Natural Conditions Provisions).[30,31]

Proposed

Due to the information required for the performance-based approach, we propose having a separate rule document, Ecology publication 24-10-017 "A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington", that provides details and requirements of the performance-based approach as noted in the proposed section WAC 173-201A-470(1)(b).

Expected impact

This proposed amendment, in combination with others in this rulemaking, will restore Ecology's ability to establish site-specific criteria equal to the natural conditions of a water body, as amended, in water quality standards. In particular, the proposed amendments will allow future TMDL studies and those currently under development to protect aquatic life by considering required actions that would allow the water to meet site-specific criteria equal to the natural conditions of a water body without additional rulemakings.

From the current baseline the proposed amendment in this section is part of a broader natural condition provision that will provide **benefits** described above in section 2.4.1, along with operational clarity and understanding.

2.4.7 One update to reflect the latest and current revision for a referenced EPA document

Baseline

State

WAC 173-201A-430(2) cites "*Water Quality Standards Handbook*," EPA 1994, as revised.

Proposed

Update WAC 173-201A-430(2) to "*Water Quality Standards Handbook*," EPA 2023, as revised.

Expected impact

This revision is required by current state law. No impact.

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[30] https://www.epa.gov/sites/default/files/2015-02/documents/natural-conditions-framework-2015.pdf
[31] https://fortress.wa.gov/ecy/ezshare/wq/standards/EPA_ActionsNCC_Nov192021.pdf.

Chapter 3: Likely Costs of the Proposed Rule Amendments

3.1 Introduction

We analyzed the likely costs associated with the proposed rule amendments, as compared to the baseline. The proposed rule amendments and the baseline are discussed in detail in Chapter 2 of this document.

3.2 Cost analysis

As discussed in Chapter 2, the collective proposed rule amendments interact and work together to generate impacts. Given that the baseline has no federally-approved natural conditions provisions, it is not practical to analyze every component of the rulemaking individually. We proceed instead by describing the impacts of the following amendments on the behavior of affected parties **as implemented together** (e.g. restoring natural conditions, as amended, for the purposed of federal actions):

Proposed revisions to existing criteria:

- Updates to the natural conditions provision to limit use to aquatic life criteria.
- Updating allowances for human impacts to fresh and marine waters for dissolved oxygen and temperature when the natural conditions constitute the water quality criteria
- Updates to the site-specific criteria process for an allowance for natural conditions to be used as a basis for developing these criteria.

Other proposed changes:

- Adding definitions for the performance-based approach and local and regional sources of human-caused pollution.
- Adding a new section detailing the use of the performance-based approach and applicable aquatic life criteria.
- Adding a rule document referenced in the water quality standards that details the methodology of the performance-based approach.

Minor non-substantive edits:

- One update to reflect the latest and current revision for a referenced EPA document
- Update to reflect the latest and current revision for a referenced EPA document

3.2.1 Impacted Permits

The proposed rulemaking would primarily impact current and future permits associated with surface waters on the 303(d) list as currently impaired (Category 5) for temperature, pH, and/or DO. To illustrate the scope of potentially impacted permits, we queried proposed TMDL projects listed from Ecology's latest water quality assessment (Ecology, 2023a) that have the potential for natural conditions based on temperature, DO, and or pH.[32, 33]

Ecology ranks projects based on the severity of the pollution problem, risks to public health, risk to threatened and endangered species, and vulnerability of water bodies to degradation among other factors (2023a, 2023b). Projects fall under one of four priorities:

- High: projects that have already been vetted and are actively being worked on,
- Medium: projects that should begin in the next 1 to 5 years,
- Medium-Low: projects that should begin in the next 5 to 15 years, and,
- Low: Projects that do not warrant starting before the higher prioritized projects.

We narrowed our initial list to only high, medium, and medium-high priority TMDL projects to describe those that will likely be complete or nearly complete within the 20-year timeframe of this analysis. Through the filtering process, 42 TMDLs were identified across all four of Ecology's regions (Eastern, Central, Northwestern, and Southwestern) and the Puget Sound.[34]

Table 1 provides a description of the top 5 out of 18 affected permit categories associated with potentially affected TMDLs by listing criteria (see Table 3 in Appendix B for full permit list). Note that among 3,671 unique permits identified, any single permit can fall within a TMDL listed for one or multiple criteria. Therefore, permits described across columns in Table 1 are not mutually exclusive. An individual permit is for a specific discharger, while general permits cover multiple dischargers performing similar activities.

Table 1. Number of potentially impacted dischargers, Top 5 Potentially Impacted Permit Categories, by Criteria

Permit Type	Temp	DO	pH
Construction SW GP	2,263	2,549	1,163
Sand and Gravel GP	218	256	201
Industrial SW GP	182	258	176
Fruit Packer GP	70	54	54
Municipal NPDES IP	46	58	49
Total (Top 5)	**2,779**	**3,175**	**1,643**
Total Including bottom 11 (not shown)	**2,926**	**3,360**	**1,792**

[32] https://ecology.wa.gov/Water-Shorelines/Water-quality/Water-improvement/Assessment-of-state-waters-303d

[33] Based on conversations with Ecology staff, 3-5 years is an average time period for completing most TMDL studies assuming current staff capacity and omitting extreme and unpredictable cases.

[34] TMDLS in this analysis typically represent a full or partial watershed with one or multiple rivers and its tributaries. Impacts of a TMDL also potentially include upstream reaches of listed segments.

Note: GP is “General Permit” and IP “Individual Permit”, SW is “Storm Water”

3.2.2 Potential Actions

From the prospective of a permittee, amendments taken collectively in this rulemaking would result in one of the following actions (behaviors):

1. Meet waste load allocations based on natural conditions criteria developed through the TMDL process using the performance-based approach,
2. Meet site-specific criteria based on natural conditions (supported by a separate Ecology rulemaking),
3. Meet site-specific criteria based on natural conditions (supported by permittee science, followed by a separate Ecology rulemaking).

Compared to an action that would take place without the proposed rule (baseline):

a) Meet waste load allocations based on numeric criteria through the TMDL process,

b) Meet site-specific criteria based on biological study (supported by a separate Ecology rulemaking)

c) Meet site-specific criteria based on biological study (supported by permittee science, followed by a separate Ecology rulemaking)

d) Meet criteria identified through a UAA (supported by a separate Ecology rulemaking)

e) Meet criteria identified through a UAA (supported by permittee science, followed by a separate Ecology rulemaking)

Costs from the proposed rule could originate from any actions taken by permittees to comply with procedures or conditions that generate new capital expenses (e.g. technology, engineering solutions or land acquisition), labor cost (e.g. source control and monitoring), or other miscellaneous activities (studies) compared to costs experienced under baseline conditions.[35] In the face of multiple potential outcomes from the rule and baseline scenarios, this amounts to the costs for any “action pair”, made up of a numbered (1, 2, or 3) potential action taken under the proposed rule, compared to a series of potential baseline states (a, b, c, d, or e) above. There are 3 × 5 = 15 such pairs.

Based on guidance and conversations with Ecology staff (Ecology, 2004), the most likely action pair is meeting waste load allocations based on natural conditions criteria developed through the TMDL process using the performance-based approach compared to a numeric criterion, or action pair 1a. This is because establishing site-specific criteria or a UAA (with or without permittee science) is a very resource intensive process. The need to balance these resources with other water quality activities—such as permit management and TMDL work—means that site-specific criteria and UAA are taken on sparingly, and if so, on significantly extended

[35] Recognizing that the new rule still carries a non-zero cost.

timelines.[36] Actions 2 and 3 under the proposed rule will require a separate rulemaking and regulatory analysis.

For these reasons, we narrow the following analysis to action pair 1a, and briefly discuss 1b-e for completeness.

3.2.3 Costs by Action Pair

Action Pair 1a

Action pair 1a (discussed in Section 3.2.2) would lead to meeting natural conditions criteria through the TMDL study process using a performance-based approach compared to the same process using statewide numeric criteria. From a practical perspective, Ecology would only use natural conditions provisions under the rulemaking for waters that already cannot meet numeric criteria, and suspect that natural conditions, among other things, may be the cause (e.g. waters represented in Table 1).

It is reasonable to assume that alternative criteria that consider local natural conditions and seasonal variation within these waters should be more easily met through fewer actions or investments. That is, there would be no new costs associated with meeting water quality requirements that allows for equal or higher temperature criteria, and/or equal or lower DO criteria (less dissolved oxygen required in the system) compared to the baseline. Since correcting pH up *or* down in effluent may require action, values set higher or lower (or both) than baseline to consider local natural conditions and seasonal variation should also by the same logic result in no new costs.

While the argument that no (new) costs would accrue from the proposed rule is logical, we cannot quantify potential costs of this rulemaking to permits in Table 1 directly because associated TMDL studies have not yet been performed. As a proxy for future TMDL development, Ecology reviewed 8 historical TMDLs developed to protect natural conditions of the water.[37] We summarize their general differences between natural and numeric criteria, the drivers of those differences, and their use in refining standards below.

- From **temperature** modeling scenarios in the reviewed TMDLs, a few degrees Celsius typically made up the difference between natural conditions targets and numeric criteria when applicable. Though it does not reflect the general trend of a few degrees, natural conditions ranged up to 13°C higher than numeric statewide criteria in outlier cases. Natural temperatures, higher than statewide standards, were commonly attributed to limits in vegetative growth, high air temperature, and naturally low flow periods. In most instances, temperature TMDLs were written in such a way that allowed for natural conditions of the system to constitute water quality criteria during parts of

[36] Only one UAA has been completed in Washington and is still under review by the EPA.

[37] Historical TMDLs natural conditions models vary widely by geographic scale (e.g. by stream segment within a watershed), time interval, and seasonal granularity. Modeling techniques also vary over time and space with technology, site access, and available historical data. This makes a systematic review impractical.

the year when exceedances were triggered, and the numeric criterion under naturally cooler periods, so long as they were determined to remain protective.[38]

- Among **DO** modeling scenarios, the difference between numeric criteria and natural DO conditions ranged from a fraction of a mg/L to over 3 mg/L. Natural levels of DO lower than numeric standards were commonly attributed to local rates of stream bank erosion, groundwater with low DO concentrations, aquatic vegetation such as algae and elodea, and storm events. Also note that higher water temperature can have indirect effects on DO through vegetation growth and other natural processes. Like temperature, numeric criteria and the natural conditions were commonly used to develop the TMDL in such a way that refined DO limits to reflect the naturally lower DO concentrations when and where appropriate.
- From **pH** modeling scenarios in the reviewed TMDLs, natural pH values varied as much as 1.5 standard units (SU) beyond the highest/lowest numeric standards.[39] Natural variances in pH were attributed to factors and processes similar to DO such as algal productivity and groundwater contributions. Also, like temperature and DO, pH criteria in these systems were set and allocated in such a way to meet natural conditions in the system.

In historical cases reviewed by the study team, allowing for natural conditions provided the flexibility necessary to avoid paradoxical situations in which permittees would need to improve the quality of the water they discharged to beyond what is achievable without any human influence. Criteria based on natural conditions would require fewer actions or technologies to achieve and maintain protective levels of water quality compared to this reality.

We note that because of this rulemaking, future natural conditions values could be calculated differently than the historical TMDLs reviewed above. Differences come primarily from amended human impact allowances (see Section 2.4.2) and the introduction of the performance-based approach (see Sections 2.4.5 and 2.4.6).

Natural conditions calculated through this process will make up the criteria for the entire duration of the year where data allow, rather than only during periods in which exceedances occurred (e.g., due to seasonal factors like flow and air temperature). If it were determined that for one part of the year natural conditions criteria are more stringent than the biologically based criteria (e.g. lower temperatures in winter months), permittees could face new cost during this period compared to baseline.

Data limitations prevent quantifying a forecast of how often this might occur and to what degree. Bear in mind that criteria set through natural conditions would be technically

[38] In historical TMDL reviewed in this section, the natural condition of temperature was approximated by the system potential through an evaluation of the combined effect of hypothetical natural conditions of site potential riparian vegetation, microclimate improvements, and improved channel widths. The modeling software QUAL2Kw was frequently used in these settings.

[39] Standard units are given on a logarithmic scale. Each number represents a 10-fold change in the acidity/basicness of the water, where 7 is neutral. For example, a pH of five is ten times more acidic than water having a pH of six.

achievable during these periods, while numeric criteria in other parts of the year may not have been without the proposed rulemaking. [40] Compared to zero allowance in the baseline, human allowance in the proposed rule would also work to reduce cost, as would limiting allowances to local and regional sources such that they would not be absorbed by global climate change and cross-border polluters.

Outside of these caveats, evidence suggests that this proposed rulemaking would **not likely impose new costs to potentially impacted permits.** Rather, it is likely that the rulemaking represents a **cost savings (benefit),** as described further below in Chapter 4.

Impacts to Aquatic Life

A material loss in aquatic life in a water body from the proposed rulemaking would constitute a loss of ecosystem services and cost to society. This is especially true for impacts to ESA listed species with uniquely high market and cultural value such as salmonoids. It is important to note that the proposed rulemaking is intended to refine water quality criteria, whilst remaining protective of aquatic life and endangered species. This means that so long as this holds true, there is no cost expected from the proposed rule compared to the baseline. Once adopted, both would be considered protective of aquatic life and designated uses.

To ensure this is the case, Ecology utilized information from previous ESA consultations, prior EPA biological evaluations, EPA memorandums, EPA guidance documents, exploration of how other states and tribes address natural conditions, and the latest scientific information to support the proposed rule (WAC 173-201A-470) (see *inter alia* USEPA 2003, 2005, 2007, 2009, 2015b, 2021, 2023; USFWS, 2008). From similar documentation and consultation with federal agencies, Ecology also ensured that other aspects of the proposed rulemaking, such as human allowances, are *de minimis*. For example:

- The EPA determined the allowable 0.3° C increase in temperature for fresh waters under natural condition scenarios is consistent with recommendations in EPA's Temperature Guidance (EPA, 2003). This provision allows for an insignificant level of heat from human actions when natural conditions are the applicable criteria or where waters are exceeding the biologically based numeric criteria. The EPA has also noted that absent such a provision, no heat would be allowed from humans when the natural conditions criteria are the applicable criteria. The EPA believed that a 0.3° C or less temperature increase about the natural condition temperature is insignificant because monitoring measurement error for recording instruments typically used in field studies are approximately 0.2° C to 0.3°.
- The EPA determined the allowable 0.2 mg/L decrease of DO for fresh waters and lakes under natural condition scenarios are considered insignificant decreases. EPA noted that DO is a characteristic of the waterbody that can be affected by several parameters (e.g., temperature). Further, 0.2 mg/L is within the monitoring measurement error for

[40] Historical TMDLs typically focus on times of year where waters were impaired. On the extreme end, natural conditions criteria could be more stringent than numeric criteria at all times of the year. However, to our knowledge there is no historical evidence that this condition exists, or would exist in future TMDLs.

recording instruments typically used to monitor dissolved oxygen. Ecology's rule requires that a decrease in DO from natural conditions equal 10% of the water body's DO or 0.2 mg/L, whichever is lower. This amendment provides additional safeguards in naturally hypoxic waters (<2 mg/L of DO).

Action Pair 1b-c

Action pair 1b-c amounts to meeting natural conditions criteria through the TMDL study process using the performance-based approach, compared to criteria developed using biological data collected in site-specific studies.

Both alternatives in these action pairs are intended to allow for a departure from statewide numeric criteria based on local conditions. However, criteria in the baseline scenario, despite being site-specific, must still be biologically based. Like 1a, criteria considering natural conditions and seasonal variation within that system are likely to be more easily met by permittees through fewer actions or investments and present no new costs.

Beyond this general logic, to our knowledge there are no examples to draw from in which a site-specific study established biologically based criteria without natural conditions (a proxy for baseline action a); then later for the same water body, established natural conditions criteria through the TMDL process (proxy for action 1 in the proposed rule).

Because Ecology would carry out the full process of considering, proposing, and adopting site-specific criteria, there would be no administrative costs differences to permittees under 1b. If a permittee were to elect to privately fund science in support of the site-specific criteria (1c), the proposed rulemaking represents an avoided cost of such a study (i.e. a benefit, see Chapter 4).

Action Pair 1d-e

Action pair 1d-e amounts to meeting natural conditions criteria through the TMDL study process using the performance-based approach, compared to meeting a different designated use through UAA.

As with site-specific criteria discussed in 1b and 1c, there is insufficient historic data to analyze potential permittee behavior in terms of meeting natural conditions criteria, compared to meeting a different designated use through UAA.[41]

Because Ecology would carry out the full process of considering, proposing, and adopting criteria based on UAA, there would be no administrative costs differences to permittees under 1d. If a permittee were to elect to privately fund science in support of a UAA (1e), the proposed rulemaking represents an avoided cost of such a study (i.e. a benefit, see Chapter 4).

3.2.4 Cost Summary

In this section, we considered the likely costs associated with the proposed rule amendments as implemented together.

[41] Only one UAA has been completed in Washington and is still under review by the EPA.

We determined that the most likely action to occur because of this rulemaking—that would not require additional rulemaking—is meeting waste load allocations based on natural conditions criteria developed through the TMDL process using the performance-based approach compared to numeric temperature, DO, and / or pH criterion. After filtering future TMDL studies for these criteria, with potential for natural conditions, and prioritized in the next 20 years, we identified 3,671 associated permits (see Table 1).

We cannot quantify the costs of the proposed rulemaking to associated permits because future TMDL studies have not been performed yet. Historical TMDLs reviewed by the study team and the general logic of natural conditions provisions suggest that criteria considering local factors and seasonal variation would be more easily met through fewer actions or investments up to avoiding paradoxical situations in which permittees need to improve the quality of the water they discharged to beyond what is achievable without any human influence. In other words, the most likely actions, taken because of the proposed rulemaking, are **not likely to impose new costs.**[42] Rather, the proposed rulemaking likely represents a **cost savings (benefit),** as described further below in Chapter 4.

Meeting waste load allocations based on natural conditions criteria developed through the TMDL process compared to other, but unlikely, baseline scenarios such as developing site-specific criteria, or UAA, also likely carry no new costs.

The baseline conditions and proposed rulemaking (if adopted) would be considered protective of aquatic life and designated uses. Therefore, we do not expect new costs or benefits from a material change in related ecosystem services.

Chapter 4: Likely Benefits of the Proposed Rule Amendments

4.1 Introduction

We analyzed the likely benefits associated with the proposed rule amendments, as compared to the baseline. The proposed rule amendments and the baseline are discussed in detail in Chapter 2 of this document.

4.2 Benefits analysis

As discussed in Chapter 2, and reprinted from Chapter 3, the collective proposed rule amendments interact and work in tandem to generate impacts. Given that the baseline has no

[42] We note that if it were determined that for one part of the year natural conditions criteria are more stringent than the biologically based criteria (e.g. lower temperatures in winter months), permittees might face new cost during this period compared to baseline under the proposed rule. However, other aspects of the proposed rule like the human allowance and limiting allowances to local and regional sources, could mitigate these to an unknown degree. The net impact on costs would depend on the relative size of new costs and cost-savings. Ultimately, data limitations prevent us from quantifying a forecast of how often this might occur and the net cost if such a scenario.

federally-approved natural conditions provisions, it is not practical to analyze every component of the rulemaking individually. We proceed instead by describing the impacts of the following amendments on the behavior of affected parties **as implemented together** (e.g. restoring natural conditions, as amended, for the purposed of federal actions):

Proposed revisions to existing criteria:

- Updates to the natural conditions provision to limit use to aquatic life criteria.
- Updating allowances for human impacts to fresh and marine waters for dissolved oxygen and temperature when the natural conditions constitute the water quality criteria
- Updates to the site-specific criteria process for an allowance for natural conditions to be used as a basis for developing these criteria.

Other proposed changes:

- Adding definitions for the performance-based approach and local and regional sources of human-caused pollution.
- Adding a new section detailing the use of the performance-based approach and applicable aquatic life criteria.
- Adding a rule document referenced in the water quality standards that details the methodology of the performance-based approach.

Minor non-substantive edits:

- One update to reflect the latest and current revision for a referenced EPA document

4.2.1 Benefits by Action Pairs

Benefits from this rulemaking would be borne from avoiding the cost of compliance with baseline scenarios in the absence of the proposed rulemaking. This includes any additional capital expenses (e.g. technology, engineering solutions or land acquisition), labor cost (e.g. source control and monitoring), or other miscellaneous activities (e.g. scientific study) required compared to those expected under the proposed rule. Table 1 in Chapter 3 summarizes permits potentially affected by this rulemaking. Various outcomes of the proposed rulemaking and baseline alternatives, or “action pairs”, can be reviewed in Section 3.2.1.

Action Pair 1a

As noted in Section 3, action pair 1a—meeting natural conditions criteria developed through the TMDL study process using the performance-based approach compared to the same process using statewide numeric criteria—is the most likely action in this analysis and would apply in some fashion to most permits in Table 1.

Based on the general logic and intent of natural conditions criteria to refine criteria values, and Ecology’s review of historical TMDLs, this scenario is likely to generate benefits.

1. Because natural conditions are suspected to be part of the driving force behind permits exceeding numeric criteria in Table 1, it is reasonable to assume that considering local variation in temperate, DO and pH would result in fewer actions and investments required to comply with refined criteria limits.
2. Almost all historical TMDLs that develop WLA based on natural conditions (see Section 3.2.3) reviewed by the study team allowed some flexibility to permittee compliance. This amounted to small allowances for higher temperature (e.g. a couple degrees Celsius), DO (e.g. a fraction of a mg/L), and pH variation (e.g. fraction of a standard unit) in parts of the year for some segments of a water body, compared to their statewide numerical equivalents.
3. In other historic TMDLs that develop WLA based on natural conditions, naturally occurring temperature, DO, and pH, varied from numeric criteria by as much as 13°C, 3 mg/L, and 1.5 standard units respectively. To the degree that similar or larger differences exist in future TMDLs, permittees in Table 1 could face a paradoxical situation under the baseline in which they must improve the quality of the water they discharged to well beyond what is achievable, even without human influence. The proposed rulemaking could prevent major engineering solutions otherwise needed to remain in compliance, or at the extreme end, prevent ceasing operations for part of the year or all together.

Outside of likely being non-zero, we are unable to identify the exact magnitude of these benefits (avoided costs) by potentially affected permittees (Table 1). This is because WLAs under the baseline or proposed rulemaking for these are currently unknown. In addition behavior would depend on a wide variety of facility types, with potentially multiple discharges, all taking different actions in response to compliance.

Benefits – Temperature

To illustrate just one select benefit pathway, we provide a stylized example of a small adjustment to effluent temperature required in the absence of the proposed rule (i.e. a benefit of this action pair under proposed rulemaking).

In this example, we only consider permits in the top 5 permit types likely impacted to be conservative in our assessment of benefits (see Table 1). From the highest to lowest number of impacted permittees, this includes 2,263 Construction Stormwater general permittees, 218 Sand and Gravel general permittees, 182 Industrial Stormwater general permittees, 70 Fruit Packing general permittees, and 46 municipal wastewater treatment plants.

We assume that all affected permits, regardless of type, would be required to cool their discharge by at least 1 degree Fahrenheit (0.56 Celsius) for at least part of the year to meet numeric standards in the absence of the proposed rulemaking. We recognize that several of these permit types, such as construction stormwater and sand and gravel, are not commonly responsible for raising the temperature of water, nor are commonly required to cool effluent. But in a hypothetical waterbody for this analysis, it is the fact that site conditions are naturally higher (hotter) than numeric criteria that would lead all associated permits under the TMDL to be responsible for lowering effluent temperature.

The cost of a thermal reduction to surface water from effluent can vary greatly depending on application and volume. Table 2 contains a non-exhaustive list of methods recommended to decrease the temperature impacts to surface water. Values in Table 2 are presented as industrial or water treatment plant solutions, broken out by component in such a way that allows for generalization to other applications (Jenkins, 2007).

Table 2. Common Surface Water Cooling Techniques and Costs

Effluent Cooling Modifications	Description	Cost
Clarifier Covers	This method provides shade over clarifiers to reduce the amount of solar radiation reaching the wastewater before discharge.	Approximately $180,000 for a 50' diameter clarifier
Seasonal Storage	Holding treated effluent in a reservoir until stream temperature has decreased.	$0.18 to $2.60 per cubic foot of storage volume
Move Discharge Location	Discharging effluent to a different portion of the stream or to a different surface water body altogether.	$180 - $1800 per linear foot of pipeline
Multiple Port Diffusers	Releasing effluent through multi-port diffuser systems in several locations simultaneously into the receiving water.	$370 - $2800 per foot of diffuser
Effluent Blending	Mixing treated effluent with cooler groundwater or surface water prior to discharge.	$140 - $275 per foot for a well or $180 - $275 per lineal foot for a pipeline
Unlined Ponds	Contain treated effluent and allow it to percolate into the subsurface.	$0.45 - $0.90 per gallon of storage
Riparian Shading	Establishing streamside forests to provide shade over receiving water.	Example cost: Property purchase = $36,750 per acre, Plant starts = $4.60 per plant, Density = 2,614 plants per acre
Cooling Ponds	A shallow reservoir designed to receive warm water and discharge cool water, relying on evaporative and radiative heat loss.	$0.18 to $0.40 per cubic foot of storage volume

Effluent Cooling Modifications	Description	Cost
Cooling Towers	An evaporative cooling method used to dissipate heat from process water.	Example cost: $237,150 for a 0.05 MGD plant
Chillers	Devices that employ an evaporator, compressor, condenser, and refrigerant to remove heat from a liquid.	$46,000 - $110,300 per MGD per degree Fahrenheit and an additional $9,200 - $18,400 per MGD per degree Fahrenheit per year in operating costs

Note: Values in table range from 2001 to 2005 dollars depending on technology.

For construction stormwater, sand and gravel, and fruit packer general permits we estimated the price to install a small cooling pond as a low-cost option to comply to the baseline scenario. These shallow reservoirs are designed to receive warm water and discharge cool water through evaporative and radiative heat loss. Note in Table 2 that ponds may double as holding tanks for effluent until stream temperature has decreased. We assume an average engineered cooling pond, with the ability to hold 40,000 cubic feet of water, can be constructed for a fixed cost of $14,946 in 2024 dollars.[43]

Industrial stormwater general permits include air and seaports, large manufacturing facilities, refineries, and commercial food processors, with the potential of treating and discharging millions of gallons of effluent per day. Together with municipal wastewater treatment permits, more sophisticated methods of cooling would likely be required for these facilities to meet marginal cooling requirements necessary without the proposed rule. To estimate the cost of cooling effluent in these facilities, we assumed the need for more advanced technology such as cooling towers or chillers. Using information from Jenkins (2007) we estimated the cost to a mid-sized 3 million gallons per day (MGD) system using these technologies to lower effluent temperatures 1 degree Fahrenheit is $686,923 in capital costs and $114,591 per year in operating and maintenance (O&M) in 2024 dollars.[44,45]

Benefits described above will not accrue all at once upon the adoption of this rulemaking; rather, they would be staggered across time depending on TMDL priority and where the receiving permit is within its 5-year renewal cycle. To calculate the net present value over a 20-

[43] Adjusted upward from initial estimates of $7,200 from 2005 data in Jenkins, 2007. Adjustments were made using Producer Price Index by Commodity: Machinery and Equipment: Domestic Water Systems (https://fred.stlouisfed.org/series/WPU11411311). Does not include the cost of any land acquisition that, if avoided under the proposed rule, would increase this benefit.

[44] Note that in many cases these estimates are conservative with respect to facility size. For example, very large water treatment plants (upwards of 90 MGD), could require as much as $10 million in infrastructure alone and $1.6 million per year in O&M for a single plant to cool effluent by 1 degree Fahrenheit.

[45] Adjusted upward from initial capital and O&M estimates of $330,900 and $114,591 from 2005 data in Jenkins, 2007. Adjustments were made using Producer Price Index by Commodity: Machinery and Equipment: Domestic Water Systems (https://fred.stlouisfed.org/series/WPU11411311)

year period, we consider again Ecology's TMDL priority rankings (discussed in Section 3.2.1) and add 5 years to the latest date that the TMDL might begin to allow for research time and idiosyncratic lags in permit renewal. That is:

- Permittees under high priority TMDLs for temperature (1,299) receive benefits 5 years after adoption.
- Permittees under medium priority TMDLs for temperature (1,197) would begin receiving benefits 10 years after adoption.
- Permittees under medium-low priority TMDLs for temperature (283) would begin receiving benefits 20 years after adoption.

Conditional on assumptions discussed above in this exercise (e.g. a 1 degree Fahrenheit reduction, required by all permittees in the top 5 permit in the next 20 years) the total net present value of benefits from the proposed rule over a 20 year horizon would be just over $356 million.[46,47]

Benefit – DO

When high levels of nutrients fuel excessive marine plant life, such as algae, oxygen is consumed when plants later die and decompose. Nutrient removal is therefore one of the main, and potentially costly, strategies used when mitigating dissolved oxygen depletion in fresh and marine water.

We emphasize that the proposed rulemaking would not absolve impacted permittees from treating nutrients in their effluent. However, any marginal refinements to DO criteria based on natural conditions provisions could provide financial relief to facilities otherwise facing the need for additional technologies to meet numeric standards. In this way, setting DO criteria values based on natural conditions represents a potential benefit under the proposed rule.

Reiterated from above, it is not possible to know how natural conditions criteria will differ from numeric DO criteria for permits in Table 1, or how those differences would translate to nutrient requirements in TMDL waste load allocations. Available data on nutrient treatment costs are also not commonly presented in marginal units of removed nutrients (e.g. a dollar amount for every unit of nitrogen or phosphorus), making such an analysis additionally impractical.

Under these caveats, the most conservative assumption we can make with available data is that the lowest known facility cost of treatment would be sufficient to satisfy an arbitrary difference between numeric based DO requirements in the baseline and natural conditions provisions under the proposed rule. As another illustrative example, this time focused on nutrient

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[46] Discounted at 0.9%, the 20-year average of fixed real annual rates. Fixed rate of return to inflation-indexed I-Bonds by US Treasury Department (https://www.treasurydirect.gov/savings-bonds/i-bonds/i-bonds-interest-rates/).

[47] Without considering modifications by construction permits, this estimate is just under $325 million (after making assumptions discussed elsewhere in this section such as a 1 degree Fahrenheit reduction, required by all remaining permittees in the next 20 years).

removal, we apply these arbitrary facility and operational changes to permits in the top 5 likely impacted permit types (see Table 1).

Considering impacts wastewater treatment, we assume again an average municipal treatment facility size of 3 MGD. In 2011, Ecology produced a technical report identifying cost estimates for a suite of wastewater treatment technologies to achieve a range of different effluent quality performance targets with respect to nutrients (Ecology, 2011). This report, as summarized by the EPA (2015a), finds constructed or retrofitted treatment technologies for removing nutrients, such as inorganic nitrogen, come at a capital cost ranging from $0.1/MGD/year to nearly $100/MGD/year, with typical costs cited as averaging $25/MGD/year. Annual O&M for these systems ranged from $0.01/MGD/year to $1.85/MGD/year.[48,49] Applying $0.1/MGD and $0.01/MGD for capital and O&M cost, and adjusting to current price levels, the estimated cost to remove an arbitrarily small amount of nitrogen is $488,790 per facility in capital costs, and $48,879 in annual O&M.[50]

For the treatment of nutrients in industrial and agricultural applications the USEPA (2015a) points to publications that primarily draw from foodstuffs, beverages, livestock, and agricultural producers. Technologies used in these industries include enhanced aeration, modified Ludzack-Ettinger process, and chemical treatment that would apply to Fruit Packer general permits, and generalizable to many other large-footprint facilities found in Industrial stormwater general permits not directly included in the aforementioned industries. While unable to recover unit costs, the minimum estimated total cost for these technologies used to achieve a reduction in nutrients at the facility level was $241,570 in upfront capital and $119,164 annually for O&M in 2024 dollars.

Potential costs borne by construction wastewater and sand and gravel permits are even less clear. For the purposes of this exercise, we assume that complying with a small arbitrary reduction in nutrients would include moving materials such as fertilizers and landscaping material out of the path of stormwater, ensuring proper operation and maintenance of any treatments already installed, and updating plans to minimize unnecessary land disturbance. Assuming 40 hours of labor per year for these activities by existing staff, and the Bureau of Labor Statistics median pay for Environmental Engineering Technicians, ($24.51 per hour), we estimated $980.04 annually (BLS, 2023).

As with temperature, we applied benefits at the permit level over time based on permit type and TMDL priority over a 20-year horizon. We again limit this analysis to the top 5 affected permit categories described in Table 1 to be consistent and additionally conservative.

[48] Employed technologies range from activated sludge, lagoons, membrane bioreactors, rotating biological contactors, sequencing batch reactors, and trickling filters.
[49] 2012 dollars.
[50] Adjustments made using Producer Price Index by Commodity: Machinery and Equipment: Domestic Water Systems (https://fred.stlouisfed.org/series/WPU11411311).

Conditional on assumptions discussed above (e.g. an arbitrary reduction in nutrients, required by all permittees in the top 5 permit categories over 20 years), the net present value of this stream of benefits is estimated to be just over $319 million.

Benefit – pH

As with Temperature and DO requirements, benefits of avoided compliance cost with numeric pH criteria, compared to those based on an applicable natural condition criterion, would likely be positive. Due to a lack of publicly available data on the cost of pH neutralization, the study team is currently unable to illustrate these benefits quantitatively.

Action Pair 1b-c

Action pair 1b-c amounts to meeting natural conditions criteria through the TMDL study process using the performance-based approach, compared to criteria developed using biological data collected in site-specific studies.

Both alternatives in the action pair are intended to allow for a departure from statewide numeric criteria based on local conditions. However, criteria in the baseline scenario, despite being site-specific, must still be biologically based. Like in action 1a, criteria considering natural conditions and seasonal variation within that system are likely to be more easily met by permittees through fewer actions or investments, representing an avoided cost (benefit).

If a permittee were to elect to privately fund science in support of the site-specific criteria (action 1c), the proposed rulemaking represents an additional benefit in the form of avoided costs of such a study. The benefit of this avoided study component could range from tens to hundreds of thousands of dollars depending on the size, complexity, and detail needed to effectively substantiate site-specific criteria .

Action Pair 1d-e

Action pair 1d-e amounts to meeting natural conditions criteria through the TMDL study process using the performance-based approach, compared to meeting a different designated use through UAA.

There is insufficient historic data to analyze potential permittee behavior in terms of meeting natural conditions criteria, compared to meeting a different designated use through UAA. If a permittee were to elect to privately fund science in support of a UAA (1e), the proposed rulemaking represents an additional benefit in the form of avoided costs of such a study. However, there is very little data to estimate a range quantitatively. [51]

4.2.2 Benefits Summary

In this section, we considered the likely benefits associated with the proposed rule amendments as implemented together.

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[51] Only one UAA has been completed in Washington and is still under review by the EPA.

As described in Section 3, we assumed that the most likely action to occur because of this rulemaking—that would not undergo additional rulemaking—is meeting waste load allocations based on natural conditions criteria developed through the TMDL process using the performance-based approach compared to a numeric temperature, DO, and or pH criterion.

Based on historical TMDLs reviewed by the study team, and the general logic of natural conditions provisions, we expect a potentially wide range of benefits associated with the proposed rule amendments. For many, criteria considering local factors and seasonal variation under this proposed rulemaking will be more easily met through fewer actions or investments on the margin. For others, benefits would include avoiding the need to eliminate discharge and associated economic activity completely for all or part of the year completely to avoid paradoxical situations in which permittees must improve the quality of the water they discharged to beyond what is achievable without any human influence.

We cannot fully quantify the extent of potential benefits of the proposed rulemaking because future TMDL studies have not been performed yet. However, through a pair of illustrative examples, we applied a small and arbitrary temperature and DO criteria change to potentially impacted permits—akin to just one scenario when meeting natural conditions under the proposed rulemaking. We estimated a total 20-year present value benefit of $675 million through this exercise, but stress that this represents partial benefits and should be considered a conservative lower bound.

Additional, but unquantified, benefits include avoided costs of meeting numeric criteria for freshwater pH compared to a natural condition based criteria, and any avoided cost of independent science by permittees in support of Ecology performing site-specific criteria and UAA in the baseline.

The baseline conditions and proposed rulemaking (if adopted) would be considered protective of aquatic life and designated uses. Therefore, we do not expect new costs or benefits from a material change in related ecosystem services.

Chapter 5: Cost-Benefit Comparison and Conclusions

5.1 Summary of costs and benefits of the proposed rule amendments

Due to data limitations, we cannot quantify the costs of the proposed rulemaking to associated permits (see Section 3.2). However, the most likely actions taken because of the proposed rulemaking are not likely to impose new costs, but rather produce benefits in the form of avoided costs. Historical TMDLs reviewed by the study team and the general logic of natural conditions provisions suggest that criteria considering local factors and seasonal variation would be more easily met through fewer actions or investments—up to avoiding paradoxical situations in which permittees need to improve the quality of the water they discharged to beyond what is achievable without any human influence. In this way, the proposed rulemaking is not likely to impose new costs, but rater cost savings (benefit).

Due to data limitations, we cannot fully quantify the extent of potential benefits of the proposed rulemaking. However, through a pair of illustrative examples, we applied a small and arbitrary temperature and DO criteria change to a selection of potentially impacted permits—akin to just one scenario when meeting natural conditions under the proposed rulemaking. Through this exercise, we estimated a total 20-year present value benefit of $675 million, but stress that this represents partial benefits and should be considered a conservative lower bound. Additional, but unquantified, benefits include avoided costs of meeting numeric criteria for freshwater pH compared to a natural condition based criteria, and any avoided cost of independent science by permittees in support of Ecology performing site-specific criteria and UAA in the baseline.

The baseline conditions and proposed rulemaking (if adopted) would be considered protective of aquatic life and designated uses. Therefore, we do not expect new costs or benefits from a material change in related ecosystem services.

5.2 Conclusion

We conclude, based on a reasonable understanding of the quantified and qualitative costs and benefits likely to arise from the proposed rule amendments, as compared to the baseline, that the benefits of the proposed rule amendments are greater than the costs.

Chapter 6: Least-Burdensome Alternative Analysis

6.1 Introduction

RCW 34.05.328(1)(c) requires Ecology to "…[d]etermine, after considering alternative versions of the rule and the analysis required under (b), (c), and (d) of this subsection, that the rule being adopted is the least burdensome alternative for those required to comply with it that will achieve the general goals and specific objectives stated under (a) of this subsection." The referenced subsections are:

> (a) Clearly state in detail the general goals and specific objectives of the statute that the rule implements;
>
> (b) Determine that the rule is needed to achieve the general goals and specific objectives stated under (a) of this subsection, and analyze alternatives to rule making and the consequences of not adopting the rule;
>
> (c) Provide notification in the notice of proposed rulemaking under RCW 34.05.320 that a preliminary cost-benefit analysis is available. The preliminary cost-benefit analysis must fulfill the requirements of the cost-benefit analysis under (d) of this subsection. If the agency files a supplemental notice under RCW 34.05.340, the supplemental notice must include notification that a revised preliminary cost-benefit analysis is available. A final cost-benefit analysis must be available when the rule is adopted under RCW 34.05.360;
>
> (d) Determine that the probable benefits of the rule are greater than its probable costs, taking into account both the qualitative and quantitative benefits and costs and the specific directives of the statute being implemented.

In other words, to be able to adopt the rule, we must determine that the requirements of the rule are the least burdensome set of requirements that achieve the goals and objectives of the authorizing statute(s).

We assessed alternative proposed rule content and determined whether they met the goals and objectives of the authorizing statute(s). Of those that would meet the goals and objectives, we determined whether those chosen for inclusion in the proposed rule amendments were the least burdensome to those required to comply with them.

6.2 Goals and objectives of the authorizing statute

The authorizing statute for this rule is Chapter 90.48 RCW, Water Pollution Control. Its goals and objectives include the state of Washington's policy of maintaining the highest possible standards to ensure the purity of all waters of the state consistent with public health, public enjoyment, the protection of wildlife, and the industrial development of the state. This requires the use of all known available and reasonable methods to prevent and control the pollution of the waters of the state of Washington.

RCW 90.48.035, Rule-making authority, specifically authorizes Ecology to promulgate, amend, or rescind rules and regulations as deemed necessary to maintain the highest possible standards of all waters in the state. Its goals and objectives include but are not limited to rules relating to standards of quality of waters of the state and regulating substances discharged into them.

6.3 Alternatives considered and why they were excluded

We considered the following alternative rule requirements and did not include them in the proposed rule amendments. This list includes alternatives that were suggested by the public during development of the rule, with the intent of mitigating negative impacts, including environmental harms, on vulnerable populations and overburdened communities, and equitably distributing benefits. Each section below explains why we did not include these alternatives.

- Updating human allowance and natural condition provisions only (i.e., no performance-based approach).
- Updating natural condition provision only (i.e., no human allowance or performance-based approach).
- No natural condition updates

6.3.1 Updating human allowance and natural condition provisions only

We considered updating only the human allowance and natural conditions provisions in the proposed rule, but not including a performance-based approach. This alternative would potentially be more burdensome for permittees. If a water is not meeting biologically based numeric criteria, and that is due in part to natural conditions, then there would only be two pathways for determining protective criteria based on natural conditions: a use change through a Use Attainability Analysis (which could result in different criteria values); or criteria change through site-specific criteria development. Both approaches would require separate WQ Standards rulemaking and would need to undergo EPA review (including any ESA consultation with NOAA NMFS and USFWS) and approval prior to being in effect for CWA purposes.

6.3.2 Updating natural condition provision only

We considered updating only the natural condition provision in the proposed rule, but not including the human allowance or the performance-based approach. This alternative would potentially be more burdensome for permittees. If a water is not meeting biologically based numeric criteria, and that is due in part to natural conditions, then there would only be two pathways for determining protective criteria based on natural conditions if no performance-based approach exists: a use change through a Use Attainability Analysis (which could result in different criteria values); or criteria change through site-specific criteria development. Both approaches would require separate WQ Standards rulemaking and would need to undergo EPA review (including any ESA consultation with NOAA and USFWS) and approval prior to being in effect for CWA purposes.

In addition, if no human allowance is provided in rule, then when natural conditions are the applicable criteria, NO degradation for temperature or DO would be allowed. This would be unnecessary for protection of aquatic life and unnecessarily costly. See rulemaking Technical Support Document for further details.

6.3.3 No Rulemaking

We considered not doing this rulemaking. Without natural conditions criteria, the applicable biologically based numeric criteria would apply and must be met to protect existing and designated aquatic life uses. Some waters during some periods of the year may not be able to meet these criteria due to natural and seasonal variations. This could be the case even if all human impact was reversed and removed from this determination. Thus, it would be more burdensome to covered parties as applicable criteria would not be able to be met regardless of any actions taken (See Appendix A(B)(2) for additional details).

6.6.4 Alternative DO Allowance 1

We considered an alternative DO allowance that states when natural conditions constitute the water quality criteria for a site, local and regional sources of human-caused pollution considered cumulatively may not decrease DO more than 0.2 mg/L.

We excluded this possibility as we determined it would not be protective of aquatic life when waters were naturally low in DO (i.e., <2 mg/L), and therefore does not meet goals and objectives. For instance, if waters were naturally 1.0 mg/L for DO Concentration, a 0.2 mg/L decrease to 0.8 mg/L would have negative impact on aquatic life; therefore, this would not be protective and would not represent a de minimis amount of degradation.

6.6.5 Alternative DO Allowance 2

We considered an alternative DO allowance that states when natural conditions constitute the water quality criteria for a site, local and regional sources of human-caused pollution considered cumulatively may not decrease DO more than 0.2 mg/L only if the natural condition criteria of the water is > or = 2.0 mg/L. Otherwise, no further degradation of the waters are allowed.

We excluded this possibility because it would be unnecessarily stringent, and thus overly burdensome for permittees, compared to what is needed for protection of aquatic life (see EPA's 2007 Biological Evaluation regarding 0.2 mg/L for fresh water systems). Additionally, because we may be using water quality models to estimate natural condition values, there will inherently be some error associated with estimation. Trying to meet no degradation (i.e., 0) is difficult when you must account for associated model error. Thus, no allowance in this alternative prevents accounting for natural condition estimation error in our modeling process in TMDLs.

6.4 Conclusion

After considering alternatives, within the context of the goals and objectives of the authorizing statute, we determined that the proposed rule represents the least-burdensome alternative of possible rule requirements meeting the goals and objectives.

Chapter 7: Regulatory Fairness Act Compliance

We analyzed the compliance costs of the proposed rule amendments in Chapter 3 of this document. We conclude that the proposed rule amendments are not likely to result in compliance costs for any businesses. The proposed rule is likely to result only in cost-savings for dischargers, as compared to the baseline. Based on this analysis, Ecology is exempt from performing additional analyses under the Regulatory Fairness Act, under RCW 19.85.025(4) which states that, “This chapter does not apply to the adoption of a rule if an agency is able to demonstrate that the proposed rule does not affect small businesses.” Moreover, by not imposing compliance costs, the proposed rule amendments do not meet the RFA applicability standard under RCW 19.85.030(1)(a).

References

RCW 34.05.272 requires Ecology to categorize sources of information used in significant agency actions made in the Water Quality Program.

Independent peer review

Review is overseen by an independent third party.

n/a

Internal peer review

Review by staff internal to Ecology.

Jenkins, Pam. 2007. Methods to Reduce or Avoid Thermal Impacts to Surface Water (Publication 07-10-088). Available at: https://apps.ecology.wa.gov/publications/SummaryPages/0710088.html

External peer review

Review by persons that are external to and selected by Ecology.

n/a

Open review

Documented open public review process that is not limited to invited organizations or individuals.

n/a

Legal and policy documents

Documents related to the legal framework for the significant agency action, including but not limited to: federal and state statutes, court and hearings board decisions, federal and state administrative rules and regulations, and policy and regulatory documents adopted by local governments.

40 CFR Section 131.

Chapter 90.48 RCW: Water Pollution Control.

Chapter 173-201A WAC: Water quality standards for surface waters of the state of Washington.

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Independent data

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United States Environmental Protection Agency (USEPA). 2015a. A compilation of cost data associated with the impacts and control of nutrient pollution (*EPA 820-F-15-096)*. Office of Water.

Records of the best professional judgment of Ecology employees or other individuals.

n/a

Other

Sources of information that do not fit into other categories.

United States Environmental Protection Agency (USEPA). 2024. Causal Analysis/Diagnosis Decision Information System (CADDIS).

Appendix A: Administrative Procedure Act (RCW 34.05.328) Determinations

A. RCW 34.05.328(1)(a) – Clearly state in detail the general goals and specific objectives of the statute that this rule implements.

See Chapter 6.

B. RCW 34.05.328(1)(b) –

1. Determine that the rule is needed to achieve the general goals and specific objectives of the statute.

See chapters 1 and 2.

2. Analyze alternatives to rulemaking and the consequences of not adopting this rule.

A rulemaking is the only way to adopt natural conditions provisions and criteria. If we do not adopt this rule, then waters would need to meet applicable biologically based numeric aquatic life criteria. As some waters cannot meet these aquatic life numeric criteria due to natural or seasonal variations, then without this rule, these waters would not meet applicable water quality standards and may be considered impaired, even if fully protecting all existing and designated uses. In addition, if natural conditions are the sole cause of a violation of the applicable biologically based aquatic life criteria, then listing these waters as impaired would go against the intent of the legislature (RCW 90.48.570(3)).

If we do not adopt a performance-based approach during this rulemaking, then any site-specific criteria development for determining natural conditions criteria would need to go through rulemaking, including EPA review, prior to being used for state and federal Clean Water Act purposes. A consequence of such approach would be a possibly lengthy delay between developing a protective site-specific criterion based on natural conditions of the water body and the ability to use such criterion in a Clean Water Act action (e.g., TMDLs).

If we do not adopt human-use allowances for temperature and dissolved oxygen, then when natural conditions constitute the criteria for a water, there would be no allowance for any degradation by human actions. EPA has previously determined, and Ecology agrees, that such approach would be unnecessary for the protection of existing and designated uses and would be unnecessarily costly for entities with stake in those waters.

Please see the Least Burdensome Alternative Analysis, Chapter 6 of this document, for discussion of alternative rule content considered.

C. RCW 34.05.328(1)(c) - A preliminary cost-benefit analysis was made available.

When filing a rule proposal (CR-102) under RCW 34.05.320, Ecology provides notice that a preliminary cost-benefit analysis is available. At adoption (CR-103 filing) under RCW 34.05.360, Ecology provides notice of the availability of the final cost-benefit analysis.

D. RCW 34.05.328(1)(d) – Determine that probable benefits of this rule are greater than its probable costs, taking into account both the qualitative and quantitative benefits and costs and the specific directives of the statute being implemented.

See Chapters 1 – 5.

E. RCW 34.05.328 (1)(e) - Determine, after considering alternative versions of the analysis required under RCW 34.05.328 (b), (c) and (d) that the rule being adopted is the least burdensome alternative for those required to comply with it that will achieve the general goals and specific objectives stated in Chapter 6.

Please see Chapter 6.

F. RCW 34.05.328(1)(f) - Determine that the rule does not require those to whom it applies to take an action that violates requirements of another federal or state law.

Under the Federal Clean Water Act, states are required to adopt water quality standards that consist of designated uses, water quality criteria that protect those uses, and an antidegradation policy. These standards must protect the public health or welfare, enhance the quality of the water, and serve the purposes of the Act. States must adopt water quality criteria that protect designated uses. States adopt EPA recommended CWA Section 304(a) criteria, modified CWA Section 304(a) criteria that reflect site-specific conditions, or other criteria so long as they are based on sound scientific rationale and protect the designated uses of the water (40 CFR 131.11).

EPA's policy on natural conditions states that site-specific numeric aquatic life criteria can be set equal to natural background, where natural background is defined as "background concentration due only to non-anthropogenic sources, i.e., non-manmade sources." States that wish to set criteria equal to natural background must include, at minimum, in their water quality standards: (a) a definition of natural background; (b) a provision that allows setting site-specific criteria equal to natural background; and (c) a binding procedure for determining natural background.

Ecology amended and introduced new natural conditions provisions and criteria in 2003 and 2006 to be consistent with federal requirements for use of natural conditions in effect at the time. Since then, certain natural condition provisions have been reconsidered by EPA and disapproved. Any new or updated natural conditions criteria will be consistent with current federal requirements and policy for use of natural conditions, and these criteria and associated provisions are reviewed and approved by EPA before becoming effective for Clean Water Act actions.

G. RCW 34.05.328 (1)(g) - Determine that the rule does not impose more stringent performance requirements on private entities than on public entities unless required to do so by federal or state law.

No. The rule does not impose more stringent performance requirements on private entities than on public entities. Any entity, private or public, must adhere to the rules protecting water quality in the state of Washington.

H. RCW 34.05.328 (1)(h) Determine if the rule differs from any federal regulation or statute applicable to the same activity or subject matter.

No.

- If **yes**, the difference is justified because of the following:

☐ (i) A state statute explicitly allows Ecology to differ from federal standards.

☐ (ii) Substantial evidence that the difference is necessary to achieve the general goals and specific objectives stated in Chapter 6.

I. RCW 34.05.328 (1)(i) – Coordinate the rule, to the maximum extent practicable, with other federal, state, and local laws applicable to the same subject matter.

We will work with EPA to ensure that the proposed rules are approvable.

Appendix B: Additional Tables and Figures

Table 3. Potentially Impacted Permit Categories, by Criteria

Permit Type	Temp	DO	pH
Construction SW GP	2,263	2,549	1,163
Sand and Gravel GP	218	256	201
Industrial SW GP	182	258	176
Fruit Packer GP	70	54	54
Municipal NPDES IP	46	58	49
Industrial (IU) to POTW/PRIVATE SWDP IP	30	45	36
Industrial NPDES IP	22	25	24
Bridge Washing GP	16	15	11
Upland Fish Hatchery GP	15	17	13
Industrial to ground SWDP IP	14	20	17
Municipal to ground SWDP IP	11	16	18
AP Irrigation System Aquatic Weed Control GP	10	14	14
Water Treatment Plant GP	8	8	6
Puget Sound Nutrient GP	6	9	3
Boatyard GP	5	6	1
Net Pens NPDES IP	3	3	0
Reclaimed Water IP	3	3	2
Winery GP	3	3	3
Total	2,926	3,360	1,792

Note: GP is “General Permit” and IP “Individual Permit”

Washington State's Marine Dissolved Oxygen (DO) Criteria: Application to Nutrients

Bryson Finch
Watershed Management Unit
Water Quality Program

DEPARTMENT OF ECOLOGY
State of Washington

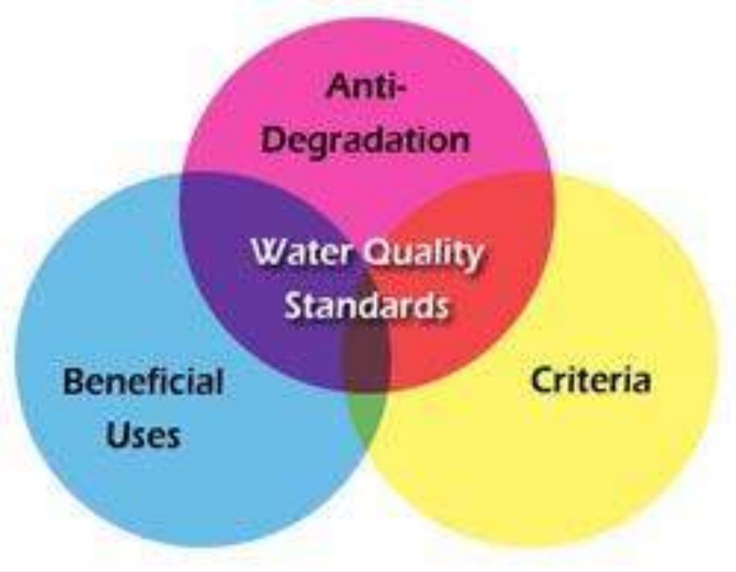
Overview

- Water Quality Standards
  - Numeric DO Criteria
  - Aesthetic Narrative Criteria
  - Anthropogenic Allowance
- History and Rationale for Marine DO Criteria
- Nutrient Criteria Alternatives
- Application of Marine DO Criteria
  - Water Column
  - Site Specific Locations
  - Anthropogenic Allowance

Water Quality Standards

Water Quality Standards

- The water quality standards set limits on pollution in our lakes, rivers and marine waters in order to protect beneficial uses, such as aquatic life and swimming.



DO Criteria

- DO criteria in the water quality standards are intended to set levels that protect healthy, robust aquatic communities, including <u>the most sensitive species</u>

- <u>Assumption</u>: if numeric criteria are met for the most sensitive organisms of each habitat, then the waterbody will protect all other species

- Criteria: **magnitude, duration,** & **frequency** component

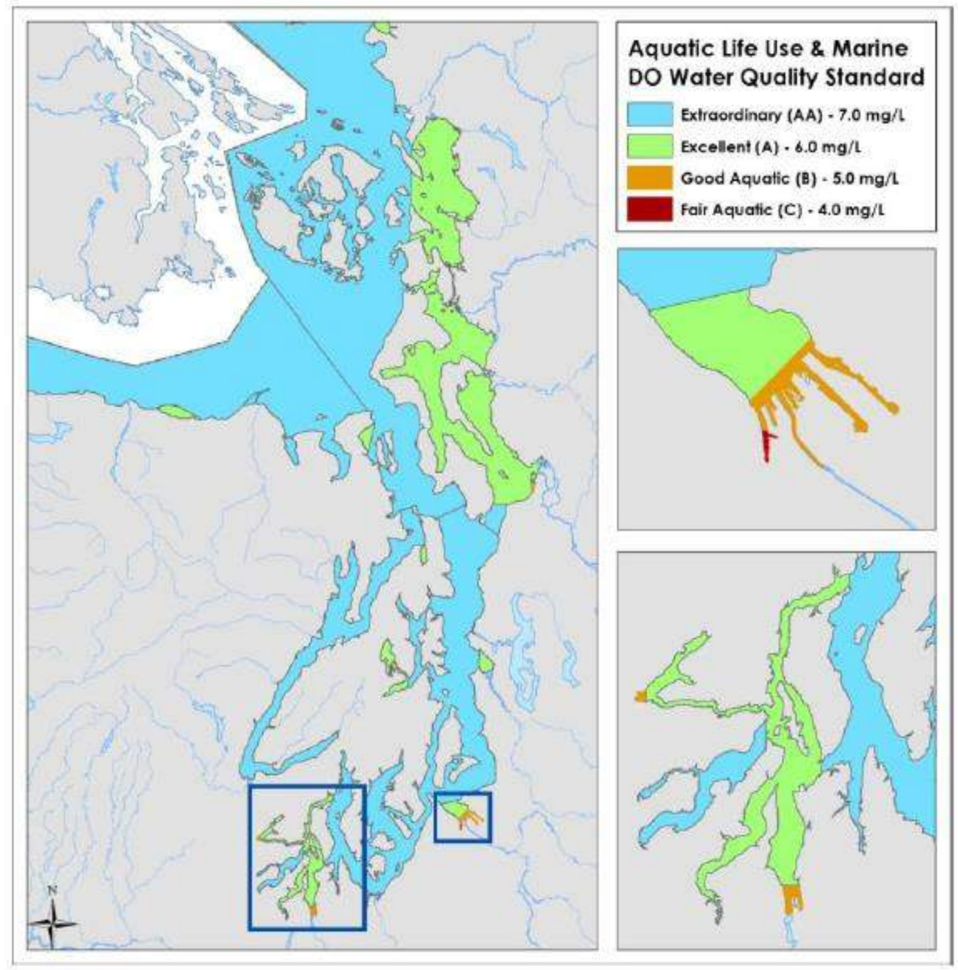
DO Numeric Criteria

Aquatic Life Use	DO Criteria (1-day min.)	General Description
Extraordinary quality	7.0 mg/L	Extraordinary quality salmonid and other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.
Excellent quality	6.0 mg/L	Excellent quality salmonid and other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.
Good quality	5.0 mg/L	Good quality salmonid migration and rearing; other fish migration, rearing, and spawning; clam, oyster, and mussel rearing and spawning; crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing and spawning.
Fair quality	4.0 mg/L	Fair quality salmonid and other fish migration.

Criteria exceedances may occur once every ten years on average.

WQ Dissolved Oxygen Standards in Puget Sound

- **7.0** mg/L - most of Puget Sound and the Straits
- **6.0** mg/L – Bellingham Bay, Samish Bay, Skagit Bay, around Whidbey, other inlets/bays
- **5.0** mg/L - Commencement Bay, Budd Inlet, and portions of some inlets
- **4.0** mg/L –finger of Commencement Bay



Aesthetics Criteria

- Aesthetic values must not be impaired by the presence of materials or their effects, excluding those of natural origin, which offend the senses of light, smell, touch, or taste.
  - Used when numeric criteria are insufficient

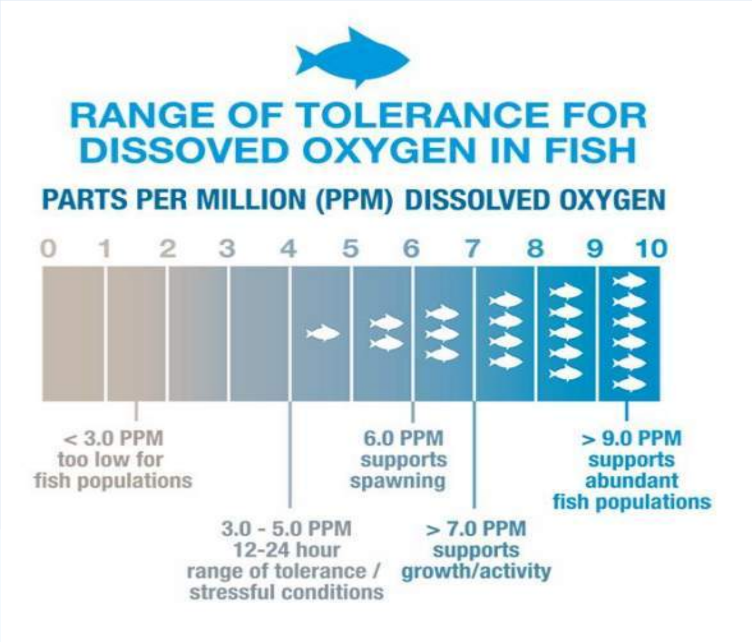
Anthropogenic Allowance

- Allowance: 0.2 mg/L DO
- Based on concept of a measurable change
  - Measurable change: change in physical, chemical, or biological quality of the water to determine that a lowering of water quality occurred
  - Represents a detectable change in water quality based on precision of the instrument
  - **Not a biologically derived value**

Marine DO Criteria Rationale

History of Marine DO Criteria

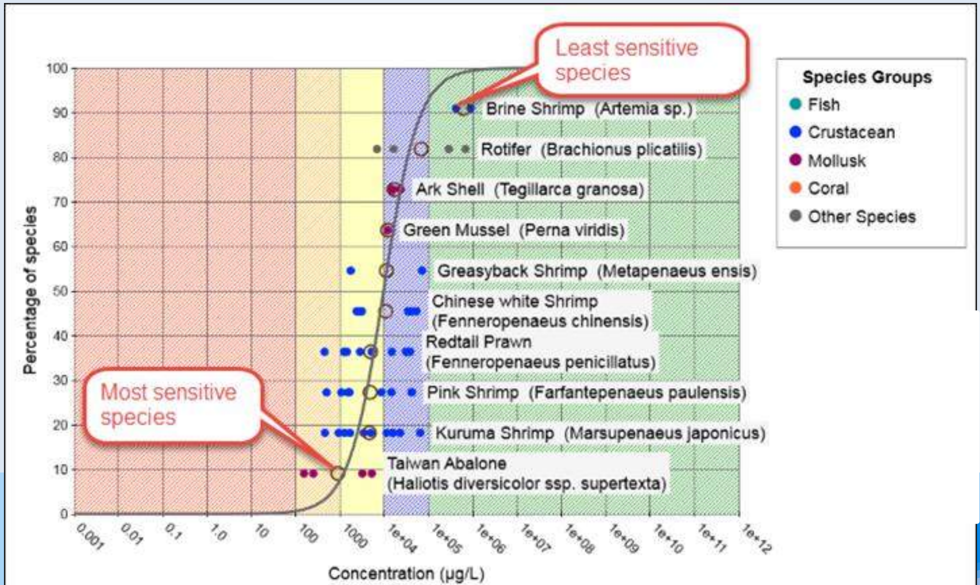
- 1968 Dept. of Interior recommendations:
  - DO levels between **5 and 8 mg/L** protect survival and growth of fish
  - Coastal wasters shall not be <5.0 mg/L
  - Estuaries & tidal tributaries shall not be <4.0 mg/L



Supporting Scientific Data

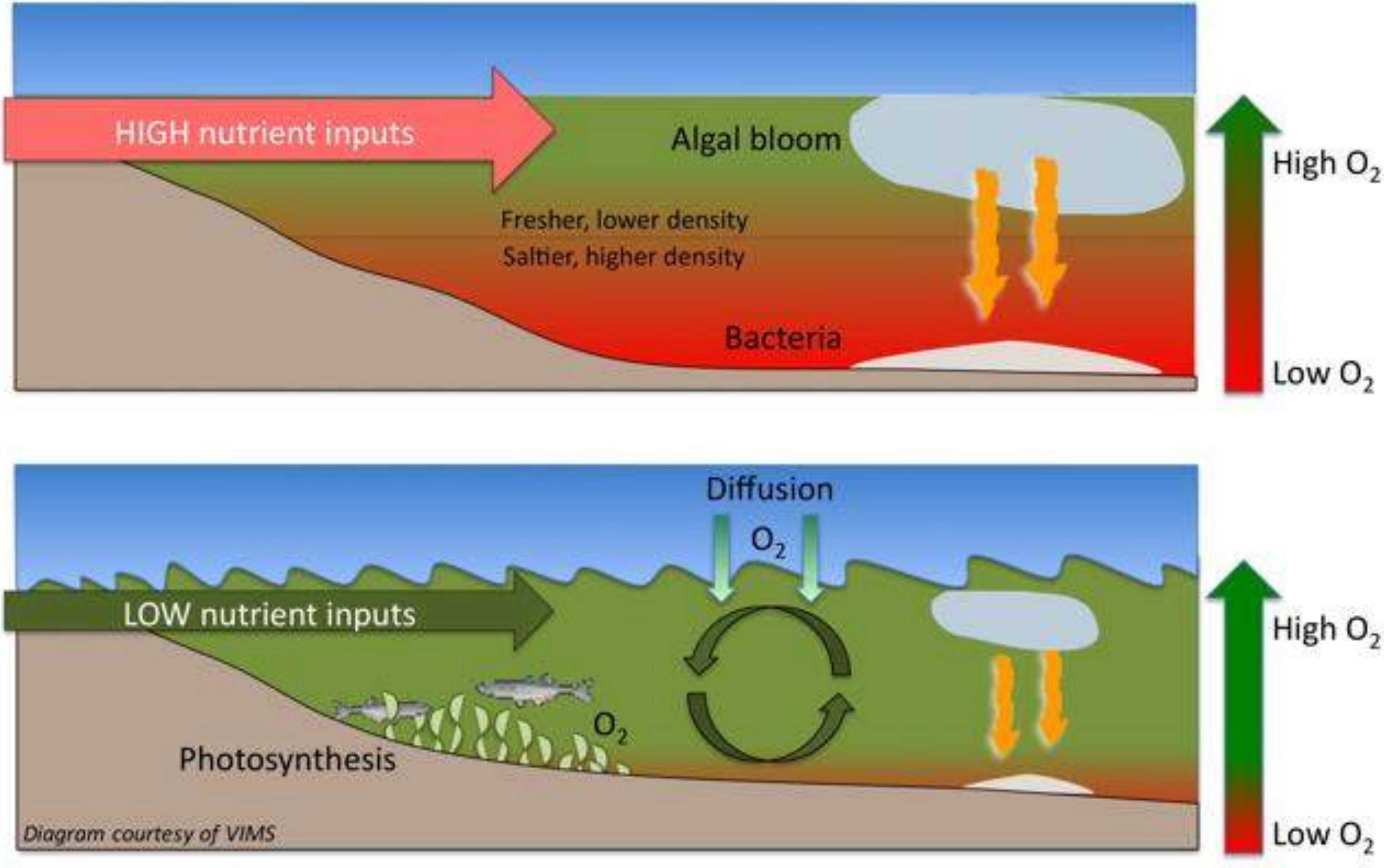
- Vaquer-Sunyer & Duarte (2008):
  - Reviewed 872 experiments spanning 206 species
    - 4.6 mg/L DO: maintain most populations & biodiversity
    - 5.0 mg/L DO: protective of sub-lethal effects for most species
      - 4.6 and 5.0 mg/L values represent 90th percentile of LC50s
      - Most sensitive species not protected at these levels

- Conclusion:
  - Full protection >>>5.0 mg/L DO



Nutrient Criteria Alternatives

DO : Nutrient Dynamics



Translating Numeric Criteria to Nutrients

Dissolved Oxygen

- Interrelationships between DO and nutrients

- Variations in DO can be associated with excessive nutrient inputs

- Marine models used to demonstrate relationships
  - Develop nutrient reduction volumes to achieve goals
  - Initiate actions to protect aquatic life

Translating Narrative Criteria to Nutrients

- Aesthetics narrative applies to effects of presence or offense to senses (light, smell, touch, taste)

- Various measures:
  - Percent oxygen saturation
  - Chlorophyll levels
  - Photographic evidence of algal mats/blooms
  - Others…

- Relationships between nutrient over-enrichment and aesthetics can be established

Application of DO Criteria

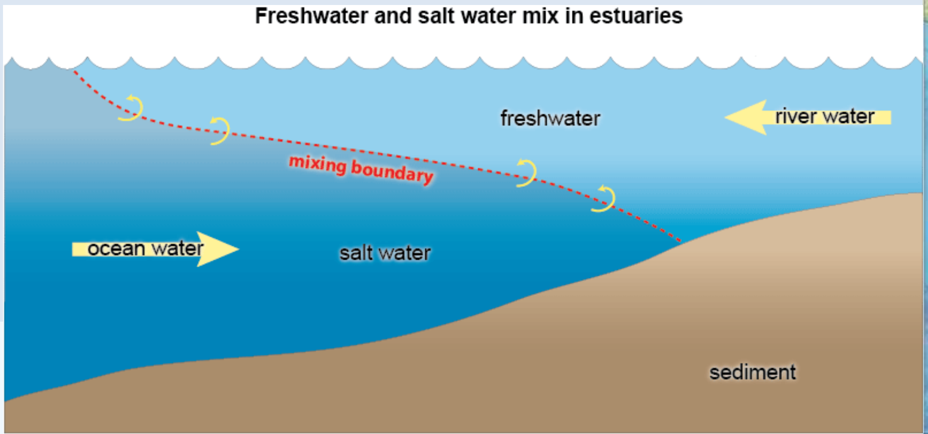
Application of DO Criteria:
Water Column

- DO measurements should represent the dominant aquatic habitat of the monitoring site
  - Samples should not be collected from shallow stagnant backwater areas, within isolated thermal refuges, at the surface or at the water's edge

- Deep waters:
  - Water samples should be assessed within:
    - Relatively homogenous conditions (e.g. euphotic zone; below or above the pycnocline; bottom waters)
    - Various dominant aquatic habitat of communities (e.g. benthic, fish, phytoplankton, zooplankton communities)

Application of DO Criteria:
Site-Specific Locations

- Water boundaries are established in the water quality standards
- Surface waters are required to be in compliance year-round at all assessment sites
- Fresh/marine water boundaries are determined by salinity measurements



Application of DO Criteria:
Anthropogenic Allowance

- Human actions considered cumulatively may not cause DO concentrations to decrease by >0.2 mg/L
  - Does not apply if water body is in compliance

- Based on 1-day minimum concentrations

- Applies year-round at all locations unless otherwise noted in WAC 173-201A

Nutrient Criteria

- EPA provides national strategies for developing nutrient criteria
  - Nationally recommended numeric criteria <u>not available</u>
  - Chesapeake Bay guidance document for various refugia
    - Serves as a good template when robust data is available

- WA has elected to use water quality responses for excessive nutrients to protect aquatic life

Questions?

- Contact Information:

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Puget Sound Wastewater Service Affordability Analysis: Implications for Implementation Strategies

2022 CRITICAL ANALYSIS SUMMARY REPORT

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Audrey Barber, Western Washington University
Nate Jo, Western Washington University

May 17, 2023

ECO RESOURCE GROUP

PUGET SOUND INSTITUTE
UNIVERSITY of WASHINGTON | TACOMA

WESTERN WASHINGTON UNIVERSITY

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The authors would like to thank Dan Thompson (City of Tacoma Wastewater Operations Division) and Judi Gladstone (Washington Association of Sewer and Water Districts) for their invaluable guidance and support during the course of study. We would also like to thank Gretchen Greene (Greene Economics/ECO Resource Group) and Marielle Larson (Puget Sound Institute) and for their thoughtful comments on and edits to an earlier draft of this report.

Lastly, we want to highlight the efforts of two student interns, Audrey Barber and Nate Jo. They made this study possible as we could not have compiled the large amount of data needed to complete the study without them. Their efforts, diligence and good humor in combing the web for data and managing US Census Bureau data tools are deeply appreciated. Any errors or misrepresentations are solely the fault of S. Burke and A. Kinney.

Recommended citation:
Burke, S., A. Kinney, K. Bogue, A. Barber, and N. Jo. 2023. Puget Sound Wastewater Service Affordability Analysis: Implications for Implementation Strategies. Critical Analysis Summary Report prepared by ECO Resource Group and Puget Sound Institute for the Stormwater Strategic Initiative and Puget Sound Partnership.

EXECUTIVE SUMMARY

Background and Objectives

In 2018, regional nutrient management efforts were initiated in response to monitoring data that revealed worrisome trends in Puget Sound's water quality. Wastewater treatment plants (WWTPs) are the largest anthropogenic source of nutrients to Puget Sound and were therefore an early focus of both nutrient management efforts. Puget Sound National Estuary Program Marine Water Quality Implementation Strategy (MWQ IS) planning efforts identified current funding levels as a barrier to reducing wastewater nutrient loads and recommended development of a funding pathway to identify new/expanded sources of local, state, and federal funding. In 2021, the Department of Ecology issued a Puget Sound Nutrient General Permit (PSNGP) requiring operators of facilities that discharge into Puget Sound marine waters to begin long-term planning for upgrades that would be needed to comply with total inorganic nitrogen (TIN) numeric effluent limits expected in future PSNGP cycles.

This analysis was initiated because participants in the MWQ IS development process expressed concerns about the impact of costly upgrades on their ratepayers. Since nutrient reduction upgrades have the potential to exacerbate existing affordability issues, additional data collection/analysis was recommended.

Research Questions

This report answers the following research questions as to whether current and PSNGP-adjusted sewer service costs:

1. Raise affordability concerns for Puget Sound households that are connected to sewer utilities? Affordability is measured using two indices, sewer bills as a percent of median household income (%MHI) and sewer bills as a percent of lowest quintile income (%LQI).
2. Contribute to equity and efficiency concerns of the MWQ IS if current and future sewer bills constitute a larger percentage of income of low-income households than high-income households?

And if the answer to these questions is yes, then can the data for this study help:

- Calculate the amount of federal and state monies needed to maintain %MHI or %LQI indices below a specified affordability threshold for individual Puget Sound utilities.
- Improve the equity outcomes when prioritizing the distribution of grant funds.

Study Methods

This analysis utilizes publicly available data to estimate the current annual household sewer bills and potential future nutrient-adjusted sewer bills for 80 Puget Sound regional sewer utilities.[1] Data compilation and analysis steps are listed below. The full database is available open access via UW libraries (Barber et al. 2022).

- Current sewer rates were obtained from utilities web pages to estimate current (2022) sewer bills.
- Nutrient-adjusted sewer bills were estimated for two different nutrient removal objectives; total inorganic nitrogen (TIN) < 8 mg/L seasonally and TIN < 3 mg/L and total phosphorus (TP) < 0.1mg/L year-round. These two objectives bookend the estimated costs of regulatory standards that were reported by the Washington Department of Ecology (Ecology) and Tetra Tech in the June 2011, *Technical Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities*.
- Household income data was obtained from the U.S. Census Bureau American Community Survey (ACS). The lowest geographic unit for which household income by quintile and population data is available is the Census Tract.
- Census tracts were corresponded to sewer district boundaries or city boundaries where utilities are operated by municipalities. This allowed us to estimate a population-weighted income for each of the 80 local wastewater service providers in the study.

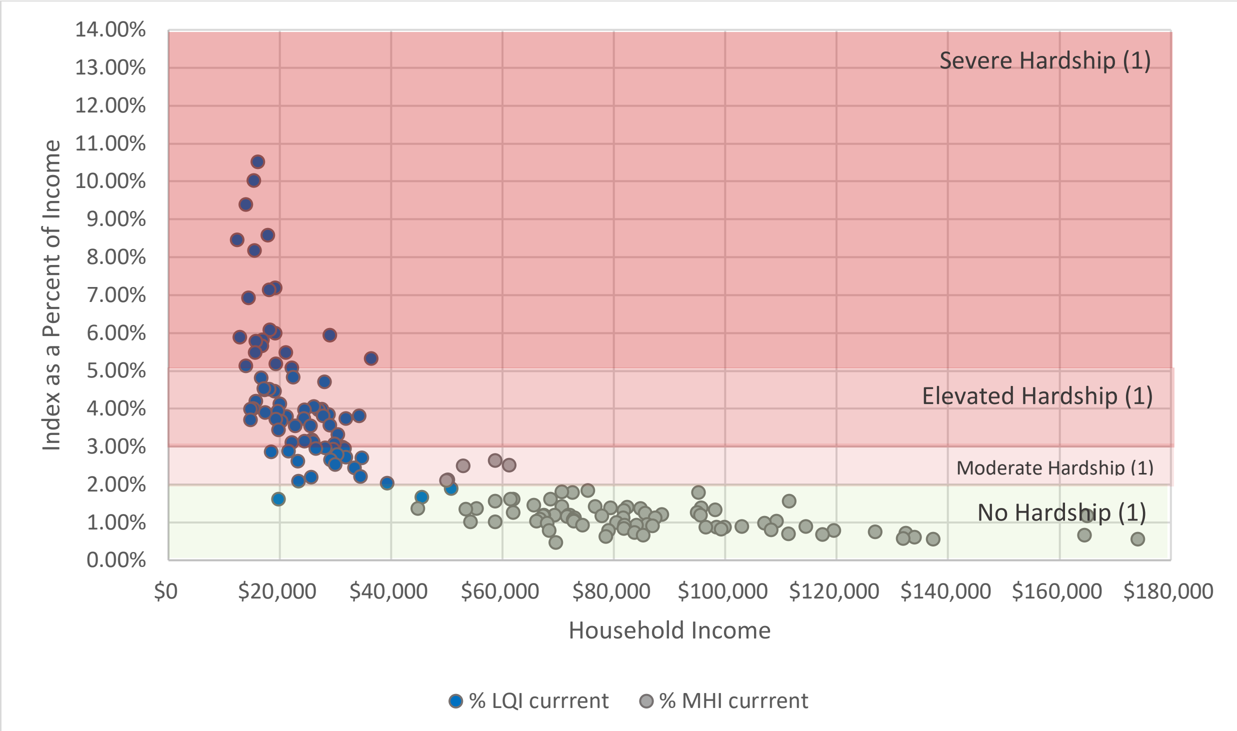
Summary Results

Current monthly sewer bills range from $27 to $161. Estimated PSNGP-adjusted monthly sewer bills ranged from $44 to $196, depending on the utility and the nutrient-reduction scenario. Estimated household income ranges widely across the region. MHI ranges from $174,078 to $44,844. LQI ranges from $50,831 to $12,425 and is, on average, 28% of MHI.

As shown in Figure ES-1, affordability metric results indicate that current sewer rates are likely:

- Not creating affordability concerns for households earning the median household income (MHI). Sewer bills were generally below 2 percent of MHI (%MHI).
- **Creating affordability concerns for households earning the lowest quintile income (LQI).** Sewer bills were often above 2 percent of LQI (%LQI), ranging between 1.61 percent of lowest quintile income (LQI) to 10.5 percent of LQI, with an average of 4.38 percent of LQI. For reference, the US Economic Research Service reports that in 2021, U.S. households spent an average of 10.3 percent of their disposable personal income on food, so on average sewer bills are a little less than half a lower quintile households' food budget.

[1] Wastewater/sewage services in the region are provided by a mix of county or municipal governments, Special Purpose Districts, and Public Utility Districts. For simplicity, we call all these local wastewater service providers utilities. Some of these utilities operate WWTPs and are PSNGP permittees, and the others are wholesale customers of those WWTP operators.

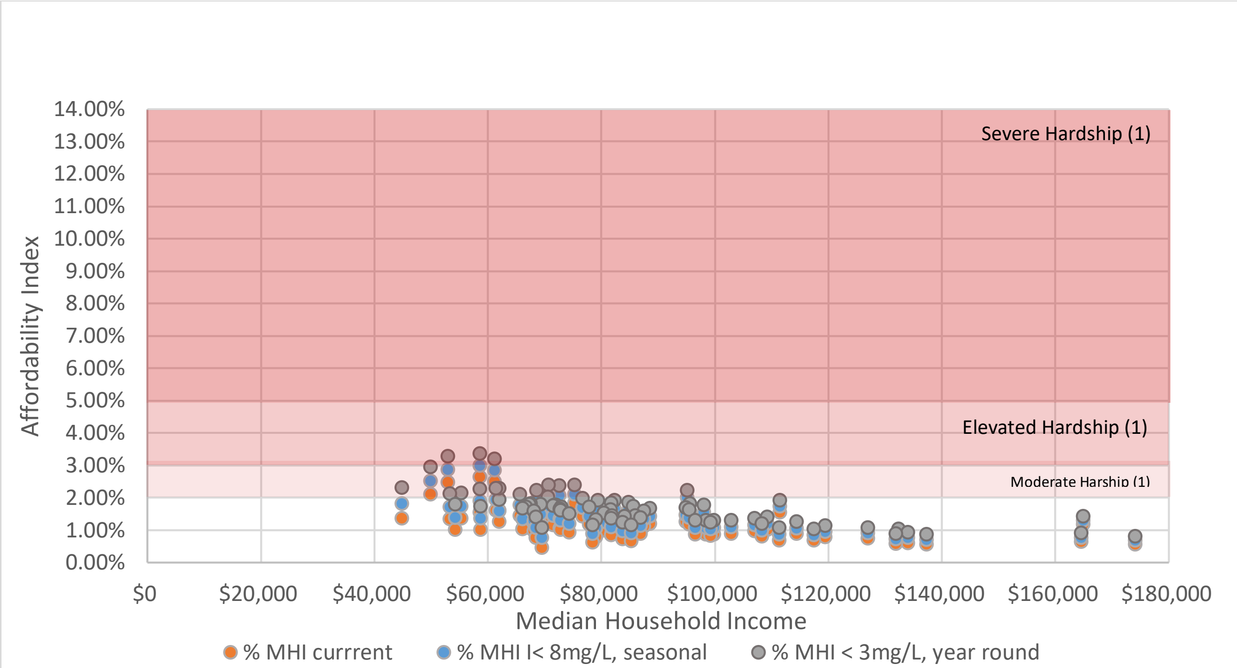


(1) Hardship categories taken from WAC 173-98-300 and apply to MHI% but not LQI%.

Figure ES-1. %MHI and %LQI Values of Estimated Current Sewer Rates for 80 Puget Sound Sewer Utilities, 2020 dollars

However, as shown in Figure ES-2, the estimated PSNGP-adjusted rates could result in sewer bills that:

- **Create affordability concerns for households earning the MHI and served by between 7 and 17** of the utilities in the study, depending on the nutrient-removal objective, e.g., %MHI values greater than 2 percent (Figure ES-2).
- **Continue to create hardship for households earning the lowest quintile income (LQI),** e.g., above 2 percent of LQI (%LQI), %LQI values greater than 2 percent for all 80 utilities ranging from 2.1 percent of LQI to 13.14 percent of LQI (Figure ES-3).



(1) Hardship categories taken from WAC 173-98-300.

Figure ES-2. Estimated current and nutrient-adjusted utility-district specific %MHI

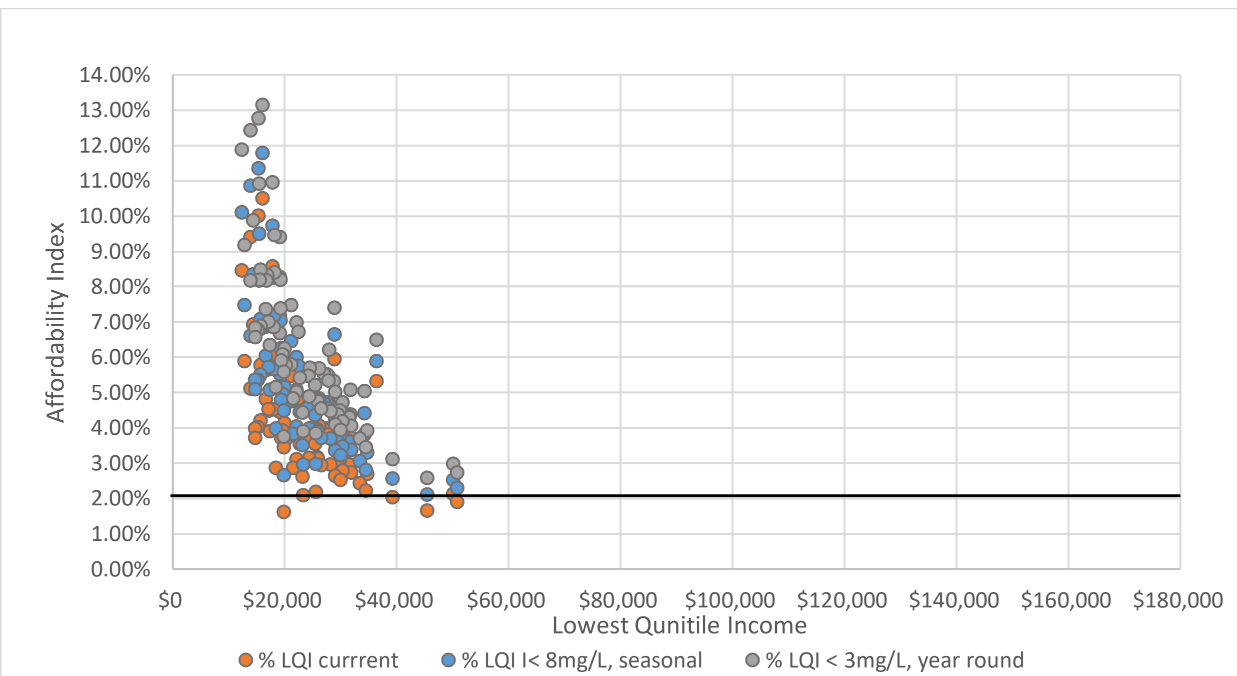


Figure ES-3. Estimated current and nutrient-adjusted utility-district specific %LQI

The range of the index values for both MHI and LQI vary widely in part because both income levels and sewer rates vary widely among the 80 utilities in the study.

With a high degree of variability in incomes and sewer bills, neither relatively high sewer bills, nor relatively low income alone predict the districts that have the highest impact index values. Rather, the %MHI and/or %LQI provides more information about the greatest need for grant funds than simply looking at the MHI levels (Figure ES-6). The correlation of both %MHI index value and %LHI index value to MHI is relatively low (R^2 of 0.2746 for %MHI and R^2 of 0.205 for %LQI). This low correlation suggests that MHI does predict the utilities that have the highest index values and therefore potentially households with the greatest need.

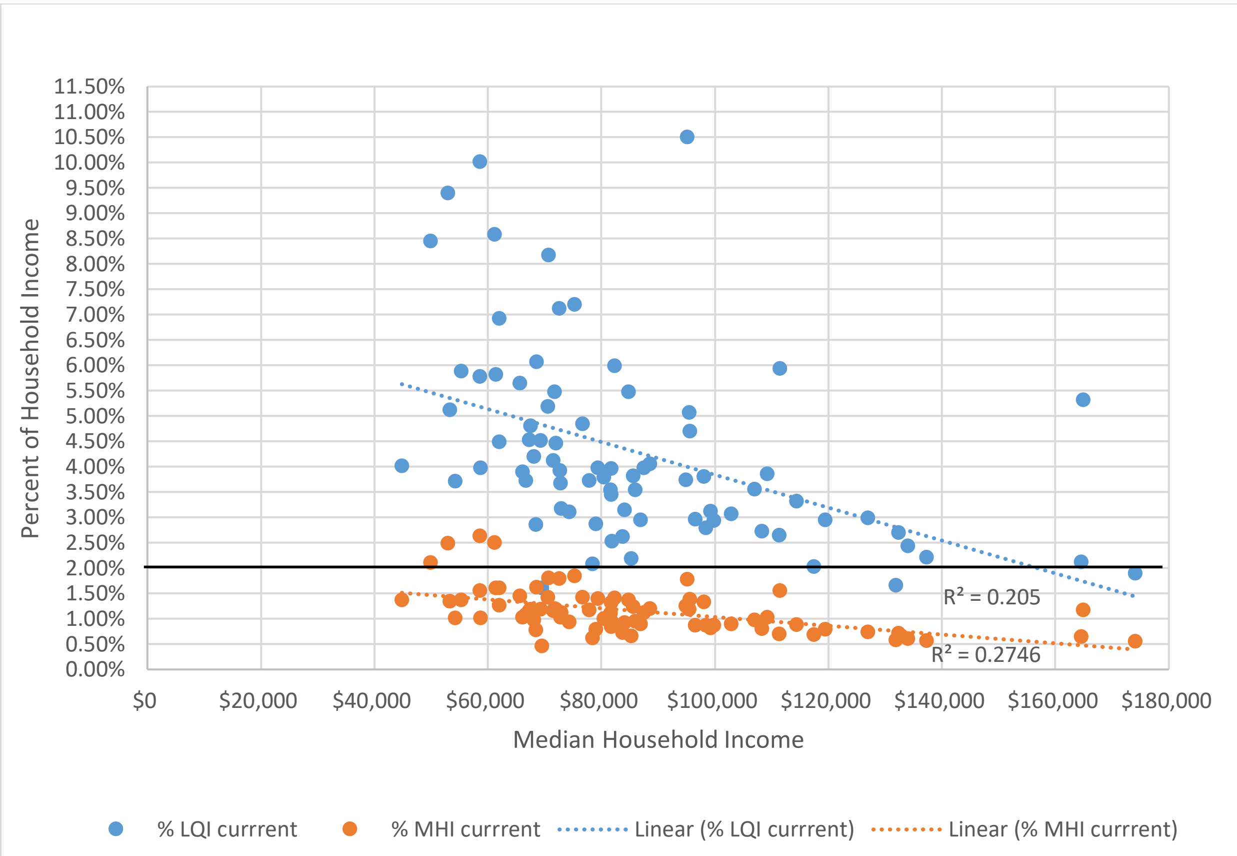


Figure ES-4. Correlation of %MHI and %LQI values to MHI

Recommendations

Our recommendations focus on identifying steps to take toward an equitable and efficient funding pathway for the MWQ IS reduce wastewater nutrient loads strategy. Non-utility public funding can contribute to the provision of a public good, in this case clean water, and help keep utility %MHI values within Ecology's "no hardship" range (below 2 percent of MHI). As funding is limited, this research helps direct available funding towards the places where it is needed most and may be used as efficiently as possible.

Four recommendations that might improve both efficiency and equity outcomes for the available grant and loans monies are:

- Utilize the data from this study to estimate the amount of federal and state capital grant monies would be needed to maintain %MHI or %LQI indices below a specified affordability threshold for individual Puget Sound utilities.
- Investigate the possibility of using the %MHI or %LQI metric in addition to other metrics used to determine financial hardship in Ecology's Grants and Loans Programs.
- Study the feasibility of a regional or state-wide low-income assistance program to aid those with the greatest need. In contrast to providing federal and state monies to pay for nutrient-related capital improvements, which could lower rates for all rate payers, a low-income assistance program would target funds to those households in greatest need of assistance.
- Consider funding a feasibility study to assess the potential benefits of restructuring rates following the model developed by the US Water Alliance's report, *A Promising Water Pricing Model for Equity and Financial Resilience* (Hara and Take 2022).

CONTENTS

TABLES AND FIGURES

LIST OF ABBREVIATIONS

CCWP	Centennial Clean Water Program
CWSRF	Clean Water State Revolving Fund
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
FCA	EPA's Financial Capability Assessment
HEAL Act	Healthy Environments for All Act
IS	Implementation Strategy
LQI	Lowest Quintile Household Income
MHI	Median Household Income
MSRC	Municipal Research and Services Center
MWQ	Marine Water Quality
NPDES	National Pollutant Discharge Elimination System
PSNGP	Puget Sound Nutrient General Permit
PSP	Puget Sound Partnership
TIN	Total Inorganic Nitrogen
WAC	Washington Administrative Code
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

This summary report describes methods, reports results, and discusses implications of a wastewater service affordability analysis conducted in support of Puget Sound National Estuary Program Marine Water Quality Implementation Strategy planning efforts. Associated data files and a data description with detailed metadata can be viewed in the companion *Puget Sound Wastewater Service Affordability Analysis Data Collection* (Barber et al. 2022), available at https://digital.lib.washington.edu/researchworks/handle/1773/49467.

Eutrophication is a process that occurs when anthropogenic nutrient inputs promote excessive growth of phytoplankton and macroalgae in water bodies, which can then cascade into other physical, chemical, and biological changes. Symptoms of eutrophication—low dissolved oxygen, loss of submerged aquatic vegetation, changes in nutrient ratios that alter planktonic species composition, and blooms of algae that produce harmful biotoxins—can intensify as the process progresses (Bricker et al. 2007).

In 2018, two regional nutrient management efforts were initiated in response to monitoring data that revealed worrisome trends in Puget Sound's water quality:

- Reporting for the Puget Sound Partnership's (PSP) "Marine Water Quality Vital Sign" implied a progression of eutrophication symptoms.[2] These findings led to development of a Marine Water Quality Implementation Strategy (MWQ IS) to provide a ***non-regulatory*** road map intended to align nutrient management efforts across agencies and programs. It was created using a collaborative process developed by PSP and is being implemented by the Stormwater Strategic Initiative.

- The Washington Department of Ecology's (Ecology) Water Quality Assessment identified 102 waterbody segments in Puget Sound that don't meet marine dissolved oxygen Water Quality Standards (i.e., they were placed on the 303(d) list of impaired waterbodies). As a result, Ecology began the Puget Sound Nutrient Reduction Project as a ***regulatory*** process to quantify needed pollutant reductions and identify management actions necessary to bring impaired waters back into compliance with the state's legally enforceable water quality standards.

Wastewater treatment plants (WWTPs) are the largest anthropogenic source of nutrients to Puget Sound and were therefore an early focus of both nutrient management efforts. Since most WWTPs in the region do not currently utilize advanced nutrient removal technologies, without facility upgrades nitrogen loading will continue to increase as the region's population grows. In 2021, Ecology issued a Puget Sound Nutrient General Permit (PSNGP) requiring operators of facilities that discharge into Puget Sound marine waters to begin long-term planning for upgrades that would be needed to comply with total inorganic nitrogen (TIN) numeric effluent limits expected in future PSNGP cycles.

[2] See PSP (2020) for the latest update on this recently replaced set of metrics.

WWTP upgrades needed to reduce TIN loading as population grows will be expensive. Capital costs associated with adding advanced nutrient removal technologies to all the municipal WWTPs subject to the PSNGP are likely to exceed $2 billion, based on a preliminary economic evaluation of potential nutrient limits by Ecology and Tetra Tech (2011) escalated to 2022 dollars. The MWQ IS identified current funding levels as a barrier to WWTP upgrades and recommended development of a funding pathway strategy to encourage alignment of federal, state, and local funding sources.

1.1 Critical Analysis Purpose

Critical analyses are a component of the Puget Sound National Estuary Program's implementation strategies (IS) framework. During development of these strategies, participants identify uncertainties that limit understanding of problems and potential solutions related to regional recovery targets. These uncertainties are catalogued by Puget Sound Institute. Each year some Environmental Protection Agency (EPA) and PSP implementation strategy assistance agreement funding is allocated for "critical analysis" to answer key questions with a targeted data collection and analysis effort.

This critical analysis was initiated because participants in the IS development process expressed concerns about the impact of costly upgrades on ratepayers. Northern Economics (2019) similarly raised questions about equitable distribution of nutrient reduction costs, and potential political implications if a subset of the region's population is to bear a disproportionate share of costs needed to achieve public benefits enjoyed by all residents. In addition, Kinney et al. (2021) and Kinney et al. (2023) had documented existing water utility service affordability challenges in the region. Since nutrient reduction upgrades have the potential to exacerbate existing affordability issues, additional data collection/analysis was recommended.

Results of this analysis are intended to inform and contribute to the discussion of how to "develop a funding pathway" strategy in the MWQ IS. Choices made about how the region is to pay for WWTP upgrades may have implications for growth management as well as equity outcomes receiving greater attention due to the White House's Justice40 Initiative and Washington's Healthy Environment for All (HEAL) Act. We hope this analysis can support development of funding strategies that improve water quality while minimizing unintended consequences for other elements of Puget Sound's socioecological system.

1.2 Critical Analysis Approach

We approach the analysis in two steps. First, we estimate and analyze the financial impact that sewer bills have on Puget Sound communities and households with municipal sewer service. Second, we discuss ways the impact analysis results could be used to develop a funding pathway strategy for the MWQ IS, specifically focused on the potential to improve economic efficiency and equity outcomes.

Sewer Bill Impact Analysis

The impact analysis answers two questions:

- How affordable are current sewer service costs in the Puget Sound region?
- How does affordability change when projected rate increases attributable to PSNGP-required upgrades are added to current service costs?

We assessed **"affordability"** by calculating sewer service costs for single family residential households as a percentage of Median Household Income (MHI) and Lowest Quintile Income (LQI). There is no single universally accepted threshold for water utility affordability, but consistent with existing literature and practice we flag results above 2% as relatively less affordable. **A %MHI value exceeding 2% begins to raise concerns at the utility/community scale and a %LQI value exceeding 2% is a potential red flag for individual households.** These generalizations were derived from two sources:

- EPA Financial Capability Assessment Guidance considers %MHI in combination with other factors when determining implementation schedules for control measures needed to meet Clean Water Act regulatory obligations.[3] Past EPA (2014) guidance suggested that wastewater costs exceeding 2% of MHI have a **"high impact"** on residents. Reliance on MHI as a measure of affordability was criticized because it understates financial impacts to low-income households (Congressional Research Service 2017, Teodoro 2018). EPA (2022a) responded by proposing new indicator metrics that incorporate LQI in their revised financial capability assessment guidance.
- WAC 173-98-300 4(b) and WAC 173-98-320 delineate three categories of **"hardship"** for Ecology to use when determining interest rates and forgivable principal eligibility for clean water loans. Moderate hardship occurs when %MHI is above <2% but less than 3%; elevated hardship is defined as %MHI between 3% and 5%; and severe hardship occurs when %MHI is above 5%.

Funding Strategy Discussion

Next, we discuss how the sewer bill impact analysis data and results could contribute to the development of a funding strategy for the MWQ IS. There is little debate that the needed nutrient-related capital infrastructure upgrades are costly and the demands for capital funds, whether from local, state, or federal sources, are limited. We focus our discussion on how the results of the impact analysis could help maximize the efficiency of state grant and loan

[3] EPA points out that their Financial Capability Assessment "is not a methodology for defining water affordability." **In this report we use the umbrella term "affordability" to encompass the general idea that water rates may be a financial burden on some households and utilities may face hardship when some of their ratepayers are unable to pay their bills.** As EPA points out, we do not intend to infer that the rates are unreasonable for the level of environmental protection that they offer.

spending, where efficiency is measured as prioritizing financial assistance to utilities and/or households with the greatest need.

The funding strategy discussion includes a brief background on the history of federal investment in water infrastructure and continues with a description of the state's grant and loan programs, specifically focused on prioritization methods. The prioritization discussion provides a basis to consider using the results of this study to improve the efficiency and equity of future grant funding.

Specifically, two potential equity issues are:

- Concerns over a subset of the region's population incurring a large portion of the expenditures needed to achieve broad public benefits.
- Whether increasing sewer rates cause lower income households to pay a disproportionate share of their incomes on sewer bills.

At the conclusion of the funding strategy discussion, we list recommendations and potential next steps.

2. SEWER BILL IMPACT ANALYSIS

The impact analysis describes the methods used to estimate the utility-specific %MHI and %LQI metrics for current and potential PSNGP-related sewer bills as well as data limitations we encountered during the analysis. We conclude the impact analysis with a description of the results. Additional information about data sources and analysis methodology can be found in the study's data collection (Barber et al. 2022).

2.1 Methods

Here we summarize the data compilation and analysis steps taken to estimate current and PSNGP-adjusted annual sewer service costs and income metrics used to calculate %MHI and %LQI.

2.1.1 Utilities Impacted by Puget Sound Nutrient General Permit

The first step was to identify all utilities[4] directly and indirectly affected by PSNGP requirements. The list of WWTP operators covered by the permit (the permittees) was obtained from Ecology (2021a and 2021b). Forty utilities operate 58 municipal WWTPs that discharge directly to Puget Sound marine waters. These utilities are directly impacted by the PSGNP because they operate the facilities that will need to be upgraded to comply with expected future TIN effluent limits.

Several permittees are wholesale providers of treatment services to neighboring utilities that do not own and operate a WWTP. The permittee charges wholesale customers a uniform rate to cover treatment costs (capital, operations, maintenance). The wholesale customer is also a retailer that bills their customers for the wholesaler's services plus the cost to operate their local collection systems (e.g., pipelines and pump stations) and convey wastewater to the wholesaler's system. These 43 utilities are impacted indirectly by the PSNGP, as they do not have to invest in treatment options, however the contract rates they pay for treatment services will likely increase. The total number of utilities that will be affected by the PSNGP is nearly twice the number of permittees.

King County is an example of a regional entity that owns/operates WWTPs and contracts treatment services to 29 local utilities. King County does not bill individual property owners; each of the 29 local utilities that King County provides services are the entities that bill individual customers. Because each of these local utilities have a unique rate structure and set their individual rates, this study calculated %MHI and %LQI for each of the local utilities.

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[4] Wastewater/sewage services in the region are provided by a mix of county or municipal governments, Special Purpose Districts, and Public Utility Districts. For simplicity, we call all these different types of service providers sewer utilities.

In total this study estimated sewer bills and utility-specific household incomes for 80 Puget Sound municipal sewer utilities.[5] State agency permittees (Department of Corrections, Washington State Parks) and non-municipal customers (Washington State Ferries, Puget Sound Naval Shipyard, Ft. Warden, Manchester Naval Fuel Depot, and Tribes) were excluded from the study. Appendix A lists the permitee and the utility district to which they provide treatment services.

2.1.2 Monthly Sewer Service Cost

CURRENT COST

We estimated monthly sewer bills for 80 utilities in Puget Sound. Rate data was obtained from the utilities' webpages. Two assumptions were used to estimate the monthly sewer bills for each utility. First, the rates are based on a ¾" residential pipe size. Second, where a variable rate was charged based on water usage, the usage was assumed to be a constant 5.5 ccf per household per month across all utilities. Assuming a constant usage rate allows for comparisons across rates that are solely based on the variable rate and not a difference in water usage. For a detailed description of the calculations see Barber et al. (2022).

The project team emailed utilities that utilize a variable rate structure, where bills are based entirely or partially on the volume of water used, to verify the estimated rates. Of 26 utilities contacted, we received responses from 12 (46% response rate). Minor corrections to our initial estimates were made where errors were identified by utilities.

PSNGP-ADJUSTED COST

In addition to estimating the current sewer bills, we also estimated potential sewer rates once PSNGP-required upgrades are added to current sewer rates. We added estimates of the nutrient-related increase in sewer rates (Table 1), published in *Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities,* (Ecology and Tetra Tech 2011) to our estimates of current sewer rates to arrive at these PSNGP-adjusted sewer costs.

Ecology and Tetra Tech (2011) show the estimated increase in monthly sewer rates for 4 different potential nitrogen effluent limits in 2010 dollars, which are displayed in Table 1. We choose to project costs for the most (<3 mg/L TIN year-round) and least (<8mg/L dry-season) stringent limits, which coincide with the most and least expensive upgrade scenarios, to provide an idea of the full range of potential impacts on sewer bills. We adjusted the estimates to 2022 dollars using the US Producer Price Index for Construction Materials.[6]

[5] We identified 89 municipal sewer utilities the discharge into Puget Sound marine waters, however only 80 are included in the study because we were unable to find service area maps or sewer rates for 9 utilities.

[6] Federal Reserve Bank of St. Louis, Economic Research, PPI by Commodity: Special Indexes: Construction Materials.

It bears mentioning that the PSNGP-adjusted sewer rates assume utilities will pay the full amount of the necessary upgrades without state or federal grants.[7] Thus, the nutrient adjusted sewer rates may be overstated if significant grant funding is made available. At the same time, the estimated upgrade costs may be understated. The expected accuracy range of the estimated monthly rate increases was +100 percent to – 50 Percent (Tetra Tech, 2011). Additionally, our PSNGP-adjusted sewer rates do not account for any other increases in service costs required for any other type of planned upgrades, for example to replace aging infrastructure. Actual future sewer costs will be even higher than our PSNGP-adjusted rates. A reminder that this analysis, the first of its kind, is intended to estimate the potential magnitude of impacts the PSNGP may have on Puget Sound utilities and households in the absence of significant new sources of state or federal funding.

Table 1. Estimated Monthly Household Sewer Rate Increase For Nutrient Removal of Puget Sound Water Resource Inventory Areas, Adjusted to 2022 dollars.

	TIN <8mg/L year-round	TIN <3 mg/L year-round	TIN <8 mg/L dry season	TIN <3 mg/L dry season
2010 (a)	$ 16.00	$ 19.48	$ 9.43	$ 11.41
2022 (b)	$ 29.05	$ 35.36	$ 17.12	$ 20.71

Sources: (a) Table ES-3 in *Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities* (Ecology and Tetra Tech 2011) (b) Costs adjusted by factor of 182 percent based on PPI by Commodity: Special Indexes, Construction Materials.

2.1.3 Household Income

Household income and population data was obtained from the 2019 U.S. Census Bureau American Community Survey (ACS). The lowest geographic unit for which household income by quintile and population data is available is the Census Tract. We downloaded data associated with 941 unique census tracts for the twelve Puget Sound counties.

Census tracts were corresponded to sewer district boundaries or city boundaries where utilities are operated by municipalities. This allowed us to estimate a population-weighted income for each of the 80 local wastewater service providers in the study. The full database is available open access via UW libraries (see Barber et al. 2022).

[7] This assumption is based on the methodology described in Tetra Tech and Ecology's 2010 report entitled Technical Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities, 2011. See Section 17.2 that describes how the weighted average monthly household sewer rate increase for nutrient removal upgrades was calculated.

2.1.4 Affordability Metrics

Using the numerators (estimated sewer bills) and denominators (estimated utility-specific household income) generated in the previous steps, we calculated six affordability metrics for each of the 80 utilities in the study:

- Current annual sewer service cost as a percent of MHI
- Current annual sewer service cost as a percent of LQI
- Annual cost of sewer service with a year-round 3 mg/L TIN limit as a percent of MHI
- Annual cost of sewer service with a year-round 3 mg/L TIN limit as a percent of LQI
- Annual cost of sewer service with a seasonal 8 mg/L TIN limit as a percent of MHI
- Annual cost of sewer service with a seasonal 8 mg/L TIN limit as a percent of LQI

Results were evaluated based on their value relative to the commonly applied 2% benchmark.

2.2 Data Limitations

The geographic scale of this evaluation is broader than an individual utility would undertake for a financial capability assessment. Results represent a snapshot in time and are intended to inform development of a regional-scale funding strategy. Here we provide a list of potential sources of error that should be considered when using this data and/or our analysis results. A more detailed description of the assumptions and the impacts that these assumptions had on our estimates can be found in Barber et al. (2022).

- Not all Puget Sound region households are included in the study. PSNGP-impacted utilities discharge directly to Puget Sound marine waters. WWTPs that discharge to rivers that flow into Puget Sound are not included. Likewise, on-site sewage treatment (septic systems) and utilities that discharge via groundwater are not included. Multifamily households were excluded from the analysis due to the differences in the ways utilities and building managers sub-meter and bill individual units.
- Corresponding the census tracts to utility district service areas required several assumptions that resulted in a lower level of confidence about than we would have liked.
- Households that use on-site sewage treatment (septic systems) but are located within the service area boundaries of a wastewater utilities were not excluded when calculating the Median Household Income and Lowest Quintile Income for those utilities.
- Our 5.5 ccf/month (4,114 gallons) water usage assumption does not explicitly include consideration of household size and seasonal variation. We decided to calculate service costs based on a standardized usage, rather that collecting data on actual usage, so that cost estimates were normalized to enable direct comparison. The standardized usage we

selected is based on a commonly applied estimate of average winter quarter usage in the region (D. Thompson, City of Tacoma Wastewater Operations Division Manager, pers. comm.). Using a rainy season average excludes outdoor/irrigation use thereby more closely approximating the generally accepted "basic use" estimate of 50 gallons per capita per day (gpcd) (approximately 6.6 ccf). Several utilities contacted to verify our service cost calculations responded that their actual annual average household usage volume was higher than 5.5 ccf/month.

- Some service providers incorporate state and local utility taxes into their rates, and some do not. We used published rates and did not account for inclusion/exclusion of taxes.
- More recent estimates of potential PSNGP compliance costs (e.g., Brown and Caldwell 2020) indicate that cost estimates provided in Ecology and Tetra Tech (2011) are very low, even adjusted to 2022 dollars.

2.3 Results

2.3.1 Utilities Impacted by the PSNGP

See Appendix A for a list of the sewer utilities included in the study. The list includes 85 utilities, 80 of which were included in the study. Five utilities were excluded because we were unable to locate a detailed map of the provider's service area or the district's web page did not report sewer rates. Two utilities, King County and LOTT, are exclusively wholesalers that do not bill any households for sewer treatment services.

2.3.2 Monthly Sewer Service Cost

Figure 1 shows our estimates for current monthly sewer bills of 80 local sewer providers. Current estimated monthly sewer cost ranges from $26.55 per month to $161.21 per month. The average across all 80 utilities was $78.36 per month with a standard deviation of $23.91. As discussed in Section 2.1.2, these costs assume 5.5 ccf of water usage for the 25 utilities with rates based on volume of water used. The remaining 55 utilities utilize a flat rate structure.

Figure 2 shows our estimates for potential future PSNGP-related sewer bills of 80 local sewer districts. The two PSNGP-related sewer bills were calculated by adding $17.12 (8mg/L seasonal scenario) and $35.36 (3mg/L year-round scenario) to estimated current sewer bills. Potential future PSNGP-adjusted monthly sewer bills associated with the 8mg/L seasonal scenario range from $43.76 per month to $178.33 per month. Potential future PSNGP-adjusted monthly sewer bills associated with the 3mg/L year-round scenario range from $62.01 per month to $196.57 per month.

This large range of estimated monthly sewer bills was curious but beyond the scope of this study to attempt to explain. A possible future study could attempt to correlate costs to factors such as number of connections, topography, underlying geology, length of pipes, number of pump stations, location (e.g., island), existing removal nutrient technology, etc.

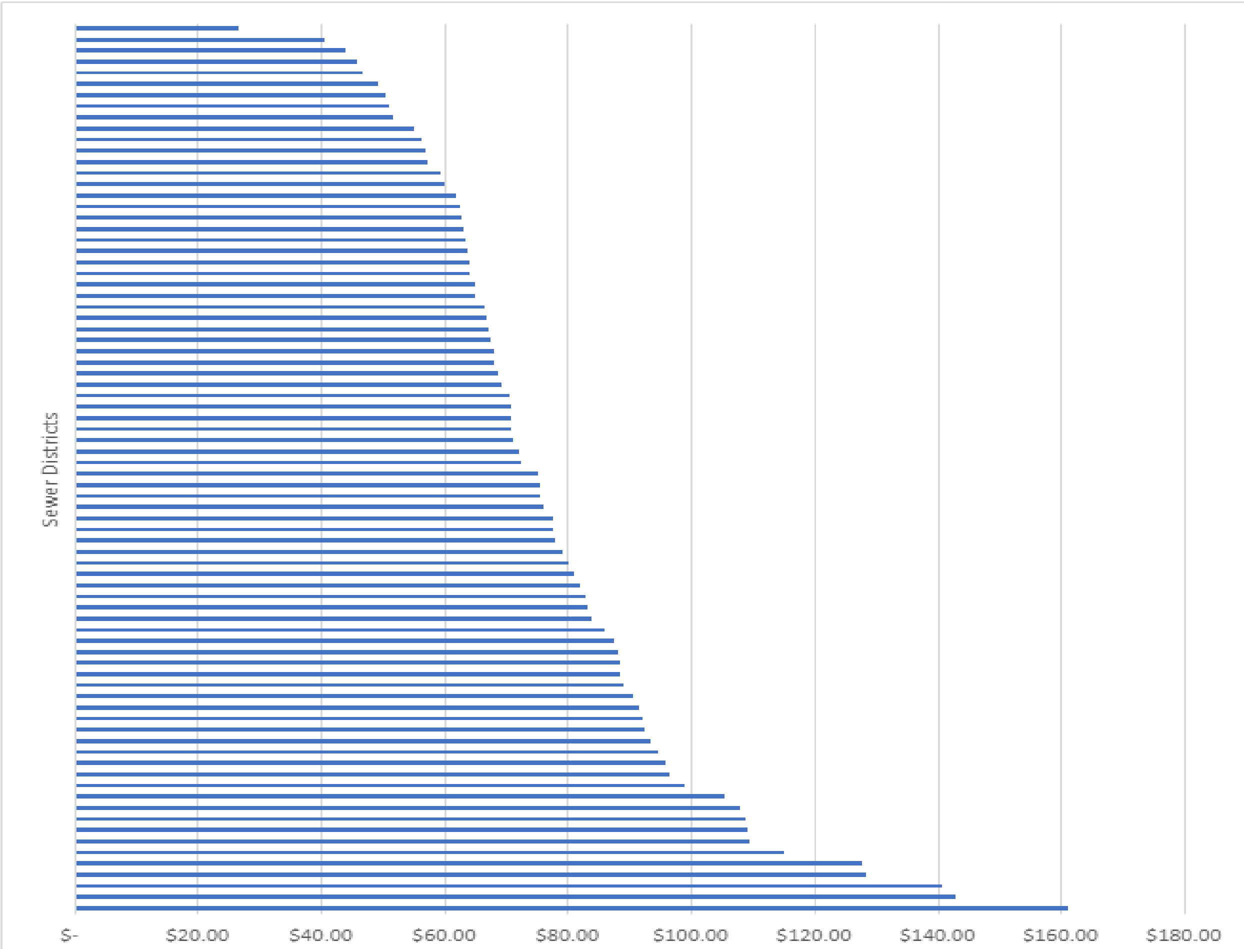


Figure 1. Estimated Current Monthly Sewer Service Costs, 80 Puget Sound Utilities

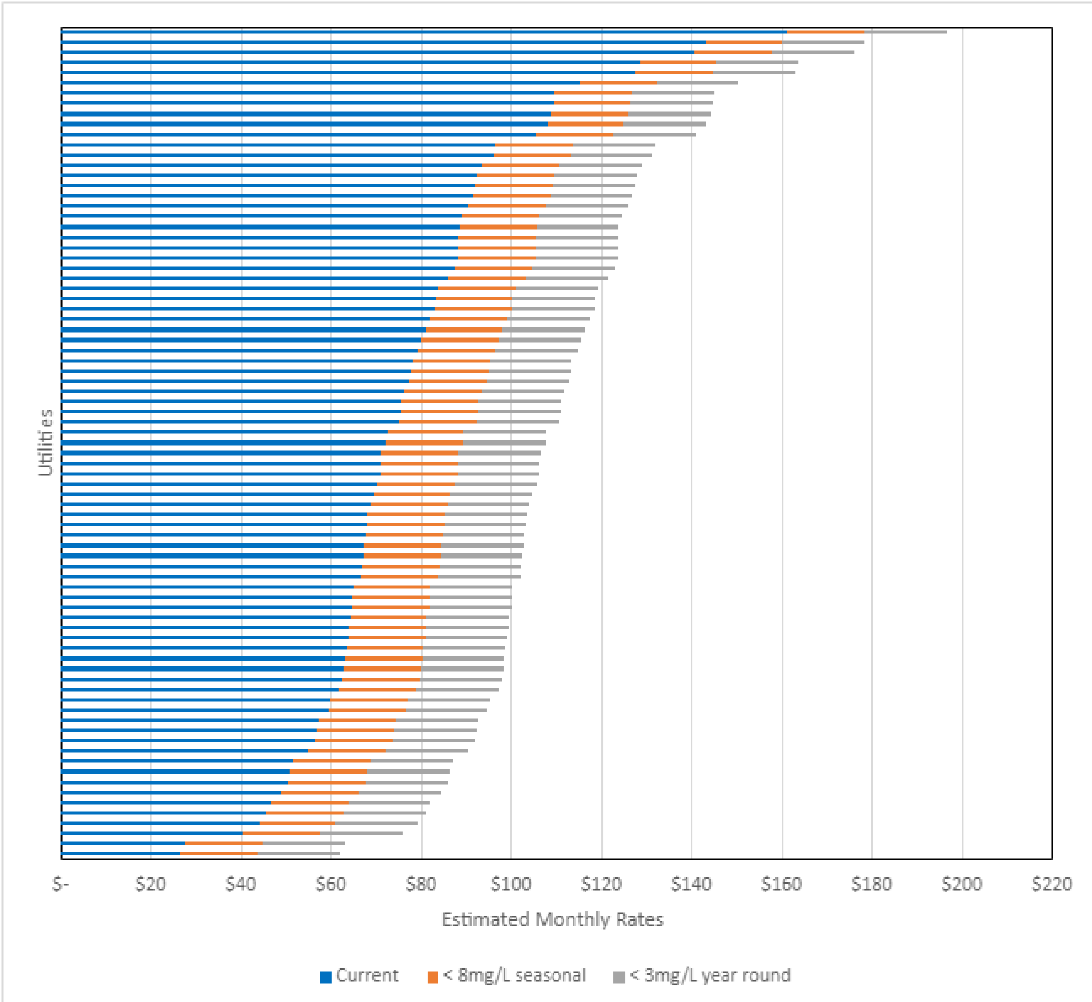


Figure 2. Estimated PSNGP-Related Monthly Sewer Service Costs, 80 Puget Sound Utilities

2.3.3 Household Income

Figure 3 shows estimated MHI and LQI in the service areas of 80 local wastewater providers. MHI ranges from a low of $44,844/year to a high of $174,078/year, with an average of $86,323/year. The estimated LQI ranges from a low of $12,425/year to a high of $50,831/year, with an average of $23,953/year. In general, the LQI is approximately 30 percent of the MHI, illustrating the extent of income disparity in the Puget Sound region (Figure 4).

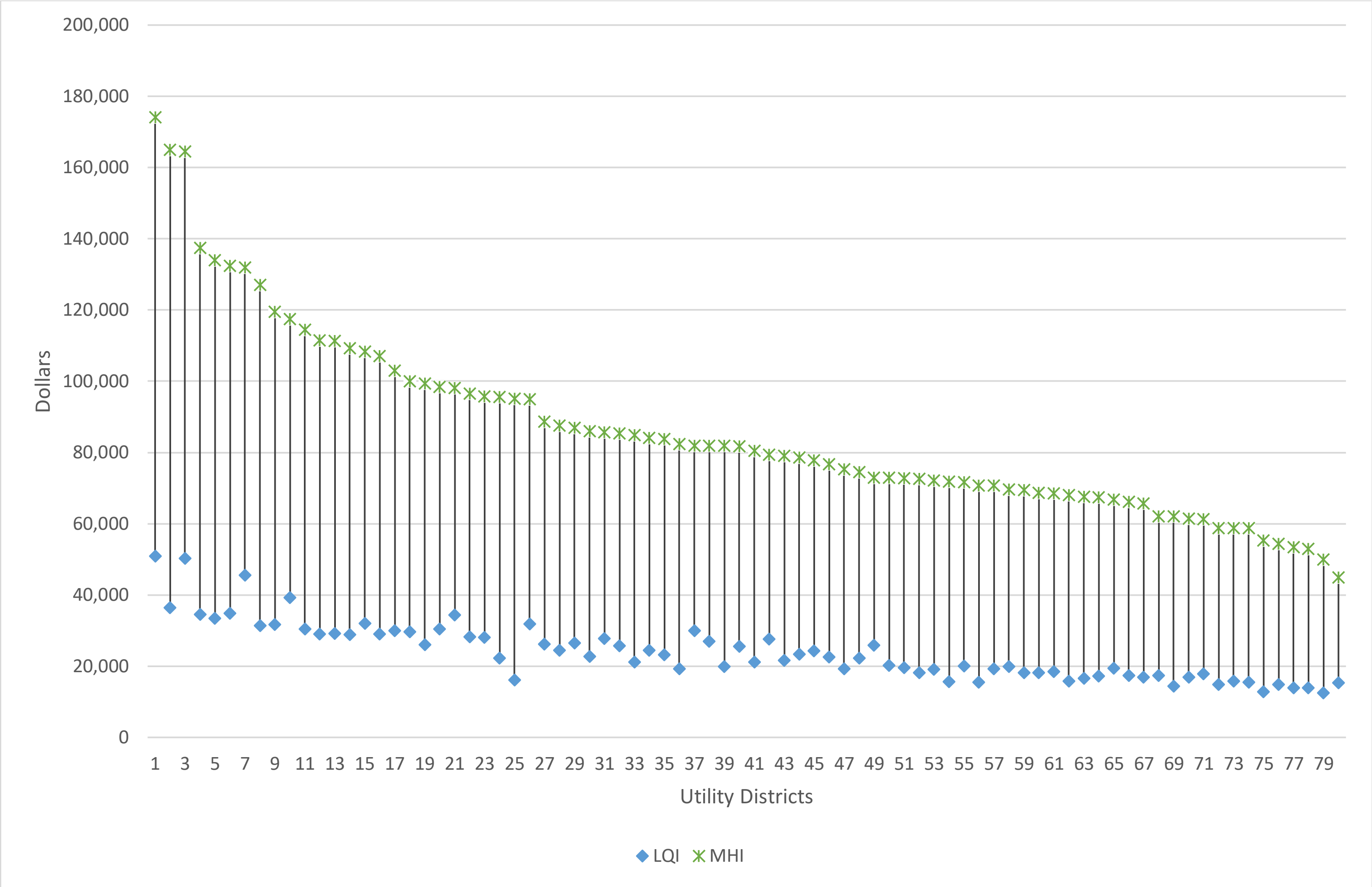


Figure 3. Estimated Household Income for 80 Puget Sound Sewer Utilities, 2020 dollars

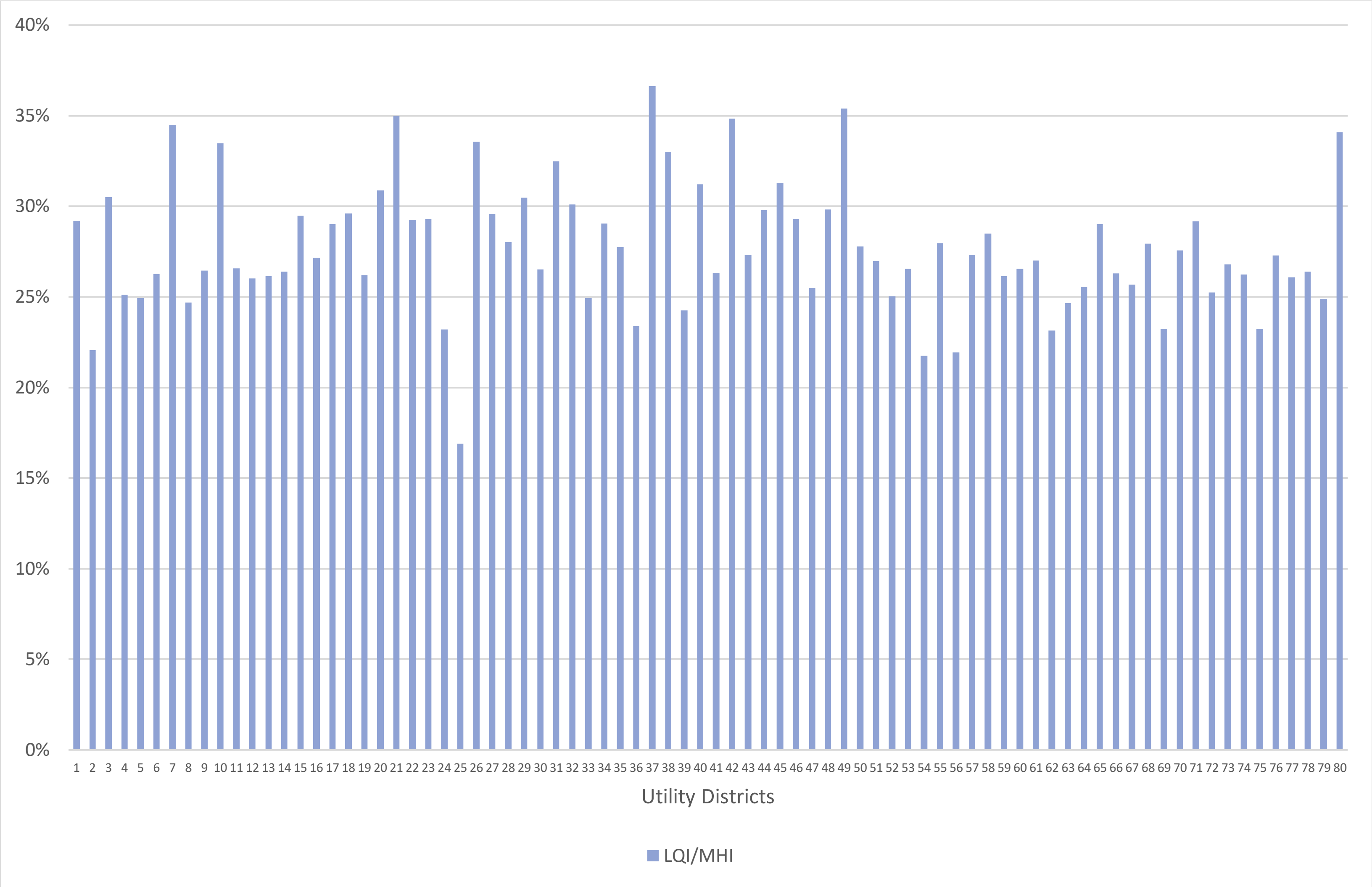


Figure 4. Lowest Quintile Income as a Percent of Median Household Income for 80 Puget Sound Sewer Utilities, 2020 dollars

2.3.4 Indicators of "Affordability"

The %MHI and %LQI results were calculated by dividing the estimated sewer costs by the utility specific MHI and LQI, respectively. Two sets of %MHI values and %LQI values were estimated, one set for current sewer costs and a second set for PSNGP-adjusted sewer costs.

Estimated %MHI and %LQI results for current sewer costs are shown in Figure 5. Values range from 0.5 %MHI to 2.6 %MHI, averaging 1.2 %MHI. These values suggest current rates are reasonably affordable when calculated using MHI. However, the %LQI results indicate sewer service costs are burdening low-income households. %LQI values range from 1.6 %LQI to 10.5 %LQI. This wide disparity in index values demonstrates one reason EPA's FCA guidance document includes utilizing LQI in some metrics. For reference, the US Economic Research Service reports that in 2021, U.S. consumers spent an average of 10.3 percent of their disposable personal income on food.

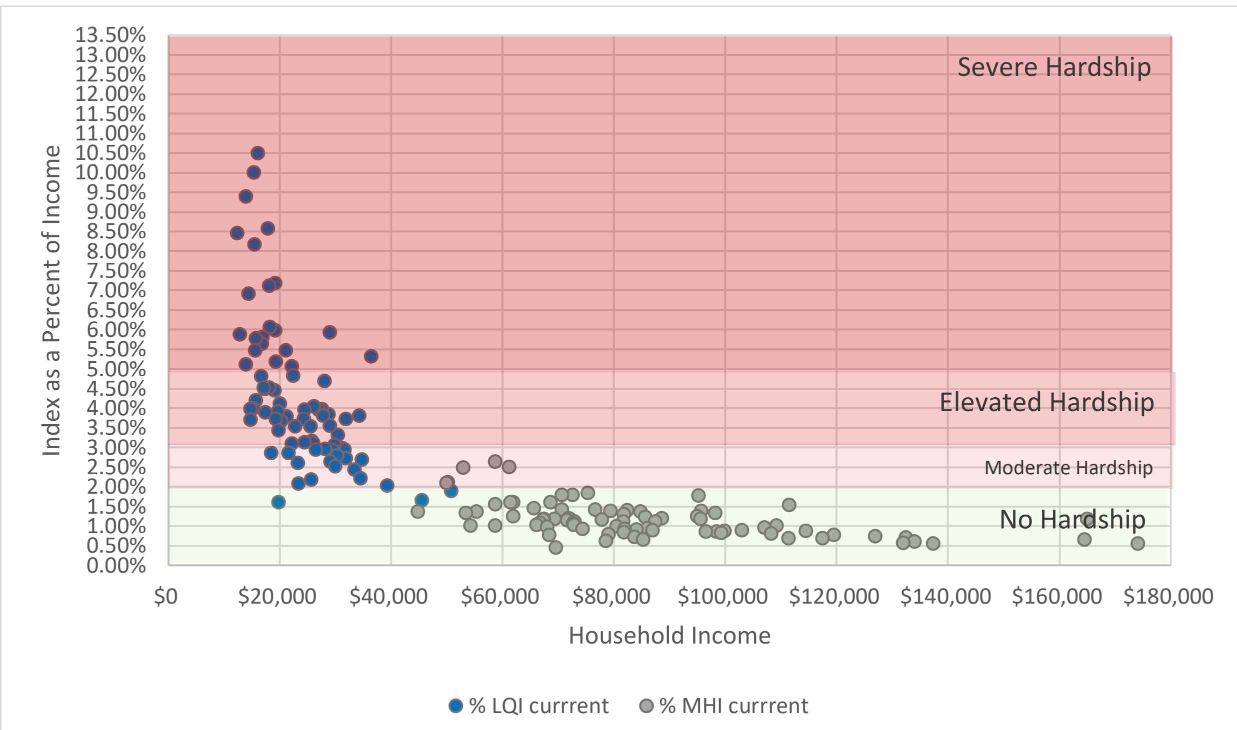


Figure 5. %MHI and %LQI Values Using Estimated Current Sewer Costs for 80 Puget Sound Sewer Utilities, 2020 dollars

The summary information presented in Figure 5 demonstrates several areas of potential concern. First, the scatter plot demonstrates the income disparity in Puget Sound, even between MHI and LQI. Where MHI ranges from approximately $40,000 to a high of $180,000. Whereas LQI range is much narrower, with the majority of households around $20,000 LQI. Second, current sewer rates may not have a high impact on Puget Sounds' household's budget using MHI, however sewer bills do have a relatively high impact, or create hardship, on low-income households. The next question to address is how might PSNGP-adjusted sewer rates impact households? This question and a detailed description of the both sets of indices (the %MHI and the %LQI) using both current and nutrient-adjusted sewer rates are discussed below.

CURRENT AND PSNGP-ADJUSTED COSTS AS A PERCENT OF MHI

The utility-specific %MHI values using current sewer rates are less than two percent in 76 of the 80 Puget Sound sewer utilities included in the analysis (Table 2). The %MHI values range between 0.46 percent of MHI and 2.63 percent of MHI, with an average of 1.16 percent of MHI, and a standard deviation of 0.44. These results indicate that for most utilities in the region current sewer costs are not high impact or causing hardship as defined by EPA and Washington State, respectively.

However, estimated %MHI values using PSNGP-adjusted sewer rates suggest that over 20 percent of Puget Sound utilities' sewer bills would cause hardship to their rate payers, absent federal or state investment in nutrient reduction upgrades (Table 2). %MHI values were estimated for two potential regulatory scenarios: <8.0mg/L TIN during dry season-only, and <3.0mg/L TIN year-round. These two scenarios bookend the potential sewer rates increases, representing both the least expensive (<8.0mg/L TIN) and most (<3.0mg/L TIN) expensive approaches to nutrient reduction.

Under the 8.0mg/L TIN scenario, 8 utilities (10%) have %MHI values greater than two percent and less than 3 percent of MHI. This %MHI range is defined by Ecology as "moderate hardship." EPA considers %MHI above 2.0 percent as high impact. The %MHI values range from 0.67 percent of MHI to 2.98 percent of MHI.

Under the 3.0mg/L effluent limit scenario, 18 utilities (23%) exceed the 2% affordability benchmark. Three of those utilities have %MHI values in the "elevated hardship" range. The %MHI values range from 0.80 %MHI to 3.35 %MHI.

In summary, the range of %MHI values indicate that current sewer bills cause moderate hardship on households served by 4 (5% of the total) Puget Sound utilities. Absent additional state or federal funding, PSNGP-required upgrades could cause moderate to severe hardship for 18 of the 80 Puget Sound sewer utilities.

Table 2. Summary of Current and PSNGP-Adjusted %MHI Values

Metric	Current	PSNGP-Adjusted (a)	
		< 8.0mg/L TIN dry season	< 3.0mg/L TIN year round
Total number of districts/utilities	80	80	80
Moderate Hardship, (e.g. index > 2.0 % and < 3%)			
Number of utilities	4	8	15
Percent of utilities	5.0%	10%	19%
Elevated Hardship, (e.g. index > 3.0 % and < 5%)			
Number of utilities	0	0	3
Percent of utilities	0.0%	0.0%	4.0%
Severe Hardship, (e.g. index > 5.0 %)			
Number of utilities	0	0	0
Percent of utilities	0.0%	0.0%	0.0%
Minimum %MHI value	0.46%	0.67%	0.80%
Maximum %MHI value	2.63%	2.98%	3.35%
Average %MHI value	1.16%	1.41%	1.69%
Std Deviation	0.44%	0.49%	0.54%

(a) **Nutrient-adjusted rates estimated using data from Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities. Publication 11-10-060, WA Dept of Ecology and Tetra Tech, 2011.**

(b) **See the Data Limitations section of the analysis for a discussion on the limitations of the population data**

Source: Barber, A., K. Bogue, S. Burke, N. Jo, and A. Kinney. 2022. Puget Sound Wastewater Service Affordability Analysis Data Collection [Data files]. 1st Version. Prepared by College of Business and Economics, Western Washington University; ECO Resources Group; and Puget Sound Institute, University of Washington Tacoma. Distributed by ResearchWorks, University of Washington Libraries.

Figure 6. presents a scatter plot of current and estimated nutrient-adjusted %MHI values and delineates the 2.0 percent benchmark for EPA's high impact and Ecology's hardship metric. The %MHI values are plotted against household income for all 80 utilities in the study, showing a correlation between higher income households and lower %MHI values (i.e., there are more utilities with higher %MHI at the low end of the MHI axis). However, the correlation is not as strong as might have been expected. For example, there are utility districts below $60,000 MHI and that still have %MHI values below 2.0% and there are utility districts above $60,000 MHI that have %MHI values above 2.0 percent. This suggests that using an MHI metric to prioritize grant funds may provide money to districts that need it less than another district with a higher %MHI value. This finding is addressed in more depth in Section 5, Implications for MWQ IS.

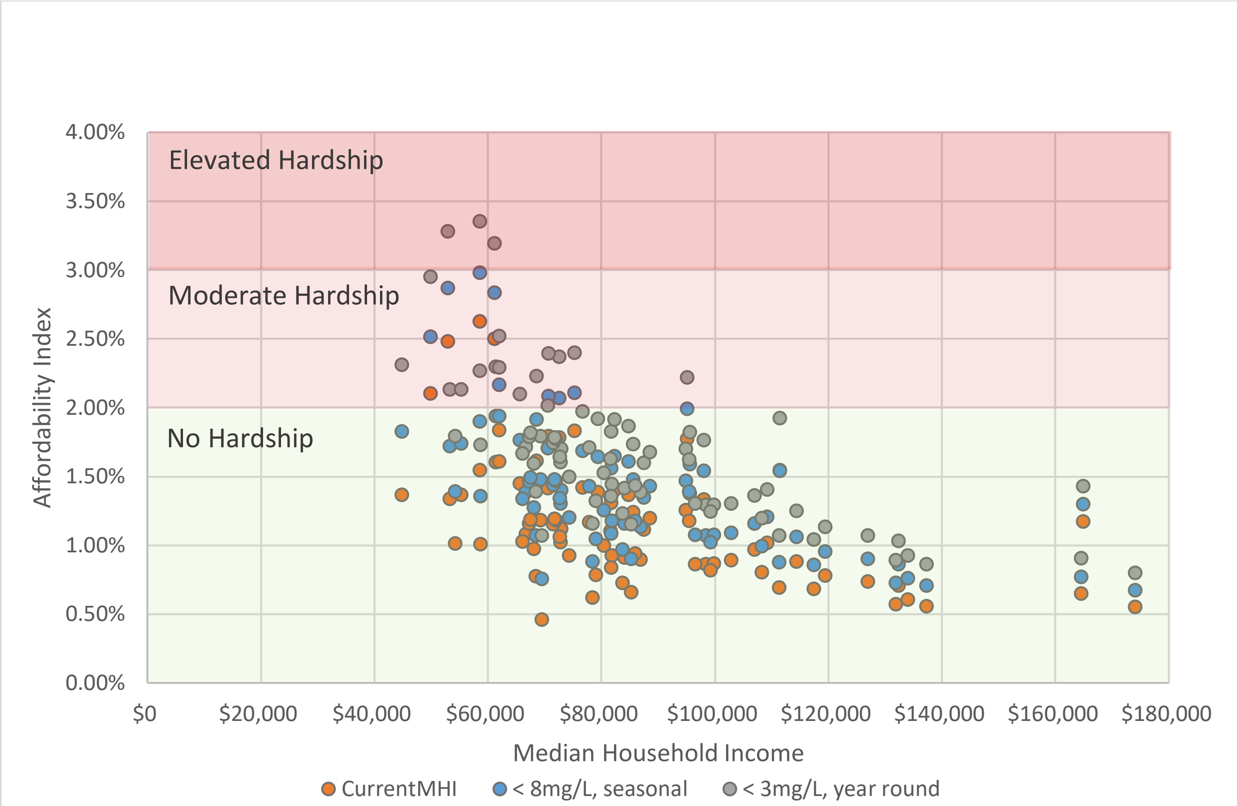


Figure 6. Estimated current and nutrient-adjusted utility-district specific %MHI

CURRENT AND PSNGP-ADJUSTED COSTS AS A PERCENT OF LQI

77 of the 80 Puget Sound sewer utilities had values exceeding 2%LQI (Table 3). 19 utilities' %LQI values were between 2% and 3%; 35 utilities' %LQI values were between 3% and 5%; and 23 utilities' %LQI values were above 5%. Current %LQI values range from 1.97% LQI to a high of 10.5% LQI, with an average of 4.4%LQI and a standard deviation of 1.97.

These estimated %LQI values suggest that approximately twenty percent of Puget Sound households served by a sewer utility are paying on average approximately 4.4% of their income on sewer bills. The lowest quintile of households in this study may spend almost half of a households' estimated food budget (per ERS 2021) on sewer bills.

Table 3. Summary of Current and PSNGP-Adjusted %LQI Values

Metric	Current	PSNGP-Adjusted (a)	
		< 8.0mg/L TIN dry season	< 3.0mg/L TIN year round
Total number of districts/utilities	80	80	80
Index > 2.0 % and < 3%			
Number of utilities	19	8	3
Percent of utilities	24.0%	10%	4%
Index > 3.0 % and < 5%			
Number of utilities	35	37	23
Percent of utilities	44.0%	46.0%	29.0%
Index > 5.0 %			
Number of utilities	23	35	54
Percent of utilities	29.0%	44.0%	68.0%
Minimum %LQI value	1.61%	2.80%	3.44%
Maximum %LQI value	10.50%	11.78%	13.14%
Average %LQI value	4.38%	5.47%	6.52%
Std Deviation	1.86%	2.05%	2.27%

(a) **Nutrient-adjusted rates estimated using data from Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities. Publication 11-10-060, WA Dept of Ecology and Tetra Tech, 2011.**

(b) **See the Data Limitations section of the analysis for a discussion on the limitations of the population data**

Source: Barber, A., K. Bogue, S. Burke, N. Jo, and A. Kinney. 2022. Puget Sound Wastewater Service Affordability Analysis Data Collection [Data files]. 1st Version. Prepared by College of Business and Economics, Western Washington University; ECO Resources Group; and Puget Sound Institute, University of Washington Tacoma. Distributed by ResearchWorks, University of Washington Libraries.

All PSNGP-adjusted costs had %LQI values above 2.0%. Under the 8.0 mg/L scenario, 8 utilities' %LQI values are between 2 percent and 3 percent of LQI; 37 utilities' %LQI values are between 3 percent and 5 percent; and 35 utilities' %LQI values are above 5 percent of LQI. Under the 3.0mg/L scenario, 3 utilities' %LQI values are between 2 percent and 3 percent of LQI; 37 utilities' %LQI values are between 3 percent and 5 percent; and 54 utilities' %LQI values are above 5 percent of LQI.

For the 8.0mg/L scenario, %LQI values range between 2.8 percent of LQI and 11.8 percent of LQI with an average of 5.47 percent of LQI. Under the 3.0mg/L scenario, %LQI values range from 3.4 percent of LQI to 13.1 percent of LQI, with an average %LQI of 6.5 percent of LQI.

Figure 7 presents a scatter plot of current and PSNGP-adjusted %LQI values. The %LQI values are plotted against household income for all 80 utilities in the study, showing a correlation between higher income households and lower %LQIs, e.g. there are more utilities with higher %LQIs at the low end of the LQI axis.

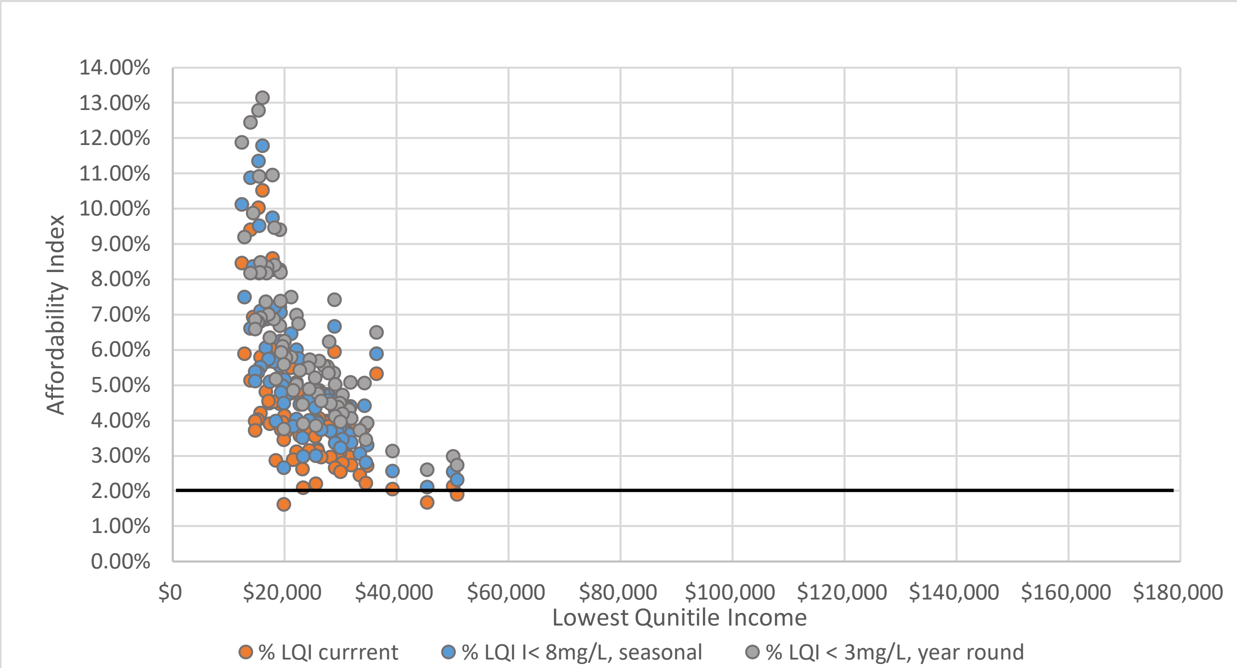


Figure 7. PSNGP-adjusted service cost as %LQI

3. FUNDING STRATEGY DISCUSSION

The findings of the impact analysis may help inform policy in in two areas:

- **Funding of public benefits**: Some industry experts and resource managers argue that sewer services provide a public benefit. We discuss this concept and the potential concern over a subset of the region's population incurring a large portion of the expenditures needed to achieve those public benefits.
- **Environmental justice/equity consequences**: Utility bills are regressive in nature and cause lower income households to pay a disproportionate share of their incomes on sewer bills. We discuss this issue using the findings of the impact analysis.

Both potential concerns are well described by the US Water Alliance in a recent publication (Hara and Take 2022) which states (emphasis added):

> For every community in our country, the availability of **wastewater services is a precondition for public health and prosperity. It is in our collective national interest** that everyone has access to clean water and sanitation. Yet, the reality is that maintaining and operating water systems is incredibly costly, **and both people who cannot pay water bills and utilities who cannot cover costs** can face severe consequences…

Lastly, we close with a discussion of implications this study has for the MWQ IS funding strategy and potentially for the Land Development and Cover IS.

3.1 Funding the Public Benefit of Sewer Services

Sewer Services as a Public Good

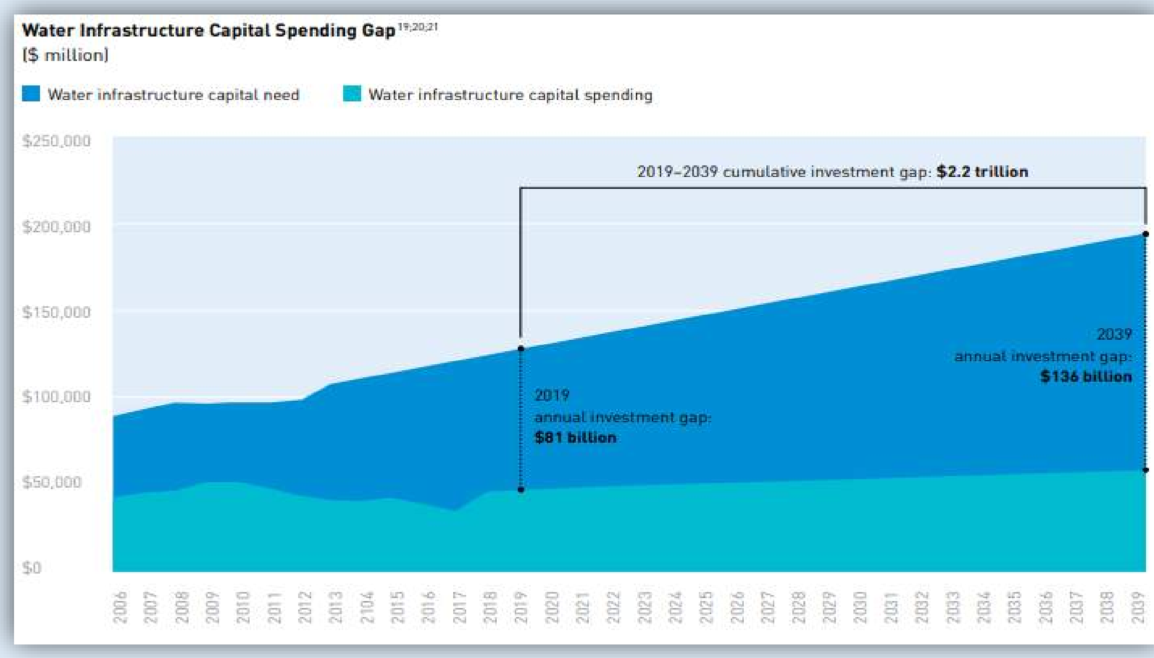
Some categories of public goods, like public education systems are funded in ways that aim to accrue and distribute the benefits of those goods to all people. For example, higher education, for which the student pays a portion of the cost, is subsidized through student loans, acknowledging the benefit to society of a well-educated population. To the extent that some of the benefits of wastewater services accrue to the public, an argument can be made for public funding for a portion of the costs of providing those services.

When public benefits do not receive appropriate levels of public funding the consequences can be under production of the public good, in this case clean water. And public funding for water infrastructure has been complicated by the fact that the federal government's funding has not kept pace with the need. The US Water Alliance estimates that, at the national level, in 2019 the gap between spending from all sources and investment needs as $81 billion (US Water Alliance, undated). This gap in federal funding places added pressure on local and state governments to bridge the gap and increases the urgency to distribute available funds to utilities with the greatest need and equity concerns (see Box 1). And the standard locally reliant utility revenue model is a precarious way to fund essential public goods that benefits more than just rate payers (Beecher, 2020).

Another consequence of a gap of public funding is the negative equity outcomes that occur if a subset of the region's households bears the greatest responsibility for paying for nutrient-related infrastructure investments. Questions have been raised about the equitable cost distribution associated with a subset of the region's population incurring a large portion of the expenditures needed to achieve public benefits (Northern Economics, 2019). Those expenditures come from households when they pay their sewer bills. Households with on-site sewage systems (septic) do not pay monthly sewage bills.

Box 1
The Economic Benefits of Investing in Water infrastructure
US Water Alliance National Water Infrastructure Spending Gap

"Meeting the drinking water and wastewater capital needs for communities across the United States will require coordinated investment at the federal, state, and local levels. Despite the growing need for water infrastructure, the federal government's share of capital investment has fallen from 31 percent in 1977 to a mere four percent in 2017. ... As federal support for water infrastructure capital needs has declined, local and state spending has provided a much greater share. Across the country, water rates are climbing to meet the costs of upgrading, expanding, and replacing water infrastructure. As costs, however, continue to rise, many communities will struggle to cover them through local rates and fees." (Page 14)



Source: US Water Alliance, The Economic Benefits of Investing in Water infrastructure, undated.

ABILITY TO PAY

A second potential unintended equity outcome of over-reliance on sewer ratepayers to fund wastewater treatment involves the potential for lower income households to either pay a disproportionate share of their income on sewer bills or be unable to pay those bills. Utility bills are regressive—they take a relatively larger share of low-income households' budgets compared to middle- and high-income households' budgets—and are therefore a form of structural inequity (Beecher 2020).

Our findings suggest that currently only three Puget Sound utilities' sewer rates result in sewer bills less than 2.0 percent of LQI. PSNGP-adjusted rates resulted in %LQI values ranging between 2.64 percent of LQI and 12.76 percent of LQI. These relatively high values indicate that sewer bills exacerbate the already regressive nature of Washington State's tax structure.

Box 2. Sewer Utilities' Income-Based Assistance Programs

Discounted utilities rates for low-income senior citizens or disabled residents are offered by many Puget Sound utilities districts. However, utility-based programs that offer low-income households - other than seniors or disabled citizens - have not been widely adopted. Furthermore, previous studies indicates that enrollment levels tend to be low compared to eligible populations (Kinney, 2022). Multiple challenges administering these programs, such as imprecise eligibility rules; extensive time and effort required for customers to apply; and a lack of trust to share income information are common (Pierce et al. 2021, Teodoro 2021).

Additional research on the effectiveness of customer assistance programs, as well as legal constraints related to such programs in Washington may be warranted (see footnote 6). For a thorough exposition of Washington State's grant, loan and assistance programs see the Marine Water Quality Base Program Analysis (Kinney and Wright, 2022). For examples of how utilities in other states are approaching these equity-based challenges see the US Water Alliance's recent study, A Promising Water Pricing Model for Equity and Financial Resilience (Hara and Take, 2023).

Although customer assistance programs for low-income households exist in Washington,[8] utility managers note that these programs are undersubscribed in their districts (see Box 2). This result is borne out in research on low-income assistance programs nationwide (Pierce, et.al, 2021 and Teodoro, 2021). Multiple challenges to administering these programs include: imprecise eligibility rules, extensive time and effort required for customers to apply, and a lack of trust to share income information.

This concern—overburdening disadvantaged or low-income households—is addressed in the Washington State Environmental Justice (EJ) Task Force Recommendations for Prioritizing EJ in Washington State Government. The recommendations of the task force resulted in the adoption of Chapter 70A.02 RCW which states, "an equitable distribution means a fair and just, but not necessarily equal, allocation intended to mitigate disparities in benefits and burdens". Washington State's concern over these equity issues is well justified, as the State ranks highest

[8] RCW 35.92.020 and RCW 35.67.020 confer authority to construct systems and *fix rates and charges* to Counties and Cities, respectively stating "the rates charged shall be uniform for the same class of customers or service" where the "factors" used to classify customers do not include low-income households. However, both RCWs do allow *assistance to aid* low-income persons in connection with services. RCW 57.08.014 provides authority to adjust or delay rates for low-income persons provided that "information on cost shifts caused by establishment of the special rates or charges shall be included in the notification of same." RCW 74.38.070 further discusses reducing rates for low-income senior citizens and other low-income citizens provided that the definitions of same are defined by appropriate ordinance or resolution adopted by the governing body of the county, city, town, public utility district or other municipal corporation. For example, Edmonds has adopted rate reductions for low-income citizens utilizing the definition of low-income established in RCW 84.36.381(5)(b)(i), Property tax exemptions, which includes a statement that to qualify individuals must be 61 years or older or disabled.

in the Tax Inequality Index (ITEP, 2018), which measures the regressive nature of states' tax structures.

Demonstrating similar concern about overburdening low-income households, EPA (2022b) instructed states to review, refine and improve as necessary their CWSRF affordability criteria to ensure that criteria are reflective of current affordability issues in the state. This instruction is an opportunity to incorporate newer thinking regarding use of LQI versus MHI in prioritizing funding decisions. These affordability metrics influence a utilities' access to grants and loans.

In addition to federal and State concerns of overburdening low-income households the industry also writes about these concerns. The US Water Alliance recently commented on the impact that the user-fee based funding structure has more broadly on communities and the environment, noting:

> *"This type of funding model exposes both individuals and communities to health and economic risks. Households that cannot pay their water bills face consequences like service shutoffs, property tax liens, and additional penalties and fees. This can push struggling customers into deeper debt, making it even harder to get current on bills. Meanwhile, utilities that cannot collect adequate revenue from rates run the risk of financial instability, putting vital operations and system maintenance at risk. Utilities that struggle financially may not be able to secure loans with favorable terms, which raises costs, leads to deferred maintenance, and drives the need for further rate increases to maintain quality levels of service. Utilities' financial dependence on customers makes them highly vulnerable to economic crises and growing income inequality." (Hara, 2022 for the US Water Alliance)*

3.2 Implications for the Land Development and Cover Implementation Strategy

The work is also relevant to the Land Cover and Development Implementation Strategy and 2022-2026 Action Agenda Strategy #1 (Advance smart development and protect intact habitats and processes by channeling population growth into attractive, transit-oriented centers with easy access to natural spaces). The high cost of living in urban centers, relative to rural communities, has been identified as a barrier to the regional goal of directing population growth into urban centers. Residents of these urban areas fund clean water services through Stormwater Utility Fees and sewer bills, while rural residents on septic systems in areas without NPDES Municipal Stormwater Permit coverage do not. This is likely one component of the "rural cost subsidy" described in the Land Cover and Development Implementation Strategy.

4. RECOMMENDATIONS

Our recommendations combine the findings of the impact analysis with the funding strategy discussion to help identify steps to take toward an efficient funding pathway for the MWQ IS. Public (i.e., non-utility) funding is required if resource managers agree that sewer services provide a public good. Additional public funding would also be required if resource managers set a target to keep utilities' %MHI values within Ecology's "no hardship" range (below 2 percent of MHI). The %MHI values of between 8 and 18 individual utilities were in either the moderate hardship range or the elevated hardship range when using the PSNGP-adjusted sewer rates. And over half the %LQI values exceeded 5%, indicating a significant impact on low-income households.

Demand for public funding, whether state or federal, frequently exceeds the supply of funding. Public funding is a finite resource. As such, developing a plan to utilize the available funding as efficiently as possible is an admirable goal. In the following four subsections, we provide recommendations that might improve both efficiency and equity outcomes for the available grant and loans monies. They are:

- Use the data collected for this study, plus newer estimates of PSNGP-related capital costs currently being developed as a PSNGP requirement, to calculate a Capital Investment Gap metric. The gap would be the amount of state/federal funding needed to maintain %MHI indices values below a specified percentage and/or the funding needed for low-income assistance programs to ensure households don't pay more for sewer service than a specified percentage of their income (Section 4.1).
- Investigate the possibility of using the %MHI or %LQI metric in addition to other metrics used to determine financial hardship in Ecology's Grants and Loans Programs (Section 4.2).
- Consider development of a regional or state-wide low-income assistance program for sewer utilities (Section 4.3).
- Consider funding a study to assess the potential equity benefits of restructuring wastewater rates using the Resilient Rate Structure model developed by the US Water Alliance (Section 4.4).

4.1 Estimate the Capital Investment Gap to maintain index values below target levels

Ecology and Tetra Tech's (2011) initial estimates of the total capital investment required to upgrade all Puget Sound WWTP for nitrogen and phosphorus removal was estimated to be between $1.4 billion and $5.9 billion depending on the level of nitrogen removal required.[9] Current estimates being completed by individual utilities are higher, but the exact amount of capital investment required to meet regulatory requirements cannot be known until nutrient effluent limits are determined by Ecology. While the final capital cost estimates are being completed by each utility, we recommend developing a methodological approach for distributing federal or state grant funds (assuming such grant funding is available) to maximize the equity outcomes and efficiency of those investments.

[9] See Tables ES-3 and Table ES-4 of the 2011 Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities, WA Dept of Ecology and Tetra Tech, adjusted for 2022 dollars.

We propose developing a Capital Investment Gap metric as shown in green on the bar chart in Figure 8. Assume for this hypothetical example that the State and/or Puget Sound regional recovery partners set a target of a 2%MHI for all Puget Sound utilities and endeavors to provide grant funds to utilities that would exceed that target due to PSNGP-required upgrades. The first bar shows a current (before nutrient removal upgrades are implemented) index value. The second bar shows how the index value would change assuming that the utility receives no state or federal grant funding and increases rates to pay for all PSNGP-required upgrade costs. The third bar shows a local share up to 2 percent, with the green stripped area above 2 percent indicating the hypothetical state or federal contribution needed to keep the %MHI index below the 2 percent threshold.

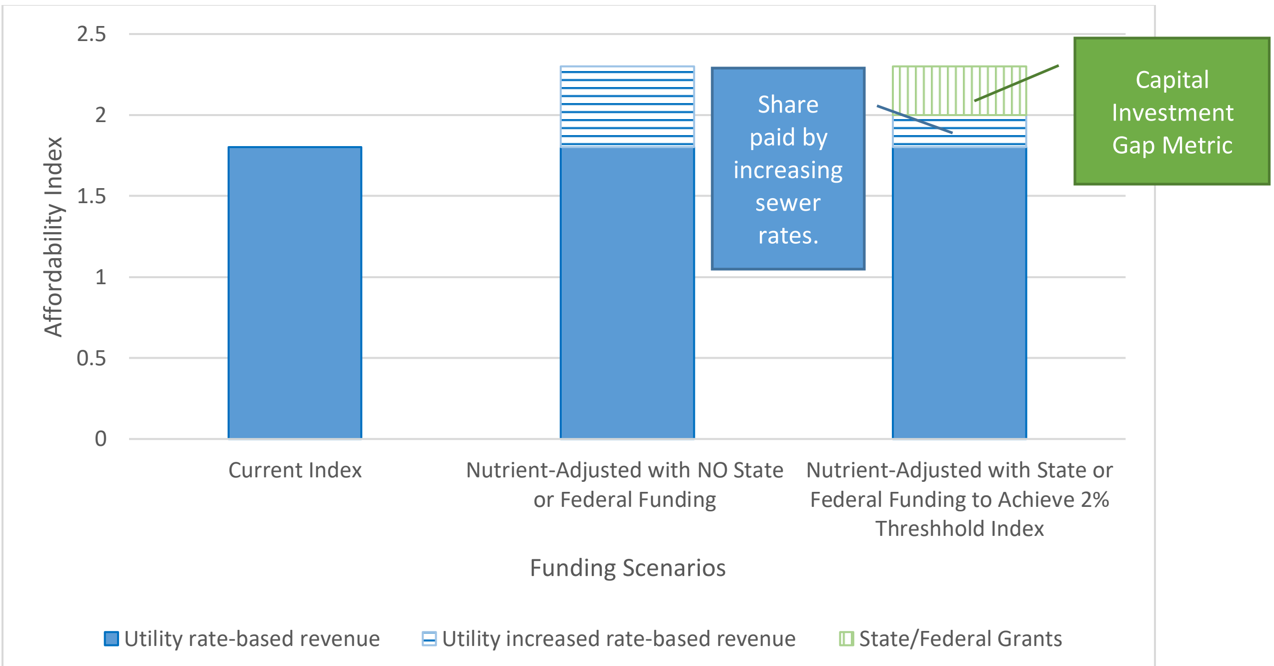


Figure 8. Proposed method to derive a Capital Investment Gap metric for quantifying state and federal funding requests to support PSNGP-required upgrades

This method would help estimate the amount of state/federal funding that could keep sewer bills below a target threshold. In this example the threshold was 2% but results could be calculated for other thresholds, such as other state hardship benchmarks like 3% and 5%. Note that this method assumes that utilities raise rates to pay for the difference between the index value under current rates and the rates up to the selected threshold. The funding need above that threshold would provide a target for state and federal funding requests.

Using utility-specific index thresholds to prioritize grant funding would help increase the economic efficiency of grant distribution. Additionally using utility specific index thresholds would help estimate how much grant money might be needed to fill the gap between what utilities can pay at a 2 percent index threshold and how much grant money might be needed to keep indices below that threshold level. In other words, utilities that have index values below 2 percent, even after the nutrient upgrades would receive a lower priority for grant funds. Instead, scarce grant funds would be prioritized to those utilities to close a gap and maintain a 2 percent index threshold.

Applying this same method using %LQI instead of %MHI could be used to estimate the annual budget needed to implement a regional low-income assistance program. Ideally, a customer assistance program would be sufficiently funded to ensure households don't pay more for sewer service than a specified percentage of their income.

Using this method to estimate the gap in capital spending, the annual budget for a low-income assistance program, or a combination of the two would help the advance the MWQ IS funding pathway strategy and increase understanding of the magnitude of the funding challenge associated with adding advanced nutrient reduction technologies to WWTPs in the region.

4.2 Utilize %MHI or %LQI in place of MHI when allocating grant/loan funding

Ecology manages grants and loans under both the Water Quality Combined Funding Programs[10] as well as the Puget Sound nutrient reduction grants program. Each of the funding programs described in Table 4 uses either %MHI or MHI as part of the prioritization process. The Ecology Water Combined Funding program, which oversees the Centennial Clean Water Program (CCWP) and the Clean Water State Revolving Fund (CWSRF), utilizes %MHI for its hardship determination. The 2022 Puget Sound Nutrient Reduction Grant Program (PSNRGP) included consideration for the average MHI of permitees.

If one of goals of a grants and loan program includes reducing hardship on those households most affected, incorporating %LQI in the hardship determination could potentially increase the efficiency and equity of the programs. However, if MHI (used for the PSNGP grant program) and %MHI (used for the CWSRF and the CCWP) values are close proxies for %LQI values then a program change would not be warranted.

[10] See Ecology's Grants and Loans web page.

Table 4. Washington State Grant and Loan Programs Available for Wastewater Infrastructure Improvements in Puget Sound

Program Name	Phase	Eligible Utilities	Current Hardship/Prioritization Metrics
Clean Water State Revolving Fund (a)	Pre-construction	All	• The existing residential population of the service area for the proposed project is 25,000 or less at the time of application. • The MHI for the proposed service area is less than 80 percent of the state MHI.
	Construction	All	• The existing residential population of the service area for the proposed project is 25,000 or less at the time of application. • Financing the project without subsidy would cause existing residential sewer fees to be two percent or more of the MHI for the service area. Hardship categories: Moderate 2% < RI < 3%; elevated 3% < RI < 5%; severe RI >5%
Centennial Clean Water Program (a)	Pre-construction & construction	All	• Managed in accordance to Chapter 70A.135RCW and Chapter 173-95A WAC where: • 70A.135 RCW give preference to Puget Sound partners (defined in 90.71.010 RCW as an entity that has been recognized by the partnership as having consistently achieved outstanding progress in implementing the 2020 action agenda • 173-95A WAC define hardship (in WAC 173-98-300) as MHI > 2%, categories as listed above under CWSRF.
Puget Sound Nutrient Reduction Grant Program (b)	Planning	43 utilities that own and operate the 58 WWTPs discharging to Puget Sound	From page 1, from legislative language for the $9M of the 2021-23 biennium: • Location of wastewater treatment facility, prioritizing facilities that are not located within a city with a population of 760,000 or more, • Age of wastewater treatment facility, prioritizing the oldest eligible facilities; and • Immediacy of need for grant funding to avoid system failure and higher magnitude of contamination. From page 3, under prioritization factors all of the above and: • Economic Status: Facilities serving populations with lower Median Household Incomes receiving higher priority.

Sources: (a) Washington State Department of Ecology, 2022. State Fiscal Year 2024 Funding Guidelines Water Quality Combined Funding Program, Pub 22-10-016 (b) Washington State Department of Ecology, 2021. 2021-2023 Puget Sound Nutrient Reduction Program Funding Guidelines, Pub 21-10-042

Figure 9 shows the correlation between MHI and %MHI values and %LQI values. The correlation between either index and MHI is moderate at best. Meaning, MHI may not be a good proxy for hardship. This demonstrates that the MHI does not identify the utilities with the highest %MHI values or %LQI values. The reason that MHI is not strongly correlated with hardship is due to the wide variability of sewer rates (Figure 1). The information suggests that, at a minimum incorporating the %MHI index into the hardship determination for the PSNRGP would increase equity outcomes significantly.

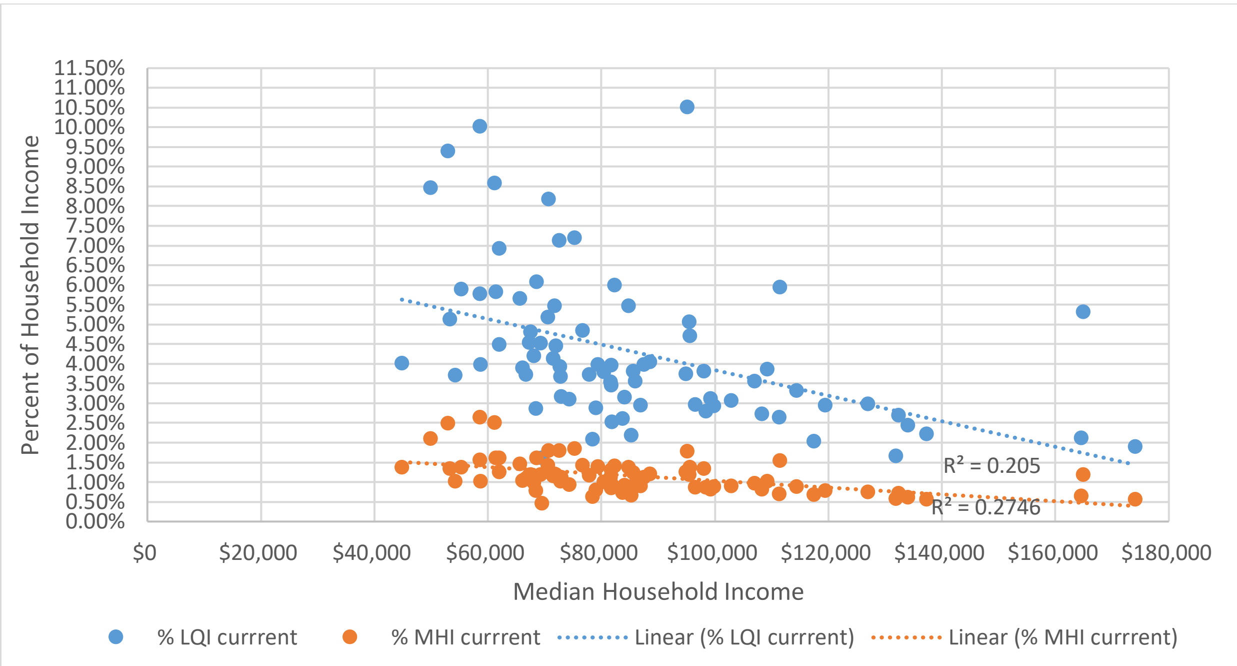


Figure 9. Correlation of %MHI and %LQI values to MHI

Figure 10 shows the correlation between %LQI values and %MHI values. Here the correlation is strong. Meaning, %MHI value may be a good proxy for hardship. There would be room for an equity improvement if %LQI was used in place of %MHI in determining hardship, but the improvement may be relatively small. The reason that %MHI values are correlated with hardship is because %MHI incorporates variability in sewer rates. The information suggests that, incorporating the %LQI value into the hardship determination for the CWSRF and CCWP may increase equity outcomes slightly.

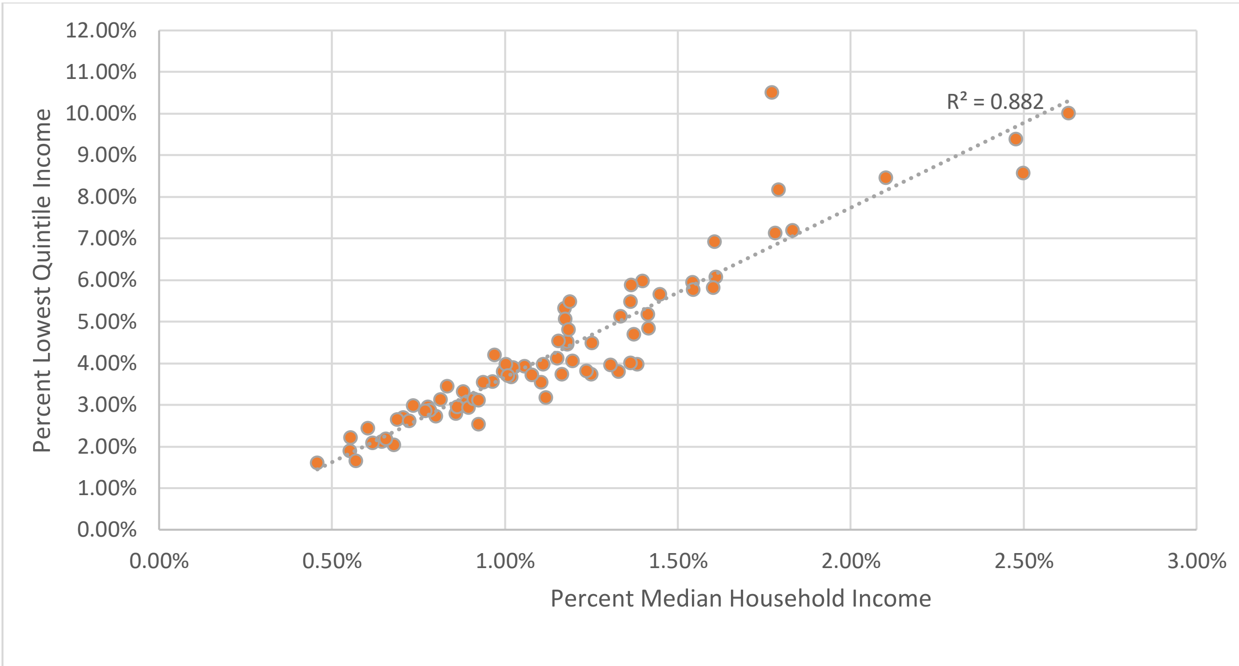


Figure 10. Correlation of %LQI to %MHI

4.3 Consider developing a regional or statewide low-income assistance program

The results of this study show that our conservatively low PSNGP-adjusted sewer service cost estimates would exceed 2% LQI for 76 of the utilities included in the study and pose a financial risk to both people who cannot pay water bills and utilities who cannot cover costs if bills are not paid. One possible improvement to equity outcomes of state grant programs would be development of a statewide or region wide low-income assistance program. Developing this program at a state or region level would lower the financial risk and administrative burden that utilities face in developing a low-income assistance program. In addition, a state-wide or region-wide program may reduce some impacts of Washington State's regressive tax system.

Several of Washington's codes provide authority for utilities to develop low-income assistance programs/rates (see footnote 6). However low-income assistance programs have not been widely adopted by utilities, except for programs for seniors and disabled individuals (see Box 2). The US Water Alliance observes this phenomenon among utilities nationwide. Utilities facing administrative burdens and legal ambiguities have errored on the side of caution with regard to low-income rates. The Municipal Research and Services Center (MRSC) describes how utilities could define eligibility on a utility-by-utility basis, emphasis added:[11]

> *Eligibility requirements for low-income and senior* ***low-income assistance are not defined by statute,*** *so agencies are free to define these as they see fit. Some only*

[11] MRSC's website at: https://mrsc.org/explore-topics/public-works/general-utility-topics/senior-and-low-income-utility-rate-discounts.

provide these assistance programs to low-income seniors, while others include persons with disabilities as well, generally defining people with disabilities to be those people who qualify for special parking privileges under chapter 46.19 RCW (formerly RCW 46.16.381) and people who are blind as defined in RCW 74.18.020.

*However, **there are a range of definitions**. Some jurisdictions may include individuals with developmental disabilities and mental illnesses, while others require proof of disability from the Social Security Administration. Some may even exempt all low-income individuals.*

*In some cases, the utility requires that qualified persons be the head of household, while in other cases there may be a restriction on the income level of any co-tenant. To ensure that **eligibility determinations are made fairly and uniformly**, the utility's legislative body should establish, by ordinance or resolution, policies or programs for utility staff to follow.*

This description provides an example of some of the administrative challenges that an individual utility may face in developing a low-income rate. Seeing similar challenges nationwide the US Water Alliance recommends:

- Establish affordability criteria to better target state funding.
- Remove legal barriers to affordability solutions.
- Create a statewide program for water bill assistance for low-income residents, citing California's programs.

A program to aid low-income sewer rate payers could be modeled after existing programs like Washington Low Income Home Energy Assistance Program (LIHEAP) (See Box 3). Additionally, a program may be able to be created with a modification to the existing Low Income Household Water Assistance Program (LIHWAP). The LIHWAP provides assistance to low-income households with water and wastewater bills that are disconnected or are in imminent threat of disconnection. A modification to the program that includes payment of monthly sewer bills may want to be considered in order to offset unintended equity outcomes that may arise from the needed investment in nutrient reduction infrastructure.

Box 3. Low Income Assistance Programs

Washington Low Income Home Energy Assistance Program (LIHEAP) (see https://www.benefits.gov/benefit/1586) Washington Low Income Home Energy Assistance Program (LIHEAP) services are provided to the public through a network of 26 local community-based nonprofit organizations and local municipalities. Services include energy assistance, client conservation education, furnace repair and replacement, and weatherization. Energy assistance benefits are paid directly to energy providers and are based on a portion of a household's annual home heating costs.

Low Income Household Water Assistance Program (LIHWAP) (see https://www.commerce.wa.gov/growing-the-economy/energy/low-income-home-energy-assistance/lihwap/) LIHWAP provides emergency assistance to low-income households who are disconnected or are in imminent threat of disconnection. LIHWAP provides water assistance to households in Washington through the same network of community action agencies and local partners that provide the Low-Income Home Energy Assistance Program (LIHEAP). These local organizations will help you determine if you're eligible and how much assistance you might receive. If you qualify, your local agency will send a payment directly to your water utility on behalf of your household. Households eligible for water assistance are also qualified for the Low-Income Home Energy Assistance Program.

4.4 Consider the feasibility of the Resilient Rate Structure

The US Water Alliance's recent publication, *Pricing Water for Public Health and Financial Resilience: An Applied Modeling Pilot, Project Description* (US Water Alliance, 2021) proposes an alternative type of rate structure to address shortcomings of a usage-only based rate structures, enhance revenue stability, and integrate equity considerations. Models of this Resilient Rate Structure are already being developed in Minnesota and Cincinnati for water bills. From the paper:

> *The water sector and community advocates need to reimagine the utility revenue model and available pricing structures to reflect water's fundamental role in a thriving society and the true costs and value of providing safe, reliable water and wastewater service. Of course, federal funding is crucial and should contribute a larger share of utility revenue than it presently does. However, utilities can use the tools at hand to begin* ***billing for water in a more sensible, equitable way while advocating for change at the federal level****. The time is right to develop innovative new ways to price and fund water that supports system sustainability, equity, and public health.*

The outcome of the feasibility study would suggest whether innovative pricing models could make sewer bills more affordable and equitable while preserving utility revenue. The resilient rate structure model would seek to allow certain amounts of costs and an associated level of sewer service for all residents to be paid for by property taxes or some other similar property-based cost recovery mechanism.

5. NEXT STEPS

When developing a funding strategy for WWTP upgrades, we encourage policy makers to consider tradeoffs between water quality and other regional recovery goals. Choices made about how the region is to pay for WWTP upgrades may have implications for growth management as well as equity outcomes receiving greater attention due to the White House's Justice40 Initiative and Washington's Healthy Environment for All (HEAL) Act. We hope this analysis can support development of funding strategies that improve water quality while minimizing unintended consequences of Puget Sound's socioecological system.

Possible next steps for this research beyond the recommendations described in the preceding section could include:

- **Addressing know data gaps and challenges**. For example: improve the accuracy of the correspondence table that links the income data (at the census tract level) with the utility district boundaries. Improving the correspondence table would not only increase the certainty of the individual utilities' households' MHI and LQI but also increase our confidence about stating the number of households effected within each income quintile. Another known data challenge is the method with which we averaged LQI. We utilized a population weighting, which does not accurately estimate the median value of the lowest quintile income. For a complete list of know data challenges see Barber et.al (2022).
- **Explore the usefulness of making the household income data easily available to Puget Sound utilities and Ecology**. While this study was done at a relatively coarse scale, the data is useful in identifying potential hardships faced by utility providers. However, this data can become quickly outdated as data on incomes is updated at least annually. Should utilities and Ecology find this data useful it could be updated annually for very little cost. If the database proved useful, updating it could become an annual exercise for student interns under the supervision of a senior researcher. For example, the income data that was gathered for this study was collected using student interns located at the Center for Business and Economic Research at Western Washington University. The cost of data collection was low and the students received invaluable work experience, that ultimately lead to permanent employment in the consulting and public sectors.
- **Explore implications of the extremely wide variation in what Puget Sound residents pay to treat a gallon of sewage**. More research is needed to characterize the distribution of clean water costs and benefits across the region's population. This effort could include analyzing the proportionality of costs among utility ratepayers in neighboring jurisdictions as well as compared to on-site sewage system users who incur sewage treatment costs on a different timeframe (i.e., system maintenance or replacement costs are usually not paid monthly).

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APPENDIX: DATA TABLES

Table A-1 lists all 89 local wastewater service providers directly and indirectly affected by the PSNGP. Those on the left are directly impacted by the PSNGP because they operate WWTPs covered by the permit. Those on the right include additional utilities indirectly impacted by the permit because they retail wastewater treatment services provided by permittees.

Table A-2 provides individual sewer cost, MHI, LQI, %MHI, and %LQI results for the 80 service providers included in the study.

Table A-3 provides summary statistics for the 80 service providers included in the study.

All data is from Barber et al. (2022).

Table A-1. Local Wastewater Service Providers Direct and Indirectly Affected by the PSNGP

WWTP Operator / PSNGP Permittee	Utility District Billing Individual Property Owners	Included in study?
Alderwood Water District	Alderwood Water District	Yes
	Silver Lake Water & Sewer District	Yes
Anacortes, City Of	Anacortes, City of	Yes
Bainbridge Island City of	Bainbridge Island City of	Yes
Bellingham-Water Division City of	Bellingham-Water Division City of	Yes
	Lake Whatcom Water and Sewer District	Yes
Birch Bay Water & Sewer District	Birch Bay Water & Sewer District	Yes
Blaine City of	Blaine City of	Yes
Bremerton City of	Bremerton City of	Yes
Clallam Bay Sekiu (Clallam County PUD)	Clallam Bay Sekiu (Clallam County PUD)	Yes
Coupeville Town of	Coupeville Town of	Yes
Eastsound Sewer and Water District	Eastsound Sewer and Water District	Yes
Edmonds, City of	Edmonds, City of	Yes
	Mountlake Terrace, City of	Yes
Everett Public Works Dept. City of	Everett Public Works Dept. City of	Yes
Fisherman Bay Water Association	Fisherman Bay Water Association	Yes
Friday Harbor Town of	Friday Harbor Town of	Yes
Gig Harbor Sanitary Sewer	Gig Harbor Sanitary Sewer	Yes
King County	King County Does Not Bill Individual Property Owners	No (1)
	Algona Water Dept	Yes
	Auburn, City of	Yes
	Bellevue City of	Yes
	Black Diamond Water Dept	Yes
	Bothell Water City of	Yes

WWTP Operator / PSNGP Permittee	Utility District Billing Individual Property Owners	Included in study?
	Brier, City of	Yes
	Cedar River Water & Sewer District	Yes
	Coal Creek Utility District	Yes
	Cross Valley Water District	Yes
	Issaquah Water System	Yes
	Kent Water Department	Yes
	Kirkland, City of	Yes
	Lake Forest Park Water District	Yes
	Lakehaven Water and Sewer District	Yes
	Mercer Island City of	Yes
	NE Sammamish Sewer & Water District	Yes
	Northshore Utility District	Yes
	Olympic View Water & Sewer District	Yes
	Pacific, City of	Yes
	Redmond Water System City of	Yes
	Renton City of	Yes
	Sammamish Plateau Water & Sewer	Yes
	Seattle Public Utilities	Yes
	Shoreline Waste Water, City of	Yes
	Skyway Water & Sewer	Yes
	Soos Creek Water & Sewer District	Yes
	Tukwila Water Department	Yes
	Valley View Sewer District	Yes
	Woodinville Water District	Yes
	Highlands Sewer District	No (2)
	Vashon Sewer District	No (2)
Kitsap County	Kitsap County	Yes
	Poulsbo City of	Yes
Kitsap County Sewer District #7	Kitsap County Sewer District #7	Yes
La Conner Water Dept	La Conner Water Dept	Yes
Lake Stevens Sewer District	Lake Stevens Sewer District	Yes
Langley City of	Langley City of	Yes
LOTT	LOTT Does Not Bill Individual Property Owners	No (1)
	Lacey Water Department	Yes
	Olympia City of	Yes
	Tumwater City of	Yes
Lynnwood, City of	Lynnwood, City of	Yes
Marysville Utilities	Marysville Utilities	Yes
Mason County	Mason County	Yes
Midway Sewer District	Midway Sewer District	Yes

WWTP Operator / PSNGP Permittee	Utility District Billing Individual Property Owners	Included in study?
Mount Vernon, City of	Mount Vernon, City of	No (2)
Mukilteo Water & Wastewater District	Mukilteo Water & Wastewater District	Yes
Oak Harbor City of	Oak Harbor City of	Yes
Penn Cove Water and Sewer District	Penn Cove Water and Sewer District	No (2)
Pierce County	Pierce County	Yes
	Steilacoom Town of	Yes
Port Angeles City of	Port Angeles City of	Yes
Port Townsend City of	Port Townsend City of	Yes
Sequim City of	Sequim City of	Yes
Shelton City of	Shelton City of	Yes
Skagit County Sewer District #2	Skagit County Sewer District #2	No (2)
Snohomish, City of	Snohomish, City of	Yes
Stanwood Water Dept City of	Stanwood Water Dept City of	Yes
SW Suburban Sewer District	SW Suburban Sewer District	Yes
Tacoma Water	Tacoma Water	Yes
	Fife Dept of Public Works	Yes
	Fircrest City of	Yes
	Ruston, City of	Yes
Thurston County	Thurston County Boston Harbor	Yes
	Thurston County Tamoshan	Yes
West Sound Utility District	West Sound Utility District	Yes

(1) King County and LOTT do not provide retail services to households, therefore do not have retail rates, and as such %MHI and %LQI cannot be calculated

(2) Barber et al. (2022) were unable to locate a detailed map of the provider's service area or the district's web page did not report sewer rates

Table A-2. Individual Results for 80 Puget Sound Wastewater Service Provider

Permitee Serving	Utility Name	Est Annual Sewer Bill	Est. Utility District Income Metric		%MHI Index			%LQI Index		
			MHI	LQI	Current	< 8mg/L, seasonal	< 3mg/L, year round	Current	< 8mg/L, seasonal	< 3mg/L, year round
Alderwood Water District	Alderwood Water District	$866	$99,925	$29,596	0.87%	1.07%	1.29%	2.93%	3.62%	4.36%
Alderwood Water District	Silver Lake Water & Sewer District	$797	$117,439	$39,324	0.68%	0.85%	1.04%	2.03%	2.55%	3.11%
Anacortes, City of	Anacortes, City of	$742	$72,862	$20,246	1.02%	1.30%	1.60%	3.67%	4.68%	5.76%
Bainbridge Island, City of	Bainbridge Island, City of	$1,007	$114,451	$30,415	0.88%	1.06%	1.25%	3.31%	3.99%	4.71%
Bellingham Water Division	Bellingham Water Division	$589	$58,703	$14,826	1.00%	1.35%	1.73%	3.97%	5.36%	6.84%
Bellingham Water Division	Lake Whatcom Water and Sewer District	$1,069	$81,832	$27,023	1.31%	1.56%	1.82%	3.95%	4.72%	5.53%
Birch Bay Sewage Treatment Plant (STP)	Birch Bay Water & Sewer District	$319	$69,617	$19,839	0.46%	0.75%	1.07%	1.61%	2.64%	3.74%
Blaine, City of	Blaine, City of	$1,381	$75,356	$19,208	1.83%	2.11%	2.40%	7.19%	8.26%	9.40%
Bremerton, City of	Bremerton, City of	$777	$62,011	$17,332	1.25%	1.58%	1.94%	4.48%	5.67%	6.93%
Clallam Bay PUD	Clallam Bay Sekiu (Clallam County PUD)	$612	$44,844	$15,291	1.36%	1.82%	2.31%	4.00%	5.35%	6.78%
Coupeville, Town of	Coupeville, Town of	$661	$68,102	$15,759	0.97%	1.27%	1.59%	4.19%	5.50%	6.89%
Eastsound Sewer and Water District	Eastsound Sewer and Water District	$756	$55,350	$12,858	1.37%	1.74%	2.13%	5.88%	7.48%	9.18%
Edmonds, City of	Edmonds, City of	$606	$83,751	$23,236	0.72%	0.97%	1.23%	2.61%	3.49%	4.44%
Edmonds, City of	Mountlake Terrace, City of	$766	$84,112	$24,426	0.91%	1.16%	1.42%	3.14%	3.98%	4.87%
Everett Public Works Dept., City of	Everett Public Works Dept., City of	$999	$70,649	$19,293	1.41%	1.70%	2.01%	5.18%	6.24%	7.38%
Fisherman Bay Water Assoc	Fisherman Bay Water Assoc	$996	$62,008	$14,400	1.61%	1.94%	2.29%	6.92%	8.34%	9.86%
Friday Harbor, Town of	Friday Harbor, Town of	$1,542	$58,690	$15,405	2.63%	2.98%	3.35%	10.01%	11.34%	12.76%
Gig Harbor Sanitary Sewer	Gig Harbor Sanitary Sewer	$810	$99,284	$26,004	0.82%	1.02%	1.24%	3.11%	3.90%	4.75%
King County	Algona Water Dept	$816	$72,942	$25,804	1.12%	1.40%	1.70%	3.16%	3.96%	4.81%
King County	Auburn, City of	$903	$81,719	$25,517	1.11%	1.36%	1.62%	3.54%	4.34%	5.20%

Permitee Serving	Utility Name	Est Annual Sewer Bill	Est. Utility District Income Metric		%MHI Index			%LQI Index		
			MHI	LQI	Current	< 8mg/L, seasonal	< 3mg/L, year round	Current	< 8mg/L, seasonal	< 3mg/L, year round
King County	Bellevue, City of	$934	$126,996	$31,343	0.74%	0.90%	1.07%	2.98%	3.64%	4.33%
King County	Black Diamond Water Dept	$868	$108,333	$31,932	0.80%	0.99%	1.19%	2.72%	3.36%	4.05%
King County	Bothell Water City of	$1,033	$107,072	$29,071	0.96%	1.16%	1.36%	3.55%	4.26%	5.01%
King County	Brier, City of	$683	$81,817	$19,841	0.83%	1.09%	1.35%	3.44%	4.48%	5.58%
King County	Cedar River Water & Sewer District	$915	$102,967	$29,889	0.89%	1.09%	1.30%	3.06%	3.75%	4.48%
King County	Coal Creek Utility District	$1,721	$111,493	$29,005	1.54%	1.54%	1.92%	5.93%	5.92%	7.40%
King County	Cross Valley Water District	$1,109	$109,257	$28,839	1.02%	1.20%	1.40%	3.85%	4.56%	5.32%
King County	Issaquah Water System	$812	$134,035	$33,442	0.61%	0.76%	0.92%	2.43%	3.04%	3.70%
King County	Kent Water Dept	$907	$77,856	$24,343	1.16%	1.43%	1.71%	3.73%	4.57%	5.47%
King County	Kirkland, City of	$931	$119,490	$31,621	0.78%	0.95%	1.13%	2.94%	3.59%	4.29%
King County	Lake Forest Park Water District	$833	$96,555	$28,221	0.86%	1.08%	1.30%	2.95%	3.68%	4.46%
King County	Lakehaven Water & Sewer District	$486	$78,554	$23,401	0.62%	0.88%	1.16%	2.08%	2.95%	3.89%
King County	Mercer Island, City of	$1,935	$165,001	$36,417	1.17%	1.30%	1.43%	5.31%	5.88%	6.48%
King County	NE Sammamish Sewer & Water District	$962	$174,078	$50,831	0.55%	0.67%	0.80%	1.89%	2.30%	2.73%
King County	Northshore Utility District	$768	$111,384	$29,127	0.69%	0.87%	1.07%	2.64%	3.34%	4.09%
King County	Olympic View Water & Sewer District	$1,061	$88,612	$26,206	1.20%	1.43%	1.68%	4.05%	4.83%	5.67%
King County	Pacific, City of	$1,099	$79,412	$27,652	1.38%	1.64%	1.92%	3.97%	4.72%	5.51%
King County	Redmond Water System, City of	$761	$137,373	$34,494	0.55%	0.70%	0.86%	2.21%	2.80%	3.44%
King County	Renton, City of	$972	$87,494	$24,511	1.11%	1.35%	1.60%	3.97%	4.80%	5.70%
King County	Sammamish Plateau Water & Sewer	$1,063	$164,576	$50,206	0.65%	0.77%	0.90%	2.12%	2.53%	2.96%
King County	Seattle Public Utilities	$1,123	$95,537	$22,177	1.18%	1.39%	1.62%	5.06%	5.99%	6.98%
King County	Shoreline Waste Water, City of	$807	$85,987	$22,798	0.94%	1.18%	1.43%	3.54%	4.44%	5.40%

Permitee Serving	Utility Name	Est Annual Sewer Bill	Est. Utility District Income Metric		%MHI Index			%LQI Index		
			MHI	LQI	Current	< 8mg/L, seasonal	< 3mg/L, year round	Current	< 8mg/L, seasonal	< 3mg/L, year round
King County	Skyway Water & Sewer	$1,295	$72,635	$18,186	1.78%	2.07%	2.37%	7.12%	8.25%	9.45%
King County	Soos Creek Water & Sewer District	$846	$98,460	$30,392	0.86%	1.07%	1.29%	2.78%	3.46%	4.18%
King County	Tukwila Water Dept	$951	$65,657	$16,851	1.45%	1.76%	2.10%	5.65%	6.86%	8.16%
King County	Valley View Sewer District	$984	$61,420	$16,922	1.60%	1.94%	2.29%	5.82%	7.03%	8.32%
King County	Woodinville Water District	$937	$132,419	$34,770	0.71%	0.86%	1.03%	2.69%	3.29%	3.91%
Kitsap County	Kitsap County	$1,059	$85,655	$27,823	1.24%	1.48%	1.73%	3.81%	4.55%	5.33%
Kitsap County Sewer Dist #7	Kitsap County Sewer Dist #7	$751	$131,979	$45,527	0.57%	0.72%	0.89%	1.65%	2.10%	2.58%
Kitsap County	Poulsbo, City of	$852	$72,083	$19,131	1.18%	1.47%	1.77%	4.45%	5.53%	6.67%
La Conner Water Dept	La Conner Water Dept	$800	$67,518	$16,657	1.19%	1.49%	1.81%	4.80%	6.04%	7.35%
Lake Stevens Sewer District	Lake Stevens Sewer District	$1,188	$94,973	$31,866	1.25%	1.47%	1.70%	3.73%	4.37%	5.06%
Langley, City of	Langley, City of	$854	$71,835	$15,624	1.19%	1.48%	1.78%	5.47%	6.78%	8.18%
LOTT	Lacey Water Dept	$825	$71,606	$20,026	1.15%	1.44%	1.74%	4.12%	5.14%	6.24%
LOTT	Olympia, City of	$819	$69,385	$18,139	1.18%	1.48%	1.79%	4.51%	5.65%	6.85%
LOTT	Thurston County Boston Harbor	$1,315	$95,664	$28,023	1.37%	1.59%	1.82%	4.69%	5.43%	6.21%
LOTT	Thurston County Olympic View	$1,266	$70,695	$15,502	1.79%	2.08%	2.39%	8.17%	9.49%	10.91%
LOTT	Tumwater City of	$770	$72,769	$19,640	1.06%	1.34%	1.64%	3.92%	4.96%	6.08%
Lynnwood, City of	Lynnwood, City of	$619	$79,032	$21,602	0.78%	1.04%	1.32%	2.87%	3.82%	4.83%
Marysville Utilities	Marysville Utilities	$560	$85,294	$25,673	0.66%	0.90%	1.15%	2.18%	2.98%	3.83%
Rustlewood, North Bay/Case Inlet, Belfair WR/Sewer	Mason County	$1,306	$98,169	$34,349	1.33%	1.54%	1.76%	3.80%	4.40%	5.04%
Midway Sewer District	Midway Sewer District	$720	$66,787	$19,372	1.08%	1.39%	1.71%	3.72%	4.78%	5.91%
Mukilteo Water & Wastewater Distr	Mukilteo Water & Wastewater Dist	$779	$86,968	$26,510	0.90%	1.13%	1.38%	2.94%	3.71%	4.54%
OAK HARBOR City of	Oak Harbor, City of	$1,532	$61,278	$17,872	2.50%	2.84%	3.19%	8.57%	9.72%	10.95%

Permitee Serving	Utility Name	Est Annual Sewer Bill	Est. Utility District Income Metric		%MHI Index			%LQI Index		
			MHI	LQI	Current	< 8mg/L, seasonal	< 3mg/L, year round	Current	< 8mg/L, seasonal	< 3mg/L, year round
Pierce County Chambers Creek Regional WWTP	Pierce County	$688	$74,435	$22,197	0.92%	1.20%	1.49%	3.10%	4.03%	5.01%
Pierce County Chambers Creek Regional WWTP	Steilacoom, Town of	$757	$81,915	$29,994	0.92%	1.18%	1.44%	2.52%	3.21%	3.94%
Port Angeles, City of	Port Angeles, City of	$1,050	$49,965	$12,425	2.10%	2.51%	2.95%	8.45%	10.10%	11.87%
Port Townsend, City of	Port Townsend, City of	$549	$54,320	$14,818	1.01%	1.39%	1.79%	3.70%	5.09%	6.57%
Sequim City of	Sequim City of	$713	$53,400	$13,928	1.33%	1.72%	2.13%	5.12%	6.59%	8.16%
Shelton City of	Shelton, City of	$1,312	$52,947	$13,978	2.48%	2.87%	3.28%	9.39%	10.86%	12.42%
Snohomish, City of	Snohomish, City of	$803	$80,539	$21,203	1.00%	1.25%	1.52%	3.79%	4.76%	5.79%
Stanwood Water Dept	Stanwood Water Dept	$1,152	$82,394	$19,269	1.40%	1.65%	1.91%	5.98%	7.04%	8.18%
SW Suburban Sewer District	SW Suburban Sewer District	$528	$68,471	$18,501	0.77%	1.07%	1.39%	2.85%	3.96%	5.15%
Tacoma Water	Fife Dept of Public Works	$1,087	$76,735	$22,490	1.42%	1.68%	1.97%	4.83%	5.75%	6.72%
Tacoma Water	Fircrest, City of	$907	$58,694	$15,722	1.55%	1.90%	2.27%	5.77%	7.08%	8.47%
Tacoma Water	Ruston, City of	$1,157	$84,868	$21,158	1.36%	1.61%	1.86%	5.47%	6.44%	7.47%
Tacoma Water	Tacoma Water	$678	$66,183	$17,410	1.02%	1.33%	1.67%	3.89%	5.07%	6.33%
Thurston County	Thurston County Ground Mound	$1,106	$68,631	$18,227	1.61%	1.91%	2.23%	6.07%	7.19%	8.39%
Thurston County	Thurston County Tamoshan	$1,688	$95,188	$16,074	1.77%	1.99%	2.22%	10.50%	11.78%	13.14%
West Sound Utility District (South Kitsap WRF)	West Sound Utility District	$779	$67,388	$17,211	1.16%	1.46%	1.79%	4.53%	5.72%	6.99%

Color Codes:

Income Metric
Lowest
Midpoint

Annual Sewer Bill
Highest
Midpoint
Lowest

Indices
Severe hardship (greater than 5%)
Elevated hardship (greater than 3% and less than 5%)
Moderate hardship (greater than 2% and less than 3%)
No hardship (less than 2%)

Table A-3. Summary Statistics for 80 Puget Sound Wastewater Service Providers

Summary Statistics:	Population weighted MHI	Population weighted LQI	%MHI Current	%MHI 8mg/L, seasonal	%MHI 3mg/L, year-round	%LQI Current	%LQI 8mg/L, seasonal	%LQI 3mg/L, year-round
Total number of utilities	80	80	80	80	80	80	80	80
utilities with index > 2% and < 3%, e.g., moderate hardship			4	7	14	19	8	3
% Utilities with index > 2% and < 3%			*5%*	*9%*	*18%*	*24%*	*10%*	*4%*
utilities with index > 3% and < 5% e.g., elevated hardship			0	0	3	35	37	23
% Utilities with index > 3% and < 5%			*0%*	*0%*	*4%*	*44%*	*46%*	*29%*
utilities with index > 5% e.g., severe hardship			0	0	0	22	35	54
% Utilities with index > 5			*0%*	*0%*	*0%*	*29%*	*44%*	*68%*
Total utilities with index > 2%						77	80	80
Minimum	$44,844	$12,425	0.46%	0.67%	0.80%	1.61%	2.10%	2.58%
Maximum	$174,078	$50,831	2.63%	2.98%	3.35%	10.50%	11.78%	13.14%
Average	$86,324	$23,953	1.16%	1.42%	1.69%	4.31%	5.25%	6.27%
Correlation to MHI			-0.5316			-0.4613		
Correlation to %MHI			NA			0.9399		

rental rights should it conclude the Department has not adequately explored a viable guardianship option.

¶48 Here, a Department caseworker testified that a guardianship was not a viable alternative to termination because the children were thriving in their current placement, and a guardianship would keep them "in limbo" with negative "consequences." The children's guardian ad litem also testified about her opinion on "guardianship versus adoption." She concluded that "adoption would be in their best interest" because of the children's ages and the "lack of stability for seven years." She reiterated that R.B. did not see his children for five of those years, has no relationship or bond with them, and has shown no "ability to parent." And the current caregiver to both children testified that her family "discussed the potential for guardianship or adoption with the Department." She said that her family preferred adoption and that their home had already "been approved for adoption." Substantial evidence supports the trial court's findings that the children's caregivers were "not interested" in being guardians and that a guardianship would diminish the children's integration into a stable and permanent home.

¶49 Because the trial court did not err when it allowed R.B. to proceed pro se and substantial evidence supports the court's findings, we affirm termination of his parental rights to G.C.B. and M.J.B.-L.

WE CONCUR:

Hazelrigg, A.C.J.

Dwyer, J.

CITY OF TACOMA, Birch Bay Water and Sewer District, Kitsap County, Southwest Suburban Sewer District, and Alderwood Water & Wastewater District, Municipal Corporations and Political Subdivisions of the State of Washington Respondents,

v.

State of Washington, DEPARTMENT OF ECOLOGY, Appellant.

No. 39494-8-III

Court of Appeals of Washington, Division 3.

Filed September 14, 2023

Background: City, along with other local governments and special purpose districts that owned or operated public sewer systems and associated wastewater treatment plants, filed petition for judicial review of two documents issued by Department of Ecology recommending and committing to action to regulate nitrogen discharges into Puget Sound, contending that documents improperly adopted three new rules in violation of rulemaking procedures under Administrative Procedure Act (APA). The Superior Court, Thurston County, Sharonda D. Amamilo, J., granted petition. Ecology appealed.

Holdings: The Court of Appeals, Lawrence-Berrey, J., held that:

(1) judicial deference to Ecology's statutory interpretation concerning its authority to promulgate rules was unwarranted;

(2) portion of water quality report discussing portions of waterway that did not meet dissolved oxygen (DO) standard did not constitute "rule" under APA;

(3) pages in report discussing human causes of DO depletion did not constitute "rule" under APA;

(4) Ecology's commitments to certain actions to reduce nitrogen discharges from wastewater treatment plants

were "of general applicability" within meaning of APA's definition of "rule";

(5) Ecology's internal directive to its staff to include new requirements for National Pollutant Discharge Elimination System (NPDES) permits constituted "directive" within meaning of APA's definition of "rule"; and

(6) new nitrogen-discharge limitations for NPDES permittees altered qualifications or requirements relating to enjoyment of privileges conferred by law.

Affirmed in part and reversed in part.

1. Environmental Law ⚷708

Whether certain provisions of documents issued by Department of Ecology discussing nitrogen pollution constituted "rules" as defined by Washington Administrative Procedure Act (APA) presented questions of statutory interpretation which Court of Appeals would review de novo. Wash. Rev. Code Ann. § 34.05.010(16).

2. Administrative Law and Procedure ⚷2288

Environmental Law ⚷708

In determining whether provisions of report issued by Department of Ecology relating to dissolved oxygen (DO) testing and sampling, as well as new limitations Ecology allegedly placed on National Pollutant Discharge Elimination System (NPDES) permits, constituted "rules" within meaning of Administrative Procedure Act (APA), such that Ecology could not adopt such provisions and limitations without going through formal rulemaking procedures, Court of Appeals would not defer to Ecology's interpretation of statutes at issue, even though Ecology was agency designated to regulate water pollution; Court of Appeals was tasked with determining scope of Ecology's authority to promulgate rules, which was improper subject for judicial deference. Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570.

3. Administrative Law and Procedure ⚷1842

Courts do not defer to an agency the power to determine the scope of its own authority.

4. Administrative Law and Procedure ⚷1164

The label that an agency assigns to its activities does not determine whether those activities constitute rulemaking under the Administrative Procedure Act (APA). Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570.

5. Administrative Law and Procedure ⚷1162, 1167

In order to determine whether an agency's statement or other activity constitutes a "rule" within the meaning of the Administrative Procedure Act (APA), a court first determines whether the purported rule is an "order, directive, or regulation of general applicability," and second, the court determines whether the purported rule falls into one of the five categories enumerated in the APA provision defining "rule"; if the purported rule fails the first part of the inquiry, the court need not address whether it falls within one of the enumerated categories in satisfaction of the second element. Wash. Rev. Code Ann. § 34.05.010(16).

6. Administrative Law and Procedure ⚷1162

Licenses ⚷3

Although an action is "of general applicability" if applied uniformly to all members of a class, for purposes of determining whether the action is a "rule" under the Administrative Procedure Act (APA), it is a logical fallacy to imply that an action is not of general applicability if not applied uniformly to all members of a class; implying this logical fallacy would make it easy for an agency to skirt the rulemaking requirements of the APA simply by imposing incremental standards on members of a class, such as permittees, rather than a single standard. Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570.

7. Statutes ⚷1123, 1181

Undefined terms in statutes are given their ordinary dictionary definition.

8. Environmental Law ⚷217

Portion of water quality report issued by Department of Ecology depicting regions of Puget Sound that did not meet dissolved oxygen (DO) standard at certain levels of water column did not constitute "directive," as necessary to constitute "rule" subject to rulemaking requirements of Administrative Procedure Act (APA); portion of report only explained how report's authors reported their results and did not impel anyone to act, and there was no indication that Ecology planned to use anything other than existing rule for measuring DO levels or for deciding whether wastewater treatment plants (WWTPs) were in violation of applicable National Pollutant Discharge Elimination System (NPDES) permits. Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570(2)(c); Wash. Admin. Code 173.201(1).

9. Environmental Law ⚷217

Pages of water quality report issued by Department of Ecology which stated that predictive computer model projected every basin but one in Puget Sound had at least one layer in water column that failed to meet dissolved oxygen (DO) standards, discussed human causes of DO depletion, and represented Puget Sound's DO levels at reference levels without human influence and at existing levels did not state any directive, and thus, did not constitute "rule" subject to Administrative Procedure Act (APA) rulemaking requirements, even if report identified noncompliant areas beyond those already subject to more stringent National Pollutant Discharge Elimination System (NPDES) permit requirements under federal law; such pages merely stated authors' conclusions and did not impel anyone to act. Federal Water Pollution Control Act § 303, 33 U.S.C.A. § 1313(d); Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570(2)(c).

10. Environmental Law ⚷217

Department of Ecology's commitments in letter denying rulemaking request, namely that Ecology would set nutrient loading limits at current levels for all National Pollutant Discharge Elimination System (NPDES) permittees, require NPDES permittees to initiate planning efforts to evaluate different effluent nutrient reduction targets, and require reissued NPDES permits for wastewater treatment plants to reflect plants' treatment efficiency, were of general applicability, as necessary for such commitments to constitute "rules" that Ecology could only promulgate through rulemaking procedures of Administrative Procedure Act (APA); commitments applied to all wastewater treatment plants. Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570(2)(c).

11. Administrative Law and Procedure ⚷1162

Where a party challenges an administrative policy applicable to all participants in a program, not its implementation under a single contract or assessment of individual benefits, the action is one of general applicability, within the Administrative Procedure Act's (APA) definition of a "rule." Wash. Rev. Code Ann. § 34.05.010(16).

12. Administrative Law and Procedure ⚷1162

A "directive," within the meaning of the Administrative Procedure Act (APA) provision defining a "rule" as an "order, directive, or regulation of general applicability" that falls within one of five enumerated categories, is something that impels action. Wash. Rev. Code Ann. § 34.05.010(16).

See publication Words and Phrases for other judicial constructions and definitions.

13. Environmental Law ⚷217

Department of Ecology's internal instruction to its staff to impose certain new restrictions on reissued individual permits and newly-created general permit under National Pollutant Discharge Elimination System (NPDES) with goal of reducing total inorganic nitrogen (TIN) discharged into Puget Sound by wastewater treatment plants constituted "directive" within meaning of Administrative Procedure Act's (APA) definition of "rule" as "order, directive, or regulation of general applicability" falling into one of five statutory categories; internal directive to add new terms for reissuing permits was nondiscretionary and had same effect as a promulgated rule governing terms of permit renewal, and Ecology could not bypass APA's rulemaking requirements by adopting renewal criteria internally. Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570(2)(c).

See publication Words and Phrases for other judicial constructions and definitions.

14. Courts ⚷92

Statements in a case that do not relate to an issue before the court and are unnecessary to decide the case constitute "obiter dictum" and need not be followed.

See publication Words and Phrases for other judicial constructions and definitions.

15. Environmental Law ⚷217

New nitrogen-discharge limitations that Department of Ecology committed to imposing as requirement for National Pollutant Discharge Elimination System (NPDES) permits issued to wastewater treatment plants in Puget Sound, as Ecology stated in letter and implemented when renewing two individual permits and creating new general permit, altered qualifications or requirements relating to the enjoyment of benefits or privileges conferred by law, as necessary for limitations to constitute "rule" subject to rulemaking procedures of Administrative Procedure Act (APA); issuance of NPDES permit was privilege conferred by law, discharging any substance into Puget Sound was prohibited without permit, and existing water quality standards did not directly regulate nitrogen, whereas new limitations did. Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570(2)(c), 90.48.160, 90.48.162.

See publication Words and Phrases for other judicial constructions and definitions.

16. Environmental Law ⚷708

On Department of Ecology's appeal from superior court's grant of city's petition for judicial review of certain statements and actions taken by Ecology, which city contended constituted "rules" that Ecology was required to adopt through rulemaking procedures of Administrative Procedure Act (APA), Court of Appeals would decline to consider whether city had standing to file petition in superior court, where issue was solely raised by amici curiae. Wash. Rev. Code Ann. §§ 34.05.010(16), 34.05.570(2)(c).

Appeal from Thurston Superior Court, Docket No:20-2-02539-6, Honorable Sharonda Amamilo, Judge.

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PUBLISHED OPINION

Lawrence-Berrey, J.

¶ 1 Respondents are all either local governments or special purpose districts that own and operate public sewer systems and associated wastewater treatment plants

(WWTPs) discharging into Puget Sound (Sound). In 2019, the Department of Ecology (Ecology) generated two documents discussing nitrogen pollution in Puget Sound. One document recommended action to regulate nitrogen discharges to the Sound and the other committed to doing so.

¶ 2 The respondents (hereafter Tacoma) sued to block regulation of their nitrogen discharges by arguing that these two documents improperly adopted three new rules in violation of the rulemaking provisions of chapter 34.05 RCW, the Administrative Procedure Act (APA). The superior court agreed with Tacoma. Ecology appeals.

¶ 3 We clarify the APA's definition of "rule" and conclude that "directive," for purposes of one APA component of "rule," includes an agency's directive to its staff to include new terms in permits. We conclude that the first and second purported rules are not "rules" within the APA's definition, but we conclude that the third purported rule is.

¶ 4 We affirm in part and reverse in part.

FACTS

¶ 5 The waters of Puget Sound extend from Olympia and the inside of the Olympic Peninsula north through the San Juan Islands up to Bellingham. Puget Sound is itself part of a greater body of water, known as the Salish Sea. The Salish Sea extends from the northern tip of Vancouver Island in British Columbia, south through the Strait of Georgia and the Strait of Juan de Fuca, continuing through the entirety of Puget Sound along the inside of the Olympic Peninsula. Some maps extend the Salish Sea further south along the Oregon Coast and include the mouth of the Columbia River.

¶ 6 Puget Sound and the Salish Sea are polluted. Some pollution is naturally caused. Other pollution is anthropogenic (i.e., human caused). Some of the human-caused sources of water pollution include shipping, fishing, fisheries, other forms of aquaculture, agricultural runoff, stormwater runoff, industrial waste, medical waste, garbage, oil and gas production, and discharges from WWTPs. This case concerns attempts to control pollution from WWTPs.

¶ 7 Since enactment of the Federal Water Pollution Control Act of 1972 (Clean Water Act or CWA), 33 U.S.C. § 1251 et seq., the United States has attempted to mitigate human-caused water pollution. Some of the mitigation tools adopted by the CWA, its amendments, and implementing regulations were monitoring and limiting discharges of biological oxygen-demanding pollutants, suspended solids, fecal coliform, pH (hydrogen ion concentration) impairing pollutants, and thermal impairing pollutants. *See* 33 U.S.C. § 1314(a). Another tool was requiring point source emitters of pollution to obtain a permit for the continued right to discharge pollutants into the waters of the United States. *See* 33 U.S.C. § 1342. These permits are known as "National Pollutant Discharge Elimination System (NPDES)" permits. Another tool was requiring industrial polluters to adopt "pretreatment" and requiring WWTPs to adopt "secondary treatment." *See* 33 U.S.C. § 1317(b), § 1311(b)(1)(B). Pretreatment seeks to reduce or eliminate nonstandard pollutants prior to the pollutant entering a WWTP.[1] 40 C.F.R. § 403.3(s). Secondary treatment typically consists of activated sludge, trickling filters, and/or biological contactors intended to remove biodegradable organic pollutants. Primary treatment typically consists of screening, skimming, and settling to remove large solids that sink, and oils and lighter solids that float to the surface. Wastewater treatment also typically includes some form of disinfection, such as application of chlorine, ozone, or ultraviolet light.

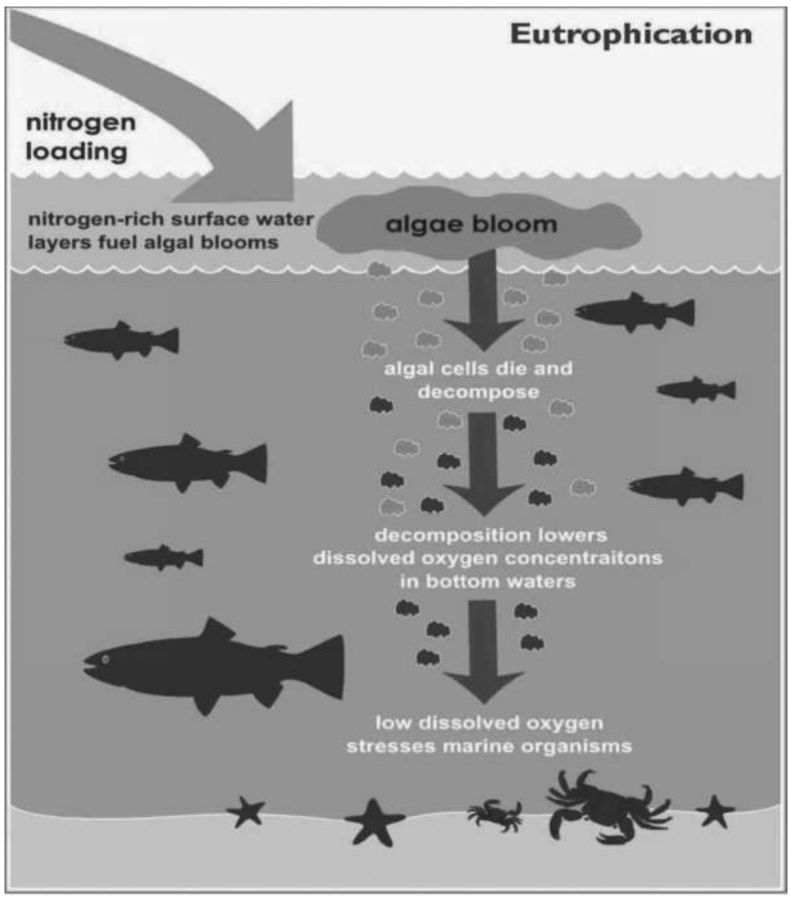
¶ 8 Despite all these forms of treatment, many pollutants still remain in wastewater discharged into the waters of the United States. As technology and scientific knowledge have continued to advance, additional forms of treatment have emerged. Additional treatment is often referred to as tertiary treatment, final treatment, or advanced secondary treatment. This additional treatment may refer to technology and agents that

1. Most WWTPs were originally designed to handle typical household and light commercial waste.

remove pharmaceutical waste, micropollutants such as plastics, phosphorus, nitrogen, or any other remaining unwanted substance. In this case, tertiary treatment is used to refer to nitrogen removal.

¶ 9 Some WWTPs in Washington already incorporate nitrogen removal, such as the Spokane Regional Water Reclamation Facility and the Budd Inlet Treatment Plant. Despite having been technologically feasible for several decades, tertiary treatment is not yet required for all WWTPs.

¶ 10 One of the primary impediments to wider adoption of tertiary treatment is cost. In 2017, the Chambers Creek Regional Wastewater Treatment Plant in Pierce County finished installation of a nitrogen removal system at a cost of $342 million. Individual plants may also be impeded by a lack of available land on which to construct new infrastructure or insufficient access to additional electricity. Other impediments are gaps in our knowledge.



¶ 11 Nitrogen, while commonly thought of as a beneficial nutrient, is also a pollutant. Simplified, excess nitrogen results in excess algal growth. Algae generate organic carbon. When carbon decomposes, it consumes oxygen. Depleted oxygen, or eutrophication, can render water incapable of supporting many forms of aquatic life.

¶ 12 Puget Sound contains many areas with low levels of dissolved oxygen (DO) as a result of excess nitrogen. More specifically, Puget Sound contains low oxygen in the strata where aquatic life has historically thrived.

¶ 13 What is unknown, at least within Puget Sound, is to what extent excess nitrogen in these strata is due to WWTPs. The Pacific Ocean is the largest source of nitrogen entering Puget Sound. The Pacific is believed to account for about 88 percent of the total nitrogen entering Puget Sound. Just because the Pacific is the largest source of nitrogen does not mean that it is the largest driver of oxygen depletion in the life-sustaining layers of the Sound.

¶ 14 Oceans and seas are complex ecosystems. The tides, water temperature, geography, and other variables impact flow and mixing among bodies of water. Most of the nitrogen that enters Puget Sound via the Pacific also flows back out. But the nitrogen entering Puget Sound from the Pacific is unlikely to have a significant negative impact on oxygen levels because water entering from the Pacific is usually colder, meaning it is denser than the water already in the Sound, causing the water from the Pacific to sink below the water already in the Sound. The negative impacts of excess nitrogen occur closer to the surface, in the euphotic zone, where the sun's light allows for photosynthesis to occur. The euphotic zone is also where most marine life is found.

¶ 15 WWTPs emit significant amounts of nitrogen. Yet it is unknown to what extent this nitrogen causes DO impairment in Puget Sound. Nitrogen at the point of discharge can be measured, but one cannot determine where this nitrogen goes once the wastewater gets carried away on the currents and mixes with the rest of the Sound. Without this information, it is not possible to reasonably regulate nitrogen discharges from WWTPs. This is because anthropogenic pollutant discharges only violate Washington's clean water standard if it can be shown that human actions "cause the D.O. of that water body to decrease more than 0.2 mg/L." WAC 173-201A-210(1)(d)(1).

Development of the Salish Sea Model

¶ 16 To fill this knowledge gap, Ecology and the Pacific Northwest National Laboratory (PNNL) spent years developing the Salish Sea Model (SSM). The SSM is a predictive computer model that lets Ecology isolate and test water quality variables based on actual water quality data and predict water quality in areas where we do not currently have actual water quality measurements. It takes months to prepare the data to run a single scenario, days to run it through the SSM on one of PNNL's high powered computers, and additional time to interpret and report the data.

¶ 17 Some of the questions the SSM helps to answer are:

- "Are human sources of nutrients in and around the Salish Sea significantly impacting water quality now? How bad might it get in the future?"
- "Where are the areas that are most sensitive to human impacts? When are those effects the most harmful?"
- "How much do we need to reduce human sources of nutrients to protect water quality in the Salish Sea?"

Administrative Record (AR) at 104. The model also allows Ecology to predict where and by how much DO levels would improve based on hypothetical nitrogen reductions. The model also allows Ecology to test and quantify its hypothesis that DO levels are most impaired in Puget Sound's remote inlets and basins due to poor circulation resulting in pollutants accumulating and spending more time in those areas.

¶ 18 Despite its immense power, the SSM does have limits. While the SSM can account for human-caused sources of pollution, the model cannot isolate the effect of individual WWTPs. However, Ecology hopes to further refine the SSM "to define discharger-specific nutrient loading limits based on localized and far-field impacts." Clerk's Papers (CP) at 127.

¶ 19 Professors Gordon Holtgrieve and Mark Scheuerell from the University of Washington, scientists working with the regulated stakeholders, have also expressed concern that Ecology is overconfident in the SSM's predictive power. Every predictive model has levels of uncertainty, often reported as confidence intervals. In lay terms, these scientists worry that the SSM is not yet ready for prime time because it appears to lack sufficient sensitivity to confidently determine which segments of Puget Sound violate the DO standard in WAC 173-201A-210 as a result of human-caused pollution. The SSM's predictive accuracy is particularly important because many areas of Puget Sound are on the edge of the state's DO water quality standard. These scientists are also concerned that Ecology has not publicly shared sufficient information for others to independently verify Ecology's interpretation of the results.

¶ 20 To be clear, this appeal is not about whether Ecology should be using the SSM to inform regulation or whether it is accurate and reliable. This appeal is about whether Ecology violated the APA by adopting rules without allowing for public comment during its efforts to investigate and respond to human causes of DO depletion in Puget Sound.

¶ 21 In January 2019, Ecology published the results of its first three scenarios using the SSM. The report, referred to as the Bounding Scenarios Report (BSR), modeled "a range of climate and ocean conditions" from 2006, 2008, and 2014. CP at 34. The report looked at current levels of pollution during those years and what would happen if nitrogen and carbon discharges were reduced at all WWTPs, only midsize and large WWTPs, and only large WWTPs. There are 79 WWTPs in the United States' portion of the Salish Sea.

¶ 22 The report's authors found that approximately 20 percent of Puget Sound did not meet Washington's DO water quality standards during each of the reference years. The modeling used in the BSR suggested that reducing nitrogen and carbon discharges from WWTPs using "seasonal biological nitrogen removal (BNR) technology" would improve DO compliance by approximately 50 percent, meaning only about 10 percent of Puget Sound would continue to not meet DO standards. CP at 37. The report's authors also found DO noncompliant areas within all of Puget Sound's basins, except Admiralty Inlet. The authors also found "[a]ll areas not meeting the water quality standard have depleted levels of DO in the water column as a result of human loadings from Washington State." CP at 36. While the SSM cannot yet quantify the effects of individual WWTPs, the model confirmed that discharges have both a near- and a far-field effect, meaning that discharges into one part of Puget Sound contribute to DO depletion in other parts of the Sound as the discharged water mixes and travels along the currents.

Northwest Environmental Advocates (NWEA) Rulemaking Petition

¶ 23 For years, Ecology has kept stakeholders updated on the development of the SSM and other water quality efforts through the Puget Sound Nutrient Forum. The forum also presented stakeholders with preliminary results from the SSM. Shortly before the official publication of the BSR, NWEA—an active participant in the Nutrient Forum—filed a petition with Ecology "to propose and adopt a rule establishing technology-based effluent limits for the discharge of nutrients and toxics from municipal wastewater treatment facilities that discharge to Puget Sound and its tributaries." AR at 231. Specifically, NWEA wanted a rule designating tertiary treatment of wastewater as "AKART." AR at 231.

¶ 24 AKART stands for "All Known, Available, and Reasonable Treatment." WAC 173-201A-020. AKART represents "the most current methodology that can be reasonably required for preventing, controlling, or abating the pollutants associated with a discharge." *Id.* Under RCW 90.52.040, Ecology is required to adopt rules requiring "wastes to be provided with all known, available, and reasonable methods of treatment prior to their discharge or entry into waters of the state." Such treatment is required regardless of whether the water quality is pristine, impaired, or anywhere in between. RCW 90.52.040. In addition to implementing state law, AKART standards also mirror parallel provisions of the Clean Water Act requiring NPDES permittees to adopt the best available technology economically achievable for eliminating the discharge of pollutants. *See* 33 U.S.C. §§ 1311, 1314. Thus, if tertiary treatment meets the definition of AKART, Ecology is obligated by statute to make tertiary treatment a precondition to issuance/reissuance of NPDES permits.

¶ 25 On January 11, 2019, Ecology sent NWEA a concise letter denying the rulemaking petition. Under the APA, Ecology had 60 days to either initiate rulemaking or issue a denial explaining the reasons for denial and "where appropriate" the alternative means Ecology would use to address NWEA's concerns. RCW 34.05.330(1). Ecology denied rulemaking because AKART technologies must be economically feasible and Ecology believed that tertiary treatment was cost prohibitive. While it may be economically feasible for some WWTPs, NWEA's petition wanted tertiary treatment mandated for all 79 Puget Sound WWTPs, regardless of any one plant's size and impact on Puget Sound. Ecology also denied rulemaking because the SSM needed further refinements before Ecology had sufficient data to craft discharger-specific limits for individual NPDES permittees.

¶ 26 Although Ecology denied rulemaking, Ecology shares NWEA's concerns and ultimate goals. It is the policy of this state

> to maintain the highest possible standards to insure the purity of all waters of the state consistent with public health and public enjoyment thereof, the propagation and protection of wild life, birds, game, fish and other aquatic life, and the industrial development of the state, and to that end require the use of all known available and reasonable methods by industries and others to prevent and control the pollution of the waters of the state of Washington.

RCW 90.48.010. In the denial letter, Ecology announced the alternative actions it would take:

> Ecology remains committed to [working with stakeholders to solve the DO problem in Puget Sound]. While this work is progressing, Ecology *will* through the individual permitting process:
>
> 1. Set nutrient loading limits at current levels from all permitted dischargers in Puget Sound and its key tributaries to prevent increases in loading that would continue to contribute to Puget Sound's impaired status.
> 2. Require permittees to initiate planning efforts to evaluate different effluent nutrient reduction targets.
> 3. For treatment plants that already use a nutrient removal process, require reissued discharge permits to reflect the treatment efficiency of the existing plant by implementing numeric effluent limits used as design parameters in facility specific engineering reports.

CP at 127 (emphasis added). Ecology also stated that it would explore development of a general permit to regulate "nutrient loading" (i.e., nitrogen discharges) into Puget Sound. CP at 127. A general permit that covers multiple discharging entities is an alternative to issuing individual NPDES permits. WAC 173-226-020, -050.

¶ 27 Unhappy with the denial of its rulemaking petition, NWEA sought judicial review. Division Two of this court affirmed Ecology's denial of the rulemaking petition. *See generally Nw. Env't Advocs. v. Dep't of Ecology*, No. 54810-1-II, 18 Wash.App.2d 1005, 2021 WL 2556573 (Wash. Ct. App. June 22, 2021) (unpublished), http://www/courts.wa.gov/opinions/pdf/548101_unp.pdf).

NPDES Permits and the Puget Sound Nutrient General Permit

¶ 28 Ecology started adding new terms to individual NPDES permits as those permits came up for renewal, requiring nitrogen discharge limits and nitrogen reduction planning. Ecology also worked to develop a general permit. The final version of the general permit went into effect January 1, 2022. It placed a limit on how many pounds of nitrogen each large and midsize WWTP could discharge per year and required all WWTPs to create nitrogen reduction plans. Any WWTP that exceeds its annual limit must spend the next year studying what caused it to exceed its limit and what corrective action it can take to not exceed its limit. If a WWTP exceeds its limit two years in a row, it must begin taking that corrective action. The validity of the general permit is currently in litigation at the Pollution Control Hearings Board. That litigation is stayed pending the resolution of this appeal.

Concerns Raised by the Regulated Community

¶ 29 The findings of the BSR, the rulemaking denial letter, and the prospect of a general permit all happened within a fairly short time frame. The commitments made in the denial letter especially alarmed the regulated community.

¶ 30 In the denial letter, Ecology promised that as each NPDES came up for renewal, it would "[s]et nutrient loading limits at current levels . . . to prevent increases in loading that would continue to contribute to Puget Sound's impaired status." CP at 127. The short-term effect of freezing nutrient loading limits impairs development because development increases demand on WWTPs. But, it is not possible to significantly reduce nitrogen in the short term. Significant nitrogen reduction requires long-term capital improvements. Immediately, the city of Tacoma (City) started putting caveats in building permits allowing the City to "rescind the permit" in the event Ecology limited the City's treatment capacity by capping nitrogen discharges. CP at 991. This put several major projects in limbo, including multifamily housing developments, a behavioral health hospital, and an expansion at Bates Technical College Medical School.

¶ 31 An internal legal memo authored by counsel for the City concisely lays out its concerns:

> The costs of such full-scale improvements are estimated to range from $250 million to over $750 million and would likely take at least six years or longer to fund, plan for and implement. In the interim, implementation of the TIN [total inorganic nitrogen] load cap would have the unintended consequence of halting development, in effect a de facto moratorium. Projects could not be approved because sewer capacity would not be available. The City will be exposed to substantial risk if it does not qualify all sewer availability notices with the right to rescind the assurance of sewer availability in the event Ecology's permit caps sewer capacity. Adding this condition will impair lending and effectively halt most development, including affordable housing, shelters, and accessory dwelling units. Further, funding of capital improvements needed to meet the new permit requirements has the potential to more than double or triple sewer rates, disproportionately affecting low-income populations.

AR at 620.

¶ 32 There were also concerns that capping nitrogen discharges at current levels, without allowing leeway for development to continue, would unintentionally force growth into rural areas. This would be in areas where septic is allowed due to a lack of sewer service. The unintended consequence of this could make matters worse, causing leaky and untreated septic waste to enter the Puget Sound.

Petition for Judicial Review

¶ 33 To prevent Ecology from limiting WWTP discharges, the City and the other respondents filed a joint petition for judicial review under RCW 34.05.570. The City alleged Ecology violated the APA by adopting three "rules" outside of the APA's rulemaking process. Two of the purported rules were in the BSR and the third purported rule was in the denial letter. The City refers to the first purported rule as the DO standard rule, the second as the DO impairment rule, and the third as the TIN cap rule.[2]

¶ 34 The City alleged the DO standard rule appeared on page 20 of the BSR, that the DO impairment rule could be found on pages 12, 60, 61, and 62 of the BSR when read together, and that the TIN cap rule could be found in the three commitments Ecology made in the denial letter.

¶ 35 With respect to the DO standard rule, the City alleged the BSR effectively amended WAC 173-201A-210(1)(d)(iii), which covers DO testing and sampling procedures. With respect to the DO impairment rule, the City alleged the BSR effectively amended the state's 303(d) list[3] of impaired water segments when the BSR reported the SSM's findings of areas not meeting Washington's DO water quality standard. With respect to the TIN cap rule, the City alleged that Ecology placed new limits in NPDES permits.

2. The phrase "total inorganic nitrogen" does not appear in the denial letter. The reason the City refers to it as the TIN cap rule is because TIN is the parameter that Ecology settled on for implementing the commitments in its letter.

3. The 303(d) list is a reference to the list states are required to periodically submit to the Environmental Protection Agency under 33 U.S.C. § 1313(d). Entities that discharge into waterways on the 303(d) list are subject to more stringent requirements in their NPDES permits.

¶ 36 In addition to arguing that the three alleged rules violated RCW 34.05.570 by not going through the rulemaking process, the City also alleged that they were arbitrary and capricious and exceeded Ecology's statutory authority.

¶ 37 The trial court agreed with the City on all grounds and remanded the matter "to Ecology for consideration of the immediate adoption of temporary emergency rules while regular rule-making proceeds." CP at 1483. Ecology appeals.

ANALYSIS

¶ 38 In its briefing to this court, the City abandoned its prior claims that Ecology's purported rules are arbitrary and capricious and exceeded Ecology's statutory authority. Accordingly, the only substantive issue is whether the three purported rules are "rules" as defined by RCW 34.05.010(16) and were therefore required to be adopted through formal rulemaking.

A. Standard of Review

[1] ¶ 39 Whether any of the three purported rules adopted by Ecology are "rules" as defined by Washington's APA are questions of statutory interpretation, the court reviews de novo. *Nw. Pulp & Paper Ass'n v. Dep't of Ecology*, 200 Wash.2d 666, 672, 520 P.3d 985 (2022).

[2, 3] ¶ 40 Ecology argues that because it is the agency designated to regulate water pollution, we should defer to its interpretation of the laws it administers. *See City of Redmond v. Cent. Puget Sound Growth Mgmt. Hr'gs Bd.*, 136 Wash.2d 38, 46, 959 P.2d 1091 (1998) (this court defers to an agency's interpretation of the law it administers). We agree with the legal principle cited by Ecology, but disagree it applies here. We are tasked here with determining the scope of Ecology's *authority* to promulgate purported rules. " '[W]e do not defer to an agency the power to determine the scope of its own authority.' " *Ass'n of Wash. Bus. v. Dep't of Ecology*, 195 Wash.2d 1, 10, 455 P.3d 1126 (2020) (internal quotation marks omitted) (quoting *Lenander v. Dep't of Ret. Sys.*, 186 Wash.2d 393, 409, 377 P.3d 199 (2016)).

B. The Purported Rules

¶ 41 The APA defines "rule" as

> any agency order, directive, or regulation of general applicability (a) the violation of which subjects a person to a penalty or administrative sanction; (b) which establishes, alters, or revokes any procedure, practice, or requirement relating to agency hearings; (c) which establishes, alters, or revokes any qualification or requirement relating to the enjoyment of benefits or privileges conferred by law; (d) which establishes, alters, or revokes any qualifications or standards for the issuance, suspension, or revocation of licenses to pursue any commercial activity, trade, or profession; or (e) which establishes, alters, or revokes any mandatory standards for any product or material which must be met before distribution or sale.

RCW 34.05.010(16).

[4] ¶ 42 No agency subject to Washington's APA may adopt a rule outside of the rulemaking process established in chapter 34.05 RCW, §§ .310-.395. RCW 34.05.570(2)(c). The label that an agency assigns to its activities does not determine whether those activities constitute rulemaking under the APA. *McGee Guest Home, Inc. v. Dep't of Soc. & Health Servs.*, 142 Wash.2d 316, 322, 12 P.3d 144 (2000).

[5] ¶ 43 The APA definition of "rule" implies a two-step inquiry. First, the court determines whether the purported rule is an " 'order, directive, or regulation of general applicability.' " *Nw. Pulp*, 200 Wash.2d at 672, 520 P.3d 985 (quoting RCW 34.05.010(16)). Second, the court determines whether the purported rule "fall[s] into one of the five enumerated categories" in RCW 34.05.010(16). *Id.* at 672-73, 520 P.3d 985. If the purported rule fails the first part of the inquiry, "we need not address whether [it] falls within one of the enumerated categories in satisfaction of the second element." *Id.* at 676, 520 P.3d 985.

¶ 44 For the first inquiry, the City argues that each of Ecology's purported rules are directives of general applicability. For the second inquiry, the City argues that each of the purported rules fit within RCW 34.05.010(16) categories (a) and (c).[4]

1. *The DO standard described on page 20 of the BSR is not a rule*

[6] ¶ 45 This court's first step is to determine whether page 20 of the BSR states a directive of general applicability. The APA does not define "directive" or "general applicability." However, the Supreme Court has previously defined the latter term: "[W]here the challenge is to a policy applicable to all participants in a program, not its implementation under a single contract or assessment of individual benefits, the action is of general applicability within the definition of a rule." *Failor's Pharm. v. Dep't of Soc. & Health Servs.*, 125 Wash.2d 488, 495, 886 P.2d 147 (1994) (citing *Simpson Tacoma Kraft Co. v. Dep't of Ecology*, 119 Wash.2d 640, 648, 835 P.2d 1030 (1992)).[5]

[7] ¶ 46 While the Supreme Court has defined "general applicability," it has not defined the term "directive" as used in the APA. Undefined terms in statutes are given their ordinary dictionary definition. *Am. Legion Post No. 32 v. City of Walla Walla*, 116 Wash.2d 1, 8, 802 P.2d 784 (1991). Webster's defines "directive" in its noun form as "something that serves to direct, guide, and usu. impel toward an action, attainment, or goal." WEBSTER'S THIRD NEW INTERNATIONAL DICTIONARY 641 (1993).

[8] ¶ 47 Applying this definition, page 20 of the BSR does not contain a directive of general applicability. Page 20 of the BSR states, in relevant part:

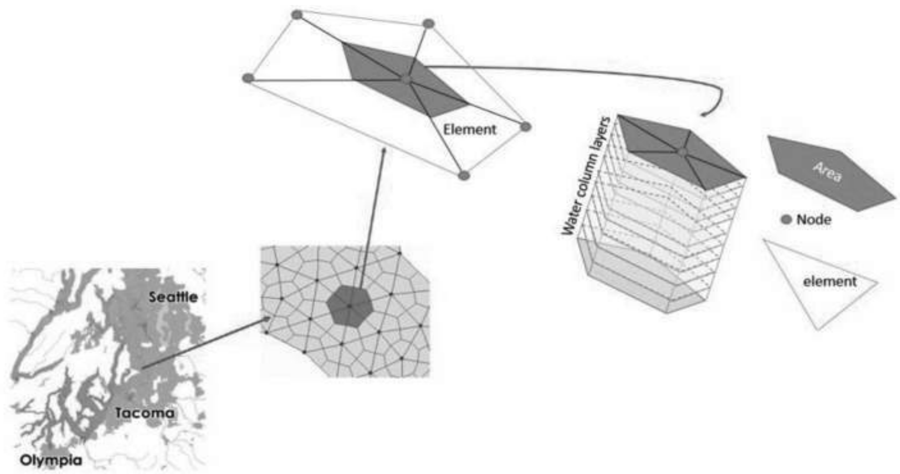
> Regions of Puget Sound that do not meet the DO standard are expressed in terms of area (e.g., acres or km2). Since the model is three dimensional, each vertical column of water is represented by ten layered grid cells. Area, in this context, refers to the surface area of the vertical column (which is equivalent to the area represented by the grid cell in Figure 4). If DO levels in one or more layers in the water column does not meet the DO standard, the surface area of that water column is counted towards the total noncompliant area.

CP at 44. Following is a graphic from the BSR depicting the SSM's water column layering.

4. In its first amended petition for judicial review, the City alleged categories (c) and (d), but not (a). Ecology argues that the City's failure to plead RCW 34.05.010(16)(a) in its petition for judicial review precludes consideration of that category. To support its argument, Ecology cites RCW 34.05.546(7). That subsection requires the petitioner to set forth in its petition for review its "reasons for believing that relief should be granted."

RCW 34.05.546(7) does not describe the required level of specificity. On its face, it might require citation only to RCW 34.05.010(16) or it might require citation to one or more of subsection 16's five categories. Because Ecology does not cite any authority to support its argument or attempt to show what level of specificity the legislature intended, we decline to consider the argument. *Holland v. City of Tacoma*, 90 Wash. App. 533, 537-38, 954 P.2d 290 (1998) (passing treatment of an issue or lack of reasoned argument is insufficient to merit judicial consideration).

5. Various cases additionally state, "[a]n action is of general applicability if applied uniformly to all members of a class." *See, e.g., Failor's Pharm.*, 125 Wash.2d at 495, 886 P.2d 147. Trial courts should not commit the logical fallacy of implying the converse; that is, by implying that an action is *not* of general applicability if *not* applied uniformly to all members of a class. Implying this logical fallacy would make it easy for an agency to skirt the rulemaking requirements of the APA simply by imposing incremental standards on permittees rather than a single standard.



CP at 45 (Fig. 4).

¶ 48 This portion of the BSR simply explains how the BSR's authors reported their results. As defined above, a directive is something that impels toward an action. Because the DO standard does not impel anyone to act, it is not a "directive" and it therefore is not a "rule" under the APA.

¶ 49 Yet the BSR report promises to "supply information [to Ecology to] design management strategies for anthropogenic nutrient inputs affecting DO" and "will be used to inform and develop the nutrient management strategy for Puget Sound." CP at 45-46. The City argues that these and other comments within the report show that the BSR approach for measuring DO will be used for determining whether they are in violation of applicable DO standards. We are unpersuaded.

¶ 50 The BSR is a tool that Ecology will use to better measure and control DO levels. There is no indication from the report or elsewhere that Ecology plans to use anything other than the existing rule, WAC 173-201A-210(1), for measuring DO levels for deciding whether any WWTP is in violation of its individual permit or a general permit.

¶ 51 Because the first purported rule does not state a "directive," this court does not address whether it meets either categories (a) or (c) of the second element.

2. *The description of DO impairment on pages 12 and 60-62 of the BSR is not a rule*

¶ 52 Page 12 of the BSR states in relevant part:

> We found the following when applying [Washington's DO] standards to the model results:
>
> - The total area of greater Puget Sound waters not meeting the marine DO standard was estimated to be around 151,000 acres (612 km2) in 2006, 132,000 acres (536 km2) in 2008, and 126,000 acres (511 km2) in 2014. These areas correspond roughly to about 23%, 20%, and 19% of greater Puget Sound in each year, respectively, excluding the intertidal zone.
> - Noncompliant areas are located within all Puget Sound basins except Admiralty Inlet. All areas not meeting the water quality standard have depleted levels of DO in the water column as a result of human loadings from Washington State. Model computations take into account multiple oceanographic, hydrographic, and climatological drivers, so that depletions due to human activity alone can be computed by excluding other influences, such as that of the Pacific Ocean.

CP at 36.

¶ 53 The above comments show that the modeling scenarios run using the SSM projected that every single basin in Puget Sound, except Admiralty, had at least one water column layer that failed to meet DO standards. As argued by Professors Holtgrieve and Scheuerell, many of these noncompliant layers might actually be compliant due to limitations in the SSM's sensitivity. For purposes of the BSR, the report's authors classified these areas as DO-impaired.

¶ 54 BSR pages 60-62 discuss the SSM's results concerning DO depletion due to human causes. Page 60 states, in relevant part:

> The cumulative impact of all human activities causes DO concentrations to decrease by more than 0.2 mg/L at multiple locations in Puget Sound. Figure 25 shows the spatial distribution of minimum water column DO for both existing and reference conditions, along with the difference between the two, for 2006, 2008, and 2014. Spatial patterns in minimum DO under the reference scenario closely resemble the existing condition patterns. The difference plot shows that maximum DO depletions (depletions below the reference condition DO levels) are predicted to occur in inlets where flushing is relatively poor compared to the main channel . . . .

CP at 84.

¶ 55 Page 61 (right) is Figure 25, a graphic representation of Puget Sound's DO levels at reference levels without human influence, at existing levels, and the difference between the two, as predicted by the SSM.

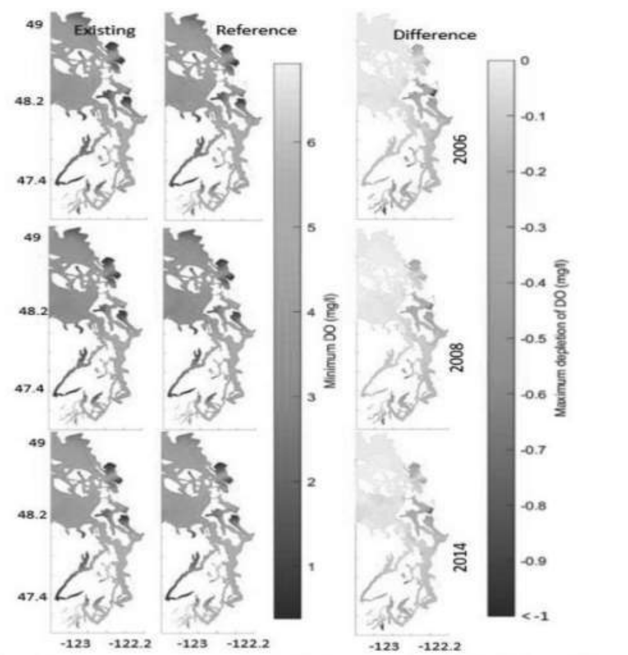


Figure 25. Comparison of the spatial distribution of predicted 2006, 2008, and 2014 minimum dissolved oxygen (DO) concentrations, corresponding reference condition scenarios, and the difference between them.
Areas that are green to blue are most sensitive to DO depletion from all human sources in Washington.

¶ 56 Page 62 reiterates the findings summarized in the abstract from page 12, but with more detail on duration and degree of DO noncompliance.

¶ 57 The City argued that when read together, the pages conclude "that all municipal WWTPs discharging to Puget Sound are causing or contributing to the alleged impairment, effectively expanding the existing list of 'impaired' or CWA 303(d) water bodies in Washington to include all of Puget Sound." CP at 1204.

[9] ¶ 58 During oral argument, the City withdrew this assignment of error.[6] We accept this concession. Similar to our conclu-

6. Wash. Court of Appeals oral argument, *City of Tacoma v. Dep't of Ecology*, No. 39494-8-III (June 7, 2023), at 40 min., 40 sec., *video recording by* TVW, Washington State's Public Affairs Network, https://tvw.org/video/division-3-court-of-appeals-2023061095/?eventID=2023061095.

sion in the previous section, BSR pages 12, 60, 61, and 62 do not state a directive. That is, they do not impel one to act. Rather, these pages state the authors' conclusions.

3. *Ecology's commitments in the denial letter and subsequent actions show it has adopted rules in violation of the APA*

¶ 59 In the abstract, it is difficult to discern whether Ecology's commitments to NWEA in the denial letter constitute a rule under the APA. It therefore is necessary to consider how Ecology has implemented its commitments.

¶ 60 We previously outlined how Ecology began implementing some of its commitments through the issuance of renewed individual permits while in the process of formulating a general permit. We now provide greater detail on this process.

The new general permit

¶ 61 Beginning in April 2018, Ecology convened meetings of the Puget Sound Nutrient Forum for the purpose of developing a nutrient reduction plan for Puget Sound. At the first meeting, Ecology outlined to stakeholders some options to address nutrient sources and some nutrient reduction strategies being used in other parts of the country. At the March 2019 meeting, representatives from around the country discussed their use of general permits to regulate nutrient pollution in their respective areas. Following these presentations, stakeholders expressed interest in a general permit that would address Puget Sound nutrient pollution. Pursuant to WAC 173-226-060, in August 2019, Ecology issued a preliminary determination to develop a general permit, and provided a 60-day comment period.

¶ 62 Ecology convened a Puget Sound Nutrient General Permit advisory committee to advise it in drafting permit requirements to reduce nutrient loads discharged into Puget Sound by WWTPs. The advisory committee represented diverse stakeholders, including WWTPs, environmental organizations, and state and federal agencies. The City was a member of the committee.

¶ 63 After several monthly meetings, Ecology developed a preliminary draft general permit and solicited public comment from January 27, 2021 through March 15, 2021. Ecology used the comments it received to develop a formal draft general permit, which it released for another round of public comment on June 16, 2021. Ecology issued the general permit on December 1, 2021.

¶ 64 The general permit categorizes permittees as dominant, moderate, or small—based on the amount of TIN they annually discharge into Puget Sound. Dominant and moderate loaders have TIN action levels that Ecology calculated to reflect the pounds of TIN each facility discharges each year. Dominant and moderate loaders are required to implement a nutrient optimization plan to maximize nitrogen removal by their existing treatment facility and submit a nutrient reduction evaluation to Ecology by December 31, 2025.

¶ 65 If a dominant loader exceeds its action level, it must submit a report with a proposed approach to reduce its annual TIN load by 10 percent but it does not need to implement the proposed approach unless it exceeds its action level two years in a row or three years during the five-year permit term.

¶ 66 If a moderate loader exceeds its action level, it must submit a report with a proposed approach to reduce its annual TIN load below its action level but does not need to implement the proposed approach unless it exceeds its action level two years in a row or three years during the five-year permit term.

¶ 67 Small loaders do not have any caps on nutrient discharges but must implement a nutrient optimization plan to maximize nitrogen removal by their existing treatment facility and submit an AKART analysis to Ecology by December 31, 2025.

¶ 68 The impact of these changes goes further than requiring the WWTPs to comply with existing water quality standards. As noted previously, these changes actually freeze existing nutrient loading limits because the action level is based on each permittee's prior year TIN load rather than existing water quality standards.

Renewal of individual permits

¶ 69 While Ecology was in the process of formulating the general permit, it imposed restrictions similar to those described in the individual permits for Birch Bay and the Big Lake WWTPs. Those individual permits became effective March 1, 2021, and do not expire until 2026.

The practical effect of the denial letter creates rules

¶ 70 Ecology argues that the denial letter cannot be a rule within the meaning of the APA because it does not direct, order, or require anything. We disagree. As explained below, it directs its own staff to impose new restrictions within NPDES permits.

First inquiry: Directive of general applicability

[10, 11] ¶ 71 The first inquiry is whether the purported rule is an order, directive, or regulation of general applicability. *Nw. Pulp*, 200 Wash.2d at 672, 520 P.3d 985. "[W]here the challenge is to a policy applicable to all participants in a program, not its implementation under a single contract or assessment of individual benefits, the action is of general applicability within the definition of a rule." *Failor's Pharm.*, 125 Wash.2d at 495, 886 P.2d 147 (citing *Simpson*, 119 Wash.2d at 648, 835 P.2d 1030). Here, Ecology's commitments in the denial letter are of general applicability because they apply to all WWTPs.

[12] ¶ 72 The parties, however, dispute whether the action is a "directive." As previously defined, a directive is something that impels action. The precise issue presented in this appeal is whether a directive can be an internal directive, e.g., a commitment by Ecology that its own staff will impose new requirements on permittees.

[13] ¶ 73 Ecology argues that including an internal directive within the APA definition of directive is inconsistent with *Sudar v. Department of Fish and Wildlife Commission*, 187 Wash. App. 22, 31-33, 347 P.3d 1090 (2015). We question some of the broad language used by the *Sudar* court.

¶ 74 We begin first by discussing *Simpson*. In *Simpson*, Ecology determined that the state's existing water quality standard required all NPDES permits issued to pulp and paper mills to limit dioxin discharges to no more than 0.13 parts per quadrillion because that was the level at which dioxin " 'may . . . adversely affect public health.' " 119 Wash.2d at 643, 835 P.2d 1030. "Ecology arrived at this numeric standard by using federal guidance and federal data, but without going through rule-making procedures." *Id.* at 643-44, 835 P.2d 1030. Ecology's staff included the new standard in all pulp and paper mills' NPDES permits. *Id.* at 644, 835 P.2d 1030.

¶ 75 The pulp and paper mills sued. They argued that this new numeric standard that Ecology's staff required in all renewed permits needed to be adopted through the rule-making process. The Supreme Court agreed. It noted that the nature of a rule is " 'it [must] apply to individuals only as members of a class.' " *Id.* at 648, 835 P.2d 1030 (quoting William R. Andersen, *The 1988 Washington Administrative Procedure Act—An Introduction*, 64 WASH. L. REV. 781, 790 (1989)). The high court concluded that the numeric standard was a directive of general applicability because it applied "uniformly to the entire class of entities which discharges dioxin into the state's waters . . . ." *Id.* It also concluded that the violation would subject the respondents to punishment if they did not comply with the new standard. *Id.* at 647, 835 P.2d 1030. Because the two inquiries for what constitute a rule were satisfied, the court concluded that the rule was invalid because Ecology failed to satisfy the APA requirements for rulemaking. *Id.* at 648-49, 835 P.2d 1030. *Simpson* stands for the proposition that "directive" includes an agency's internal directive to its staff for issuing permits.

¶ 76 In *Sudar*, the Fish and Wildlife Commission adopted Policy C-3620. The policy set "guiding principles and a series of actions it may follow to improve the management of salmon in the Columbia River Basin." 187 Wash. App. at 27, 347 P.3d 1090. The policy "outline[d] a number of objectives, including phasing out the use of nonselective gill nets in nontribal commercial fisheries . . . and the transition of gill net use to off-channel areas." *Id.* The *Sudar* court held that the policy was not a rule under the APA and distinguished *Simpson* on the basis that the policy was "unenforceable until and unless the Department promulgates rules that can be enforced on violators." *Id.* at 32, 347 P.3d 1090. This is not an apt distinction. In *Simpson*, the directive to the agency employees was not a promulgated rule. Rather, the agency's employees were directed to include a new standard in all renewed permits and, by doing so, the permitees were subject to punishment if they violated the new standard.

¶ 77 Ecology argues that construing directive as including an internal directive is inconsistent with *Northwest Pulp*. We conclude that the language relied on by Ecology is nonbinding dicta.

¶ 78 In *Northwest Pulp*, our Supreme Court reviewed a challenge to Ecology's adoption, in its manual, of two new methods for identifying the source of polychlorinated biphenyls (PCBs) in water, Methods 1668C and 8082A. 200 Wash.2d at 670, 520 P.3d 985. There, permit writers were required to use Method 608.3 to determine compliance with PCB limits but had discretion whether to use data collected by Methods 1668C and 8082A when evaluating the source of PCBs. *Id.* at 670-71, 520 P.3d 985. There, the court agreed with the lower appellate court's distillation of what characterizes a rule of general applicability: an agency action is not a rule when it " '(1) allows staff to exercise discretion, (2) provides for case-by-case analysis of variables rather than uniform application of a standard, and (3) is not binding on the regulated community . . . .' " *Id.* at 673, 520 P.3d 985 (quoting *Nw. Pulp & Paper Ass'n v. Dep't of Ecology*, 20 Wash. App. 2d 533, 500 P.3d 231 (2021), *aff'd*, 200 Wash.2d 666, 520 P.3d 985). Applying those standards, the court concluded that the challenged methods were not rules because permit writers had discretion to choose the best method for measuring PCB sources on a case-by-case basis. *Id.* at 674, 520 P.3d 985.

[14] ¶ 79 Admittedly, later in the opinion, the court noted that Ecology's internal manual had no independent regulatory effect. *Id.* at 676, 520 P.3d 985. This is the comment Ecology relies on for implying that only regulations can be a rule. We disagree for two reasons. First, there is no functional difference between a promulgated rule that adds new terms for renewing a permit and a directive to staff to add new terms for reissuing a permit. Second, the *Northwest Pulp* court's comment was surplusage and, taken literally, would have overruled *Simpson*. It is well established that statements in a case that do not relate to an issue before the court and are unnecessary to decide the case constitute obiter dictum and need not be followed. *Malted Mousse, Inc. v. Steinmetz*, 150 Wash.2d 518, 531, 79 P.3d 1154 (2003). If the court's passing comment was intended to change precedent, agencies could adopt rules internally without the rulemaking process simply by directing staff to include the new rules in every renewed permit. This would render the APA's requirement for rulemaking meaningless.

¶ 80 Here, unlike *Northwest Pulp*, Ecology directed its staff to include new requirements in both the individual permits and the general permit. The record indicates these requirements were nondiscretionary and were part and parcel of the commitments Ecology made to NWEA.

<u>Second inquiry:</u> *The action establishes, alters, or revokes any qualification or requirement relating to the enjoyment of benefits or privileges conferred by law*

¶ 81 To prove that the denial letter established a "rule" under RCW 34.05.010(16)(c), the City relies heavily on *Failor's Pharmacy* and *Hillis v. Department of Ecology*, 131 Wash.2d 373, 932 P.2d 139 (1997).

¶ 82 In *Failor's Pharmacy*, the Department of Social and Health Services (DSHS) issued policy memoranda changing the way DSHS calculated Medicaid pharmacy reimbursement rates. 125 Wash.2d at 491-92, 886 P.2d 147.[7] The policy memoranda established

7. *Failor's Pharmacy* was decided under a prior version of the APA when it was codified under chapter 34.04 RCW; however, the definition of "rule" and its five categories were the same then as today.

reimbursement tiers based on a pharmacy's business volume. *Id.* After several years operating under these new rate calculations, multiple pharmacies sued. *Id.* at 492, 886 P.2d 147.[8]

¶ 83 The pharmacies argued that the policy memoranda instituted invalid rules because they were orders/directives/regulations of general applicability that established, altered, or revoked a qualification or requirement relating to the enjoyment of benefits or privileges conferred by law. *Id.* at 494, 886 P.2d 147. DSHS responded that the policy memoranda did not " 'relat[e] to the enjoyment of benefits or privileges conferred by law' " under former RCW 34.04.010(2)(c) (1988) because pharmacies have "neither statutory nor contractual rights to payment until performance and can withdraw from the program at any time ...." *Id.* at 496, 886 P.2d 147. DSHS additionally responded that Medicaid participation was voluntary and the pharmacies were free to accept or reject Medicaid clients. *Id.*

¶ 84 The Supreme Court disagreed with DSHS by focusing on Medicaid patients. While federal case law suggested that Medicaid participation was not a benefit or a privilege conferred by law to Medicaid providers, Medicaid was a benefit conferred to Medicaid patients. *Id.* at 496-97, 886 P.2d 147. In holding that the policy memoranda instituted invalid rules, the court stated:

> [T]he inclusion of the reimbursement schedules in a unilateral contract does not preclude their status as a rule. ... The benefit of the Medicaid program runs to the Medicaid patient, RCW 74.09.200, and its enjoyment is altered by the change in reimbursement rates. By insulating reimbursement schedule changes from rule-making requirements Defendant denied notice and comment to those intended beneficiaries of the program.

Id. at 497, 886 P.2d 147 (citations omitted).

[15] ¶ 85 *Failor's Pharmacy* directly supports the City's argument. The challenged portion of the denial letter promised that Ecology's permit writers would alter the qualifications and requirements for NPDES permits. A letter mandating that new performative language be included in all NPDES permits is indistinguishable from the memoranda in *Failor's Pharmacy* mandating new price terms in Medicaid reimbursement contracts. Furthermore, issuance of an NPDES permit is a privilege conferred by law because without an NPDES permit, no person or entity may discharge any substance into Puget Sound. RCW 90.48.160, .162.

¶ 86 Ecology attempts to distinguish *Failor's Pharmacy* by arguing that the new requirements in the permits are mandated by WAC 173-201A-510, which prohibits WWTPs from violating existing water quality standards. We disagree that the new permit requirements merely require the WWTPs to comply with existing water quality standards. Existing water quality standards set numeric levels for DO in Puget Sound but do not regulate or set numeric levels for nitrogen discharges. While nitrogen is one of several causes of DO impairment, it has never been subject to direct regulation until now.

¶ 87 We conclude that the City has satisfied both parts of the two-part inquiry and that the commitments in the denial letter are "rules," as defined by the APA. We further conclude that the new requirements in the individual permits and the general permit are unlawful. If Ecology desires to keep its commitments to NWEA, it must do so through the rulemaking procedures of the APA.

[16] ¶ 88 Affirm in part; reverse in part.[9]

8. Similar to this case, the pharmacies were affected by the agency's policy memorandum only indirectly, by the agency requiring its staff to include the new terms in its Medicaid reimbursement contracts. An additional similarity is the presence of a tiered system based on volume rather than a uniform requirement.

9. Amici raise the question of whether the City had standing to file suit in superior court. Ecology did not raise standing as an issue before this court. We generally decline to address issues raised solely by amici. *State v. J.W.M.*, 1 Wash.3d 58, 74 n.4, 524 P.3d 596 (2023); *State v. Hirschfelder*, 170 Wash.2d 536,552, 242 P.3d 876 (2010); *Teamsters Local 839* v. *Benton County*, 15 Wash. App. 2d 335, 352, 475 P.3d 984 (2020). For this reason, we decline to address the issue of standing.

WE CONCUR:

Fearing, C.J.

Pennell, J.

WASHINGTON STATE NURSES ASSOCIATION, UFCW 3000 and SEIU Healthcare 1199NW on behalf of certain of the employees they represent, Respondent,

v.

MULTICARE HEALTH SYSTEM, Appellant.

No. 84660-4-I

Court of Appeals of Washington, Division 1.

Filed September 18, 2023

Background: Unions representing employees sued employer that unilaterally recouped overpayments to employees, alleging that employer violated regulation allowing it to unilaterally recoup "inadvertent" and "infrequent" overpayments, and sought injunctive and declaratory relief. Employer removed the action, asserting that the claims were preempted by federal law. The United States District Court for the Western District of Washington, Lauren King, J., 2022 WL 3042013, disagreed and granted union's request to remand on question of whether adjustments complied with regulation. On remand, the Superior Court, King County, Douglass A. North, J., granted summary judgment in favor of unions. Employer appealed.

Holdings: In a case of first impression, the Court of Appeals, Diaz, J., held that:

(1) genuine issue of material fact existed as to whether employer's overpayments were "rare," so as to be "infrequent";

(2) genuine issue of material fact existed as to whether overpayments were "unintentional," so as to be "inadvertent";

(3) genuine issue of material fact existed as to whether overpayments were not deliberately done, so as to be "inadvertent";

(4) unions were not judicially estopped from raising claim that employer violated regulation; and

(5) unions' claims were not preempted by the National Labor Relations Act (NLRA).

Reversed and remanded.

1. Summary Judgment ⇨78

If the moving party does not satisfy its initial burden of proof to show by uncontroverted facts that there is no genuine issue of material fact, summary judgment should not be granted, regardless of whether the nonmoving party has submitted affidavits or other evidence in opposition to the motion.

2. Summary Judgment ⇨50

Summary judgment should be granted only if, from all the evidence, a reasonable person could reach only one conclusion.

3. Administrative Law and Procedure ⇨1241

Regulations are interpreted similarly to statutes.

4. Administrative Law and Procedure ⇨1245

In interpreting a regulation, the court construes the act as a whole, giving effect to all of the language used.

5. Administrative Law and Procedure ⇨1243

If a regulation is unambiguous, intent can be determined from the language alone, and the court will not look beyond the plain meaning of the words of the regulation.

6. Labor and Employment ⇨62, 2191

Under the Industrial Insurance Act, the State Department of Labor and Industries (L&I) has the authority to supervise, administer, and enforce all laws pertaining to em-

Elements of a Comprehensive Puget Sound Nutrients Program

Michael Connor, Ph.D., [1] and William Stelle[2]

A. Introduction

Continuing and projected human population growth and development in western Washington is generating a variety of water quality problems that threaten the health and aquatic productivity of Puget Sound, undercutting our efforts to recover salmon, the orca, and other aquatic life. These include the "conventional" pollutants like excess water temperatures in certain rivers and estuarine areas, low levels of dissolved oxygen in certain shallow embayments, and an array of "toxics" from runoff, spills and a variety of other sources. The Department of Ecology (DOE) has worked diligently over the last decade to examine whether excess nutrients are choking the system, and last fall proposed a new "general permit" to address an important component of the problem – increasing amounts of nutrients and other related pollutants from sewage treatment plants discharging directly into the Sound. DOE has invited public comments on its proposed permit, which as a general matter provides a good and creative framework from which to work. Below we offer both organizational and technical refinements to advance an approach that is designed to bolster the financial capability and a decision-making and science apparatus to do it effectively and efficiently. We also offer in part D a set of technical observations which dive deeper into the science and modeling issues which underscore the design and execution of an effective nutrients strategy. We see this as a generational opportunity to help rebuild the productivity of Puget Sound if we can get the details right. The most important ingredient for success will be the active leadership of both the regulatory community -- led by DOE and EPA -- and the water utilities which will shoulder a significant share of its funding and implementation.

B. Objectives

We write to recommend modernizing the conventional water quality regulatory machinery that builds upon the innovations which have occurred in several of the major estuaries around the coastal United States over the last two decades, including Chesapeake Bay, San Francisco Bay, the Gulf of Mexico and Massachusetts Bay. The approach embraces several objectives:

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[1] Mike Connor has worked for 45 years on coastal eutrophication issues as an academic (WHOI/MIT Ph.D. and Harvard School of Public Health post-doc), POTW manager (Boston Harbor Clean-up chief scientist for MWRA and GM of East Bay Dischargers Authority), NGO environmental manager (San Francisco Estuary Institute General Manager and New England Aquarium VP), and government regulator (founding EPA staffer for three New England National Estuary Programs and EPA consultant to John Armstrong when he started the Puget Sound Estuary Program at EPA10). He is a frequent Olympic Peninsula tourist and a recent retiree hoping to relocate there.

[2] Will Stelle has been deeply involved with salmon recovery in the Pacific northwest and California for years. He is currently the President of the Washington Water Trust Board and is a former two-term Regional Administrator of NOAA Fisheries during the Clinton and Obama administrations, where he managed the listings of multiple salmon populations in the Pacific northwest and California and implemented the first stages of ESA salmon recovery efforts, emphasizing reforms in the four "H's" of harvest, hatcheries, hydropower and habitat. He has also been heavily involved with Puget Sound conservation, serving as co-chair of its Federal Caucus during his second tour of NOAA duty. The views expressed here are personal and do not reflect the Washington Water Trust or other organizations with whom he is affiliated.

1. Adopting a comprehensive approach that addresses the major sources of nutrients into the watershed, both from pipeline discharges[3] *and other sources*;
2. Embracing multiple geographic scales that gets at the big picture by designing local strategies tailored to the local ecology;
3. Designing a phased implementation approach that starts immediately on those actions which can be taken with current capabilities while planning and building the needed improvements which will take years;
4. Providing the financial capacity to do the job effectively and efficiently, funding the necessary planning, implementation, compliance and effectiveness monitoring and continuing to invest in new science to steer the effort; and
5. Embracing other necessary imperatives including the use of "green infrastructure" where possible, reducing greenhouse gas emissions and accounting for other climate change adaptations; reflecting social equity and fairness imperatives, and honoring Tribal Treaty rights and obligations.

C. Key Elements

Our approach recognizes that the challenges in tackling nutrients and DO problems successfully go far beyond the normal permit-by-permit, pipeline-by-pipeline approach, which is how the permitting machinery typically works. It presents a wonderful opportunity to strengthen the way that regional water quality improvements are planned, permitted, and implemented, and potentially tied into other riverine/estuarine habitat objectives that are vital to salmon recovery. Because Puget Sound is not nearly as impacted as the other major national estuaries, we've got time to develop a new framework for managing these challenges under the umbrella of a new general permit, which should include the following:

1. A new, invigorated collaboration for developing and implementing the strategy which includes the Department of Ecology, other government regulators, Tribal sovereigns, the local entities representing the major sources of nutrients, and other essential stakeholders. The recent engagements around nutrients have unfortunately been far too polarized, with the various "camps" seemingly talking past one another rather than addressing the significant unresolved issues. We need to change the dynamic and spend less time arguing positions and more time resolving issues successfully, steered by clear-eyed science about what we know and don't know about how things work. DOE has provided in its proposal a good platform from which to advance which opens the door to creative solutions, but we seem to be defaulting into hardened "positions" as we advance;

2. A new consortium of municipal sewage agencies to serve as the permit holder and shoulder the responsibility for coordinated planning, implementation, monitoring, information-sharing and adaptation on a collective basis;

3. An expert science institution to provide independent analysis, modeling, monitoring, information sharing, and performance tracking capabilities to verify if we are achieving the desired outcomes and enable us to adjust as needed;

[3] We encourage including under the general permit both pipeline discharges into marine waters and also discharges into the rivers upstream which flow into the Salish Sea.

4. Increased funding for modeling and monitoring provided by new nutrient discharge permit fees tied to nutrient loading levels and coupled with state matching grant support to help fund the institutional capacity to do the work and provide immediate and direct financial incentives to reduce loadings;

5. Consistent planning for potential nutrient discharge upgrades across large and small dischargers to ensure shared access to good information, local ownership and timely implementation; and

6. Updating science-based water quality goals that are based on now-outdated decades-old framing of oxygen standards to be reflective of the hypoxia area-time framework used by Long Island Sound, the Gulf of Mexico, and the Chesapeake Bay.

D. More Specific Comments on the Draft Nutrients General Permit

We include below more technical background and specifics for the general ideas expressed above.

1. **Puget Sound's eutrophication problem is slowly progressing.** Puget Sound's oxygen status has been measurably declining for more than 60 years. The declines have proceeded slowly, and the specific actions to most cost-effectively solve the problems are not yet clear. DOE and the region overall has time to get the science and policy right. In the interim, DOE's plans for freezing loads and encouraging optimization as an important first step are well-supported.

   DOE emphasizes the comparison to other estuaries around the US that have faced the same issue. While comparisons are difficult since different agencies use slightly different assumptions, a rough comparison of the nitrogen loading to the Sound to other major US estuaries[4] with active nutrient management programs suggests that Puget Sound has a number of qualities in its favor. These characteristics have mitigated the impact of its discharges and need to be better understood so as to gauge the effectiveness of any particular regulatory strategy. The ratio of Puget Sound's population to its water area suggests it is in slightly better shape than the other estuaries, and Puget Sound has two other advantages that allow the region and DOE time to respond:
   a. Its average depth is much deeper than the other urban coastal areas giving it a significantly reduced load of nitrogen per volume of water. Because the load is diluted

[4] This comparison builds on an approach by Kelly (2008) https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1046&context=usepapapers and adds some data from Puget Sound (https://apps.ecology.wa.gov/publications/SummaryPages/1203049.html) and SF Bay (loadings only include POTW discharges, not rivers like the SSM). The Boston Harbor data are from before the Boston Harbor Project that moved the outfall offshore. The data should be considered illustrative of the overall points being made. They are very rough estimates with variability of at least 30-40% even including such parameters as area and volume. The comparison does point out the importance of understanding the zone of impact of deep discharges of nutrients and the exchange with surface waters that would allow light to reach enriched waters and grow phytoplankton.

over a much larger volume, the overall nitrogen concentration contributed by POTWs is reduced.

b. Puget Sound also differs significantly from these estuaries in that the import of nitrogen from deep offshore coastal waters dominates its nutrient loads.[5] As a result, reducing loadings from pipeline discharges across-the-board are less certain to achieve results than locally-tailored strategies.[6]

Estuary	Population	Area	Volume	Depth	Residence Time	Annual N load	Load per volume	Concentration
Units	Millions	sq.mi	Tr gal	(avg ft)	months	million lbs	uM/m3-yr	uM Nitrogen
N. Gulf of Mexico	18	7700	158	100	6	4004	217	108
Chesapeake	16	4480	18	21	7.6	250	156	99
Long Island Sound	15	1320	22	78	6	186	1770	37
SF Bay	8	550	3	14	0.8	40	317	21
Puget Sound	4	1020	44	450	2	104	49	12
old Boston Harbor	2.5	50	0.2	17	0.27	31	3927	87

2. **An integrated nutrient strategy needs to include all POTWs discharging into or upstream of Puget Sound, and needs to be based upon an overall nitrogen budget which encompasses all sources of nutrients -- both pipeline discharges and other "non-point" sources.** The proposed permit's focus on POTWs directly discharging into Puget Sound fails to recognize the importance of other "direct dischargers" of nitrogen upstream of Puget Sound. Moreover, an overall nitrogen budget for Puget Sound is crucial to making a convincing argument that the actions proposed by DOE will have measurable impacts and result in the intended outcomes..

   The draft permit indicates that the nutrient loads that POTWs are discharging into the rivers upstream are only 15-20% less than those being discharging directly into Puget Sound, yet riverine POTW discharges are not proposed to be covered by the general permit. DOE states that only deep water, POTW-derived, summertime nitrogen loads need consideration. Some of the assumptions about the interaction and seasonality of POTW and riverine discharges are illustrated by virtual dye models, but the assumptions would be much more compelling if they were documented by the Salish Sea Model (SSM) outputs for eutrophication. A detailed look at this issue by Banas et., 2015[7] concluded that biological parameters such as bacteria and nutrients have much less long-distance transport than standard salinity measures. Besides just tracking the movement of dye particles, the SSM should use its capacity to determine what the percentage contribution of distant sources to local sources for the areas of concern. Since the problems in the Sound are correlated with long residence times of 100-200 days, this assumption needs validation by a model—consider the counter example of the agricultural runoff to the Mississippi River causing the Gulf of Mexico dead zone.

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[5] Mackas and Harrison (1997) estimate the nutrient loads exchanging through the Juan de Fuca and Admiralty Straits to be about 6-8 times greater than the wastewater load (https://apps.ecology.wa.gov/publications/documents/1103057.pdf).

[6] Even zeroing out all anthropogenic loads from the rivers and the POTWs is predicted by DOD to have a small cumulative effect on algal biomass (~5.4%) and Sediment Oxygen Demand (~17%) (https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2017JC013650).

[7] https://www.jstor.org/stable/44851502?seq=1

Finally, back to the big picture, much of the human-derived load input originates from Canada from their POTWs and Frasier River discharges. These are obviously not under DOE's jurisdiction, but they suggest that a parallel effort to secure a bilateral commitment from our northern neighbors to stabilize and reduce these loads will be important for success..

3. **Name a regional consortium as the permit lead.** The permit recognizes that regulating nutrients requires an estuary-wide approach. Rather than having 50+ individual agencies providing contrasting information using different assumptions, it should allow compliance through a new consortium of the POTWs, and commit to using more than half of the $9 million provided by the legislature to fund this organization's start-up. The consortium would be charged with providing annual reports that summarize agency data collection, integration of those data to become regional information, development of consistent agency optimization plans, tracking implementation and effectiveness of those optimization activities, and an evaluation of the costs of implementing further nutrient reduction.[8] Charging the consortium to develop the framework of optimization plans for its agencies would allow more rapid development of a consistent set of the most cost-efficient solutions possible. While optimization plans need to be tailored to individual facilities, there are a standard set of tools that agencies can use.

4. **Long-term wastewater planning is not effective dealing with single issues**. A strict limit on one item (3 ppm of total nitrogen) may not be effective for maximizing the productivity of Puget Sound. Other wastewater treatment issues--e.g. control of Combined Sewer Overflows or Sanitary System Overflows, maximizing the use of recycled water, maximizing freshwater stream flow, treating first-flush stormwater, minimizing toxics discharges-- may be more cost-effective. . A 3-ppm nitrogen goal is certainly not consistent with minimizing the carbon footprint.[9] The permit should encourage the integration of long-term nutrient reductions into overall, long-term wastewater plans for the wastewater utilities. These plans should be updated every permit cycle and reflected in each utility's individual capital plans. Finally, the permit should encourage these long-term plans to consider "green engineering" designs such as increased recycling, wetlands discharges, or sea level rise protections, etc. These "green" solutions would be things the wastewater utilities and the broader Puget Sound community would embrace. POTW capital plans are multi-decade commitments. A "trade" that allows flat nitrogen loads for XX years with implementation of a "green" engineering solution would encourage action.

5. **Charge the POTW consortium with developing a plan to reduce hypoxic zones in the Sound**. Besides nutrient loads, there are several other early actions that may be quicker to implement and more cost-effective (e.g., summertime nitrification; receiving water aeration; effluent aeration; effluent diversion for irrigation; integrating stormwater first flush treatment; wet

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[8] A pertinent example is the San Francisco Bay Area nutrient general permit (https://www.waterboards.ca.gov/sanfranciscobay/board_decisions/adopted_orders/2019/R2-2019-0017.pdf) which uses the Bay Area Clean Water Agency (BACWA), a joint powers agency that represents the 40+ wastewater agencies to compile monitoring data, funding for monitoring and modeling of the Bay for eutrophication, development of regional strategies for the area's POTWs to reach different nutrient load targets, and summarizing regional implementation of load reduction efforts.

[9] The higher carbon footprint required by a 3-ppm goal (due to the required addition of methanol or other carbon sources and much higher energy usage for pumping and aeration) was documented in DOE's November 13, 2020 forum.

weather controls for minimizing DO impacts). Some of these actions could be tested in the early stages of permit implementation.

6. **Use incentives to increase early adoption.** Given the newness of the nutrient general permit, the permit "sticks" for exceeding action limits should be delayed until the next cycle and replaced by "carrots" of assuring agencies that meet the action limits for these five years (or even better performance) shall have the same action levels in the next permit cycle. The major challenge in the SF Bay nutrient permit has been how to encourage early implementation. What we've found is that given the challenges of capital accumulation, spending, and permitting, the major thing the agencies need is time**.** Two permit terms would give them the planning certainty to incorporate into their capital planning. For example, the costs of "sidestream" treatment would be easier to absorb if they allowed compliance with the nutrient permit for 20 years.

7. **Consider nutrient fees**. Nutrient discharge fees have been used successfully in Long Island Sound and the North Sea to develop the most cost-effective solutions for nutrient removal. Both regions have found that ~$6 per pound of nitrogen becomes an efficient trace-off for maximizing nutrient reduction. Charging a nutrient discharge fee (similar to carbon pricing) is probably the most cost-efficient method for providing regional equity. Adopting a small fee (e.g. $.05-.10 per pound of nitrogen discharged) early would enable funding of the consortium's regional planning study, an independent model evaluation group, or cost-sharing for implementing any nitrogen optimization plans proposed by member POTWs. Such fees also provide a structure for additional Clean Water funding provided by the state by showing serious POTW agency intent.

8. **One Sound, One Science.**[10] The multi-billion capital costs that may result from the permit requires an open Puget Sound science community that works together to build a common body of scientific knowledge. Puget Sound has many different agencies providing information about the Sound that needs to be summarized regularly to ensure the regulatory and conservation agenda is driven by a process that tries to reach consensus on the science of the Sound. This open science community will have the capacity to adapt and inform future water, societal, and environmental decisions across multiple organizations and programs. "One Sound, One Science" will accelerate the discovery of facts and innovation within the open science community by exploring genuine differences in scientific opinion and addressing them in a transparent manner. Ver significant costs of managing nutrient discharges to the Sound will be (and should be) borne by public wastewater utilities, who will then pass those costs along to all of us. They deserve a role in the governance of how to ensure collaboration and communication among Sound scientists, agencies, and stakeholders that may have independent scientific missions to fulfill. An open science community that is well-connected with the policy and management community and other users of science has the capacity to inform decisions, adapt to change, and improve the existing science infrastructure.

   Of most importance to this "One Sound, One Science" principle is independent peer review of the Salish Sea Model (SSM), as undertaken for the Chesapeake Bay, Long Island Sound, Great Lakes, and Massachusetts Bay models. While the model results have passed a limited peer

[10] This concept appears in many regions of the country, The slogan is borrowed from the Sacramento delta.

review appropriate for scientific publication[11], its multi-billion dollar impact on the nutrient management strategy selection requires a more extensive review by an independent Model Evaluation Group (MEG). The review needs to extend to estimate the model's uncertainty in its prediction of management scenarios. As good as the model is, it is significantly limited by a paucity of data for biological transformation processes that are crucial to its conclusions -- as is very well recognized by its authors. It is quite simplistic in its handling of primary production, sediment diagenesis, zooplankton grazing, light penetration, and it uses settling velocities of carbon five times higher than normal to reproduce the hypoxic zone in Hood Canal and the southern Sound to match with one year of data. Eutrophication models are extraordinarily sensitive to light-limitation and grazing-limitation , which can overwhelm the benefits of nutrient control measures. The existing model outputs make it hard to evaluate this issue.

9. **Make DOE's DO Standard more relevant to estuarine eutrophication.** Before capital planning by the POTWs is finalized, DOE needs to develop a much more sophisticated approach to its DO standards to ensure that money spent on improving Puget Sound's productivity is more intelligently spent. The driver for reducing nitrogen loading is to comply with the state standard of preventing a decline of 0.2 ppm from baseline when water quality standards are violated. As a driver, this standard has two limitations: 1. It is not tied to a specific biological impact; and 2. It is beyond the predicted confidence level of even very sophisticated models. EPA's water quality standards are based on data from exposing organisms to different concentrations of parameters of concern, determining the actual level of impact, and incorporating a safety factor. Estuarine scientists in the Chesapeake, Long Island Sound, or Gulf of Mexico have developed a more advanced approach to consider the time and volume of water that is within certain ranges of percent saturation or absolute concentrations based on effects to local species. The general permit also presents hypoxic zones in the Sound, and it would be easy to adapt the new nutrient goals to address the size and timing of hypoxic zones. This characteristic is much more amenable to monitoring and modeling. Most scientists would argue that large scale estuarine DO models are hard-pressed to characterize DO to 0.5 ppm.[12] Often diurnal changes can vary DO by several parts per million and seasonal changes by twice that. The most obvious alternative to the DOE approach would be to use the same TMDL approach it uses for every other contaminant and use the SSM to calculate what nitrogen loads will allow Puget Sound to meet its DO standard. Such an approach would also give the POTW community clear guidance for their future capital plans.

[11] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2017JC013650

[12] See DOE's model's Table 2 in https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2017JC013650)

Final Treatment Plant
Financial Capability Assessment Guidance
Puget Sound Nutrient General Permit

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[1] www.ecology.wa.gov/contact

Department of Ecology's Regional Offices

Map of Counties Served

Region	Counties served	Mailing Address	Phone
Southwest	Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, Mason, Lewis, Pacific, Pierce, Skamania, Thurston, Wahkiakum	P.O. Box 47775 Olympia, WA 98504	360-407-6300
Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	P.O. Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 West Alder Street Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 North Monroe Spokane, WA 99205	509-329-3400
Headquarters	Statewide	P.O. Box 46700 Olympia, WA 98504	360-407-6000

Final Financial Capability Assessment Guidance

Puget Sound Nutrient General Permit

Updated 10/2024

Water Quality Program
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DEPARTMENT OF
ECOLOGY
State of Washington

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Abbreviations and Acronyms

ACS	American Community Survey
AWC	Association of Washington Cities
AKART	All Known, Available, and Reasonable Methods of Prevention, Control, and Treatment
BLS	Bureau of Labor Statistics
CAP	Consumer Assistance Program
CDP	Census Designated Place
CPH	Pollution Control Cost per Household
CWA	Clean Water Act
CWSRF	Clean Water State Revolving Fund
EPA	US Environmental Protection Agency
FAA	Financial Alternatives Analysis
FCA	Financial Capability Assessment
FPL	Federal Poverty Level
LQI	Lowest Quintile of Income
LQPI	Lowest Quintile Poverty Indicator
MHI	Median Household Income
PSNGP	Puget Sound Nutrient General Permit
RCW	Revised Code of Washington
TIN	Total Inorganic Nitrogen
WWTP	Waste Water Treatment Plants
WQS	Water Quality Standards

1. The Purpose of Ecology's Guidance

The Washington State Department of Ecology (Ecology) issued the Puget Sound Nutrient General Permit (Nutrient Permit) on December 1, 2021. The Nutrient Permit requires 58 publicly owned domestic wastewater treatment plants (WWTPs) that discharge wastewater into Puget Sound, to prepare and submit a report to Ecology that identifies reasonable treatment alternatives as part of a required AKART (all known, available, and reasonable methods of prevention control and treatment) analysis for reducing nutrient discharges. The Puget Sound Nutrient General Permit has assigned a category of small, moderate, or dominant to each WWTP based on their percentage of the total inorganic nitrogen (TIN) load currently discharged to Puget Sound.

Wastewater Treatment Plants with Dominant or Moderate TIN loads are required to prepare a Nutrient Reduction Evaluation, which includes an AKART analysis and an Economic Evaluation of reasonable treatment alternatives. For WWTPs with Dominant or Moderate TIN loads, permittees must develop reasonable treatment alternatives for achieving two different levels of treatment: (1.) AKART for nitrogen removal (annual basis) and (2.) 3 mg/L TIN (or equivalent load), as a seasonal average (April through October).

Wastewater Treatment Plants with Small TIN loads are required to prepare an AKART analysis and an Economic Evaluation of reasonable treatment alternatives to maintain an annual TIN average of < 10 mg/L.

For all the WWTPs regulated by the Nutrient Permit, an Economic Evaluation of reasonable treatment alternatives includes completion of an affordability assessment to help identify an economically reasonable level of treatment in the context of AKART.

As referenced on Ecology's website and in the 2022 Fact Sheet, Ecology has used the US Environmental Protection Agency's (EPA) Financial Capability Assessment (FCA) guidance when looking at options for assessing financial capabilities of municipal WWTPs to implement requirements under the Clean Water Act.[2] Specifically, the EPA assessment helps identify the feasibility of permittees to take on the financial costs of an upgrade or municipal wastewater capital improvement reducing nutrients in wastewater effluent by considering factors such as debt capacity of a community, affordability of wastewater utility rate increases to impacted households, and disproportionate impacts to low income and impoverished populations.

Background

In February 2023, the EPA updated its Clean Water Act Financial Capability Assessment Guidance (2023 EPA guidance) to supplement and describe the following: 1995 Interim Economic Guidance for Water Quality Standards (1995 EPA guidance from here on) and 1997 Combined Sewer overflows Guidance for Financial Capability Assessment and Schedule

2 https://ecology.wa.gov/regulations-permits/permits-certifications/nutrient-permit#:~:text=The%20Nutrient%20General%20Permit%20applies,the%20WWTPs'%20existing%20individual%20permits.

Development (1997 EPA guidance from here on).[3,4,5] The largest additions to otherwise similar calculations across both historical guidance approaches is the Lowest Quintile Poverty Indicator (LQPI) that defines disadvantaged households within a community, and the "Expanded Economic Impacts Matrix" that combines the LPQI with previous measures of financial health.

Refining calculations: While Ecology recommends continued use of EPA's FCA guidance, the release of the February 2023 version (revised March 2024) and an updated EPA spreadsheet tool created an opportunity to review and improve its usefulness for evaluating public project impacts in the context of state-specific data.

For example, at the time of this writing, EPA's FCA spreadsheet tool provides calculations necessary to evaluate wastewater treatment projects under "Alternative 1" in the 2023 EPA guidance. However, Alternative 1 (based on 1997 FCA guidance) is intended for schedule development and negotiation, and Section 3 (based on 1995 Water Quality Standards (WQS) guidance) is intended to guide states in evaluating the economic impact of water quality decisions (2023 EPA guidance pg. 34). Despite the former approach garnishing an outsized level of detail and support in EPA's 2023 guidance document and spreadsheet tool, the context of the latter is more applicable to requirements of the Nutrient Permit. In addition, the EPA's LQPI leverages national baselines in its calculation and reports impacts in total (i.e. existing and project impact together) that could limit fair and robust evaluation in the Washington state context. [6]

To be consistent with EPA's 2023 guidance and available tools, whilst better assisting Washington public sector wastewater entities, Ecology developed an amended EPA FCA spreadsheet tool (hereafter referenced as Ecology's spreadsheet tool, located on Ecology's Puget Sound Nutrient General Permit web page). Ecology's spreadsheet tool aligns calculations with Section 3 of EPA's 2023 guidance "economic impact analysis for WQS decisions for the public sector." To this, Ecology's spreadsheet tool also reports total impacts and non-project baselines, state-regional level baselines, and alternative measures like costs as a percent of lowest quintile of income (LQI).

No new data inputs are needed to complete Ecology's spreadsheet tool beyond what was already required in EPA's configuration. Ecology's spreadsheet tool also fully maintains EPA's original Alternative 1 results and overall layout to the degree that they are useful for other federal or state consultation.

The purpose of this guidance document is to:

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[3] https://www.epa.gov/system/files/documents/2023-01/cwa-financial-capability-assessment-guidance.pdf

[4] https://www.epa.gov/system/files/documents/2024-01/interim-economic-guidance-water-quality-standards-workbook-1995.pdf

[5] https://www3.epa.gov/npdes/pubs/csofc.pdf

[6] Note that other versions and vintages, reflecting adjustments to the EPA's FCA calculator may be in use elsewhere throughout state government, including Ecology. If completing an FCA for a use outside of Nutrient Permit purposes, be sure to consult with appropriate contacts.

- Provide tips for completing Ecology's spreadsheet and steps for submitting materials to Ecology (Section 2),
- Describe Ecology's motivation in amending EPA guidance (Section3), and
- Give updated information on funding opportunities for public wastewater treatment plants in Washington state (Section 4).

Environmental justice considerations

> Environmental justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations, and policies (**RCW** **70A.02.005**).

Ecology supports state and local government evaluation of environmental justice impacts of permitted actions on rate payers and vulnerable populations and corresponding efforts to mitigate negative impacts for communities that have the greatest environmental and health burdens.

This FCA guidance and the assessment results are not intended to be an absolute or comprehensive picture of the environmental justice impacts from municipal wastewater management, including any nutrient reduction actions to comply with the Nutrient Permit. Permittees are required to assess environmental justice broadly and identify strategies to mitigate harms and amplify benefits for people experiencing the greatest environmental and health burdens in the Nutrient Permit (page 18).[7]

In this FCA guidance, Ecology provides tools to understand the *financial* impacts of anticipated permitted actions. These financial impacts include economic justice considerations such as, income inequality, poverty, and income-based food assistance among other measures. Permittees should incorporate the recommended justice considerations within their FCA, particularly the lowest quintile of income (LQPI), with the broader environmental justice review in the Nutrient Permit to develop a fuller understanding of the equity considerations of each permitted project.

2. Analytical Steps and Deliverables

Governments have the authority to levy taxes and distribute pollution control costs among households and businesses according to the tax base. Similarly, sewage authorities charge for services, and thus can recover pollution control costs through user fees. Whether or not the community faces substantial impacts from the Nutrient Permit depend on existing pollution control burdens, the cost of new pollution control projects, the financial health of the community, and its socioeconomic vulnerability, among other factors.

[7] https://apps.ecology.wa.gov/paris/DownloadDocument.aspx?Id=390719

To provide a standardized categorization of these impacts, **we recommend the following steps outlined in Ecology's FCA spreadsheet tool (tab references in red below), and related analytical sections of the 2023 EPA FCA guidance**.[8] This multistep approach includes:

1. Identifying your affected community (**Instructions_Demographic, Inputs_Demographic**),
2. Calculating pollution control cost per household as a percent of median household income (%MHI) and upper limit of the lowest quintile income (%LQI) (**Instructions_RI, Inputs_RI**),
3. Determining initial financial capability through a combination of %MHI and an index of six socioeconomic, debt, and financial indicators (**Instructions_FCI, Inputs_FCI**),
4. Calculating the Lowest Quintile Poverty Indicator (LQPI) score (**Instructions_Results_LQPI, Results_LQPI**),
5. Combining the results of the Initial Economic Impact and the LQPI score to determine the Expanded Economic Impact (**Results_FCA_ECY**),
6. Performing a Financial Alternatives Analysis (FAA) (**Instructions_Checklist_FAAs , Checklist_FAA**),
7. Iterating step 1-6 as needed with any updates resulting from the financial alternative analysis and related research.

Upon completion, we recommend permittees submit, at a minimum, the following materials to Ecology's Water Quality Permitting Portal (WQWebPortal):

1. The Ecology FCA spreadsheet tool, filled out with required information. This includes providing links or citations for non-automatically generated data inputs (in comments and sources columns, where applicable). Please attach documentation if an internal source is used. The WWTP should provide this information for chosen treatment alternatives. Permittees may also include in materials for context additional instances of the tool, related to the consideration of other options (please clearly mark as non-chosen alternatives).
2. A document discussing results of the Expanded Financial Capability Assessment (Results_FCA_ECY). This should include, but is not limited to:
    - Screenshot(s) of the expanded FCA matrix with and without project(s), along with intermediate statistics such as %MHI and %LQI.

[8] Caveats and additions to note when comparing EPA's current online FCA spreadsheet tool and Ecology's spreadsheet tool are discussed in greater detail in Section 2.2.

  - Project and community details that may drive (or attenuate) impacts.
  - Other key inputs and unique characteristics of the affected community that the permittee feels are not fully captured by the analysis (an example could include a community that imposes restrictions on property taxes).
  - Summaries of similar relevant analysis performed by, or known to, the permittee. This could include data, presentations, local rate studies, surveys, or interviews.
3. A completed FAA. This can be printed from the completed Ecology FCA spreadsheet tool (Checklist_FAA), or a word document if room for additional discussion and formatting is desired.[9, 10]
4. Supplemental material as needed.

When preparing materials, keep in mind that break points between categories in the FCA analysis are not, nor are intended to be, an absolute or comprehensive demarcation of financial capability.

Identifying overburdened communities and barriers to affordability do not relieve jurisdictions from meeting Water Quality Standards. On one hand, low-income households may pay a higher percentage of their total income for basic services and clean water, but on the other, if water quality standards of a community remain lower, overburdened and/or low-income neighborhoods will likely continue to suffer impacts to human health and use of the state's waters for activities such as swimming, and fishing. In short, if one of the intended goals of the permit is to address impacts to residents, allowing lower water quality may have the opposite effect by increasing pollution in the neighborhoods where they live, recreate, or consume local fish and shellfish.

While the Financial Alternatives Analysis (FAA) provides permittees, Ecology, and the public, information about mitigating efforts, where high impacts are found, it is especially critical that communities develop a solution that accommodates the need to protect the receiving water while also providing a level of service to all residents within their community. In these instances, Ecology encourages permittees to evaluate, or re-evaluate, tiered or other alternative rate structures to offset adverse effects to the lowest income populations within the sewer service area or other innovative measures (e.g., fixed vs. variable charges, efficiency-

[9] We highly recommend first reviewing Chapter 4 of this guidance for funding and rate assistance options, and Appendix C of EPA's 2023 FCA Guidance for additional details and resources associated with FAA question.

[10] See EPA compendium of Drinking Water and Wastewater Customer Assistance Programs that describes the benefits, implementation, and examples of customer assistance programs (CAPs) throughout the country (https://www.epa.gov/waterfinancecenter/compendium-drinking-water-and-wastewater-customer-assistance-programs). EPA's financial leadership guidance offers additional discussion on several themes found in the FAA (https://www.epa.gov/waterfinancecenter/water-infrastructure-financial-leadership).

oriented rate design, or usage based rates) that ensure affordability when adopting a new rate structure to support treatment upgrades.

The Association of Washington Cities (AWC) 2018 Utility Rate Survey is an excellent resource for sewer rates and examples.[11] These data allow permittees to compare utility rates, rate structures, number of connections, and other characteristics for up to three cities at a time (note there are no counties or special purpose districts included in the AWC data). Out of 295 communities Ecology surveyed in 2016, 116 offered a discounted rate based on criteria determined by the billing entity or city ordinance.[12]

2.1 Notes on Identifying the Affected Community

It is important to first define the affected community prior to completing other steps in the FCA. This is to ensure that fiscal and socioeconomic data is appropriately described throughout the analysis. For the purposes of the FCA, the "affected community" is typically made up of households at the city, town, or Census designated place (CDP) level, in a utility or water-sewer district service area responsible for paying the compliance costs of water treatment (see 57 RCW for water-sewer district definitions). We reference "city" hereafter for simplicity.

In the simple case (Case A), water-sewer districts generally line up with the jurisdictional boundaries of a single city, while in more complex cases, others may serve just portions of a city, multiple cities, or some combination of cities and portions of cities.

- **Case A (Simple):** When all households in a single city pay compliance costs of water treatment, the city is the affected community.

  Case B. When all households in two or more cities pay compliance costs of water treatment, multiple cities make up the affected community.

- **Case C**. One or more cities with partial service can make up the affected community if a predominant share of households within each are responsible for paying the compliance costs of water treatment.

  What constitutes a "predominant share" should be dependent on several factors. Generally, at least 75% of all households in the city should be responsible for paying the compliance costs of water treatment. More importantly, households that are not in the service area but included by way of city level reporting should not skew fiscal and social information in a material way. Permittees should provide, to the extent possible, quantitative or qualitative information about the balance of these households including but not limited to income, average assessed property value, and unemployment rates. Documented plans to connect

[11] https://datadatadata-awcnet.opendata.arcgis.com/pages/utrs2018
[12] Summary report: https://apps.ecology.wa.gov/publications/documents/1710024.pdf . Data available at: https://data.wa.gov/Natural-Resources-Environment/2016-Residential-Sewer-Rate-Survey/sibs-5k6j/data

the balance of households to services in the foreseeable future may be another justification for including otherwise partially served cities as the affected community.[13]

- Any combination of **Case B** and **Case C** can make up the affected community
- **Case D**. If only a portion of a single city is served (e.g., less than 75% of households served in a small special district), and limited in reporting standard fiscal and socioeconomic data, you may consider the city as the affected community. As with **Case C** above, permittees should take efforts to consider whether socioeconomic information at the city level would misrepresent the subset of households responsible for compliance cost. If so, describe to the best of your ability how, or contact Ecology for additional guidance.

A Note on Tribal Service Agreements

Permittees may have agreements with Tribes to provide wastewater services on Tribal reservation lands. Therefore, we encourage permittees to consider the following questions for each Tribe impacted by this permit:

1. Do you have a wastewater service agreement with neighboring Tribe(s)?
2. What is your relationship with the Tribal government?
3. Is the Tribe (Tribal government) aware that you will report social and economic data to Ecology for this permit?

Before collecting any Tribal information, permittees should discuss the data required by the FCA with the Tribes included in their wastewater service agreements. These discussions should describe the purpose of the PSNGP and the FCA and whether publicly available data accurately describes the portion of the Tribe affected by the service agreement.

Ecology recommends breaking these communications into two categories:

1) Household level data from the US Census Bureau,

The FCA requires collection of household demographic data. Census data at the city, town, or CDP level, may not accurately represent data for households on the Tribal reservation. One way to incorporate this Tribal data into Residential indicators (RI) and Lowest Quintile

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[13] For complex service areas, electronic Geographic Information System (GIS) shapefiles can be analyzed with census electronic shapefiles, allowing a more precise characterization. This includes but is not limited to intersecting parcel maps with permittee service areas. Ultimately, it is the applicant's responsibility to describe these data, and their limitations. We recommend including any service maps, Census data, and files/code used in this step with materials submitted to Ecology.

Poverty Indicator (LQPI) scores, is to rely on data from the US Census at the "American Indian Area" level.[14, 15]

However, if a Tribe or permittee feels that the "American Indian Area" level misrepresent households within the service area, the Tribe or permittee may provide alternative data. An example is if service agreements do not extend to an entire "American Indian Area" level but Census data is not available below the reservation level. In this instance, the Tribe could provide more localized data, or a Tribe could confirm that alternate publicly available data is a good proxy for the portion of the reservation receiving services.

2) Government level finances

Financial obligations of a Tribe that are shared with the local government responsible for running the permittee's facility should be reflected in the permittee's certified annual financial reports, local governments assessor's office records, or other standard budgeting and accounting materials. This is similar to overlapping debt with non-Tribal local governments with service agreements (see Instructions_FCI tab in Ecology's spreadsheet tool for additional details) and might include debt held by a Tribe for public services that are partially chargeable to the permittee's non-Tribal government annually for their use, such as a local park or law enforcement.

We encourage permittees and Tribes to discuss and coordinate on how to report shared financial agreements. If using Ecology's spreadsheet tool, overlapping debt shares can be itemized on the "Inputs_FCI" tab.

2.2 Notes on Project Costs

Permittees shall provide project costs at the Class 5 level of estimates as established by the Association for the Advancement of Cost Engineering International (**Inputs_RI**).

[14] To find data on Tribal geographies, navigate to https://data.census.gov/, select "All Geographies" on the left hand side pane, and then "American Indian Areas". After selecting relevant Tribal areas, data tables can be searched for in the Census website's search bar. See the "Census Bureau Data" table on the "Inputs Demographic" tab of Ecology's spreadsheet tool for exact table numbers. Permittees will need to paste (hardcode) these data into Ecology's spreadsheet because only CDPs, towns, or cities are currently available as an auto-populate features in the Census Bureau Demographic Data Generator (see Inputs_Demographic tab).

[15] If unemployment rates are not available from the BLS in Tribal areas, consider 5-year ACS data on unemployment rate for populations 16 years and over, in the civilian labor force on table DP03 for American Indian Area geographies.

3. Ecology Additions and Motivation

The following subsections describe Ecology's amendments to EPA's 2023 guidance and online FCA spreadsheet tool (as of 09/2024) in more detail. Note that these amendments are automatically incorporated into the results of Ecology's FCA spreadsheet tool in tab "Results_FCA_ECY" and require no new input or calculation on the permittee's part beyond what is already required by the EPA's original tool.

3.1 Puget Sound Regional Baselines

State level baselines for some calculations are recommended by EPA's 2023 guidance when calculating public sector impacts, as opposed to national baselines (see Section 3). It is also the only substantive statistical difference between "Alternative 1" and "Section 3" results in EPA's guidance beyond naming conventions and terminology.[16]

Ecology's guidance and spreadsheet tool makes an additional baseline distinction within the state between the Puget Sound, and other regions such as western Washington non-Puget sound, and eastern Washington. For the purposes of Ecology's FCA spreadsheet tool, the Puget Sound baseline is made up of counties defined by the University of Washington's Puget Sound Institute and the United States Geologic Survey (USGS), excluding Lewis County.[17, 18] Other state-regional baselines, such as Western Washington non-Puget Sound and Eastern Washington are available in Ecology's spreadsheet tool and may be considered for non-PSNGP applications.

[16] See Section 1(3)(b) of EPA's 2023 guidance for additional discussion.
[17] https://www.eopugetsound.org/terms/85
18 Lewis County is hydrologically linked to the Puget Sound through drainages and therefor in the watershed, however it does not contain PSNGPs which are defined as direct dischargers into the Sound. It is also absent of some economic features that characterize counties directly adjacent to the Puget sound such as ports, water views, and direct recreational access.

Figure 1. Counties in the Puget Sound Regional Baseline

Ecology's spreadsheet tool retains Alternative 1 labeling and references throughout the calculator for consistency with other helpful portions of EPA's guidance, such as robust technical appendices describing Alternative 1 calculations and data sources. Ecology's spreadsheet tool also provides a separate section producing all results using national baselines.

3.1.1 Household Income Baseline

Comparing service area income to broader conditions in the Puget Sound region is a practically important feature. Considering that median household income in the Puget Sound region was $102,551 in 2022 (Figure 2), or over 30% higher than the broader US ($75,149).[19] In this way, Puget Sound communities would appear arbitrarily strong against national or statewide baselines when calculating components of the FCI. But because of unique regional characteristics—chief among them a higher cost of living—results would not accurately capture local hardship.

In consultation with the EPA, and response to feedback from stakeholders during public comment, Ecology's amended spreadsheet tool calculates relevant FCI results from the Puget Sound regional baseline (with alternative options for Western Washington Non-Puget Sound, and Eastern Washington baselines, if relevant). [20]

[19] Using 2022 ACS 5-year estimates https://data.census.gov/table?q=b19013.
[20] Regional baseline statistics are summarized from county level ACS 5-year estimates, weighted by the proportion of households each county represents in the region.

Figure 2. Median Household Income by Region

3.1.2 Lowest Quintile Poverty Indicator Baselines

The Lowest Quintile Poverty Indicator (LQPI) aids in assessing the severity and prevalence of poverty in the affected community. In EPA's original formulation, the weighted index is made up of 6 measures, which take on a 1, 2, or 3 to describe poverty conditions, mid-range, or strong (good) conditions respectively after comparing the affected community with national averages. Inputs into the LQPI (other than "Trend in Household Growth") are evaluated using a ±25% benchmark to national figures.[21] This bracketing methodology is commonly used to characterize outliers on either end of the data distribution. Using a ±25% benchmark closely aligns with the middle quintile of data for the parameter, which can characterize the "middle class."

As with concerns over household income in FCI calculation above, comparing LQPI measures in Washington to a national baseline may misrepresent local hardship. For example, the Percentage of Population with Income Below 200% of the Federal Poverty Level (FPL) in the US is 28.8% (2022 ACS 5-year estimates), while in parts of Washington State, such as the Puget Sound region, is only 20%.[22] Again, this differential does not necessarily suggest households in

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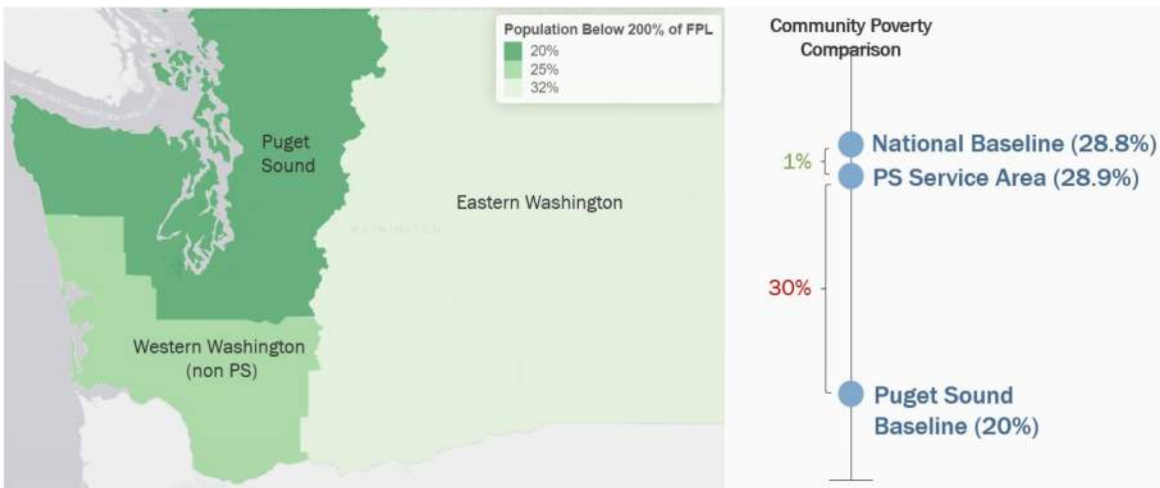
[21] Note that "Trend in Household Growth," the fifth indicator, is based on 5-year Geometric Average Growth Rates instead of quintiles. $5\ Year\ Geometric\ Growth\ Rate = (1 + (HH_n - HH_{n-5})/\ HH_{n-5})^{1/5} - 1$; where HH is the number of occupied housing units, and n is most recent Census data year. For example, if a community had 15,500 occupied housing units in the most recent census data year and had 15,000 occupied units five census data years prior, the 5-year average geometric growth rate would be 0.66% = $(1 + (15{,}500 - 15{,}000)/\ 15{,}000)^{1/5} - 1$.

[22] Table S1701 (https://data.census.gov/table/ACSST5Y2022.S1701?q=S1701&g=040XX00US53). Note that outside of Alaska and Hawaii, the threshold establishing federal poverty is the same for all states.

the Puget Sound are better off financially than other parts of the state or country. Rather, it partially reflects the cost of living in the region, the income necessary to support basic needs, and the fact the federal poverty levels are fixed for all contiguous states.

Consider a single Puget Sound community as a service area. Here, the Census reported that 28.9% of its population fell below 200% of FPL in 2022 (ACS 5-year estimate). Since that statistic is almost identical to the national average (1% lower), the service area would fall into the LQPI's "mid-range" using the standard EPA formula (Figure 3). Conversely, when compared to its state-regional peers, poverty in this community is shown to be 30% higher, and therefore would fall into the LQPI's "weak" (high poverty) category.

Figure 3. Percent of Population Below 200% of FPL and Baseline Comparison



In consultation with the EPA, and response to feedback from stakeholders during public comment, Ecology's amended spreadsheet tool calculates relevant LQPI results from the Puget Sound regional baseline (with alternative options for Western Washington Non-Puget Sound, and Eastern Washington baselines, if relevant). [23]

3.2 Impacts of Wastewater Treatment With and without Project

Capturing baseline impacts of wastewater treatment in a community is critical when comparing to the same community with the proposed project(s). Ecology's spreadsheet tool presents a side-by-side comparison simultaneously which aids permittees and Ecology in understanding the impacts of permit requirements, and their potential contribution to cumulative burden on ratepayers.

[23] Regional baseline statistics are summarized from county level ACS 5-year estimates, weighted by the proportion of households each county represents in the region.

3.3 Costs in Terms of Percent of Upper Limit of Lowest Quintile Income

While the upper limit of the lowest quintile of income (LQI) is incorporated into results through baseline comparisons in the LQPI, we calculate and report existing and new treatment costs as a percentage of LQI as a standalone statistic. This isolates additional information about impacts beyond median income households, impact disparities, and changes in disparity across treatment alternatives when compared with %MHI.

4. Assistance and Funding Sources to Consider

Ecology's water quality financial management section (FMS) provides technical assistance, in coordination with the EPA, Rural Community Assistance Corporation (RCAC), Evergreen Rural Water of Washington (ERWoW), and the Washington State Department of Commerce's Small Communities Initiative (SCI). With a single application to Water Quality Combined Fund, Ecology can identify water quality-related opportunities, that best match the financial needs of project applicants.[24] This coordinated effort offers a wide variety of resources for supporting communities in accessing funds, and identifying support for managing and implementing infrastructure improvements.[25] Particularly relevant loans and grants administered through the Combined Fund:

- Puget Sound nutrient reduction grants program. In the 2021-23 biennial budget, the state Legislature appropriated $9 million for the to help municipalities prepare and plan for future treatment facility upgrades and implement operational modifications necessary to maximize nutrient removal from existing treatment processes. Ecology is currently working on the next phase of funds in the form of a budget request for the next biennium (beginning August 2025). If funds are approved, eligible applicants are the 42 municipalities that operate the 58 wastewater treatment plants that discharge to Puget Sound and are covered by the permit.[26]
- The Clean Water State Revolving Fund (CWSRF) which provides low-interest and forgivable principal loan funding for wastewater treatment construction projects, eligible nonpoint source pollution control projects, and eligible "green" projects. Established by the federal Clean Water Act (CWA), the CWSRF is funded through an annual EPA capitalization grant, state matching funds, and principal and interest repayments on past program loans.
- Income and need based programs, including the Centennial Clean Water Program, that provides wastewater treatment construction projects for financially distressed communities.

[24] https://ecology.wa.gov/water-shorelines/water-quality/water-quality-grants-and-loans
[25] For this permit, technical assistance can be requested by contacting Stephanie Allen (sall461@ecy.wa.gov).
[26] https://ecology.wa.gov/About-us/Payments-contracts-grants/Grants-loans/Find-a-grant-or-loan/Puget-Sound-Nutrient-Reduction[27] Active and available at the time of this writing.

In addition to State, federal technical assistance is also available, largely from the EPA.[27] These include, but are not limited to:

- EPA's Environmental Finance Centers, which deliver targeted technical assistance to local governments, states, tribes, and non-governmental organizations to protect public health, safeguard the environment, and mitigate environmental justice concerns.[28] The EFCs serve an important role in helping to ensure that communities that have difficulty in securing public funding receive the help they need to access resources to support infrastructure improvements. Requests for technical assistance can be made through EPA's Water Technical Assistance Program or by emailing WaterTA@epa.gov
- EPA's Training and Technical Assistance for Small Systems Funding provides technical assistance through national providers via grant funding to support small drinking water and wastewater systems that serve small and rural communities.[29] EPA is committed to helping communities across America upgrade and maintain water infrastructure that is essential to public health and environmental protection.
- EPA's Environmental Justice Small Grants Program, which supports and empowers communities working on solutions to local environmental and public health issues.[30] The program is designed to help communities understand and address exposure to multiple environmental harms and risks.
- EPA resources associated with the Bipartisan Infrastructure Law (BIL), including Closing America's Wastewater Access Gap Community Initiative.[31,32]

Federal and private water infrastructure funding, active and available at the time of this writing including but not limited to:

- Water Infrastructure Finance and Innovation Act (WIFIA): https://www.epa.gov/wifia
- The Environmental Justice Collaborative Problem-Solving (CPS) Cooperative Agreement Program: https://www.epa.gov/environmental-justice/environmental-justice-collaborative-problem-solving-cooperative-agreement
- Source Reduction Assistance (SRA) Grant Program: https://www.epa.gov/p2/source-reduction-assistance-grants
- CoBank's Rural Water and Wastewater Lending: https://www.cobank.com/corporate/industry/water

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[27] Active and available at the time of this writing.
[28] https://www.epa.gov/waterfinancecenter/efcn
[29] https://www.epa.gov/dwcapacity/training-and-technical-assistance-small-systems-funding
[30]https://www.epa.gov/environmentaljustice/environmental-justice-small-grants-program[31] https://www.epa.gov/infrastructure
[31] https://www.epa.gov/infrastructure
[32] https://www.epa.gov/water-infrastructure/closing-americas-wastewater-access-gap

- National Rural Water Association (NRWA)'s Rural Water Loan Fund: https://nrwa.org/members/products-services-portfolio/rural-water-loan-fund/
- U.S. Department of Agriculture (USDA)'s Water and Waste Disposal Guaranteed Loan Program: https://www.rd.usda.gov/programs-services/water-waste-disposal-loan-guarantees
- USDA's Water & Environmental Programs (WEP): https://www.rd.usda.gov/programs-services/all-programs/water-environmental-programs
- USDA's Water & Wastewater Projects Revolving Fund Program: https://www.rd.usda.gov/programs-services/revolving-funds-for-financing-water-and-wastewater-projects
- USDA's Water & Waste Disposal Loan & Grant Program: https://www.rd.usda.gov/programs-services/water-waste-disposal-loan-grant-program
- USDA's Water & Waste Disposal Predevelopment Planning Grants: https://www.rd.usda.gov/programs-services/water-waste-disposal-predevelopment-planning-grants
- U.S. Department of Commerce – Economic Development Administration (EDA)'s funding and technical assistance: https://www.eda.gov/funding/programs
- U.S. Department of Health and Human Services – Indian Health Service (IHS)'s Sanitation Facilities Construction (SFC) Program: https://www.ihs.gov/dsfc/
- U.S. Department of Housing and Urban Development (HUD)'s Community Development Block Grant (CDBG) Program: https://www.hud.gov/program_offices/comm_planning/communitydevelopment
- HUD's Section 108 Loan Guarantee Program: https://www.hudexchange.info/programs/section-108/
- Others, including private funding, can be

Bipartisan Infrastructure Law (BIL) Resources

- Overview BIL: https://www.epa.gov/infrastructure
- Closing America's Wastewater Access Gap Community Initiative: https://www.epa.gov/water-infrastructure/closing-americas-wastewater-access-gap-community-initiative
- Bipartisan Infrastructure Law SRF Memorandum: https://www.epa.gov/dwsrf/bipartisan-infrastructure-law-srf-memorandum

- Frequent Questions about BIL State Revolving Funds: https://www.epa.gov/system/files/documents/2024-10/bil-srf-qs-and-as-10-01-2024_1.pdf

SEPA[1] Environmental Checklist

Purpose of checklist

Governmental agencies use this checklist to help determine whether the environmental impacts of your proposal are significant. This information is also helpful to determine if available avoidance, minimization, or compensatory mitigation measures will address the probable significant impacts or if an environmental impact statement will be prepared to further analyze the proposal.

Instructions for applicants

This environmental checklist asks you to describe some basic information about your proposal. Please answer each question accurately and carefully, to the best of your knowledge. You may need to consult with an agency specialist or private consultant for some questions. **You may use "not applicable" or "does not apply" only when you can explain why it does not apply and not when the answer is unknown.** You may also attach or incorporate by reference additional studies reports. Complete and accurate answers to these questions often avoid delays with the SEPA process as well as later in the decision-making process.

The checklist questions apply to **all parts of your proposal**, even if you plan to do them over a period of time or on different parcels of land. Attach any additional information that will help describe your proposal or its environmental effects. The agency to which you submit this checklist may ask you to explain your answers or provide additional information reasonably related to determining if there may be significant adverse impact.

Instructions for lead agencies

Please adjust the format of this template as needed. Additional information may be necessary to evaluate the existing environment, all interrelated aspects of the proposal and an analysis of adverse impacts. The checklist is considered the first but not necessarily the only source of information needed to make an adequate threshold determination. Once a threshold determination is made, the lead agency is responsible for the completeness and accuracy of the checklist and other supporting documents.

Use of checklist for nonproject proposals

For nonproject proposals (such as ordinances, regulations, plans and programs), complete the applicable parts of sections A and B, plus the Supplemental Sheet for Nonproject Actions (Part D). Please completely answer all questions that apply and note that the words "project," "applicant," and "property or site" should be read as "proposal," "proponent," and "affected geographic area," respectively. The lead agency may exclude (for non-projects) questions in "Part B: Environmental Elements" that do not contribute meaningfully to the analysis of the proposal.

[1] https://ecology.wa.gov/Regulations-Permits/SEPA/Environmental-review/SEPA-guidance/Checklist-guidance

A.Background

Find help answering background questions[2]

1. **Name of proposed project, if applicable:**

   Rulemaking – Chapter 173-201A WAC, Water Quality Standards for Surface Waters of the State of Washington (Natural Conditions)

2. **Name of applicant:**

   Washington State Department of Ecology (Ecology), Water Quality Program

3. **Address and phone number of applicant and contact person:**

   Vince McGowan, Water Quality Program Manager

   Department of Ecology

   PO Box 47600

   Olympia, WA 98504-7600

   Marla Koberstein, Rulemaking Lead

   swqs@ecy.wa.gov

   360-628-6376

4. **Date checklist prepared:**

   March 28, 2024

5. **Agency requesting checklist:**

   N/A – Nonproject SEPA for rulemaking

6. **Proposed timing of schedule (including phasing, if applicable):**

September 27, 2022	Announce start of rulemaking (file CR-101)
May 9, 2024	Propose formal draft rule (file CR-102)
July 12, 2024	End public comment period
Fall 2024	Make decision on rule adoption (file CR-103)

7. **Do you have any plans for future additions, expansion, or further activity related to or connected with this proposal? If yes, explain.**

   No.

8. **List any environmental information you know about that has been prepared, or will be prepared, directly related to this proposal.**

[2] https://ecology.wa.gov/Regulations-Permits/SEPA/Environmental-review/SEPA-guidance/SEPA-checklist-guidance/SEPA-Checklist-Section-A-Background

Supporting documents for the proposed rule can be found on the rulemaking webpage[3] and includes:

- Draft Technical Support Document
- Preliminary Regulatory Analysis
- Draft Rule Implementation Plan
- Citation List

9. Do you know whether applications are pending for governmental approvals of other proposals directly affecting the property covered by your proposal? If yes, explain.

No.

10. List any government approvals or permits that will be needed for your proposal, if known.

The U.S. Environmental Protection Agency must approve any state water quality standards that have been adopted before they can be used for Clean Water Act purposes.

11. Give brief, complete description of your proposal, including the proposed uses and the size of the project and site. There are several questions later in this checklist that ask you to describe certain aspects of your proposal. You do not need to repeat those answers on this page. (Lead agencies may modify this form to include additional specific information on project description.)

Ecology is proposing revisions to chapter 173-201A WAC, Water Quality Standards for Surface Waters of the State of Washington. We are proposing the following revisions in this rulemaking:

- WAC 173-201A-020, Definitions: adding a definition for a performance-based approach method and adding a definition for local and regional sources of human-caused pollution.
- WAC 173-201A-200(1)(c), Aquatic life temperature criteria, subsection (i): updating the allowable insignificant changes to freshwater temperature criteria when natural conditions are the applicable criteria.
- WAC 173-201A-200(1)(d), Aquatic life dissolved oxygen (D.O.) criteria, subsection (i): updating the allowable insignificant changes to freshwater dissolved oxygen criteria when natural conditions are the applicable criteria.
- WAC 173-201A-210(1)(c), Aquatic life temperature criteria, subsection (i) updating the allowable insignificant changes to marine water temperature when natural conditions are the applicable criteria.
- WAC 173-201A-210(1)(d), Aquatic life dissolved oxygen (D.O.), subsection (i): updating the allowable insignificant changes to marine water dissolved oxygen when natural conditions are the applicable criteria.

[3] https://ecology.wa.gov/regulations-permits/laws-rules-rulemaking/rulemaking/wac-173-201a-natural-conditions

- WAC 173-201A-260(1), Natural and irreversible human conditions: updating the natural conditions criteria language and describing methods for determining natural conditions criteria values.
- WAC 173-201A-430(2), Site-specific criteria: updating how analyses must be conducted.
- WAC 173-201A-470, Performance-based approach: adding this new section to describe and reference the methodology to determine natural conditions criteria values.
- Ecology publication 24-10-017, A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington, a separate rule document that provides the methodology to determine natural conditions criteria values.
- Minor non-substantive edits to rule language in WAC 173-201A-430(2) to reflect the latest version of referenced documents.

We are proposing revisions to natural conditions provisions in our surface water quality standards to provide water quality protection for aquatic life organisms and to establish possible methods for deriving those protective values. As part of this rule proposal, we:

- Evaluated the latest scientific data, methods, modeling tools, and approaches to update the natural conditions provisions necessary for refining aquatic life protection.
- Considered the U.S. Environmental Protection Agency's recommend approaches for natural conditions in water quality standards, including a performance-based approach for determining protective natural conditions criteria.
- Considered the U.S. Environmental Protection Agency's draft, deliberative, and Washington-specific recommendations for the performance-based approach methodology.

12. Location of the proposal. Give sufficient information for a person to understand the precise location of your proposed project, including a street address, if any, and section, township, and range, if known. If a proposal would occur over a range of area, provide the range or boundaries of the site(s). Provide a legal description, site plan, vicinity map, and topographic map, if reasonably available. While you should submit any plans required by the agency, you are not required to duplicate maps or detailed plans submitted with any permit applications related to this checklist.

The proposed revisions to the water quality standards will apply to all waterbodies in the state of Washington. In addition, some of the proposed revisions can be applied on a site-by-site basis when the underlying requirements are met.

B.Environmental Elements

This is a nonproject SEPA that involves a rulemaking for the Washington State surface water quality standards. The rulemaking, if concluded, will revise natural conditions provisions for the protection of aquatic species. The environmental elements are not applicable because the rulemaking action being considered will not result in any physical changes to any waters of the state where the new rules will apply.

C. Signature

Find help about who should sign[4]

The above answers are true and complete to the best of my knowledge. I understand that the lead agency is relying on them to make its decision.

5/1/2024

X Kalman Bugica

Signed by: Bugica, Kalman (ECY)

Type name of signee: Kalman Bugica

Position and agency/organization: Water Quality Standards, Washington State Department of Ecology.

Date submitted: May 10, 2024

D. Supplemental sheet for nonproject actions

Find help for the nonproject actions worksheet[5]

Do not use this section for project actions.

Because these questions are very general, it may be helpful to read them in conjunction with the list of the elements of the environment.

When answering these questions, be aware of the extent the proposal, or the types of activities likely to result from the proposal, would affect the item at a greater intensity or at a faster rate than if the proposal were not implemented. Respond briefly and in general terms.

1. **How would the proposal be likely to increase discharge to water; emissions to air; production, storage, or release of toxic or hazardous substances; or production of noise?**

   The proposal will not increase any of the above-mentioned environmental impacts. The rulemaking proposal will not cause or result in any physical changes to any water of the state where the new rules will apply.

[4] https://ecology.wa.gov/Regulations-Permits/SEPA/Environmental-review/SEPA-guidance/SEPA-checklist-guidance/SEPA-Checklist-Section-C-Signature

[5] https://ecology.wa.gov/regulations-permits/sepa/environmental-review/sepa-guidance/sepa-checklist-guidance/sepa-checklist-section-d-non-project-actions

- **Proposed measures to avoid or reduce such increases are:**

Not applicable.

2. **How would the proposal be likely to affect plants, animals, fish, or marine life?**

The proposal will not adversely affect plants, animals, fish, or marine life. The proposal is intended to provide water quality and habitat protection for all aquatic life.

The protection is reflected by revising natural conditions provisions, which recognize that conditions in some surface waters during some seasons and in some areas naturally do not meet biologically based numeric criteria. For example, a naturally low-flowing stream in a natural prairie without any human alteration or human-caused pollution may have seasonally higher temperatures than the limit set to protect fish. These inconsistencies may be due to natural processes or seasonal conditions that prevent a waterbody from meeting the applicable aquatic life criteria. Our proposed revisions refine the natural conditions provisions to protect characteristics inherent and unique to a specific water.

- **Proposed measures to protect or conserve plants, animals, fish, or marine life are:**

No additional measures are needed as a result of this rulemaking. The proposed rule revisions are designed to provide protection for endangered species and their populations. These protections align with EPA policy for protecting aquatic life using the natural condition of a water.

3. **How would the proposal be likely to deplete energy or natural resources?**

The proposal will not deplete energy or natural resources.

- **Proposed measures to protect or conserve energy and natural resources are:**

Not applicable.

4. **How would the proposal be likely to use or affect environmentally sensitive areas or areas designated (or eligible or under study) for governmental protection, such as parks, wilderness, wild and scenic rivers, threatened or endangered species habitat, historic or cultural sites, wetlands, floodplains, or prime farmlands?**

Not applicable.

- **Proposed measures to protect such resources or to avoid or reduce impacts are:**

Not applicable.

5. **How would the proposal be likely to affect land and shoreline use, including whether it would allow or encourage land or shoreline uses incompatible with existing plans?**

Not applicable.

- **Proposed measures to avoid or reduce shoreline and land use impacts are:**

Not applicable.

6. **How would the proposal be likely to increase demands on transportation or public services and utilities?**

The proposal will not result in increased demands on transportation or public services and utilities.

- **Proposed measures to reduce or respond to such demand(s) are:**

Not applicable.

7. **Identify, if possible, whether the proposal may conflict with local, state, or federal laws or requirements for the protection of the environment.**

The proposal will not conflict with local, state, or federal laws or requirements since the Washington State Department of Ecology is the sole agency responsible for developing water quality standards under the Federal Clean Water Act. The final rule, once adopted, will need to receive federal approval from the U.S. Environmental Protection Agency before it can be used for Clean Water Act purposes.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 10
1200 Sixth Avenue, Suite 155
Seattle, WA 98101

WATER
DIVISION

November 19, 2021

Mr. Vince McGowan
Water Quality Program Manager
Washington State Department of Ecology
PO Box 47600
Olympia, Washington 98504-7600

Re: EPA's Action on Revisions to the Washington State Department of Ecology's Surface Water Quality Standards for Natural Conditions Provisions

Dear Mr. McGowan:

The U.S. Environmental Protection Agency (EPA) has completed the review and reconsideration of Washington's natural conditions provisions (WAC 173-201A-200(1)(c)(i), 173-201A-210(1)(c)(i), 173-201A-200(1)(c)(v), 173-201A-200(1)(d)(i), 173-201A-210(1)(d)(i), 173-201A-200(1)(d)(ii), and 173-201A-260(1)(a)), which were submitted to EPA by the Washington Department of Ecology in 2003 and 2006. Under section 303(c) of the Clean Water Act (CWA), 33 U.S.C. § 1313(c), states must submit new and revised water quality standards to EPA for review and action, and EPA approves those water quality standards if they meet the requirements of the CWA and EPA's implementing regulations. EPA's review and reconsideration is outlined below and further described in the enclosed Technical Support Document.

As you are aware, on February 10, 2014, the Northwest Environmental Advocates filed a complaint in U.S. District Court for the Western District of Washington (Case No. 2:14-cv-0196-RSM) challenging, in part, EPA's February 11, 2008 CWA section 303(c) approval of the natural conditions provisions identified above. On October 17, 2018, the Court issued an Order Granting a Stay (Dkt. 95) pending EPA's reconsideration of its prior determinations. The Court subsequently granted an extension for EPA to complete its reconsideration by November 19, 2021 (Dkt. 118).

EPA's CWA section 303(c) action applies only to waters in the State of Washington and does not apply to waters that are within Indian Country, as defined in 18 U.S.C. § 1151. Nothing in the enclosed decision document shall constitute an approval or disapproval of a water quality standard that applies to waters within Indian Country. EPA, or authorized Indian Tribes, as appropriate, will retain responsibilities for water quality standards for waters within Indian Country.

Summary of EPA's Action

EPA has completed its reconsideration, as contemplated by the Court's Order, and is not changing its February 11, 2008 approval of the revisions to the following sections of WAC Chapter 173-201A.

- WAC 173-201A-200(1)(c)(v): Natural condition narrative aquatic life temperature criteria for lakes

- WAC 173-201A-200(1)(d)(ii): Natural condition narrative aquatic life dissolved oxygen criteria for lakes

Because EPA is not changing its earlier approval, it is taking no new action with respect to those provisions.

EPA has completed its reconsideration, as contemplated by the Court's Order, and is disapproving revisions to the following sections of WAC Chapter 173-201A pursuant to its authority under section 303(c)(3) of the CWA, 33 U.S.C. § 1313(c)(3), and 40 CFR Part 131:

- WAC 173-201A-260(1)(a): Natural and irreversible human conditions
- WAC 173-201A-200(1)(c)(i) and WAC 173-201A-210(1)(c)(i): Allowable human contribution to natural conditions provisions for aquatic life temperature (fresh water and marine water, respectively)
- WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i): Allowable human contribution to natural conditions provisions for aquatic life dissolved oxygen (fresh water and marine water, respectively)

EPA appreciates Ecology's commitment and ongoing work to update Washington's water quality standards. We also appreciate the collaboration by your staff to address the complexities associated with criteria revisions. If you have any questions regarding this letter, please contact me at (206) 553-1855 or Lindsay Guzzo, EPA staff lead, at (206) 553-0268 or Guzzo.Lindsay@epa.gov.

Sincerely,

DANIEL OPALSKI

Digitally signed by DANIEL OPALSKI
Date: 2021.11.19 09:38:35 -08'00'

Daniel D. Opalski
Director

Enclosure: Technical Support Document

cc (e-Copy): Ms. Melissa Gildersleeve, Water Quality Management Section Manager, Ecology
Mr. Chad Brown, Water Quality Management Unit Supervisor, Ecology

Technical Support Document

EPA's Clean Water Act Action on Revisions to the Washington State Department of Ecology's Surface Water Quality Standards for Natural Conditions Provisions

November 19, 2021

I. Clean Water Act Requirements for Water Quality Standards

The objective of the Clean Water Act (CWA) is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters with an interim goal, where attainable, to achieve water quality that provides for the protection and propagation of fish, shellfish, and wildlife and recreation in and on the water. Under section 303(c) of the CWA and federal implementing regulations at 40 CFR § 131.4, states (and authorized tribes) have the primary responsibility for reviewing, establishing, and revising water quality standards (WQS). These standards include the designated uses of a waterbody or waterbody segment, the water quality criteria that protect those designated uses, and an antidegradation policy. This statutory and regulatory framework allows states to work with local communities to adopt appropriate designated uses (as required at 40 CFR § 131.10(a)) and to adopt criteria to protect those designated uses (as required at 40 CFR § 131.11(a)).

States are required to hold public hearings for the purpose of reviewing applicable WQS periodically but at least once every three years and, as appropriate, modify and adopt these standards (40 CFR § 131.20). Each state must follow applicable legal procedures for revising or adopting such standards (40 CFR § 131.5(a)(6)) and submit certification by the state's attorney general, or other appropriate legal authority within the state, that the WQS were duly adopted pursuant to state law (40 CFR §131.6(e)). The U.S. Environmental Protection Agency's (EPA) review authority and the minimum requirements for state WQS submittals are described at 40 CFR § 131.5 and 131.6, respectively.

States are required by 40 CFR § 131.11(a) to adopt water quality criteria that protect their designated uses. In adopting such criteria, states should establish numeric values based on one of the following:

(1) CWA section 304(a) guidance;
(2) CWA section 304(a) guidance modified to reflect site-specific conditions; or,
(3) Other scientifically defensible methods (40 CFR § 131.11(b)(1)).

In addition, states should establish narrative criteria where numeric criteria cannot be established or to supplement numeric criteria (see 40 CFR § 131.11(b)(2)).

Section 303(c) of the CWA requires states to submit new or revised WQS to EPA for review and action. EPA reviews these changes and approves the WQS if they meet the requirements of the CWA and EPA's implementing regulations.

EPA considers four questions (described below) when evaluating whether a particular provision is a new or revised WQS. If all four questions are answered "yes" then the provision would likely constitute a new or revised WQS that EPA has the authority and duty to approve or disapprove under CWA § 303(c)(3).[1]

1. Is it a legally binding provision adopted or established pursuant to state or tribal law?
2. Does the provision address designated uses, water quality criteria (narrative or numeric) to protect designated uses, and/or antidegradation requirements for waters of the United States?

[1] *What is a New or Revised Water Quality Standard under 303(c)(3)? Frequently Asked Questions*, EPA No. 820F12017 (Oct. 2012). Available at https://www.epa.gov/sites/production/files/2014-11/documents/cwa303faq.pdf

3. Does the provision express or establish the desired condition (e.g., uses, criteria) or instream level of protection (e.g., antidegradation requirements) for waters of the United States immediately or mandate how it will be expressed or established for such waters in the future?
4. Does the provision establish a new WQS or revise an existing WQS?

If EPA approves a state's WQS submission, such standard(s) shall thereafter be the applicable standard for CWA purposes. When EPA disapproves a state's WQS, EPA shall notify the state and specify why the WQS is not in compliance with the requirements of the CWA and federal WQS regulations and specify any changes that are needed to meet such requirements (33 U.S.C. § 1313(c)(3); 40 CFR § 131.21).

Finally, EPA considers non-substantive edits to existing WQS to constitute new or revised WQS that EPA has the authority to approve or disapprove under § 303(c)(3). While such edits and changes do not substantively change the meaning or intent of the existing WQS, EPA believes it is reasonable to treat such edits and changes in this manner to ensure public transparency as to which provisions are applicable for purposes of the CWA. EPA notes that the scope of its review and action on non-substantive edits or editorial changes extends only to the edits or changes themselves. EPA does not re-open or reconsider the underlying WQS that are the subject of the non-substantive edits or editorial changes.

II. Background

On February 10, 2014, the Northwest Environmental Advocates filed a complaint in U.S. District Court for the Western District of Washington (Case No. 2:14-cv-0196-RSM) challenging, in part, EPA's February 11, 2008 CWA section 303(c) approval of the natural conditions provisions. On October 17, 2018, the Court issued an Order Granting a Stay (Dkt. 95) pending EPA's reconsideration of its prior determinations. The Order noted that EPA may complete its reconsideration by October 17, 2021, by making approval or disapproval decisions, or a final determination that such provisions are not water quality standards. The Court subsequently granted an extension for EPA to complete its reconsideration by November 19, 2021 (Dkt. 118).

This Technical Support Document constitutes EPA's reconsideration of the remaining provisions subject to the Court Order. EPA previously completed its review and reconsideration of the other provisions in actions dated April 30, 2019, October 13, 2020, and September 30, 2021.

III. Results of EPA's Reconsideration

In its February 11, 2008 action, EPA approved the revised natural conditions provisions at:

- WAC 173-201A-200(1)(c)(i) and WAC 173-201A-210(1)(c)(i): Allowable human contribution to natural conditions provisions for aquatic life temperature (fresh water and marine water, respectively);
- WAC 173-201A-200(1)(c)(v): Natural condition narrative aquatic life temperature criteria for lakes;
- WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i): Allowable human contribution to natural conditions provisions for aquatic life dissolved oxygen (for fresh water and marine water, respectively);

- WAC 173-201A-200(1)(d)(ii): Natural condition narrative aquatic life dissolved oxygen criteria for lakes; and
- WAC 173-201A-260(1)(a): Natural and Irreversible Human Conditions.

Upon reconsideration, EPA is not changing and taking no action with respect to the February 11, 2008 approval of the provisions at WAC 173-201A-200(1)(c)(v) and WAC 173-201A-200(1)(d)(ii). EPA is disapproving the provisions at WAC 173-201A-200(1)(c)(i), WAC 173-201A-210(1)(c)(i), WAC 173-201A-200(1)(d)(i), WAC 173-201A-210(1)(d)(i), and WAC 173-201A-260(1)(a).

EPA's CWA section 303(c) action and the associated rationales are provided below. Today's action applies only to waters within the jurisdiction of the State of Washington and does not apply to waters that are within Indian Country, as defined in 18 U.S.C. § 1151. Nothing in this decision document shall constitute an approval or disapproval of a WQS that applies to waters within Indian Country. EPA, or authorized Indian Tribes, as appropriate, retain the authority to establish WQS for waters within Indian Country.

1. Natural Conditions Narrative Criteria For Lakes

In its February 11, 2008 action, EPA approved the revised temperature and dissolved oxygen natural conditions narrative criteria for lakes at WAC 173-201A-200(1)(c)(v) and WAC 173-201A-200(1)(d)(ii), respectively. More detail and information regarding EPA's action can be found in the 2008 decision document.[2]

The underlined text indicates the new and/or revised language from Ecology's 2006 WQS submittal, and strikeout text indicates Ecology's previous text, which had been replaced by the new or revised text.

Aquatic life temperature criteria for lakes

> **WAC 173-201A-200(1)(c)(v):** For lakes, human actions considered cumulatively may not increase the 7-DADMax temperature more than 0.3°C (0.54°F) above natural conditions. ~~Temperature - no measurable change from natural conditions.~~

Aquatic life dissolved oxygen criteria for lakes

> **WAC 173- 201A-200(1)(d)(ii):** For lakes, human actions considered cumulatively may not decrease the dissolved oxygen concentration more than 0.2 mg/L below natural conditions. ~~Dissolved oxygen - no measurable decrease from natural conditions.~~

EPA's Reconsideration: EPA has completed its reconsideration and is taking no action with respect to its February 11, 2008 approval of the revisions at WAC 173-201A-200(1)(c)(v) and WAC 173-201A-200(1)(d)(ii).

EPA Rationale for the 2008 approval:
In 2006, Ecology submitted revisions to the temperature and dissolved oxygen aquatic life criteria for lakes. The revisions clarified and quantified the previous criteria of "no measurable change from natural

[2] February 11, 2008. Letter from Michael F. Gearheard, Director, Office of Water & Watersheds, EPA Region 10, to David C. Peeler, Program Manager, Department of Ecology, re: EPA Approval of the 2003/2006 Revisions to the Washington Water Quality Standards Regulations. Available at: https://www.epa.gov/sites/production/files/2017-10/documents/wawqs-letter-02112008.pdf

conditions" (for temperature) and "no measurable decrease from natural conditions" (for dissolved oxygen) by identifying a 0.3°C increase in temperature and a 0.2 mg/L decrease in dissolved oxygen as what would constitute a "measurable" departure from natural conditions. For temperature, the revision also added a 7-DADMax metric to the criterion.

In the February 11, 2008, Technical Support Document, EPA concluded that a 0.3°C increase in temperature from natural conditions was insignificant and well within the range of uncertainty of the thermal requirements for salmon, which is approximately +/- 0.5°C. EPA also noted that 0.3°C was consistent with reliable field detection levels for temperature and is therefore considered within the error band associated with typical temperature monitors (pp. 27-28). The revised temperature criterion also added the 7-DADMax metric recommended for temperature standards by the *Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards* (EPA910-B-03-002, April 2003, hereinafter referred to as "Temperature Guidance") and that EPA determined to be scientifically defensible (p.4). EPA's 2008 approval, therefore, concluded that Washington's revisions to the aquatic life temperature criterion for lakes were protective of designated uses and scientifically defensible.

In assessing Washington's revisions to the dissolved oxygen criterion for lakes, EPA similarly concluded that a 0.2 mg/L decrease from natural conditions was insignificant. The 2008 approval rationale explained that an allowable decrease of 0.2 mg/L is within the monitoring measurement error for recording instruments typically used to monitor dissolved oxygen. EPA also explained that numerous factors impact oxygen levels in lakes and without at least some allowance for insignificant decreases a natural conditions criterion for dissolved oxygen in lakes would be unnecessarily restrictive for the protection of designated uses (p. 32). EPA's 2008 approval, therefore, concluded that Washington's revisions to the aquatic life dissolved oxygen criterion for lakes was protective of designated uses and scientifically defensible.

The narrative criteria are the applicable temperature and dissolved oxygen criteria for lakes in Washington, and leaving in place EPA's 2008 approval of these criteria ensures that aquatic life criteria for temperature and dissolved oxygen in lakes remain in effect for CWA purposes.

2. Natural and Irreversible Human Conditions

In its February 11, 2008 action, EPA approved the new narrative natural conditions provision at WAC 173-201A-260(1)(a) and took no action on the irreversible human conditions provision at WAC 173-201A-260(1)(b) after concluding the provision is not a WQS that EPA has the authority to approve or disapprove under section 303(c) of the CWA. More detail and information regarding EPA's action can be found in the 2008 decision document.[3]

With respect to WAC 173-201A-260(1)(a), EPA's 2008 decision stated that it is acceptable, under certain circumstances, for water quality criteria to reflect the natural condition of a water body as an alternative to the generally applicable numeric criteria. The rationale for this was that Washington's designated uses were supported by the water in its natural condition, prior to any human effects on water quality.

[3] February 11, 2008. Letter from Michael F. Gearheard, Director, Office of Water & Watersheds, EPA Region 10, to David C. Peeler, Program Manager, Department of Ecology, re: EPA Approval of the 2003/2006 Revisions to the Washington Water Quality Standards Regulations. Available at: https://www.epa.gov/sites/production/files/2017-10/documents/wawqs-letter-02112008.pdf

The text of the provision first appeared in a 2003 water quality standards submittal to EPA and again in a 2006 submittal and is excerpted below.

> **WAC 173-201A-260(1):** Natural and irreversible human conditions.
> (a) It is recognized that portions of many water bodies cannot meet the assigned criteria due to the natural conditions of the water body. When a water body does not meet its assigned criteria due to natural climatic or landscape attributes, the natural conditions constitute the water quality criteria.

EPA's Reconsideration: EPA has completed its reconsideration and in accordance with its CWA authority, 33 U.S.C. § 1313(c)(3) and 40 CFR Part 131, disapproves the provision at WAC 173-201A-260(1)(a).

EPA Rationale: The natural conditions narrative provision at WAC 173-201A-260(1)(a) is broadly drafted and does not specify the types of criteria or pollutants to which it applies. On reconsideration, EPA concludes that as written this provision could be applied to a wide range of naturally occuring pollutants, including toxic pollutants, and could even allow an exception from otherwise applicable numeric human health criteria. Therefore, it is not consistent with EPA's interpretation of the relationship between natural conditions and the protection of designated human health uses, which is articulated in EPA's November 5, 1997 policy guidance entitled ''Establishing Site Specific Aquatic Life Criteria Equal to Natural Background.''[4] EPA's 2008 decision document cited to the 1997 policy guidance, as well as to language in an Advance Notice of Proposed Rulemaking for the Water Quality Standards program (*see* 63 Fed. Reg. 36,724, 36761 (Jul. 7, 1998)), as setting forth the relevant policy considerations for establishing water quality criteria based on natural conditions. However, what EPA failed to appropriately consider in its 2008 decision is that these documents only addressed the establishment of aquatic life criteria for pollutants at levels equal to the natural background condition, and expressly did not apply to human health uses, whereas the provision at WAC 173-201A-260(1)(a) is not similarly limited in scope to aquatic life uses or to specific pollutants.

In contrast with aquatic life uses, a naturally occurring level of a pollutant does not necessarily protect designated human health uses. Naturally occurring levels of a pollutant are assumed to protect aquatic life species that have naturally developed in the affected waters. However, humans generally do not adapt to higher ambient pollutant levels, even if they are naturally caused. Consequently, the same assumptions of protectiveness cannot be made with regard to designated uses that affect human health (*e.g.,* people eating fish or shellfish from Washington waters, and recreating in Washington waters). For this reason, EPA's 1997 guidance also states that where the natural background concentration exceeds the state-adopted human health criterion, at a minimum, states should re-evaluate the human health use designation.[5]

No Changes Necessary to Address the Disapproval: The effect of EPA's disapproval is that, as of the date of this action, the provision at WAC 173-210A-260(1)(a) is no longer an applicable WQS for CWA purposes. Because Washington's WQS currently include applicable numeric criteria that EPA determined to be protective of designated uses, no changes to Washington's WQS are necessary to meet the requirements of the CWA. Therefore, EPA is not specifying any changes that Washington must

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[4] Davies, Tudor T., *Establishing Site Specific Aquatic Life Criteria Equal to Natural Background,* EPA Memorandum to Water Management Division Directors, Regions 1–10, State and Tribal Water Quality Management Program Directors, posted at: *https://www.epa.gov/sites/default/files/2014-08/documents/naturalbackground-memo.pdf*
[5] *Id.* at p. 2.

adopt to meet CWA requirements. EPA provides the following discretionary recommendations for the State's consideration.

EPA understands that WAC 173-201A-260(1)(a) was developed in parallel with numeric aquatic life criteria for marine and fresh waters, and that Washington intended to rely on the natural condition narrative to address circumstances where waterbody conditions are naturally less stringent than the adopted biologically-based numeric aquatic life criteria. In this respect the availability of a criterion that accounts for less stringent natural conditions was an important consideration in the establishment of numeric criteria for aquatic life. EPA continues to believe that appropriately drafted natural condition provisions can serve an important role in state WQS by reflecting a naturally occuring spatial and temporal variability in water quality that is protective of uses. A new general natural condition provision that is narrowly tailored to aquatic life uses could be adopted as a narrative criterion where numerical criteria cannot be established or to supplement numerical criteria (40 C.F.R. § 131.11(b)(2)). Alternatively, the adoption of a performance-based approach could be used to establish aquatic life criteria reflecting a natural condition for specific pollutants (see discussion for temperature and dissolved oxygen below).

EPA recommends removing the current WAC 173-201A-260(1)(a) from the State's WQS regulations to avoid confusion and provide greater clarity as to what is in effect for CWA purposes.

3. Allowable Human Contribution to Natural Conditions Provisions for Aquatic Life Temperature and Dissolved Oxygen Criteria For Fresh and Marine Waters

In its February 11, 2008 action, EPA approved the new and revised natural conditions provisions for temperature in fresh and marine waters at WAC 173-201A-200(1)(c)(i) and WAC 173-201A-210(1)(c)(i), respectively; and for dissolved oxygen in fresh and marine waters at WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i), respectively. More detail and information regarding EPA's action can be found in the 2008 decision document.[6]

In the 2008 approval, EPA determined that insignificant temperature increases or insignificant decreases of dissolved oxygen concentrations above or below the natural condition were protective of the applicable designated uses because such insignificant departures from the natural condition were within the range of scientific uncertainty of effects on designated uses and/or within the error band associated with typical monitoring equipment. Specific to temperature, these "de minimis" allowable human-caused increases above natural conditions are consistent with the Temperature Guidance.[7]

The texts of each of the provisions are excerpted below.

Allowable human contribution to natural conditions provisions for aquatic life temperature:

> **Freshwater, WAC 173-201A-200(1)(c)(i):** When a water body's temperature is warmer than the criteria in Table 200 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to

[6] February 11, 2008. Letter from Michael F. Gearheard, Director, Office of Water & Watersheds, EPA Region 10, to David C. Peeler, Program Manager, Department of Ecology, re: EPA Approval of the 2003/2006 Revisions to the Washington Water Quality Standards Regulations. Available at: https://www.epa.gov/sites/production/files/2017-10/documents/wawqs-letter-02112008.pdf

[7] EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. EPA-910-B-03-002. April 2003. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi/P1004IUI.PDF?Dockey=P1004IUI.PDF

natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).

Marine water, WAC 173-201A-210(1)(c)(i): When a water body's temperature is warmer than the criteria in Table 210 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).

Allowable human contribution to natural conditions provisions for aquatic life dissolved oxygen:

Freshwater, WAC 173- 201A-200(1)(d)(i): When a water body's D.O. is lower than the criteria in Table 200 (1)(d) (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the D.O. of that water body to decrease more than 0.2 mg/L.

Marine water, WAC 173-201A-210(1)(d)(i): When a water body's D.O. is lower than the criteria in Table 210 (1)(d) (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the D.O. of that water body to decrease more than 0.2 mg/L.

EPA's Reconsideration: EPA has completed its reconsideration and in accordance with its CWA authority, 33 U.S.C. § 1313(c)(3) and 40 CFR Part 131, disapproves the provisions at WAC 173-201A-200(1)(c)(i), WAC 173-201A-210(1)(c)(i), WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i).

EPA Rationale:
The allowable human contribution to natural condition provisions for temperature (WAC 173-201A-200(1)(c)(i) and 210(1)(c)(i)) and disolved oxygen (WAC 173-201A-200(1)(d)(i) and 210(1)(d)(i)) allow for human actions considered cumulatively to cause insignificant increases in temperature (0.3ºC) or decreases in dissolved oxygen (0.2mg/L) from the natural condition of the waterbody. As discussed above, EPA is disapproving the provision at WAC 173-201A-260(1)(a) that allows for the natural condition of a waterbody to constitute the applicable criteria when the natural condition is less stringent than otherwise applicable numeric criteria.[8] Absent an approved WQS that allows for the natural condition to constitute the applicable water quality criteria, the applicable criteria for temperature and dissolved oxygen in Washington waters are the numeric criteria in Tables 200(1)(c) and (1)(d) and 210(1)(c) and (1)(d). However, the temperature and dissolved oxygen natural condition provisions are based on the natural condition of the waterbody; the provisions do not authorize human actions to cause insignificant exceedances to the applicable numeric criteria. EPA is therefore disapproving the temperature and dissolved oxygen provisions that allow insignificant human impacts to the natural condition because such impacts are not tied to approved criteria that are in effect under the CWA.

No Changes Necessary to Address the Disapproval: The effect of EPA's disapproval is that, as of the date of this action, the provisions at WAC 173-201A-200(1)(c)(i), WAC 173-201A-210(1)(c)(i), WAC 173-201A-200(1)(d)(i), and WAC 173-201A-210(1)(d)(i) are no longer applicable WQS for CWA purposes. Because Washington's WQS currently include applicable biologically-based numeric criteria

[8] EPA's interpretation of WAC 173-201A-260(1)(a) is consistent with Ecology's January 29, 2016 letter in which it stated "[t]he rule makes it clear that where Ecology identifies a natural condition that is less stringent than the numeric criteria in the state's water quality standards, the natural condition supersedes the numeric criteria." Letter from David C. Peeler, Water Quality Program Manager, Ecology, to Michael Gearheard, EPA Region 10, Re: Ecology Responses to USEPA Region 10 Questions Regarding Washington's 2003 Adopted Water Quality Standards, p. 2.

for temperature and dissolved oxygen that EPA determined to be protective of designated uses, no changes to Washington's WQS are necessary to meet the requirements of the CWA. Therefore, EPA is not specifying any changes that Washington must adopt to meet CWA requirements. EPA provides the following discretionary recommendations for the State's consideration.

Washington, at its discretion, could adopt new natural conditions criteria specific to temperature and/or dissolved oxygen. One possibility would be for Washington to adopt into its WQS a performance-based approach for establishing temperature and/or dissolved oxygen criteria representative of the natural condition of a waterbody. A performance-based approach is a binding methodology that provides a transparent, predictable, repeatable, and scientifically defensible procedure to derive numeric criteria or to translate a narrative criterion into quantifiable measures that are protective of designated uses. The performance-based approach relies on the adoption of a systematic process (i.e., a criterion derivation methodology) rather than a specific outcome (i.e., concentration limit for a pollutant) consistent with 40 CFR Sections 131.11 and 131.13. When such a performance-based approach is sufficiently detailed and has suitable safeguards to ensure predictable, repeatable outcomes, EPA approval of such an approach also serves as approval of the outcomes as well. *See EPA Review and Approval of State Water Quality Standards*, 65 FR 24,641, 24,649 (Apr. 27, 2000).

A second possibility would be for Washington to adopt numeric temperature and dissolved oxygen criteria that account for natural conditions using the best available relevant data. EPA encourages Washington to consider magnitude, frequency, and duration components in setting water quality criteria to protect against acute and chronic effects.[9] This may include establishing protective site-specific criteria accounting for specific characteristics, such as unique temperature and/or dissolved oxygen regimes in different waterbodies (see EPA's Temperature Guidance).[10] Site-specific criteria established in this manner would be subject to CWA section 303(c) review.

Washington, at its discretion, could also choose to adopt new WQS provisions that allow for human actions, considered cumulatively, to cause insignificant exceedances in temperature and dissolved oxygen. As articulated in the 2008 Technical Support Document, EPA believes insignificant or de minimis exceedances to applicable temperature and/or dissolved oxygen criteria caused by human actions, considered cumulatively, may still be protective of designated uses.[11] Any such human use allowance provision must be scientifically defensible and tied to approved criteria that are protective of designated uses, which could include criteria based on the natural condition of the waterbody.

EPA recommends removing the disapproved provisions from the State's WQS regulations to avoid confusion and provide greater clarity to what is in effect for CWA purposes.

[9] EPA Water Quality Standards Handbook – Chapter 3: Water Quality Criteria. EPA-823—B-17-001; 2017. Available at https://www.epa.gov/sites/production/files/2014-10/documents/handbook-chapter3.pdf

[10] EPA Issue Paper 3: Spatial and Temporal Patterns of Stream Temperature (Revised), October 2001. EPA-910-D-01-003, pages 2-9. Available at https://www.epa.gov/sites/production/files/2018-01/documents/r10-water-quality-temperature-issue-paper3-2001.pdf

[11] 2008 TSD at pp. 20-21, 32.

SCHOOL OF AQUATIC AND FISHERY SCIENCES
UNIVERSITY of WASHINGTON

March 27, 2020

Opinion on Puget Sound Nutrient Source Reduction Project Dissolved Oxygen Modeling and Bounding Scenarios (Ahmed et al. 2019)

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The Salish Sea Model is being used by Washington Department of Ecology to predict dissolved oxygen (DO) throughout the Salish Sea at multiple depths to assess whether any areas are out of compliance with the Washington Water Quality Standard of 0.2 mg/L decrease in dissolved oxygen due to human activities. Results of initial bounding scenarios are presented in Ahmed et al. 2019[i], where existing dissolved oxygen concentration (with human influence) were modeled for 2006, 2008, and 2014. Assumed "reference" conditions (conditions without human impact) for each year were also modeled where watershed and marine source nitrogen and carbon loads were set to an estimated natural level. The report concludes that regional nutrient contributions from humans exacerbate low DO causing approximately 20% (19%–23%) of the greater Puget Sound (by surface area) to fall below the dissolved oxygen standards (pg. 62). The opinions expressed below are based on our reading of this report and two subsequent conversations between Holtgrieve and Washington Department of Ecology staff about the modeling process (hereafter, Ecology).

Our overall concern is that the inappropriate treatment of uncertainty in the analysis, and the minimal effort to communicate that uncertainty, leads to a general overconfidence that nutrients are in fact a meaningful problem in the Puget Sound. A proper uncertainty assessment will decrease the surface area of Puget Sound considered out of compliance substantially (visually estimated to be a more than 80% reduction). Washington Department of Ecology, in essence, assumes their model is a perfect understanding of dissolved oxygen in Puget Sound. In fact, we know the model does not represent *in situ* dissolved oxygen conditions well enough to determine if a particular point on the map is not in compliance at the level of certainty expressed in the report (0.030–0.049 mg/L, page 59). All models have uncertainty, including uncertainty about the model itself, uncertainty in the parameters, and uncertainty in the data used to calibrate the model. This fundamental fact dictates that environmental modeling in support of decision-making must accurately and transparently incorporate uncertainty into analyses and policy documents.[ii] To make effective decisions, you must know not only the best scientific estimate of what is happening but also the chance of being wrong, which in this case is quite high. The information provided by Ahmed et al. 2019 falls well short of what can be considered appropriate treatment of uncertainty in environmental decision-making.[iii]

In establishing whether or not a location in Puget Sound at a given time is in compliance, there are two tests, conducted in series, and the site is considered out of compliance if both answers are affirmative:

1) Is the reference condition model prediction of dissolved oxygen below a threshold? The threshold is from 4 to 7 mg/L, varying by location.[iv]
2) Is the difference of existing and reference dissolved oxygen ≥ 0.2 mg/L? This is a comparison of two model runs, one for existing condition and a second for reference conditions.

There is uncertainty associated with both tests that must be considered. Currently the process only considers uncertainty for the second question and treats the first as being completely without error. This is incorrect. Furthermore, the calculation of the uncertainty of the difference between existing and reference conditions (i.e., question 2) as defined on page 59 of Ahmed et al. 2019 is incorrect. Ahmed et al. 2019 incorrectly treat the models' root mean squared error (RMSE) as equivalent to the standard deviation (SD) of the predictions. Third, in estimating the covariance of model runs, Ahmed et al. 2019 greatly inflate their sample size by treating all individual predictions for each cell and depth layer as independent. This artificially raises the covariance between model runs, which in-turn artificially shrinks their estimated standard deviation. Ahmed et al. 2019 also does not formally consider that predictions of unobservable conditions (i.e., the reference conditions) are inherently more uncertain than prediction of observed data – that is, they do not include predication intervals as would be standard for any regression model used to estimate a value that is unobservable.

The document appended below — written by my co-author Mark Scheuerell — details the specifics of why the Ahmed et al. 2019 uncertainty estimates are incorrect; it shows that using RMSE will substantially underestimate the uncertainty and why predictions of unobserved states are inherently more uncertain than comparing model outputs to data. ***Our initial reanalysis demonstrates the true standard deviation of the difference between model predictions is 0.32 mg/L, about 8 times greater than 0.041 mg/L reported in Ahmed et al. 2019 for 2014.*** Note this reanalysis addresses only one of at least four statistical problems.

With a standard deviation of 0.32 mg/L, the 95% prediction interval for the mean is conservatively on the order of ± 0.9 mg/L (assuming a very large sample size; see page 6 in the appendix). Put another way, if the model predicts a value of 6 mg/L for some place and time, we can say the true value is somewhere between 5.1 and 6.9 mg/L with only a 5% chance of being wrong about that. If we want only a 1% chance of being wrong, then we have to expand the possible range to between 4.7 and 7.3 mg/L. If we want to limit the range to being between 5.8 and 6.2 mg/L, then there is roughly a 72% chance of the true value being *outside* that range. This example is highly conservative and is an underestimate of the true uncertainty. ***Nonetheless, the uncertainty of a single prediction is <u>at least</u> 4.5-times higher than the 0.2 mg/L threshold criteria*** when using a 5% acceptable error rate.

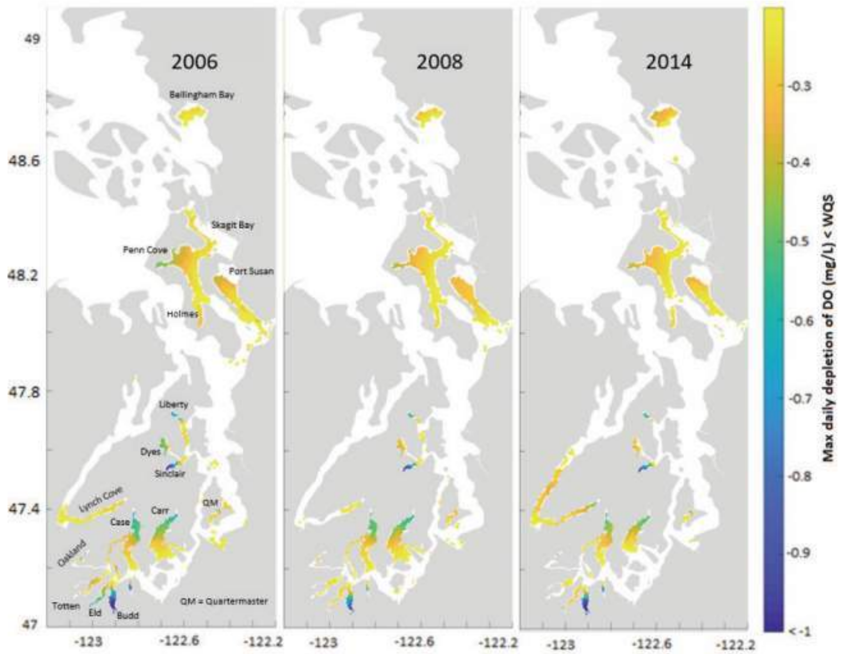

Figure 26 from Ahmed et al. 2019: Maximum dissolved oxygen (DO) depletions from anthropogenic sources in 2006, 2008, and 2014, leading to noncompliance with the water quality standards (WQS).

Given the above and to the extent the information in Ahmed et al. 2019 is true and meaningful, we can say that in order to be 95% confident that a given area of Puget Sound is in fact out of compliance, the model must predict a ≥ 0.9 mg/L depletion of dissolved oxygen. Figure 26 from Ahmed et al. 2019 above shows areas in Puget Sound with >0.2 mg/L depletion (darker areas are more depleted in DO). Only the darkest blue colors are ≥ 0.9 mg/L. ***Therefore, a very small fraction of the areas previously deemed out of compliance meet this 0.9 mg/L threshold for conclusively determining a human effect.*** In fact, most areas in Puget Sound that are currently considered out of compliance are very near the 0.2 mg/L criteria, which means there has been no measurable change in dissolved oxygen given uncertainty in the modeling process.

The four statistical errors described above and in the appended document — 1) not considering errors in prediction of reference dissolved oxygen, 2) use of RMSE in the variance calculations, 3) inflation of sample size, and 4) using confidence estimates rather than prediction estimates — are significant, and we demonstrate that these substantially change the assessment of compliance to the dissolved oxygen standard. In all cases, these statistical errors result in an underestimate of uncertainty that is meaningful for decision-making. We also note that the report does not include a full description of the modeling process, so it is very possible other statistical errors have occurred.

We recommend to Ecology the following:

1. Correct mistakes in calculating model uncertainty. Specifically, specify the standard deviation of the model fits to data rather than using RMSE, remove inflation of covariance by appropriately specifying the sample size, provide prediction intervals for forecasts, and consider uncertainty in both steps of compliance assessment process. We also recommend that validation procedures be employed, were parts of the observed data are held back, the

model parameters are fit, then the predicted results compared to the reserved data using RMSE or, preferably, formal cross-validation.

2. Allow an independent review of the uncertainty analysis related to compliance standards and incorporate all relevant suggestions into a new presentation of results.
3. Present the model uncertainties in a more transparent way that acknowledges that the model has large errors in predicting both absolute concentration and change in dissolved oxygen. Thus, the question about compliance is not really yes or no, but yes or no with a specified chance of being wrong. Policymakers must be presented an analysis with a correctly specified errors that accurately portray current scientific understanding.
4. Present the areas predicted to be out of compliance with an associated type I error probability. That is, make a map of areas that are predicted out of compliance at a 95% level of certainty, also maybe at the 90% and 80% levels. This will let policymakers judge for themselves how willing they are to be wrong, given the inherent communicated uncertainty in the modeling process. ***Acceptable error rate is an important policy decision.***

It is critically important that uncertainty in the model predictions be adequately considered and transparently reported to policymakers, as it will dramatically change the definition of the problem we aim to solve. Ahmed et al. 2019 fails to accomplish this critical task and thus is inconsistent with what is currently considered best practices. ***Mistakes in Ahmed et al. 2019 lead to at least an eight-fold underestimate of uncertainty and overconfidence in the model results, which leads to a systematic overestimate of the area expected to be out of compliance.*** A complete error analysis will undoubtedly increase the error level even more. If/when uncertainty is properly considered, the areas and times deemed out of compliance with the dissolved oxygen standard will decrease dramatically, fundamentally redefining the problem we aim to solve. It is therefore absolutely critical this part of the analysis be done correctly before any decisions are made.

We stand ready to assist Ecology in their analysis if requested.

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[i] Ahmed, A., C. Figueroa-Kaminsky, J. Gala, T. Mohamedali, G. Pelletier, S. McCarthy. 2019. Puget Sound Nutrient Source Reduction Project, Volume 1: Model Updates and Bounding Scenarios. Washington Department of Ecology, Publication No. 19-03-001.

[ii] Clark et al. (2001) Science 293(5530): 657-660.

[iii] Regan et al. (2005) Ecological Applications 15(4): 1471–1477

[iv] This part of the criteria remains a point of confusion and emphasizes the need for greater transparency in compliance assessment. We originally thought that the comparison was with respect to current conditions, as this seems most relevant to the issue at hand. However, on 3 June 2019, Christiana Figueroa-Kaminsky (Ecology) wrote in an email “Please note that to determine compliance with the standard—the first step is to compare natural or reference condition (not existing) with the 5 or 6 mg/L in most inlets. There are no observations for reference condition, so we have no statistics to present there. If the reference condition is below 5 or 6 mg/L for the inlets, we have to use the difference of the model runs (existing minus reference). This is by far the most common type of DO noncompliance found in our region. So, the difference of model runs method is the only way to compute compliance or not in more than about 95% of the instances.” Regardless, considering uncertainty in predictions of absolute concentration (step 1) is necessary but has thus far been ignored.

Critique of model evaluation by the Washington Department of Ecology

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Comparison of existing and reference scenarios

The focus of the modeling analysis is a comparison of results obtained with two scenarios: a "reference" case that represents a system without anthropogenic inputs, and an "existing" case that represents contemporary conditions. Specifically, Ecology is interested in the difference between the modeled concentration of dissolved oxygen estimated via the two models. In addition, Ecology would like to know the estimated uncertainty in that difference.

Variance of predictions

In the section titled "Uncertainty in Dissolved Oxygen Depletion Estimates" (p59), it states,

> The RMSE of differences is calculated to understand the uncertainty associated with the result of subtracting one model scenario from another model scenario (i.e., the difference between two model scenarios). In this case, we calculated the error associated with the DO depletions computed from the difference between the existing and reference model scenarios.

The section then goes on to describe how the calculations were made using the estimated root mean squared error (RMSE) between the predictions and observations, but there is a mistake in the assumed relationship between the standard deviation of the predictions and the RMSE.

Variance of predictions

To demonstrate this, consider this simple equation that relates individual observations (o_i) and predictions (p_i):

$$o_i = p_i + e_i,$$

where e_i are the model prediction errors (i.e., the difference between the observed and predicted values). From this relationship we know that the variance of the observations is a function of the variances of both the predictions and errors, and their covariance, such that

$$\text{Var}(o) = \text{Var}(p) + \text{Var}(e) + 2\ \text{Cov}(p, e)$$

We can rewrite the above equation to show that the variance of the predictions is

$$\text{Var}(p) = \text{Var}(o) - \text{Var}(e) + 2\ \text{Cov}(p, e).$$

Variance in the difference of predictions

In this case Ecology is interested in the uncertainty (variance) in the difference between the predictions from the two models representing existing and reference conditions, which we write as p_{ex} and p_{ref}, respectively. We then define the difference δ as

$$\delta = p_{ex} - p_{ref}$$

and hence

$$\begin{aligned} \text{Var}(\delta) &= \text{Var}(p_{ex}) + \text{Var}(p_{ref}) - 2\ \text{Cov}(p_{ex}, p_{ref}) \\ &= \text{Var}(p_{ex}) + \text{Var}(p_{ref}) - 2\ \text{Cor}(p_{ex}, p_{ref})\ \text{SD}(p_{ex})\ \text{SD}(p_{ref}) \end{aligned}$$

This is where Ecology gets their calculations wrong. In a forecasting context, the hope is that the predictions match the observations very closely and hence the errors are small. One measure of forecast skill is the root mean-squared error (RMSE), which equals the standard deviation of the errors. More specifically,

$$\text{RMSE}_{o,p} = \text{SD}(e) = \sqrt{\text{Var}(e)} = \sqrt{\frac{\sum(p_i - o_i)^2}{N}}.$$

Importantly, however, the $\text{RMSE}_{o,p}$ is not equal to the variance of the predictions, $\text{Var}(p)$, which is required for the calculations of the error in differences.

Re-analysis

The Ecology report does not provide estimates of the variance in the model predictions, but we can generate approximations from the information provided and a simple assumption. For most of the DO models, $\text{RMSE}_{ex} \approx 1$ (Table 7) and the correlation between the predicted and observed values is about 0.85 (Table 8). Recognizing that

$$\text{RMSE}_{ex} = \sqrt{(1 - R^2)}\ \text{SD}(o),$$

we can estimate the SD of the observations as

$$\text{SD}(o) = \frac{\text{RMSE}_{ex}}{\sqrt{(1-R^2)}} \approx \frac{1}{\sqrt{(1-0.85^2)}} \approx 1.9$$

and hence the variance of the observations is

$$\text{Var}(o) = \text{SD}(o)^2 \approx 1.9^2 = 3.61.$$

Now we can estimate the variance of the predictions for the model with existing conditions as above, with

$$\begin{aligned}
\text{Var}(p_{ex}) &= \text{Var}(o) - \text{Var}(e) + 2\ \text{Cov}(p_{ex}, e) \\
&= \text{Var}(o) - \text{RMSE}_{ex}^2 + 2\ \text{Cov}(p_{ex}, e) \\
&\approx 3.6 - 1^2 + 2\ \text{Cov}(p_{ex}, e).
\end{aligned}$$

Absent information on the covariance between the predicted values and the model errors, we will assume that the model is well behaved and $\text{Cov}(p_{ex}, e) \approx 0$, such that

$$\text{Var}(p_{ex}) \approx 3.6 - 1^2 + 2(0) = 2.6$$

To the extent that $\text{Cov}(p_{ex}, e)$ is positive (negative), $\text{Var}(p_{ex})$ will be larger (smaller) than this estimate.

If we also assume, as Ecology did, that $\text{Var}(p_{ex}) = \text{Var}(p_{ref})$, then we can estimate the variance in the difference (δ) between the predictions from the two models as above, such that

$$\begin{aligned}
\text{Var}(\delta) &= \text{Var}(p_{ex}) + \text{Var}(p_{ref}) - 2\ \text{Cor}(p_{ex}, p_{ref})\ \text{SD}(p_{ex})\ \text{SD}(p_{ref}) \\
&= \text{Var}(p_{ex}) + \text{Var}(p_{ex}) - 2\ \text{Cor}(p_{ex}, p_{ref})\ \text{SD}(p_{ex})\ \text{SD}(p_{ex}) \\
&= 2\ \text{Var}(p_{ex}) - 2\ \text{Cor}(p_{ex}, p_{ref})\ \text{Var}(p_{ex}) \\
&= 2\ \text{Var}(p_{ex})\,(1 - \text{Cor}(p_{ex}, p_{ref})) \\
&= 2(2.6)\,(1 - \text{Cor}(p_{ex}, p_{ref}))\,.
\end{aligned}$$

Thus, if $\text{Cor}(p_{ex}, p_{ref}) = 0$, then $\text{Var}(\delta) = 5.2 \Rightarrow \text{SD}(\delta) \approx 2.3$; conversely, as $\text{Cor}(p_{ex}, p_{ref}) \to 1$ then $\text{Var}(\delta) \to 0$.

Although Ecology's report did not say what $\text{Cor}(p_{ex}, p_{ref})$ was, but we can estimate it from the calculations on p59. For example, if we assume that $\text{Var}(\delta) = 0.041$ as for Ecology's model in 2014, then analogous to above we have

$$\text{Var}(\delta) = \text{Var}(p_{ex}) + \text{Var}(p_{ref}) - 2\ \text{Cor}(p_{ex}, p_{ref})\ \text{SD}(p_{ex})\ \text{SD}(p_{ref})$$

$$\Downarrow$$

$$\text{Cor}(p_{ex}, p_{ref}) = \frac{(\text{Var}(\delta) - \text{Var}(p_{ex}) - \text{Var}(p_{ref}))}{-2\ \text{SD}(p_{ex})\ \text{SD}(p_{ref})}$$

$$\approx \frac{(0.041 - 1^2 - 1^2)}{-2(1)(1)}$$

$$\approx 0.98$$

This correlation is remarkably high, indicating that the two models produce nearly identical predictions of DO. Inserting this correlation coefficient into the equation for $\text{Var}(\delta)$ gives $\text{Var}(\delta) = 2(2.6)(1 - 0.98) = 0.104$, and hence $\text{SD}(\delta) \approx 0.32$. This value is about eight times greater than those reported in Ecology's document. Thus, if the treshhold concentration for DO depletion is 0.2 mg/L, then the estimated coefficient of variation (CV) around it is 160%.

Example of SD versus RMSE

Here is a simple example that shows how $\text{SD}(\hat{y})$ and $\text{RMSE}(\hat{y})$ are different. Consider a case where we had reason to believe that a variable y was a function of another variable x. In effort to undercover the nature of their relationship, we collected 20 samples of both y and x (Figure 1).

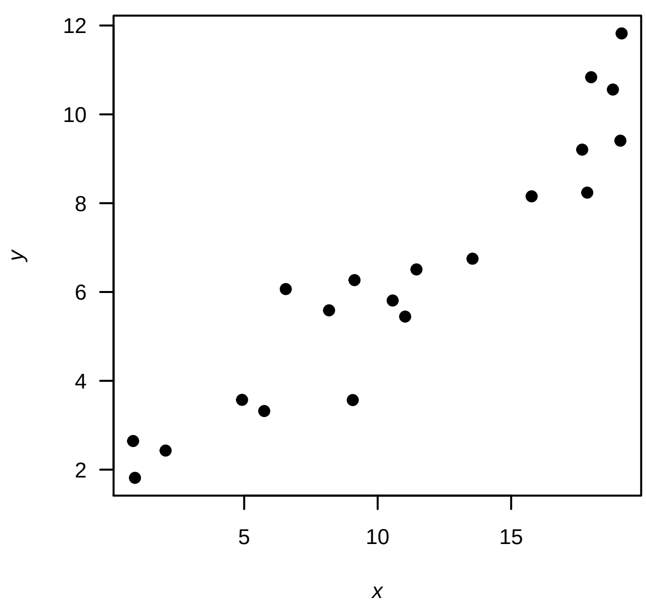

Figure 1. Plot of some hypothetical data.

Based on the apparent relationship between x and y, we might assume that each of the observed values y_i is a linear combination of an intercept β_0, the effect β_1 of a covariate x_i, and some random observation error ϵ_i, such that

$$y_i = \beta_0 + \beta_1 x_i + \epsilon_i,$$

and $\epsilon_i \sim \text{N}(0, \sigma)$. We could easily estimate the unknown parameters in this model (β_0, β_1, σ), and then use the deterministic portion of the model to make predictions to compare with each of the observed values. Specifically, the predictions ($\hat{y}_i$) would be given by a straight line, such that

$$\hat{y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_i.$$

We could then estimate the SD of these predictions and the model's RMSE (Figure 2). It turns out that the SD of $\hat{y}$ is ~2.82, but the RMSE is only ~0.94, which is about 3 times less.

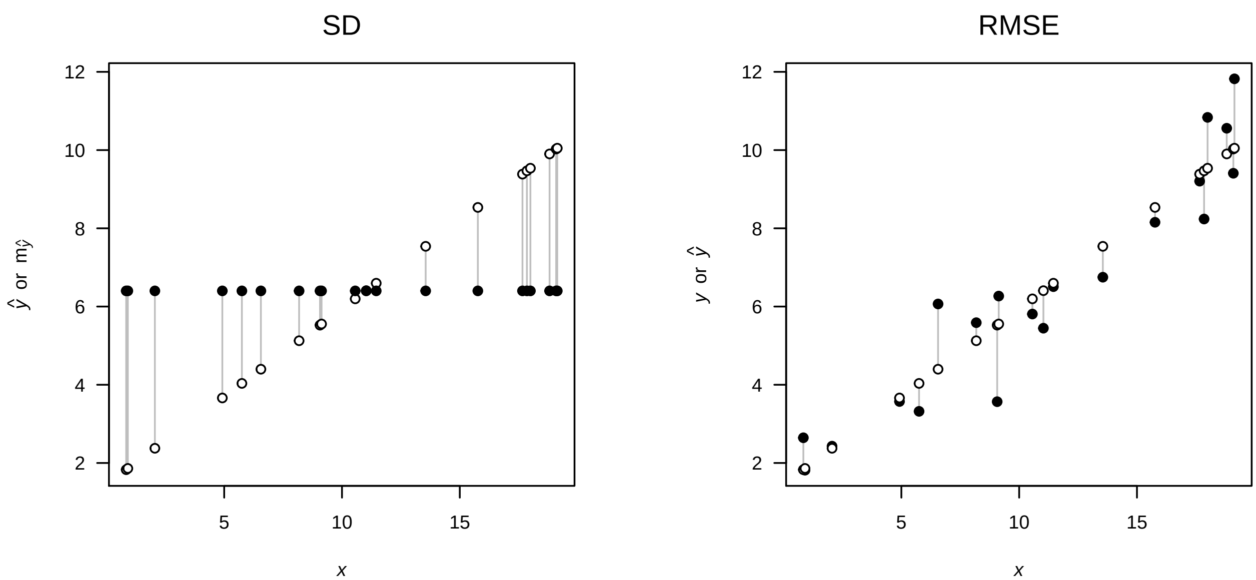

Figure 2. Graphical examples of the difference between the SD of the predictions (left) and the RMSE of the predictions (right). For the SD, the comparison is based upon the differences between the predictions (open circles) and their mean (filled circles). For the RMSE, the comparison is based upon differences between the predictions (open circles) and the observed data (filled circles). In both cases, one would square the length of each of the vertical gray lines, sum them up, and divide by the number of them before finally taking the square root.

Prediction errors

The above example dismisses an important aspect of RMSE: it should be used to compare "out of sample" predictions. Furthermore, RMSE give us an indication as to the predictive error, *on average*, rather than the uncertainty in a specific prediction.

Returning to our example above, we could estimate our uncertainty around the fitted relationship between x and y with a confidence interval (CI), which would give us an indication of the range of where the "true" fitted values would lie had we repeated our sampling exercise many times.

Specifically, a $(1-\alpha)100\%$ CI on the expected relationship between x and y at some value x_k is given by

$$\hat{y}_i \pm t_{\alpha/2,n-2}\sqrt{\sigma\left(\frac{1}{n}+\frac{(x_k-\bar{x})^2}{\sum(x_i-\bar{x})^2}\right)}.$$

The interval increases as the distance between x_k and $\bar{x}$ increases (Figure 3).

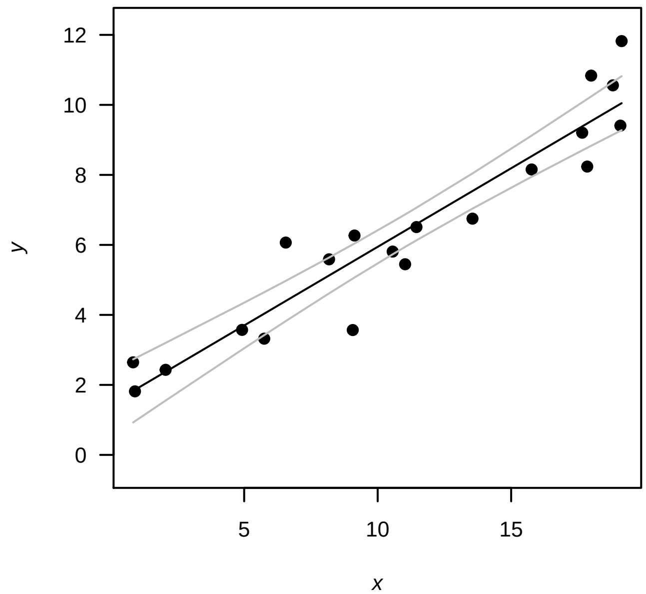

Figure 3. Example of a 95% confidence interval (gray lines) around the expected relationship between x and y (black line).

In a case like this, however, where we wish to make out-of-sample predictions about some new state of nature, our uncertainty around any single prediction will be necessarily greater. Specifically, a $(1-\alpha)100\%$ prediction interval (PI) around $\hat{y}$ at some value x_k is given by

$$\hat{y} \pm t_{\alpha/2,n-2}\sqrt{\sigma\left(1+\frac{1}{n}+\frac{(x_k-\bar{x})^2}{\sum(x_i-\bar{x})^2}\right)}.$$

Here the paranthetic multiplier on the residual variance σ has increased by 1, which means the prediction interval is wider (less certain) than the confidence interval (Figure 4). This is because the CI only needs to account for uncertainty in estimating the expected value of y whereas the PI needs to account for a random future value of y that tend to fall away from the mean.

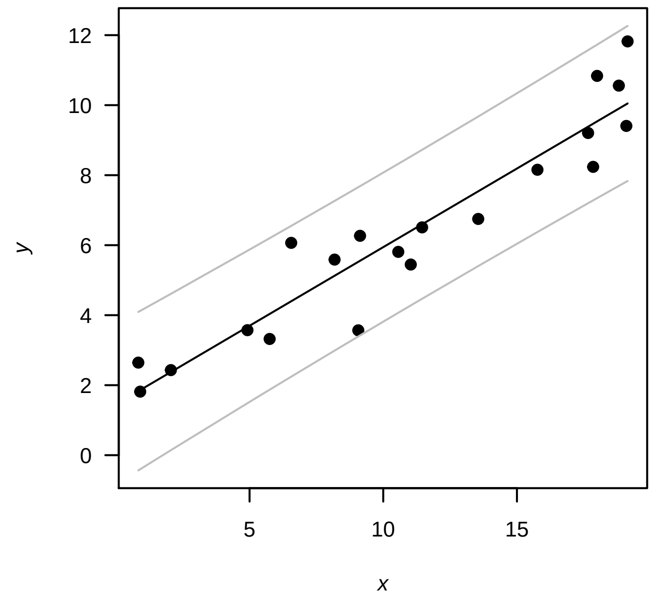

Figure 4. Example of a 95% prediction interval (gray lines) for future unobserved values of y.

So, for example, if we wanted to predict, with 95% certainty, what we would observe for y if $x = 10$, we would get 5.94 ± 2.13 (Figure 5). The relatively wide prediction interval suggests that it might be difficult to discern the prediction for y when $x = 10$ to the expected values for y if x were as low as 5 or as high as 15.

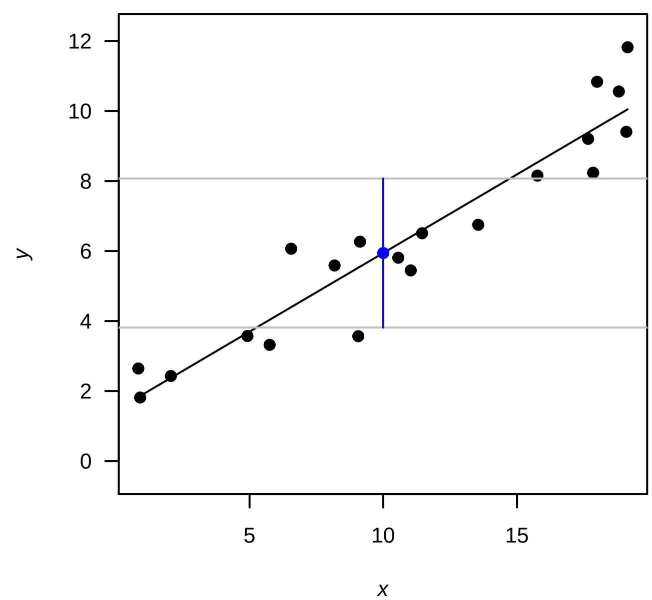

Figure 5. Example of the uncertainty around a new prediction for y when $x = 10$.

Memo

From: Lincoln Loehr
To: Scott Redman
Date: February 29, 2020 (minor corrections April 3, 2020)
Subject: Scientific perspective re dissolved oxygen criteria

It is virtually certain that the dissolved oxygen criteria are not biologically based, and have no documented scientific foundation. The dissolved oxygen criteria are the driver in the modeling efforts to date, and in the Department of Ecology's assertions of reasonable potential for all the dischargers to be contributing to violations of the criteria.

Ecology admits that the criteria were adopted in 1967 by a predecessor agency, and that the archives provide no documentation of the basis for the criteria other than a comment letter stating the need to allow some human degradation beyond natural levels in marine waters during periods of upwelling (which the criteria did accommodate). (Letter from Ecology's water quality standards coordinator Mark Hicks to Lincoln Loehr, July 8, 1998.)

Ecology asserts that the criteria were based on a 19**6**8 Department of the Interior criteria document. (Nutrient Forum presentation on May 30, 2018). However, the adopted dissolved oxygen criteria for both marine and freshwater bear no resemblance to the DOI document and it is virtually certain that the predecessor agency did not rely on that document.

Ecology acknowledges that the 0.2 mg/L difference from human causes component of the criteria is not biologically based. (Nutrient Forum presentation on May 30, 2018.)

The predecessor agency made no effort to understand actual dissolved oxygen levels throughout our inland marine waters before adopting the criteria (Eugene E. Collias, personal communication in the 1970s). Hence, the classifications applied to our inland marine waters (Extraordinary, Excellent, Good, and Fair) and their associated dissolved oxygen criteria had no relationship to what the waters actually exhibited.

The states bordering Chesapeake Bay, confronting the need for nutrient reductions, realized that the dissolved oxygen criteria they had could not work and with EPA's help, developed new dissolved oxygen criteria that recognized 5 different types of water, incorporated averaging considerations, as well as differences in depth and seasons and complied with endangered species consultation requirements with NMFS and USFWS. In developing new recommended dissolved oxygen criteria for Chesapeake Bay, EPA emphasized that 40 CFR 131.11 requires that states must adopt water quality criteria that protect the designated uses, that such criteria must be based on sound scientific rationale, and that such criteria must be based on scientifically defensible methods.

Washington's criteria were adopted before there was an EPA, before there was a Clean Water Act, and before EPA had developed the implementing regulations, which includes 40 CFR 131.11. Washington's criteria are 5**3** years old, are not biologically based, are without scientific rationale, and do not match well with what the real world looks like. The State Agency is negligent in its failure to develop new dissolved oxygen criteria meeting the requirements of 40 CFR 131.11. 303(d) listings of impaired waters for dissolved oxygen are based on the criteria, and the modeling to date is driven by the criteria. The flawed and non-biologically based dissolved oxygen criteria, make the necessity of the General Permit for nutrient reduction questionable.

I look forward to discussions about this concern at the mid-May meeting.

Lincoln Loehr
Oceanographer, water quality/permitting consultant

Attachments:

July 8, 1998 letter from Mark Hicks to Lincoln Loehr
40 CFR 131.11

Volume 17/Number 11/November 1986

Marine Pollution Bulletin, Volume 17, No. 11, pp. 489–493, 1986.
Printed in Great Britain.

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VIEWPOINT

Viewpoint is a column which allows authors to express their own opinions about current events.

The Exclusion of Science from Major Water Quality Decisions

LINCOLN C. LOEHR

Mr Loehr is an oceanographer who has participated in many oceanographic cruises in Puget Sound, Washington. He has become active in the political process seeking to change the state's law requiring secondary treatment of all municipal wastes discharged to marine waters.

A recent interpretation of the State law has determined that the state could not consider water quality as a factor when evaluating whether municipal sewage treatment plants discharging to Puget Sound or adjacent marine waters could be permitted to discharge at less than full secondary treatment level. The Federal law requires secondary treatment but has a waiver provision by which a discharger may present information that may permit a case-by-case decision on the level of treatment necessary. The information required by the Federal law to make this case-by-case decision is essentially scientific. Scientific information is irrelevant to the State law. To receive a waiver it is necessary for both the State Department of Ecology and the Federal Environmental Protection Agency to concur. Since the State Department of Ecology could not consider water quality, they denied virtually all waiver applicants. Given this State denial, the Environmental Protection Agency did not have to review the scientific information and issued denials. Thus we are launched on a program that ultimately will cost between $1 000 000 000 and $2 000 000 000. The scientific community is in general agreement that it will do little or nothing towards solving any of the real pollution problems that exist in Puget Sound. The public, however, rightfully expects that this should result in major improvements to the environment. Politics, environmental groups and press sensationalism have played a major role in shaping public opinion.

In 1982, 32 municipal sewage treatment plants (STPs) discharging to marine waters in the state of Washington applied for waivers of the Federal secondary treatment requirement under guidelines developed by the Environmental Protection Agency (EPA). Waivers are permitted under Section 301(h) of the Federal Clean Water Act.

Law Governing Issuance of a Section 301(h) Modified Permit

Section 301(h) of the Clean Water Act provides that:

The Administrator, with the concurrence of the State, may issue a permit under section 402 which modifies the requirements of subsection (b) (1) (B) of this section with respect to the discharge of any pollutant from a publicly owned treatment works into marine waters, if the applicant demonstrates to the satisfaction of the Administrator that:

1. there is an applicable water quality standard specific to the pollutant for which the modification is requested, which has been identified under section 304(a) (6) of this Act:

2. such modified requirement will not interfere with the attainment or maintenance of that water quality which assures protection of public water supplies and the protection and propogation of a balanced, indigenous population of shellfish, fish and wildlife, and allows recreational activities in and on the water.

3. the applicant has established a system for monitoring the impact of such discharge on a representative sample of aquatic biota, to the extent practicable;

4. such modified requirements will not result in any additional requirements on any other point or nonpoint source;

5. all applicable pretreatment requirements for sources introducing waste into such treatment works will be enforced;

6. to the extent practicable, the applicant has established a schedule of activities designed to eliminate the entrance of toxic pollutants from non-industrial sources into such treatment works;

7. there will be no new or substantially increased discharges from the point source of the pollutant to which

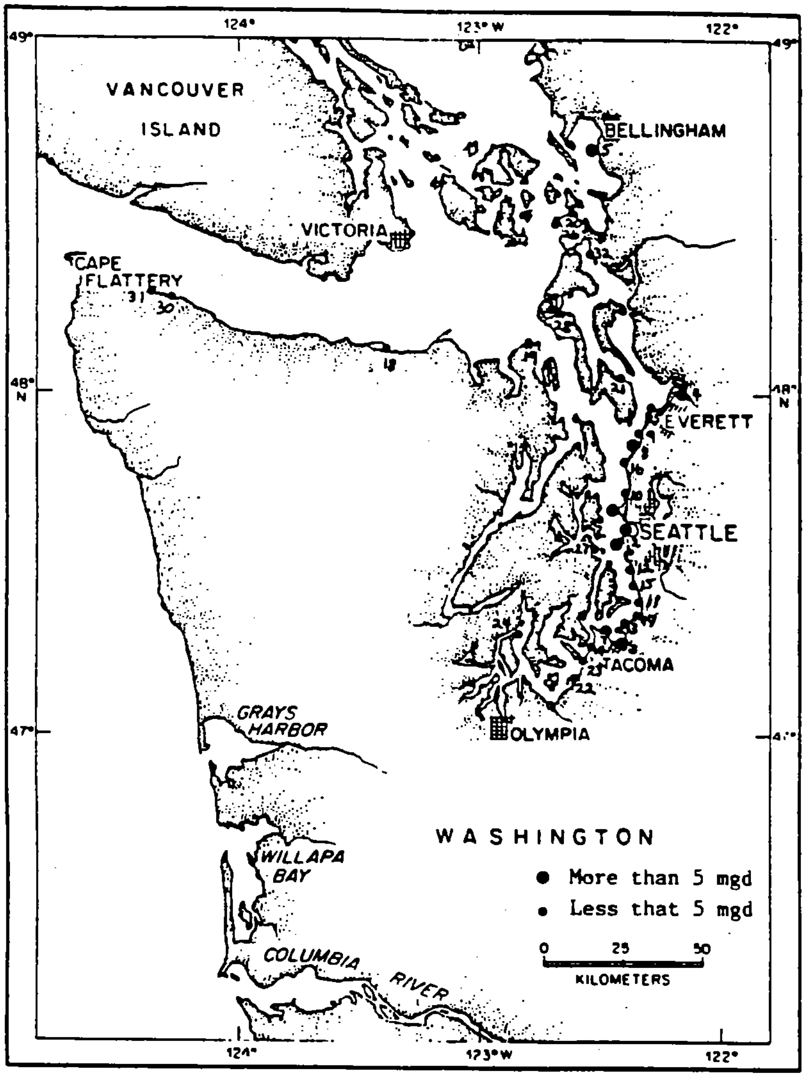

Fig. 1 Sewer discharges in the State of Washington that applied for waivers of the secondary treatment requirement.

the modification applies above that volume of discharge specified in the permit.

For the purposes of this subsection the phrase 'the discharge of any pollutant into marine waters' refers to a discharge into deep waters of the territorial sea or the waters of the contiguous zone, or into saline estuarine waters where there is strong tidal movement and other hydrological and geological characteristics which the Administrator determines necessary to allow compliance with paragraph (2) of this subsection, and section 110(a) (2) of this Act. A municipality which applies secondary treatment shall be eligible to receive a permit pursuant to this subsection which modifies the requirements of subsection (b) (1) (B) of this section with respect to the discharge of any pollutant from any treatment works owned by such municipality into marine waters. No permit issued under this subsection shall authorize the discharge of sewage sludge into marine waters. (Source: *Fed. Reg.*, Vol. 47, No. 228, 26 November, 1982.)

The 32 waiver applicants for the state of Washington are listed in Table 1 and their locations are shown in Fig. 1. All knew that applying did not assure them of a waiver, but they had definite reason to expect a thorough, case-by-case review of the environmental information that EPA required, and that approval or denial would be based on that review. EPA had even encouraged many of the smaller dischargers to apply for the waiver even though the information requirements were costly and EPA had originally imposed unrealistic time frames for the collection of this information.

There are other sewage treatment facilities discharging to Puget Sound that are at secondary treatment. Generally these were built to discharge secondary-treated effluent in recognition of site-specific environmental constraints (usually depth, mixing and flushing characteristics drove this decision). In some cases, environmental degredation from secondary treated effluent occurs because the volume of flow exceeds what the area in the vicinity of the discharge can handle. Proper outfall siting is critical and should also avoid commercially significant shellfish beds as well as seeking optimum physical parameters.

The time-line showing significant events in the development and implementation of the waiver process pertains to these dischargers, is as follows:

1972 Federal Water Pollution Control Act passed (later called the Clean Water Act).

1974 Municipality of Metropolitan Seattle (METRO) commenced detailed evaluation of impacts from its primary and secondary treatment facilities.

1976 METRO lobbied Congress to change the law to allow consideration of waivers on case-by-case basis. Los Angeles STPs joined in this effort.

1977 US Congress passes Section 301(h) amendments to the Clean Water Act. EPA tasked with developing the rules and regulations to implement this section.

1979 EPA promulgates 301(h) rules and regulations in June. Deadline for completed applications was September. In August, Region X EPA administrator sent letters to small dischargers urging them to apply for the waivers. Regulations stated that EPA would review, and that if they approved, the States would then review. Concurrence by both EPA and State necessary for granting of waiver.

1981 US General Accounting Office investigates EPA on subject of the 301(h) rules and determines that 'Billions could be saved' if EPA would make the rules more reasonable, especially for the smaller dischargers.

1982 US Congressional Investigations and Oversight Committee issues report blasting EPA for not carrying out the intent of Congress with regards to Section 301(h). Report was subtitled, 'A Case Study of Lawmaking by Rulemakers'.

1982 EPA tentatively decides to approve some Puget Sound waivers, including METRO's biggest facility at West Point. Decision now passed to State.

1982 EPA issues new 301(h) rules and regulations as well as detailed guidelines for answering the applicant questionnaire. Relaxed rules for small discharges (less than 5 mgd). Shifted review requirements to the State first, after which EPA would review if the State tentatively approved an application. All State dischargers who applied under the 1979 rules chose to reapply under the new rules.

1983 32 applications submitted, State Department of Ecology commences review. Some doubt raised about whether State law permitted them to consider water quality in this review.

1983 State Attorney General's office issues an opinion on the State law. 'All known, available, reasonable technology' must be used, *regardless of water quality*. Wording goes back to 1944.

1983 Effort to change State law. Bill passed in the House, died in Senate Park's and Ecology Committee.

1983 Puget Sound Water Quality Authority created by law, appointed by Governor, 21 members, *no marine scientists appointed.*

1983 Department of Ecology determines secondary treatment is reasonable, meaning (1) affordable, and (2) subject to environmental site-specific constraints but, (3) *without consideration of water quality*. Review of applications continues but all scientific information presented is now ignored in the review as it is irrelevant to the State law.

1984 Six grey whales die in Puget Sound. Considerable press interest in pollution stories. Election year and both Governor candidates make Puget Sound clean-up a political priority. A veterinarian autopsies one whale and proclaims Puget Sound pollution killed it. Greenpeace also blames pollution. National Marine Fisheries Service concludes pollution not the cause of death, and deaths viewed as from natural causes.

1984 Department of Ecology denies virtually all waivers except two of the smallest and the largest. These were considered unreasonable for secondary treatment on the basis of cost or environmental site-specific constraints. The two smallest (Sneehosh Beach and Manchester) would have had very high treatment costs of $75 to $98 per month per house, and the West Point facility would have had to fill in 20 acres of intertidal land to expand to secondary treatment.

1984 Puget Sound Alliance (a coalition of environmental groups) forms. They are strong on environmental activism and lobbying, but they are lacking in marine science participation in defining their goals.

1984 Washington Environmental Council and Friends of the Earth file a lawsuit with METRO for discharging less than secondary treated effluent.

TABLE 1
Waiver Applicants in Washington State
(see Fig. 1 for locations)

		Flow (mgd)
1	Seattle (West Point)	125.000
2	Seattle (Duwamish)	43.300
3	Tacoma (Central)	28.000
4	Everett	20.390
5	Bellingham	10.400
6	Seattle (Alki)	10.000
7	Tacoma (North End)	10.000
8	Edmonds	5.700
9	Lynnwood	4.000
10	Seattle (Carkeek)	3.400
11	Des Moines	3.380
12	SWSSD (Salmon Creek)	3.200
13	Lakehaven (Lakota)	3.040
14	Tacoma (Western Slopes)	3.000
15	SWSSD (Miller Creek)	2.850
16	Seattle (Richmond Beach)	2.500
17	Lakehaven (Redondo)	2.200
18	Port Angeles	1.830
19	Port Townsend	1.030
20	Anacortes (Main Plant)	0.890
21	Langley	0.500
22	Steilacoom	0.500
23	Westside S.D.	0.500
24	Mason County (Hartstene Point)	0.353
25	Mukilteo	0.250
26	Anacortes (Skyline)	0.230
27	Kitsap County (Manchester)	0.140
28	Coupeville	0.125
29	Penn Cove	0.060
30	Clallam County (Clallam Bay)	0.040
31	Clallam County (Seiku)	0.030
32	Skagit County (Snee-oosh Beach)	0.010

Source: Region X EPA

(The Clean Water Act does permit virtually anyone to sue a discharger, the State and the EPA on water quality issues such as secondary treatment).

1984 The Puget Sound Water Quality Authority endorses secondary treatment for all Puget Sound dischargers after debating the resolution for 20 minutes.

1984 The EPA commenced review and the new Regional Administrator decides to deny the waiver for the West Point facility.

1984 Five small dischargers decide to appeal through the State Pollution Control Hearings Board. The other dischargers do not appeal or even withdraw their applications.

1985 Select House Panel on Puget Sound Clean-Up formed in State Capitol and holds hearings twice a week for several months. Puget Sound Alliance actively lobbying. Informal group of marine scientists testify, questioning the wholesale conversion to secondary treatment and asking for the law to be changed to allow case-by-case decisions.

1985 Effort again made to change State law. Bill again passed in the House but dies in Senate Park's and Ecology Committee. One State Senator (Phil Talmadge) considered to be the individual who stopped the bill from going to the full Senate for voting in each case. He is identified here because of the pivotal role he has played in this very expensive undertaking. Depending upon one's point of view, he either deserves full credit or full blame.

1985 Appeals heard. During one appeal the Department of Ecology argued that the Pollution Control Hearings Board should not permit any testimony regarding Puget Sound, circulation, toxicants, water quality or the biota as it was irrelevant and prejudicial to the Department of Ecology's case. During another appeal, the Department of Ecology admitted that their departmental review of the application determined secondary treatment was not needed for water quality purposes. The decisions on the first three appeals have been made and the Hearings Board determined that State law did indeed prohibit them from considering water quality and the first three waiver appeals were denied.

While the above time-line effectively tells much of the story, there are some additional points to elaborate on. The Chairman of the Pollution Control Hearings Board did not sign the orders in which the board turned down the waiver denial appeals of Bellingham, Port Angeles and Lynnwood. Rather, he wrote a 6 page concurring statement. In it he repeated the Federal law (Section 301(h)) and the State law, and clearly identified that the requirement for secondary treatment here lay with the State law, not the Federal law. He clearly stated that the evidence supported the position that these communities' primary-treated effluents were not having significant impacts on the marine environment, and that there were significant impacts related to economic costs and the added requirements of disposing of additional sludge which outweighed the undefined benefits of secondary treatment. He stated several times that the State had to change the law to prevent this wasteful situation which, 'violates any standard of fairness'.

The main problems in Puget Sound are toxi[illegible] spots in the sediments and shellfish bed closures [illegible] bacteria. The toxic hot spots are site-specific and are related to past, or possibly present discharges from industries, industrial runoff, and urban storm sewer/combined sewer overflows to intertidal areas. The problems are not related to the majority of the sewer outfalls in Puget Sound. Because of the active circulation within Puget Sound and the tremendous volume of deep water which acts as a nutrient and dissolved oxygen buffer, there is not a problem associated with nutrient enhancement or dissolved oxygen depletion associated with most of the sewage treatment plants. A glacial fjord with good tidal circulation is considerably different from a shallow drowned river valley type of estuary.

During the recent debate on secondary treatment, I have been especially concerned with the position taken by the EPA. The regional administrator, Ms. Ernesta Barnes, has emphasized how the Federal law requires secondary treatment. She has downplayed the waiver provision. In testifying before the Select House Panel on Puget Sound on 25 March 1985 she emphasized how Congress intended secondary treatment and that the waiver provision only contemplated discharges to the open ocean. She emphasized that Puget Sound is not an open ocean. Note that the Federal Law itself (presented in this article) defines a discharge into marine wate[illegible] including 'saline estuarine waters where there is st[illegible] tidal movement and other hydrological and geological characteristics which the Administrator determines necessary to allow compliance . . .' The following paragraphs are quoted from the Congressional Investigation titled 'Implementation of the Clean Water Act concerning Ocean Discharge Waivers (A Case Study of Lawmaking by Rulemakers)' which was prepared in 1982.

> The 1977 ocean discharge waiver provision was controversial from the outset, due primarily to the fact that it represented the first breach in the new national approach to water pollution abatement adopted in 1972: the basing of cleanup requirements on the performance capability of treatment technologies. While communities discharging to fresh waters would still be required to meet the statute's minimum, 'technology based', secondary treatment requirement, qualified coastal communities would now have an opportunity to temper this mandate, based on assessment of the ocean's 'assimilative capacity', that is, the extent to which it could absorb pollution without harm.
>
> There were two basic reasons underlying Congress' willingness to make this limited exception: first, Congress recognized that the physical and chemical characteristics of the marine environment are significantly different from those of inland fresh waters[illegible]

that full secondary treatment was not necessary in all cases to achieve national water quality goals.

Second, Congress wanted to avoid treatment for treatment's sake, particularly given the multi-million dollar cost of the additional margin of wastewater treatment capability that would otherwise be required by many coastal communities. For those able to comply with the law's several strict prerequisites to a waiver, this expense could be avoided.

Subsequent investigation by the Subcommittee, and an additional day of hearings, on 18 February 1982, disclosed that the attitude of those EPA officials involved was one of at least reluctant acceptance of this amendment to the law, if not outright defiance. The record clearly shows that the regulations that the EPA proposed, and the regulations as finally adopted, along with other statements and actions of agency officials had the effect of preventing communities from obtaining waivers from the law's full municipal secondary treatment requirement.

The answers to the questions of how and why this happened can be seen in the collective set of attitudes, actions, and statements and written records of those EPA officials involved. Key, was the ability of the EPA rulemakers to transform their negative attitudes about the waiver amendment into both procedural and substantive constraints to its application. And underlying all of these actions was a functional, if not formal policy adhered to by the agency rulemakers; to avoid regulatory concessions that 'might weaken our no-retreat-from-secondary position'.

The subcommittee's oversight of the EPA's implementation of the 1977 ocean discharge waiver provision was not intended to review the 'environmental' merits of that amendment. Rather, it was initially concerned with why there had been so much delay in carrying out that amendment, and, later, *with the role and influence, respectively, that administrative agencies and their officials play in shaping or altering the intent and ultimate results of laws enacted by Congress.*

The record of what has transpired under the ocean discharge waiver provision of the Clean Water Act underscores the need for Congress to maintain close oversight of Executive departments and agencies. And to the extent that Congress continues to delegate rulemaking authority to the Executive, it must also be cognizant of the actions and comments of the rulemakers themselves.

It is essential that the State legislature change the State law so that the tremendous investment of secondary treatment is only spent where it is truly needed. This will make it easier then to fund clean-up actions that are necessary (e.g. site-specific toxic sediments and bacterial contamination of commercial shellfish beds). If the State law is changed, we can anticipate problems with EPA refusing to reopen the files of applicants who decided against appealing or who withdrew their applications. Those actions were taken in recognition of the futility of waivers under the State law, the public attitudes as formulated by the press and, the rhetoric of politicians. Congressional assistance may then be needed to grant an exception to EPA's time requirements for review of the waiver applications.

In view of the position taken by EPA in influencing this state's legislature regarding waivers, I believe it is time that the Congress again opens its investigations into EPA's role in implementing the Clean Water Act. We still are plagued by lawmaking by rulemakers!

Author's address: 12215 9th NW, Seattle, WA 98177, USA.

Barnes, Ernesta. Testimony of Region 10 Administrator Environmental Protection Agency, March 25, 1985, before the Select Committee on the Clean-Up and Management of Puget Sound. Transcripts prepared by the Office of Program Research, House of Representatives, State of Washington.

Eikenberry, Kenneth O. (Washington State Attorney General). 5 April 1985. Motion in Limine Regarding Water Quality Evidence filed before the Pollution Control Hearings Board, State of Washington on behalf of the State of Washington Department of Ecology at the start of hearings regarding the City of Lynnwood's appeal of the State's denial of their 301(h) application for the waiver of the secondary treatment requirements. PCHP Case No. 84-206.

Faulk, Lawrence J. (Chairman of the Washington State Pollution Control Hearings Board). 19 June 1985. Concurring opinion in the decision of the Pollution Control Hearings Board in the Case of the City of Bellingham's appeal of the state's denial of their 301(h) application for the waiver of the secondary treatment requirement (PCHB Case No. 84-211).

Faulk, Lawrence J. (Chairman of the Washington State Pollution Control Hearings Board). 3 October 1985. Concurring opinion in the decision of the Pollution Control Hearings Board in the Case of the City of Port Angeles' appeal of the state's denial of their 301(h) application for the waiver of the secondary treatment requirement (PCHB Case No. 84-178).

Faulk, Lawrence J. (Chairman of the Washington State Pollution Control Hearings Board). 3 October 1985. Concurring opinion in the decision of the Pollution Control Hearings Board in the Case of the City of Lynnwood's appeal of the state's denial of their 301(h) application for the waiver of the secondary treatment requirement (PCHB Case No. 84-206).

Federal Register, Vol. 46, No. 228, Friday, November 26, 1982, Part VI, Environmental Protection Agency, 'Modification of Secondary Treatment Requirements for Discharges Into Marine Waters; Final Rule'.

Pollution Control Hearings Board (Washington State). 19 June 1985. Final findings of fact, conclusions of law and order in the matter of City of Bellingham (appellant) v. State of Washington Department of Ecology (respondent) regarding the City of Bellingham's application for a waiver from the secondary treatment requirement.

Pollution Control Hearings Board (Washington State). 3 October 1985. Final findings of fact, conclusions of law and order in the matter of City of Port Angeles (appellant) v. State of Washignton Department of Ecology (respondent) regarding the City of Port Angeles' application for a waiver from the secondary treatment requirement.

Pollution Control Hearings Board (Washington State). 3 October 1985. Final findings of fact, conclusions of law and order in the matter of City of Lynnwood (appellant) v. State of Washington Department of Ecology (respondent) regarding the City of Lynnwood's application for a waiver from the secondary treatment requirement.

US Environmental Protection Agency. August 1984. Analysis of the Section 301(h) Secondary Treatment Variance Application for Municipality of Metropolitan Seattle (METRO) Seattle, Washington West Point Treatment Plant.

US General Accounting Office. 1982. 'Billions Could Be Saved Through Waivers for Coastal Wastewater Treatment Plants. Report to the Congress. 55 pp.

US House of Representatives. Committee on Public Works and Transportation. Subcommittee on Investigations and Oversight. December 1982. 'Implementation of the Clean Water Act concerning Ocean Discharge Waivers (A Case Study of Lawmaking by Rulemakers).

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 10
1200 Sixth Avenue, Suite 155
Seattle, WA 98101

WATER
DIVISION

November 19, 2021

Mr. Vince McGowan
Water Quality Program Manager
Washington State Department of Ecology
PO Box 47600
Olympia, Washington 98504-7600

Re: EPA's Action on Revisions to the Washington State Department of Ecology's Surface Water Quality Standards for Natural Conditions Provisions

Dear Mr. McGowan:

The U.S. Environmental Protection Agency (EPA) has completed the review and reconsideration of Washington's natural conditions provisions (WAC 173-201A-200(1)(c)(i), 173-201A-210(1)(c)(i), 173-201A-200(1)(c)(v), 173-201A-200(1)(d)(i), 173-201A-210(1)(d)(i), 173-201A-200(1)(d)(ii), and 173-201A-260(1)(a)), which were submitted to EPA by the Washington Department of Ecology in 2003 and 2006. Under section 303(c) of the Clean Water Act (CWA), 33 U.S.C. § 1313(c), states must submit new and revised water quality standards to EPA for review and action, and EPA approves those water quality standards if they meet the requirements of the CWA and EPA's implementing regulations. EPA's review and reconsideration is outlined below and further described in the enclosed Technical Support Document.

As you are aware, on February 10, 2014, the Northwest Environmental Advocates filed a complaint in U.S. District Court for the Western District of Washington (Case No. 2:14-cv-0196-RSM) challenging, in part, EPA's February 11, 2008 CWA section 303(c) approval of the natural conditions provisions identified above. On October 17, 2018, the Court issued an Order Granting a Stay (Dkt. 95) pending EPA's reconsideration of its prior determinations. The Court subsequently granted an extension for EPA to complete its reconsideration by November 19, 2021 (Dkt. 118).

EPA's CWA section 303(c) action applies only to waters in the State of Washington and does not apply to waters that are within Indian Country, as defined in 18 U.S.C. § 1151. Nothing in the enclosed decision document shall constitute an approval or disapproval of a water quality standard that applies to waters within Indian Country. EPA, or authorized Indian Tribes, as appropriate, will retain responsibilities for water quality standards for waters within Indian Country.

Summary of EPA's Action

EPA has completed its reconsideration, as contemplated by the Court's Order, and is not changing its February 11, 2008 approval of the revisions to the following sections of WAC Chapter 173-201A.

- WAC 173-201A-200(1)(c)(v): Natural condition narrative aquatic life temperature criteria for lakes

- WAC 173-201A-200(1)(d)(ii): Natural condition narrative aquatic life dissolved oxygen criteria for lakes

Because EPA is not changing its earlier approval, it is taking no new action with respect to those provisions.

EPA has completed its reconsideration, as contemplated by the Court's Order, and is disapproving revisions to the following sections of WAC Chapter 173-201A pursuant to its authority under section 303(c)(3) of the CWA, 33 U.S.C. § 1313(c)(3), and 40 CFR Part 131:

- WAC 173-201A-260(1)(a): Natural and irreversible human conditions
- WAC 173-201A-200(1)(c)(i) and WAC 173-201A-210(1)(c)(i): Allowable human contribution to natural conditions provisions for aquatic life temperature (fresh water and marine water, respectively)
- WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i): Allowable human contribution to natural conditions provisions for aquatic life dissolved oxygen (fresh water and marine water, respectively)

EPA appreciates Ecology's commitment and ongoing work to update Washington's water quality standards. We also appreciate the collaboration by your staff to address the complexities associated with criteria revisions. If you have any questions regarding this letter, please contact me at (206) 553-1855 or Lindsay Guzzo, EPA staff lead, at (206) 553-0268 or Guzzo.Lindsay@epa.gov.

Sincerely,

DANIEL OPALSKI

Digitally signed by DANIEL OPALSKI
Date: 2021.11.19 09:38:35 -08'00'

Daniel D. Opalski
Director

Enclosure: Technical Support Document

cc (e-Copy): Ms. Melissa Gildersleeve, Water Quality Management Section Manager, Ecology
Mr. Chad Brown, Water Quality Management Unit Supervisor, Ecology

U.S. ENVIRONMENTAL PROTECTION AGENCY – REGION 10

Technical Support Document

EPA's Clean Water Act Action on Revisions to the Washington State Department of Ecology's Surface Water Quality Standards for Natural Conditions Provisions

November 19, 2021

I. Clean Water Act Requirements for Water Quality Standards

The objective of the Clean Water Act (CWA) is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters with an interim goal, where attainable, to achieve water quality that provides for the protection and propagation of fish, shellfish, and wildlife and recreation in and on the water. Under section 303(c) of the CWA and federal implementing regulations at 40 CFR § 131.4, states (and authorized tribes) have the primary responsibility for reviewing, establishing, and revising water quality standards (WQS). These standards include the designated uses of a waterbody or waterbody segment, the water quality criteria that protect those designated uses, and an antidegradation policy. This statutory and regulatory framework allows states to work with local communities to adopt appropriate designated uses (as required at 40 CFR § 131.10(a)) and to adopt criteria to protect those designated uses (as required at 40 CFR § 131.11(a)).

States are required to hold public hearings for the purpose of reviewing applicable WQS periodically but at least once every three years and, as appropriate, modify and adopt these standards (40 CFR § 131.20). Each state must follow applicable legal procedures for revising or adopting such standards (40 CFR § 131.5(a)(6)) and submit certification by the state's attorney general, or other appropriate legal authority within the state, that the WQS were duly adopted pursuant to state law (40 CFR §131.6(e)). The U.S. Environmental Protection Agency's (EPA) review authority and the minimum requirements for state WQS submittals are described at 40 CFR § 131.5 and 131.6, respectively.

States are required by 40 CFR § 131.11(a) to adopt water quality criteria that protect their designated uses. In adopting such criteria, states should establish numeric values based on one of the following:

(1) CWA section 304(a) guidance;
(2) CWA section 304(a) guidance modified to reflect site-specific conditions; or,
(3) Other scientifically defensible methods (40 CFR § 131.11(b)(1)).

In addition, states should establish narrative criteria where numeric criteria cannot be established or to supplement numeric criteria (see 40 CFR § 131.11(b)(2)).

Section 303(c) of the CWA requires states to submit new or revised WQS to EPA for review and action. EPA reviews these changes and approves the WQS if they meet the requirements of the CWA and EPA's implementing regulations.

EPA considers four questions (described below) when evaluating whether a particular provision is a new or revised WQS. If all four questions are answered "yes" then the provision would likely constitute a new or revised WQS that EPA has the authority and duty to approve or disapprove under CWA § 303(c)(3).[1]

1. Is it a legally binding provision adopted or established pursuant to state or tribal law?
2. Does the provision address designated uses, water quality criteria (narrative or numeric) to protect designated uses, and/or antidegradation requirements for waters of the United States?

[1] *What is a New or Revised Water Quality Standard under 303(c)(3)? Frequently Asked Questions*, EPA No. 820F12017 (Oct. 2012). Available at https://www.epa.gov/sites/production/files/2014-11/documents/cwa303faq.pdf

3. Does the provision express or establish the desired condition (e.g., uses, criteria) or instream level of protection (e.g., antidegradation requirements) for waters of the United States immediately or mandate how it will be expressed or established for such waters in the future?
4. Does the provision establish a new WQS or revise an existing WQS?

If EPA approves a state's WQS submission, such standard(s) shall thereafter be the applicable standard for CWA purposes. When EPA disapproves a state's WQS, EPA shall notify the state and specify why the WQS is not in compliance with the requirements of the CWA and federal WQS regulations and specify any changes that are needed to meet such requirements (33 U.S.C. § 1313(c)(3); 40 CFR § 131.21).

Finally, EPA considers non-substantive edits to existing WQS to constitute new or revised WQS that EPA has the authority to approve or disapprove under § 303(c)(3). While such edits and changes do not substantively change the meaning or intent of the existing WQS, EPA believes it is reasonable to treat such edits and changes in this manner to ensure public transparency as to which provisions are applicable for purposes of the CWA. EPA notes that the scope of its review and action on non-substantive edits or editorial changes extends only to the edits or changes themselves. EPA does not re-open or reconsider the underlying WQS that are the subject of the non-substantive edits or editorial changes.

II. Background

On February 10, 2014, the Northwest Environmental Advocates filed a complaint in U.S. District Court for the Western District of Washington (Case No. 2:14-cv-0196-RSM) challenging, in part, EPA's February 11, 2008 CWA section 303(c) approval of the natural conditions provisions. On October 17, 2018, the Court issued an Order Granting a Stay (Dkt. 95) pending EPA's reconsideration of its prior determinations. The Order noted that EPA may complete its reconsideration by October 17, 2021, by making approval or disapproval decisions, or a final determination that such provisions are not water quality standards. The Court subsequently granted an extension for EPA to complete its reconsideration by November 19, 2021 (Dkt. 118).

This Technical Support Document constitutes EPA's reconsideration of the remaining provisions subject to the Court Order. EPA previously completed its review and reconsideration of the other provisions in actions dated April 30, 2019, October 13, 2020, and September 30, 2021.

III. Results of EPA's Reconsideration

In its February 11, 2008 action, EPA approved the revised natural conditions provisions at:

- WAC 173-201A-200(1)(c)(i) and WAC 173-201A-210(1)(c)(i): Allowable human contribution to natural conditions provisions for aquatic life temperature (fresh water and marine water, respectively);
- WAC 173-201A-200(1)(c)(v): Natural condition narrative aquatic life temperature criteria for lakes;
- WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i): Allowable human contribution to natural conditions provisions for aquatic life dissolved oxygen (for fresh water and marine water, respectively);

- WAC 173-201A-200(1)(d)(ii): Natural condition narrative aquatic life dissolved oxygen criteria for lakes; and
- WAC 173-201A-260(1)(a): Natural and Irreversible Human Conditions.

Upon reconsideration, EPA is not changing and taking no action with respect to the February 11, 2008 approval of the provisions at WAC 173-201A-200(1)(c)(v) and WAC 173-201A-200(1)(d)(ii). EPA is disapproving the provisions at WAC 173-201A-200(1)(c)(i), WAC 173-201A-210(1)(c)(i), WAC 173-201A-200(1)(d)(i), WAC 173-201A-210(1)(d)(i), and WAC 173-201A-260(1)(a).

EPA's CWA section 303(c) action and the associated rationales are provided below. Today's action applies only to waters within the jurisdiction of the State of Washington and does not apply to waters that are within Indian Country, as defined in 18 U.S.C. § 1151. Nothing in this decision document shall constitute an approval or disapproval of a WQS that applies to waters within Indian Country. EPA, or authorized Indian Tribes, as appropriate, retain the authority to establish WQS for waters within Indian Country.

1. Natural Conditions Narrative Criteria For Lakes

In its February 11, 2008 action, EPA approved the revised temperature and dissolved oxygen natural conditions narrative criteria for lakes at WAC 173-201A-200(1)(c)(v) and WAC 173-201A-200(1)(d)(ii), respectively. More detail and information regarding EPA's action can be found in the 2008 decision document.[2]

The underlined text indicates the new and/or revised language from Ecology's 2006 WQS submittal, and strikeout text indicates Ecology's previous text, which had been replaced by the new or revised text.

Aquatic life temperature criteria for lakes

> **WAC 173-201A-200(1)(c)(v):** For lakes, human actions considered cumulatively may not increase the 7-DADMax temperature more than 0.3°C (0.54°F) above natural conditions. ~~Temperature - no measurable change from natural conditions.~~

Aquatic life dissolved oxygen criteria for lakes

> **WAC 173- 201A-200(1)(d)(ii):** For lakes, human actions considered cumulatively may not decrease the dissolved oxygen concentration more than 0.2 mg/L below natural conditions. ~~Dissolved oxygen - no measurable decrease from natural conditions.~~

EPA's Reconsideration: EPA has completed its reconsideration and is taking no action with respect to its February 11, 2008 approval of the revisions at WAC 173-201A-200(1)(c)(v) and WAC 173-201A-200(1)(d)(ii).

EPA Rationale for the 2008 approval:
In 2006, Ecology submitted revisions to the temperature and dissolved oxygen aquatic life criteria for lakes. The revisions clarified and quantified the previous criteria of "no measurable change from natural

[2] February 11, 2008. Letter from Michael F. Gearheard, Director, Office of Water & Watersheds, EPA Region 10, to David C. Peeler, Program Manager, Department of Ecology, re: EPA Approval of the 2003/2006 Revisions to the Washington Water Quality Standards Regulations. Available at: https://www.epa.gov/sites/production/files/2017-10/documents/wawqs-letter-02112008.pdf

conditions" (for temperature) and "no measurable decrease from natural conditions" (for dissolved oxygen) by identifying a 0.3ºC increase in temperature and a 0.2 mg/L decrease in dissolved oxygen as what would constitute a "measurable" departure from natural conditions. For temperature, the revision also added a 7-DADMax metric to the criterion.

In the February 11, 2008, Technical Support Document, EPA concluded that a 0.3ºC increase in temperature from natural conditions was insignificant and well within the range of uncertainty of the thermal requirements for salmon, which is approximately +/- 0.5ºC. EPA also noted that 0.3ºC was consistent with reliable field detection levels for temperature and is therefore considered within the error band associated with typical temperature monitors (pp. 27-28). The revised temperature criterion also added the 7-DADMax metric recommended for temperature standards by the *Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards* (EPA910-B-03-002, April 2003, hereinafter referred to as "Temperature Guidance") and that EPA determined to be scientifically defensible (p.4). EPA's 2008 approval, therefore, concluded that Washington's revisions to the aquatic life temperature criterion for lakes were protective of designated uses and scientifically defensible.

In assessing Washington's revisions to the dissolved oxygen criterion for lakes, EPA similarly concluded that a 0.2 mg/L decrease from natural conditions was insignificant. The 2008 approval rationale explained that an allowable decrease of 0.2 mg/L is within the monitoring measurement error for recording instruments typically used to monitor dissolved oxygen. EPA also explained that numerous factors impact oxygen levels in lakes and without at least some allowance for insignificant decreases a natural conditions criterion for dissolved oxygen in lakes would be unnecessarily restrictive for the protection of designated uses (p. 32). EPA's 2008 approval, therefore, concluded that Washington's revisions to the aquatic life dissolved oxygen criterion for lakes was protective of designated uses and scientifically defensible.

The narrative criteria are the applicable temperature and dissolved oxygen criteria for lakes in Washington, and leaving in place EPA's 2008 approval of these criteria ensures that aquatic life criteria for temperature and dissolved oxygen in lakes remain in effect for CWA purposes.

2. <u>Natural and Irreversible Human Conditions</u>

In its February 11, 2008 action, EPA approved the new narrative natural conditions provision at WAC 173-201A-260(1)(a) and took no action on the irreversible human conditions provision at WAC 173-201A-260(1)(b) after concluding the provision is not a WQS that EPA has the authority to approve or disapprove under section 303(c) of the CWA. More detail and information regarding EPA's action can be found in the 2008 decision document.[3]

With respect to WAC 173-201A-260(1)(a), EPA's 2008 decision stated that it is acceptable, under certain circumstances, for water quality criteria to reflect the natural condition of a water body as an alternative to the generally applicable numeric criteria. The rationale for this was that Washington's designated uses were supported by the water in its natural condition, prior to any human effects on water quality.

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[3] February 11, 2008. Letter from Michael F. Gearheard, Director, Office of Water & Watersheds, EPA Region 10, to David C. Peeler, Program Manager, Department of Ecology, re: EPA Approval of the 2003/2006 Revisions to the Washington Water Quality Standards Regulations. Available at: https://www.epa.gov/sites/production/files/2017-10/documents/wawqs-letter-02112008.pdf

The text of the provision first appeared in a 2003 water quality standards submittal to EPA and again in a 2006 submittal and is excerpted below.

> **WAC 173-201A-260(1):** Natural and irreversible human conditions.
> (a) It is recognized that portions of many water bodies cannot meet the assigned criteria due to the natural conditions of the water body. When a water body does not meet its assigned criteria due to natural climatic or landscape attributes, the natural conditions constitute the water quality criteria.

EPA's Reconsideration: EPA has completed its reconsideration and in accordance with its CWA authority, 33 U.S.C. § 1313(c)(3) and 40 CFR Part 131, disapproves the provision at WAC 173-201A-260(1)(a).

EPA Rationale: The natural conditions narrative provision at WAC 173-201A-260(1)(a) is broadly drafted and does not specify the types of criteria or pollutants to which it applies. On reconsideration, EPA concludes that as written this provision could be applied to a wide range of naturally occuring pollutants, including toxic pollutants, and could even allow an exception from otherwise applicable numeric human health criteria. Therefore, it is not consistent with EPA's interpretation of the relationship between natural conditions and the protection of designated human health uses, which is articulated in EPA's November 5, 1997 policy guidance entitled ''Establishing Site Specific Aquatic Life Criteria Equal to Natural Background.''[4] EPA's 2008 decision document cited to the 1997 policy guidance, as well as to language in an Advance Notice of Proposed Rulemaking for the Water Quality Standards program (*see* 63 Fed. Reg. 36,724, 36761 (Jul. 7, 1998)), as setting forth the relevant policy considerations for establishing water quality criteria based on natural conditions. However, what EPA failed to appropriately consider in its 2008 decision is that these documents only addressed the establishment of aquatic life criteria for pollutants at levels equal to the natural background condition, and expressly did not apply to human health uses, whereas the provision at WAC 173-201A-260(1)(a) is not similarly limited in scope to aquatic life uses or to specific pollutants.

In contrast with aquatic life uses, a naturally occurring level of a pollutant does not necessarily protect designated human health uses. Naturally occurring levels of a pollutant are assumed to protect aquatic life species that have naturally developed in the affected waters. However, humans generally do not adapt to higher ambient pollutant levels, even if they are naturally caused. Consequently, the same assumptions of protectiveness cannot be made with regard to designated uses that affect human health (*e.g.,* people eating fish or shellfish from Washington waters, and recreating in Washington waters). For this reason, EPA's 1997 guidance also states that where the natural background concentration exceeds the state-adopted human health criterion, at a minimum, states should re-evaluate the human health use designation.[5]

No Changes Necessary to Address the Disapproval: The effect of EPA's disapproval is that, as of the date of this action, the provision at WAC 173-210A-260(1)(a) is no longer an applicable WQS for CWA purposes. Because Washington's WQS currently include applicable numeric criteria that EPA determined to be protective of designated uses, no changes to Washington's WQS are necessary to meet the requirements of the CWA. Therefore, EPA is not specifying any changes that Washington must

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[4] Davies, Tudor T., *Establishing Site Specific Aquatic Life Criteria Equal to Natural Background,* EPA Memorandum to Water Management Division Directors, Regions 1–10, State and Tribal Water Quality Management Program Directors, posted at: *https://www.epa.gov/sites/default/files/2014-08/documents/naturalbackground-memo.pdf*
[5] *Id.* at p. 2.

adopt to meet CWA requirements. EPA provides the following discretionary recommendations for the State's consideration.

EPA understands that WAC 173-201A-260(1)(a) was developed in parallel with numeric aquatic life criteria for marine and fresh waters, and that Washington intended to rely on the natural condition narrative to address circumstances where waterbody conditions are naturally less stringent than the adopted biologically-based numeric aquatic life criteria. In this respect the availability of a criterion that accounts for less stringent natural conditions was an important consideration in the establishment of numeric criteria for aquatic life. EPA continues to believe that appropriately drafted natural condition provisions can serve an important role in state WQS by reflecting a naturally occuring spatial and temporal variability in water quality that is protective of uses. A new general natural condition provision that is narrowly tailored to aquatic life uses could be adopted as a narrative criterion where numerical criteria cannot be established or to supplement numerical criteria (40 C.F.R. § 131.11(b)(2)). Alternatively, the adoption of a performance-based approach could be used to establish aquatic life criteria reflecting a natural condition for specific pollutants (see discussion for temperature and dissolved oxygen below).

EPA recommends removing the current WAC 173-201A-260(1)(a) from the State's WQS regulations to avoid confusion and provide greater clarity as to what is in effect for CWA purposes.

3. Allowable Human Contribution to Natural Conditions Provisions for Aquatic Life Temperature and Dissolved Oxygen Criteria For Fresh and Marine Waters

In its February 11, 2008 action, EPA approved the new and revised natural conditions provisions for temperature in fresh and marine waters at WAC 173-201A-200(1)(c)(i) and WAC 173-201A-210(1)(c)(i), respectively; and for dissolved oxygen in fresh and marine waters at WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i), respectively. More detail and information regarding EPA's action can be found in the 2008 decision document.[6]

In the 2008 approval, EPA determined that insignificant temperature increases or insignificant decreases of dissolved oxygen concentrations above or below the natural condition were protective of the applicable designated uses because such insignificant departures from the natural condition were within the range of scientific uncertainty of effects on designated uses and/or within the error band associated with typical monitoring equipment. Specific to temperature, these "de minimis" allowable human-caused increases above natural conditions are consistent with the Temperature Guidance.[7]

The texts of each of the provisions are excerpted below.

Allowable human contribution to natural conditions provisions for aquatic life temperature:

> **Freshwater, WAC 173-201A-200(1)(c)(i):** When a water body's temperature is warmer than the criteria in Table 200 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to

[6] February 11, 2008. Letter from Michael F. Gearheard, Director, Office of Water & Watersheds, EPA Region 10, to David C. Peeler, Program Manager, Department of Ecology, re: EPA Approval of the 2003/2006 Revisions to the Washington Water Quality Standards Regulations. Available at: https://www.epa.gov/sites/production/files/2017-10/documents/wawqs-letter-02112008.pdf

[7] EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. EPA-910-B-03-002. April 2003. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi/P1004IUI.PDF?Dockey=P1004IUI.PDF

natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).

Marine water, WAC 173-201A-210(1)(c)(i): When a water body's temperature is warmer than the criteria in Table 210 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).

Allowable human contribution to natural conditions provisions for aquatic life dissolved oxygen:

Freshwater, WAC 173- 201A-200(1)(d)(i): When a water body's D.O. is lower than the criteria in Table 200 (1)(d) (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the D.O. of that water body to decrease more than 0.2 mg/L.

Marine water, WAC 173-201A-210(1)(d)(i): When a water body's D.O. is lower than the criteria in Table 210 (1)(d) (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the D.O. of that water body to decrease more than 0.2 mg/L.

EPA's Reconsideration: EPA has completed its reconsideration and in accordance with its CWA authority, 33 U.S.C. § 1313(c)(3) and 40 CFR Part 131, disapproves the provisions at WAC 173-201A-200(1)(c)(i), WAC 173-201A-210(1)(c)(i), WAC 173-201A-200(1)(d)(i) and WAC 173-201A-210(1)(d)(i).

EPA Rationale:
The allowable human contribution to natural condition provisions for temperature (WAC 173-201A-200(1)(c)(i) and 210(1)(c)(i)) and disolved oxygen (WAC 173-201A-200(1)(d)(i) and 210(1)(d)(i)) allow for human actions considered cumulatively to cause insignificant increases in temperature (0.3ºC) or decreases in dissolved oxygen (0.2mg/L) from the natural condition of the waterbody. As discussed above, EPA is disapproving the provision at WAC 173-201A-260(1)(a) that allows for the natural condition of a waterbody to constitute the applicable criteria when the natural condition is less stringent than otherwise applicable numeric criteria.[8] Absent an approved WQS that allows for the natural condition to constitute the applicable water quality criteria, the applicable criteria for temperature and dissolved oxygen in Washington waters are the numeric criteria in Tables 200(1)(c) and (1)(d) and 210(1)(c) and (1)(d). However, the temperature and dissolved oxygen natural condition provisions are based on the natural condition of the waterbody; the provisions do not authorize human actions to cause insignificant exceedances to the applicable numeric criteria. EPA is therefore disapproving the temperature and dissolved oxygen provisions that allow insignificant human impacts to the natural condition because such impacts are not tied to approved criteria that are in effect under the CWA.

No Changes Necessary to Address the Disapproval: The effect of EPA's disapproval is that, as of the date of this action, the provisions at WAC 173-201A-200(1)(c)(i), WAC 173-201A-210(1)(c)(i), WAC 173-201A-200(1)(d)(i), and WAC 173-201A-210(1)(d)(i) are no longer applicable WQS for CWA purposes. Because Washington's WQS currently include applicable biologically-based numeric criteria

[8] EPA's interpretation of WAC 173-201A-260(1)(a) is consistent with Ecology's January 29, 2016 letter in which it stated "[t]he rule makes it clear that where Ecology identifies a natural condition that is less stringent than the numeric criteria in the state's water quality standards, the natural condition supersedes the numeric criteria." Letter from David C. Peeler, Water Quality Program Manager, Ecology, to Michael Gearheard, EPA Region 10, Re: Ecology Responses to USEPA Region 10 Questions Regarding Washington's 2003 Adopted Water Quality Standards, p. 2.

for temperature and dissolved oxygen that EPA determined to be protective of designated uses, no changes to Washington's WQS are necessary to meet the requirements of the CWA. Therefore, EPA is not specifying any changes that Washington must adopt to meet CWA requirements. EPA provides the following discretionary recommendations for the State's consideration.

Washington, at its discretion, could adopt new natural conditions criteria specific to temperature and/or dissolved oxygen. One possibility would be for Washington to adopt into its WQS a performance-based approach for establishing temperature and/or dissolved oxygen criteria representative of the natural condition of a waterbody. A performance-based approach is a binding methodology that provides a transparent, predictable, repeatable, and scientifically defensible procedure to derive numeric criteria or to translate a narrative criterion into quantifiable measures that are protective of designated uses. The performance-based approach relies on the adoption of a systematic process (i.e., a criterion derivation methodology) rather than a specific outcome (i.e., concentration limit for a pollutant) consistent with 40 CFR Sections 131.11 and 131.13. When such a performance-based approach is sufficiently detailed and has suitable safeguards to ensure predictable, repeatable outcomes, EPA approval of such an approach also serves as approval of the outcomes as well. *See EPA Review and Approval of State Water Quality Standards*, 65 FR 24,641, 24,649 (Apr. 27, 2000).

A second possibility would be for Washington to adopt numeric temperature and dissolved oxygen criteria that account for natural conditions using the best available relevant data. EPA encourages Washington to consider magnitude, frequency, and duration components in setting water quality criteria to protect against acute and chronic effects.[9] This may include establishing protective site-specific criteria accounting for specific characteristics, such as unique temperature and/or dissolved oxygen regimes in different waterbodies (see EPA's Temperature Guidance).[10] Site-specific criteria established in this manner would be subject to CWA section 303(c) review.

Washington, at its discretion, could also choose to adopt new WQS provisions that allow for human actions, considered cumulatively, to cause insignificant exceedances in temperature and dissolved oxygen. As articulated in the 2008 Technical Support Document, EPA believes insignificant or de minimis exceedances to applicable temperature and/or dissolved oxygen criteria caused by human actions, considered cumulatively, may still be protective of designated uses.[11] Any such human use allowance provision must be scientifically defensible and tied to approved criteria that are protective of designated uses, which could include criteria based on the natural condition of the waterbody.

EPA recommends removing the disapproved provisions from the State's WQS regulations to avoid confusion and provide greater clarity to what is in effect for CWA purposes.

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[9] EPA Water Quality Standards Handbook – Chapter 3: Water Quality Criteria. EPA-823—B-17-001; 2017. Available at https://www.epa.gov/sites/production/files/2014-10/documents/handbook-chapter3.pdf

[10] EPA Issue Paper 3: Spatial and Temporal Patterns of Stream Temperature (Revised), October 2001. EPA-910-D-01-003, pages 2-9. Available at https://www.epa.gov/sites/production/files/2018-01/documents/r10-water-quality-temperature-issue-paper3-2001.pdf

[11] 2008 TSD at pp. 20-21, 32.

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Washington State Department of Ecology

Olympia, Washington

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Department of Ecology's Regional Offices

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Region	Counties served	Mailing Address	Phone
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Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	PO Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
Headquarters	Across Washington	PO Box 46700 Olympia, WA 98504	360-407-6000

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DEPARTMENT OF
ECOLOGY
State of Washington

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Introduction and Background

Introduction and purpose

This publication is part of Chapter 173-201A Washington Administrative Code (WAC) Water Quality Standards for Surface Waters of the State of Washington.

Washington Department of Ecology (Ecology) recognizes that in some portions of some water bodies, the assigned aquatic life criteria may not be met due, in part, to the natural conditions of the water body, as acknowledged in EPA memorandum and guidance (Davies, 1997; EPA 2015). Therefore, if these natural climatic or landscape attributes are preventing attainment of applicable numeric aquatic life criteria, then the natural conditions of the system constitute the water quality criteria (see WAC 173-201A-260(1)(a)).

When the natural conditions of a waterbody are used to establish aquatic life water quality criteria, criteria values may be determined by use of various approaches, including the performance-based approach (see DRAFT WAC 173-201A-470).

When the performance-based approach is chosen to establish aquatic life water quality criteria for natural condition scenarios, development of these criteria values must follow the procedures in this document as per DRAFT WAC 173-201A-470. This performance-based approach can only be used for the following water quality parameters:

- Dissolved oxygen (DO; fresh water and marine water)
- pH (fresh water)
- Temperature (fresh water and marine water)

If the determination of aquatic life criteria values cannot meet the requirements set forth in this document, then alternative approaches, such as site-specific criteria, may be considered.

Regulatory information

Federal

The Clean Water Act requires states to adopt water quality standards that consist of designated uses, water quality criteria, and an antidegradation policy. Section 303(c)(2)(A) of the Clean Water Act gives the responsibility for adopting water quality standards to states and authorized Tribes, and that these standards will protect the public health or welfare, enhance the quality of water, and serve the purposes of the Act.

40 CFR 131.3(b) defines criteria as elements of the water quality standards (expressed as constituent concentrations, levels, or narrative statements) that represent a quality of water that supports a particular use such that when criteria are met, water quality will generally protect the designated use.

States and authorized Tribes must adopt water quality criteria that protect these designated uses (see 40 CFR 131.11). States and authorized Tribes may adopt, where appropriate, other criteria that differ from EPA's recommendations, so long as the criteria are:

- Based on sound scientific rationale,
- Contain sufficient parameters or constituents to protect the designated use or uses, and
- Support the most sensitive designated use of the waterbody.

States and authorized Tribes can adopt criteria that are modified to reflect site-specific conditions (see 40 CFR 131.11(b)(1)(ii)), so long as they are based on sound scientific rationale and protect designated uses. EPA has provided guidance for derivation of site-specific criteria outlined in *Water Quality Standards Handbook Chapter 3: Water Quality Criteria* (USEPA, 2023).

In 1997, EPA's Director of Office of Science and Technology Tudor T. Davies released a memo entitled *Establishing Site Specific Aquatic Life Criteria Equal to Natural Background* (Davies, 1997). In this memo, EPA recognized that naturally occurring concentrations of pollutants may exceed national criteria recommendations published under Section 304(a) of the Clean Water Act. EPA described how states and authorized Tribes may establish site-specific numeric aquatic life water quality criteria for waterbodies by setting the criterion value equal to natural background. Natural background was defined as "background concentration due only to non-anthropogenic sources; i.e., non-manmade sources" (Davies, 1997).

The memorandum recommends that the following elements should be included, at minimum, in a state's or tribe's water quality standards when setting criteria equal to natural background:

- A definition of natural background that states natural background is defined as the background concentration due only to non-anthropogenic sources, i.e., non-manmade sources.
- A provision that states site-specific criteria may be set equal to natural background.
- A procedure for determining natural background or a reference in the water quality standards to another document describing the binding procedure that will be used.

EPA has also developed additional documentation to provide clarity and direction for establishing site-specific criteria for temperature, dissolved oxygen, and pH (USEPA, 2015). This document provides a framework that includes recommendations for developing natural conditions criteria, including when using a performance-based approach for determining criteria values.

State

Water pollution control in the State of Washington is regulated under Chapter 90.48 Revised Code of Washington (RCW). This includes 90.48.010 RCW which declares that it is the public policy of the state to maintain the highest possible standard to ensure purity of waters consistent with public health, public enjoyment, and propagation and protection of wildlife, birds, game, fish, and other aquatic life.

90.48.035 RCW establishes the rule-making authority for the Department to promulgate rules and regulations necessary to carry out the provisions of Chapter 90.48, including water quality standards for the state.

Chapter 173-201A Washington Administrative Code (WAC) is the Water Quality Standards for Surface Waters of the State of Washington. This chapter establishes standards for public health and public enjoyment of waters in the State and for propagation and protection of fish, shellfish, and wildlife. The Water Quality Standards include, but are not limited to, the following sections regarding natural conditions criteria:

- WAC 173-201A-020 Definitions
    - Defines natural conditions or natural background levels, which means surface water quality present before any human-caused pollution.
- WAC 173-201A-260(1) Natural conditions and other water quality criteria and applications
    - Recognizes that portions of water bodies cannot meet the assigned aquatic life criteria due to natural conditions. When this occurs, this section establishes that the natural conditions constitute the water quality criteria.
- WAC 173-201A-430 Site Specific Criteria
    - Lists the requirements for determining site-specific criteria, which includes conducting development of such criteria that are scientifically justifiable.
- DRAFT WAC 173-201A-470 Performance-based approach
    - Lists the requirements for determining site-specific criteria using a performance-based approach. Criteria developed under this approach must be derived using procedures found in this document, which is adopted by reference into regulation.

Performance-Based Approach Use

Overview

Use of the performance-based approach may be considered when developing site-specific natural conditions criteria when all applicable and prerequisite state and federal regulations are met. This includes, but is not limited to, the natural conditions provision at WAC 173-201A-260(1)(a) and the performance-based approach at DRAFT WAC 173-201A-470.

Aquatic life water quality criteria values developed using the performance-based approach are applicable to the waterbody immediately following the performance-based approach derivation process, so long as all requirements set forth in this document are met. This document serves to meet the minimum recommendations in EPA's 1997 Memorandum that recommends water quality standards include a binding procedure that will be used for determining natural background (Davies, 1997).

Applicable parameters

Use of the performance-based approach is limited to the following parameters:

- Dissolved Oxygen, Fresh Water
- Dissolved Oxygen, Marine Water
- pH, Fresh Water
- Temperature, Fresh Water
- Temperature, Marine Water

Other parameters

This performance-based approach can only be used to establish natural conditions aquatic life criteria for water quality parameters listed in the above "Applicable Parameters" section. Natural conditions aquatic life criteria for other water quality parameters may be developed using alternative approaches specified at WAC 173-201A-260(1)(a), as applicable, and must follow all state and federal rulemaking regulations prior to becoming effective for state and federal Clean Water Act actions.

Natural conditions water quality criteria are appropriate only for the protection of aquatic life uses, not human health uses.

Process-Based Modeling Approach

Introduction

The process-based modeling approach characterizes the natural water quality for a parameter of interest through application of tools such as a water quality model. The water quality model determines the water quality dynamics for the parameter observed at the site of interest under current and natural conditions. This approach will allow quantification of effects at a site on the parameter of interest from both human sources and natural sources.

This approach can be used when there are indications that nonattainment of water quality criteria is due in part to natural processes. This approach can be used regardless of the level of human disturbance to the water body being evaluated, so long as the natural conditions for the parameter and site of interest can be quantified via the approach (i.e., the performance-based approach can be followed in its entirety).

In this approach, developing the natural conditions criteria consists of:

1. Defining where natural conditions will apply (site boundary).
2. Compiling existing, readily available, and credible current and historical water quality and site data.
3. Developing a Quality Assurance Project Plan (QAPP).
4. Obtaining new field data, if required in the QAPP.
5. Compiling, reviewing, and assessing any new field data to ensure it meets quality assurance (QA) / quality control (QC) goals.
6. Developing and calibrating a predictive model of the existing conditions of the waterbody or watershed, including defining temporal and spatial boundaries.
7. Evaluating model performance.
8. Determining whether nonattainment of numeric water quality standards is due, in part, to natural processes.
9. Calculating the natural conditions criteria values by removing known and estimated human-caused impacts from the predictive model.

The analysis of data and development of the criteria values must be documented. If the developed criteria values are used in subsequent state or federal Clean Water Act actions, then: (a) this documentation must be included with the documentation for the CWA action; and (b) the criteria values must be accessible to the public.

Define site boundaries

The first step in developing natural conditions criteria using this approach is defining site boundaries. The boundaries of the site of interest must be defined and documented. Boundary information should include geospatial information. The site boundary consists of the entire model domain, which may include multiple assessment units of interest to the project. Natural conditions criteria for each assessment unit will be derived based on the resolution of the model and the spatial and temporal variability of its predictions.

Project Quality Assurance Project Plan requirements

The next step in developing natural conditions criteria using this approach is developing the project Quality Assurance Project Plan (QAPP). Data quality objectives and measurement quality objectives must be established within the QAPP to ensure proper model calibration and evaluation such that, once met, the output of the model could be used to inform the selection of appropriate natural conditions criteria. Additional programmatic, departmental, or other requirements may exist for inclusion in any project QAPP.

The project QAPP must provide:

1. Key objectives, goals, and questions that are to be addressed by this project.
2. Observational data quality objectives.
3. Description of the data to be used, identified data needs, and data sources.
4. Model capability descriptions or references, including identification of key processes that drive water quality.
5. Model peer-review approach and/or documentation.
6. How spatial and temporal variability will be addressed in any model or models to ensure that natural condition estimates protect designated and existing uses.
7. Model approaches and key assumptions, which may include boundary conditions and associated determinations, initial or existing conditions, model resolution, inflow loads, or watershed inputs.
8. Description of the computational setup.
9. Model quality objectives, including how model calibration performance and model skill will be evaluated using both quantitative statistics, skill metrics, and qualitative methods.
    a) Model segment or grid size descriptions and rationale as to appropriateness linked to (4).
    b) Description of reasonable fit or other statistics between model-estimated and measured conditions following model calibration.
    c) Performance goal targets.
    d) Any model limitation, uncertainties, and assumptions, and how these could impact (if applicable) the reasonableness to meet the goals and objectives of the project.
    e) Quality Assurance and Quality Control considerations, such as adherence to the Department's programmatic QAPP for assessing impaired waters.

Data sources

All existing, readily available, and credible water quality and site characterization data for the site of interest and waters that affect the site of interest must be considered. Credible water quality data are defined by Washington's Water Quality Data Act in RCW 90.48.585 and discussed in Water Quality Policy 1-11 Chapter 2, Ecology publication 21-10-032. Waters that affect the site of interest include upstream waters (e.g., tributaries), groundwater, oceanic inputs, and waters outside the jurisdiction of the State of Washington (e.g., waters from another state or country) where relevant. The description of the data compiled and data sources must be documented in the project QAPP.

Water quality data

Water quality data must include data for the parameter(s) of interest in natural condition criteria value development. Additional water quality data may be necessary (e.g., salinity, ambient air temperature) to further demonstrate that nonattainment of an aquatic life criterion is due, in part, to natural causes or to characterize the site of interest. These data requirements will be detailed in the QAPP as they are project specific. For these data, including initial conditions data for model setup, the data must be from a range of years that encompasses the natural variability of a site, waterbody type, and parameter of interest.

Sources of readily available data include state and federal water quality databases. Washington maintains the Environmental Information Management[2] (EIM) database, which contains environmental monitoring data collected by Ecology scientists and partners. Federal water quality data includes data in the Water Quality Portal[3], which integrates data from the United States Geological Survey (USGS), EPA, and other state, federal, tribal, and local agencies. Other sources of information could include datasets related to forests and grasslands (such as from the United States Department of Agriculture Forest Service), water quality data collected by the United States Army Corps of Engineers, United States Department of Interior (including the Bureau of Reclamation) data, other state water quality databases, tribal water quality data, or other credible water quality data from outside the United States.

Existing, available, and credible data may also be found in academic and literature sources, and these published data from reputable research journals must be obtained and considered. Additional sources of data may include data collected under state or federally approved quality assurance project plans, private and public facilities (e.g., data collected as part of National Pollutant Discharge Elimination System, or NPDES, permits), and utilities (e.g., drinking water facilities).

Finally, Ecology has gathered relevant external data sets useful and applicable for water quality impairment studies. A list of these data sources, quality assurance information, and links to data are available in Appendix A of Ecology's Programmatic QAPP[4] (Ecology, 2017). This programmatic QAPP references data sets for water quality process-based modeling which are used to develop natural conditions aquatic life criteria. Data used should follow the quality objectives outlined in the section "Quality Objectives" of the above-referenced document.

[2] https://apps.ecology.wa.gov/eim/search/default.aspx
[3] https://www.waterqualitydata.us/
[4] https://apps.ecology.wa.gov/publications/SummaryPages/1703107.html

Site characterization data

In addition to water quality data, additional data must be identified to characterize the site of interest using all existing, readily available, and credible data. These data must also be sourced for waters that affect the site of interest (e.g., tributaries, upstream waters). These data may be necessary to characterize the site of interest and the application of the model (e.g., model validity), or data may be necessary to assist with other processes (e.g., modeling hydrodynamics, thermodynamics). Specific data needs must be addressed in the project specific QAPP.

Site characterization data information includes, but is not limited to, the following (required unless marked as optional):

- Data characterizing the boundary and initial conditions of the site.
    - Include data for any relevant or appropriate headwaters, tributaries, and groundwaters.
    - This may include applicable water quality data (e.g., dissolved oxygen, sediment characteristics, turbidity). This may also include information regarding nutrient fluxes (e.g., phosphorus, nitrogen, dissolved organic carbon), sediment fluxes, site alkalinity, or planktonic data.
    - Data should be from a range of conditions, both current and natural, encompassing the expected natural and impacted variability of a site and parameter of interest.
        - Conservative assumptions reflective of natural conditions will be made based upon sensitivity (range) testing.
    - Data gaps may be present. See the section "Data Gaps" below on how data gaps are addressed.
- Description of surrounding vegetation and riparian conditions.
    - This may include, but is not limited to, tree canopy cover data, system shade potential, any applicable stream buffer zones, or estimates of the fraction of solar radiation reaching the water surface.
- Waterbody morphology.
    - This includes size, shape (such as measured by shoreline development factor), and connectivity (such as via intersection with surface flow lines).
- Hydrodynamics and physical properties.
    - Including, but not limited to, density, salinity, and tidal attributes (where relevant).
- Light availability.

    - Data characterizing light availability throughout the water column.
- Sediment mobilization and concentrations in the water column.
- Bio-geochemical concentrations and characteristics.
    - Includes relevant water quality and related parameters such as dissolved oxygen, nutrients, photosynthetic pigments, carbonate system concentrations, and metals.
- Sources of groundwater connected to the surface waters of interest.
    - Data could include groundwater quality data and characterization, flow rates, and sources of withdrawal or recharge.
- Hydrological modifications.
    - This may include identification of dams or impoundments, channelization (e.g., dredging, bank erosion) information, impacts to natural flow regimes, and evaluations of bottom roughness and gradient.
- Point source discharges.
    - Identification of all point-source discharges, including NPDES permits. Information related to the discharge should be sourced, such as effluent characteristics, discharge locations, and mixing zone boundaries.
- Non-point source discharges.
    - Identification of all known non-point sources, including those discharges within and upstream of the site of interest.
    - This includes runoff from all sources present that could impact the site, which includes all human activities including but not limited to: agriculture activities; septic systems; mining; presence of non-native vegetation; impervious surfaces; and forestry activities.
        - This could also include surface and groundwater non-point source load information.
    - Provide estimations for nutrient and organic carbon loads for dissolved oxygen and pH natural conditions calculations.
    - This includes water quality data associated with the non-point sources, volume of water from these discharges, and distance between runoff and the site of interest.
- Meteorological data.

    - This includes data such as ambient air temperature, precipitation, humidity, or wind as required by the modeling platform selected (refer to model documentation).
    - These data should capture the expected natural and impacted variability.
- Atmospheric deposition data.
    - Include information relevant to parameters of interest (e.g., nutrient deposition, inorganic carbon or sulfur deposition).
- Other climatic data.
    - This includes long-term data (collected or estimated through climatic models) that describe how humans have impacted the site from a global scale (e.g., watershed temperature increases due to emissions).
- Kinetic and physical rates and ratio data.
    - This includes, but is not limited to, attributes of a site such as primary production rates, aeration, organic carbon decomposition rates, and nutrient limitation rates.
    - Natural conditions parameterization of rate process and kinetic functions must rely on site-specific data, if available.
    - Kinetic and physical rates and ratio values must be consistent with model literature and understanding of natural dynamics for the site and parameter of interest.
- Invasive species.
    - Invasive species information should be sourced, including known habitat.
- Biological indices or other measures (optional).
    - Collect any available information regarding previously reported, scientifically applicable biological indices or other measures that characterize aquatic life health of the system. Indices or measures should be: published in reputable scientific journals or by local, state, tribal, or federal agencies; and peer reviewed.

Types of data

Data sourced for water quality and site characterization is not limited to numeric datasets. In addition to numeric data, all existing, readily available, and credible data could include, but is not limited to, data in the form of:

- GIS data (e.g., maps).

    - Such as maps of the site of interest and surrounding area, including upstream, that indicates historical and current land cover or land use.
- Site-survey data.
    - Data in, near, and around the site of interest, including road coverage and density, hydrological alterations, or other human-constructed structures.
- Site photographs.
    - These could show the presence or extent of riparian vegetation, tree canopy, and waterbody morphology.
- Records from relevant state or federal agencies.
    - This may include information such as historic or current mining activities, forest logging, or other major human actions (e.g., NPDES permits) within or upstream of the site.
- Cultural histories, interviews, or other tribal information of the watershed.
    - This could be used to demonstrate historical uses of the waters.

Data timeframe and metadata requirements

There are no restrictions or limits on obtaining applicable data other than those previously identified (i.e., all existing, readily available, and credible data). Ideal datasets will include long-term data[5] for the water quality parameter(s) of interest and data that represents pre-industrial periods or before large-scale human impacts.

If combining data across multiple time frames to estimate natural conditions, the methodology used in combining data sets must be documented and will be appropriately conservative to capture the range of conditions that protect existing and designated uses across the scales of aggregation.

All associated metadata must be included alongside the sourced water quality and site characterization data. This includes any quality assurance or quality control information, geospatial information, and data collection information (e.g., time of collection, depth).

Data gaps

Any data gaps in the data compilation should be identified. If data gaps are filled (such as through estimation), or any data are estimated for the project, the process for doing so must be described in the project QAPP and final report, and its use must be supported with best professional and scientific judgement.

[5] Defined as data collected regularly (e.g., monthly) over at least ten years.

Model development and requirements

The process-based modeling approach considers the use of a model or models to estimate natural conditions of a system, which can be used to determine appropriate natural conditions criteria for the site of interest. Any models used in this approach must follow the requirements set forth in the project QAPP as well as the following requirements:

- The model must allow for reproducibility of results.
  - This means the model code should be open source, with existing and reference input and output files, alongside data sources, and made available to the public.
- The model framework, including the model code, will have undergone a formal peer-review process before application, or be recognized as widely-used code in the published literature, if not peer reviewed previously and fully documented.
  - Documentation of the peer-review process must be described in the project QAPP or final report associated with this approach.
- Model selection will be from a set of best available modeling tools applicable for the specific purpose to estimate natural conditions based on the project requirements and best professional judgement.
- The model or models chosen must be able to simulate all key processes and sources affecting the parameters of interest.
- Calibration of the model must be done using reasonable adjustments of model parameters, as defined using best professional judgement and comparison to typical parameter ranges documented in literature, peer-reviewed reports, and other similar studies, to achieve a reasonable fit between model-estimated and measured conditions based upon the peer review of the individual model, or by comparing to documented model fit statistics from other similar applications using the same model.
  - The quality of the model calibration must be documented and include both qualitative and quantitative evaluations.
- The model should be able to recreate the existing condition scenarios with the quality specified in the project QAPP.
  - Model calculated outputs must be compared with measured data at calibration locations. A sufficient number of calibration locations will be defined and identified prior to model application.
  - Modeled hydrodynamics and relevant parameters (e.g., DO, temperature, pH) for all waterbody types simulated must be evaluated.
- Model documentation should information about and what are the unknowns and uncertainties in model outputs.
- The model must have sufficient resolution (and such resolution is documented) to:
  - Predict horizontal and vertical variations in water quality (e.g., tributary confluences, varied depths in stratified reservoirs). These predictions must be generated on least an hourly basis.

    - Capture the impacts to all designed uses, including the most sensitive designated use, and provide rationale for this determination in the project QAPP or final report.
    - Identify criteria outcomes that are fully protective of the designated or existing uses.
- The model domain must be large enough to encompass the entire system of interest while sufficiently accounting for boundary conditions.
- All model parameter values must be documented.
- The flow and water quality information for any groundwater, tributaries, upstream inflows, and open boundary inflows must be set at estimated natural conditions of those waters based on readily available and credible information.
    - The methods used and assumptions made must be documented.
- Sensitivity testing must be conducted on the means and ranges on parameters which affect the natural condition outcome.

All technically feasible steps to improve model performance and representativeness of the model, based on available information, must be taken prior to model acceptance and use to estimate natural conditions.

Determining that nonattainment is due, in part, to natural processes

Introduction

Use of the process-based modeling approach must include an evaluation that determines the extent of how the nonattainment of the applicable water quality criteria is due to a natural process or variation. In this determination, use of this approach must consider all required elements listed in this section during site characterization and evaluation. If any required element is not applicable or relevant to a site (e.g., there are no hydromodifications within or upstream of the site of interest), then its non-applicability or non-relevancy must be justified using firm scientific rationale or professional judgement.

Due to hydrological differences, required elements are split between fresh waters and marine waters. Use WAC 173-201A-260(3)(e) to determine whether fresh water or marine water criteria apply to the site of interest.

Accounting for human-caused impacts and pollution

In the process for determining the extent of natural conditions' impact on nonattainment of the applicable water quality criteria, analysis of the various elements will include factors related to human-caused impacts to surface water quality. Ultimately, these impacts will need to be accounted for and removed in the natural condition estimation.

Specifically, human-caused sources of pollution originating within the boundaries of the State of Washington impacting surface waters of the State must be accounted for and removed in the natural condition mechanistic model. This includes accounting for all known sources of heat, oxygen-demanding pollutants, and pH-altering pollutants, including but not limited to those listed within each element.

All other human-caused sources of pollution that impact the site must be accounted for as best as possible using existing, readily available, and credible information (e.g., global climate change, boundary inputs from sources outside the United States). These sources can be excluded from the model if it is not feasible to model it, but the impact of these sources must be estimated outside the model before deriving the final criteria values. While data used to address these other sources of pollution must meet credibility requirements, it may not meet other resolution or frequency requirements established in the project QAPP. Further, these data may range in database size and complexity, from simple numeric datasets to complex models that have previously been developed to estimate human impacts to water quality on a global scale.

Any source or stressor that are not part of any model used in this approach must have a rationale for exclusion. These sources must not affect the parameter or site of interest.

Any final natural conditions criteria values used for further state and federal Clean Water Act actions must represent the natural conditions of the water of interest as defined in WAC 173-201A-020: that the natural conditions reflect the water before any human-caused pollution.

Human structural changes

The performance- based approach may not be used to derive criteria for specific assessment units of waters that contain human structural changes that cannot be effectively remedied (see WAC 173-201A-260(1)(b)). In these situations, alternative criteria may be developed (e.g., site-specific criteria, through a use attainability analysis).

The performance-based approach, however, may be used for other assessment units that are impacted by a waterbody containing human structural changes (as per WAC 173-201A-260(1)(b)), so long as the regional natural condition values with an underlying scientific basis defined in the project-specific QAPP or relevant documentation are used to remove the potential impacts of the irreversible structural changes.

Elements – fresh waters

Each element contains a description of the information to be evaluated in the model. The use of each of these elements and subsequent analyses based on corresponding data should be documented in the final report.

Boundary and initial conditions of site

The boundary or initial conditions of the site includes any relevant or appropriate headwaters, tributaries, and groundwaters. These site conditions are used to define flow, water quality concentrations (including but not limited to nutrients, carbon, dissolved oxygen, and temperature), and other biological, chemical, and physical parameters in the spatial area of interest for the model. Boundary conditions must be set at estimated natural conditions of these waters, based on readily available and credible data. All methods used and assumptions made in setting boundary conditions for natural condition predictions must be documented in the final report. This documentation must include rationale for boundary siting within the model domain as well as water quality conditions.

Impacts by humans on boundary or initial conditions of the site must be accounted for and removed in the natural condition estimation. This includes but is not limited to:

- Any impacts by humans on tributaries which influence the site of interest.
- Loss of stream baseflow or other flow changes (e.g., stagnant conditions)
- Decreased groundwater availability due to human withdrawals.
- Human recharge to groundwater that results in discharges that affect DO levels and nutrient concentrations in streams.
- Increased sedimentation, including fine sediment.
- Changes to benthic submerged aquatic vegetation.
- Changes in residence time of the system.

All methods and procedures to characterize how these will be accounted for and removed will be included in the QAPP and documented in the application of the PBA.

Hydrologic or hydraulic modifications

Hydrologic or hydraulic modification data are evaluated to understand how modifications to the site have changed over time, regardless of whether anthropogenically or naturally caused. This information will be used to:

- Demonstrate changes in the water compared to historical records, including identification where and when major hydrological projects occurred.
- Estimate natural channel widths to system potential shade calculations.
- Model water system changes with the removal or alteration of any hydrological or hydraulic modifications (i.e., dams, culverts, and other modifications removed in the natural simulation).
- Demonstrate the impact of groundwater fluxes into the system including groundwater restoration in the natural simulation.
- Account for withdrawals or pumping outside of boundary conditions and adjust inflow accordingly such that it reflects natural flows.
- Explicitly model surface withdrawals as point abstractions in current conditions flow balance then remove withdrawals for natural condition determinations.

Impacts to water quality must be accounted for and removed in the natural conditions' estimation, and the process for doing so must be in the project specific QAPP. This includes:

- Upstream and downstream impacts from dams.
    - Stream temperature impact, including but not limited to timing and depth changes of seasonal thermoclines.

- Dissolved oxygen impacts, including but not limited to releases of water with low DO concentrations and changes in primary productivity and respiration.
    - pH impacts, including but not limited to impacts during water thermal stratification and changes in primary productivity and respiration.
- Loss of channel complexity.

See “Human Structural Changes” for additional information.

Riparian conditions

Data regarding the riparian conditions of the site must be reported and analyzed. Riparian differences between existing conditions and natural conditions may be a driver in impact of solar radiation on the water body of interest. This information could be used in:

- System potential shade estimations.
- Comparison of vegetation height or density to applicable reference sites.
- Making historic tree height comparisons.
- Perform analyses using tree diameter data, which is used to estimate tree heights using known species-specific relationships.

The loss of riparian shade or other vegetation impacts along the shoreline due to human actions must be accounted for and removed in natural condition estimations.[6] The methods used must be documented.

Meteorological conditions

Applicable meteorological conditions and data must be reported and evaluated based on the project requirements. Analyses of meteorological conditions will be used to:

- Develop hydrodynamic and thermodynamic simulations based on a range of conditions.
- Investigate differences between current and unaltered habitats.
- Demonstrate how reduction of air temperatures could reflect small changes in riparian climates.
- Measure climate change impact on the natural conditions of a system over time.

Impacts must be accounted for and removed (e.g., climate change impacts on air temperature). As these impacts will vary by project and possibly over time, the specific impacts identified, accounted for, and removed must be documented and provided in the final report.

Point source discharges

Impacts by all point source discharges within and upstream of the site of interest must be documented and evaluated. This information may be useful to:

[6] For example, determine system potential tree height based on General Land Office survey bearing tree records converted to tree heights using known species-specific relationships between diameters and height.

- Model how removal or reduction of a pollutant in discharged effluent would affect the water quality parameters of interest.
- Demonstrate how effluent flow rate adjustments would influence the system under evaluation.

These impacts from discharges (e.g., NPDES permitted discharges, wastewater, stormwater outfalls) must be accounted for and removed in natural condition estimations.[7] This includes but is not limited to:

- Accounting for impact of point source effluent on dissolved oxygen, including biochemical oxygen demand and nutrient loads.
- Discharge impacts on water temperature.
- Effects on pH (including changes or increases in pH range or extremities).

Non-point source discharges

All readily available non-point source discharges within and upstream of the site of interest must be evaluated for impact to the site of interest. This includes surface and groundwater non-point source loads. This element is to understand the pollutants entering the site waters dispersed from any land-based or water-based activity that is not otherwise regulated under a state surface water discharge permit or NPDES permit. This information will be used to:

- Demonstrate how alterations or reductions of these discharges could influence water quality of the site.
- Compare data to reference sites to estimate non-point impact.
- Develop a reference natural condition land-use condition for further analysis in any developed water quality model.

Any impacts from non-point source discharges, including human development in the watershed, must be accounted for, and removed, when estimating natural conditions of the site.[8] This includes accounting for impact of non-point source discharge on the biochemical oxygen demand, dissolved oxygen, nutrients, temperature, and pH of the water. All processes and methods used must be included in documentation and the final report.

Kinetic and physical rates and ratios

Kinetic and physical rates and ratios relate to temporal or speed attributes at which chemical, biological, or physical reactions or processes take place. The values assigned to rates are estimated in the model calibration process. If there is information indicating that a rate or ratio is impacted by human-caused factors, these impacts to the rates or ratio must be accounted for and removed when estimated natural conditions.

[7] No discharges allowed in natural condition estimations.
[8] For example, using a reference natural condition land use condition.

Invasive species

Information regarding invasive species should be provided and evaluated. In the context of this approach, "invasive species" refers to non-native plants or animals that have been introduced into the site of interest since the start of the industrial era, or native plants or animals that have hyper-aggressively propagated due to human-conditioned environments. This information may be used to:

- Demonstrate the impact that invasive species have on shade changes over time in shade analyses.
- Demonstrate impact to water quality with reduction or removal of invasive species.

Impacts of invasive species must be accounted for and removed in natural condition estimations. This may include evaluating impact of invasive species on lower trophic level organisms or aquatic life (e.g., benthic vegetation) and how invasive species may have caused changes in water quality. Methods and data sources for invasive species and methods for capturing return to non-invasive status must be documented and included in final report.

Elements – marine waters

Each element contains a description of the information to be evaluated as well as examples of how analysts may use this information. The use of each of these elements and subsequent analyses based on corresponding data should be contained in the final report.

Boundary and initial conditions of site

The boundary or initial conditions of the site includes any relevant or appropriate headwaters, tributaries, and groundwaters. These site conditions are used to define flow, water quality concentrations, and other biological, chemical, and physical parameters in the spatial area of interest for the model. These must be set at estimated natural conditions of these waters, based on readily available and credible data. All methods used and assumptions made in setting boundary conditions for natural condition predictions must be documented in the final report.

Impacts by humans on boundary or initial conditions of the site must be accounted for and removed in the natural condition estimation.

Hydrologic or hydraulic modifications

Hydrologic or hydraulic modification data are evaluated to understand how modifications to the site have changed over time, regardless of whether anthropogenically or naturally caused. This information could be used to:

- Demonstrate changes in the water compared to historical records, including identification where and when major hydrological projects occurred.
- Model water system changes with the removal or alteration of any hydrological or hydraulic modifications.
- Account for withdrawals or pumping outside of boundary conditions and adjust inflow accordingly.

Impacts to water quality must be accounted for and removed in the natural conditions' estimation. See "Human Structural Changes" for additional information.

Meteorological conditions

Applicable meteorological conditions and data should be reported and evaluated based on the project requirements. Analyses of meteorological conditions may be used to:

- Investigate differences in these conditions between current and unaltered habitats.
- Evaluate scale-appropriate inputs that influence factors such as algal photosynthesis, productivity, mixing, or stratification.

When using this element in the mechanistic approach, generally use the same meteorological observational or model-based meteorological files for natural conditions as existing conditions, unless specified otherwise in the project QAPP or there exists a firm scientific basis.[9]

In estimating natural conditions criteria, impacts must be accounted for and removed, and the methods and process must be included in documentation and the final report.

Point source discharges

Impacts by all point source discharges within and upstream of the site of interest must be documented and evaluated. This information may be useful to:

- Model how removal or reduction of a pollutant in discharged effluent would affect the water quality parameters of interest.
- Demonstrate changes in water quality if effluent concentrations into marine or brackish waters (including those from freshwater systems) were set to natural ambient levels.

These impacts from discharges (e.g., NPDES permitted discharges, wastewater, stormwater outfalls) must be accounted for and removed in natural condition estimations. Methods and process for doing so must be included in documentation and the final report. This includes but is not limited to:

- Accounting for impact of point source effluent on the biochemical oxygen demand.
- Discharge impacts on water temperature outside mixing zones.
- Effects on pH (including changes or increases in pH range or extremities).

Non-point source discharges

All non-point source discharges must be evaluated for impact to the site of interest. This element is to understand the pollutants entering the site waters dispersed from any land-based or water-based activity that is not otherwise regulated under a state surface water discharge permit or NPDES permit. This information may be used to:

[9] For example, some projects may have this element based on published literature and will not be modeled.

- Demonstrate how alterations or reductions of these discharges could influence water quality of the site.
- Make comparisons to reference sites to estimate non-point impact.

Any impacts from non-point source discharges, including human development in the watershed, should be accounted for, and removed, when estimating natural conditions of the site. This includes accounting for impact of non-point source discharge on the parameter of interest, such as biochemical oxygen demand, temperature, and pH of the water. The methods and process for doing so must be included in documentation and in the final report.

Kinetic and physical rates and ratios

Kinetic and physical rates and ratios relate to temporal or speed attributes at which chemical, biological, or physical reactions or processes take place. This information may be used in:

- Model calibration process.
- Specify rates or ratios for natural conditions when there is a scientific basis to do so.

Impacts to these rates and ratios must be accounted for and removed when estimating natural conditions. The methods and process for doing so must be included in documentation and in the final report. This includes:

- Evaluating the ability of the water to hold dissolve oxygen, and subsequently, determining loss of that ability based on increases of water temperature due to human-caused impacts.
- Analyzing changes to algal and plant photosynthetic rates due to eutrophication driven by human causes (e.g., point- and non-point loading of nitrogen and phosphorus).
- Evaluation of human-driven changes in biological productivity.

Determining natural conditions criteria values

Criteria magnitude

The process-based modeling approach uses a model to estimate natural conditions of a system, which can be used to determine appropriate natural conditions criteria for the site of interest. Development of the applicable natural condition criteria magnitudes must consider all existing, readily available, and credible data for the site of interest. Any biogeochemical and physical relationships used for determining natural conditions must be established based upon known relationships for pristine or pre-anthropogenic conditions.

Natural condition criteria magnitude estimations must reflect the natural conditions of the system without any human impacts. See “Accounting For Human-Caused Impacts and Pollution” for additional details.

Modeling outputs and subsequent analysis must include a demonstration of the natural extent of the parameter.[10] This includes:

- Describing long term (multi-week to inter-annual) range and variation in the parameter.
- Calculations of summary statistics, including low or high percentiles, as appropriate, of the natural condition estimations.
- Demonstration of how input variability (e.g., flows, temperatures) impacts the magnitude of the parameter(s) under investigation.

Determination of the natural condition criteria magnitudes must be done on a specified cell by cell or node by node (depending upon the model) basis. The basis for these decisions must be documented, and the resulting criteria values must provide protection for all designated and existing aquatic life uses. Natural conditions criteria cannot be developed for areas where reliable estimates of the natural conditions cannot be produced.

Model outputs that estimate natural conditions represent the system potential conditions of the site. The model output resolution will vary by project design (as described in the QAPP), data availability, and model choice. The highest resolution model outputs that represent the natural conditions criteria magnitudes of the site must:

- Meet the precision and accuracy requirements set forth in the project QAPP,
- Reflect the parameter (DO, temperature, pH) biologically based numeric criteria metrics,
- Abide by the data and modeling requirements in this performance-based approach, and
- Protect designated and existing uses by removing all human-caused impacts and pollution to the water of interest.

If various model outputs are used in analysis (such as from using multiple model runs across different years), then the model run(s) chosen must best reflect the long-term natural condition of the system and capture the range of long-term conditions.

If aggregating estimated natural condition criteria values to "simplify" the final natural conditions criteria,[11] then criteria values must be aggregated in such a way that:

- Any aggregated groupings (e.g., water assessment units) are scientifically or professionally justifiable.
- The natural condition criterion value determined post-aggregation is fully protective of aquatic life across the entire grouping.[12]

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[10] Such as the range of magnitude of the parameter.
[11] Such as determining a single criterion value that applies to two assessment units.
[12] For example, consider a temperature determination scenario aggregating two assessment units that are abutting in a freshwater stream. If the natural condition criterion value determined for one assessment unit is estimated to be 16.2°C and the other assessment unit criterion value is estimated to be 16.8°C, then the final aggregated natural condition temperature criterion value that protects aquatic life across the grouping would be 16.2°C.

This process of aggregation, support for the groupings used, and calculations for the natural condition criteria values must be documented and have a firm scientific basis. Further, these criteria values must fully protect designated and existing uses.

Finally, criteria magnitudes determined may reflect a singular or combination of values[13], and these values must protect designated and existing uses based on the chosen statistical metrics (e.g., 7-DADMax, no more than one exceedance in a 10-year period).[14] This includes protections against acute and chronic impacts of the parameter on aquatic life.

Criteria duration and frequency

Any developed natural conditions criteria must include duration and frequency components. In estimation of the natural conditions, the statistical metric will be the biologically based numeric criteria for each parameter simulated. The duration and frequency of these natural condition estimates should match the duration and frequency requirements of the applicable biologically based numeric aquatic life criteria within WAC 173-201A.[15]

Criteria evaluation and application

Developed natural conditions criteria must include the periods of the year when the criteria values apply, if applicable. For example, the criteria might only be applicable for the summer period or during low flow conditions. If natural conditions criteria were calculated using such restrictions (e.g., seasonal boundaries), then any developed natural conditions criteria values have the same restrictions. The period of application for natural conditions criteria will not include times or conditions where limited or no data are available; the existing biologically based numeric criteria would continue to apply during these times or conditions.

Site-specific numeric aquatic life criteria derived in accordance with the performance-based approach are the applicable numeric aquatic life criteria for the site (as identified in "Define Site Boundaries" upon derivation). This includes times or conditions where analysis demonstrates that the natural conditions criteria are more stringent than the existing biologically based numeric criteria. Further, criteria values developed using the performance-based approach must protect existing and designated uses in downstream waters and must not cause degradation of downstream receiving waters.

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[13] This determination is project specific. For instance, the final natural conditions criteria magnitudes could be a singular value that applies across the entire year, or the final criteria could be multiple values with each singular value representing a seasonal criterion. The determination of the criteria magnitudes and any restrictions for when they apply (e.g., seasonal) must be documented and provided in the final report.

[14] See "Criteria Duration and Frequency."

[15] For example, if developing natural conditions criteria for temperature in a riverine system that cannot meet the applicable biologically based criteria in Table 200(1)(c), the natural conditions criteria determined in this process would have calculated magnitude values that are 7-DADMax criteria not to be exceeded at a probability frequency of more than once in ten years.

Documentation and use

Once the natural conditions criteria values (including magnitude, duration, frequency) are determined, these values can be used for state and federal Clean Water Act actions, such as for Water Quality Assessments or in Total Maximum Daily Load development. If using this value for these state and federal actions, then all evaluation, analyses, data, and decision points from this process-based modeling approach must be documented and reported, and this must be provided alongside the calculated values and project QAPP. The report format should follow accepted agency templates or protocols.

The final report must include sources of model uncertainty in summarized form. The report will also include how the model output was used to establish natural conditions criteria, identifying outcomes for each site-specific determination as applicable. This will include documentation on how model outputs and external jurisdictional data were analyzed to calculate the natural conditions criteria values.

The report must also include information on natural condition estimates, including but not limited to:

- Summary tables
- Cumulative relative frequency tables
- Natural variation and central tendencies for simulated waters
- Spatial and temporal considerations
- Changes from the project QAPP
- An appendix that includes all sources of data, approaches, and references not previously documented and used in the analysis

This report will undergo agency peer review through established departmental processes with a specific mention for reviewers to focus on the natural conditions analyses. This peer review must be completed prior to the use of these natural condition criteria values in further state and federal Clean Water Act actions (e.g., TMDLs, NPDES permits, CWA 401 certifications).

All documentation (including, but not limited to the project specific QAPP, final report, and criteria) must be made available to the public if using the natural condition criteria values in further state and federal Clean Water Act actions.

Appendix A. References

Davies, Tudor T. 1997. Establishing Site Specific Aquatic Life Criteria Equal to Natural Background. Memorandum to Water Management Division Directors, EPA Regions 1-10, and State and Tribal Water Quality Management Program Directors. Dated 5 November 1997. Office of Water, Office of Science and Technology. Washington, D.C.

United States Environmental Protection Agency (USEPA). 2015. A Framework for Defining and Documenting Natural Conditions for Development of Site-Specific Natural Background Aquatic Life Criteria for Temperature, Dissolved Oxygen, and pH: Interim Document. Office of Water, Office of Science and Technology. Washington, D.C. EPA 820-R-15-001.

United States Environmental Protection Agency (USEPA). 2023. Water Quality Standards Handbook Chapter 3: Water Quality Criteria. Office of Water, Office of Science and Technology. Washington, D.C. EPA 823-B-23-001.

Washington State Department of Ecology (Ecology). 2017. Programmatic Quality Assurance Project Plan. Water Quality Impairment Studies. Olympia, Washington. Publication No. 17-03-107.

A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington (Second Draft)

Water Quality Program

Washington State Department of Ecology

Olympia, Washington

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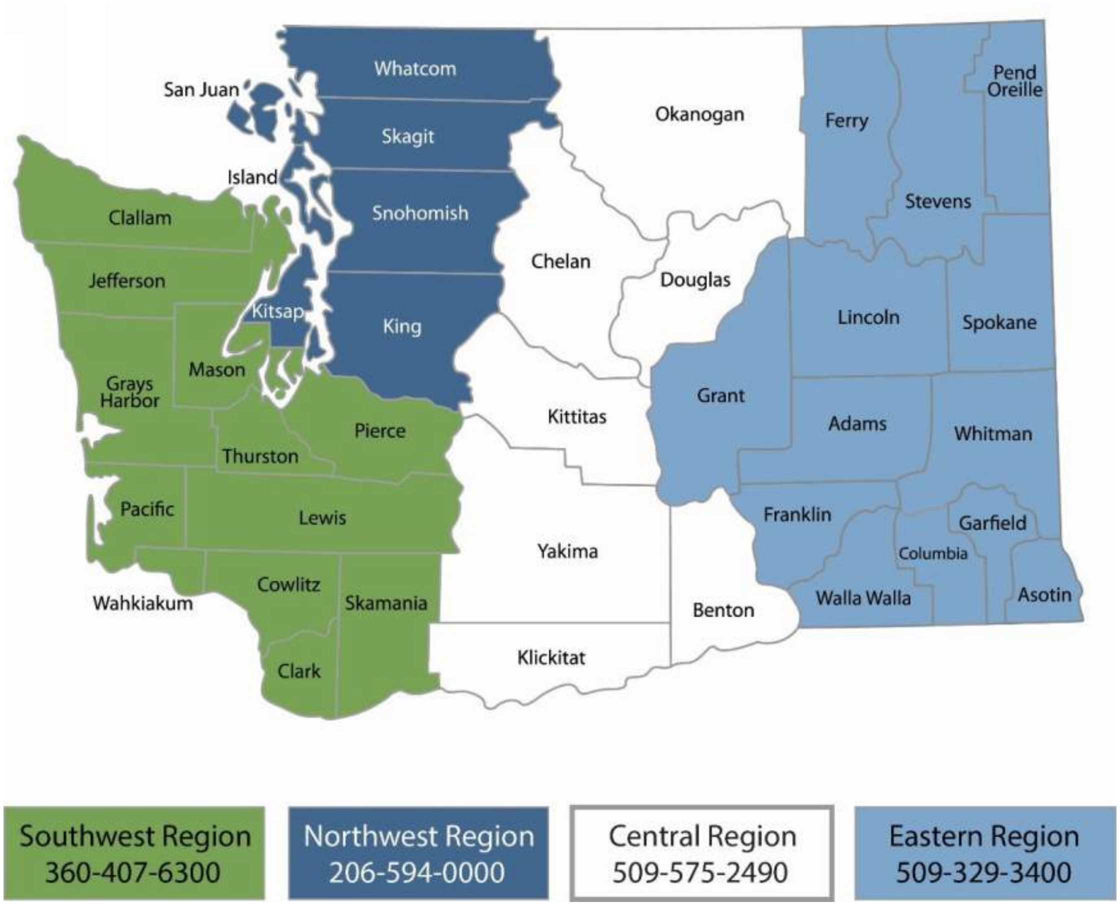
Department of Ecology's Regional Offices

Map of Counties Served



Region	Counties served	Mailing Address	Phone
Southwest	Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, Mason, Lewis, Pacific, Pierce, Skamania, Thurston, Wahkiakum	PO Box 47775 Olympia, WA 98504	360-407-6300
Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	PO Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
Headquarters	Across Washington	PO Box 46700 Olympia, WA 98504	360-407-6000

A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington

Water Quality Program
Washington State Department of Ecology
Olympia, WA

March 2025 | Publication 25-10-022

DEPARTMENT OF
ECOLOGY
State of Washington

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Introduction and Background

Introduction and purpose

Washington Department of Ecology (Ecology) recognizes that in some portions of some waterbodies, the assigned aquatic life criteria may not be met due, in part, to the natural conditions of the waterbody. Therefore, if these natural climatic or landscape attributes are preventing attainment of applicable numeric aquatic life criteria, then site-specific numeric aquatic life criteria representing these natural conditions can be calculated following processes listed at Washington Administrative Code (WAC) 173-201A-260(1)(a)). This includes the performance-based approach (WAC 173-201A-260(1)(a)(i) and WAC 173-201A-470).

When the performance-based approach is used by Ecology to establish natural condition aquatic life water quality criteria, development of these criteria values must follow the procedures and methods in this document as per WAC 173-201A-470. The perrformance-based approach is limited by WAC 173-201A-470 to the following water quality parameters:

- Dissolved oxygen (DO; fresh water and marine water)
- pH (fresh water)
- Temperature (fresh water and marine water)

If the determination of aquatic life criteria values cannot meet the requirements set forth in this document, then site-specific criteria can be established by following the alternatives listed at WAC 173-201A-260(1)(a)(i).

Regulatory information

Federal

The Clean Water Act (CWA) requires states to adopt water quality standards that consist of designated uses, water quality criteria, and an antidegradation policy. Section 303(c)(2)(A) of the CWA gives the responsibility for adopting water quality standards to states and authorized Tribes, and that these standards will protect the public health or welfare, enhance the quality of water, and serve the purposes of the Act.

40 CFR 131.3(b) defines criteria as elements of the water quality standards (expressed as constituent concentrations, levels, or narrative statements) that represent a quality of water that supports a particular use such that when criteria are met, water quality will generally protect the designated use.

States and authorized Tribes must adopt water quality criteria that protect these designated uses (see 40 CFR 131.11). States and authorized Tribes may adopt, where appropriate, other criteria that differ from the Environmental Protection Agency's (EPA's) recommendations, so long as the criteria are:

- Based on sound scientific rationale,
- Contain sufficient parameters or constituents to protect the designated use or uses, and
- Support the most sensitive designated use of the waterbody.

States and authorized Tribes can adopt criteria that are modified to reflect site-specific conditions (see 40 CFR 131.11(b)(1)(ii)), so long as they are based on sound scientific rationale and protect designated uses. EPA has provided guidance for derivation of site-specific criteria outlined in *Water Quality Standards Handbook Chapter 3: Water Quality Criteria*.[2]

Any new or revised criteria adopted by states or authorized Tribes must be submitted to EPA for review to determine if the criteria meet the requirements of the CWA and its implementing regulations (33 USC 1313(c)(3)). If approved by EPA, the criteria become applicable for CWA purposes and remain the applicable criteria until EPA approves a change, deletion, or until EPA promulgates more stringent criteria if necessary to meet CWA requirements (40 CFR 131.21(c), (e)).

State

Water pollution control in the State of Washington is regulated under Chapter 90.48 Revised Code of Washington (RCW). This includes 90.48.010 RCW which states that it is the public policy of the state to maintain the highest possible standard to ensure purity of waters consistent with public health, public enjoyment, and propagation and protection of wildlife, birds, game, fish, and other aquatic life.

90.48.035 RCW establishes the rule-making authority for the Department to promulgate rules and regulations necessary to carry out the provisions of Chapter 90.48, including water quality standards for the state.

The Water Quality Standards for Surface Waters of the State of Washington are codified at WAC Chapter 173-201A. This chapter establishes standards for public health and public enjoyment of waters in the State and for propagation and protection of fish, shellfish, and wildlife.

[2] United States Environmental Protection Agency (USEPA). 2023. Water Quality Standards Handbook Chapter 3: Water Quality Criteria. Office of Water, Office of Science and Technology. Washington, D.C. EPA 823-B-23-001.

Performance-Based Approach

Overview

A performance-based approach is a binding methodology that provides a transparent, predictable, repeatable, and scientifically defensible procedure to derive numeric criteria protective of designated uses. When a performance-based approach is sufficiently detailed and has suitable safeguards to ensure predictable, repeatable outcomes, EPA's approval of the approach also serves as an approval of criteria derived consistent with the approach.

Aquatic life water quality criteria values developed using the performance-based approach are applicable to the waterbody upon derivation, so long as all requirements set forth in this document are met.

Applicability

Use of the performance-based approach is limited to the parameters listed at WAC 173-201A-470(2). Natural conditions aquatic life criteria for other water quality parameters must be developed using site-specific criteria pursuant to WAC 173-201A-430 (as specified at WAC 173-201A-260(1)(a)(ii)), as applicable, and must follow all state and federal rulemaking regulations prior to becoming effective for state and federal CWA actions. Natural conditions water quality criteria are appropriate only for the protection of aquatic life designated uses, not human health uses.

Chapter 1: Marine Dissolved Oxygen

Introduction

This is a binding approach for deriving natural condition aquatic life water quality criteria for marine dissolved oxygen (DO) through the use of water quality models. Water quality models determine the water quality dynamics for marine DO observed at the site of interest under current and natural conditions. This approach will allow quantification of effects at a site from both human sources and natural sources.

In this process, developing the natural conditions criteria consists of:

1. Defining where natural conditions apply (i.e., the site boundary) and the model domain.
2. Compiling existing, readily available, and credible current and historical water quality and site data.
3. Developing a Quality Assurance Project Plan (QAPP).
4. Obtaining new field data, if needed.
5. Compiling, reviewing, and assessing any new field data to ensure it meets quality assurance (QA) / quality control (QC) goals.
6. Developing and calibrating a model of the existing conditions of the waterbody or watershed, including defining temporal and spatial boundaries.
7. Evaluating model performance.
8. Estimating natural condition inputs to the model by removing known and estimated human-caused impacts.
9. Calculating the natural conditions criteria values by running the model with natural condition inputs.
10. Documentation of performance-based approach use.

The performance-based approach will generally be conducted step-wise; however, as modeling is an adaptive process, it may be necessary to repeat or circle back through certain steps during the project.

The analysis of data and development of the criteria values must be documented. If the developed criteria values are used in subsequent state or federal CWA actions, then: (a) this documentation must be included with the documentation for the CWA action; and (b) the criteria values must be accessible to the public.

Step 1: Define site boundaries and model domain

The first step in this process is defining the site boundaries, model domain, and model cell resolution. The site boundaries encompass where natural conditions criteria are being determined. The model domain must include the site boundaries and contributing waters to the area where the natural conditions criteria are being determined. The site and model domain may include multiple CWA 303(d) assessment units of interest to the project. The site boundaries and model domain for the site of interest must be defined and documented.

Boundary information must include geospatial information. This information must be documented in the respective project QAPP and/or other documentation as part of this performance-based approach.

For cell resolution, it must be sufficient to predict horizontal and vertical variations in water quality on at least an hourly basis. Establishing the model grid is project specific, and therefore, the process for doing so must be documented in the respective project QAPP and/or other documentation. When establishing the model grid and selecting cell resolution, considerations include, but are not limited to, the following:

- Sufficiently fine to resolve features of the site (e.g., shoreline, islands, watersheds, river mouths).
- Allow for selected temporal simulation (e.g., year-long).
- Bathymetry information and accuracy for the site.
- Ensuring representation of identified subbasins in large model domains.
- Simulation of key location-specific biogeochemical forcings (e.g., incorporation of eelgrass meadows is a step towards modeling water quality in the nearshore).

Step 2: Compile data

All existing, readily available, and credible data and information to characterize the site of interest and waters that affect the site of interest must be considered to model current and natural conditions. Waters that affect the site of interest include, but are not limited to:

- Upstream waters (e.g., tributaries, groundwaer, wetlands), and
- Oceanic inputs

A description of the data compiled and data sources must be documented in the project QAPP. For these data, including initial conditions for model setup, the data must encompass the natural variability of a site, waterbody type, and parameter of interest. Table 1 provides typical data needs for modeling both the current and natural conditions.

Table 1. Data needs for modeling current and natural conditions.

Category	Current Conditions	Natural Conditions
Water Quality Observations, Marine Water	Marine water quality observations (e.g., salinity, temperature, photosynthetically active radiation, chlorophyll-*a,* dissolved oxygen, dissolved and particulate fractions of speciated nutrients, density)	--
Water Quality Observations, Fresh Water	Freshwater quality observations (e.g., nutrients, temperature)	Freshwater quality observations (e.g., nutrients)
Hydrodynamics	Hydrodynamic data (tides and currents)	--
Other Observational Data	E.g., sediment oxygen demand, respiration, productivity	As applicable
Freshwater Nutrient Inputs	Nutrient inputs (e.g., total nitrogen, organic carbon)	Nutrient inputs (e.g., total nitrogen, organic carbon) without anthropogenic influence
Point-Source Marine Discharges	Nutrient loadings for direct marine point source discharges	Nutrient loadings for direct marine point source discharges reflective of no anthropogenic influence
Meteorology	Meteorology (e.g., air temperature, solar radiation, wind velocity) and changes to meteorological variables (e.g., air temperature)	Meteorological variables (e.g., air temperature, solar radiation)
Hydrology	Freshwater hydrology (e.g., flows, precipitation)	Freshwater hydrology (e.g., flows, precipitation)
Oceanic Boundary Conditions	Oceanic boundary conditions (e.g., water chemistry, tidal pulses)	--
Morphology	Waterbody morphology and bathymetry	Waterbody morphology
Other Human Activity	Other human activity information	Other human activity information
Site Information	E.g., site photographs	E.g., site photographs, historical records

Existing, readily available, and credible data

Sources of existing and readily available data include, but are not limited to, state and federal water quality databases. Washington maintains the Environmental Information Management[3] (EIM) database, which contains environmental monitoring data collected by Ecology scientists, local governments, other state agencies, Tribes, non-profit organizations, and other partners. Federal water quality data includes data in the Water Quality Portal[4], which integrates data from the United States Geological Survey (USGS), EPA, and other state, federal, tribal, and local agencies. Other sources of information may include water quality data collected by the United States Army Corps of Engineers, United States Department of Interior (including the Bureau of Reclamation) data, other state water quality databases, tribal water quality data, or other credible water quality data from outside the United States.

Any data obtained from academic and literature works (e.g., research journals) must be from published and reputable sources. Additional sources of data may include data collected under state or federally approved QAPPs, private and public facilities (e.g., data collected as part of National Pollutant Discharge Elimination System, or NPDES, permits), and utilities (e.g., drinking water facilities).

Ecology has gathered relevant external data sets useful and applicable for water quality impairment studies, and Ecology may use these external datasets in this performance-based approach. A list of these data sources, quality assurance information, and links to data are available in Appendix A of Ecology's Programmatic QAPP for Water Quality Impairment Studies[5]. This programmatic QAPP references data sets for water quality process-based modeling which are used to develop natural conditions aquatic life criteria. Data used must follow the quality objectives outlined in the section "Quality Objectives" of the above-referenced document.

Finally, determination of whether data and information are credible must follow Washington's Water Quality Data Act in RCW 90.48.585, which is further discussed in Ecology's Water Quality Policy 1-11 Chapter 2,[6] publication 21-10-032. If Ecology determines that a lack of credible data will impede estimating natural conditions, in order to proceed with this performance-based approach, Ecology must collect additional data under an amended QAPP, project-specific QAPP, or scope of work (*see* Steps 4 and 5 of this chapter).

[3] https://apps.ecology.wa.gov/eim/search/default.aspx

[4] https://www.waterqualitydata.us/

[5] https://apps.ecology.wa.gov/publications/SummaryPages/1703107.html

[6] https://apps.ecology.wa.gov/publications/SummaryPages/2110032.html

Site characterization data

In addition to water quality data, all existing and readily available data and information must be considered for use to characterize current and natural conditions at the site. These data must also be sourced from waters that affect the site of interest. Site characterization data information include, but are not limited to:

- Boundary conditions (including oceanic boundaries).
- Waterbody morphology.
- Hydrodynamics and physical properties (e.g., salinity).
- Light availability.
- Hydrological modifications (e.g., water withdrawals).
- Point source discharges.
- Nonpoint source discharges (including tributary boundaries).
- Meteorology.
- Kinetic and physical rates and ratio data.

Data timeframe and metadata requirements

There are no restrictions or limits on obtaining applicable data other than those previously identified (i.e., all existing, readily available, and credible data). Ideal datasets will include long-term data[7] for the water quality parameter of interest and data that represents pre-industrial periods or before large-scale human impacts.

If combining data across multiple time frames to estimate natural conditions, the methodology used in combining data sets must be documented and must be appropriately conservative to capture the range of conditions that protect existing and designated aquatic life uses across the scales of aggregation.

All associated metadata and data sources must be included and documented alongside the sourced water quality and site characterization data, such as in the project QAPP. This includes all quality assurance or quality control information, geospatial information, and data collection information (e.g., time of collection, depth).

Data gaps

Any data gaps must be identified. If data gaps are filled using estimates, the process for doing so must be documented and justified. Methods to estimate data gaps include, but are not limited to: interpolation, regression, and using information from regional models.

[7] Defined as data collected regularly (e.g., monthly) over at least ten years.

If Ecology determines that a lack of credible data will impede estimating natural conditions, in order to proceed with the performance-based approach, Ecology must collect additional data under an amended QAPP, project-specific QAPP, or scope of work (*see* Steps 4 and 5 of this chapter).

Step 3: Develop A Project Quality Assurance Project Plan

A Quality Assurance Project Plan (QAPP) must be developed and followed. Data quality objectives and measurement quality objectives must be established within the QAPP to ensure proper model calibration and evaluation such that, once met, the output of the model informs the determination of appropriate criteria.

The project QAPP must provide:

1. Key objectives, goals, and questions that are to be addressed by this project.
2. Observational data quality objectives.
3. Description of the data to be used, identified data needs, and data sources.
4. Model capability descriptions or references, including identification of key processes that drive water quality.
5. Model peer-review approach and/or documentation.
6. How spatial and temporal variability will be addressed in any model to ensure that natural condition estimates protect designated and existing uses.
7. Model approaches and key assumptions, which may include boundary conditions and associated determinations, initial or existing conditions, model resolution, inflow loads, or watershed inputs.
8. Description of the computational setup.
9. Model quality objectives, including how model calibration performance and model skill will be evaluated using both quantitative statistics, skill metrics, and qualitative methods.
    a) Model segment or grid size descriptions and rationale as to appropriateness linked to (4).
    b) Description of reasonable fit or other statistics between model-estimated and measured conditions following model calibration.
    c) Performance goal targets.
    d) Any model limitation, uncertainties, and assumptions, and how these could impact (if applicable) the reasonableness to meet the goals and objectives of the project.
    e) Quality Assurance and Quality Control considerations, such as adherence to the Department's programmatic QAPP for assessing impaired waters.

Step 4: Collect new data

If Ecology determines that existing, readily available, and credible data are insufficient and will impede estimating natural conditions and the ability to proceed with the performance-based approach, Ecology must collect additional data under an amended QAPP, project-specific QAPP, or scope of work, and there must be information that details the spatial and temporal scope of data collection and any other requirements for collection. The QAPP or scope of work must include the methods used to collect new data. This may include Ecology's standard operating procedures for watershed health monitoring.[8] Collected data must meet requirements for data listed in Step 2 of this document.

Step 5: Ensure new data meets quality assurance and control goals

If any new field data are collected (Step 4 of this chapter), then compiling, reviewing, and assessing these data must be done to ensure it meets Ecology's quality assurance and quality control goals outlined in the project QAPP. These processes must be documented, such as in the project QAPP. Additional information on Ecology's quality assurance and quality control is found on Ecology's Quality Assurance webpage.[9]

Step 6: Develop and calibrate the model

The performance-based approach includes developing a water quality model for current conditions and then uses the model to estimate natural conditions of a system. Any model(s) used must follow the requirements set forth in the project QAPP (Step 3) as well as the following requirements:

- The model must allow for reproducibility of results.
    - Model code must be open source, with existing and reference input and output files, alongside data sources, made available to the public.
- The model framework, including model code, must have undergone a formal peer-review process before application, or if not previously peer reviewed, must be recognized as widely-used code in the published literature and fully documented.
    - Documentation of the peer-review process must be described in the project QAPP or other documentation as part of the performance-based approach.
- Model selection must be from a set of best available modeling tools applicable for the specific purpose to estimate current and natural conditions based on the project requirements.
    - This includes, but is not limited to, the Salish Sea Model[10] and other models of comparable rigor.
- Model or models chosen must simulate all key processes and sources affecting marine DO, and must be described in the model documentation.

[8] https://apps.ecology.wa.gov/publications/UIPages/PublicationList.aspx?IndexTypeName=Topic&NameValue=Standard+Operating+Procedure+(SOP)+%e2%80%94+Watershed+Health+Monitoring&DocumentTypeName=Publication.
[9] https://ecology.wa.gov/issues-and-local-projects/investing-in-communities/scientific-services/quality-assurance
[10] https://ecology.wa.gov/research-data/data-resources/models-spreadsheets/modeling-the-environment/salish-sea-modeling

    - Processes include, but are not limited to, those identified in the QAPP for a Dissolved Oxygen Modeling Study for Puget Sound[11] (e.g., microbial rates, circulation or residence time, phytoplankton dynamics).
- Model calibration must be done using reasonable adjustments of model parameters to achieve a reasonable fit between model-estimated and measured conditions based upon peer review of the individual model, or by comparing to documented model fit statistics from other similar applications using the same model.
    - The quality of the model calibration must be documented and include both qualitative and quantitative evaluations.
- Model calculated outputs must be compared with measured data.
    - A sufficient number of calibration locations must be defined and identified prior to model application.
- Modeled hydrodynamics and relevant parameters for all waterbody types simulated must be evaluated.
- Model documentation must include information about any unknowns and uncertainties in model outputs.
- The model must have sufficient resolution[12] (and such resolution must be documented) to:
    - Predict horizontal and vertical variations in water quality. These predictions must be generated on least an hourly basis.
    - Capture the impacts to all designated uses, including the most sensitive designated use, and provide rationale for this determination in the project QAPP or other report generated as part of this performance-based approach.
    - Resolve features of the site (e.g., shoreline, islands, watersheds, river mouths).
    - Allow for selected temporal simulation (e.g., year-long).
    - Reflect available bathymetry information.
    - Ensure representation of identified subbasins in large model domains.
    - Incorporate simulation of key location-specific biogeochemical forcings (e.g., incorporation of eelgrass meadows for modeling water quality in the nearshore).
- All model parameter values must be documented.
- Sensitivity testing must be conducted on the means and ranges on selected key parameters which could significantly affect the natural condition outcome.

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[11] https://apps.ecology.wa.gov/publications/SummaryPages/0903110.html. Page 42, titled "3. What are the dominant processes affecting dissolved oxygen?"

[12] Model resolution will depend on available data and site of interest. See Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate Scale Water Quality Model (https://apps.ecology.wa.gov/publications/documents/1203049.pdf) or Puget Sound Nutrient Souce Reduction Project Volume 1: Model Updates and Bounding Scenarios (https://apps.ecology.wa.gov/publications/SummaryPages/1903001.html) for examples of how cell sizes were determined for the Salish Sea Model, as an example.

All feasible and practicable steps to improve model performance and representativeness of the model must be taken prior to model acceptance and use to estimate natural conditions.

Step 7: Evaluating model performance

Model performance must be evaluated and documented. Methods and approaches for model evaluation must be included within the project QAPP. Performance documentation must include comparisons of model outputs to historic or collected field data, summary statistics, figures, or data tables. The model must meet any quality assurance, quality control, and performance minimum requirements outlined in the project QAPP. Model evaluation includes, but is not limited to: sensitivity tests; uncertainty analyses; and evaluation of observed water quality conditions during specified years and simulating the effects of various, alternative nutrient-loading scenarios.[13]

All feasible and practicable steps to improve model performance and representativeness of the model must be taken prior to model acceptance and use to estimate natural conditions. If the model performance cannot meet these requirements, then the performance-based approach cannot be used to develop marine DO aquatic life criteria based on the natural conditions of a site.

Step 8: Estimating Natural Conditions

Introduction

When estimating natural conditions, use of performance-based approach must consider all required elements listed in this step. If any required element is not applicable or relevant to a site, then its non-applicability or non-relevancy must be documented.

Developing a scenario without human-caused impacts and pollution

Various elements in the current condition model include human-caused impacts to surface water quality, such as point sources discharging into marine waters. To model natural conditions, a model scenario needs to be developed that represents conditions in the absence of pollution and human-caused impacts. All human-caused impacts must be accounted for and removed using all existing, readily available, and credible information to develop the natural conditions scenarios.

Natural conditions are estimated through modeling by removing all anthropogenic sources from the model simulation for those sources where it is feasible and practicable to model, and then estimating and removing the remaining anthropogenic sources where it is not feasible or practicable to model where existing and credible data are readily available. After all sources of anthropogic pollution have been removed, natural conditions criteria are identified (Step 9).

[13] Such as was done in the Dissolved Oxygen Modeling Study for Puget Sound (https://apps.ecology.wa.gov/publications/SummaryPages/0903110.html).

All data used to address anthropogenic sources of pollution must meet data credibility requirements. For those data where it is not feasible or practicable to model, data does not need to meet other resolution or frequency requirements established in the project QAPP.

Human structural changes

The performance-based approach will not be used to derive criteria for specific assessment units of waters that contain human structural changes that cannot be effectively remedied (see WAC 173-201A-260(1)(b)).

Required elements

The use of each of these elements and subsequent analyses based on corresponding data must be documented in any final report associated with this performance-based approach. These elements must be accounted for and removed when estimating natural conditions, and elements include but are not limited to:

- Establishing oceanic open boundary and initial conditions.
    - Oceanic water temperature, salinity, dissolved oxygen, nitrogen, organic carbon, and Chlorophyll-*a*.
    - Global-scale ocean circulation changes, if any.
- Establishing freshwater input loads.
    - Must account for and remove human activities that may affect regional hydrodynamics.
    - Flow and water quality information.
    - Natural background nutrient concentrations, including but not limited to upstream tributaries, adjacent wetlands, and groundwater inputs.
- Other sources, as identified, that affect boundary conditions, such as legacy sources.
- Point source discharges.
- Non-point sources.
- Activities affecting hydrodynamics, channel morphology, channel complexity, light availability, riparian environments, and sediment mobilization.
- Meteorological conditions (e.g., air temperature changes, climate).
- Submerged aquatic vegetation.
- Invasive species.
- Any necessary kinetic and physical model rate changes.
    - Kinetics include, but is not limited to, those connected with eutrophication, such nutrient cycling, algal dynamics, sediment and biogeochemical oxygen demand.[14]

[14] For example, Section 2.1 Process Description of the Puget Sound Dissolved Oxygen Modeling Study (https://apps.ecology.wa.gov/publications/SummaryPages/1203049.html) describes kinetics simulated in the intermediate-scale water quality model.

Model outputs

Modeling outputs and subsequent analyses must represent the natural variability of marine DO (such as the range of values). This includes, but is not limited to:

- Description of long-term (e.g., multi-week, intra-annual) range and variation in marine DO.
- Demonstration of how variability of selected key inputs (e.g., freshwater flows, temperature) impact the magnitude of marine DO.[15]

Model outputs that estimate natural conditions represent the potential conditions of the site. The model output resolution will vary by project design (as described in the QAPP), data availability, and model choice. The model outputs of the site must:

- Abide by the data and modeling requirements in this performance-based approach chapter, and
- Protect designated and existing aquatic life uses by removing all human-caused impacts and pollution to the water of interest.

If various model outputs are used in analysis (such as from using multiple runs), then the model runs chosen must best reflect the natural conditions of the site and capture the range of conditions.

Other Considerations

Freshwater hydrology as it was reflected in a hindcast year modeled may be used. Water quality conditions (e.g., concentrations) must be set at estimated natural conditions. The methods used and any assumptions made must be documented. Finally, all feasible and practicable steps to improve representativeness of the model used to estimate natural conditions must be taken.

Step 9: Determining natural conditions criteria values

Criteria magnitude

The performance-based approach estimates the natural conditions of marine DO at a site (Step 8), which are used to determine natural conditions criteria for the site. Natural condition criteria must reflect the natural conditions of the system without any human impacts; see Step 8 for further details and requirements.

Once estimates of natural conditions are produced, then outputs are aggregated. Criteria values must not be over-aggregated in space (vertically or horizontally) or in time.

[15] For example, see the analyses performed and reported in Volume 1 of the Puget Sound Nutrient Source Reduction Project (https://apps.ecology.wa.gov/publications/SummaryPages/1903001.html).

First, volume-weighted horizontal aggregations are performed on model results. Horiziontal groupings must reflect Washington's CWA Section 303(d) assessment units as defined in Section 1C of *Water Quality Program Policy 1-11 Chapter 1: Washington's Water Quality Assessment Listing Methodology to Meet Clean Water Act Requirements*.[16] Horizontal aggregations use the mean value for concurrent temporal outputs across the assessment unit at each depth layer in the model.

Second, the time series values (e.g., hourly) within each assessment unit *and* each depth layer are reduced to daily minimum DO values for each day of the simulation.

The results of this aggregation process are criteria values for marine DO for each day within the temporal window of the model (e.g., summer growing season), each assessment unit, *and* each depth layer within each assessment unit. There is no vertical aggregation allowed. These natural condition criteria values are protective of existing and designation aquatic life uses. The aggregation process used to calculate criteria values must be documented.

Criteria duration and frequency

Any developed natural conditions criteria must include duration and frequency components in addition to magnitude values. The duration and frequency components must match the duration and frequency of the biologically-based numeric marine DO criteria at WAC 173-201A-210(1)(d).

Criteria evaluation and application

Developed natural conditions criteria must only include the periods of the year when natural conditions were estimated. For example, the criteria values may only be applicable for the summer period if the natural conditions were estimated using such bounds (e.g., seasonal). Any developed natural condition criteria values have the same bounds or restrictions as the methods used for estimation. For all other times when natural conditions were not estimated, the existing and applicable biologically-based numeric criteria continue to apply.

Step 10: Documentation and use

Once the natural conditions criteria values (including magnitude, duration, frequency) are determined, these values are applicable for use in state and federal CWA actions. If used, all evaluation, analyses, data, and decision points from this approach must be documented. Any reports generated from use of the PBA must follow accepted agency templates or protocols.

[16] https://apps.ecology.wa.gov/publications/SummaryPages/1810035.html

Documentation must include sources of model uncertainty in summarized form. Further, documentation must show how the model outputs were used to establish natural conditions criteria, also include information on natural condition estimates, including but not limited to:

- Summary tables
- Cumulative relative frequency tables
- Natural variation and central tendencies for simulated waters
- Spatial and temporal considerations
- Amendments to the project QAPP.
    - Any amendments to the project QAPP must be consistent with the PBA requirements.
- Sources of data, approaches, and references not previously documented and used in the analysis

All documentation (including, but not limited to, the project specific QAPP, model outputs, and determined natural conditions criteria) must be made available to the public when using the natural condition criteria in subsequent state and federal CWA actions.

Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities

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TETRA TECH

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Washington State Department of Ecology

TECHNICAL AND ECONOMIC EVALUATION OF NITROGEN AND PHOSPHORUS REMOVAL AT MUNICIPAL WASTEWATER TREATMENT FACILITIES

JUNE 2011

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Washington State Department of Ecology

Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities

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EXECUTIVE SUMMARY

When discharged to surface waters, the nutrients phosphorus and nitrogen can contribute to water quality problems that adversely affect fish, wildlife, aesthetics, recreation and navigation. Common water quality problems associated with high levels of these nutrients are reduced concentrations of dissolved oxygen, daily swings in pH, and algae blooms. In extreme cases, high nutrient concentrations in surface waters can even pose risks to human and animal health by contributing to the spread of toxic algae.

Studies have shown that municipal sewage treatment plants are significant contributors to these problems. This report presents an evaluation of two approaches to reducing treatment plant discharge of nutrients to surface water:

- Improving treatment processes to remove more nitrogen or phosphorus and thus reduce their concentration in the treatment plant effluent
- Improving treatment processes to achieve effluent quality suitable for use as reclaimed water to recharge groundwater sources, rather than being discharged to surface waters.

The effectiveness and cost of various technology upgrades were evaluated for generic models of the numerous types of treatment plants used in Washington State. The results of the evaluations can be used by regulatory agencies, engineers, planners and the public to assess the likely implications of such treatment plant upgrades.

BACKGROUND

There are over 300 municipal treatment plants in Washington, using many types of treatment processes. Figure ES-1 shows the prevalent facility types, the number of plants of each type, and their cumulative capacities as a percentage of total municipal capacity in the state.

Since state and federal secondary treatment requirements were established in the 1970s, advances have been made in treatment technology that allow much greater removal of nutrients at an economical cost. Municipalities across Washington are working to evaluate the types of treatment available, the reliability and performance of different treatment options, the potential costs, and other factors associated with removing nutrients to meet surface water quality standards and with using reclaimed wastewater for groundwater recharge.

This report presents preliminary analyses for how nutrient removal and water reclamation can be achieved and roughly how much they cost. It is an early step in a public process to determine levels of nutrient removal that could be required in Washington. Significant additional work is needed before any such nutrient limits can be adopted. Information in this report must be reviewed by agencies, municipalities, the public and other stakeholders. An appropriate level of nutrient removal to apply statewide or regionally must be determined. Funding for this report came from a U.S. Environmental Protection Agency (EPA) National Estuary Grant.

EVALUATION APPROACH FOR NUTRIENT REMOVAL

Six potential nutrient-removal objectives were evaluated to determine their technical and economic impacts. These objectives represent regulatory standards that could be adopted to set limits on concentrations of total inorganic nitrogen (TIN) or total phosphorus (TP) in municipal treatment plant effluent.

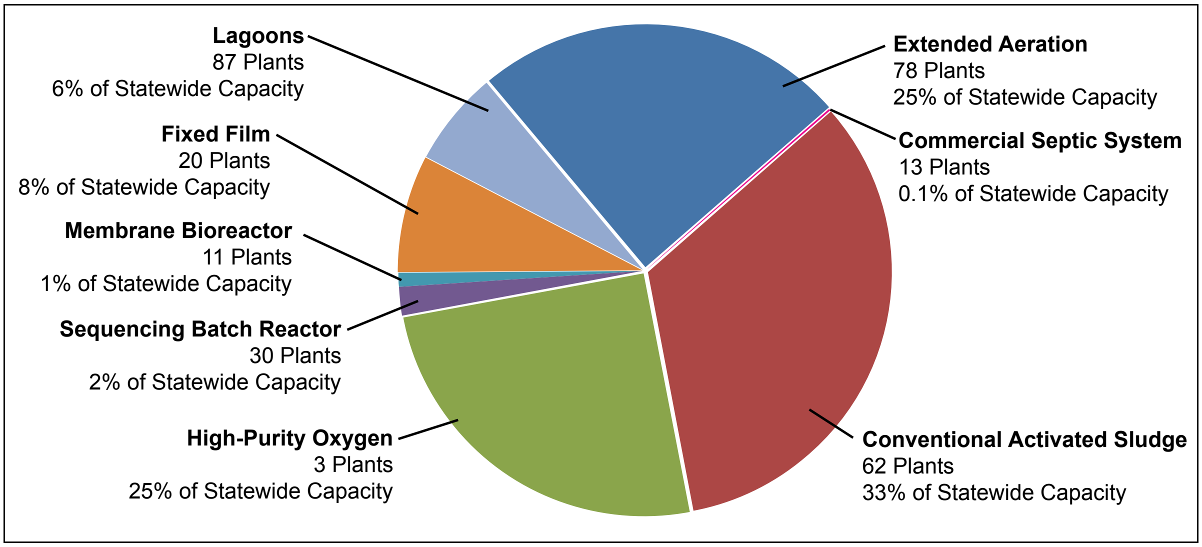


Figure ES-1. Distribution of Washington Municipal Treatment Plants by Type of Technology

The objectives evaluated, based on generally accepted performance of established nutrient removal technologies, are as follows:

- Objective A—Effluent TIN < 8 mg/L
- Objective B—Effluent TIN < 3 mg/L
- Objective C—Effluent TP < 1 mg/L
- Objective D—Effluent TP < 0.1 mg/L
- Objective E—Effluent TIN < 8 mg/L and effluent TP < 1 mg/L
- Objective F—Effluent TIN < 3 mg/L and effluent TP < 0.1 mg/L.

For each objective, analyses were performed of the improvements needed to achieve the objective year-round or to achieve it only during the dry season, when warm weather and low flows in receiving waters present the greatest risk of nutrients in effluent contributing to algae problems. The year-round and dry-season-only conditions represent the most and least expensive approaches to achieving each objective. The evaluations were performed for each of the main types of municipal treatment plant currently used in Washington. It was assumed that the technologies used to achieve the nutrient removal objectives for each type of treatment plant would be as shown in Table ES-1.

The analyses were performed for generic, typical existing plants with assumed representative wastewater characteristics and design criteria. Three sizes of plant capacity were assessed for each plant type, representing the range of sizes of plants of that type in Washington. The following parameters were calculated for each objective for each type of existing treatment plant:

- **Recycled loads**—Recycled loads are the quantities of nutrients in sludge that has gone through initial treatment at the treatment plant and is returned to the head of the plant for additional treatment. Plants with significant recycled loads require larger treatment units to achieve treatment objectives, which affects capital cost for the upgrades. Estimates of recycled loads also help point out potential drawbacks to proposed upgrades. For example, in the analyses of objectives that target only nitrogen removal, the recycled load estimates for some types of treatment plant showed that the nitrogen reduction would be accompanied by an increase in phosphorus in the plant effluent.

TABLE ES-1.
TREATMENT PROCESS UPGRADES EVALUATED TO ACHIEVE NUTRIENT-REMOVAL OBJECTIVES

	Objective A	Objective B	Objective C	Objective D	Objective E	Objective F
Definition of Objective						
Effluent TIN	< 8 mg/L	< 3 mg/L	—	—	< 8 mg/L	< 3 mg/L
Effluent TP	—	—	< 1 mg/L	< 0.1 mg/L	< 1 mg/L	< 0.1 mg/L
	Treatment Processes to Achieve Objective					
Existing Extended Aeration Plant						
Year-Round	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Existing Conventional Activated Sludge Plant						
Year-Round	MLE+MBR	4BDP+MBR+M	C	C+F	MLE+MBR+C	4BDP+MBR+M+C
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Existing Sequencing Batch Reactor Plant						
Year-Round	SBR	SBR+DNF+M	SBR+C	SBR+C+F	SBR+C	SBR+DNF+C+F+M
Seasonal	SBR	SBR+DNF+M	SBR+C	SBR+C+F	SBR+C	SBR+DNF+C+F+M
Existing Trickling Filter, Trickling Filter/Solids Contact, or Rotating Biological Contactor Plant						
Year-Round	MLE+MBR	4BDP+MBR+M	C	C+F	MLE+MBR+C	4BDP+MBR+M+C
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Existing Membrane Bioreactor Plant						
Year-Round	OC	M	C	C	C	C+M
Seasonal	OC	M	C	C	C	C+M
Existing High-Purity Oxygen Activated Sludge Plant						
Year-Round	MLE+MBR	4BDP+MBR	—	—	—	—
Seasonal	MLE	4BDP+M	—	—	—	—
Existing Aerated Lagoon or Facultative Lagoon Plant						
Year-Round	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F

4BDP = Four-stage Bardenpho system for denitrification
C = Chemical addition: alum for phosphorous removal, magnesium hydroxide for pH control
DNF = Denitrification filters
F = Tertiary filters for phosphorus removal
M = Methanol addition for denitrification
MBR = Membrane bioreactors for denitrification
MLE = Modified Ludzack Ettinger process for denitrification
OC = Operational changes only
SBR = Sequencing batch reactor (capacity increased for denitrification)

- **Sludge production**—Sludge is a treatment plant byproduct that ultimately must be disposed of in one way or another. The amount of sludge produced at the plant therefore represents an ongoing operation cost associated with its disposal. The cost associated with disposing of more sludge, or the savings associated with disposing of less sludge, must be accounted for in the estimated cost of nutrient-removal upgrades.
- **Energy consumption**—Energy consumption represents an ongoing cost of plant operation, so any change in energy consumption associated with a nutrient-removal upgrade must be accounted for in assessing the cost of that upgrade. Energy consumption also correlates with the generation of greenhouse gases, so estimates of changes in energy consumption provide a qualitative indication of potential environmental impact or benefit.
- **Chemical usage**—Chemical usage represents an ongoing cost of plant operation, so any change in chemical usage associated with a nutrient-removal upgrade must be accounted for in assessing the cost of that upgrade.
- **Footprint requirements**—Footprint requirement is the area of ground that would be covered by any new structures that must be built as part of a nutrient-removal upgrade. Increases or decreases in overall treatment plant footprint were estimated to provide a general sense of how easily a nutrient-removal upgrade could fit within the limits of the existing treatment plant. At plants where land is already available to expand the overall plant area without property acquisition costs, it may be more effective to implement treatment technologies that require more footprint but cost less than those evaluated in this report.

EVALUATION APPROACH FOR WATER RECLAMATION

The State of Washington at Chapter 90 Article 90.46 of the Revised Code of Washington (90.46 RCW) defines reclaimed water as "effluent derived in any part from wastewater with a domestic wastewater component that has been adequately and reliably treated, so that it can be used for beneficial purposes. Reclaimed water is not considered a wastewater." State standards define four classes of reclaimed water (A, B, C and D).

The evaluation of water reclamation for this report is based on the standards for Class A reclaimed water suitable for groundwater recharge by surface percolation. Cost estimates were developed for producing Class A reclaimed water year-round and seasonally for each type of existing plant for the same capacity ranges evaluated in the nutrient-removal assessment. To achieve this standard, the following upgrades to existing treatment plants were assumed:

- Upgrades previously described to achieve nutrient-removal Objective A (TIN < 8 mg/L)
- Upgrade or replacement of the disinfection process to a UV process that reliably achieves Class A standards
- A post-chlorination process using bulk-delivered sodium hypochlorite to maintain a minimum chlorine residual of 0.5 mg/L to the point of application of the water for recharge
- A new filtration process with coagulation/flocculation (only for upgraded plants that would not include membrane bioreactors)

In many circumstances it may be possible to eliminate the need for a post disinfection system for the conveyance of the reclaimed water, however this needs to be evaluated and approved on a case by case basis. Individual cost curves were develop for replacing existing chlorination systems with UV disinfection, post-chlorination, filtration, as well as for nitrogen removal to provide a cost estimating tool that can be easily adapted to develop cost for process needs requiring one, two, three or all four of the processes. The evaluation assumed that each plant's existing method for wastewater disposal will be retained as a backup should the effluent fail to meet Class A reclaimed water requirements; therefore no capital costs or operational costs were developed for standby or redundant process equipment.

SUMMARY OF COST FINDINGS

Nutrient Removal

The initial results of the nutrient removal evaluation were cost curves showing estimated capital and operation and maintenance (O&M) costs by plant capacity for each objective for each type of existing treatment plant. These estimates, based on evaluations of generic treatment plants, were then applied to the list of actual existing treatment plants in Washington to estimate the aggregate costs for achieving each of the identified nutrient-removal objectives. The following costs were estimated using this approach:

- Capital, O&M and combined annual costs for upgrading all treatment plants in Washington to achieve each objective, year-round and seasonally.
- Average statewide household sewer rate increases associated with upgrading each type of treatment plant in Washington to achieve each objective, year-round and seasonally.
- Capital and O&M costs for upgrading all treatment plants in each of Washington's 62 Water Resource Inventory Areas (WRIAs) to achieve each objective, year-round and seasonally. This allows an assessment of costs associated with addressing nutrient-related water quality problems in a specific watershed.

Tables ES-2 through ES-4 summarize the key results of the cost analysis. The accuracy of the estimated costs and rate impacts is in the range of -50 percent to +100 percent, consistent with a Class 5 Planning Estimate as defined by the Association for the Advancement of Cost Engineering.

Water Reclamation

Costs associated with upgrading treatment plants to achieve Class A reclaimed water standards were compared to the costs of upgrading the plants to achieve nutrient-removal Objective A (TIN < 8 mg/L). Objective A was selected because it would meet a new rule being considered by the state that would set a limit of 10 mg/L of TIN for Class A reclaimed water for groundwater discharge. In some circumstances the level of nitrogen removal may need to greater in order to protect exceptional quality groundwater resources in order to achieve compliance with Federal and State antidegradation regulations. Incremental upgrade costs beyond that represent the cost to meet other elements of the Class A standard. These incremental costs were estimated for three plant capacities for each type of wastewater treatment plant. Table ES-5 summarizes the range of cost increments over the capacities evaluated for each type of plant.

CONCLUSIONS

Nitrogen Removal

For nitrogen removal, seasonal operation is slightly more cost-effective (per pound of nitrogen removed) than year-round operation. Year-round removal requires significantly more capital investment to upgrade treatment facilities. However, seasonal removal generally would provide only about 60 percent of the nitrogen removal provided by year-round removal, on an annual mass basis.

Implementing nitrogen removal generally would slightly reduce the amount of sludge produced at a treatment plant (up to 3 percent). Reducing nitrogen to 3 mg/L, however, generally requires the addition of a carbon substrate, which would produce additional sludge—up to 5 percent above existing rates.

Energy consumption for nitrogen removal would be significant. Reducing the TIN effluent concentration statewide to less than 8 mg/L would require approximately two to three times the amount of electrical energy currently used by municipal wastewater treatment facilities. Moreover, existing energy recovery processes at treatment facilities that rely on the production of methane gas from sludge would produce approximately 5 to 10 percent less energy as a consequence of the removal of nitrogen.

Phosphorus Removal

For phosphorus removal, seasonal removal is generally less cost-effective (per pound of phosphorus removed) than year-round removal. Both approaches require about the same capital investment to upgrade treatment facilities, but seasonal removal generally would provide only about 60 percent of the phosphorus removal provided by year-round removal, on an annual mass basis.

Phosphorus removal by chemical precipitation produces significantly more sludge than existing processes—approximately 25 to 35 percent more.

Energy consumption would increase for phosphorus removal, but significantly less than for nitrogen removal. Reducing the TP effluent concentration statewide to less than 1 mg/L would increase treatment plant electrical energy consumption by approximately 15 to 20 percent.

TABLE ES-2.
ESTIMATED ANNUAL CAPITAL AND O&M COSTS FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Estimated Annual Cost ($ millions, 2010)[1]					
Existing Plant Type	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	14	29	11	23	31	50
Extended Aeration (Diffused Aeration)	0	0	1	1	1	2
Extended Aeration (with Biological Nutrient Removal)	2	9	21	55	17	66
Conventional Activated Sludge	154	176	64	106	206	273
Sequencing Batch Reactor	1	11	2	7	1	17
Trickling Filter	17	20	6	10	22	29
Rotating Biological Contactor	14	16	4	8	18	24
Trickling Filter/Solids Contact	17	19	7	11	22	29
Membrane Bioreactor	0	0	2	2	2	2
Lagoons (Aerated)	75	81	21	27	87	100
Lagoons (Facultative)	19	21	5	7	22	26
High Purity Oxygen	108	129	N/A	N/A	108[2]	129[2]
Statewide Total	**$421**	**$513**	**$143**	**$256**	**$537**	**$748**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	21	27	8	14	30	42
Extended Aeration (Diffused Aeration)	0	0	1	1	1	2
Extended Aeration (with Biological Nutrient Removal)	3	5	15	36	15	47
Conventional Activated Sludge	55	66	53	78	98	141
Sequencing Batch Reactor	0	10	2	5	2	14
Trickling Filter	9	11	5	7	13	18
Rotating Biological Contactor	8	9	4	6	12	15
Trickling Filter/Solids Contact	7	8	5	8	10	15
Membrane Bioreactor	0	0	2	2	2	2
Lagoons (Aerated)	75	81	21	27	87	100
Lagoons (Facultative)	18	19	4	6	21	23
High Purity Oxygen	51	64	N/A	N/A	51[2]	64[2]
Statewide Total	**$248**	**$300**	**$120**	**$190**	**$344**	**$483**

Notes: (1) Capital cost were annualized for 20 years at 3% discount rate

(2) Cost is for nitrogen removal only

TABLE ES-3.
ESTIMATED MONTHLY HOUSEHOLD SEWER RATE INCREASE FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Estimated Monthly Household Sewer Rate Increase (1)					
Existing Plant Type	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	$11.29	$24.30	$9.26	$18.96	$25.20	$41.13
Extended Aeration (Diffused Aeration)	$4.09	$7.01	$9.91	$22.18	$15.29	$36.23
Extended Aeration (with Biological Nutrient Removal)	$0.37	$1.66	$4.07	$10.50	$3.31	$12.68
Conventional Activated Sludge	$17.48	$19.95	$7.25	$12.03	$23.33	$30.97
Sequencing Batch Reactor	$1.16	$22.37	$4.71	$13.09	$2.45	$33.21
Trickling Filter	$27.43	$31.48	$8.85	$15.26	$35.23	$46.42
Rotating Biological Contactor	$29.77	$34.14	$9.24	$15.92	$38.27	$49.99
Trickling Filter/Solids Contact	$17.79	$20.08	$6.86	$11.38	$22.33	$30.00
Membrane Bioreactor	$0.00	$0.81	$9.46	$10.67	$9.46	$11.46
Lagoons (Aerated)	$57.67	$62.05	$15.87	$20.91	$66.71	$76.37
Lagoons (Facultative)	$66.89	$74.14	$16.43	$23.38	$78.62	$94.66
High Purity Oxygen	$16.24	$19.47	N/A	N/A	$16.24	$19.47
Weighted Average	**$16.00**	**$19.48**	**$7.29**	**$13.02**	**$20.40**	**$28.43**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	$17.71	$22.12	$6.25	$11.73	$24.88	$34.67
Extended Aeration (Diffused Aeration)	$2.34	$4.73	$8.45	$14.66	$15.55	$28.56
Extended Aeration (with Biological Nutrient Removal)	$0.48	$0.98	$2.96	$6.98	$2.97	$8.99
Conventional Activated Sludge	$6.23	$7.46	$6.01	$8.78	$11.15	$16.02
Sequencing Batch Reactor	$0.83	$18.88	$4.54	$10.35	$4.68	$27.51
Trickling Filter	$14.74	$17.01	$7.69	$11.32	$21.47	$28.34
Rotating Biological Contactor	$16.93	$19.46	$8.06	$11.80	$24.21	$31.42
Trickling Filter/Solids Contact	$7.20	$8.19	$5.66	$8.37	$10.84	$15.53
Membrane Bioreactor	$0.00	$0.66	$8.60	$8.77	$8.60	$9.39
Lagoons (Aerated)	$57.67	$62.05	$15.87	$20.91	$66.71	$76.37
Lagoons (Facultative)	$64.37	$68.74	$14.66	$19.74	$73.51	$83.15
High Purity Oxygen	$7.68	$9.70	N/A	N/A	$7.69(2)	$9.70(2)
Weighted Average	**$9.43**	**$11.41**	**$6.08**	**$9.64**	**$13.05**	**$23.28**

Assumptions:
- Maximum-month wastewater flow per capita = 160 gallons
- Population served by treatment plants = 5,484,396
- 2.5 persons per household
- Existing households = 75% of households at design capacity

Notes (1) Capital cost were annualized for 20 years at 3% discount rate
(2) Cost is for nitrogen removal only

**TABLE ES-4.
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR YEAR-ROUND NUTRIENT REMOVAL**

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 1	236.4	7.1	260.5	9.8	28.1	3.4	61.1	4.6	248.8	10.9	306.5	14.4
WRIA 2	6.9	0.3	8.6	0.8	2.4	0.2	5.3	0.3	8.2	0.5	12.6	1.1
WRIA 3	63.2	1.7	76.8	2.9	14.1	3.7	53.0	5.5	72.0	5.2	123.2	8.7
WRIA 4	127.7	3.4	155.3	5.8	29.0	7.6	107.4	11.2	146.2	10.6	249.5	17.6
WRIA 5	10.5	0.2	13.5	1.3	2.9	0.4	9.5	0.7	12.2	0.8	21.7	2.0
WRIA 6	42.2	1.6	46.7	2.6	10.0	0.6	17.5	0.8	46.5	2.5	58.5	3.5
WRIA 7	365.7	7.3	388.2	11.0	54.0	8.6	129.0	11.2	383.8	15.7	482.9	21.7
WRIA 8	1235.6	45.4	1408.5	54.6	40.4	19.8	167.5	25.0	1253.4	61.1	1538.3	78.0
WRIA 9	227.8	6.7	249.7	8.4	19.2	6.2	74.0	7.7	238.4	12.6	313.5	16.5
WRIA 10	481.5	17.1	548.3	21.2	29.0	10.1	111.0	13.4	495.8	25.7	638.6	35.1
WRIA 11	7.3	0.3	9.9	1.2	2.7	0.3	7.1	0.4	9.1	0.5	16.0	1.5
WRIA 12	117.6	3.2	127.6	4.0	9.5	4.0	38.3	5.0	124.1	6.4	160.1	8.7
WRIA 13	0.3	0.0	22.6	0.6	14.2	3.1	43.2	5.1	20.9	2.3	58.2	6.1
WRIA 14	14.8	0.0	18.2	1.2	3.2	0.8	11.3	1.1	16.8	1.1	28.4	2.3
WRIA 15	98.7	2.9	112.2	4.2	14.3	3.9	47.7	5.0	110.8	6.6	155.9	9.2
WRIA 17	12.1	0.2	14.3	0.7	1.9	0.5	7.4	0.7	13.6	0.9	21.2	1.4
WRIA 18	39.8	0.9	44.6	1.6	4.2	1.2	15.8	1.6	42.1	2.1	58.3	3.0
WRIA 19	5.5	0.3	6.1	0.4	0.9	0.1	1.9	0.1	6.2	0.4	7.6	0.4
WRIA 20	15.0	0.6	15.7	0.7	2.9	0.2	4.1	0.3	16.3	0.8	18.0	0.9
WRIA 21	1.6	0.0	1.9	0.2	0.6	0.1	1.5	0.1	2.1	0.2	3.3	0.3
WRIA 22	78.1	1.6	89.6	3.8	9.7	2.9	38.9	4.0	85.6	5.0	125.3	7.7
WRIA 23	5.1	0.0	15.8	1.7	11.3	2.0	43.6	3.9	9.8	2.1	52.6	6.1
WRIA 24	42.8	1.9	47.0	2.8	10.0	0.7	18.4	0.9	47.3	2.6	59.9	3.8
WRIA 25	39.2	1.6	42.1	1.9	9.2	0.4	14.2	0.5	42.4	2.2	50.4	2.7
WRIA 26	14.6	0.5	16.1	1.4	4.3	0.7	9.4	0.9	18.0	1.4	24.5	1.9
WRIA 27	4.6	0.2	8.3	1.2	3.2	0.3	11.0	0.7	6.6	0.5	18.2	1.9
WRIA 28	9.4	0.0	45.2	0.5	29.3	6.8	105.7	11.6	34.8	5.8	131.9	13.9
WRIA 29	5.7	0.0	6.8	0.5	0.9	0.2	4.0	0.4	6.2	0.5	10.5	0.8
WRIA 30	45.4	1.4	47.2	1.7	9.6	0.6	14.0	0.7	49.5	1.9	55.5	2.3
WRIA 31	100.3	1.8	101.9	2.3	22.5	0.9	33.9	1.2	107.8	2.9	122.4	3.7
WRIA 32	10.3	0.0	17.9	0.9	8.7	1.8	31.5	3.0	14.3	2.0	44.5	4.6
WRIA 34	143.2	5.2	158.8	6.8	34.8	2.6	65.4	3.6	156.9	8.5	202.9	11.3
WRIA 35	15.9	0.6	18.2	0.9	2.1	0.5	7.2	0.6	17.8	1.0	24.9	1.4

TABLE ES-4 (continued).
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR YEAR-ROUND NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 36	48.5	2.0	52.5	2.3	7.5	1.2	16.3	1.4	53.2	2.8	65.0	3.5
WRIA 37	197.5	5.9	217.8	8.1	22.5	5.8	72.9	7.4	213.1	10.9	280.5	15.0
WRIA 38	13.2	0.4	15.3	0.8	1.9	0.5	6.6	0.6	14.9	0.9	21.5	1.3
WRIA 39	49.6	1.6	57.0	2.9	7.4	1.5	24.7	2.2	54.7	2.8	78.3	4.9
WRIA 40	53.8	1.6	59.6	2.0	5.1	1.8	19.9	2.3	58.0	3.1	77.5	4.2
WRIA 41	83.5	2.5	89.3	3.1	17.9	1.6	34.7	2.0	91.7	4.0	114.3	5.4
WRIA 42	11.8	0.6	12.6	0.7	2.4	0.2	3.7	0.3	13.0	0.7	14.8	0.9
WRIA 43	36.5	1.5	40.3	1.8	4.9	1.0	13.0	1.3	40.0	2.2	51.1	2.8
WRIA 44	21.9	0.7	24.8	1.1	2.5	0.7	9.2	0.9	24.1	1.4	33.3	1.8
WRIA 45	55.1	1.7	60.5	2.6	9.4	1.5	21.8	1.9	61.2	3.2	78.3	4.3
WRIA 47	13.3	0.5	14.9	0.6	1.3	0.3	4.9	0.4	14.4	0.8	19.5	1.1
WRIA 48	11.1	0.4	12.5	0.7	1.9	0.3	4.9	0.4	12.4	0.7	16.5	1.0
WRIA 49	19.4	0.4	22.7	1.2	2.8	0.7	11.1	1.0	21.5	1.5	33.0	2.1
WRIA 50	10.1	0.4	10.6	0.5	2.0	0.2	2.9	0.2	11.0	0.5	12.3	0.6
WRIA 52	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 53	2.6	0.2	2.8	0.2	0.5	0.1	0.6	0.1	2.9	0.2	3.1	0.2
WRIA 54	29.4	0.0	45.4	0.0	0.2	0.0	63.1	5.1	38.3	-2.8	114.7	4.5
WRIA 55	3.8	0.3	4.0	0.3	0.7	0.1	0.9	0.1	4.1	0.3	4.5	0.3
WRIA 56	53.7	1.9	57.0	2.7	10.0	1.2	18.5	1.5	58.3	3.0	69.6	3.8
WRIA 60	0.8	0.1	0.9	0.1	0.1	0.0	0.2	0.0	0.9	0.1	1.0	0.1
WRIA 61	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 62	17.4	0.8	20.0	1.0	5.1	0.6	11.0	0.8	19.9	1.3	27.9	1.9

TABLE ES-5.
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR DRY-SEASON NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 1	160.6	5.7	177.7	7.4	28.3	2.6	51.2	3.4	174.3	8.5	215.5	11.1
WRIA 2	6.6	0.3	8.1	0.7	2.4	0.2	4.3	0.3	8.3	0.5	11.6	1.0
WRIA 3	27.5	1.3	35.5	1.8	15.2	2.7	38.7	3.7	38.0	3.9	70.0	5.9
WRIA 4	55.3	2.6	71.5	3.6	31.2	5.4	78.4	7.4	77.1	7.9	141.7	12.0
WRIA 5	10.1	0.5	12.6	1.2	2.8	0.3	7.3	0.5	12.3	0.8	19.2	1.6
WRIA 6	38.1	1.7	40.4	2.3	9.0	0.5	13.6	0.7	42.4	2.2	49.5	2.9
WRIA 7	253.6	5.1	264.8	7.0	58.9	6.6	108.7	8.3	273.2	11.4	343.8	15.4
WRIA 8	477.6	22.8	564.0	28.2	59.6	13.7	139.6	16.6	497.7	35.1	694.0	44.5
WRIA 9	113.5	3.2	124.1	4.2	23.7	4.8	54.6	5.7	122.0	8.4	169.0	10.8
WRIA 10	182.2	8.3	220.7	10.9	37.2	7.3	86.8	9.2	200.1	15.5	299.1	21.1
WRIA 11	5.1	0.3	7.3	1.0	2.7	0.3	5.9	0.4	6.9	0.5	12.3	1.3
WRIA 12	41.1	1.0	45.3	1.4	13.1	2.9	30.3	3.5	47.6	3.7	73.8	5.0
WRIA 13	0.3	0.0	5.0	0.6	14.3	2.0	35.6	3.1	8.0	1.8	33.3	4.0
WRIA 14	13.5	0.4	16.1	1.1	3.1	0.5	8.0	0.7	16.6	1.0	24.1	1.9
WRIA 15	35.0	1.7	42.8	2.3	15.8	3.1	33.7	3.7	47.1	4.6	75.2	6.2
WRIA 17	8.6	0.4	10.1	0.6	1.9	0.4	4.8	0.5	10.6	0.8	15.1	1.2
WRIA 18	19.0	0.5	21.6	0.8	5.0	0.9	11.3	1.2	21.3	1.4	31.2	2.0
WRIA 19	4.5	0.3	5.0	0.4	0.9	0.1	1.5	0.1	5.1	0.4	6.1	0.4
WRIA 20	15.0	0.6	15.7	0.7	2.9	0.2	4.1	0.3	16.3	0.8	18.0	0.9
WRIA 21	1.4	0.2	1.7	0.2	0.6	0.1	1.0	0.1	2.1	0.2	2.8	0.2
WRIA 22	40.9	1.5	48.0	2.6	10.6	2.2	27.2	2.8	49.8	3.8	74.7	5.5
WRIA 23	4.6	0.3	12.4	1.3	11.3	1.4	32.7	2.4	12.3	1.7	40.7	4.3
WRIA 24	37.6	1.8	40.6	2.6	9.2	0.6	14.8	0.8	42.1	2.4	50.5	3.3
WRIA 25	37.8	1.5	38.9	1.7	8.1	0.4	11.6	0.5	40.9	1.9	45.6	2.2
WRIA 26	12.4	1.1	14.0	1.2	4.2	0.6	6.7	0.7	16.5	1.5	20.4	1.8
WRIA 27	1.8	0.1	4.9	1.0	3.1	0.3	8.3	0.5	4.2	0.4	12.5	1.5
WRIA 28	8.1	0.3	20.9	0.5	29.8	4.2	81.3	6.9	25.6	4.6	87.6	9.1
WRIA 29	5.2	0.4	6.0	0.5	0.9	0.2	2.4	0.2	6.4	0.5	8.8	0.7
WRIA 30	44.7	1.4	46.5	1.7	9.6	0.6	13.8	0.7	48.8	1.9	54.5	2.3
WRIA 31	98.3	1.8	99.8	2.3	22.5	0.9	33.3	1.2	105.8	2.9	119.6	3.7
WRIA 32	9.8	0.3	15.2	0.8	8.8	1.2	22.8	1.9	16.8	1.7	35.6	3.4
WRIA 34	132.7	5.3	139.9	6.2	31.0	2.2	50.7	2.8	147.4	7.4	174.4	9.3
WRIA 35	6.4	0.5	7.8	0.6	2.3	0.4	4.9	0.5	8.1	0.8	12.3	1.0

**TABLE ES-5 (continued).
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR DRY-SEASON NUTRIENT REMOVAL**

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 36	33.8	1.6	36.8	1.9	8.0	1.1	13.6	1.2	38.2	2.4	46.8	2.9
WRIA 37	92.2	3.3	103.6	4.6	26.3	4.6	56.0	5.5	106.8	7.5	152.6	10.1
WRIA 38	5.0	0.4	6.3	0.5	2.1	0.4	4.4	0.4	6.7	0.7	10.6	1.0
WRIA 39	23.5	0.9	28.4	1.9	8.3	1.3	19.5	1.6	28.3	2.0	45.4	3.4
WRIA 40	18.1	0.6	21.0	0.9	6.5	1.4	14.9	1.7	22.1	1.9	35.1	2.6
WRIA 41	70.3	2.3	75.0	2.8	18.0	1.4	29.2	1.8	79.2	3.7	95.3	4.8
WRIA 42	11.6	0.6	12.4	0.7	2.4	0.2	3.4	0.3	12.9	0.8	14.5	0.9
WRIA 43	20.4	1.1	22.8	1.3	5.4	0.9	10.2	1.0	23.7	1.7	31.2	2.2
WRIA 44	7.9	0.5	9.6	0.6	2.9	0.6	6.5	0.7	10.0	1.0	15.7	1.3
WRIA 45	35.8	1.4	39.4	1.9	10.0	1.3	17.6	1.5	42.1	2.6	53.8	3.4
WRIA 47	7.2	0.3	8.1	0.4	1.5	0.3	3.3	0.3	8.1	0.6	11.0	0.8
WRIA 48	8.8	0.5	9.8	0.6	1.9	0.3	3.6	0.3	10.2	0.7	12.8	0.9
WRIA 49	13.9	0.8	16.2	1.1	2.7	0.5	6.9	0.7	16.8	1.3	23.2	1.8
WRIA 50	10.1	0.5	10.6	0.5	2.0	0.2	2.9	0.2	11.0	0.5	12.2	0.6
WRIA 52	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 53	2.6	0.2	2.8	0.2	0.5	0.1	0.6	0.1	2.9	0.2	3.1	0.2
WRIA 54	38.0	0.0	41.8	0.0	0.2	0.0	51.3	2.7	19.1	0.1	72.7	6.4
WRIA 55	3.8	0.3	4.0	0.3	0.7	0.1	0.9	0.1	4.1	0.3	4.5	0.3
WRIA 56	52.8	2.2	56.0	2.6	9.9	1.0	16.2	1.2	58.3	3.0	67.0	3.6
WRIA 60	0.8	0.1	0.9	0.1	0.1	0.0	0.2	0.0	0.9	0.1	1.0	0.1
WRIA 61	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 62	16.9	0.9	19.1	1.0	5.1	0.5	8.7	0.7	20.3	1.3	25.6	1.7

TABLE ES-6.
RECLAIMED-WATER UPGRADE COST RELATIVE TO
OBJECTIVE A NUTRIENT-REMOVAL UPGRADE COST

	Reclaimed-Water Upgrade Cost as Percent of Nutrient-Removal Upgrade Cost			
	Annualized Capital Cost		Annual O&M Cost	
Treatment Plant Type	Year-Round	Seasonal	Year-Round	Seasonal
Extended Aeration (Mechanical)	199 – 214	149 – 208	(417) – 1,486	180 – 681
Extended Aeration (Diffused)	886 – 1,502	600 – 1,043	(1,500) – 2,665	(698) – 1,516
Conventional Activated Sludge	88 – 103	186 – 300	64 – 125	54 – 219
Sequencing Batch Reactor	Undefined	Undefined	4,895 – 7,415	(115,891) – 41,656
Trickling Filter	71 – 90	93 – 127	51 – 126	39 – 223
Rotating Biological Contactor	71 – 89	92 – 125	43 – 117	31 – 173
Trickling Filter/Solids Contact	84 – 98	148 – 167	83 – 144	81 – 420
Membrane Bioreactor	Undefined	Undefined	Undefined	Undefined
High-Purity Oxygen	109	216 – 273	64 – 68	251 – 311
Facultative Lagoon	48 – 80	35 – 55	51 – 71	46 – 64
Aerated Lagoon	47 – 79	34 – 55	67 - 105	60 – 91

Notes:

a. Ranges indicate low and high values for the range of plant capacities evaluated
b. Negative values (in parentheses) indicate that the nutrient-removal upgrade provides a cost savings; percentage show represents the ratio of reclaimed-water upgrade cost to nutrient-removal upgrade savings
c. Undefined indicates that there is no cost or savings associated with the nutrient-removal upgrade because no changes are required to achieve the nutrient-removal objective.
d. Annualized capital cost based on 3% discount rate over 20 years.
e. Annual O&M cost includes labor, materials, chemicals and energy.

ABBREVIATIONS

^0C	Degree Celsius
4BDP	4-stage Bardenpho continuous-flow suspended-growth process with alternating anoxic/aerobic/anoxic/aerobic stages; used to remove TN
AACE	Association for the Advancement of Civil Engineering
ADWF	Average Dry Weather Flow
AL	Aerated Lagoon
Alum	Hydrated Aluminum Sulfate having an approximate molecular formula of $Al_2(SO_4)_3 \cdot 14H_2O$
AS	Activated Sludge
AWWF	Average Wet Weather Flow
BAF	Biologically Aerated Filter
BioWin	BioWin is a Microsoft Windows-based computer simulation model used for analysis and design of wastewater treatment plants distributed by EnvioSims, Ltd.
BNR	Biological Nutrient Removal
BOD	Biochemcial Oxygen Demand
BOD_5	Biochemcial Oxygen Demand (5-day)
C	Chemical Addition
$CaCO_3$	Calcium Carbonate
CapdetWorks	CapdetWorks is a preliminary design and costing program for evaluating a variety of wastewater treatment plant processes originally developed by the US Army Corps of Engineers and EPA that is updated and distributed by Hydromantis, Environmental Software Solutions, Inc.
CAS	Conventional Activated Sludge process
CBOD	Carbonaceous fraction of the Biochemical Oxygen Demand
cfm	Cubic Feet per Minute
DA	Diffused Aeration
DIN	Dissolved Inorganic Nitrogen
DNF	Denitrifying Filter
DO	Dissolved Oxygen
DOE	Washington State Department of Ecology
EA	Extended Aeration Activated sludge process
EPA	Environmental Protection Agency
F	Filtration
FF	Fixed Film process (e.g. RBC and TF)
FL	Facultative Lagoon
gpcd	Gallons per Capita per Day
gpd	Gallons per Day
HPO	High Purity Oxygen Activated Sludge process
HRT	hydraulic retention time
IFAS	Integrated Fixed Film Activated Sludge

M	Methanol Addition
MA	Mechanical Aeration
MBBR	Moving Bed Bioreactor
MBR	Membrane Bioreactor
MG	Millions of Gallons
$Mg(OH)_2$	Magnesium Hydroxide
mg/L	Milligrams per Liter
mgd	Million Gallons per Day
mg-N/L	Milligrams Nitrogen per Liter
mg-P/Liter	Milligrams Phosphorus per Liter
ML	Mixed Liquor (i.e., combination of wastewater and biological mass typically found in the aeration tank of a activated sludge plant)
MLE	Modified Ludzack-Ettinger Process – continuous-flow suspended-growth process with an initial anoxic stage followed by an aerobic stage; used to remove TN
MLSS	Mixed Liquor Suspended Solids
MMDWF	Maximum Month Dry Weather Flow
MMWWF	Maximum Month Wet Weather Flow
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium ion
NO_2^{-2}	Nitrite
NO_3^-	Nitrate
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and Maintenance
OC	Operational Changes
POTW	Publically Owned Treatment Works
ppcd	Pounds per Capita per Day
ppd	Pounds per Day
Q	Influent Flow Rate
RAS	Return Activated Sludge
SF	Square Foot
SPT	Septic Tank on-site treatment process
SRT	Solids Retention Time
TDS	Total Dissolved Solids
TF	Tricking Filter process
TF/SC	Tricking Filter /Solids Contact process
TIN	Total Inorganic Nitrogen
TKN	Total Kjeldahl Nitrogen (i.e., ammonia nitrogen plus organic nitrogen)
TMDL	Total Maximum Daily Load
TP	Total Phosphorus
TS	Total Solids (Total Recoverable Residue). TSS plus TDS
TSS	Total Suspended Solids

UV	Ultraviolet light used for disinfection
WAS	Waste Activated Sludge
WWTP	Wastewater Treatment Plant
RBC	Rotating Biological Contactor
Poly	Polymer
Cl_2	Chlorine
WRIA	Water Resource Inventory Area
NaOCl	Sodium hypochlorite; a liquid form of chlorine that can used for disinfection of wastewater
mJ/cm2	milli-joules per square centimeter
nm	nanometer; a wave length of light that used for ultra violet light disinfection
MPN	most probable number
ERU	Equivalent Residential Unit
P	Phosphorus
N	Nitrogen
kW	kilowatt
kW-hours	kilowatt hours
VSS	Volatile Suspended Solids
PDF	Peak Daily Flow
SBR	Sequencing Batch Reactor process

CHAPTER 1.
INTRODUCTION

Excessive loads of nutrients—specifically nitrogen and phosphorus—are the leading cause of water quality impairment in the United States and in the State of Washington. Impairments caused by excessive nutrients include excessive growth of algae and aquatic plants, low dissolved oxygen concentrations, fish and shellfish kills, foul odors, degraded drinking water supplies, and degraded recreational uses. The Washington Department of Ecology's 2008 Water Quality Assessment report identifies 524 Category 5 listings for the federal 303(d) list of impaired water bodies that may be attributable to excess nutrients.

The primary sources of nitrogen and phosphorus pollution are municipal wastewater, urban stormwater, agricultural (livestock and row crop) runoff, other non-point sources, and industrial wastewater. The contribution from each of these sources is dependent on the extent of development in the watershed of interest. Although nitrogen and phosphorus loads from other sources may be greater, nutrient loads from municipal wastewater treatment plants can be significant; such loads also are more manageable from a regulatory perspective.

1.1 BACKGROUND

1.1.1 National Trends

The Clean Water Act of 1972 authorized the U.S. Environmental Protection Agency (EPA) to establish standards for municipal wastewater treatment plants to restore and maintain the chemical, physical and biological integrity of the nation's waters. Minimum standards for municipal wastewater treatment plant effluent were promulgated into public law in 1973. The standards are based on the best treatment technology economically achievable, regardless of the condition of the receiving water. These standards are commonly known as the standards for secondary treatment. They were established for four conventional pollutant parameters: 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), fecal coliform bacteria, and pH. In 1984, the EPA allowed the use of a test for 5-day carbonaceous biochemical oxygen demand ($CBOD_5$) rather than for BOD_5, thereby eliminating the effects of residual nitrogen (principally ammonia) on the BOD test.

While conventional secondary treatment reliably removes more than 90 percent of CBOD and TSS, it only removes about 10 to 15 percent of the total nitrogen (TN) contained in raw wastewater and 20 to 30 percent of the total phosphorus (TP). For some receiving waters, this level of nutrient removal has been inadequate to achieve water quality objectives. The Clean Water Act allows permitting agencies to impose more stringent effluent limits if the technology-based limits are not adequate to prevent violation of water quality standards.

Significant advances have been made in wastewater treatment technology since enactment of the secondary treatment standards. Several processes have proven to be reliable and cost-effective in removing nitrogen and phosphorus from municipal wastewater. The EPA recently published (September 2008) a comprehensive document that identifies and evaluates the performance and costs of nitrogen and phosphorus removal technologies applied to municipal wastewater treatment plants throughout the United States.

1.1.2 Washington State Trends

Pollutant loads to municipal wastewater plants are primarily driven by population—as the population grows, so does the quantity of nitrogen and phosphorus. U.S. Census Bureau data indicate that population increased 13.1 percent in the last 10 years in Washington, compared to 9 percent nationwide. In the last 50 years, the population of Washington has increased approximately 180 percent.

In 1998, the EPA published the *National Strategy for Development of Regional Nutrient Criteria*. In turn, the State of Washington promulgated numeric water standards (WAC Chapter 173-201A) for phosphorus for lakes and reservoirs and for a reach of the Spokane River, extending from Long Lake Dam to the Nine Mile Bridge. Currently there are no numeric water quality standards for nitrogen in the State of Washington.

There are about 300 municipal wastewater treatment plants operating in the State of Washington, using a wide assortment of treatment technologies—ranging from simple facultative lagoons to complex automated mechanical treatment plants. Their current conditions are estimated as follows:

- The plants range in annual average flow capacity from less than 10,000 gallons per day (gpd) to 210 million gallons per day (mgd), with a combined maximum month rated capacity of approximately 1,172 mgd.
- Assuming that all these plants are operating at 70 percent of their design capacity with respect to flows and pollutant loads characteristic of municipal wastewater, the existing plants serve an equivalent population of 5.13 million.
- Collectively, these plants are estimated to treat about 187 billion gallons of wastewater per year.
- The estimated mass of total nitrogen in effluent currently discharged by these plants is in the range of 22,000 to 26,000 tons per year. More than 90 percent of this nitrogen is in the form of inorganic nitrogen (ammonia, nitrate, and nitrite). This estimate is based on nitrogen removal efficiency of 10 to 15 percent for conventional activated sludge, fixed film systems, high purity oxygen plants, lagoons and septic tanks, and 30 percent to 50 percent for SBR, extended aeration, and membrane bioreactor plants.
- The estimated mass of total phosphorus contained in effluent currently discharged by these plants is in the range of 4,800 to 5,400 tons per year. This estimate is based on 30 percent of the extended aeration plant capacity achieving 80 percent phosphorus removal during the dry weather season and the remaining capacity of the extended aeration plants achieving 20 percent to 30 percent phosphorus removal. Existing SBR and MBR plants were estimated to have a phosphorus removal efficiency of 70 percent. All of the other treatment process category types were assume to have phosphorus removal efficiency in the range of 20 percent to 30 percent.

With a few exceptions, most municipal wastewater treatment plants in Washington only remove nitrogen and phosphorus to levels generally reported for conventional secondary treatment.

A few municipal wastewater treatment plants in Washington were designed and are operated to remove a greater percentage of nutrients than conventional secondary treatment does. Plants that produce reclaimed water for irrigation often are required to reduce TN to less than 10 milligrams per liter expressed as nitrogen (10 mg-N/L). Water-quality-based effluent limitations for nitrogen and phosphorus have been established for a few wastewater treatment plants in Washington (fewer than 10) based on total maximum daily load (TMDL) allocations.

1.2 PURPOSE OF THIS REPORT

This report evaluates the effectiveness and economics of advanced technologies to remove nitrogen and phosphorus from the discharges of existing municipal wastewater treatment facilities in Washington. It was prepared to assist municipal decision makers and regional and state regulators in planning for nutrient removal specifically from municipal wastewater treatment plants. Similar evaluations have been conducted across the nation—for Chesapeake Bay, Maryland, Pennsylvania, Virginia, Minnesota and Wisconsin—but they focused principally on phosphorus removal.

This report does not identify and evaluate all established, emerging, or innovative nutrient removal technologies. It is generally accepted that established wastewater treatment technologies can reliably reduce total inorganic nitrogen to 3 mg/L and TP to 0.1 mg/L. This report identifies a range of established technologies that are available and economically reasonable and have been applied in Washington and elsewhere in the United States to upgrade municipal wastewater treatment plants to achieve specific nitrogen and phosphorus reduction goals.

This report provides the information and tools to help regulatory agencies, engineers, planners and the general public understand the technologies and economic impact of upgrading wastewater treatment plants to reduce nitrogen and phosphorus loads.

1.3 DEVELOPMENT AND ORGANIZATION OF THE REPORT

In March 2009, the Washington Department of Ecology contracted with Tetra Tech to conduct the technical and economic evaluation of nitrogen and phosphorus removal at municipal wastewater treatment facilities in Washington. The original scope of work provided for up to 30 case studies of existing wastewater treatment facilities in Washington using a variety of technologies to achieve nitrogen and phosphorus removal.

As an initial effort, Tetra Tech completed case studies for two of the state's largest treatment plants: King County's South Treatment Plant and the City of Spokane's Riverside Treatment Plant. The case studies were reviewed by the Department of Ecology, EPA Region 10, a technical review committee, representatives from the studied facilities, and other interested parties, and a review workshop was held.

Lessons learned from the two case studies prompted Tetra Tech and the Department of Ecology to amend the scope of work. Under the revised work plan, six potential nutrient-removal objectives were evaluated to determine their technical and economic impacts on treatment plants. These objectives represent regulatory standards that could be adopted to set limits on concentrations of total inorganic nitrogen (TIN) or total phosphorus (TP) in municipal treatment plant effluent. The evaluations were performed for each of the main types of municipal treatment plant currently used in Washington. For each objective, analyses were performed of the improvements needed to achieve the objective year-round or to achieve it only during the dry season, when warm weather and low flows in receiving waters present the greatest risk of nutrients in effluent contributing to algae problems. The year-round and dry-season-only conditions represent the most and least expensive approaches to achieving each objective.

Table 1-1 summarizes the revised work plan and where each element of the work plan is presented in this report. In addition to the content summarized in Table 1-1, Chapter 2 provides detailed descriptions of the nutrient-removal objectives evaluated and the types of treatment plants for which each objective was analyzed, and Chapter 3 explains the methodology used in the analysis.

**TABLE 1-1.
PROJECT WORK PLAN AND REPORT ORGANIZATION**

Work Plan Element	Location in Report
Develop process and cost models for upgrading seven generic (hypothetical) wastewater treatment plant process categories with unit process design criteria consistent with those typically applied for wastewater treatment plants in the state and the Department of Ecology's Criteria for Sewage Works Design (Ecology, 2008).	Details of the models developed for this project are presented in Appendix A. Summaries of the process modeling results are presented in Chapters 4 – 10 (each chapter presents the results for one treatment plant type) and the cost results are summarized in Chapters 11 – 16 (each chapter presents costs for a separate nutrient-removal objective)
Evaluate capital and incremental operational costs to achieve six nutrient removal goals for several technologies at existing municipal treatment plants in Washington.	Nutrient-removal upgrade costs for the six nutrient-removal objectives are presented in Chapters 11 – 16 (each chapter presents costs for a separate objective)
Develop cost models (curves) for capital construction, incremental annual operation and maintenance (O&M), and 20-year life cycle costs for upgrading each of the seven categories of treatment plants for six different nutrient removal objectives.	Nutrient-removal upgrade cost curves for the six nutrient-removal objectives are presented in Chapters 11 – 16 (each chapter presents costs for a separate objective)
Estimate incremental capital, O&M, and 20-year life cycle costs to achieve the six different nutrient removal objectives for all wastewater municipal wastewater treatment facilities in Washington.	Estimated cumulative costs for upgrading municipal wastewater treatment plants statewide are presented in Chapter 17.
Compare process technology upgrade requirements and costs for upgrading existing municipal treatment plants in Washington to remove nutrients with upgrading plants to produce reclaimed water that meets the State of Washington's Class A reuse standards (WAC 173-221) for groundwater recharge	Incremental costs for providing treatment to achieve Class A water reuse standards are presented in Chapter 18.

CHAPTER 2.
NUTRIENT REMOVAL OBJECTIVES AND TREATMENT PLANTS EVALUATED

2.1 NUTRIENT REMOVAL OBJECTIVES

Six nutrient removal objectives stipulated by Ecology and EPA were identified for analysis. These objectives were selected based on the generally accepted performance associated with established nutrient removal technologies for municipal wastewater treatment plants. The objectives for this report are defined by the concentration of the nutrient of concern (nitrogen and/or phosphorus) remaining in the treated effluent, as follows:

- Objective A—Total inorganic nitrogen (TIN) <8 mg/L
- Objective B—TIN <3 mg/L
- Objective C—Total Phosphorus (TP) <1 mg/L
- Objective D—TP <0.1 mg/L
- Objective E—TIN <8 mg/L & TP <1 mg/L
- Objective F—TIN <3 mg/L & TP <0.1 mg/L

2.2 EXISTING MUNICIPAL WASTEWATER TREATMENT PLANTS

The Department of Ecology maintains a database of detailed information on each municipal wastewater treatment plant in the state. (The database was known as the Water Quality Permit Life Cycle System until 2010, when it was replaced with the Permit and Reporting Information System, or "PARIS.") For this study, Ecology provided Excel spreadsheets from each of its regional offices listing the names of all plants managed by that region, with pertinent information about each plant: design capacity (based on maximum-month flows), type of liquid stream treatment processes used, type of sludge treatment system, and where the final effluent is discharged (freshwater, marine water, groundwater or reuse). The secondary treatment processes used at the listed plants can be categorized as follows:

- Extended aeration (EA)
- Conventional activated sludge (CAS)
- Sequencing batch reactors (SBR)
- Fixed film systems (FF)
- Membrane bioreactors (MBR)
- High-purity oxygen activated sludge (HPO)
- Lagoons
- Septic treatment (SPT).

Tables 2-1 and 2-2 and Figures 2-1 and 2-2 summarize key data from the Ecology spreadsheets by treatment process type, number of plants, individual plant capacity and collective treatment capacity. The data are discussed in detail in the following sections.

TABLE 2-1.
NUMBER OF PLANTS BY SECONDARY TREATMENT PROCESS CATEGORY AND MAXIMUM-MONTH RATED PLANT CAPACITY

	Number of Plants							
Process Category	Capacity = 0 to 0.5 mgd	Capacity >0.5 to 5 mgd	Capacity >5 to 10 mgd	Capacity >10 to 20 mgd	Capacity >20 to 50 mgd	Capacity >50 to 100 mgd	Capacity > 100 mgd	**Total**
EA	31	36	5	3	2	1	0	**78**
CAS	30	18	7	3	2	1	1	**62**
SBR	17	12	1	0	0	0	0	**30**
FF	6	7	6	0	1	0	0	**20**
MBR	7	4	0	0	0	0	0	**11**
HPO	0	0	0	0	1	1	1	**3**
Lagoons	70	13	2	2	0	0	0	**87**
SPT	13	0	0	0	0	0	0	**13**
Total	**174**	**90**	**21**	**8**	**6**	**3**	**2**	**304**
% of Plants Statewide	57%	30%	7%	3%	2%	1%	1%	
% of Plants ≤ range	57%	87%	94%	96%	98%	99%	100%	

TABLE 2-2.
COLLECTIVE CAPACITY OF PLANTS BY SECONDARY TREATMENT PROCESS CATEGORY AND MAXIMUM-MONTH RATED PLANT CAPACITY

	Collective Treatment Capacity (mgd)							
Process Category	Plant Capacity = 0 to 0.5 mgd	Plant Capacity >0.5 to 5 mgd	Plant Capacity >5 to 10 mgd	Plant Capacity >10 to 20 mgd	Plant Capacity >20 to 50 mgd	Plant Capacity >50 to 100 mgd	Plant Capacity > 100 mgd	**Total**
EA	5	68	39	41	56	80	0	**289**
CAS	6	48	51	33	50	60	144	**392**
SBR	2	15	6	0	0	0	0	**23**
FF	1	11	44	0	36	0	0	**92**
MBR	9	0	0	0	0	0	0	**9**
HPO	0	0	0	0	20	60	215	**295**
Lagoons	10	22	16	23	0	0	0	**71**
SPT	1	0	0	0	0	0	0	**1**
Total	**34**	**163**	**154**	**98**	**163**	**200**	**359**	**1,171**
% of Statewide Capacity	3%	14%	13%	8%	14%	17%	31%	
% of Capacity ≤ range	3%	17%	30%	38%	52%	69%	100%	

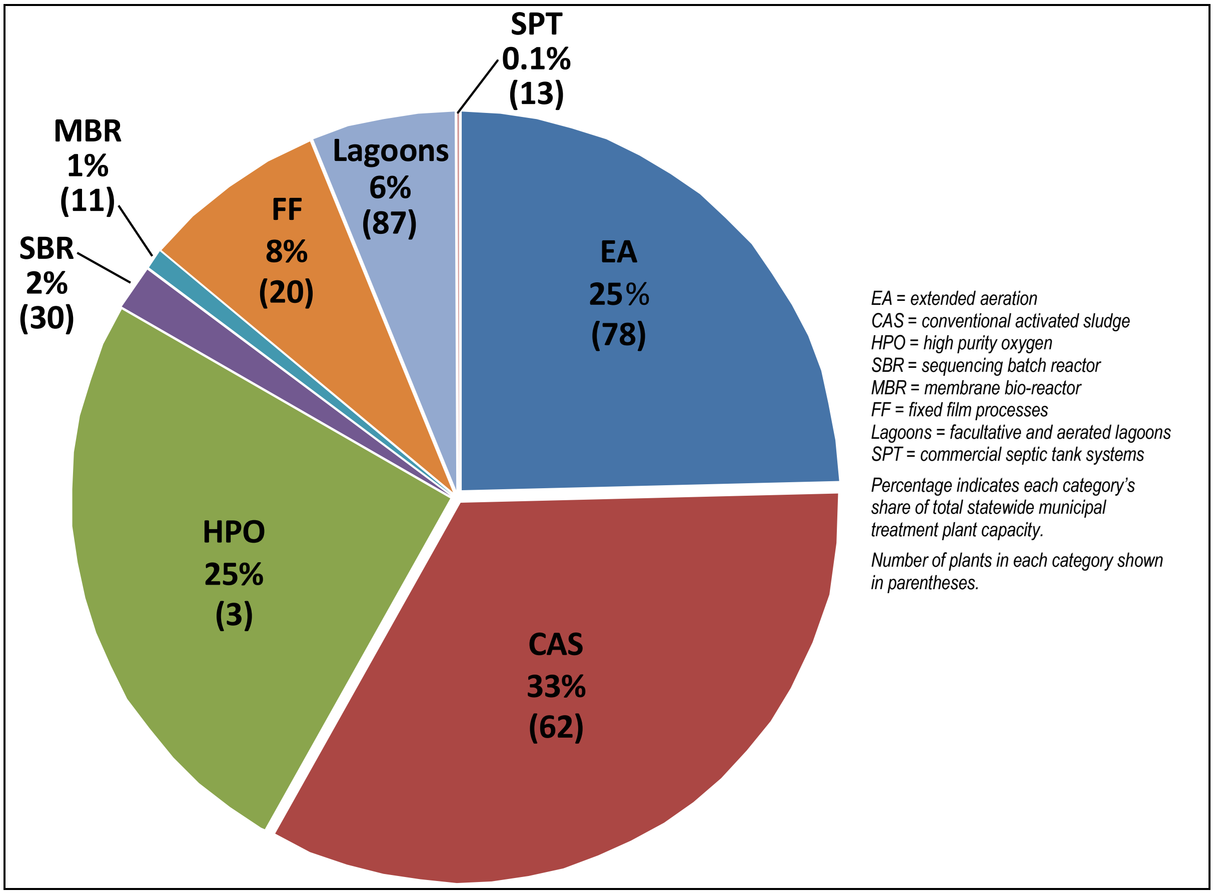


Figure 2-1. Number of Plants and Percentage of Total Statewide Treatment Capacity by Process Type

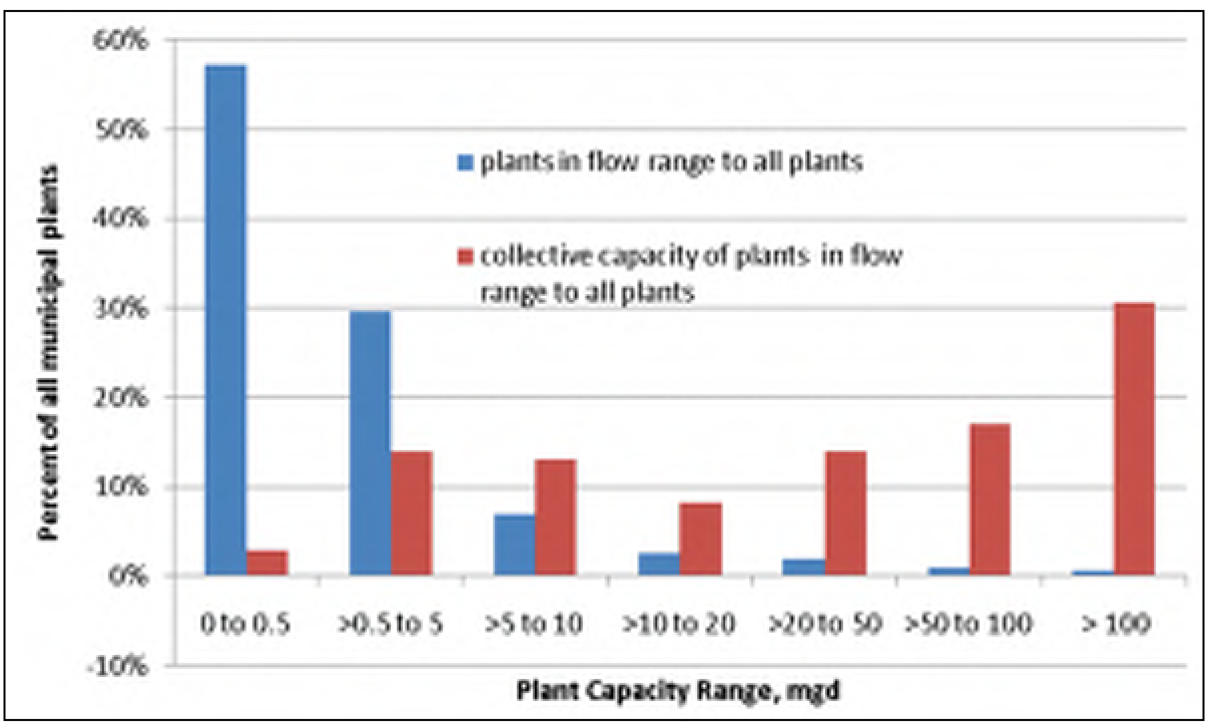


Figure 2-2. Distribution of Municipal Wastewater Treatment Plants in Washington by Capacity Range

2.2.1 Treatment Process Types

Extended Aeration Treatment Plants

The extended aeration plant category, which includes oxidation ditches, is the second most common municipal wastewater treatment process in Washington (after lagoon plants), with 78 EA plants representing 26 percent of all municipal wastewater treatment plants in the state. Collectively these plants can treat 289 mgd, which represents about 25 percent of total statewide capacity. The rated capacity of Washington's EA plants ranges from 0.012 to 79.8 mgd. The average capacity is 3.7 mgd and the median is 0.8 mgd. Most of these plants use aerobic digestion to stabilize their sludge; a few plants transport or convey their sludge to another treatment plant or to an independent biosolids recycling facility.

Conventional Activated Sludge Treatment Plants

Conventional activated sludge is the third most common municipal wastewater treatment process in Washington, with 62 CAS plants representing 20 percent of all municipal wastewater treatment plants in the state. Collectively these plants can treat 392 mgd, which represents about 33 percent of total statewide capacity. The rated capacity of Washington's CAS plants ranges from 0.018 to 144 mgd. The average capacity is 6.3 mgd and the median is 0.66 mgd. Most of these plants use anaerobic digestion to stabilize their sludge; a few plants dewater and incinerate their primary and waste activated sludge.

Sequencing Batch Reactor Treatment Plants

Sequencing batch reactors are frequently used for municipal wastewater plants with capacities below 10 mgd. The 30 SBR plants in Washington represent about 10 percent of all municipal wastewater treatment plants in the state. Collectively these plants can treat 22.5 mgd, which represents about 2 percent of total statewide capacity. The rated capacity of Washington's SBR plants ranges from 0.005 to 6 mgd. The average capacity is 0.75 mgd and the median is 0.2 mgd.

Fixed Film Treatment Plants

Fixed film plants include trickling filters, trickling filter/solids contact, and rotating biological contactor processes. The 20 fixed film municipal wastewater treatment plants in Washington represent 7 percent of all municipal wastewater treatment plants in the state. Collectively these plants can treat 92 mgd, which represents about 8 percent of total statewide capacity. The rated capacity of Washington's fixed film treatment plants ranges from 0.04 to 36.3 mgd. The average capacity is 4.6 mgd and the median is 1.785 mgd.

Membrane Bioreactor Treatment Plants

Membrane bioreactors represent a relatively new wastewater treatment process. The first full-scale MBR municipal treatment plant began operation for the Tulalip Tribes in 2003. The process has gained popularity for small- to medium-capacity plants because it requires a significantly smaller footprint than other technologies and produces a final effluent that often can meet Washington's Class A reclaimed water standard without additional treatment. Currently there are 11 Ecology-permitted MBR treatment plants in Washington ranging in capacity from 19,000 gpd to 4.2 mgd. The average capacity is 0.85 mgd and the median is 0.2 mgd. King County is currently constructing the Brightwater Treatment Plant; which is reported to be designed to treat up to 36 mgd with the MBR process.

High-Purity-Oxygen Activated Sludge Treatment Plants

High-purity-oxygen activated sludge is the least common municipal wastewater treatment process in Washington. There are only three HPO plants in Washington, about 1 percent of all municipal wastewater treatment plants in the state. Collectively these plants can treat 295 mgd, which represents about

25 percent of total statewide capacity. The rated capacity of Washington's HPO plants ranges from 20 to 210 mgd. The average capacity is 98 mgd and the median is 60 mgd. Two of the plants (King County West Point and City of Tacoma Central) stabilize their primary and waste activated sludge using anaerobic digestion; the City of Bellingham incinerates its primary and waste activated sludge.

Lagoon Treatment Plants

Lagoons are the most common wastewater treatment plant type in Washington. The 87 lagoon plants represent 29 percent of all municipal wastewater treatment plants in the state. Their collective capacity of 71 mgd represents 6 percent of the total statewide capacity. The rated capacity of lagoon plants in Washington ranges from 0.005 mgd to 12.7 mgd. The average capacity is 0.8 mgd and the median is 0.15 mgd.

Septic Treatment Plants

Wastewater treatment systems based on individual domestic septic tanks are used primarily in rural areas not served by a municipal sewer system and treatment plant. These individual on-site systems are not evaluated in this study. There are 13 commercial on-site septic tank based treatment systems permitted by Ecology. Seven of these facilities discharge treated effluent to ground under a State Waste Discharge permit; the remaining six discharge to natural surface water courses. Nine of these facilities have supplemental polishing treatment processes to improve effluent quality: seven have recirculating sand or gravel filters and two have polishing wetlands. Collectively these facilities have a treatment capacity of 1.4 mgd, which represents only 0.1 percent of the total statewide capacity. The rated capacity of these commercial septic treatment systems ranges from 4,000 gpd to 0.4 mgd. The average capacity is 0.11 mgd and the median is 50,000 gpd.

2.2.2 Treatment Plant Capacity

Capacity Up to 0.5 MGD

Plants with maximum-month capacities up to 0.5 mgd account for 57 percent of all municipal wastewater treatment plants in Washington, but their collectively treatment capacity is only about 3 percent of total statewide capacity. All of the process categories are represented in this size class except HPO, which is used in Washington only for plants with capacities over 20 mgd. Lagoons are the most common treatment processes in this capacity range, accounting for 40 percent of the plants, followed by extended aeration processes at 18 percent. CAS plants make up 17 percent of this capacity class. All commercial septic tank systems in the state are in this capacity class, representing 7.5 percent of plants this size. MBR and FF process plants each represent less than 4 percent of the plants in this class.

Capacity from 0.5 MGD to 5 MGD

Plants with maximum-month capacities greater than 0.5 mgd and up to 5 mgd account for 30 percent of all municipal wastewater treatment plants in Washington. Extended aeration treatment plants account for 40 percent of the plants in this range; CAS plants account for 20 percent; lagoon plants account for 14 percent; SBR plants account for 13 percent; fixed film plants account for 8 percent; and MBR plants account for 5 percent. Collective capacity of plants in this capacity class represents 14 percent of total statewide capacity.

Capacity from 5 MGD to 10 MGD

Plants with maximum-month capacities greater than 5 mgd and up to 10 mgd account for 7 percent of the plants statewide and 13 percent of the total statewide capacity. CAS is the most common treatment process in this class, representing 33 percent of the number of plants and 33 percent of the collective treatment capacity. FF and EA plants are also significant in this class, providing 25 percent and 29 percent, respectively, of the collective capacity of this range of plants.

2.2.3 Nutrient Removal Quantities

Conventional secondary treatment processes generally have similar nutrient removal efficiencies. Assuming that all existing treatment processes have equivalent nutrient removal efficiencies, then the relative mass of nutrients discharged by a treatment plant is directly proportional to the flow of wastewater treated. Based on the data in Tables 2-1 and 2-2, this leads to the following estimates of nutrient removal quantities:

- 97 percent of the nutrients discharged by municipal wastewater treatment plants in Washington is discharged by the 43 percent of plants with rated capacities greater than 0.5 mgd.
- 83 percent of the nutrients discharged by municipal wastewater treatment plants in Washington is discharged by the 13 percent of plants with rated capacities greater than 5 mgd.
- 70 percent of the nutrients discharged by municipal wastewater treatment plants in Washington is discharged by the 6 percent of plants with rated capacities greater than 10 mgd.

2.3 WASTEWATER FLOW AND LOAD CHARACTERISTICS

Influent wastewater characteristics influence the concentration of nitrogen and phosphorus remaining in a treatment plant's effluent. In the absence of significant high-strength, carbon-rich industrial wastewater, municipal wastewater generally contains more inorganic nitrogen and phosphorus than can be removed by conventional secondary biological treatment processes.

Influent nitrogen and phosphorus concentrations and loads are available for only a few of the wastewater treatment plants in the Ecology database. The limited data available in the database show nutrient concentrations and loads consistent with generally recognized typical values for untreated municipal wastewater. Rather than establishing influent flows and pollutant loads for this study from any site-specific wastewater treatment plant record, it was decided to use commonly reported generic values, as summarized in Table 2-3. These values were used to calculate the concentration of nutrients and other constituents of concern in the influent wastewater to be treated. The flows and loads are population-driven with no specific allowance for industrial and commercial loads. Future facility-specific evaluations for nutrient removal should adjust the values to represent actual flows and loads contributed by the facility's residential, commercial and industrial users.

TABLE 2-3.
DESIGN CRITERIA FOR INFLUENT FLOWS AND LOADS

Constituent	Design Criteria
Annual Average Flow	100 gallons per capita per day (gpcd)
Average Wet-Weather Flow	120 gpcd
Maximum-Month Wet-Weather Flow	160 gpcd
Average Dry-Weather Flow	80 gpcd
Maximum-Month Dry-Weather Flow	110 gpcd
Peak-Day Flow	275 gpcd
BOD_5	0.22 pounds per capita per day (ppcd)[a]
TSS	0.25 ppcd[a]
Total Kjeldahl Nitrogen (TKN) as N	0.032 ppcd[a]
Organic Nitrogen as N	0.013 ppcd[a]
Ammonia as N	0.019 ppcd[a]
Total Phosphorus as P	0.0076 ppcd[a]
Organic Phosphorus as P	0.0028 ppcd[a]
Inorganic Phosphorus as P	0.0048 ppcd[a]

a. Values are from Table 3-12 Metcalf &Eddy 2003

CHAPTER 3.
EVALUATION APPROACH

This chapter describes the methodology used to evaluate the implementation of technology upgrades to improve nutrient removal at existing municipal wastewater treatment plants in Washington. The evaluation assessed the following:

- The general feasibility of upgrading
- The general nature and extent of process modifications that would need to be implemented
- Capital and operation and maintenance costs associated with the upgraded plants.

3.1 TREATMENT PROCESS UPGRADES EVALUATED

The evaluation covered a wide range of existing plants and potential improvements:

- Upgrades were evaluated for seven of the eight existing treatment process types described in Chapter 2. Septic treatment plants represent only 1 percent of the total statewide treatment capacity and were not included in the scope of work.
- For each type of existing treatment process evaluated except HPO, upgrades were assessed for achieving each of the six nutrient removal objectives described in Chapter 2. For HPO, the objectives that include phosphorus removal were not evaluated.
- For each existing treatment process type and each nutrient removal objective, upgrades were evaluated for providing nutrient removal year-round or providing it only seasonally, during the dry-weather season.

The project scope of work describes the processes to be implemented for each upgrade scenario. Table 3-1 summarizes these processes.

3.2 BIOWIN MODELING

Biowin is a modeling program used to design and simulate treatment plants. The model can evaluate many different treatment processes for both liquid and solid streams. Biowin models were developed to establish the performance of each existing treatment plant technology and to evaluate upgrades for achieving the defined nutrient removal objectives. Generic hypothetical treatment plants typical of those in Washington were used as the basis of the analysis.

3.2.1 Modeling Assumptions

The following general assumptions were made for modeling the treatment technologies using Biowin:

- Base Case/Existing System Model:
  - For each existing treatment process type, a 1-mgd hypothetical base case was generated, based on maximum-month wet-weather flow (MMWWF) and loading conditions.
  - For the base case system, tank sizes and process parameters such as hydraulic retention time (HRT), solids retention time (SRT), etc. were established according to standards set forth in the Department of Ecology's *Criteria for Sewage Works Design* ("The Orange Book").

**TABLE 3-1.
TREATMENT PROCESS UPGRADES EVALUATED
TO ACHIEVE NUTRIENT-REMOVAL OBJECTIVES**

	Objective A	Objective B	Objective C	Objective D	Objective E	Objective F
Definition of Objective						
Effluent TIN	< 8 mg/L	< 3 mg/L	—	—	< 8 mg/L	< 3 mg/L
Effluent TP	—	—	< 1 mg/L	< 0.1 mg/L	< 1 mg/L	< 0.1 mg/L
	Treatment Processes to Achieve Objective					
Existing Extended Aeration Plant						
Year-Round	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Existing Conventional Activated Sludge Plant						
Year-Round	MLE+MBR	4BDP+MBR+M	C	C+F	MLE+MBR+C	4BDP+MBR+M+C
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Existing Sequencing Batch Reactor Plant						
Year-Round	SBR	SBR+DNF+M	SBR+C	SBR+C+F	SBR+C	SBR+DNF+C+F+M
Seasonal	SBR	SBR+DNF+M	SBR+C	SBR+C+F	SBR+C	SBR+DNF+C+F+M
Existing Trickling Filter, Trickling Filter/Solids Contact, or Rotating Biological Contactor Plant						
Year-Round	MLE+MBR	4BDP+MBR+M	C	C+F	MLE+MBR+C	4BDP+MBR+M+C
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Existing Membrane Bioreactor Plant						
Year-Round	OC	M	C	C	C	C+M
Seasonal	OC	M	C	C	C	C+M
Existing High-Purity Oxygen Activated Sludge Plant						
Year-Round	MLE+MBR	4BDP+MBR	—	—	—	—
Seasonal	MLE	4BDP+M	—	—	—	—
Existing Aerated Lagoon or Facultative Lagoon Plant						
Year-Round	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F
Seasonal	MLE	4BDP+M	C	C+F	MLE+C	4BDP+M+C+F

4BDP = Four-stage Bardenpho system for denitrification
C = Chemical addition: alum for phosphorous removal, magnesium hydroxide for pH control
DNF = Denitrification filters
F = Tertiary filters for phosphorus removal
M = Methanol addition for denitrification
MBR = Membrane bioreactors for denitrification
MLE = Modified Ludzack Ettinger process for denitrification
OC = Operational changes only
SBR = Sequencing batch reactor (capacity increased for denitrification)

- Clarifiers for existing treatment processes were sized based on peak-day flows using overflow rates defined in the Orange Book:
  - Fixed Film Systems: 1,200 gallons per day per square foot (gpd/ft^2)
  - Complete Mix Activated System: 1200 gpd/ft^2
  - Extended Aeration System: 500 gpd/ft^2
- Existing plant O&M requirements were calculated at average wet-weather flow (AWWF) for six months at 10ºC and average dry-weather flow (ADWF) for six months at 15ºC.

• Year-Round Model Assumptions:
  - Capital Facilities (tanks and equipment sizing):
    - 1-mgd models were developed for the upgrades required to achieve each nutrient removal treatment objective for each treatment process type.
    - Process parameters for capital facilities such as tanks and aeration blowers were designed using MMWWF and loadings.
  - O&M Assumptions:
    - O&M requirements such as aeration energy and chemical usage were calculated at AWWF for 6 months at 10ºC and ADWF for 6 months at 15ºC using capital facilities designed for MMWWF.

• Seasonal Model Assumptions:
  - Capital Facilities (tanks and equipment sizing):
    - 1-mgd models were developed for the upgrades required to achieve each nutrient removal treatment objective for each treatment process type.
    - Process parameters for capital facilities such as tanks and aeration blowers were designed to reliably achieve the nutrient removal objectives at maximum-month dry-weather flow (MMDWF) and to provide not less than the existing level of treatment during the MMWWF.
  - O&M Assumptions:
    - O&M requirements such as aeration energy and chemical usage were calculated at ADWF for 6 months at 15ºC using capital facilities designed at MMDWF.

3.2.2 Modeling Design Criteria

Table 3-2 shows design criteria flows and loads for the hypothetical 1-mgd MMWWF model. Values were calculated as follows:

- Flows other than MMWWF for the hypothetical model were calculated by applying flow ratios from Table 2-3 to the MMWWF value of 1 mgd. For example, Table 2-3 gives per capita flows of 275 gpcd for peak-day flow (PDF) and 160 gpcd for MMWWF, so the ratio of PDF to MMWWF is 1.72. The PDF for the hypothetical model, therefore, is 1.72 times 1 mgd, or 1.72 mgd.
- pH was assumed to be slightly less than neutral for wet weather conditions, at 6.8, and neutral for dry weather, at 7.0.
- Based on the per capita MMWWF of 160 gpcd from Table 2-3, the population to generate the hypothetical MMWWF of 1 mgd is 6,250. This population was used with the per capita loading rates in Table 2-3 to calculate loading rates for the hypothetical model for nitrogen, phosphorus, BOD_5 and TSS.

TABLE 3-2.
DESIGN CRITERIA FLOWS AND LOADINGS FOR 1-MGD HYPOTHETICAL MODEL

		Annual Average	Max Month Wet Weather	Average Wet Weather	Max Month Dry Weather	Average Dry Weather	Peak Day
Flow (mgd)		0.63	1.00	0.75	0.69	0.50	1.72
pH (units)		7.0	6.8	6.8	7.0	7.0	7.0
	Loading Rate (lbs/day)	Concentration (mg/L)					
BOD_5	1,376	265	165	221	241	331	96
TSS	1,564	301	188	251	273	376	109
VSS[a]	1,095	210	132	175	191	263	77
TKN as N	200	38.5	24.1	32.1	35.0	48.1	14.0
Organic Nitrogen as N	81	15.6	9.8	13.0	14.2	19.5	5.7
Ammonia as N	119	22.9	14.3	19.1	20.8	28.6	8.3
Total Phosphorus as P	48	9.1	5.7	7.6	8.3	11.4	3.3
Organic Phosphorus as P	18	3.4	2.1	2.8	3.1	4.2	1.2
Inorganic Phosphorus as P	30	5.8	3.6	4.8	5.2	7.2	2.1
Alkalinity	835	161	100	134	146	200	58.4
Calcium	63	12.0	7.5	10.0	10.9	15.0	4.4
Magnesium	25	4.8	3.0	4.0	4.4	6.0	1.8

a. VSS = volatile suspended solids (assumed to equal 0.7 * TSS)

- Concentrations are calculated by dividing the mass loading by the flow rate, with multipliers to convert to correct units.
- Influent alkalinity during average dry weather conditions was assumed to be 200 mg/L, representing medium-strength wastewater. Concentrations for other flows were calculated using flow ratios from Table 2-3.
- Calcium was assumed to be 15 mg/L during average dry weather conditions. Concentrations for other flows were calculated using flow ratios from Table 2-3.
- Magnesium was assumed to be 6 mg/L during average dry weather conditions. Concentrations for other flows were calculated using flow ratios from Table 2-3.

3.3 COST EVALUATION

3.3.1 Treatment Plant Capacities Evaluated

Cost curves were developed for capital and O&M costs associated with the evaluated improvements. The curves were based on estimates for three plant capacities for each existing treatment process type, as shown in Table 3-3. The plant capacities chosen cover the full range of existing plants for each existing treatment process type. Sizing tables for different plant capacities were developed using process modeling results for each treatment plant upgrade.

TABLE 3-3.
MAXIMUM-MONTH TREATMENT PLANT CAPACITIES EVALUATED FOR COST CURVES

Existing Treatment Process Type	Number of Capacities Evaluated	Maximum-Month Plant Capacity (mgd) Low	Mid	High
Extended Aeration	3	1	10	100
Sequencing Batch Reactor	3	0.5	2	10
Conventional Activated Sludge	3	1.0	10	150
Fixed Film	3	1.0	10	150
Membrane Bioreactor	3	1.0	10	100
High-Purity-Oxygen Activated Sludge	2	20	NA	220
Lagoons	3	0.5	5.0	50

3.3.2 Unit Costs and Rates

Biowin models were developed for each base case system and upgrade system to confirm size and capacity of major process elements required to achieve the treatment objectives. CapdetWorks 2.5 software was then used to develop capital and O&M cost estimates, with cost indices updated to January 2010 values. Costs for processes that are not part of the CapdetWorks library, such as MBRs, were developed using data from recent facilities constructed in Washington and from system vendors. Unit cost and rates used for the cost models are shown in Table 3-4.

3.3.3 Assumptions and Methods

Capital cost estimates assumed that all technology improvements were necessary to achieve the selected nutrient removal objective. Capital cost estimates assumed maximum-month flow and maximum-month load conditions, including internal recycle from any solids processing systems. Cost curves, cost model equations, and a goodness of fit indicators (i.e. correlation coefficient) were developed using the "power" curve fitting function in Microsoft Excel 2007. The accuracy of the estimated costs is in the range of -50 percent to +100 percent, consistent with a Class 5 Planning Estimate as defined by the Association for the Advancement of Cost Engineering.

Capital and O&M costs were determined by estimating first the current constructed value of existing process facilities and then the constructed value of process facilities after implementation of the necessary process upgrades. The incremental capital cost was the difference between the capital cost of the retained portion of the existing secondary treatment process and the cost to construct a complete new secondary treatment process that would achieve the nutrient removal objective. Cost estimates included the following:

- An additional 12 percent of the construction cost calculated by CapdetWorks was added to both the existing and the upgraded plants to account for the cost for construction of instrumentation and control systems.
- An allowance of 7 percent of the resultant cost for the upgrade was added to account for general site, structural, and electrical modifications.
- When an existing unit needs to be demolished, a 10 percent cost of that unit will be added as the demolition cost.

TABLE 3-4.
UNIT COSTS AND RATES

Unit Costs	
Building Cost	$150/ft^2
Excavation	$8/cubic yard
Wall Concrete	$800/ cubic yard
Slab Concrete	$500/ cubic yard
Crane Rental	$200/hour
Canopy Roof	$16/ft^2
Electricity	$0.1/kW-hour
Hand Rail	$75/foot
Land Costs	$0/acre
Labor Rates	
Construction Labor Rate	$45/hour
Operator Labor Rate	$70/hour
Administration Labor Rate	$35/hour
Laboratory Labor Rate	$45/hour
Chemical Costs (all costs are per mass of the dry form)	
$AL_2(SO_4)_3$*14 H_2O as 42.8%	$0.06/lb
Magnesium hydroxide	$0.21/lb
Methanol	$3/gallon
Polymer	$4/lb
Citric Acid	$3/gallon
Sodium Hypochlorite	$0.80/gallon
Financial	
Interest Rate	3%
Construction Period	3 years
Construction loan period	20 years
Operating Life of Plant	40 years
Other Costs	
Engineering Design Fee	15%
Miscellaneous	15%
Administration/Legal	2%
Inspection	8%
Contingency	30%
Technical	7%
Profit and Overhead	15%
Cost Indices	
Marshall and Swift Index	1448.3 (January 2010)
Engineering News Records Cost Index	8660.1 (January 2010)
Pipe Cost Index	794.5 (January 2010)

- The capital and O&M costs for chemical storage and feed systems for alum and methanol were determined using CapdetWorks based on the dosage requirements shown in the sizing tables.
- CapdetWorks does not provide costs for magnesium hydroxide storage and feed systems, so an equivalent capacity hydrated lime dosing system was used to represent the costs of magnesium hydroxide storage and feed.
- The annual cost of alum, magnesium hydroxide and methanol were determined based on calculated annual usage and the unit prices shown in Table 3-4.

The CapdetWorks model does not currently provide costing information for MBR treatment systems. Costs for MBR equipment were interpolated from vendor information provided by Enviroquip, and Zenon for 1, 10 and, 135 mgd. MBR processes require fine screening of the influent to reduce physical damage to the membranes. A 1.5-mm to 2.5-mm fine screening process is included in the cost estimates for upgrades involving MBR technology. The cost related to the MBR tankage and aeration system was estimated using CapdetWorks model.

3.3.4 Use of Cost Modeling Results

Capital, incremental O&M and 20-year life cycle costs associated with upgrades for each nutrient removal objective are presented in Chapters 12 through 17. The results from this type of analysis are likely to vary significantly from real costs of upgrading a particular treatment plant facility, depending on the facility's specific conditions. The cost models could be applied to all municipal wastewater treatment plants within a specific watershed to develop a preliminary estimate of costs associated with addressing regional nutrient-related water quality concerns.

Cost budgets for implementing nutrient removal at any specific facility should be based on a site-specific engineering report so that concerns, needs and constraints specific to the site, community and facility can be thoroughly addressed. Site-specific factors such as wastewater characteristics, site constraints, geotechnical conditions, and the condition and layout of the existing facility can have a dramatic impact on the ultimate cost of a treatment plant upgrade project.

CHAPTER 4.
TECHNOLOGICAL EVALUATION
FOR EXTENDED AERATION PLANTS

4.1 BASE CASE/EXISTING SYSTEM

Two base case Biowin models were developed to represent existing extended aeration activated (EA) sludge plants: one with a complete-mixed aeration tank with diffused aeration (DA) and the other an oxidation ditch with mechanical aeration (MA). Figure 4-1 shows the process flow schematic for the liquid and solids treatment for a hypothetical DA extended aeration plant with a design MMWWF capacity of 1.0 mgd. The process flow schematic for an MA plant would be similar, with the aeration tank replaced by an oxidation ditch. Design data for both plants is presented in Table 4-1.

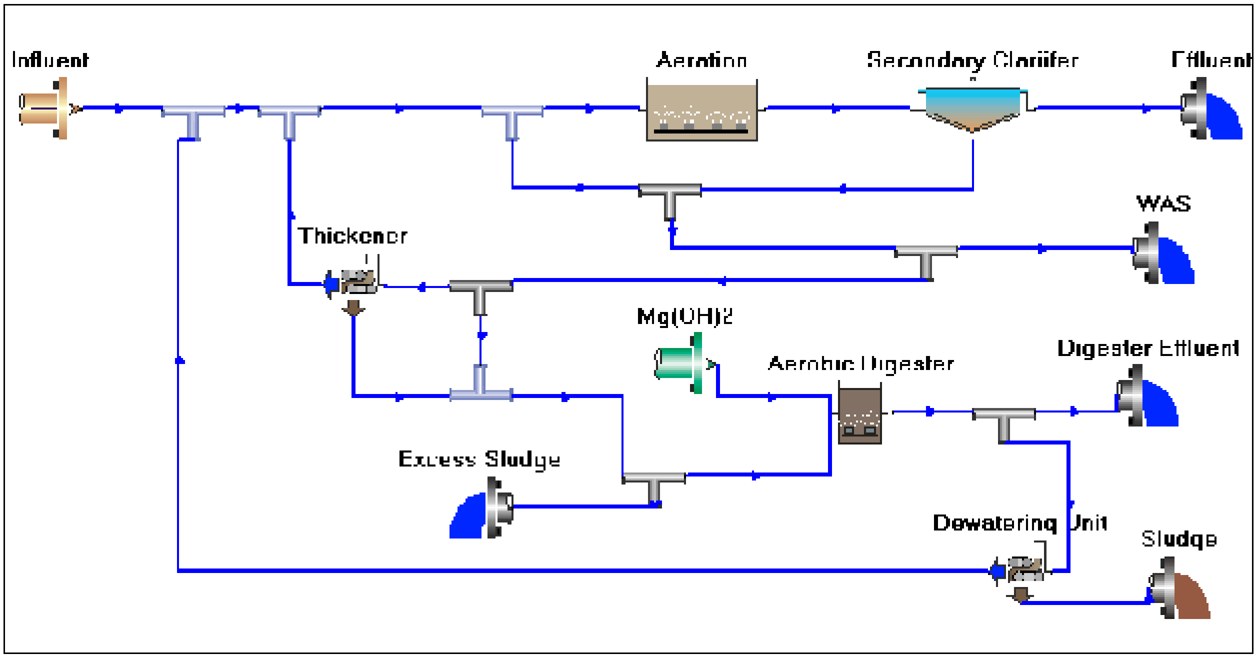


Figure 4-1. Process Flow Schematic of an Extended Aeration Treatment Plant with Aeration Tank

The DA and MA extended aeration models produced similar effluent quality: BOD_5 concentration of less than 30 mg/L, TSS concentration of less than 30 mg/L and a total ammonia-nitrogen concentration of less than 2 mg/L. It was assumed that these existing plants are currently operated to remove ammonia by the nitrification process but not to denitrify to any significant extent. The modeled secondary clarifiers were sized for peak-day flow conditions, with an overflow rate of 500 gallons per day per square foot (gpd/ft^2), which is consistent with the recommendations in the 1998 Washington State Orange Book. For modeling purposes, it was assumed that the plant thickens its waste activated sludge prior to digestion, stabilizes the sludge using aerobic digestion, and mechanically dewaters the digested sludge.

TABLE 4-1
BASE CASE/EXISTING SYSTEM FOR EXTENDED AERATION PLANT

Description	Mechanical Aeration (MA)	Diffused Aeration (DA)
MMWWF (mgd)	1.0	1.0
Temperature (ºC)	10	10
Oxidation Ditch/Aeration Tank		
Tank Volume (million gallons (MG))	1.00	1.00
HRT (hrs)	24	24
Mixed Liquor Suspended Solids (mg/L)	2,809	2,807
DO Concentration (mg/L)	2	2
Ditch Power Uptake (HP)	80	
Aeration Tank Airflow rate (cubic feet/minute)		904
Biowin SRT (days)	18.01	18.01
RAS Recycle Rate	0.5Q	0.5Q
Clarifier		
Area (SF)	3,500	3,500
Surface Overflow Rate (gal/ft^2)	286	286
Aerobic Digester		
Solids % from Clarifier	0.8%	0.8%
Solids % from Thickener	5.0%	5.0%
Combined Solids % to Aerobic Digester	3.5%	3.5%
VSS loading to Digester (pounds/day)	730	730
TSS loading to Digester (pounds/day)	1,301	1,301
Volume (MG)	0.25	0.25
Digester Sludge Age (days)	56.33	56.33
Sludge Production		
Dry Sludge Production (pounds/day)	923	923
Effluent		
BOD (mg/L)	1.85	1.85
TSS (mg/L)	4.5	4.5
Total Phosphorous (mg/L)	4.27	4.27
Ammonia N (mg/L)	0.63	0.61
TIN (mg/L)	15.97	16.05
pH	6.53	6.58

4.2 YEAR-ROUND NUTRIENT REMOVAL

Improvements required to provide year-round nutrient removal to achieve each treatment objective are described below. It was assumed that existing plants with mechanical aeration would be upgraded to diffused aeration in order to meet the all the nutrient removal objectives except those involving only phosphorus removal (Objectives C and D). Process design data for all objectives are included in Table 4-2, which is attached at the end of this chapter.

4.2.1 Objective A

Process Description

The upgrade evaluated for achieving Objective A (TIN <8 mg/L) for an extended aeration plant is to convert the existing system to a Modified Ludzack-Ettinger (MLE) activated sludge process, retaining the existing clarifiers. The MLE process is a continuous-flow suspended-growth process with an anoxic zone followed by an aeration zone and a clarifier. Denitrification is achieved by recycling nitrate produced by the aeration zone back to the upstream anoxic zone, as shown in Figure 4-2.

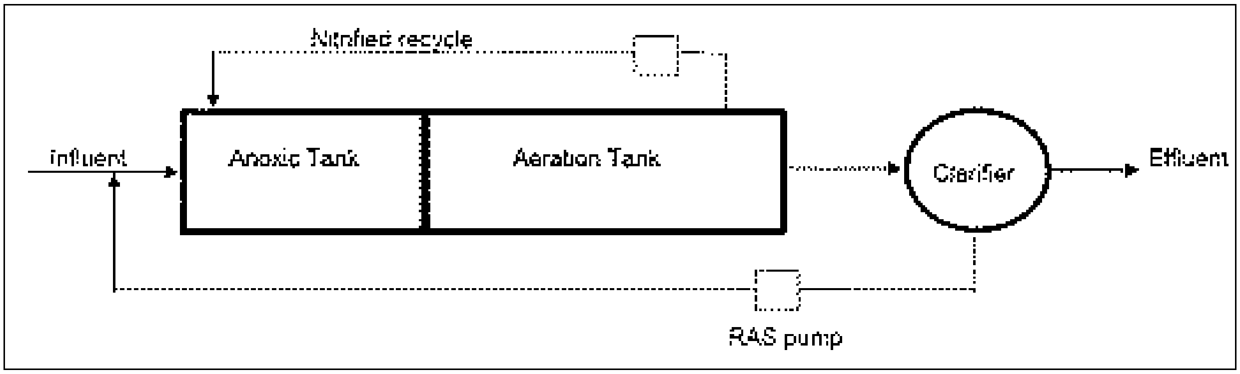


Figure 4-2. Modified Ludzack-Ettinger Process Flow Schematic

Influent wastewater, return sludge from the clarifier and nitrate-rich mixed liquor recycled from the aeration tank are mixed in the anoxic zone. When the dissolved oxygen concentration is near zero, some facultative heterotrophic bacteria can draw oxygen from nitrate in order to use the organic carbon in raw wastewater as an energy source and a carbon source for growth. The influent wastewater provides the carbon source and the return activated sludge (RAS) from the clarifier provides microorganisms.

The upgraded capital facilities were sized with capacity for the MMWWF. The upgrade includes partitioning the existing 1.0-million-gallon (MG) aeration tank into two compartments: a 0.3-MG anoxic compartment and a 0.7-MG aeration compartment. New internal recycle pumps would be required for pumping nitrate-rich mixed liquor from the aeration compartment to the anoxic compartment. The internal recycle ratio would be 6 times the influent flow (6Q). New mixers would be installed in the anoxic tank to mix the contents of the tank and to prevent sedimentation of solids. Figure 4-3 shows the upgraded process flow schematic. Table 4-2 summarizes the process design data. Detailed reports of the Biowin model are contained in Appendix A.

Recycled Loads

Process side streams generated by the thickening of the waste activated sludge prior to digestion and the dewatering of the aerobically digested sludge would be returned and blended with the influent wastewater. The percentage of total nitrogen (TN) and total phosphorus (TP) contained in these recycle streams relative to the mass contained in raw influent wastewater was calculated using Biowin model outputs. The results indicate that approximately 18 percent of the total nitrogen entering the existing plant is recycled. Upgrading the plant to achieve Objective A reduces the mass of total nitrogen recycled by approximately 2 percent on an annual basis. Although phosphorus removal is not part of Objective A, the upgrade will increase the amount of phosphorus recycled in the plant from about 23 percent to 50 percent on an annual basis. Table 4-3 summarizes the nitrogen and phosphorus recycle loads for the existing plant and the upgraded plant.

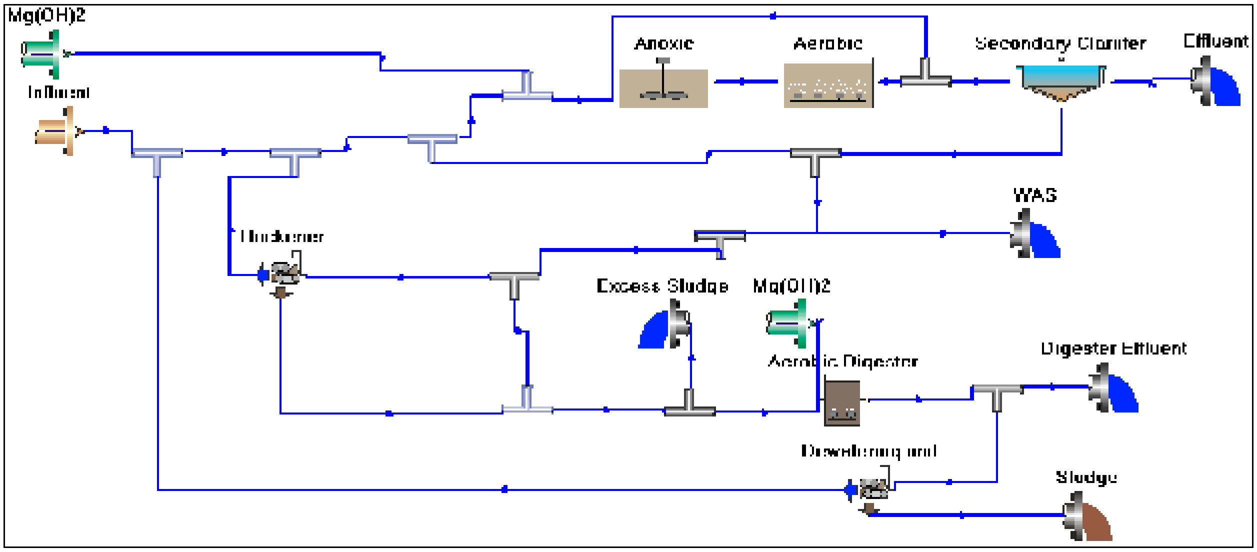


Figure 4-3. Process Schematic of Extended Aeration Plant Upgraded for Objective A Year-Round

TABLE 4-3.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE A YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	18.0%	17.9%	23.9%	23.3%
Objective A Year-Round	16.3%	15.5%	48.7%	64.1%

Sludge Production

From Table 4-2, average sludge produced per day (the average of the AWWF and ADWF sludge production) is 949 pounds per day (ppd) (0.7 pound per pound of BOD_5 applied) for the existing system and 939 ppd for Objective A year-round. This reduction in sludge production associated with achieving Objective A is not significant; there should be no significant change in the overall mass of sludge produced.

Energy Consumption

For year-round flows, energy usage costs were determined based on annual average conditions, calculated as the average of AWWF and ADWF energy usage. As a result of implementing the MLE denitrification process, the average air flow rate to meet Objective A is approximately 20 percent less than the rate required for the existing DA system (see Table 4-2). However, the increased energy demand for mixing and pumping the internal mixed liquor to the anoxic compartment exceeds the energy savings associated with the reduction in process air demand.

MA Plant

Upgrading the MA plant to achieve Objective A year-round would increase the plant energy requirements by 11,500 kW-hours/year, or about 1 percent, as shown in Table 4-4. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 50 kW-hours per million gallons of influent wastewater treated.

TABLE 4-4.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective A Year-Round	1,010,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	11,500 kW-hours/year
Percent	1.2%
Increase per Volume of Plant Flow	50 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective A year-round would increase the plant energy requirements by 159,500 kW-hours/year, or about 19 percent, as shown in Table 4-5. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 700 kW-hours per million gallons of influent wastewater treated.

TABLE 4-5.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective A Year-Round	1,010,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	159,500 kW-hours/year
Percent	19%
Increase per Volume of Plant Flow	699 kW-hours/MG

Chemical Consumption

For year-round flows, chemical usage costs were determined based on annual average conditions, calculated as the average of AWWF and ADWF chemical usage.

Upgrades to achieve Objective A would require the use of chemicals only for alkalinity control. EA plants require alkalinity supplementation to maintain the pH of the effluent at or above 6.5. Diffused aeration systems are less efficient than mechanical aeration systems in stripping surplus carbon dioxide from the wastewater, so they generally require more alkalinity supplementation.

Upgrades for Objective A would reduce the need to supplement alkalinity that is consumed by nitrification (7.14 pounds of alkalinity as $CaCO_3$ consumed per pound of ammonia-nitrogen converted to nitrate). Complete denitrification of nitrate to nitrogen gas generates alkalinity that can offset up to

50 percent of the alkalinity consumed by nitrification (3.57 pounds of alkalinity as $CaCO_3$ recovered per pound of nitrate-nitrogen converted to nitrogen gas).

For an MA plant upgraded to achieve Objective A year-round, the annual quantity of magnesium hydroxide required to control alkalinity would be reduced about 50 percent, from 7,300 gallons to 3,650 gallons. This is a reduction of about 16 gallons of magnesium hydroxide per million gallons of plant influent flow.

For a DA plant upgraded to achieve Objective A year-round, the annual quantity of magnesium hydroxide required to control alkalinity would be reduced about 89 percent, from 33,000 gallons to 3,650 gallons. This is a reduction of about 128 gallons of magnesium hydroxide per million gallons of plant influent flow.

Footprint Requirements

Footprint requirements were calculated using the CapdetWorks costing model:

- No additional tanks are required to upgrade the existing DA system to achieve Objective A as the existing aeration tank would be partitioned into anoxic and aeration tanks. Since the amount of air required for Objective A is less than for the existing system, no additional blowers would be required. No new pump building would be required for the internal recycle pumps as they would be installed in the existing aeration tank.
- Upgrading an MA plant to achieve Objective A would require conversion to a DA plant. New blower buildings would be constructed to supply air to the new diffused aeration system. The existing ditch rotors would be removed and replaced with fine bubble diffusers. Based on CapdetWorks, for a 1.0-mgd plant, the required site area for the new blower building would be approximately 0.3 acres.

Table 4-6 compares the additional site area requirements, or footprint area, for upgrading existing MA and DA plants to achieve Objective A for the three generic plant capacities. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems. The existing secondary footprint includes existing aeration tanks or oxidation ditches and secondary clarifiers.

TABLE 4-6.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING EXTENDED AERATION PLANTS TO ACHIEVE OBJECTIVE A

Plant Design Capacity (mgd)	Additional Area Required for MA Plants (square feet)	Additional Area Required for DA Plants (square feet)
1	1,050	250
10	1,800	300
100	3,300	600

4.2.2 Objective B

Process Description

The upgrade evaluated for achieving Objective B (TIN <3 mg/L) is to convert the existing system into a four-stage Bardenpho activated sludge process. The Bardenpho system consists of a first anoxic tank (pre-anoxic tank), a first aeration tank, a second anoxic tank (post-anoxic tank) and a second aeration tank, as shown in Figure 4-4.

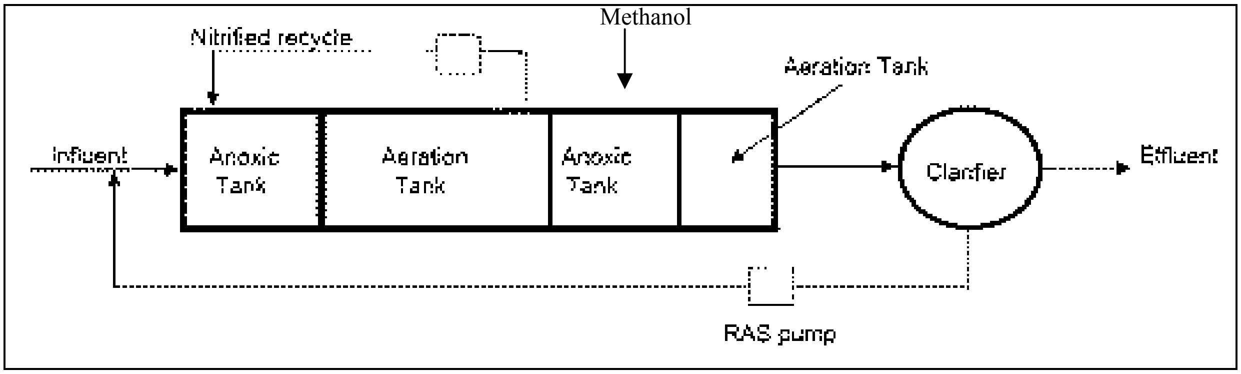


Figure 4-4 Four-Stage Bardenpho Process Flow Schematic

Wastewater enters into the pre-anoxic tank, where nitrate from the first aeration tank and the RAS from the secondary clarifier are recycled. Using carbon present in the raw wastewater, denitrification takes place in this tank by reduction of nitrate, with subsequent release of nitrogen gas. Ammonia in the raw wastewater passes through the pre-anoxic tank and is nitrified in the first aeration tank. A portion of the nitrate produced is recycled to the pre-anoxic tank and the rest of the flow passes to the second anoxic tank. Methanol is added as an additional carbon source in this zone to drive the denitrification process. The second aeration tank aids in stripping the nitrogen gas produced by denitrification in the second anoxic tank and provides a dissolved oxygen residual that improves sludge settleability.

The upgrade to achieve Objective B would consist of partitioning the existing 1.0-MG aeration tank to create a 0.2-MG pre-anoxic tank, a 0.5-MG first aeration tank, a 0.2-MG post-anoxic tank, and a 0.1-MG second aeration tank. Mechanical mixers would be provided in both the pre- and post-anoxic tanks to maintain the mixed liquor in suspension and to prevent dead zones and hydraulic short-circuiting. Methanol storage and dosing systems would be added to provide the needed carbon substrate to drive the denitrification process in the post-anoxic tank. Magnesium hydroxide storage and dosing systems would need to be added to keep the pH of the effluent at or above 6.5. Figure 4-5 shows the upgraded process flow schematic. Table 4-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

In the absence of competitive reactions for methanol, the theoretical quantity of methanol required for denitrification is 1.91 pounds of methanol per pound of nitrate-nitrogen converted to nitrogen gas. Because there will be some aerobic biologically mediated oxidation of methanol, an empirical dose of 3.0 pounds of methanol per pound of nitrate-nitrogen converted to nitrogen gas was used for the second anoxic tank. Table 4-7 summarizes the methanol dosage requirements for different flow conditions. To minimize site footprint impacts, a minimum storage capacity of 14 days at the maximum use rate was modeled.

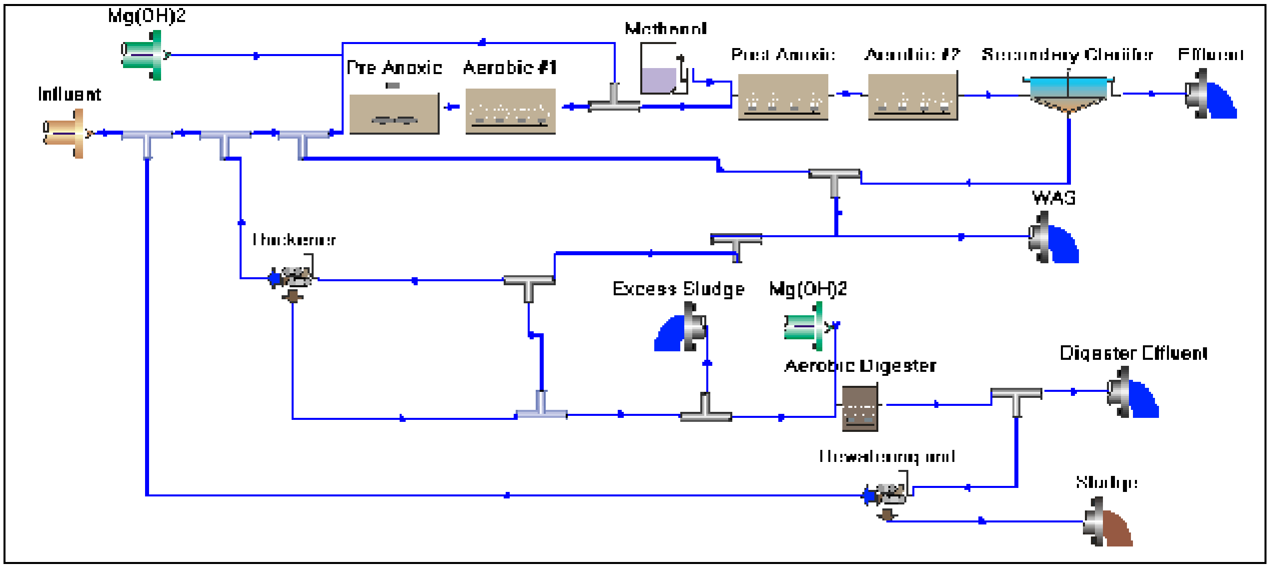


Figure 4-5. Process Schematic of Extended Aeration Plant Upgraded for Objective B Year-Round

TABLE 4-7.
METHANOL DOSAGE CALCULATION

	Flow rate (mgd)	TIN removed (mg/L)	TIN removed (ppd)	Methanol Dosage (lbs per lb of TIN removed)	Methanol Dosage (ppd)	Density of Methanol (lbs/gal)	Methanol dosage (gal/day)
MMWWF	1	5	41.7	3	125.1	6.6	19.0
ADWF	0.5	5	20.9	3	62.6	6.6	9.5
AWWF	0.75	5	31.3	3	93.8	6.6	14.2
MMDWF	0.69	5	28.8	3	86.3	6.6	13.1

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. The nutrient recycle loads for Objective B are presented in Table 4-8 and are similar those observed for Objective A.

TABLE 4-8.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE B YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	18.0%	17.9%	23.9%	23.3%
Objective B Year-Round	17.2%	15.9%	55.7%	61.7%

Sludge Production

From Table 4-2, average sludge produced per day for Objective B year-round is 951 ppd, which is 0.2 percent greater than for the existing plant and 1.2 percent greater than for Objective A. This increase in sludge production is the result of amending the carbon content of the wastewater with methanol to drive the denitrification process. It amounts to 0.37 tons of dry solids per year (0.0016 tons per million gallons of wastewater treated) more than the existing plant and 2.2 tons of sludge per year (0.0096 tons per million gallons of wastewater treated) more than Objective A year-round.

Energy Consumption

The average annual process air required for the upgrades to achieve Objective B year-round is 803 cubic feet per minute (cfm), which is 16 percent less than the existing system (961 cfm). As with Objective A, the overall energy required to achieve Objective B year-round exceeds the existing energy requirements for both MA and DA plants.

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective B year-round would increase the plant energy requirements by 294,000 kW-hours/year, or about 29 percent, as shown in Table 4-9. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 1,289 kW-hours per million gallons of influent wastewater treated.

TABLE 4-9.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective B Year-Round	1,292,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	294,000 kW-hours/year
Percent	29%
Increase per Volume of Plant Flow	1,289 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective B year-round would increase the plant energy requirements by 442,000 kW-hours/year, or about 52 percent, as shown in Table 4-10. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 1,938 kW-hours per million gallons of influent wastewater treated.

TABLE 4-10.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective B Year-Round	1,292,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	442,000 kW-hours/year
Percent	52%
Increase per Volume of Plant Flow	1,938 kW-hours/MG

Chemical Usage

Upgrades to achieve Objective B year-round would require methanol for carbon supplementation and magnesium hydroxide for pH and alkalinity control. The methanol requirement would be approximately 6,400 gallons of methanol per year, or 28 gallons of methanol per million gallons of wastewater treated. Requirements for magnesium hydroxide would be the same as described for Objective A.

Footprint Requirements

No additional tanks are required to convert an existing EA plant to achieve Objective B year-round, but the upgrade would require partitioning of existing aeration tanks. Since the amount of air required for Objective B is less than for the existing system, no additional blowers are required.

An existing MA plant would have to be converted to a DA plant. A new blower building with blowers and process air piping and air diffusion system would need to be installed in the aerobic compartment of the existing aeration tank. The existing ditch rotors would be removed and replaced with fine bubble diffusers.

Table 4-11 compares the additional footprint area required for implementation of Objective B year-round for the three plant capacities. For existing MA plants, additional area is required for the new blower building and the methanol storage and dosing system. For DA plants, additional area is only required for the methanol storage and dosing systems. Refer to Appendix C for a detail summary of the area requirement or existing and upgraded treatment systems. The percent changes in footprint are similar to those for Objective A system as no additional tanks are needed for Objective B.

TABLE 4-11.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING EXTENDED AERATION PLANTS TO ACHIEVE OBJECTIVE B

Plant Design Capacity (mgd)	Additional Area Required for MA Plants (square feet)	Additional Area Required for DA Plants (square feet)
1	1,400	600
10	2,500	1,000
100	6,000	3,300

4.2.3 Objective C

Process Description

Chemical phosphorus removal is achieved by adding chemicals such as alum, poly-aluminum chloride, or ferric chloride to the wastewater at a well-mixed location, followed by flocculation and solids removal. The effluent phosphorus concentration is determined by the dose and other chemical reactions. An effluent of 0.5 to 1 mg/L can typically be achieved without constructing post-secondary treatment facilities such as tertiary clarifiers or filters. The upgrade evaluated to achieve Objective C (TP <1 mg/L) consists of adding alum to precipitate phosphorus removal and magnesium hydroxide for pH control. Figure 4-6 represents the process flow schematic for Objective C. Table 4-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

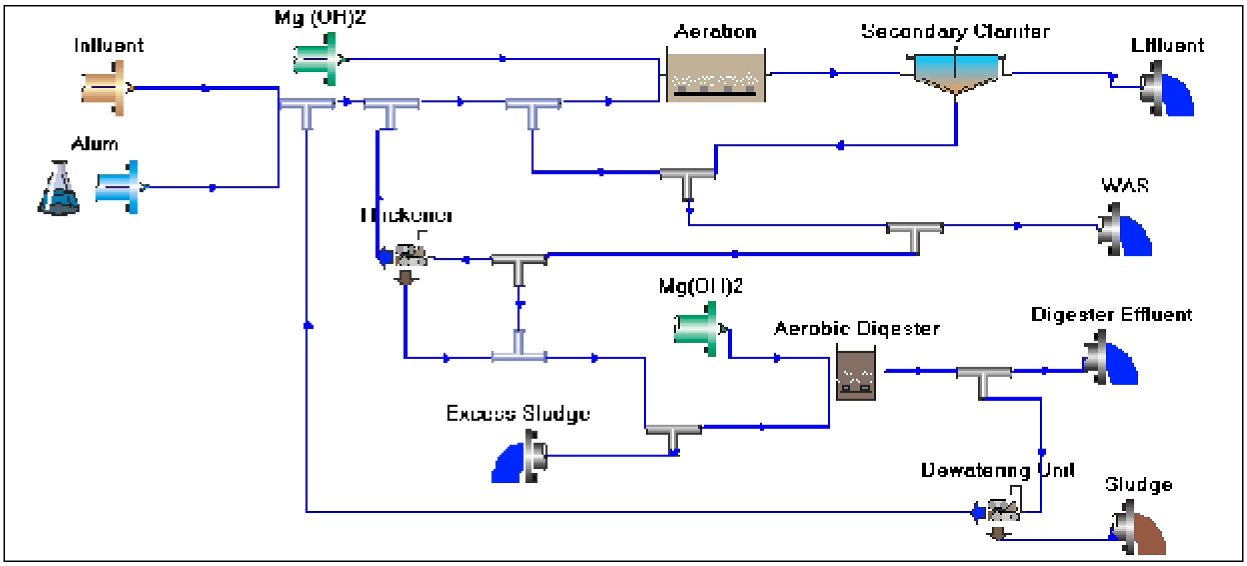


Figure 4-6. Process Schematic of Extended Aeration Plant Upgraded for Objective C Year-Round

Phosphorus is generally present in wastewater as organic and inorganic phosphates. Organic phosphate is bound to plant or animal tissues and is formed primarily by biological process. Inorganic phosphate is not associated with organic material and includes orthophosphate and polyphosphates. Orthophosphate (PO_4^{-3}) is also referred to as "reactive phosphorus" and is the most stable form of phosphate. Polyphosphates, also known as metaphosphates or condensed phosphates, are strong complexing agents for some metal ions. In wastewater, polyphosphates are unstable and eventually are converted to orthophosphate.

Metal salts frequently used for phosphorus removal include aluminum (Al(III)), ferric (Fe(III)) and calcium (Ca(II)). These metal salts can be added in existing treatment plants before a primary clarifier or other solids separation device. Use of these metal salts frequently increases the total dissolved solids content of the final effluent and the salinity of the sludge. Precipitation of phosphorus upstream or in conjunction with the biological treatment process can cause phosphorus to become a growth-limiting nutrient for the biological treatment process if the weight ratio of BOD_5 to phosphate-phosphorus exceeds 100 for SRTs less than 6 days and about 250 for SRTs greater than 12 days.

Aluminum present in alum can combine with phosphate ions to form aluminum phosphate. The reaction of alum with orthophosphate can be written as follows:

$$Al_2(SO_4)_3.14H_20 + 2PO_4^{-3} \rightarrow 2A1PO_4 + 3SO_4^{-2} + 14H_20$$

This reaction indicates that 1 lb-mole of alum (594 pounds) will react with 2 lb-moles (190 pounds) of $2PO_4^{-3}$ containing 62 pounds of phosphorus to form 2 lb-moles (244 pounds) of $AlPO_4$. The weight ratio of alum to phosphorus is therefore 9.58:1. Empirical results at several plants indicate that higher than stoichiometric quantities of alum are necessary to reduce phosphorus concentration below 1 mg/L. The ratios of alum (9.1-percent aluminum) to phosphorous listed in Table 4-12 were considered to be representative of chemical removal of phosphorus from municipal wastewater by alum addition (EPA 1976).

TABLE 4-12.
ALUM TO PHOSPHORUS RATIO FOR PHOSPHORUS REDUCTION

Required P Reduction	Mole Ratios (Aluminum to Phosphorus)	Alum-to-Phosphorus Weight Ratio
75%	1.38 : 1	13:1
85%	1.72 : 1	16:1
95%	2.31 : 1	22:1

These ratios were used to determine the required alum dosage based on the initial phosphate-phosphorus concentration of the wastewater. For example, to achieve 85-percent phosphorus removal from wastewater containing 11 mg/L of influent phosphorus, the alum dosage needed would be

11 * [Alum : P wt ratio (16:1 @ 85%)] = 176 mg/L or 1,470 lb/MG

Alum dosage required in gallons per day was calculated for all wet and dry weather flow conditions based on the concentration of soluble phosphate present in each reactor (i.e., aeration basin compartment) as determined from the Biowin model. Phosphorus reduction rates at different flow conditions were calculated using the aeration tank soluble phosphate as the influent value and a total phosphorus objective (1 mg/L) as the effluent value. The reduction rates ranged from 75 to 85 percent. In order to simplify the calculations, the following mole ratios were used:

- A mole ratio of 1.5 for 75 to 85 percent removal
- A mole ratio of 2.0 for 85 to 95 percent removal
- A mole ratio of 2.3 for >95 percent removal

Table 4-13 summarizes alum dosages at wet and dry weather flow conditions.

The calculated alum dosages were used in Biowin to determine the final effluent TP concentration. In most cases, the effluent TP concentration calculated by Biowin was less than 1 mg/L. Since the Al: P mole ratios were approximated, the Biowin dosages for some model runs varied slightly from the calculated dosages. Table 4-2 summarizes the alum dosage numbers used in the Biowin model at different flow conditions.

Addition of alum to wastewater lowers the pH of the wastewater due to neutralization of alkalinity and release of carbon dioxide. Dissolved aluminum in excess of the amount required to precipitate phosphorus is generally precipitated concurrently with aluminum hydroxide. The extent of pH reduction will depend on the initial alkalinity of the wastewater. The higher the alkalinity, the less is the reduction in pH for a given alum dosage. For this study, it is assumed that magnesium hydroxide would be used for supplemental alkalinity if needed to maintain the pH of the wastewater at or above.

TABLE 4-13.
REQUIRED ALUM DOSAGE FOR OBJECTIVE C PHOSPHORUS REDUCTION

Flow rate (a)	Soluble PO_4 in Aeration Tank (b)	Final Effluent Phosphorus (c)	Removal Rate (d)=((b-c)/b)	Mole Ratio (e)	Alum Dosage Required		
					In mg/L (f = b*d*e* 9.58)	In ppd (g = a* f* 8.34)	In gpd (= g/(11.14*0.48))
ADWF (0.5 mgd)	8.46 mg/L	1 mg/L	88.18%	2	142.9 mg/L	596 ppd	111.0 gpd
AWWF (0.75 mgd)	5.64 mg/L	1 mg/L	82.27%	1.5	66.7 mg/L	417 ppd	77.7 gpd
MMWWF (1.0 mgd)	4.2 mg/L	1 mg/L	76.19%	1.5	46.0 mg/L	384 ppd	71.4 gpd
MMDWF (0.69 mgd)	6.15 mg/L	1 mg/L	83.74%	1.5	74.0 mg/L	426 ppd	79.3 gpd

Note:

Alum is available as liquid hydrated alum solution that consists of 48.2% by weight alum. The density of liquid alum is 11.14 lbs/gallon.

Alum concentration (mg/L) = (0.482 * alum dosage gal/d * alum density lbs/gal)/(flow * 8.34)

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and then digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-14 summarizes the results. Chemical phosphorus removal nearly doubles the quantity of phosphorus recycled from solids processing operations, however this phosphorus recycle is associated with the increased phosphorus content of the solids and not due to an increase in phosphate.

TABLE 4-14.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE C YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	18.0%	17.9%	23.9%	23.3%
Objective C Year-Round	18.0%	17.9%	44.9%	46.8%

Sludge Production

Chemical phosphorus removal used to achieve Objective C on a year-round basis increases sludge production relative to the existing plant by 27 percent, or an additional 46 tons of dry solids per year (0.2 tons per million gallons treated). This increase is the result of the chemical precipitation of phosphorus as aluminum phosphate and aluminum hydroxide.

Energy Consumption

Biowin modeling results indicate the process air requirements for the upgraded plant to achieve Objective C year-round would be about 1 percent less than for the existing system; this is not considered significant for this level of analysis. The overall energy requirements would be slightly higher due to the operation of chemical dosing pumps and rapid mixing systems as well as extended operating time for solids thickening and dewatering systems.

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective C year-round would increase the plant energy requirements by 10,500 kW-hours/year, or about 1 percent, as shown in Table 4-15. More than 95 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective C. The annual energy consumption for the upgraded plant would increase by about 46 kW-hours per million gallons of influent wastewater treated.

TABLE 4-15.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective C Year-Round	1,009,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	10,500 kW-hours/year
Percent	1.1%
Increase per Volume of Plant Flow	46 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective C year-round would increase the plant energy requirements by 10,500 kW-hours/year, or about 1 percent, as shown in Table 4-16. More than 95 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective C. The annual energy consumption for the upgraded plant would increase by about 46 kW-hours per million gallons of influent wastewater treated.

TABLE 4-16.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective C Year-Round	861,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	10,500 kW-hours/year
Percent	1.2%
Increase per Volume of Plant Flow	46 kW-hours/MG

Chemical Usage

Existing MA plants that would be upgraded to achieve Objective C year-round would require approximately 188 gallons of alum and an additional 184 gallons of magnesium hydroxide per million gallons of influent wastewater treated.

Existing DA plants that would be upgraded to achieve Objective C year-round would require approximately 188 gallons of alum and an additional 72 gallons of magnesium hydroxide per million gallons of influent wastewater treated.

Footprint Requirements

New structures required for Objective C would be required for alum and magnesium hydroxide chemical storage tanks and feeding systems. These storage tanks would be sized to maintain at least two weeks of chemical storage based on the maximum chemical consumption rate. It is assumed that for smaller plants, 55-gallon drums or 250- to 400-gallon totes would be used. For larger plants, HDPE tanks or FRP tanks would be required.

Table 4-17 summarizes the approximate additional area required for constructing the alum and magnesium hydroxide storage tanks and feeding systems for the Objective C upgrade. The only change in footprint is the required area for chemical storage tanks. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems.

**TABLE 4-17.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING EXTENDED AERATION PLANTS TO ACHIEVE OBJECTIVE C**

Plant Design Capacity (mgd)	Additional Area Required for MA Plants (square feet)	Additional Area Required for DA Plants (square feet)
1	500	500
10	2,000	2,000
100	11,000	11,000

4.2.4 Objective D

Process Description

The upgrade evaluated to achieve Objective D (TP <0.1 mg/L) is to add tertiary filters after the secondary clarifier as shown Figure 4-7. Tertiary filtration polishes effluent phosphorus to achieve greater reliability and reduces phosphorus to lower limits. Table 4-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Gravity deep bed media filtration involves the removal of particulate material suspended in a liquid by passing the liquid through a filter bed made of a granular or compressible filter medium. Conventional and continuously backwashing up-flow filtration systems have proven effective in removing suspended solids from wastewater biological and chemical treatment process effluent to reduce the mass of solids in the effluent. Chemical precipitation followed by gravity clarification followed by single-stage filtration can reliably remove TP to less than 0.1 mg/L; two-stage filtration can reliably achieve TP concentrations of less than 0.05 mg/L.

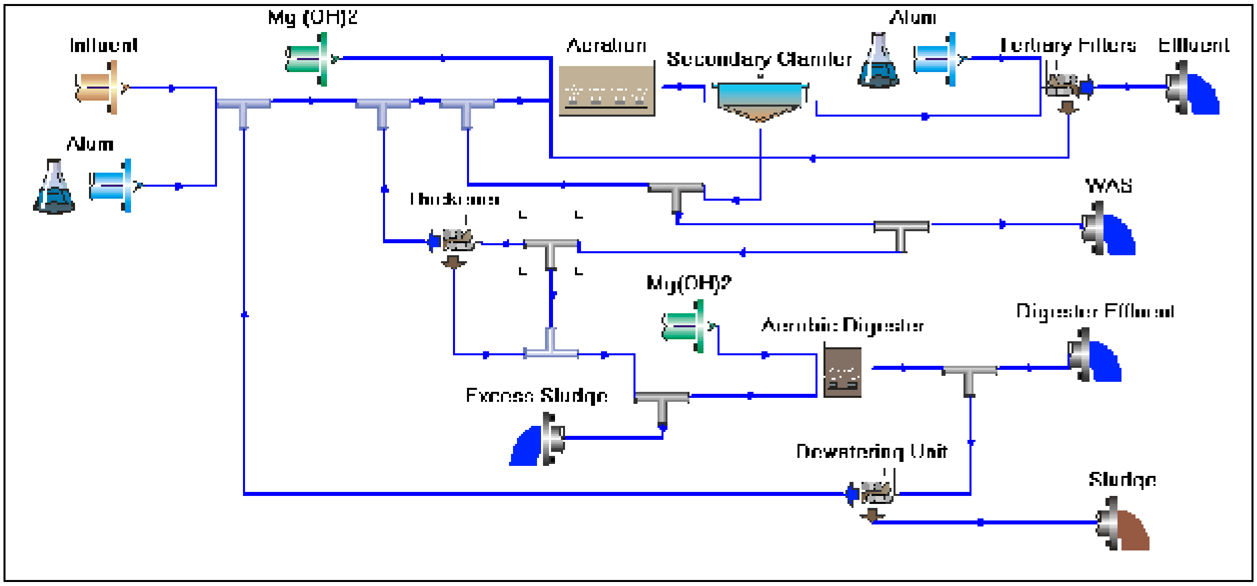


Figure 4-7. Process Schematic of Extended Aeration Plant Upgraded for Objective D Year-Round

To achieve Objective D, alum would be applied as described for Objective C and additionally to the clarified wastewater feed to the filters. Continuous backwash filters were modeled with the dirty backwash from the filters recycled to the head of the plant. Biowin results confirm that effluent total phosphorus concentration of less than 0.1 mg/L would be achieved. As discussed for Objective C, alum dosage requirements were initially computed stochiometrically and applied to the Biowin model. Table 4-18 summarizes the alum dosage requirements for Objective D. As described for Objective C, the mole ratio of aluminum to phosphorus for a removal rate greater than 95 percent is 2.3; the Biowin results indicate that a stoichiometric ratio of 2.3 is not adequate to achieve 98-percent or greater removal. Table 4-2 summarizes the alum dosages applied to the Biowin model at different flow conditions.

TABLE 4-18.
REQUIRED ALUM DOSAGE FOR OBJECTIVE D PHOSPHORUS REDUCTION

Flow rate (a)	Soluble PO_4 in Aeration Tank (b)	Final Effluent Phosphorus (c)	Removal Rate (d)=((b-c)/b)	Mole Ratio (d)	Alum Dosage Required: In mg/L (f = b*d*e* 9.58)	Alum Dosage Required: In ppd (g = a*f*8.34)	Alum Dosage Required: In gpd (=g/(11.14*0.482))
ADWF (0.5 mgd)	8.46 mg/L	0.1 mg/L	98.82%	2.3	184.2 mg/L	768 ppd	143.1 gpd
AWWF (0.75 mgd)	5.64 mg/L	0.1 mg/L	98.23%	2.3	122.1 mg/L	764 ppd	142.2 gpd
MMWWF (1.0 mgd)	4.2 mg/L	0.1 mg/L	97.62%	2.3	90.3 mg/L	753 ppd	140.3 gpd
MMDWF (0.69 mgd)	6.15 mg/L	0.1 mg/L	98.37%	2.3	133.3 mg/L	767 ppd	142.9 gpd

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-19 summarizes the results.

**TABLE 4-19.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS,
OBJECTIVE D YEAR-ROUND NUTRIENT REMOVAL**

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	18.0%	17.9%	23.9%	23.3%
Objective D Year-Round	18.2%	18.3%	49.0%	36.8%

Sludge Production

Chemical phosphorus removal used to achieve Objective D year-round will increase the mass of sludge produced by 32 percent on an annual basis, adding 56 tons of dry solids per year (0.25 tons per million gallons of wastewater treated). This increase in sludge is the result of the chemical precipitation of phosphorus as aluminum phosphate and aluminum hydroxide.

Energy Consumption

Biowin modeling results indicate the process air requirements for the upgraded plant to achieve Objective D year-round would be about 1 percent less than the existing system; this is not considered significant for this level of analysis. The overall energy requirements would be higher than for Objective C due to the extended operation of chemical (alum and magnesium hydroxide) dosing pumps, rapid mixing systems, filtration system, as well as extended operating time for solids thickening and dewatering systems.

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective D year-round would increase the plant energy requirements by 36,500 kW-hours/year, or about 4 percent, as shown in Table 4-20. About 80 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective D, with the remainder mostly attributable to the operation of the filters. The annual energy consumption for the upgraded plant would increase by about 160 kW-hours per million gallons of influent wastewater treated.

**TABLE 4-20.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND**

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective D Year-Round	1,035,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	36,500 kW-hours/year
Percent	4%
Increase per Volume of Plant Flow	160 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective D year-round would increase the plant energy requirements by 42,500 kW-hours/year, or about 5 percent, as shown in Table 4-21. About 80 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective D, with the remainder mostly attributable to the operation of the filters. The annual energy consumption for the upgraded plant would increase by about 184 kW-hours per million gallons of influent wastewater treated.

TABLE 4-21.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective D Year-Round	892,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	42,500 kW-hours/year
Percent	5%
Increase per Volume of Plant Flow	184 kW-hours/MG

Chemical Usage

Existing MA plants upgraded to achieve Objective D year-round would require approximately 260 gallons of alum per million gallons treated and an additional 256 gallons of magnesium hydroxide per million gallons treated.

Existing DA plants upgraded to achieve Objective D year-round would require approximately 260 gallons of alum per million gallons treated and an additional 144 gallons of magnesium hydroxide per million gallons treated.

Footprint Requirements

New structures required for Objective D are the filters and the alum and magnesium hydroxide storage tanks and dosing facilities, similar to those identified for Objective C. Appendix B provides detailed storage tank calculations and dosing system requirements.

Table 4-22 summarizes the additional footprint requirements to achieve Objective D relative to the existing system. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems.

**TABLE 4-22.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING EXTENDED AERATION PLANTS TO ACHIEVE OBJECTIVE D**

Plant Design Capacity (mgd)	Additional Area Required for MA Plants (square feet)	Additional Area Required for DA Plants (square feet)
1	1,400	1,400
10	11,000	11,000
100	97,000	97,000

4.2.5 Objective E

Process Description

Objective E (TIN <8 mg/L and TP <1 mg/L) can be achieved by converting the existing extended aeration system to the MLE process as described for Objective A and by adding alum to the influent for phosphorus removal as described for Objective C. Alum dosages were calculated for soluble PO_4 concentrations in the aeration tank based on the Objective A model. These alum dosages were then entered into the Biowin model to achieve effluent TP <1 mg/L. Assumptions made for Objectives A and C were also used for this objective. Table 4-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-23 summarizes the results.

**TABLE 4-23.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE E YEAR-ROUND NUTRIENT REMOVAL**

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	18.0%	17.9%	23.9%	23.3%
Objective E Year-Round	18.0%	15.2%	35.9%	50.4%

Sludge Production

Chemical phosphorus removal used to achieve Objective E year-round will increase the mass of sludge produced by 24 percent on an annual basis, adding 41.7 tons of dry solids per year (0.18 tons per million gallons treated). This increase in sludge production is the result of chemical precipitation of phosphorus as aluminum phosphate and aluminum hydroxide.

Energy Consumption

Biowin modeling results indicate the process air requirements for the upgraded plant to achieve Objective E year-round would be about 18 percent less than the existing system. The overall energy requirements would be higher due to the operation of anoxic basin mixing systems, internal mixed liquor recycle pumps, chemical (methanol, alum and magnesium hydroxide) dosing pumps, and rapid mixing systems, as well as extended operating time for solids thickening and dewatering systems.

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective E year-round would increase the plant energy requirements by 23,500 kW-hours/year, or about 2 percent, as shown in Table 4-24. About 50 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective E, with the remainder mostly attributable to the operation of the liquid process. The annual energy consumption for the upgraded plant would increase by about 103 kW-hours per million gallons of influent wastewater treated. This energy increase is significantly lower than required to upgrade a DA plant for Objective E year-round, because of the energy savings achieved by converting the MA system to a DA system.

TABLE 4-24.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective E Year-Round	1,022,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	23,500 kW-hours/year
Percent	2%
Increase per Volume of Plant Flow	103 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective E year-round would increase the plant energy requirements by 171,500 kW-hours/year, or about 20 percent, as shown in Table 4-25. About 6.5 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective E, with the remainder mostly attributable to the operation of the liquid process. The annual energy consumption for the upgraded plant would increase by about 752 kW-hours per million gallons of influent wastewater treated.

Chemical Usage

Alum and magnesium hydroxide would be required to reduce total phosphorus to <1.0 mg/L and to maintain adequate alkalinity and pH for nitrification.

An MA plant upgraded to achieve Objective E year-round would require approximately 188 gallons of alum per million gallons treated and an additional 80 gallons of magnesium hydroxide per million gallons treated.

TABLE 4-25.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective E Year-Round	1,022,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	171,500 kW-hours/year
Percent	20%
Increase per Volume of Plant Flow	752 kW-hours/MG

A DA plant upgraded to achieve Objective E year-round would require approximately 188 gallons of alum per million gallons treated and 32 gallons less magnesium hydroxide per million gallons treated than required for the existing plant.

Footprint Requirements

New structures required for Objective E are alum and magnesium hydroxide storage tanks and dosing systems, which would require use of additional area as indicated for Objective C and as shown in Table 4-26.

TABLE 4-26.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING EXTENDED AERATION PLANTS TO ACHIEVE OBJECTIVE E

Plant Design Capacity (mgd)	Additional Area Required for MA Plants (square feet)	Additional Area Required for DA Plants (square feet)
1	1,700	900
10	3,600	2,100
100	12,700	10,000

4.2.6 Objective F

Process Description

Objective F (TIN <3 mg/L and TP <0.1 mg/L) can be achieved by converting the existing extended aeration system into a four-stage Bardenpho (4BDP) process as described for Objective B and by installing tertiary filters and alum addition as discussed in Objective D. Alum dosages were calculated for soluble PO_4 concentrations in the aeration tank based on the Objective B model. These alum dosages were then entered into the Biowin model to achieve effluent TP <0.1 mg/L. Assumptions made for Objectives B and D were also used for this objective. Table 4-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-27 summarizes the results.

TABLE 4-27.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE F YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	18.0%	17.9%	23.9%	23.3%
Objective F Year-Round	16.5%	15.3%	36.5%	36.6%

Sludge Production

Chemical phosphorus removal used to achieve Objective F year-round will increase the mass of sludge produced by 30 percent on an annual basis, adding 53 tons of dry solids per year (0.23 tons per million gallons treated). This increase in sludge is the result of the chemical precipitation of phosphorus as aluminum phosphate and aluminum hydroxide.

Energy Consumption

Biowin modeling results indicate the process air requirements for the upgraded plant to achieve Objective F year-round would be about 14 percent less than the existing system. However, overall energy consumption would be significantly greater than for the existing plant, due to the operation of anoxic basin mixing systems, internal mixed liquor recycle pumps, chemical (methanol, alum and magnesium hydroxide) dosing pumps, rapid mixing and filtration systems, as well as extended operating time for solids thickening and dewatering systems.

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective F year-round would increase the plant energy requirements by 319,000 kW-hours/year, or about 32 percent, as shown in Table 4-28. About 5.6 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective F, with the remainder attributable to the operation of the liquid process. The annual energy consumption for the upgraded plant would increase by about 1,319 kW-hours per million gallons of influent wastewater treated.

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective F year-round would increase the plant energy requirements by 467,000 kW-hours/year, or about 55 percent, as shown in Table 4-29. About 3.8 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective F, with the remainder attributable to the operation of the liquid process. The annual energy consumption for the upgraded plant would increase by about 2,047 kW-hours per million gallons of influent wastewater treated.

TABLE 4-28.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective F Year-Round	1,317,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	319,000 kW-hours/year
Percent	32%
Increase per Volume of Plant Flow	1,319 kW-hours/MG

TABLE 4-29.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective F Year-Round	1,317,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	467,000 kW-hours/year
Percent	55%
Increase per Volume of Plant Flow	2,047 kW-hours/MG

Chemical Usage

Three new chemical storage and dosing systems would be required to achieve Objective F year-round. Alum and magnesium hydroxide would be required to reduce total phosphorus to <1.0 mg/L and to maintain adequate alkalinity and pH for nitrification. Methanol or an equivalent carbon source would be required to drive the denitrification process as described for Objective B.

For upgraded MA plants to achieve Objective F year-round would require approximately 256 gallons of alum, an additional 136 gallons of magnesium hydroxide, and 32 gallons methanol per million gallons treated.

For upgraded DA plants to achieve Objective F year-round would require approximately 256 gallons of alum, an additional 24 gallons of magnesium hydroxide, and 32 gallons methanol per million gallons treated.

Footprint Requirements

New structures required for Objective F are alum, magnesium hydroxide and methanol storage tanks. These tanks were sized as described for Objectives B and D, with the following sizes estimated for a 1-mgd plant (Appendix B provides detailed storage tank calculations for other plant capacities):

- Two alum storage tanks are required, each 8 feet deep and 5.2 feet in diameter.
- Two magnesium hydroxide storage tanks are required, each 8 feet deep and 4.5 feet in diameter.

- A 3-foot-deep, 120-square-foot containment tank is required for the alum storage tank.
- A 2.6-foot-deep, 95-square-foot containment tank is required for the magnesium hydroxide storage tank.
- One horizontal methanol tank is required, 4 feet in diameter and 5.1 feet long.
- A 45-square-foot containment tank is required to contain the methanol tank.

Table 4-30 summarizes the footprint requirements between the existing system and Objective F upgrade. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems.

**TABLE 4-30.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING EXTENDED AERATION PLANTS TO ACHIEVE OBJECTIVE F**

Plant Design Capacity (mgd)	Additional Area Required for MA Plants (square feet)	Additional Area Required for DA Plants (square feet)
1	2,700	1,900
10	13,500	12,000
100	98,000	98,000

4.3 SEASONAL NUTRIENT REMOVAL

Improvements required to provide seasonal nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 4-31, which is attached at the end of this chapter.

4.3.1 Objective A

Process Description

The Objective A (TIN <8 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs would be based on ADWF instead of AWWF. No additional aeration tanks or oxygen transfer systems are required for nutrient removal. Chemical storage tanks would be designed based on maximum usage of chemical during either MMDWF or ADWF. Refer to Section 4.2.1 for detailed process description and flow schematics. Process design data are included in Table 4-31.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-32 summarizes the results.

**TABLE 4-32.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE A SEASONAL NUTRIENT REMOVAL**

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	17.9%	23.3%
Objective A Seasonal	15.5%	64.1%

Sludge Production

From Table 4-31, average sludge produced per day is 949 pounds per day (ppd) for the existing extended aeration system and 943 ppd for seasonal treatment under Objective A. This increase in sludge production associated with achieving Objective A is not significant; there should be no significant change in the overall mass of sludge produced.

Energy Consumption

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective A seasonally would reduce the plant energy requirements by 60,000 kW-hours/year, or about 6.4 percent, as shown in Table 4-33. There would be no change in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would decrease by about 263 kW-hours per million gallons of influent wastewater treated. This energy savings is attributable to the upgrade in the aeration process from MA to DA.

**TABLE 4-33.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE A SEASONALLY**

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective A, Seasonal	938,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(60,000) kW-hours/year
Percent	(6.4%)
Increase per Volume of Plant Flow	(263) kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective A seasonally would increase the plant energy requirements by 88,000 kW-hours/year, or about 10.3 percent, as shown in Table 4-34. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 386 kW-hours per million gallons of influent wastewater treated. There would be no change in the energy requirements for solids processes. On an annual basis, seasonal operation requires approximately 55 percent of the increased energy required to achieve Objective A year-round.

**TABLE 4-34.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE A SEASONALLY**

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective A, Seasonal	938,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	88,000 kW-hours/year
Percent	10.3%
Increase per Volume of Plant Flow	386 kW-hours/MG

Chemical Usage

If an existing MA plant is operated to achieve Objective A during dry weather and to maintain existing plant performance during the wet season, then the annual quantity of magnesium hydroxide required to control alkalinity would increase 150% relative to the existing annual usage; this equates to an incremental increase of 48 gallons of magnesium hydroxide per million gallons of wastewater treated annually.

If an existing DA plant is operated to achieve Objective A during dry weather and to maintain existing plant performance during the wet season, then the annual quantity of magnesium hydroxide required to control alkalinity would be reduced approximately 65% relative to the existing annual usage; this equates to an incremental decrease of 64 gallons of magnesium hydroxide per million gallons of wastewater treated annually.

Footprint Requirements

Space requirements to accommodate new process equipment needed to achieve Objective E on a seasonal basis would be the same as described for achieving this objective year-round, as indicated in Table 4-6.

4.3.2 Objective B

Process Description

The Objective B (TIN <3 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs would be based on ADWF instead of AWWF. No additional aeration tanks are required for nutrient removal. Chemical storage tanks would be designed based on maximum usage of chemical during either MMDWF or ADWF. Refer to Section 4.2.2 for detailed process description and flow schematics. Process design data are included in Table 4-31.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-35 summarizes the results.

**TABLE 4-35.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS,
OBJECTIVE B SEASONAL NUTRIENT REMOVAL**

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	17.9%	23.3%
Objective B Seasonal	15.9%	61.7%

Sludge Production

From Table 4-31, average sludge produced per day for Objective B seasonal nutrient removal is 953 ppd, which is 0.3 percent higher than for the existing plant. This increase in sludge is the result of the addition of methanol to the post-anoxic tank for denitrification. If Objective B is achieved only during dry weather, then the annual sludge production would increase 0.32 percent on an annual basis, adding 0.55 tons of dry solids per year (0.0024 tons per million gallons of wastewater treated).

Energy Consumption

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective B seasonally would increase the plant energy requirements by 44,000 kW-hours/year, or about 4 percent, as shown in Table 4-36. There would be no change in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 193 kW-hours per million gallons of influent wastewater treated. On an annual basis, seasonal operation requires approximately 15 percent of the increased energy required to achieve Objective B year-round.

**TABLE 4-36.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE B SEASONALLY**

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective B, Seasonal	1,042,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	44,000 kW-hours/year
Percent	4%
Increase per Volume of Plant Flow	193 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective B seasonally would increase the plant energy requirements by 192,000 kW-hours/year, or about 23 percent, as shown in Table 4-37. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 835 kW-hours per million gallons of influent wastewater treated. There would be no change in the energy requirements for solids processes. On an annual basis, seasonal operation requires approximately 43 percent of the increased energy required to achieve Objective B year-round.

TABLE 4-37.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective B, Seasonal	1,042,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	192,000 kW-hours/year
Percent	23%
Increase per Volume of Plant Flow	835 kW-hours/MG

Chemical Usage

To achieve Objective B nutrient removal on a seasonal basis, the annual methanol requirement would be approximately 3,650 gallons or 16 gallons of methanol per million gallons of wastewater treated. Use of magnesium hydroxide for pH and alkalinity control would be the same as for Objective A seasonal nutrient removal.

Footprint Requirements

Space requirements to accommodate new process equipment needed to achieve Objective B on a seasonal basis would be the same as described for achieving this objective year-round as indicated in Table 4-11.

4.3.3 Objective C

Process Description

The Objective C (TP <1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs would be based on ADWF instead of AWWF. No additional aeration tanks are required for nutrient removal. Chemical storage tanks would be designed based on maximum usage of chemical during either MMDWF or ADWF. Refer to Section 4.2.3 for detailed process description and flow schematics. Process design data are included in Table 4-31.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-38 summarizes the results.

TABLE 4-38.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE C SEASONAL NUTRIENT REMOVAL

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	17.9%	23.3%
Objective C Seasonal	17.9%	46.8%

Sludge Production

From Table 4-31, if Objective C is achieved only during dry weather, then sludge production would increase 13.8 percent on an annual basis, adding 24 tons of dry solids per year, or 0.11 tons per million gallons of wastewater treated.

Energy Consumption

MA Plant

Upgrading the MA plant to achieve Objective C seasonally would increase the plant energy requirements by 1,000 kW-hours/year, or about 0.1 percent, as shown in Table 4-39. Approximately 50 percent of this increase would be attributable to the additional operation of the solids processes associated with achieving Objective C. The annual energy consumption for the upgraded plant would increase by about 4 kW-hours per million gallons of influent wastewater treated. On an annual basis, seasonal operation requires approximately 9 percent of the increased energy required to achieve Objective C year-round.

TABLE 4-39.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective C, Seasonal	999,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	1,000 kW-hours/year
Percent	0.1%
Increase per Volume of Plant Flow	4 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective C seasonally would increase the plant energy requirements by 3,000 kW-hours/year, or about 0.3 percent, as shown in Table 4-40. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 13 kW-hours per million gallons of influent wastewater treated. Approximately 17 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective C. On an annual basis, seasonal operation requires approximately 28 percent of the increased energy required to achieve Objective C year-round.

Chemical Usage

To achieve Objective C nutrient removal on a seasonal basis, upgraded MA plants would require approximately 100 gallons of alum and an additional 64 gallons of magnesium hydroxide per million gallons treated. Upgraded DA plants would require approximately 100 gallons of alum and reduce the usage magnesium hydroxide approximately 48 gallons of magnesium hydroxide per million gallons treated.

Footprint Requirements

Space requirements to accommodate new process equipment needed to achieve Objective C on a seasonal basis would be the same as described for achieving this objective on a year-round basis as indicated in Table 4-17.

**TABLE 4-40.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE C SEASONALLY**

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective C, Seasonal	853,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	3,000 kW-hours/year
Percent	0.3%
Increase per Volume of Plant Flow	13 kW-hours/MG

4.3.4 Objective D

Process Description

The Objective D (TP <0.1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs would be based on ADWF instead of AWWF. No additional aeration tanks are required for nutrient removal. Refer to Section 4.2.4 for detailed process description and flow schematics. Process design data are included in Table 4-31.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-41 summarizes the results.

**TABLE 4-41.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE D SEASONAL NUTRIENT REMOVAL**

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	17.9%	23.3%
Objective D Seasonal	18.3%	36.8%

Sludge Production

If Objective D is achieved only during dry weather, then annual sludge production would increase 16 percent, adding 28.4 tons of dry solids per year, or 0.12 tons per million gallons of wastewater treated.

Energy Consumption

MA Plant

Upgrading the MA plant to achieve Objective D seasonally would increase the plant energy requirements by 16,500 kW-hours/year, or about 2 percent, as shown in Table 4-42. This is more than 16 times the energy increase required for Objective C seasonal nutrient removal. Approximately 90 percent of this increase would be attributable to the additional operation of the solids processes associated with achieving

Objective D. The annual energy consumption for the upgraded plant would increase by about 72 kW-hours per million gallons of influent wastewater treated. On an annual basis, seasonal operation requires approximately 45 percent of the increased energy required to achieve Objective D year-round.

TABLE 4-42.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective D, Seasonal	1,015,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	16,500 kW-hours/year
Percent	2%
Increase per Volume of Plant Flow	72 kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective D seasonally would increase the plant energy requirements by 19,500 kW-hours/year, or about 2 percent, as shown in Table 4-43. There would be no increase in the energy requirements for solids processes. The annual energy consumption for the upgraded plant would increase by about 85 kW-hours per million gallons of influent wastewater treated. Approximately 45 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective D. On an annual basis, seasonal operation requires approximately 46 percent of the increased energy required to achieve Objective D year-round.

TABLE 4-43.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective D, Seasonal	870,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	19,500 kW-hours/year
Percent	2%
Increase per Volume of Plant Flow	85 kW-hours/MG

Chemical Usage

To achieve Objective D on a seasonal basis, upgraded MA plants would require 132 gallons of alum and an additional 144 gallons of magnesium hydroxide per million gallons treated. Upgraded DA plants would require 132 gallons of alum and an additional 32 gallons of magnesium hydroxide per million gallons treated.

Footprint Requirements

Space requirements to accommodate new process equipment required to achieve Objective D on a seasonal basis would be the same as described for achieving this objective on a year-round basis as indicated in Table 4-22.

4.3.5 Objective E

Process Description

The Objective E (TIN <8 mg/L and TP <1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs would be based on ADWF instead of AWWF. No additional aeration tanks are required for nutrient removal. Refer to Section 4.2.5 for detailed process description and flow schematics. Process design data are included in Table 4-31.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-44 summarizes the results.

TABLE 4-44.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE E SEASONAL NUTRIENT REMOVAL

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	17.9%	23.3%
Objective E Seasonal	15.2%	50.4%

Sludge Production

If Objective E is achieved only during dry weather, then sludge production would increase 13 percent on an annual basis, adding 21.7 tons of dry solids per year, or 0.12 tons per million gallons treated.

Energy Consumption

MA Plant

Upgrading the MA plant secondary treatment process to achieve Objective E seasonally would reduce the plant energy requirements by 58,500 kW-hours/year, or about 6 percent, as shown in Table 4-45. Total annual energy requirement would be about 8 percent less than required to achieve Objective E year-round. The energy required for the solids processing would be slightly greater (< 1 percent) than for the existing plant. Total annual energy consumption for the upgraded plant would decrease by 256 kW-hours per million gallons of influent wastewater treated.

TABLE 4-45.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective E, Seasonal	940,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(58,500) kW-hours/year
Percent	(6%)
Increase per Volume of Plant Flow	(256) kW-hours/MG

DA Plant

Upgrading the DA plant secondary treatment process to achieve Objective E seasonally would increase the plant energy requirements by 89,500 kW-hours/year, or about 11 percent, as shown in Table 4-46. Less than 1 percent of the increase energy demand would be attributable to the increased operation of the solids processes associated with achieving Objective E. The annual energy consumption for the upgraded plant would increase by about 392 kW-hours per million gallons of influent wastewater treated. Approximately 17 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective E. On an annual basis, seasonal operation requires approximately 52 percent of the increased energy required to achieve Objective E year-round.

TABLE 4-46.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective E, Seasonal	940,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	89,500 kW-hours/year
Percent	11%
Increase per Volume of Plant Flow	392 kW-hours/MG

Chemical Usage

To achieve Objective E on a seasonal basis, upgraded MA plants would require 100 gallons of alum and an additional 96 gallons of magnesium hydroxide per million gallons treated. Upgraded DA plants would require 100 gallons of alum per million gallons treated and 16 gallons less of magnesium hydroxide per million gallons treated than the existing plant.

Footprint Requirements

Space requirements to accommodate new process equipment required to achieve Objective E on a seasonal basis would be the same as described for achieving this objective on a year-round basis as indicated in Table 4-26.

4.3.6 Objective F

Process Description

The Objective F (TIN <3 mg/L and TP <0.1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. No additional aeration tanks are required for nutrient removal. Chemical storage tanks would be designed based on maximum usage of chemical during either MMDWF or ADWF. Refer to Section 4.2.6 for detailed process description and flow schematics. Process design data are included in Table 4-31.

Recycled Loads

Sludge wasted from the secondary clarifier will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 4-47 summarizes the results.

TABLE 4-47.
NUTRIENT RECYCLING COMPARISON FOR EXTENDED AERATION SYSTEMS, OBJECTIVE F SEASONAL NUTRIENT REMOVAL

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	17.9%	23.3%
Objective F Seasonal	15.3%	36.6%

Sludge Production

Chemical phosphorus removal to achieve Objective F seasonally will increase the sludge produced by 18 percent annually, adding 32.3 tons of dry solids per year (0.14 tons per million gallons treated).

Energy Consumption

MA Plant

Upgrading the MA plant to achieve Objective F seasonally would increase the plant energy requirements by 46,500 kW-hours/year, or about 5 percent, as shown in Table 4-48. Less than 1 percent of this increase would be attributable to the additional operation of the solids processes associated with achieving Objective F. The annual energy consumption for the upgraded plant would increase by about 204 kW-hours per million gallons of influent wastewater treated. On an annual basis, seasonal operation requires approximately 15 percent of the increased energy required to achieve Objective F year-round.

DA Plant

Upgrading the DA plant to achieve Objective F seasonally would increase the plant energy requirements by 194,500 kW-hours/year, or about 23 percent, as shown in Table 4-49. Less than 1 percent of the increase energy demand would be attributable to the increased operation of the solids processes associated with achieving Objective F. The annual energy consumption for the upgraded plant would increase by about 853 kW-hours per million gallons of influent wastewater treated. Approximately 45 percent of this increase would be attributable to the operation of the solids processes associated with achieving Objective F. On an annual basis, seasonal operation requires approximately 42 percent of the increased energy required to achieve Objective F year-round.

TABLE 4-48.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MA PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing MA Plant	998,500 kW-hours/year
Objective F, Seasonal	1,045,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	46,500 kW-hours/year
Percent	5%
Increase per Volume of Plant Flow	204 kW-hours/MG

TABLE 4-49.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING DA PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing DA Plant	850,500 kW-hours/year
Objective F, Seasonal	1,045,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	194,500 kW-hours/year
Percent	23%
Increase per Volume of Plant Flow	853 kW-hours/MG

Chemical Usage

To achieve Objective F on a seasonal basis, upgraded MA plants would require 128 gallons of alum, an additional 120 gallons of magnesium hydroxide, and 16 gallons of methanol per million gallons treated. Upgraded DA plants would require 128 gallons of alum, an additional 8 gallons of magnesium hydroxide, and 16 gallons of methanol per million gallons treated.

Footprint Requirements

Space requirements to accommodate new process equipment required to achieve Objective F on a seasonal basis would be the same as described for achieving this objective on a year-round basis as indicated in Table 4-30.

TABLE 4-2
EXTENDED AERATION PLANT BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

	PROCESS DESIGN - MMWW FLOWS								WET SEASON - AWW FLOWS								DRY SEASON - ADW FLOWS							
	Existing Plant		Upgraded Plant						Existing Plant		Upgraded Plant						Existing Plant		Upgraded Plant					
Description	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals																								
TIN (mg/L)			< 8	< 3			< 8	< 3			< 8	< 3			< 8	< 3			< 8	< 3			< 8	< 3
TP (mg/L)					< 1	< 0.1	< 1	< 0.1					< 1	< 0.1	< 1	< 0.1					< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature																								
Influent Flow, mgd	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.5	0.50	0.50	0.50	0.50
Temp, ^{o}C	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15	15	15	15	15
Influent Loads																								
BOD	165	165	165	165	165	165	165	165	221	221	221	221	221	221	221	221	331	331	331	331	331	331	331	331
TSS	188	188	188	188	188	188	188	188	251	251	251	251	251	251	251	251	376	376	376	376	376	376	376	376
VSS	132	132	132	132	132	132	132	132	176	176	176	176	176	176	176	176	263	263	263	263	263	263	263	263
TKN	24	24	24	24	24	24	24	24	32	32	32	32	32	32	32	32	48	48	48	48	48	48	48	48
TP	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Alkalinity	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.68	2.68	2.68	2.68	2.68	2.68	2.68	2.68	4	4	4	4	4	4	4	4
pH	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	7	7	7	7	7	7	7	7
Oxidation Ditch / Aeration Tank																								
Tank Volume, MG	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50
HRT, hrs	24	24	16.8	12	24	24	16.8	12	32	32	22.4	16	32	32	22.4	16	48	48	33.6	24	48	48	33.6	24
MLSS Conc., mg/L	2,809	2,807	2,812	2,944	3,378	3,459	3,255	3,298	2,909	2,909	2,958	3,054	3,576	3,697	3,437	3,642	2,943	2,943	3,062	3,134	3,634	3,597	3,588	3,558
DO Concentration, mg/L	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Ditch Power Uptake, HP	80								81								96							
Aeration Tank Airflow rate, cfm		904	756	651	906	899	771	639		936	751	651	916	920	771	657		986	781	716	986	980	807	722
BioWin SRT, days	18.01	18.01	18.02	18.1	18	17.14	18	17.2	18.26	18.26	18.28	18.38	18.25	18.25	18.27	18.32	18.78	18.78	18.79	18.91	18.77	18.06	18.79	18.18
RAS Recyle Rate	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q
Pre - Anoxic Tank																								
Tank Volume, MG			0.30	0.20			0.30	0.20			0.30	0.20			0.30	0.20			0.30	0.20			0.30	0.20
HRT, hrs			7.2	4.8			7.2	4.8			9.6	6.4			9.6	6.4			14.4	9.6			14.4	9.6
Internal Recycle Rate			6Q	6Q			6Q	6Q			6Q	6Q			6Q	6Q			`	6Q			6Q	6Q
Post - Anoxic Tank																								
Tank Volume, MG				0.20				0.20				0.20				0.20				0.20				0.20
HRT, hrs				4.8				4.8				6.4				6.4				9.6				9.6
Aerobic Tank																								
Tank Volume, MG				0.10				0.10				0.10				0.10				0.10				0.10
HRT, hrs				2.4				2.4				3.2				3.2				4.8				4.8
Air Supply Rate, cfm				128				156				125				146				115				130
Clarifier																								
Area, SF	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
Surface Overflow Rate, gal/ft^2	286	286	286	286	286	286	286	286	214	214	214	214	214	214	214	142	142	142	142	142	142	142	142	142
Tertiary Filters																								
Filter Area (ft2) (from Capdet)						551		551						551		551						551		551
Chemical Addition																								
Methanol, gpd				20				20				15				20				20				20
Alum Dosage, gpd					110	160	80	125					110	160	110	160					125	165	125	160
Magnesium Hydroxide Dosage, gpd	25	120	40	40	150	200	80	120		100	20	20	150	200	80	120	40	80	NR	NR	120	160	60	90
Magnesium Hydroxide Conc., meq/L	14,500	14,500	14,500	14,500	14,500	14,500	14,500	14,500		14,500	14,500	14,500	14,500	14,500	14,500	14,500	14,500	14,500			14,500	14,500	14,500	14,500

TABLE 4-2
EXTENDED AERATION PLANT BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

	PROCESS DESIGN - MMWW FLOWS							
	Existing Plant		Upgraded Plant					
Description	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Aerobic Digester								
Solids % from Clarifier	0.8%	0.8%	0.8%	0.9%	1.0%	1.0%	1.0%	1.0%
Solids % from Thickener	5.0%	5.0%	5.0%	5.2%	6.0%	6.0%	5.8%	5.9%
Combined Solids % to Aerobic Digester	3.5%	3.5%	3.5%	3.6%	4.2%	4.3%	4.1%	4.1%
VSS loading to Digester, ppd	730	730	710	745	732	753	712	741
TSS loading to Digester, ppd	1,301	1,301	1,303	1,354	1,565	1,684	1,508	1,605
Volume, MG	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Hydraulic Residence Time, hrs	1352	1352	1352	1352	1352	1288	1352	1352
Digester Sludge Age, days	56.33	56.33	56.33	56.33	56.33	53.67	56.33	56.33
Total Sludge Age, days	74.34	74.34	74.35	74.43	74.33	70.81	74.33	73.53
Digester Airflow rate cfm	139	139	140	150	139	139	139	154
VSS destruction %	27.21%	27.21%	28.25%	28.97%	27.14%	27.40%	28.20%	29.19%
SOUR, mg/L of O_2/hr/g TSS (< = 1.5)	0.256	0.256	0.262	0.271	0.206	0.208	0.218	0.229
Magnesium Hydroxide addition, gal/day	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Sludge Production								
Dry Sludge Production, ppd	923	923	906	928	1148	1241	1088	1179
Effluent								
BOD, mg/L	1.85	1.85	1.8	1.7	1.73	1.37	1.71	1.86
TSS, mg/L	4.5	4.5	4.5	4.6	4.6	3.4	4.6	3.0
Phosphorous, mg/L	4.27	4.27	4.11	3.88	0.8	0.05	0.82	0.05
Ammonia N, mg/L	0.63	0.61	1.03	1.07	0.62	0.72	1	1.34
TIN, mg/L	15.97	16.05	2.92	2.45	16.16	16.16	2.91	2.60
pH	6.53	6.58	6.54	6.56	6.55	6.53	6.58	6.56
Recycle Loads								
TN recycled from thickener, ppd	12.37	12.37	10.18	10.64	12.42	12.42	10.2	12.84
TN recycled from Digester, ppd	22.52	22.52	21.92	23.36	23.42	23.42	22.79	24.18
Total Nitrogen Recycled, ppd	34.89	34.89	32.1	34	35.84	35.84	32.99	37.02
Phosphorus Recycle from Thickener, ppd	3.7	3.7	4.75	5.43	8.69	9.79	9.11	8.9
Phosphorus Recycle from Digester, ppd	7.37	7.37	12.75	15.83	12.3	13	15.16	8.33
Total Phosphorus Recycled, ppd	11.07	11.07	17.5	21.26	20.99	22.79	24.27	17.23
% TN recycled	17.4%	17.4%	16.0%	17.0%	17.9%	17.9%	16.5%	18.5%
% TP Recycled	23.3%	23.3%	36.8%	44.7%	44.1%	47.9%	51.0%	36.2%

	WET SEASON - AWW FLOWS							
	Existing Plant		Upgraded Plant					
Description	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Aerobic Digester								
Solids % from Clarifier	0.9%	0.9%	0.9%	0.9%	1.0%	1.1%	1.0%	1.1%
Solids % from Thickener	5.2%	5.2%	5.3%	5.4%	6.3%	6.6%	6.1%	6.3%
Combined Solids % to Aerobic Digester	3.6%	3.6%	3.7%	3.8%	4.4%	4.6%	4.3%	4.4%
VSS loading to Digester, ppd	739	739	722	747	740	747	710	727
TSS loading to Digester, ppd	1,329	1,328	1,351	1,381	1,371	1,690	1,570	1,656
Volume, MG	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Hydraulic Residence Time, hrs	1372	1372	1372	1372	1371	1371	1372	1357
Digester Sludge Age, days	57.17	57.17	57	57	57	57	57	57
Total Sludge Age, days	75.43	75.43	75	76	75	75	75	75
Digester Airflow rate cfm	139	139	139	150	164	139	139	125
VSS destruction %	26.83%	26.83%	27.8%	28.6%	26.8%	26.6%	27.9%	28.2%
SOUR, mg/L of O_2/hr/g TSS (< = 1.5)	0.246	0.246	0.251	0.260	0.198	0.186	0.200	0.196
Magnesium Hydroxide addition, gal/day	20.0	20.0	20	20	20	20	20	20
Sludge Production								
Dry Sludge Production, ppd	947	947	934	948	1190	1253	1166	1225
Effluent								
BOD, mg/L	1.63	1.63	1.57	1.35	1.54	1.2	1.68	1.65
TSS, mg/L	3.3	3.3	3.3	3.3	3.4	3.9	3.4	3.9
Phosphorous, mg/L	5.68	5.66	5.2	4.95	0.93	0.05	0.13	0.04
Ammonia N, mg/L	0.6	0.6	1	0.95	0.59	0.58	1.25	1.12
TIN, mg/L	21.82	21.89	3.6	2.85	21.82	21.82	3.79	2.85
pH	6.84	6.61	6.56	6.64	6.65	6.6	6.6	6.57
Recycle Loads								
TN recycled from thickener, ppd	13.29	13.29	10.44	10.72	13.31	13.41	13.31	10.4
TN recycled from Digester, ppd	22.8	22.8	22.14	23.71	22.83	22.95	22.83	22.58
Total Nitrogen Recycled, ppd	36.09	36.09	32.58	34.43	36.14	36.36	36.14	32.98
Phosphorus Recycle from Thickener, ppd	3.92	3.92	5.9	6.55	8.86	9.81	8.8	8.98
Phosphorus Recycle from Digester, ppd	7.44	7.44	17.27	19.94	12.51	13.5	8.26	8.36
Total Phosphorus Recycled, ppd	11.36	11.36	23.17	26.49	21.37	23.31	17.06	17.34
% TN recycled	18.0%	18.0%	16.3%	17.2%	18.0%	18.2%	18.0%	16.5%
% TP Recycled	23.9%	23.9%	48.7%	55.7%	44.9%	49.0%	35.9%	36.5%

	DRY SEASON - ADW FLOWS							
	Existing Plant		Upgraded Plant					
Description	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Aerobic Digester								
Solids % from Clarifier	0.9%	0.9%	0.9%	0.9%	1.1%	1.1%	1.0%	1.1%
Solids % from Thickener	5.3%	5.2%	5.5%	5.5%	6.5%	6.4%	6.4%	6.3%
Combined Solids % to Aerobic Digester	3.7%	3.7%	3.8%	3.9%	4.5%	4.4%	4.5%	4.4%
VSS loading to Digester, ppd	719	718	706	725	719	728	693	697
TSS loading to Digester, ppd	1,308	1,307	1,360	1,377	1,615	1,661	1,594	1,630
Volume, MG	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Hydraulic Residence Time, hrs	1418	1411	1411	1411	1410	1357	1411	1357
Digester Sludge Age, days	59	59	59	59	59	57	59	57
Total Sludge Age, days	78	78	78	78	78	75	78	75
Digester Airflow rate cfm	119	119	120	127	119	123	120	125
VSS destruction %	24.4%	24.3%	25.4%	26.0%	24.3%	24.7%	25.4%	26.0%
SOUR, mg/L of O_2/hr/g TSS (< = 1.5)	0.180	0.210	0.211	0.220	0.165	0.170	0.167	0.175
Magnesium Hydroxide addition, gal/day	20	20	20	20	20	20	20	20
Sludge Production								
Dry Sludge Production, ppd	950	950	943	953	1212	1258	1188	1231
Effluent								
BOD, mg/L	1.37	1.37	1.3	1.07	1.32	1.26	1.3	1.32
TSS, mg/L	2.2	2.2	2.2	2.2	2.2	5.5	2.2	5.5
Phosphorous, mg/L	8.51	8.49	7.31	7.26	0.3	0.03	0.32	0.03
Ammonia N, mg/L	0.39	0.38	0.57	0.39	0.39	0.44	0.56	0.47
TIN, mg/L	33.38	33.55	4.72	2.86	33.55	33.48	4.7	2.85
pH	6.66	6.67	6.62	6.66	6.64	6.5	6.7	6.53
Recycle Loads								
TN recycled from thickener, ppd	14.51	14.51	10.36	10.42	14.52	14.83	10.16	9.99
TN recycled from Digester, ppd	21.35	21.35	20.62	21.48	21.37	21.84	20.21	20.74
Total Nitrogen Recycled, ppd	35.86	35.86	30.98	31.9	35.89	36.67	30.37	30.73
Phosphorus Recycle from Thickener, ppd	4.19	4.19	7.43	7.29	9.55	9.02	9.78	9.01
Phosphorus Recycle from Digester, ppd	6.91	6.91	23.08	22.08	12.7	8.5	14.21	8.38
Total Phosphorus Recycled, ppd	11.1	11.1	30.51	29.37	22.25	17.52	23.99	17.39
% TN recycled	17.9%	17.9%	15.5%	15.9%	17.9%	18.3%	15.2%	15.3%
% TP Recycled	23.3%	23.3%	64.1%	61.7%	46.8%	36.8%	50.4%	36.6%

TABLE 4-31

EXTENDED AERATION PLANT BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

	PROCESS DESIGN - MMDW FLOWS								DRY SEASON - ADW FLOWS							
	Existing Plant		Upgraded Plant						Existing Plant		Upgraded Plant					
Description	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals																
TIN (mg/L)			< 8	< 3			< 8	< 3			< 8	< 3			< 8	< 3
TP (mg/L)					< 1	< 0.1	< 1	< 0.1					< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature																
Influent Flow, mgd	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.50	0.50	0.50	0.5	0.50	0.50	0.50	0.50
Temp, ^{o}C	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Influent Loads																
BOD	241	241	241	241	241	241	241	241	331	331	331	331	331	331	331	331
TSS	273	273	273	273	273	273	273	273	376	376	376	376	376	376	376	376
VSS	191	191	191	191	191	191	191	191	263	263	263	263	263	263	263	263
TKN	35	35	35	35	35	35	35	35	48	48	48	48	48	48	48	48
TP	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Alkalinity	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	4	4	4	4	4	4	4	4
pH	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Oxidation Ditch / Aeration Tank																
Tank Volume, MG	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50	1.00	1.00	0.70	0.50
HRT, hrs	34.8	34.8	24.3	17.4	34.8	34.8	24.3	17.4	48	48	33.6	24	48	48	33.6	24
MLSS Conc., mg/L	2,873	2,873	2,941	3,042	3,413	3,511	3,380	3,323	2,943	2,943	3,062	3,134	3,634	3,597	3,588	3,543
DO Concentration, mg/L	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Ditch Power Uptake, HP	94								96							
Aeration Tank Airflow rate ft3/min		983	800	718	983	975	801	718		986	781	716	986	980	807	722
BioWin SRT, days	18.36	18.36	18.37	18.47	18.36	17.48	18.37	18.47	18.78	18.78	18.79	18.91	18.77	18.06	18.79	18.18
RAS Recyle Rate	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q
Pre - Anoxic Tank																
Tank Volume, MG			0.30	0.20			0.30	0.20			0.30	0.20			0.30	0.20
HRT, hrs			10.4	7.0			10.4	7.0			14.4	9.6			14.4	9.6
Internal Recycle Rate			6Q	6Q			6Q	6Q			6Q	6Q			6Q	6Q
Post - Anoxic Tank																
Tank Volume, MG				0.20				0.20				0.20				0.20
HRT, hrs				7.0				7.0				9.6				9.6
Aerobic Tank																
Tank Volume, MG				0.10				0.10				0.10				0.10
HRT, hrs				3.5				3.5				4.8				4.8
Air Supply Rate, ft^{3}/min				131				143				115				130
Clarifier																
Area, SF	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500	3,500
Surface Overflow Rate, gal/ft^{2}	197	197	197	197	197	197	197	197	142	142	142	142	142	142	142	142
Tertiary Filters																
Filter Area (ft2) (from Capdet)						380		380						380		380

TABLE 4-31
EXTENDED AERATION PLANT BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

	PROCESS DESIGN - MMDW FLOWS								DRY SEASON - ADW FLOWS							
	Existing Plant		Upgraded Plant						Existing Plant		Upgraded Plant					
Description	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F	Mechanical Aeration	Diffused Aeration	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Chemical Addition																
Methanol, gal/d				20				20				20				20
Alum Dosage, gal/day					90	165	80	125					125	165	125	160
Magnesium Hydroxide Dosage, gal/day	40	80	NR	NR	120	180	60	90	40	80	NR	NR	120	160	60	90
Magnesium Hydroxide Conc., meq/L	14,500	14,500			14,500	14,500	14,500	14,500	14,500	14,500			14,500	14,500	14,500	14,500
Aerobic Digester																
Solids % from Clarifier	0.86%	0.86%	0.9%	0.9%	1.00%	1.00%	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%	1.1%	1.1%	1.0%	1.1%
Solids % from Thickener	5.10%	5.10%	5.2%	5.4%	6.10%	6.30%	6.0%	5.9%	5.3%	5.2%	5.5%	5.5%	6.5%	6.4%	6.4%	6.3%
Combined Solids % to Aerobic Digester	3.60%	3.60%	3.7%	3.8%	4.30%	4.40%	4.2%	4.1%	3.7%	3.7%	3.8%	3.9%	4.5%	4.4%	4.5%	4.4%
VSS loading to Digester, lbs/day	720	720	707	730	721	734	706	713	719	718	706	725	719	728	706	697
TSS loading to Digester, lbs/day	1,305	1,305	1,337	1,369	1,552	1,676	1,537	1,586	1,308	1,307	1,360	1,377	1,615	1,661	1,594	1,624
Volume, MG	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Hydraulic Residence Time, hrs	1379	1379	1379	1379	1379	1313	1379	1379	1418	1411	1411	1411	1410	1357	1411	1357
Digester Sludge Age, days	57	57	57	57	57	55	57	57	59	59	59	59	59	57	59	57
Total Sludge Age, days	76	76	76	76	76	72	76	76	78	78	78	78	78	75	78	75
Digester Airflow rate ft3/min	122	122	123	131	122	122	123	131	119	119	120	127	119	123	120	125
VSS destruction %	24.7%	24.7%	25.8%	26.5%	24.7%	25.1%	25.8%	26.5%	24.4%	24.3%	25.4%	26.0%	24.3%	24.7%	25.4%	26.0%
SOUR, mg/L of O_2/hr/g TSS (< = 1.5)	0.220	0.219	0.224	0.233	0.180	0.178	0.188	0.197	0.180	0.210	0.211	0.220	0.165	0.170	0.172	0.176
Magnesium hydroxide, gal/day	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Sludge Production																
Dry Sludge Production, ppd	946	946	935	949	1155	1267	1118	1186	950	950	943	953	1212	1258	1158	1225
Effluent																
BOD, mg/L	1.51	1.51	1.46	1.26	1.45	1.29	1.4	1.5	1.37	1.37	1.3	1.07	1.32	1.26	1.3	1.32
TSS, mg/L	3.0	3.0	3.0	3.0	3.1	4.3	3.1	3.6	2.2	2.2	2.2	2.2	2.2	5.5	2.2	5.2
Phosphorous, mg/L	6.2	6.2	5.61	5.41	0.54	0.03	0.84	0.04	8.51	8.49	7.31	7.26	0.29	0.03	0.32	0.03
Ammonia N, mg/L	0.38	0.4	0.6	0.47	0.39	0.45	0.57	0.51	0.39	0.38	0.57	0.39	0.38	0.44	0.56	0.47
TIN, mg/L	24.14	24.13	3.57	2.39	24.13	24.09	3.54	2.24	33.38	33.55	4.72	2.86	33.55	33.48	4.7	2.85
pH	6.82	6.55	6.5	6.53	6.61	6.51	6.67	6.56	6.66	6.67	6.62	6.66	6.64	6.5	6.7	6.56
Recycle Loads																
TN recycled from thickener	13.3	13.3	10.16	10.48	13.32	13.68	10.17	10.13	14.51	14.51	10.36	10.42	14.52	14.83	10.16	9.99
TN recycled from Digester	22.55	22.55	21.96	22.95	22.57	23.2	21.96	22.76	21.35	21.35	20.62	21.48	21.37	21.84	20.21	20.74
TN recycled from solids processing	35.85	35.85	32.12	33.43	35.89	36.88	32.13	32.89	35.86	35.86	30.98	31.9	35.89	36.67	30.37	30.73
Phosphorus Recycle from Thickener, ppd	3.9	3.9	6.21	6.58	9.28	8.41	10.08	9.03	4.19	4.19	7.43	7.29	9.55	9.02	9.78	9.01
Phosphorus Recycle from Digester, ppd	6.92	6.92	18.4	19.74	12.43	8	18.94	8.41	6.91	6.91	23.08	22.08	12.7	8.5	14.21	8.38
Total Phosphorus Recycled, ppd	10.82	10.82	24.61	26.32	21.71	16.41	29.02	17.44	11.1	11.1	30.51	29.37	22.25	17.52	23.99	17.39
% TN recycled	17.9%	17.9%	16.0%	16.7%	17.9%	18.4%	16.0%	16.4%	17.9%	17.9%	15.5%	15.9%	17.9%	18.3%	15.2%	15.3%
% TP Recycled	22.7%	22.7%	51.7%	55.3%	45.6%	34.5%	61.0%	36.7%	23.3%	23.3%	64.1%	61.7%	46.8%	36.8%	50.4%	36.6%

CHAPTER 5.
TECHNOLOGICAL EVALUATION
FOR CONVENTIONAL ACTIVATED SLUDGE PLANTS

5.1 BASE CASE/EXISTING SYSTEM

A base case model was developed in Biowin to represent a conventional activated sludge (CAS) plant with a MMWWF capacity of 1.0 mgd. Figure 5-1 shows the process flow schematic for the modeled CAS treatment plant. The plant consists of a primary clarifier, an aeration tank and a secondary clarifier to treat the liquid stream. Sludge wasted from the secondary clarifier is sent to a thickening unit and then combined with the primary sludge before being digested in an anaerobic digester.

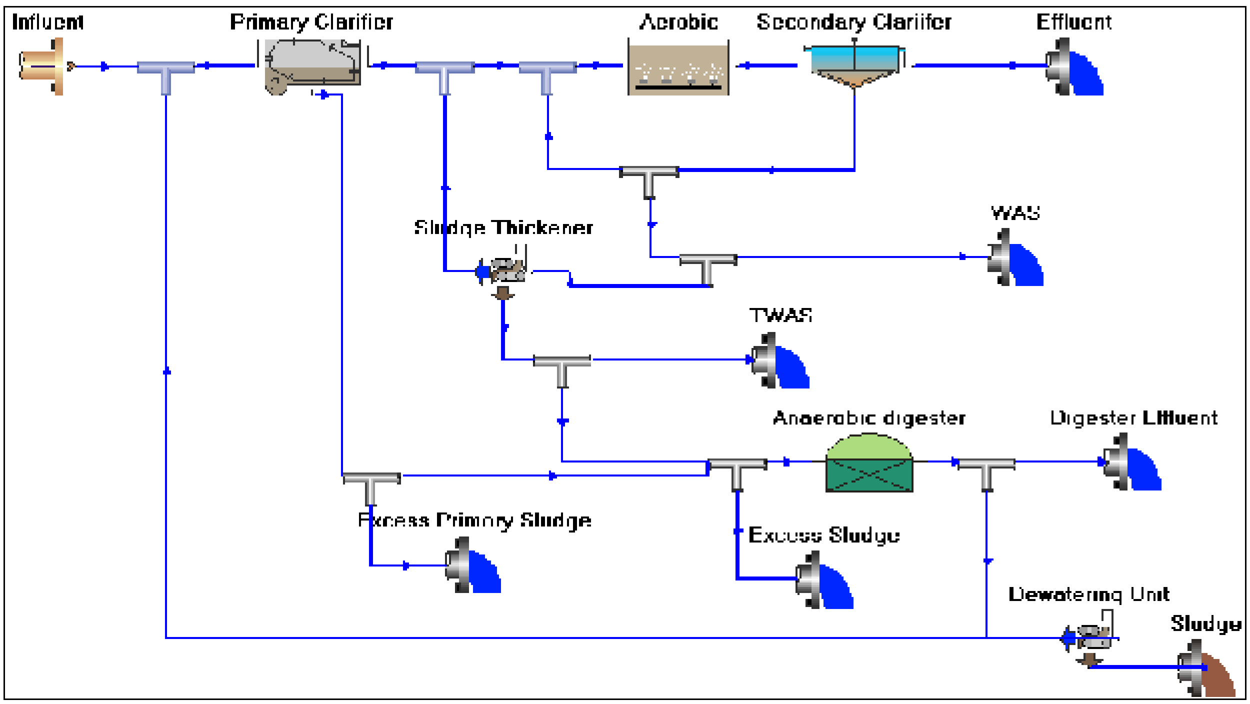


Figure 5-1. Process Flow Schematic of Conventional Activated Sludge Treatment Plant

The Biowin CAS model was developed based on the 1998 Washington State Orange Book and the general sizing and operational criteria listed in Table 5-1. Although the existing treatment process system is very effective in removing BOD and TSS (~95-percent removal), it removes only about 34 percent of influent nitrogen and 25 percent of influent phosphorus.

5.2 YEAR-ROUND NUTRIENT REMOVAL

Improvements required to provide year-round nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 5-2, which is attached at the end of this chapter.

TABLE 5-1
BASE CASE/EXISTING SYSTEM FOR CONVENTIONAL ACTIVATED SLUDGE PLANT

MMWWF	1.0 mgd
Temperature	10 ºC
Primary Clarifier	
Area	1,020 ft^2
Surface Overflow Rate	979 gal/ft^2
Aerobic Tank	
Tank Volume	0.2 MG
HRT	4.8 hours
Mixed Liquor Suspended Solids Concentration	2,046 mg/L
DO Concentration	1 mg/L
Air Supply Rate	336 cfm
Biowin SRT	5.25 days
RAS Recycle Rate	0.5 mgd
Secondary Clarifier	
Area	1,450 ft^2
Surface Overflow Rate	689 gal/ft^2
Anaerobic Digester	
TSS wasted from Aerobic Tank	650 ppd
Total loading to Digester	1,779 ppd
Total Volatile Solids loading to Digester	1,255 ppd
Volume	0.15 MG
Hydraulic Residence Time	19.8 days
Sludge Production	
Sludge Production	936 ppd
Effluent	
BOD	6.79 mg/L
TSS	12.8 mg/L
Phosphorous	4.27 mg/L
Ammonia N	15 mg/L
TIN	15.59 mg/L
pH	6.58

5.2.1 Objective A

Process Description

The upgrade evaluated for achieving Objective A (TIN <8 mg/L) for a conventional activated sludge plant consisted of converting the existing CAS process to a Modified Ludzack-Ettinger (MLE) process, demolishing the existing clarifiers and replacing them with a membrane bioreactor (MBR). Figure 5-2 shows the upgraded process flow schematic. Table 5-2 summarizes the process design data. Detailed Biowin model reports for the existing and upgraded plant are presented in Appendix A.

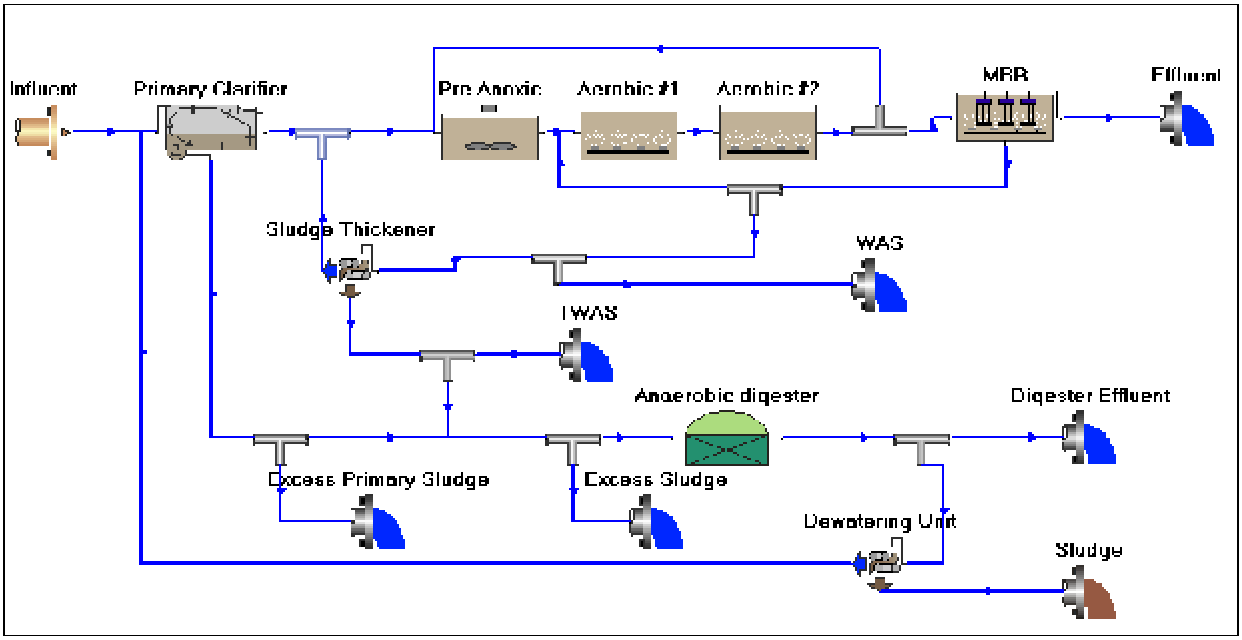


Figure 5-2. Process Schematic of CAS Plant Upgraded for Objective A Year-Round

Section 4.2.1 provides a detailed description of the MLE process. Since the volume of the aeration tank in the modeled existing secondary treatment process is only 0.2 MG, additional tanks would be needed for an MLE process that could meet the nutrient removal objective. A new 0.1-MG anoxic tank would need to be constructed upstream of the existing aeration system. Aeration capacity would be upgraded to meet the increased oxygen demand associated with the nitrification process and the longer sludge age. The DO in the tank would be maintained at 2.0 mg/L.

MBRs combine activated sludge treatment with a membrane liquid-solid separation process. The membrane component uses low-pressure microfiltration or ultra-filtration membranes, eliminating the need for clarification. The membranes are typically immersed in the aeration tank, although some applications use a separate membrane tank. An MBR process effectively overcomes the limitations associated with poor settling of sludge due to upsets in the CAS processes. MBRs can be operated at higher mixed liquor suspended solids (MLSS) concentrations, ranging from 8,000 to 10,000 mg/L (compared to 1,500 to 3,000 mg/L for the conventional CAS process with gravity clarifiers). The elevated biomass concentration in the MBR process allows for effective removal of both soluble and particulate biodegradable materials at higher loading rates. The small footprint of MBR systems and the high quality effluent produced make them particularly useful for nutrient removal projects at treatment plants where there is little or no available area for process alternatives with a significantly greater footprint.

The MBR tank was sized at 20,000 gallons with a membrane flux rate of 15.31 gpd/ft^2 at an MMWWF of 1.0 mgd. The DO in the MBR tank would be maintained at 6.0 mg/L, with an MLSS concentration of 8,300 mg/L. Mixed liquor from the MBR tank would be recycled to the aeration tank at a flow rate of 1.5 mgd, and mixed liquor from the terminal end of the aeration tank would be recycled to the anoxic tank at a rate of 5 mgd. The MLE-MBR system would have an SRT of 23 days.

Recycled Loads

Solids treatment for a CAS consists of a thickener for waste activated sludge (WAS) from the secondary clarifier and an anaerobic digester for the combined primary and secondary sludge. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. The modeling results indicate upgrading to achieve Objective A would reduce the annual quantity of TN contained in the recycle streams approximately 33 percent and the annual quantity of TP recycled by 28 percent. Table 5-3 summarizes the results.

TABLE 5-3.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE A YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	22.6%	22.0%	38.2%	40.7%
Objective A Year-Round	15.2%	14.6%	27.6%	28.4%

Sludge Production

From Table 5-2, average annual sludge produced by the existing CAS plant (the average of the AWWF and ADWF sludge production) is 168 tons/year, or 0.74 dry tons of solids per million gallons of wastewater treated. With upgrade of the plant to achieve Objective A, the plant's overall sludge production would increase to 174 tons/year, or 0.76 dry tons of solids per million gallons of wastewater treated. This 3-percent increase would be attributable to the improved capture of solids associated with the membrane filtration process. Objective A upgrades would result in a 12.5-percent decrease in the total volatile solids loading to the anaerobic digester and in methane production.

Energy Consumption

The process air requirements on an average annual basis would be approximately 150 percent greater for the upgraded plant to achieve Objective A than for the existing CAS system. The additional process air is required to satisfy the oxygen demand associated with nitrification and the longer sludge age, and to provide air scour of the membranes, which accounts for approximately 75 percent of the increased process air demand.

Upgrading the CAS plant to achieve Objective A year-round would increase the plant energy requirements by 476,300 kW-hours/year, or about 230 percent, as shown in Table 5-4. Less than 1 percent of this increase would be attributable to the operation of solids processes associated with achieving Objective A. The energy consumption for the upgraded plant would increase by about 2,088 kW-hours per million gallons of influent wastewater treated.

TABLE 5-4.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective A Year-Round	683,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	476,300 kW-hours/year
Percent	230%
Increase per Volume of Plant Flow	2,088 kW-hours/MG

Chemical Usage

No additional use of chemicals would be required to reduce nutrients as required for this objective, but 8,600 gallons each of 50-percent citric acid and 12.5-percent sodium hypochlorite would be required per year for membrane cleaning, which would need to be done periodically throughout the year. This equates to 38 gallons each of citric acid and sodium hypochlorite per million gallons of wastewater treated.

Footprint Requirements

To achieve Objective A for the 1-mgd CAS plant, the existing secondary clarifiers would be demolished to provide area for new process elements. The total area required for the new process elements would be approximately 2,000 square feet allocated as follows:

- 960 square feet for new anoxic tanks, including fine screening of primary clarifier effluent
- 270 square feet for new membrane tanks
- 730 square feet for a membrane blower building.

The area liberated by demolition of the existing secondary clarifiers would be approximately the same as that required for the upgrade, so no additional area would be required.

Table 5-5 compares the additional site area requirements, or footprint area, for upgrading existing CAS plants to achieve Objective A for the three generic plant capacities. Objective A upgrades at larger plants would liberate more site area than required, if all secondary clarifiers were demolished. Additional area is not required for the larger plants because the footprint requirement for the blower building does not increase at the same rate as the anoxic tanks and MBR tank size. For some plants, it may be beneficial to retain some of the existing secondary clarifiers to handle unusually high peak flow events. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 5-5.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE A YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	0
10	(6,000)
150	(142,000)

Note: Values in parentheses indicate area currently occupied by existing treatment facilities that could become available for future use.

5.2.2 Objective B

Process Description

The upgrade evaluated for achieving Objective B (TIN <3 mg/L) is to convert the existing CAS system into a four-stage Bardenpho process (4BDP) with the addition of methanol and to replace the existing clarifiers with an MBR. Figure 5-3 shows the upgraded process flow schematic. Table 5-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

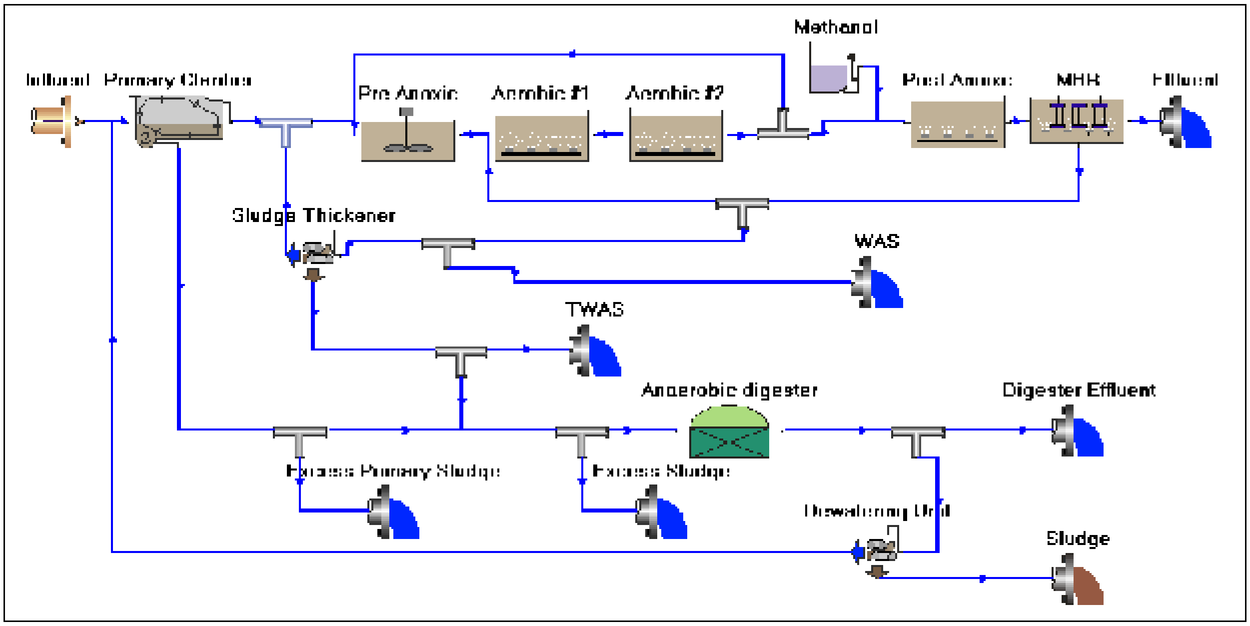


Figure 5-3. Process Schematic of CAS Plant Upgraded for Objective B Year-Round

The existing CAS process does not have adequate tank volume to maintain an adequate sludge age to achieve nitrification and denitrification. Therefore, additional tankage would need to be constructed. For the modeled 1-mgd plant, a new pre-anoxic tank of 0.1 MG and a new post-anoxic tank of 0.05 MG would be required. The MBR tank, which would be aerated, would act as a post-aeration basin to strip the nitrogen gas formed during the denitrification process. Methanol would be added to the post-anoxic tank as a supplemental carbon source to drive the denitrification process. Methanol dosages were determined as described in Chapter 4 for the 4BDP upgraded extended aeration plants. The existing secondary clarifier would be demolished and replaced with the MBR, as described for upgrading CAS plants to achieve Objective A year-round.

Recycled Loads

Solids treatment for a CAS consists of a thickener for WAS, an anaerobic digester for the combined primary and thickened sludge, and a digested-sludge dewatering system. The percentage of TN and TP returning in the recycle streams from solids handling and treatment processes was calculated using the Biowin model outputs. The results indicate that upgrades to achieve Objective B would reduce the quantity of total nitrogen in the recycle streams approximately 34 percent and the quantity of phosphorus in the recycle streams approximately 15 percent. Table 5-6 summarizes the results.

TABLE 5-6.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE B YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	22.6%	22.0%	38.2%	40.7%
Objective B Year-Round	14.9%	14.8%	32.7%	33.8%

Sludge Production

From Table 5-2, average sludge produced by the upgraded plant to achieve Objective B is 970 ppd. This is about 5 percent greater than for the existing plant and 1.4 percent greater than for Objective A. The average annual sludge produced by the plant would increase approximately 5 percent, to about 177 tons/year or 0.78 dry tons of solids per million gallons of wastewater treated. This increase would be attributable to the improved capture of solids associated with membrane filtration and the addition of methanol to the post-anoxic tank for denitrification, which accounts for 0.01 tons of the additional sludge per million gallons of wastewater. Objective B upgrades would result in an 18.5-percent decrease in the total volatile solids loading to the anaerobic digester, reducing methane by the same percentage.

Energy Consumption

Upgrades to achieve Objective B year-round would increase average annual process air requirements by 147 percent. The process air required by the MBR system accounts for 76 percent of this increase. Additional energy would be required for intra-process pumping and mixing.

Upgrading the CAS plant to achieve Objective B year-round would increase the plant energy requirements by 580,800 kW-hours/year, or about 280 percent, as shown in Table 5-7. Less than 1 percent of this increase would be attributable to the operation of solids processes associated with achieving Objective B. The energy consumption for the upgraded plant would increase by about 2,546 kW-hours per million gallons of influent wastewater treated. Objective B upgrades require about 22 percent more energy than Objective A upgrades.

TABLE 5-7.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective B Year-Round	788,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	580,800 kW-hours/year
Percent	280%
Increase per Volume of Plant Flow	2,546 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective B year-round would require 4,563 gallons of methanol per year for carbon supplementation to drive the denitrification process, or 20 gallons of methanol per million gallons of wastewater treated. Additionally, 8,600 gallon each of 50-percent citric acid and 12.5-percent sodium hypochlorite would be required per year for periodic cleaning of the membranes. This equates to 38 gallons each of citric acid and sodium hypochlorite per million gallons of wastewater treated.

Footprint Requirements

To achieve Objective B, additional facility footprint area is required to accommodate the pre-anoxic tank, the post-anoxic tank, the membrane tank, the blower building for the MBR process and the methanol storage tank and feed system. The total area required for these new process elements for a 1-mgd plant would be approximately 3,300 square feet. Demolition of the existing secondary clarifiers would liberate approximately 2,000 square feet, so an additional 1,300 square feet would be required.

Table 5-8 compares the additional footprint area for upgrading existing CAS plants to achieve Objective B for the three generic plant capacities. Objective B upgrades at larger plants would liberate more site area than required, if all of the secondary clarifiers were demolished. Additional area is not required for the larger plants because the footprint requirement for the blower building does not increase at the same rate as the anoxic tanks and MBR tank size. For some plants, it may be beneficial to retain some of the existing secondary clarifiers to handle unusually high peak flow events. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 5-8.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE B YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	1,300
10	0
150	(130,000)

Note: Values in parentheses indicate area currently occupied by existing treatment facilities that could become available for future use.

5.2.3 Objective C

Process Description

The upgrade to achieve Objective C (TP <1 mg/L) consists of alum addition for precipitation of phosphorus and magnesium hydroxide addition for pH control. The aluminum phosphate and aluminum hydroxide precipitates would be incorporated into the activated sludge mixed liquor and removed with the waste activated sludge. Storage tanks and feed pumps for alum and magnesium hydroxide would be sized for the usage required during MMWWF. The method for determining alum dosage is described in Section 4.2.3. It was assumed that existing solids facilities have the capacity to accommodate the increased sludge produced by chemical precipitation. Figure 5-4 shows the upgraded process flow schematic. Table 5-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Solids treatment for a CAS consists of a thickener for WAS, an anaerobic digester for the combined primary and thickened sludge, and a digested-sludge dewatering system. The percentage of TN and TP returning in the recycle streams from solids processes was calculated using the Biowin model outputs. The results indicate that upgrades to achieve Objective C would have no significant effect (<1 percent) on the quantity of total nitrogen in the recycle streams but would increase the quantity of phosphorus in the recycle streams approximately 41 percent. Table 5-9 summarizes the results.

Sludge Production

With upgrades to achieve Objective C, the overall sludge production for the plant would increase approximately 27 percent to 213 tons/year, or 0.94 dry tons of solids per million gallons of wastewater treated. This increase would be attributable to the presence of the aluminum phosphate and the aluminum hydroxide in the sludge, resulting from the chemical precipitation process. Objective C upgrades would not significantly change the total volatile solids loading to the anaerobic digester; therefore, no changes would be anticipated with regard to methane production by the anaerobic digestion process.

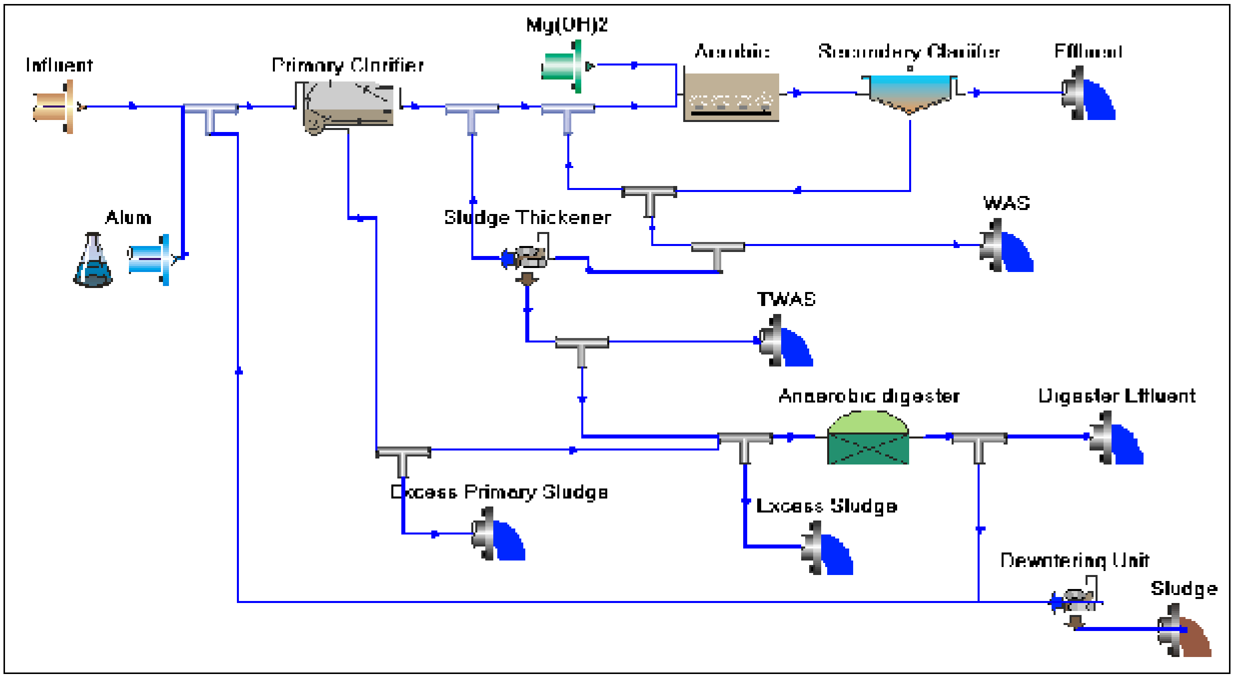


Figure 5-4. Process Schematic of CAS Plant Upgraded for Objective C Year-Round

**TABLE 5-9.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE C YEAR-ROUND NUTRIENT REMOVAL**

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	22.6%	22.0%	38.2%	40.7%
Objective C Year-Round	23.2%	21.7%	55.7%	56.8%

Energy Consumption

Average annual process air required for the upgraded plant to achieve Objective C plant is about the same as required for the existing CAS plant. The upgrades would increase the energy requirements for the treatment plant by 28,300 kW-hours/year, as shown in Table 5-10. This represents about a 14-percent increase in the annual energy consumption. The increase would be attributable to the operation of chemical feed systems and the extended operation of the solids processes associated with achieving Objective C. The energy consumption for the upgraded plant would increase by about 124 kW-hours per million gallons of influent wastewater treated.

Chemical Usage

The upgraded plant to achieve Objective C year-round would require approximately 43,800 gallons of alum per year to precipitate phosphorus and approximately 16,430 gallons of magnesium hydroxide for pH control. These chemical usage rates equate to 192 gallons of alum per million gallons of wastewater treated and 72 gallons of magnesium hydroxide per million gallons of wastewater treated.

**TABLE 5-10.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND**

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective C Year-Round	235,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	28,300 kW-hours/year
Percent	14%
Increase per Volume of Plant Flow	124 kW-hours/MG

Footprint Requirements

Table 5-11 presents the additional site area that would be required for the three generic plant capacities. The additional footprint required for plant upgrades to achieve Objective C would be for the alum and magnesium hydroxide storage tanks and feed systems.

**TABLE 5-11.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE C YEAR-ROUND**

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	400
10	1,600
150	12,700

5.2.4 Objective D

Process Description

The upgrade evaluated to achieve Objective D (TP <0.1 mg/L) would be to add tertiary filters to the improvements described for Objective C, as shown Figure 5-5. Alum would be added at two locations in the process: at the influent to the primary clarifiers; and after the secondary clarifiers, ahead of the filters. Dirty backwash water from the filters would be returned to the head of the plant. The methodology for determining appropriate alum dosage is described in Section 4.2.4. Table 5-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Solids treatment for a CAS consists of a WAS thickener, an anaerobic digester for the combined primary and thickened sludge, and a digested-sludge dewatering unit. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. The results indicate that implementation of the upgrades to achieve Objective D would have no significant effect on annual nitrogen and phosphorus recycle loads. Table 5-12 summarizes the results.

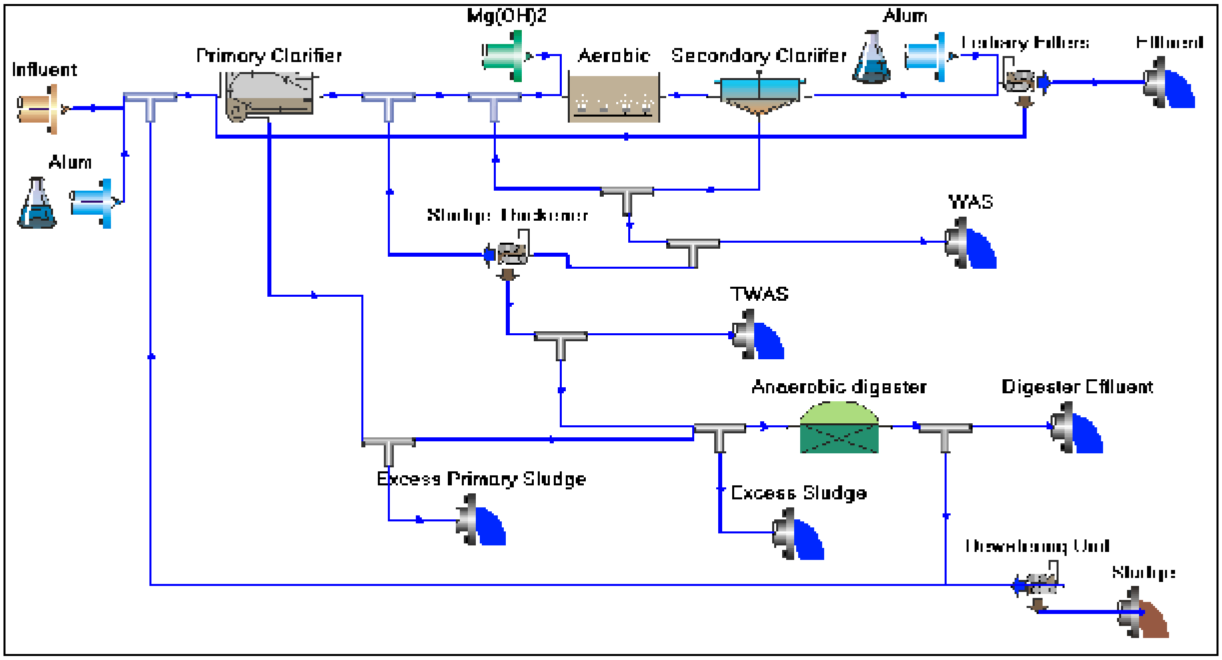


Figure 5-5. Process Schematic of CAS Plant Upgraded for Objective D Year-Round

TABLE 5-12.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE D YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	22.6%	22.0%	38.2%	40.7%
Objective D Year-Round	23.7%	21.0%	55.3%	23.8%

Sludge Production

With upgrades to achieve Objective D, the overall sludge production for the plant would increase approximately 36 percent to 229 tons/year, or 1.0 dry tons of solids per million gallons of wastewater treated. This increase would be attributable to the presence of the aluminum phosphate and the aluminum hydroxide in the sludge, resulting from the chemical precipitation process. Objective D upgrades would not significantly change the total volatile solids loading to the anaerobic digester; therefore, no changes would be anticipated with regard to methane production by the anaerobic digestion process.

Energy Consumption

Average annual process air required for the upgraded plant to achieve Objective D is about the same as required for the existing CAS plant. The upgrades would increase the annual energy requirements for the treatment plant by 43,800 kW-hours/year, as shown in Table 5-13. This represents a 21-percent increase in the annual energy consumption, or about 192 kW-hours per million gallons of influent wastewater treated. This increase would be attributable to the operation of filters, chemical feed systems and the extended operation of the solids processes associated with achieving Objective D.

TABLE 5-13.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective D Year-Round	251,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	43,800 kW-hours/year
Percent	21%
Increase per Volume of Plant Flow	192 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective D year-round would require approximately 58,400 gallons of alum per year to precipitate phosphorus and approximately 29,200 gallons of magnesium hydroxide for pH control. These chemical usage rates equate to 256 gallons of alum per million gallons of wastewater treated and 128 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

The new process elements required to achieve Objective D on a year-round basis would include alum and magnesium hydroxide storage tanks and feed systems, and filters to remove suspended and colloidal solids from the secondary effluent. For the modeled 1-mgd plant, the total site area footprint required for new process elements would be approximately 1,200 square feet:

- 200 square feet for alum storage tanks and feed systems
- 150 square feet for magnesium hydroxide storage tanks and feed systems
- 850 square feet for new filters.

Table 5-14 presents the additional site area that would be required for the three generic plant capacities.

TABLE 5-14.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE D YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	1,200
10	10,100
150	139,100

5.2.5 Objective E

Process Description

An existing CAS plant may be upgraded to achieve Objective E (TIN <8 mg/L and TP <1 mg/L) by converting the existing CAS system to an MLE-MBR process as described in Section 5.2.1 and by adding alum and magnesium hydroxide for phosphorus as described in Section 5.2.3. The process flow schematic for the upgraded plant would be as shown for Objective A plus the addition of alum and magnesium hydroxide to the influent as shown for Objective C.

The biological SRT for Objective E would be less than for Objective A due to increased MLSS concentration resulting from chemical precipitation of phosphorus. Alum dosage values were calculated for soluble PO_4 concentrations in the aeration tank based on the Objective A model. These alum dosages were then entered in Biowin to achieve effluent TP <1 mg/L. Assumptions made for Objectives A and C were also used for this objective. Table 5-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

The percentage of TN and TP returning from the solids handling and treatment processes were calculated using Biowin model outputs. The results indicate that upgrades to achieve Objective E would reduce the annual quantity of total nitrogen in the recycle streams approximately 29 percent and reduce the annual quantity of phosphorus recycled by 3 percent. Table 5-15 summarizes the results.

**TABLE 5-15.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE E YEAR-ROUND NUTRIENT REMOVAL**

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	22.6%	22.0%	38.2%	40.7%
Objective E Year-Round	16.5%	15.1%	51.1%	25.0%

Sludge Production

With upgrades to achieve Objective E, the overall sludge production for the plant would increase approximately 27 percent to 216 tons/year, or 0.95 dry tons of solids per million gallons of wastewater treated. This increase would be attributable to the presence of the aluminum phosphate and the aluminum hydroxide in the sludge, resulting from the chemical precipitation process. Objective E upgrades would reduce the total volatile solids loading on the anaerobic digester approximately 11 percent; an equivalent reduction would be anticipated with regard to methane production by the anaerobic digestion process.

Energy Consumption

Average annual process air required for the upgraded plant to achieve Objective E would be approximately 233 percent greater than for the existing CAS plant, about the same as required to achieve Objective A. The additional process air, which is required to satisfy the oxygen demand associated with nitrification and the longer sludge age and to provide air scour of the membranes, accounts for approximately 96 percent of the increased energy demand. The upgrades would increase the total plant annual energy requirements 483,300 kW-hours/year, as shown in Table 5-16. This represents a 233 percent increase in the annual energy consumption, or about 2,119 kW-hours per million gallons of influent wastewater treated.

TABLE 5-16.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective E Year-Round	690,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	483,300 kW-hours/year
Percent	233%
Increase per Volume of Plant Flow	2,119 kW-hours/MG

Chemical Usage

Year-round nutrient removal to achieve Objective E would require the following chemical usage:

- 180 gallons of alum per million gallons of wastewater treated
- 96 gallons of magnesium hydroxide per million gallons of wastewater treated
- 38 gallons of 50-percent citric acid citric acid per million gallons of wastewater treated
- 38 gallons of 12.5-percent sodium hypochlorite per million gallons of wastewater treated.

Footprint Requirements

This alternative requires all the tanks that are required for Objective A as well as chemical storage tanks for alum and magnesium hydroxide as described for Objective C. Table 5-17 presents the additional site area that would be required for the three generic plant capacities. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 5-17.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE E YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	400
10	(4,400)
150	(104,500)

Note: Values in parentheses indicate area currently occupied by existing treatment facilities that could become available for future use.

5.2.6 Objective F

Process Description

Objective F (TIN <3 mg/L and TP <0.1 mg/L) can be achieved by converting the existing CAS system to a 4BDP-MBR system and adding methanol, as described for Objective B, and adding alum and magnesium hydroxide, as described for Objective D. The flow schematic for this option is similar to that of Objective B, combined with the addition of alum and magnesium hydroxide, as shown for Objective D.

Alum dosage values were calculated based on the Objective B model for soluble PO_4 concentration in the aeration tank. These alum dosages were entered in Biowin to achieve effluent TP <0.1 mg/L. Assumptions made for Objectives B and D were used for this objective. Similar to Objective E, additional MBR blowers would be required for air scour of membranes. Table 5-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. Table 5-18 summarizes the results.

TABLE 5-18.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE F YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	22.6%	22.0%	38.2%	40.7%
Objective F Year-Round	15.7%	15.4%	26.4%	26.5%

Sludge Production

With upgrades to achieve Objective F, the overall sludge production for the plant would increase approximately 37.5 percent to 231 tons/year, or 1.01 dry tons of solids per million gallons of wastewater treated. The increase would be attributable to aluminum phosphate and aluminum hydroxide in the sludge, resulting from chemical precipitation, and from the addition of methanol. Objective E upgrades would reduce total volatile solids in the anaerobic digester approximately 5.6 percent; an equivalent reduction would be anticipated with regard to methane production by the anaerobic digestion process.

Energy Consumption

Average annual process air required for the upgraded plant to achieve Objective F would be approximately 37 percent greater than for the existing CAS plant. The upgrade would increase the annual energy requirements for the treatment plant by 613,100 kW-hours/year, as shown in Table 5-19. This represents a 296-percent increase in the annual energy consumption, or about 2,688 kW-hours per million gallons of influent wastewater treated.

Chemical Usage

Year-round nutrient removal to achieve Objective F would require the following chemical usage:

- 32 gallons of methanol per million gallons of wastewater treated
- 256 gallons of alum per million gallons of wastewater treated
- 96 gallons of magnesium hydroxide per million gallons of wastewater treated
- 38 gallons of 50-percent citric acid citric acid per million gallons of wastewater treated
- 38 gallons of 12.5-percent sodium hypochlorite per million gallons of wastewater treated.

**TABLE 5-19.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective F Year-Round	820,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	613,100 kW-hours/year
Percent	296%
Increase per Volume of Plant Flow	2,688 kW-hours/MG

Footprint Requirements

This alternative requires partitioning of existing tanks and construction of new membrane tanks on the footprint currently occupied by the existing secondary clarifiers. Chemical storage tanks and feed systems for methanol, alum, magnesium hydroxide, citric acid and sodium hypochlorite would also need to be constructed in the area liberated by demolition of the secondary clarifiers. Table 5-20 presents the additional site area that would be required for the three generic plant capacities, assuming that the existing secondary clarifiers are demolished to allow for construction of the new process facilities.

**TABLE 5-20.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	500
10	(3,000)
150	(131,000)

Note: Values in parentheses indicate area currently occupied by existing treatment facilities that could become available for future use.

5.3 SEASONAL NUTRIENT REMOVAL

Improvements required to provide seasonal nutrient removal to achieve each treatment objective are described below. Process design data are included in Table 5-21, attached at the end of this chapter.

5.3.1 Objective A

Process Description

The Objective A (TIN <8 mg/L) treatment process for seasonal nutrient removal would be an MLE system. Unlike the upgrade for year-round treatment for this objective, membrane bioreactors would not be added, and the existing clarifiers would be retained. A new 0.1-MG anoxic tank would be constructed upstream of the existing aeration system. Aeration tank DO concentration would be maintained at 2.0 mg/L. Figure 5-6 shows the upgraded process flow schematic. Table 5-21 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

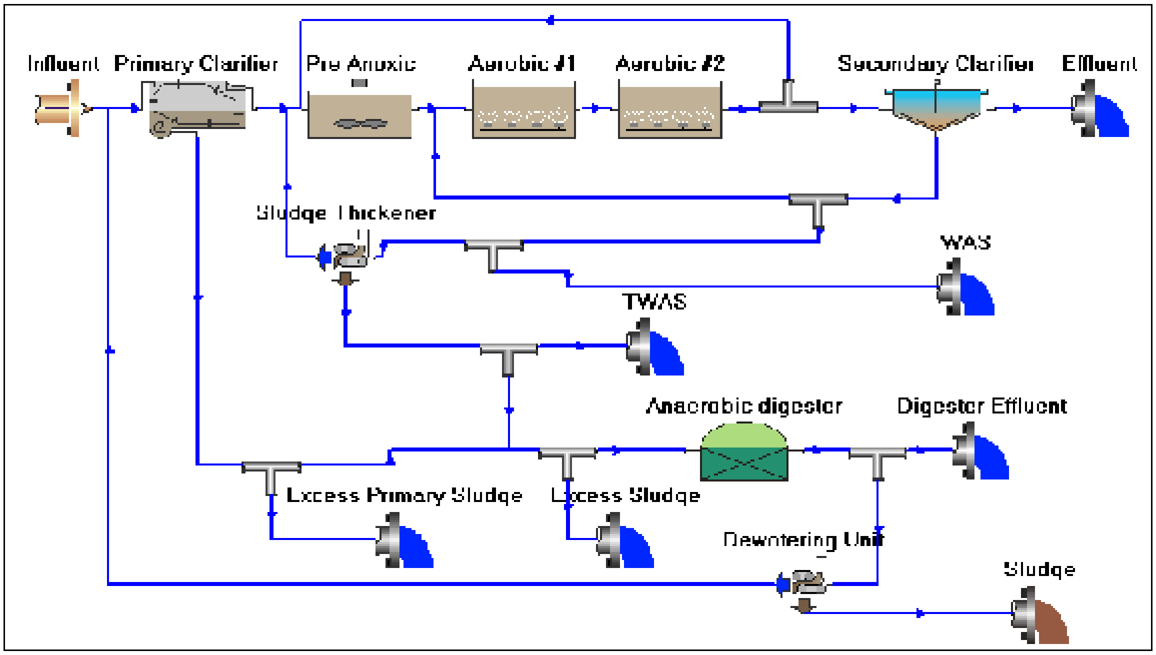


Figure 5-6. Process Schematic of CAS Plant Upgraded for Objective A, Seasonal

In the MLE process, nitrification takes place in the aeration tank, where ammonia is converted into nitrate, and denitrification occurs in the anoxic tank, where the nitrate is converted into nitrite, nitrous oxide and eventually into nitrogen gas. The anoxic tank consists of a mixer for continuous mixing of the influent and the nitrates that are recycled from the aeration tank. The conversion of ammonia nitrogen (NH_3/NH_4^+) to nitrate nitrogen (NO_3^-) is directly dependent on solids retention time. A longer SRT will result in conversion of ammonia to nitrate. SRT is calculated as follows:

- SRT (days) = MLSS in Aeration Tank (lbs)/MLSS Wasted in the Sludge (lbs/day)

In order to achieve Objective A, the SRT of the system should be about 14 days.

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. The modeling results indicate that upgrades to achieve Objective A only during the dry season would reduce the quantity of total nitrogen in the recycle streams during the dry season approximately 32 percent and reduce the quantity of phosphorus approximately 8 percent. This is equivalent to an annual nitrogen recycle load reduction of 12 percent and an annual phosphorus load reduction of 4 percent. Table 5-22 summarizes the results.

Sludge Production

From Tables 5-2 and 5-21, the Objective A seasonal nutrient removal upgrade would reduce average overall sludge production approximately 1 ton per year, to 167 tons per year. This corresponds to an equivalent annual average sludge production of 0.73 tons per million gallons of wastewater treated. The annual average volatile solids loading to the digester would be reduced approximately 6 percent; and a similar reduction would be anticipated in production of digester gas.

**TABLE 5-22.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE A SEASONAL NUTRIENT REMOVAL**

	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	22.0%	40.7%
Objective A Seasonal	16.7%	37.5%

Energy Consumption

Upgrading the plant for seasonal treatment to achieve Objective A would require a 17-percent increase in the overall annual plant energy requirements, as shown in Table 5-23. This equates to an annual energy increase of 754 kW-hours per million gallons of influent wastewater treated. The additional energy would be attributed to additional process aeration, mixer operation in the anoxic compartment, and internal recycling of mixed liquor from the terminal end of the aeration tank to the inlet of the anoxic tank.

**TABLE 5-23.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE A SEASONALLY**

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective A, Seasonal	379,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	172,000 kW-hours/year
Percent	17%
Increase per Volume of Plant Flow	754 kW-hours/MG

Chemical Usage

No additional chemicals are required to achieve Objective A on a seasonal basis.

Footprint Requirements

To achieve Objective A seasonally, approximately 1,000 square feet of additional new process footprint area would need to be accommodated:

- 955 square feet for construction of anoxic tanks
- Up to 60 square feet to accommodate the upgrade of the existing process air blower system.

Table 5-24 compares the additional footprint area for upgrading existing CAS plants to achieve Objective A seasonally for the three generic plant capacities.

TABLE 5-24.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE A SEASONALLY

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	1,000
10	10,000
150	150,000

5.3.2 Objective B

Process Description

The treatment plant upgrades modeled for achieving Objective B (TIN <3 mg/L) for dry season nutrient removal included conversion of the CAS system to a four-stage Bardenpho process with the addition of methanol. Refer to Section 4.2.2 for a description of the 4BDP process. The first half of the existing aeration tank (0.1 MG) would be converted to an anoxic reactor and the second half would be fully aerated. New tankage would need to be constructed to provide the additional aerobic reactor (0.1 MG), the post-anoxic reactor (0.05 MG), and the post-aeration (nitrogen gas stripping) reactor (0.05 MG). Methanol would be added to the post-anoxic tank to provide the necessary carbon source to drive the denitrification process. Figure 5-7 shows the upgraded process flow schematic. Table 5-21 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

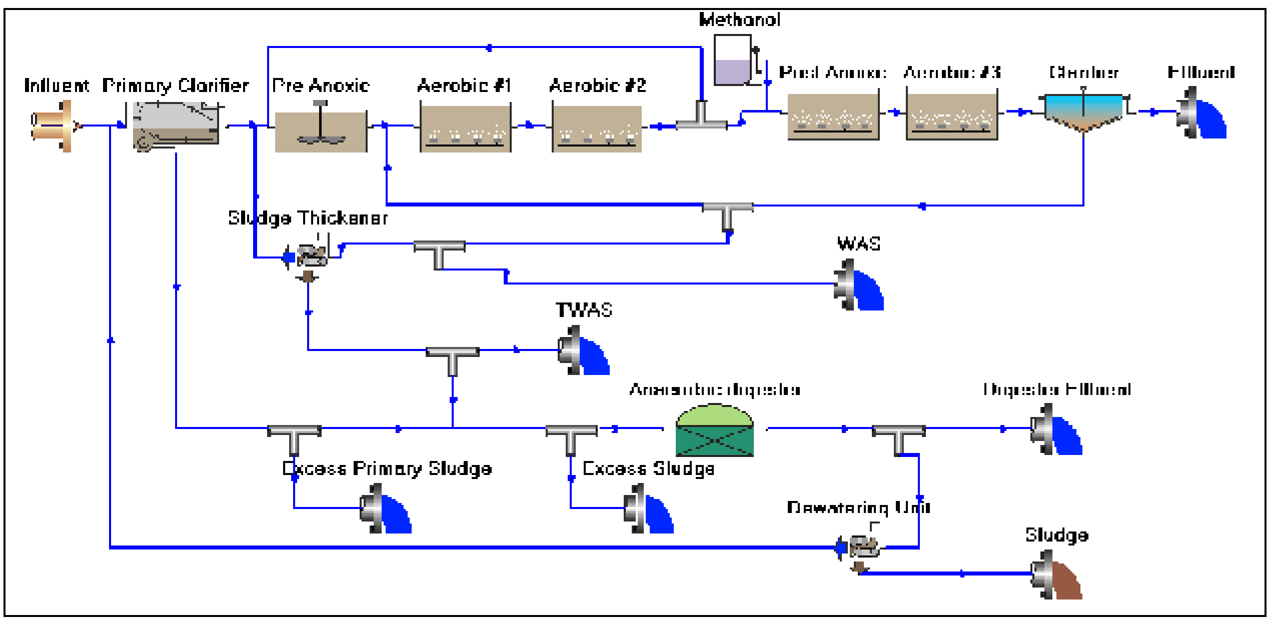


Figure 5-7. Process Schematic of CAS Plant Upgraded for Objective B, Seasonal

Recycled Loads

The percentage of TN and TP returning from the solids handling and dewatering treatment processes relative to the raw influent plant loads was calculated using Biowin model outputs. The results indicate that upgrades to achieve Objective B on a seasonal basis would reduce the quantity of total nitrogen in the recycle streams during the dry-weather period approximately 23 percent—only 11 percent on an annual basis. The upgrades would increase the quantity of total phosphorus in the recycle streams approximately 40 percent during the dry weather period and 20 percent on an annual basis. Table 5-25 summarizes the results.

TABLE 5-25.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE B SEASONAL NUTRIENT REMOVAL

	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	22.0%	40.7%
Objective B Seasonal	17.0%	56.8%

Sludge Production

From Table 5-2 and 5-21, the Objective B seasonal nutrient removal upgrade would not significantly change the average overall sludge production. However, the upgrades would reduce the average annual volatile solids loading on the digesters approximately 5 percent. Consequently, digester gas production would be reduced by an equivalent percentage.

Energy Consumption

Upgrading the plant for seasonal treatment to achieve Objective B would require an 18-percent increase in the overall plant energy requirements, as shown in Table 5-26. This equates to an annual energy increase of 815 kW-hours per million gallons of influent wastewater treated. The additional energy would be attributed to additional process aeration, mixer operation in the anoxic compartments, and internal recycling of mixed liquor from the terminal end of the aeration tank to the inlet of the anoxic tank.

Chemical Usage

Upgrading the plant for seasonal nutrient removal to achieve Objective B would require 1,825 gallons of methanol per year, which would be equivalent to annual use of 8 gallons of methanol per million gallons of influent wastewater treated.

TABLE 5-26.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective B, Seasonal	393,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	186,000 kW-hours/year
Percent	18%
Increase per Volume of Plant Flow	815 kW-hours/MG

Footprint Requirements

To achieve Objective B seasonally, the following additional facility footprint area is required:

- 955 square feet of anoxic tank
- 480 square feet of post-anoxic tank
- Up to 60 additional square feet for expansion of the existing process air blower building
- 100 square feet of methanol storage tanks and containment to store methanol for two weeks (refer to detailed calculations in Appendix B).

Table 5-27 compares the additional footprint area for upgrading existing CAS plants to achieve Objective B seasonally for the three generic plant capacities.

**TABLE 5-27.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE B SEASONALLY**

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	1,600
10	16,000
150	225,000

5.3.3 Objective C

Process Description

To achieve Objective C at CAS plants, the only difference between the year-round and the seasonal nutrient removal is that the chemical storage and feeding system upgrades would be sized for MMDWF instead of the MMWWF. Table 5-21 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

The percentage of TN and TP returning from the solids handling and dewatering treatment processes relative to the raw influent plant loads were calculated using Biowin model outputs. Upgrades to achieve Objective C on a seasonal basis would reduce the quantity of total phosphorus in the recycle streams during the dry weather period approximately 40 percent—about 20 percent on an annual basis. The upgrades would reduce the quantity of total nitrogen in the recycle streams during the dry weather period approximately 23 percent during the dry weather period, about 11 percent on an annual basis. Table 5-28 summarizes the results.

Sludge Production

From Tables 5-2 and 5-21, the average sludge produced by the upgraded plant to achieve Objective C seasonally would be 193 tons per year. This is a 15-percent increase compared to the existing plant but 10 percent less sludge than produced by upgrades for year-round nutrient removal to achieve Objective C. The upgrades would not significantly affect the average annual volatile solids loading on the digesters; therefore, no significant changes would be anticipated in the production of digester gas.

TABLE 5-28.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE C SEASONAL NUTRIENT REMOVAL

	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	22.0%	40.7%
Objective C Seasonal	21.7%	56.8%

Energy Consumption

The annual energy requirements for the upgraded treatment plant to achieve Objective C seasonally would increase 25,100 kW-hours/year as shown in Table 5-29. This represents an increase in the annual energy consumption of approximately 12 percent, or 110 kW-hours per million gallons of influent wastewater treated.

TABLE 5-29.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective C, Seasonal	232,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	25,100 kW-hours/year
Percent	12%
Increase per Volume of Plant Flow	110 kW-hours/MG

Chemical Usage

The upgraded plant for seasonal removal of phosphorus to achieve Objective C would require 23,725 gallons of alum per year to precipitate phosphorus and 16,430 gallons of magnesium hydroxide for pH control. These chemical usage rates equate to 104 gallons of alum and 72 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

The additional process elements required for plant upgrades to achieve Objective C seasonally are alum and magnesium hydroxide storage tanks and feed systems. The additional site area required for these systems would be the same as presented for the year-round model as shown in Table 5-11.

5.3.4 Objective D

Process Description

To achieve Objective D only during the dry season would require upgrades similar to those for Objective D year-round. Nutrient removal processes would be sized for the MMDWF instead of the MMWWF. Refer to the Section 5.2.4 for a detailed process description. Table 5-21 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

The percentage of TN and TP returning from the solids handling and dewatering processes relative to the influent plant loads was calculated using Biowin outputs. Upgrades to achieve Objective D on a seasonal basis would reduce the quantity of total phosphorus in the recycle streams during the dry weather period approximately 42 percent—about 27 percent on an annual basis. Implementation of Objective D on a seasonal basis would reduce the quantity of total nitrogen in the recycle streams approximately 5 percent during the dry weather period, or 4 percent on an annual basis. Table 5-30 summarizes the results.

TABLE 5-30.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE D SEASONAL NUTRIENT REMOVAL

	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	22.0%	40.7%
Objective D Seasonal	21.0%	23.8%

Sludge Production

From Tables 5-2 and 5-21, the average sludge produced by the upgraded 1-mgd modeled plant to achieve Objective D only during the dry-weather season would be 198 tons per year, or 0.87 tons per million gallons treated on an annual basis. This represents a 16-percent increase in sludge production compared to the existing plant but 15 percent less sludge than produced by implementation of Objective D year-round. The upgrades would not significantly affect the average annual volatile solids loading on the digesters; therefore, no significant changes would be anticipated in the production of digester gas.

Energy and Chemical Usage

Upgrades to achieve Objective D seasonally would increase the energy requirements for the treatment plant by 26,100 kW-hours/year, as shown in Table 5-31. This represents a 13-percent increase annually, or 114 kW-hours per million gallons of influent wastewater. The increase would be attributable to the operation of filters and chemical feed systems and the extended operation of the solids processes.

Chemical Usage

For seasonal nutrient removal to achieve Objective D, a 1-mgd plant would require 29,200 gallons of alum per year to precipitate phosphorus and 18,250 gallons of magnesium hydroxide for pH control. These chemical usage rates translate to 128 gallons of alum per million gallons of wastewater treated and 80 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

The process elements that need to be constructed to achieve Objective D seasonally include alum and magnesium hydroxide storage tanks and secondary effluent filters. The footprint of the chemical storage and feeding systems would be the same as for the year-round nutrient removal upgrades; the area required for the filters would be less because they would only need to treat the maximum dry-weather flow, not the maximum wet-weather flow. Table 5-32 compares the additional footprint area for upgrading existing CAS plants to achieve Objective D seasonally for the three generic plant capacities.

TABLE 5-31.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective D, Seasonal	233,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	26,100 kW-hours/year
Percent	13%
Increase per Volume of Plant Flow	114 kW-hours/MG

TABLE 5-32.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE D SEASONALLY

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	1000
10	7,500
150	99,500

5.3.5 Objective E

Process Description

To achieve Objective E (TIN <8 mg/L and TP <1 mg/L) only during the dry-weather season would require conversion of the existing CAS plant to an MLE process and adding alum and magnesium hydroxide for chemical precipitation of phosphorus. Conversion to an MLE plant would require doubling the capacity of the existing mixed liquor tanks. In the case of the 1-mgd modeled facility, this would consist of adding 0.1 MG of tankage for an anoxic reactor prior to aeration, a 0.05-MG post-anoxic tank, and a 0.05-MG post-aeration tank. The alum and magnesium hydroxide tanks for this objective would be sized based on MMDWF instead of MMWWF. Table 5-21 summarizes the process design data.

Recycled Loads

The percentage of TN and TP returning from the solids handling and dewatering treatment processes relative to the raw influent plant loads were calculated using Biowin model outputs. Upgrades to achieve Objective E on a seasonal basis would reduce the quantity of total nitrogen in the recycle streams approximately 25 percent during the dry weather period, or 14 percent on an annual basis. The upgrades would increase the quantity of total phosphorus in the recycle streams approximately 19 percent during the dry weather period, which is equivalent to a 10-percent increase on an annual basis. Table 5-33 summarizes the results.

**TABLE 5-33.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE E SEASONAL NUTRIENT REMOVAL**

	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	22.0%	40.7%
Objective E Seasonal	16.5%	48.5%

Sludge Production

From Tables 5-2 and 5-21, average sludge produced by the upgraded 1 mgd model plant to achieve Objective E only during the dry-weather season would be 191 tons per year, or 0.83 tons per million gallons treated on an annual basis. This is a 17-percent increase in sludge production compared to the existing plant but 13 percent less sludge than produced by implementation of Objective E year-round. The upgrades would result in an annual reduction of 5 percent in the volatile solids loading on the digesters, with an equivalent reduction in the annual production of digester gas.

Energy Consumption

Upgrades to achieve Objective E only during the dry season would increase the annual energy requirements for the treatment plant by 183,000 kW-hours/year, as shown in Table 5-34. This is an 88-percent increase in the annual energy plant consumption, or 802 kW-hours per million gallons of influent wastewater treated. The increase would be attributable to additional aeration, mixers in the anoxic reactors, internal mixed liquor recycle pumps, chemical feed systems, and extended operation of the solids processes.

**TABLE 5-34.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective E, Seasonal	390,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	183,000 kW-hours/year
Percent	88%
Increase per Volume of Plant Flow	802 kW-hours/MG

Chemical Usage

Upgrades to achieve Objective E seasonally would require storage and feed systems for alum and magnesium hydroxide:

- 104 gallons of alum per million gallons of wastewater treated annually
- 61 gallons of magnesium hydroxide per million gallons of wastewater treated annually.

Footprint Requirements

This alternative requires all the tanks that are required for Objective A (seasonal) and chemical storage tanks and feed systems for alum and magnesium hydroxide identified for Objective C (seasonal). Table 5-35 compares the additional footprint area for upgrading existing CAS plants to achieve Objective E seasonally for the three generic plant capacities.

TABLE 5-35.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE E SEASONALLY

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	1,400
10	11,600
150	162,700

5.3.6 Objective F

Process Description

Objective F (TIN <3 mg/L and TP <0.1 mg/L) can be achieved by converting the existing CAS system into a 4BDP process, adding methanol, alum and magnesium hydroxide, and providing tertiary filtration. The alum and magnesium hydroxide tanks would be sized based on the MMDWF instead of the MMWWF. Table 5-21 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

The percentage of TN and TP recycled from the solids handling and dewatering treatment processes relative to the raw influent plant loads were calculated using Biowin model outputs. Upgrades to achieve Objective F on a seasonal basis would reduce the quantity of total nitrogen in the recycle streams approximately 31 percent during the dry weather period, or 15.5 percent on an annual basis. The upgrades would reduce the quantity of total phosphorus in the recycle streams approximately 40 percent during the dry weather period and 28 percent on an annual basis. Table 5-36 summarizes the results.

TABLE 5-36.
NUTRIENT RECYCLING COMPARISON FOR CONVENTIONAL ACTIVATED SLUDGE SYSTEMS, OBJECTIVE F SEASONAL NUTRIENT REMOVAL

	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	22.0%	40.7%
Objective F Seasonal	15.1%	24.6%

Sludge Production

From Tables 5-2 and 5-21, the average sludge produced by the upgraded 1 mgd model plant to achieve Objective E only during the dry weather season would be 198 tons per year, or 0.87 tons per million gallons treated on an annual basis. This is an 18-percent increase in sludge production compared to the existing plant, but approximately 14 percent less sludge than produced by implementation of Objective F year-round. The upgrades would result in an annual reduction of 5 percent in the volatile solids loading on the digesters, and an equivalent reduction in the annual production of digester gas.

Energy Consumption

Upgrades to achieve Objective F for the dry season only would increase the annual energy requirements for the treatment plant by 207,100 kW-hours/year, as shown in Table 5-37. This is a 100-percent increase in the annual energy plant consumption, or 908 kW-hours per million gallons of influent wastewater treated. The increase would be attributable to additional aeration, mixers in the anoxic reactors, internal mixed liquor recycle pumps, chemical feed systems and extended operation of the solids processes.

TABLE 5-37.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing CAS Plant	207,200 kW-hours/year
Objective F, Seasonal	414,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	207,100 kW-hours/year
Percent	100%
Increase per Volume of Plant Flow	908 kW-hours/MG

Chemical Usage

Implementation of upgrades to achieve Objective F would require storage and feed systems for methanol, alum and magnesium hydroxide:

- 8 gallons of methanol per million gallons of wastewater treated annually
- 140 gallons of alum per million gallons of wastewater treated annually
- 80 gallons of magnesium hydroxide per million gallons of wastewater treated annually.

Footprint Requirements

This alternative requires all the mixed liquor tanks and methanol storage tanks and feed systems required to upgrade the plant to achieve Objective B during the dry weather season; in addition, it requires the tertiary filters and alum and chemical storage tanks described for implementation of Objective D during the dry weather season. Table 5-38 compares the additional footprint area for upgrading existing CAS plants to achieve Objective F seasonally for the three generic plant capacities.

**TABLE 5-38.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING CONVENTIONAL ACTIVATED SLUDGE PLANTS TO ACHIEVE OBJECTIVE F SEASONALLY**

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	2,100
10	23,500
150	259,500

TABLE 5-2
CONVENTIONAL ACTIVATED SLUDGE PLANT BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

Description	PROCESS DESIGN - MMWW FLOWS						
	Existing CAS Plant	Upgraded Plant					
		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals							
TIN (mg/L)		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature							
Influent Flow, mgd	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Temp, ^{o}C	10	10	10	10	10	10	10
Influent							
BOD	165	165	165	165	165	165	165
TSS	188	188	188	188	188	188	188
VSS	132	132	132	132	132	132	132
TKN	24	24	24	24	24	24	24
TP	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Alkalinity	2.01	2.01	2.01	2.01	2.01	2.01	2.01
pH	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Primary Clarifier							
Area, ft^2	1,020	1,020	1,020	1,020	1,020	1,020	1,020
Surface Overflow Rate, gal/ft^2	979	979	979	979	979	979	979
Aerobic Tank							
Tank Volume, MG	0.2	0.2	0.2	0.2	0.2	0.2	0.2
HRT, hrs	4.8	4.8	4.8	4.8	4.8	4.8	4.8
MLSS Conc., mg/L	2,046	4,925	4,784	2,483	2,389	4,637	4,619
DO Concentration, mg/L	1	2, 0.5	2, 0.5	1	1	2, 0.5	2, 0.5
Air Supply Rate, ft^3/min	336	589	572	352	325	567	560
BioWin SRT, days	5.25	23.35	24.71	5.25	5.25	16.55	17.41
RAS Recyle Rate	0.5Q	1.5Q	1.5Q	0.5Q	0.5Q	1.5Q	1.5Q
Pre - Anoxic Tank							
Tank Volume, MG		0.1	0.1				
HRT, hrs		2.4	2.4				
Internal Recycle Rate		5Q	5Q				
Post - Anoxic Tank							
Tank Volume, MG			0.05				
HRT, hrs			1.2				
Membrane Bioreactor							
Tank Volume, MG		0.02	0.02			0.02	0.02
No. of Cassettes		4	4			4	4
Area of each Cassette, ft^2		16,320	16,320			16,320	16,320
HRT, hrs		0.48	0.48			0.48	0.48
MLSS Conc., mg/L		8,200	7,967			8,733	8,730
DO Concentration, mg/L		6	6			6	6
Air Supply Rate, ft^3/min		595.4	745			566	871
Membrane Flux, gpd/ft^2		15.31	15.31			15.31	15.31

Description	WET SEASON - AWW FLOWS						
	Existing CAS Plant	Upgraded Plant					
		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals							
TIN (mg/L)		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature							
Influent Flow, mgd	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Temp, ^{o}C	10	10	10	10	10	10	10
Influent							
BOD	221	221	221	221	221	221	221
TSS	251	251	251	251	251	251	251
VSS	176	176	176	176	176	176	176
TKN	32	32	32	32	32	32	32
TP	7.6	7.6	7.6	7.6	7.6	7.6	7.6
Alkalinity	2.68	2.68	2.68	2.68	2.68	2.68	2.68
pH	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Primary Clarifier							
Area, ft^2	1,020	1,020	1,020	1,020	1,020	1,020	1,020
Surface Overflow Rate, gal/ft^2	734	734	734	734	734	734	734
Aerobic Tank							
Tank Volume, MG	0.2	0.2	0.2	0.2	0.2	0.2	0.2
HRT, hrs	6.4	6.4	6.4	6.4	6.4	6.4	6.4
MLSS Conc., mg/L	2,208	4,954	5,253	2,676	2,624	5,111	5,161
DO Concentration, mg/L	1	2, 0.5	2, 0.5	1	1	2, 0.5	2, 0.5
Air Supply Rate, ft^3/min	389	615	581	338	347	597	589
BioWin SRT, days	5.24	23.21	27.35	5.22	5.24	17.91	19.75
RAS Recyle Rate	0.5Q	1.5Q	1.5Q	0.5Q	0.5Q	1.5Q	1.5Q
Pre - Anoxic Tank							
Tank Volume, MG		0.1	0.1			0.1	0.1
HRT, hrs		3.2	3.2			3.2	3.2
Internal Recycle Rate		5Q	5Q			5Q	5Q
Post - Anoxic Tank							
Tank Volume, MG			0.05				0.05
HRT, hrs			1.6				1.6
Membrane Bioreactor							
Tank Volume, MG		0.02	0.02			0.02	0.02
No. of Cassettes		4	4			4	4
Area of each Cassette, ft^2		16,320	16,320			16,320	16,320
HRT, hrs		0.64	0.64			0.64	0.64
MLSS Conc., mg/L		8,247	8,746			8,520	8,385
DO Concentration, mg/L		6	6			6	6
Air Supply Rate, ft^3/min		512	569			508	588
Membrane Flux, gpd/ft^2		11.48	11.48			11.48	11.49

Description	DRY SEASON - ADW FLOWS						
	Existing CAS Plant	Upgraded Plant					
		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals							
TIN (mg/L)		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature							
Influent Flow, mgd	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Temp, ^{o}C	15	15	15	15	15	15	15
Influent							
BOD	331	331	331	331	331	331	331
TSS	376	376	376	376	376	376	376
VSS	263	263	263	263	263	263	263
TKN	48	48	48	48	48	48	48
TP	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Alkalinity	4	4	4	4	4	4	4
pH	7	7	7	7	7	7	7
Primary Clarifier							
Area, ft^2	1,020	1,020	1,020	1,020	1,020	1,020	1,020
Surface Overflow Rate, gal/ft^2	490	490	490	490	490	490	490
Aerobic Tank							
Tank Volume, MG	0.2	0.2	0.2	0.2	0.2	0.2	0.2
HRT, hrs	9.6	9.6	9.6	9.6	9.6	9.6	9.6
MLSS Conc., mg/L	2,235	4,929	4,954	2,608	2,575	5,110	4,920
DO Concentration, mg/L	1	2, 0.5	2, 0.5	1	1	2, 0.5	2, 0.5
Air Supply Rate, ft^3/min	528	685	659	588	558	660	636
BioWin SRT, days	5.24	23.89	27.1	5.25	5.24	18.48	19.77
RAS Recyle Rate	0.5Q	1.5Q	1.5Q	0.5Q	0.5Q	1.5Q	1.5Q
Pre - Anoxic Tank							
Tank Volume, MG		0.1	0.1			0.1	0.1
HRT, hrs		4.8	4.8			4.8	4.8
Internal Recycle Rate		5Q	5Q			5Q	5Q
Post - Anoxic Tank							
Tank Volume, MG			0.05				0.05
HRT, hrs			2.4				2.4
Membrane Bioreactor							
Tank Volume, MG		0.02	0.02			0.02	0.02
No. of Cassettes		4	4			4	4
Area of each Cassette, ft^2		16,320	16,320			16,320	16,320
HRT, hrs		0.96	0.96			0.96	0.96
MLSS Conc., mg/L		8,200	8,242			8,516	8,200
DO Concentration, mg/L		6	6			6	6
Air Supply Rate, ft^3/min		450	461			456	482
Membrane Flux, gpd/ft^2		7.65	7.65			7.65	7.66

TABLE 5-2
CONVENTIONAL ACTIVATED SLUDGE PLANT BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

	PROCESS DESIGN - MMWW FLOWS							WET SEASON - AWW FLOWS							DRY SEASON - ADW FLOWS						
	Existing CAS Plant	Upgraded Plant						Existing CAS Plant	Upgraded Plant						Existing CAS Plant	Upgraded Plant					
Description		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Clarifier																					
Area, ft^2	1,450			1,450	1,450			1,450			1,450	1,450			1,450			1,450	1,450		
Surface Overflow Rate, gal/ft^2	689			689	689			517			517	517			345			345	345		
Tertiary Filters																					
Filter Area, ft2					552		552					552		552					552		552
Chemical Addition																					
Methanol, gpd			20				30			15				30			10				10
Alum Dosage, gpd				90	160	90	160				90	160	95	160				130	160	130	160
Magnesium Hydroxide Dosage, gpd				40	80	60	60					60	60	60				90	100	60	60
Magnesium Hydroxide Conc., meq/L												14,500	14,500	14,500				14,500	14,500	14,500	14,500
Anaerobic Digester																					
TSS wasted from Aerobic Tank, ppd	650	552	588	792	760	733	805	691	559	583	854	835	748	794	712	541	555	831	821	725	756
TSS loading to Digester, ppd	1,779	1,684	1,721	2,016	2,179	1,964	2,100	1,820	1,690	1,810	2,082	2,219	1,979	2,091	1,837	1,666	1,681	2,160	2,190	1,976	2,045
VS loading to Digester, ppd								1,254	1,107	1,176	1,255	1,283	1,133	1,159	1,255	1,090	1,097	1,259	1,269	1,112	1,119
Volume, MG	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Hydraulic Residence Time, days	19.8	19.8	19.8	19.7	19.8	19.8	19.8	26.3	26.4	26.4	26.3	24.8	26.3	26.2	39.1	39.4	39.4	39.1	37.3	39.3	39.3
Sludge Production																					
Sludge Production, ppd	936	975	993	1,136	1,283	1,188	1,312	931	955	1,015	1,154	1,262	1,179	1,290	913	955	924	1,186	1,243	1,191	1,241
Effluent																					
BOD, mg/L	6.79	0.85	1.1	6.12	6.79	0.86	1.42	5.14	0.84	0.93	4.8	2.56	0.87	1.51	3.61	0.79	0.81	3.4	2.1	0.9	0.94
TSS, mg/L	12.8	0.0	0.0	13.4	12.8	0	0	8.9	0.0	0.0	9.2	5.2	0.0	0.0	5.5	0.0	0.0	5.6	1.2	0.0	0
Total Phosphorous, mg/L	4.27	4.29	4.16	0.64	4.27	0.32	0.01	5.73	5.81	5.69	0.41	0.08	0.22	0.01	8.75	8.89	8.76	0.25	0.04	0.01	0.01
Ammonia N, mg/L	15	0.4	0.55	13.9	15	0.35	0.86	16.71	0.27	0.34	21.49	20.9	0.29	0.6	11.08	0.07	0.09	4.84	6.84	0.1	0.16
TIN, mg/L	15.59	4.29	1.78	15.48	15.59	4.64	3	21.45	5.26	1.61	21.64	21.63	5.5	2.83	32.89	7.81	1.76	32.87	32.52	7.94	2.2
pH	6.58	6.28	6.41	6.58	6.58	6.58	6.5	6.59	6.39	6.52	6.53	6.56	6.6	6.62	6.27	6.57	6.71	6.42	6.48	6.56	6.68
Recycle Loads																					
Nitrogen Recycle from Thickener, ppd	9.34	5.31	5.78	9.34	9.65	6	6.6	10.12	5.43	5.42	10.72	10.74	5.92	6.36	9.49	5.17	5.28	8.79	9	5.61	5.72
Nitrogen Recycle from Digester, ppd	34	24	25	33.2	33.37	25	26	35	25	24.33	35.7	36.7	27	25	34.41	24	24.22	34.6	33	24.5	25
Total Nitrogen Recycled, ppd	43.34	29.31	30.78	42.54	43.02	31	32.6	45.12	30.43	29.75	46.42	47.44	32.92	31.36	43.9	29.17	29.5	43.39	42	30.11	30.72
Total Phosphorus Recycle from Thickener, ppd	2.37	1.96	2.72	5.94	3.29	6	4.2	3.15	2.12	2.54	6.48	5.02	6.29	4.17	3.54	2.26	2.72	5.12	3.26	3.77	4.2
Total Phosphorus Recycle from Digester, ppd	14	10.42	13.67	19.3	12	17	8.4	15	11	13	20	21.3	18	8.4	15.82	11.27	13.38	21.9	8.07	8.1	8.4
Total Phosphorus Recycled, ppd	16.37	12.38	16.39	25.24	15.29	23	12.6	18.15	13.12	15.54	26.48	26.32	24.29	12.57	19.36	13.53	16.1	27.02	11.33	11.87	12.6
% TN Recycled	21.7%	14.7%	15.4%	21.3%	21.5%	15.5%	16.3%	22.6%	15.2%	14.9%	23.2%	23.7%	16.5%	15.7%	22.0%	14.6%	14.8%	21.7%	21.0%	15.1%	15.4%
% TP Recycled	34.4%	26.0%	34.5%	53.1%	32.1%	48.3%	26.5%	38.2%	27.6%	32.7%	55.7%	55.3%	51.1%	26.4%	40.7%	28.4%	33.8%	56.8%	23.8%	25.0%	26.5%

TABLE 5-21
CONVENTIONAL ACTIVATED SLUDGE PLANT BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

	PROCESS DESIGN - MMDW FLOWS							DRY SEASON - ADW FLOWS						
	Existing CAS Plant	Upgraded Plant						Existing CAS Plant	Upgraded Plant					
Description		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals														
TIN (mg/L)		< 8	< 3			< 8	< 3		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature														
Influent Flow, mgd	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Temp, ^{o}C	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Influent														
BOD	241	241	241	241	241	241	241	331	331	331	331	331	331	331
TSS	273	273	273	273	273	273	273	376	376	376	376	376	376	376
VSS	191	191	191	191	191	191	191	263	263	263	263	263	263	263
TKN	35	35	35	35	35	35	35	48	48	48	48	48	48	48
TP	8.3	8.3	8.3	8.3	8.3	8.3	8.3	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Alkalinity	2.92	2.92	2.92	2.92	2.92	2.92	2.92	4	4	4	4	4	4	4
pH	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Primary Clarifier														
Area, ft^2	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020	1,020
Surface Overflow Rate, gal/ft^2	676	676	676	676	676	676	676	490	490	490	490	490	490	490
Aerobic Tank														
Tank Volume, MG	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
HRT, hrs	7.0	7.0	7.0	7.0	7.0	7.0	7.0	9.6	9.6	9.6	9.6	9.6	9.6	9.6
MLSS Conc., mg/L	2,185	3,280	3,239	2,489	2,542	3,758	3,558	2,235	3,388	3,334	2,608	2,575	4,014	3,553
DO Concentration, mg/L	1	2	2, 0.5, 2	1	1	2	2, 0.5, 2	1	2, 0.5	2, 0.5, 2	1	1	2, 0.5	2, 0.5, 2
Air Supply Rate, ft^3/min	514	710	697	624	562	700	720	528	715	677	588	558	720	691
BioWin SRT, days	5.24	13.95	15.24	5.24	5.24	13.95	14.49	5.24	13.96	15	5.25	5.24	13.78	14.31
RAS Recyle Rate	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q
Pre - Anoxic Tank														
Tank Volume, MG		0.1	0.1			0.1	0.1		0.1	0.1			0.1	0.1
HRT, hrs		3.5	3.5			3.5	3.5		4.8	4.8			4.8	4.8
Internal Recycle Rate		5Q	5Q			5Q	5Q		5Q	5Q			5Q	5Q
Post - Anoxic Tank														
Tank Volume, MG			0.05				0.05			0.05				0.05
HRT, hrs			1.7				1.7			2.4				2.4
Clarifier														
Area, ft^2	1,450	1,450	1,450	1,450	1,450	1,450	1,450	1,450	1,450	1,450	1,450	1,450	1,450	1,450
Surface Overflow Rate, gal/ft^2	476	476	476	476	476	476	476	345	345	345	345	345	345	345

TABLE 5-21

CONVENTIONAL ACTIVATED SLUDGE PLANT BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

	PROCESS DESIGN - MMDW FLOWS							DRY SEASON - ADW FLOWS						
	Existing CAS Plant	Upgraded Plant						Existing CAS Plant	Upgraded Plant					
Description		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F		Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Tertiary Filters														
Filter Area (ft^2)					380		380					380		380
Chemical Addition														
Methanol, gpd			15				15			10				10
Alum Dosage, gpd				95	160	100	175				130	160	130	175
Magnesium Hydroxide Dosage, gpd				120	120	80	120				90	100	80	100
Magnesium Hydroxide Conc., meq/L											14500	14500	14,500	14,500
Anaerobic Digester														
TSS wasted from Aerobic Tank, ppd	695	557	600	792	809	638	682	712	575	617	831	821	691	690
TSS loading to Digester, ppd	1,825	1,683	1,729	2,090	2,200	1,941	2,073	1,837	1,699	1,741	2,160	2,190	2,019	2,061
VS loading to Digester, ppd								1,255	1,111	1,134	1,259	1,269	1,134	1,123
Volume, MG	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Hydraulic Residence Time, days	28.5	28.7	28.7	28.5	28.5	28.7	27.3	39.1	39.5	39.5	39.1	37.3	39.3	37.5
Sludge Production														
Sludge Production, ppd	934	912	927	1,156	1,278	1,141	1,264	913	899	910	1,186	1,243	1,171	1,234
Effluent														
BOD, mg/L	4.61	3.26	3.16	4.38	2.34	3.12	1.58	3.61	2.44	2.32	3.4	2.1	2.23	1.28
TSS, mg/L	8	8.5	8.5	0.2	1.8	8.8	5.3	5.5	5.8	5.8	5.6	1.2	5.9	6.0
Total Phosphorous, mg/L	6.29	6.43	6.09	0.32	0.05	0.28	0.06	8.75	8.39	8.47	0.25	0.04	0.45	0.05
Ammonia N, mg/L	8.95	0.58	0.21	2.02	3.93	0.67	0.27	11.08	0.42	0.14	4.84	6.84	0.36	0.22
TIN, mg/L	23.66	5.31	1.93	23.29	22.92	5.06	2.08	32.89	7.24	1.99	32.87	32.52	7.34	2.38
pH	6.23	6.29	6.38	6.61	6.57	6.67	6.52	6.27	6.38	6.52	6.42	6.48	6.64	6.52
Recycle Loads														
Nitrogen Recycle from Thickener, ppd	9.04	5.72	5.88	8.31	8.56	5.73	5.88	9.49	5.87	5.99	8.79	9	5.92	5.88
Nitrogen Recycle from Digester, ppd	35	27	28	33.5	31	24	26	34.41	27.5	28	34.6	33	27	24.29
Total Nitrogen Recycled, ppd	44.04	32.72	33.88	41.81	39.56	29.73	31.88	43.9	33.37	33.99	43.39	42	32.92	30.17
Total Phosphorus Recycle from Thickener, ppd	3.18	2.17	4.1	4.88	3.31	3.52	3.27	3.54	2.35	4.4	5.12	3.26	4.4	3.36
Total Phosphorus Recycle from Digester, ppd	15	12	21	21	8.38	13.8	8.37	15.82	15.5	22.6	21.9	8.07	18.66	8.36
Total Phosphorus Recycled, ppd	18.18	14.17	25.1	25.88	11.69	17.32	11.64	19.36	17.85	27	27.02	11.33	23.06	11.72
% TN Recycled	22.0%	16.4%	16.9%	20.9%	19.8%	14.9%	15.9%	22.0%	16.7%	17.0%	21.7%	21.0%	16.5%	15.1%
% TP Recycled	38.2%	29.8%	52.8%	54.4%	24.6%	36.4%	24.5%	40.7%	37.5%	56.8%	56.8%	23.8%	48.5%	24.6%

CHAPTER 6.
TECHNOLOGICAL EVALUATION
FOR SEQUENCING BATCH REACTOR PLANTS

6.1 BASE CASE/EXISTING SYSTEM

A base case model was developed in Biowin representing a sequencing batch reactor (SBR) plant with capacity for an MMWWF of 1.0 mgd. Unlike a typical extended aeration plant, where screened wastewater is aerated in a reactor sized for large retention time, followed by settlement of the biomass in a separate tank (final clarifier), in the SBR system, filling, reacting and settling of the biomass all take place in the same reactor tank, over sequential time periods.

It is assumed that the existing SBR system performs BOD removal and nitrification. Each of two SBR tanks operates on an 8-hour cycle, with 75 percent of the time for fill and react modes, 18.75 percent for settling, and 6 percent for decanting. The cycles of the two SBR tanks are offset 4 hours from one another. Only the liquid treatment process of the SBR was modeled; recycle flows and loads were assumed to be the same as those calculated for the extended aeration plant models.

Figure 6-1 represents the process flow schematic for the modeled existing SBR system. Table 6-1 summarizes the design data. SBR plants, in general are effective in removing nitrogen and biological phosphorus without the addition of chemicals. Biowin modeling of the base case SBR plant predicted an effluent TP concentration of less than 1.0 mg/L and a total inorganic nitrogen concentration of less than 10 mg/L. However, to be conservative, effluent TP from the existing plant was assumed to be 2 mg/L for the evaluation of process alternatives to achieve nutrient removal objectives.

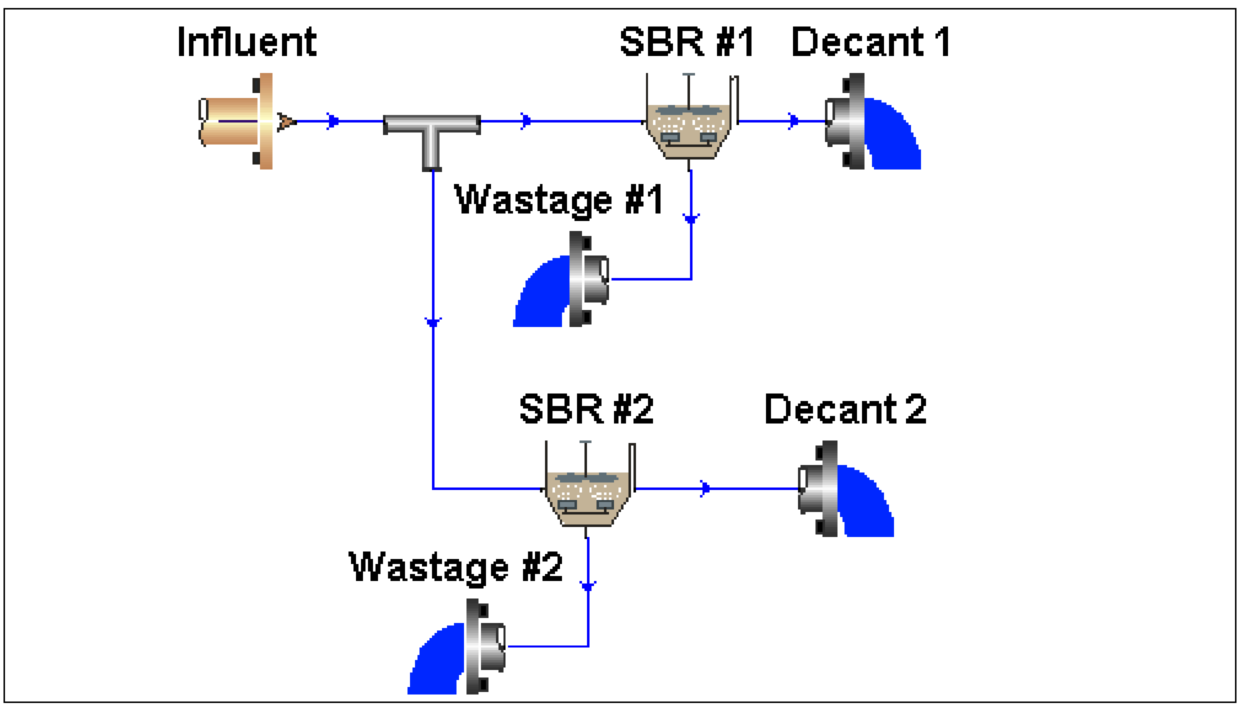


Figure 6-1. Process Flow Schematic of Sequencing Batch Reactor Treatment Plant

TABLE 6-1.
BASE CASE/EXISTING SYSTEM FOR SEQUENCING BATCH REACTOR PLANT

Influent + Recycle Flow	1.021 mgd
Temperature	10ºC
SBR Tank	
No of Tanks	2
Each Tank Volume	0.50 MG
HRT	23.5 hours
MLSS Concentration	3,000 mg/L
DO Concentration	2 mg/L
Air Supply Rate	720 cfm
Cycle Time	8 hours
SRT	16 days
Chemical Addition	
Magnesium Hydroxide Dosage	40 gpd
Effluent	
BOD	4.5 mg/L
TSS	16.0 mg/L
Phosphorous	2 mg/L
Ammonia N	5.2 mg/L
TIN	9.4 mg/L
pH	6.4

6.2 YEAR-ROUND NUTRIENT REMOVAL

Improvements required to provide year-round nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 6-2, which is attached at the end of this chapter.

6.2.1 Objective A

Process Description

Total inorganic nitrogen (TIN) effluent concentration as modeled for the existing system is 9.4 mg/L. TIN could be reduced to the Objective A target of 8 mg/L by increasing the volume of each existing SBR tank from 0.5 MG each to 0.65 MG. It was assumed that required additional volume would be provided by enlarging the footprint the existing tanks; at some facilities, the additional volume might be achievable by raising the walls of the existing tank or a combination of increasing the footprint and raising the tank walls. At some facilities, it might be appropriate to provide increased volume by constructing an additional SBR tank. Magnesium hydroxide would need to be applied to maintain the pH of the system at or above 6.5 and to balance the alkalinity.

Recycled Loads

The TN and TP recycle loads for SBR plants are same as for extended aeration plants. Refer to the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Since the solids treatment process was not included in the SBR model, extended aeration model solids treatment removal rates were used to estimate the daily sludge production values. Based on the amount of sludge wasted per day and using the removal efficiencies from the extended aeration model, the annual average quantity of sludge produced by the complete existing SBR plant is 1,118 ppd dry solids; this is equivalent to 0.89 tons of dry solids per million gallons of wastewater treated on an annual basis. The modeled upgraded SBR plant to achieve Objective A would 1,074 ppd dry solids, which is equivalent to 0.86 tons of dry solids per million gallons of wastewater treated. Therefore, upgrading SBR plant to achieve Objective A would result in a 4-percent reduction in annual quantity of sludge produced by the plant. This is equivalent to a reduction in sludge production of approximately 71 pounds (0.036 tons) per million gallons of wastewater treated.

Energy Consumption

Upgrading the 1-mgd model SBR plant secondary treatment process to achieve Objective A year-round would increase the total plant energy requirements by 11,000 kW-hours/year, or about 1 percent, as shown in Table 6-3. There would be a slight decrease in the energy requirements for solids processes as a result of the reduced volatile solids loading on the aerobic digester. The annual energy consumption for the upgraded plant would increase by about 48 kW-hours per million gallons of influent wastewater treated.

TABLE 6-3.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective A Year-Round	1,025,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	11,000 kW-hours/year
Percent	1%
Increase per Volume of Plant Flow	48 kW-hours/MG

Chemical Usage

The model predicts that both the existing and the upgraded SBR plants would need supplemental addition of alkalinity to sustain the nitrification process and to maintain the pH of the secondary effluent above 6.5. Upgrade of the existing SBR plant to achieve Objective A would reduce the quantity of supplemental alkalinity addition by 7.6 percent on an annual flow basis. The existing SBR plant would require approximately 52 gallons of magnesium hydroxide per million gallons treated on an annual basis and the upgraded SBR plant would require only 48 gallons per million gallons of wastewater treated.

Footprint Requirements

Increasing the volume of the SBR tanks to achieve Objective A would require additional site area, as indicated in Table 6-4.

TABLE 6-4.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE A YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
0.5	1,500
1.0	3,000
2.0	6,000
10	30,000

6.2.2 Objective B

Process Description

The upgrade evaluated for an SBR plant to achieve Objective B (TIN <3 mg/L) includes increasing SBR tank volume as identified for Objective A, installing denitrification filters, and providing a methanol feed and storage tank system for a carbon source to drive the denitrification process. If the existing plant does not have an equalization basin, then a new equalization tank is needed to maintain a relatively constant flow to the denitrification filters. Biowin does not have an option to size and model denitrification filters, so they were sized separately. Table 6-2 summarizes the process design data.

Denitrification filters are used as a polishing treatment process for nitrogen removal. The denitrification filters remove nitrate-nitrogen by the biologically mediated process that converts the nitrate-nitrogen to nitrogen gas and concurrently removes suspended solids from the secondary effluent stream. Two types of denitrification filters are available:

- Downflow continuous backwash filters—Downflow denitrification filters operate in a conventional filtration mode and consist of media and support gravel supported by an underdrain. Denitrification takes place through the filter system due to limited or anoxic conditions, and the nitrate-nitrogen is converted to nitrogen gas, which is embedded in the filter media and removed through nitrogen-release cycles. The piping for the filter influent and backwash is similar to that of conventional filters. Backwash is required at regular intervals.
- Upflow filters—In an upflow filter, wastewater moves up through the filter media and filtrate is discharged from the upper portion.

Downflow denitrification filters were assumed for the Objective B upgrade, with two duty filters at an application rate of 3 gallons per minute per square foot (gpm/ft^2). The filters were sized for 115 percent capacity, which included a 5-percent capacity allowance for backwashing. The filters were sized as follows:

- MMWWF = 1 mgd (694.4 gpm)
- Design the filter at 110% of MMWWF capacity
- Provide 5% allowance for backwashing
- Design capacity + Backwash = 798.6 gpm
- Filter Application Rate = 3 gpm/ft^2
- Required Filter Area = 266.2 square feet

- Area of each Filter = 133.1 square feet

The head loss of the system increases as the nitrogen gas accumulates in the filter media. This requires periodic release of the nitrogen gas during backwashes. This can be achieved by removing a reactor from service and applying backwash water for a short period of time. Therefore, three filters are needed, in order to provide continuous filtration. The total filter area with three filters—two operating and one for backwash—would be 400 square feet.

The equalization tank would need to be sized to store one SBR decant volume during peak flow. The total number of cycles in a day for each SBR tank is three (each cycle is eight hours). With two SBR tanks, the plant performs a total of six cycles per day. Thus, for a peak flow of 1.72 mgd, the required volume of the equalization tank is 1.72 mgd ÷ 6 cycles per day, or approximately 0.3 MG.

Methanol feed and storage tanks systems would be sized as described in Chapter 4 for upgrading the extended aeration systems.

Recycled Loads

The TN and TP recycle loads for SBR plants would be the same as presented for upgraded extended aeration plants meeting this objective. Refer to the Chapter 4 extended aeration Objective B recycle loads discussion.

Sludge Production

Since the Objective B SBR system was not modeled using Biowin, it was assumed that the difference in sludge produced compared to an existing SBR would be similar to the difference between the Objective B extended aeration system (951 ppd) and the existing extended aeration system (949 ppd). This 2-ppd difference was added to the existing SBR average daily sludge value (1,118 ppd) to yield an average sludge production rate for Objective B SBRs of 1,120 ppd. The average sludge production increase associated with achieving Objective B would be negligible at less than 0.2 percent. The increased sludge production associated with upgrading the existing plant to achieve Objective B would be equivalent to approximately 1.8 pounds per million gallons of wastewater treated on an annual basis.

Energy Consumption

The upgraded plant to achieve Objective B will consume approximately 16 percent more energy than the existing SBR plant, as shown in Table 6-5. This increase in energy consumption is mostly attributable to the operation of the denitrification filters and the chemical feed systems. Energy requirements associated with the solids handling and dewatering processes would be approximately the same as for the existing plant.

Chemical Usage

The Objective B upgrade would require the same amount of alkalinity supplementation as the Objective A upgrade. It would reduce the annual quantity of alkalinity addition 7.6 percent, from about 52 gallons of magnesium hydroxide per million gallons treated for the existing plant to 48 gallons per million gallons treated for the upgraded plant. The methanol requirement for carbon supplementation to achieve Objective B year-round would be approximately 3,700 gallons of methanol per year, or 16 gallons per million gallons of wastewater treated.

**TABLE 6-5.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND**

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective A Year-Round	1,178,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	164,000 kW-hours/year
Percent	16%
Increase per Volume of Plant Flow	719 kW-hours/MG

Footprint Requirements

The additional process footprint area required to achieve Objective B would include the expansion of the SBR tanks as described for Objective A plus the area required for a secondary flow equalization tank, denitrification filters and methanol storage tanks and feed system. The footprint for the denitrification filters includes the filter column area, the area of internal recycle pumping, and the area of wash water pumping. Table 6-6 presents the additional footprint area required to upgrade the existing SBR plants to achieve Objective B year round for the four generic plant capacities.

**TABLE 6-6.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE B YEAR-ROUND**

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)				
	SBR Tank Expansion	Denitrification Filters	Methanol Storage & Feed	Equalization Basin	**Total**
0.5	1,500	1,200	400	1,500	**4,600**
1.0	3,000	2,400	600	3,000	**9,000**
2.0	6,000	4,000	800	6,000	**16,800**
10	30,000	9,000	1,000	16,000	**56,000**

6.2.3 Objective C

Process Description

The upgrade evaluated to achieve Objective C (TP <1 mg/L) includes adding alum for chemical precipitation of orthophosphate and magnesium hydroxide for pH control. The quantity of alum required to reduce TP to less than 1.0 mg/L from the assumed existing effluent concentration of 2.0 mg/L was calculated stochiometrically; no Biowin model was generated. Magnesium hydroxide dose was determined based on the alum-to-magnesium-hydroxide ratio applied to the extended aeration system Objective C upgrade presented in Chapter 4. For year-round nutrient removal, alum and magnesium hydroxide storage tanks were sized for maximum chemical consumption during MMWWF, AWWF or ADWF. Table 6-2 presents the alum and magnesium hydroxide dosage rates for the 1-mgd SBR plant.

Recycled Loads

The TN and TP recycle loads for SBR plants would be the same as for extended aeration plants. See the extended aeration recycled loads for Objective C discussions in Chapter 4 for a detailed description.

Sludge Production

Sludge production rates for the upgraded SBR plant achieving Objective C were extrapolated from the Biowin results for upgraded extended aeration plants. It was assumed that the difference in sludge produced compared to an existing SBR will be similar to the difference between the Objective C extended aeration system (1,201 ppd) and the existing extended aeration system (949 ppd). This 252-ppd difference was correlated to an average alum dose of 118 gpd, which equates to 2.14 pounds of additional dry sludge solids per gallon of alum applied. The SBR plant was determined to require only 21 percent of the alum dose needed for the extended aeration system. Thus the increase in sludge production for the 1-mgd SBR plant would be 53 ppd, or 4.7 percent. This represents 0.04 tons of dry solids per million gallons of wastewater treated.

Energy Consumption

There would be very little increase (less than 1 percent) in energy consumption for the upgraded SBR plant to achieve Objective C. As shown in Table 6-7, the incremental increase in the consumption of energy would be equivalent to 18 kW-hours per million gallons of wastewater treated.

**TABLE 6-7.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND**

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective C Year-Round	1,018,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	4,000 kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	18 kW-hours/MG

Chemical Usage

To meet Objective C would not require more alkalinity supplementation than required by the existing plant. Based on an existing final effluent total phosphorus concentration of 2 mg/L, the average annual alum usage would be approximately 40 gallons per million gallons of wastewater treated to achieve Objective C.

Footprint Requirements

Table 6-8 compares the secondary footprint area for existing SBR plants to the area required to achieve Objective C for the four plant capacities. The additional footprint area is required for alum storage and feed systems.

**TABLE 6-8.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE C YEAR-ROUND**

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
0.5	300
1.0	500
2.0	1,000
10	2,000

6.2.4 Objective D

Process Description

The upgrade evaluated to achieve Objective D (TP <0.1 mg/L) is to provide chemical precipitation using alum and magnesium hydroxide and to add final effluent flow equalization and tertiary filters to the existing SBR system. It is assumed that the phosphorus in the final effluent produced by the existing treatment plant is 2 mg/L.

Alum required to reduce TP from 2.0 mg/L to 0.1 mg/L was calculated stochiometrically as described in Chapter 4; no Biowin model was generated. Magnesium hydroxide dosage was determined based on extrapolation of the alum-to-magnesium-hydroxide ratio described in Objective C. For year-round nutrient removal, alum and magnesium hydroxide storage tanks were sized for maximum chemical consumption during MMWWF, AWWF or ADWF. Refer to Table 6-2 for alum and magnesium hydroxide dosage rates.

Recycled Loads

The TN and TP recycle loads for SBR plants would be the same as for extended aeration plants. See the extended aeration recycled loads for Objective D discussions in Chapter 4 for a detailed description.

Sludge Production

The methodology for determining the effect on sludge production of upgrading the existing SBR plant to achieve Objective D was similar to that described for Objective C. It was assumed that the difference in sludge produced by an upgraded SBR plant to achieve Objective D would be similar to an extended aeration plant achieving the same objective. The incremental increase in sludge production associated with upgrading an extended aeration plant to achieve Objective D year-round was determined to be approximately 1.9 pounds of additional sludge per gallon of alum applied. The 1-mgd SBR plant upgraded to achieve Objective D would require 24,445 gallons of alum, so the additional sludge produced would be 23.1 tons of dry solids per year. This corresponds to an annual sludge production increase of 202 pounds (0.10 tons) of additional dry solids per million gallons of influent wastewater treated, an increase of 18 percent.

Energy Consumption

As shown in Table 6-9, there would be a small increase in energy consumption to achieve Objective D for an SBR plant, principally due to operation of the filters.

TABLE 6-9.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective D Year-Round	1,038,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	24,000 kW-hours/year
Percent	2%
Increase per Volume of Plant Flow	105 kW-hours/MG

Chemical Usage

The average annual alum usage to meet Objective D year-round would be 107 gallons per million gallons of wastewater treated. Additional alkalinity supplementation would be required to compensate for the alum dose; the magnesium hydroxide usage would increase 13,700 gallons per year for the 1-mgd model plant, or an additional 60 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

The footprint expansion required for the year-round Objective D upgrade would be for the tertiary filters, the equalization storage, and the chemical storage tanks. Table 6-10 presents the increased footprint area required for the four generic plant capacities.

TABLE 6-10.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE D YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)			
	Alum Storage and Feed Systems	Equalization Basin	Filters	**Total**
0.5	300	1,500	420	**2,220**
1.0	520	3,000	830	**4,350**
2.0	1,000	6,000	1,660	**8,660**
10	2,500	16,000	8,300	**26,800**

6.2.5 Objective E

Process Description

Existing SBR plants can be upgraded to achieve Objective E (TIN <8 mg/L and TP <1 mg/L) by completing the upgrades described for both Objective A and Objective C. For the 1-mgd plant, the upgrade would be to increase the capacity of the two existing SBR tanks from 0.5 MG to 0.65 MG and to construct chemical feed and storage tank systems. Dosages rates for alum and magnesium hydroxide would be the same as presented in Table 6-2 for Objective B.

Recycled Loads

The TN and TP recycle loads for SBR plants were assumed to be the same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Sludge production rates for the upgraded SBR plant achieving Objective E were extrapolated from Biowin modeled results for upgraded extended aeration plants. It was assumed that the difference in sludge produced compared to an existing SBR will be similar to the sludge production difference between the extended aeration plant upgraded to achieve Objective E (1,201 ppd) and the existing extended aeration system (949 ppd). This 366-ppd of additional sludge per million gallons of wastewater treated is correlated to an average alum dose of 118 gpd, which equates to 1.9 pounds of additional dry sludge solids per gallon of alum applied. The SBR plant upgrade was determined to require only 33.8 percent of the alum dose needed to upgrade the extended aeration system for Objective E. The increased sludge production for a 1-mgd SBR plant would be only 76 ppd, or 6.7 percent. This represents an increase of 0.06 tons of dry solids per million gallons of wastewater treated.

Energy Consumption

As shown in Table 6-11, there would be a slight increase (<1%) in energy consumption for the plant upgraded to achieve Objective E. Although there would be more sludge generated by the upgraded plant, there would be slightly less energy required for the solids handling process due to the longer sludge age maintained in the SBR process.

TABLE 6-11.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective E Year-Round	1,017,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	3,000 kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	13 kW-hours/MG

Chemical Usage

To meet Objective E, the upgraded SBR plant would not require more alkalinity supplementation than required by the existing plant. The average annual alum usage to achieve Objective E would be approximately 40 gallons per million gallons of wastewater treated.

Footprint Requirements

The increased footprint requirements for upgrading the existing SBR plant to achieve Objective E would be for expansion of the SBR tankage as described for Objective A and for chemical storage and feeding systems as described for Objective C. Table 6-12 summarizes the footprint area requirement for the four generic plant capacities.

TABLE 6-12.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE E YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)		
	SBR Tank Expansion	Alum Storage and Feed Systems	**Total**
0.5	1,500	300	**1,800**
1.0	3,000	520	**3,520**
2.0	6,000	1,000	**7,000**
10	30,000	2,500	**32,500**

6.2.6 Objective F

Process Description

Objective F (TIN <3 mg/L and TP <0.1 mg/L) can be achieved by simultaneously completing the upgrades described for both Objective B and Objective D:

- Increase the volume of SBR tanks approximately 18 percent.
- Install denitrification filters.
- Add methanol as a supplemental carbon source.
- Add a flow equalization basin for secondary effluent decants from the SBR reactors to provide a relatively uniform rate of flow to the filters and to minimize the size and cost of the filtration facilities.
- Provide chemical precipitation using alum and expand alkalinity control using magnesium hydroxide.

Recycled Loads

The TN and TP recycle loads for SBR plants are same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Following the procedure outlined for the other objectives, upgrading the existing SBR plant to achieve Objective F would increase the annual sludge production approximately 17 percent on an annual basis, compared to the existing plant. This is equivalent to an annual increase of 190 pounds (0.095 tons) of sludge per million gallons wastewater treated. The increase would be primarily a consequence of precipitating phosphorus with alum.

Energy Consumption

Based on extended aeration total phosphorus removal results, 17 percent more energy would be required for the upgraded SBR plant to achieve Objective F than for the existing plant, as shown in Table 6-13. Although there would be more sludge generated by the upgraded plant, there would be slightly less energy required for solids handling due to the longer sludge age maintained in the SBR process.

**TABLE 6-13.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective F Year-Round	1,190,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	176,000 kW-hours/year
Percent	17%
Increase per Volume of Plant Flow	772 kW-hours/MG

Chemical Usage

The average annual alum usage for the upgraded SBR plant to meet Objective F would be 106.4 gallons per million gallons of wastewater treated. Magnesium hydroxide dosage would increase 39 percent, an incremental increase equivalent to 20 gallons per million gallons of wastewater treated.

Footprint Requirements

The increased process footprint requirements for upgrading the existing SBR plant to achieve Objective F would include: expansion of the SBR tankage and addition of denitrification filters and methanol storage and feedings system as described for Objective B; and addition of alum storage and feeding and tertiary filtration system as described for Objective D. For the purposes of this analysis, it was assumed that the tertiary filtration and denitrification filters would be a combined filtration system. Table 6-14 summarizes the footprint area requirement for the four generic plant capacities.

**TABLE 6-14.
ADDITIONAL PROCESS FOOTPRINT AREA REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE F YEAR-ROUND**

	Additional Area Required for Upgrade (square feet)					
Plant Design Capacity (mgd)	SBR Tank Expansion	Methanol Storage & Feed	Alum Storage and Feed Systems	Equalization Basin	Filters	**Total**
0.5	1,500	400	300	1,500	420	**4,120**
1.0	3,000	600	520	3,000	830	**7,950**
2.0	6,000	800	1,000	6,000	1,660	**15,460**
10	30,000	1,000	2,500	16,000	8,300	**57,800**

6.3 SEASONAL NUTRIENT REMOVAL

Improvements required to provide seasonal nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 6-15, which is attached at the end of this chapter.

6.3.1 Objective A

Process Description

The Objective A (TIN <8 mg/L) treatment process upgrades for seasonal nutrient removal would be the same as for year-round nutrient removal (the capacity of the existing aeration tanks would need to be increased) except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs would be based on ADWF instead of AWWF. Refer to Section 6.2.1 for detailed process description. Process design data are included in Table 6-15.

Recycled Loads

The TN and TP recycle loads for SBR plants are same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Sludge production would decrease approximately 4 percent during dry season with the operation of the Objective A upgraded plant. On an average annual basis, seasonal operation of the upgraded SBR plant to achieve Objective A would decrease sludge production about 2 percent, or 0.0175 tons of dry solids per million gallons of influent wastewater treated.

Energy Consumption

Upgrading the SBR plant secondary treatment process to achieve Objective A for dry-season nutrient removal would increase the total plant energy requirements by 5,000 kW-hours/year, or <1 percent, as shown in Table 6-16. There would be a slight decrease in the energy requirement for solids processes as a result of the reduced volatile solids loading. The annual energy consumption for the upgraded plant would increase by about 22 kW-hours per million gallons of influent wastewater treated.

TABLE 6-16.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective A Dry Season	1,019,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	5,000 kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	22 kW-hours/MG

Chemical Usage

The model predicts that the both the existing and the upgraded SBR plants would need supplemental addition of alkalinity to sustain the nitrification process and to maintain the pH of the secondary effluent above 6.5. Upgrade of the existing SBR plant to achieve Objective A seasonally would increase the annual quantity of supplemental alkalinity addition by 7.6 percent—an additional 4 gallons of magnesium hydroxide per million gallons treated per year.

Footprint Requirements

Process footprint requirements associated with upgrading an existing SBR plant to achieve Objective A seasonally would be the same as presented for year-round nutrient removal in Section 6.2.1. Refer to Table 6-4.

6.3.2 Objective B

Process Description

The Objective B (TIN <3 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. Refer to Section 6.2.2 for detailed process description. Process design data are included in Table 6-15.

Recycled Loads

The TN and TP recycle loads for SBR plants are same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

The sludge production would increase slightly as a result of seasonal implementation of Objective B—about 0.1 percent on an annual basis, or 0.9 pounds per million gallons of influent wastewater treated. This would be an annual increase of only 205 pounds of dry solids for an upgraded 1-mgd SBR plant.

Energy Consumption

Upgrading the SBR plant secondary treatment process to achieve Objective B for dry-season nutrient removal would increase the total plant energy requirements by 67,000 kW-hours/year, or about 7 percent, as shown in Table 6-17. There would be slight decrease in the energy requirements for solids processes as a result of the reduced volatile solids loading on the aerobic digester. The annual energy consumption for the upgraded plant would increase by about 294 kW-hours per million gallons of influent wastewater treated.

TABLE 6-17.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective B Dry Season	1,081,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	67,000 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	294 kW-hours/MG

Chemical Usage

Upgrade of the existing SBR plant to achieve Objective B would reduce the quantity of supplemental alkalinity required by 15.4 percent on an annual flow basis. The upgraded plant would require an additional 8 gallons of magnesium hydroxide per million gallons treated on an annual basis. It also would require the addition of methanol at a rate of approximately 8 gallons of methanol per million gallons of wastewater treated on an annual basis.

Footprint Requirements

Table 6-18 presents the additional footprint area required for upgrading existing SBR plants to achieve Objective B on a dry weather season basis for the four generic plant capacities.

TABLE 6-18.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE B SEASONALLY

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)				
	SBR Tank Expansion	Denitrification Filters	Methanol Storage & Feed	Equalization Basin	**Total**
0.5	1,500	800	400	1,000	3,800
1.0	3,000	1,700	600	2,000	7,300
2.0	6,000	2,800	800	4,200	13,800
10	30,000	6,300	1,000	11,200	48,500

6.3.3 Objective C

Process Description

The Objective C (TP <1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF.

Recycled Loads

The TN and TP recycle loads for SBR plants are assumed to be same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Sludge production for the upgraded 1-mgd SBR plant to achieve Objective C seasonally would be 53 ppd greater than for the existing plant during the dry weather season, a 2.3-percent increase in the annual mass of sludge produced by the plant. The increase represents 42.4 pounds (0.02 tons) of dry solids per million gallons of influent wastewater treated on an annual basis.

Energy Consumption

Upgrading the SBR plant secondary treatment process to achieve Objective C for dry season nutrient removal would slightly reduce the total plant energy requirements as shown in Table 6-19.

TABLE 6-19.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective C Dry Season	1,009,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(5000) kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	(22) kW-hours/MG

Chemical Usage

Upgrade of the existing SBR plant to achieve Objective C would require an additional 8 gallons of magnesium hydroxide per million gallons treated on an annual basis. The upgrade would require the addition of alum to remove phosphorus at an average rate of 66 gallons per million gallons of wastewater treated during seasonal dry weather, or 26.4 gallons per million gallons of wastewater treated on an annual basis.

Footprint Requirements

The site area requirements to accommodate the process upgrades to achieve Objective C on a seasonal basis would be the same as for the Objective C year-round upgrade.

6.3.4 Objective D

Process Description

The Objective D (TP <0.1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. Refer to Section 6.2.4 for detailed process description. Process design data are included in Table 6-15.

Recycled Loads

The TN and TP recycle loads for SBR plants are same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Sludge production for the upgraded 1-mgd SBR plant to achieve Objective D on a seasonal dry weather basis would be approximately 126 ppd greater than for the existing plant during the dry weather season, a 5.6 percent increase in the annual mass of sludge produced. This represents 101 pounds (0.05 tons) of dry solids per million gallons of influent wastewater treated on an annual basis.

Energy Consumption

As shown in Table 6-20, there would be a small increase in energy consumption to achieve Objective D seasonally for an SBR plant, principally due to the operation of the filters.

TABLE 6-20.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective D Dry Season	1,024,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	10,000 kW-hours/year
Percent	1%
Increase per Volume of Plant Flow	44 kW-hours/MG

Chemical Usage

The average annual alum usage to achieve Objective D seasonally would be 26.8 gallons per million gallons of wastewater treated. The magnesium hydroxide usage would increase 3,650 gallons per year for the 1-mgd model plant, or an additional 16 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

The footprint expansion required for the seasonal Objective D upgrade would be for the tertiary filters, the equalization storage, and the chemical storage tanks. Table 6-21 presents the increased footprint area required for the four generic plant capacities.

TABLE 6-21.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE D SEASONALLY

Plant Design	Additional Area Required for Upgrade (square feet)			
Capacity (mgd)	Alum Storage and Feed Systems	Equalization Basin	Filters	**Total**
0.5	300	1,100	320	**1,720**
1.0	520	2,250	630	**3,400**
2.0	1,000	4,500	1,250	**7,650**
10	2,500	12,000	6,300	**20,800**

6.3.5 Objective E

Process Description

The Objective E (TIN <8 mg/L and TP <1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. Refer to Section 6.2.5 for detailed process description. Process design data are included in Table 6-15.

Recycled Loads

The TN and TP recycle loads for SBR plants are same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Sludge production for the 1-mgd SBR plant upgraded to achieve Objective E on a seasonal basis would be 76 ppd greater than for the existing plant, a 3.3 percent increase in the annual mass of sludge produced. This represents an increase of 61 pounds (0.03 tons) of dry solids per million gallons of influent wastewater treated on an annual basis.

Energy Consumption

As shown in Table 6-22 there would be a slight reduction (<1%) in the energy consumption by the upgraded plant to achieve Objective E on a seasonal dry weather basis. Although there would be more sludge generated by the upgraded plant, there would be slightly less energy required for the solids handling process due to the longer sludge age maintained in the SBR process.

TABLE 6-22.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE E SEASONAL

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective E Dry Season	1,008,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(6,000) kW-hours/year
Percent	<-1%
Increase per Volume of Plant Flow	(26) kW-hours/MG

Chemical Usage

The upgrade to achieve Objective E on a seasonal basis would require the addition of alum and magnesium hydroxide, and the usage rates would be equivalent to those required to achieve Objective C on a seasonal basis. Methanol would not be required.

Footprint Requirements

The increased footprint requirements associated with upgrading the existing SBR plant to achieve Objective E during seasonal dry weather would be for expansion of the SBR tankage as described for Objective A and for chemical storage and feeding systems as described for Objective C. Table 6-23 summarizes the footprint area requirement for upgrading existing SBR plant to achieve Objective E for the four generic plant capacities.

TABLE 6-23.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE E SEASONALLY

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)		
	SBR Tank Expansion	Alum Storage and Feed Systems	**Total**
0.5	1,500	300	**1,800**
1.0	3,000	520	**3,520**
2.0	6,000	1,000	**7,000**
10	30,000	2,500	**32,500**

6.3.6 Objective F

Process Description

The Objective F (TIN <3 mg/L and TP <0.1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round nutrient removal except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. Refer to Section 6.2.6 for detailed process description. Process design data are included in Table 6-15.

Recycled Loads

The TN and TP recycle loads for SBR plants are same as for extended aeration plants. See the extended aeration recycled loads discussions in Chapter 4 for a detailed description.

Sludge Production

Sludge production for the 1-mgd SBR plant upgraded to achieve Objective F on a seasonal dry weather basis would be 119 ppd greater than for the existing plant, a 5.3-percent in the annual mass of sludge produced by the plant. This represents an increase of 95 pounds (0.048 tons) of dry solids per million gallons of influent wastewater treated on an annual basis.

Energy Consumption

Although there would be more sludge generated by the upgraded plant, there would be slightly less energy required for the solids handling process due to the longer sludge age maintained in the SBR. The effect of upgrading the existing SBR plant to achieve Objective F on a seasonal basis would increase the annual power requirements approximately 7 percent or 311 kW-hours per million gallons of influent wastewater treated on an annual basis, as shown in Table 6-24.

Chemical Usage

The average annual alum usage to achieve Objective F seasonally would be 134 gallons per million gallons of wastewater treated during the dry season, or 84 gallons per million gallons of influent wastewater treated on an annual basis. Magnesium hydroxide dosage would increase 19 percent on an annual basis, which equates to an incremental increase of 8 gallons per million gallons of influent wastewater treated. Methanol would be required as a supplemental carbon source to drive the denitrification process in the filters. Methanol usage would be equal to 8 gallons per million gallons of influent wastewater treated on an annual basis.

TABLE 6-24.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE F SEASONAL

Yearly Energy Required	
Existing SBR Plant	1,014,000 kW-hours/year
Objective F Dry Season	1,190,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	71,000 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	311 kW-hours/MG

Footprint Requirements

The increased process footprint requirements associated with upgrading the existing SBR plant to achieve Objective F for dry season nutrient removal would include: expansion of the SBR tankage and addition of denitrification filters and methanol storage and feedings system as described for Objective B; and addition of alum storage and feeding and tertiary filtration system as described for Objective D. For the purposes of this analysis, it was assumed that the tertiary filtration and denitrification filters would be a combined filtration system. Table 6-25 summarizes the footprint area requirement for the four generic plant capacities.

TABLE 6-25.
ADDITIONAL PROCESS FOOTPRINT AREA REQUIRED FOR UPGRADING SBR PLANTS TO ACHIEVE OBJECTIVE F SEASONALLY

	Additional Area Required for Upgrade (square feet)					
Plant Design Capacity (mgd)	SBR Tank Expansion	Methanol Storage & Feed	Alum Storage and Feed Systems	Equalization Basin	Filters	**Total**
0.5	1,500	400	300	1,100	320	**2,120**
1.0	3,000	600	520	2,250	630	**4,300**
2.0	6,000	800	1,000	4,500	1,250	**13,550**
10	30,000	1,000	2,500	12,000	6,300	**51,800**

TABLE 6-2.
SEQUENCING BATCH REACTOR PLANT BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

	PROCESS DESIGN - MMWW FLOWS							WET SEASON - AWW FLOWS							DRY SEASON - ADW FLOWS						
		Upgraded Plant							Upgraded Plant							Upgraded Plant					
Description	Existing SBR	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F	Existing SBR	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F	Existing SBR	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals																					
TIN (mg/L)		< 8	< 3			< 8	< 3		< 8	< 3			< 8	< 3		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1				< 1	< 0.1	< 1	< 0.1				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature																					
Influent + Recycle Flow, mgd	1.021	1.021	1.021	1.021	1.021	1.021	1.021	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Temp, ^{o}C	10	10	10	10	10	10	10	10	10	10	10	10	10	10	15	15	15	15	15	15	15
Influent with Recycle Loads																					
BOD	166	166	166	166	166	166	166	221	221	221	221	221	221	221	326	326	326	326	326	326	326
TSS	228	228	228	228	228	228	228	304	304	304	304	304	304	304	449	449	449	449	449	449	449
VSS	152	152	152	152	152	152	152	202	202	202	202	202	202	202	258	258	258	258	258	258	258
TKN	27.6	27.6	27.6	27.6	27.6	27.6	27.6	36.76	36.76	36.76	36.76	36.76	36.76	36.76	54.41	54.41	54.41	54.41	54.41	54.41	54.41
TP	6.8	7.64	8.09	8.05	8.31	8.43	7.6	9.16	11	11.52	10.72	11.02	10.06	10.09	13.52	17.99	17.72	16.08	14.97	16.48	14.94
Alkalinity	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.68	2.68	2.68	2.68	2.68	2.68	2.68	4	4	4	4	4	4	4
pH	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	7	7	7	7	7	7	7
SBR Tank																					
No of Tanks	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Each Tank Volume, MG	0.50	0.65	0.65	0.50	0.50	0.65	0.65	0.50	0.65	0.65	0.50	0.50	0.65	0.65	0.50	0.65	0.65	0.50	0.50	0.65	0.65
HRT, hrs	23.5	30.6	30.6	23.5	23.5	30.6	30.6	31.2	20.3	40.5	31.2	31.2	40.5	40.5	23.1	30.0	60.0	46.2	46.2	60.0	60.0
MLSS Conc., mg/L	3,000	2,800	2,800	3,000	3,000	2,800	2,800	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,500	3,300	3,300	3,500	3,500	3,300	3,300
DO Concentration, mg/L	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Air Supply Rate, ft3/min	720	840	840	720	720	840	840	780	900	900	780	780	900	900	1,050	1,180	1,180	1,050	1,050	1,180	1,180
Cycle Time, hrs	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SRT, days	16	20.8	20.8	16	16	20.8	20.8	16	20.8	20.8	16	16	20.8	20.8	16	20.8	20.8	16	16	20.8	20.8
Equalization Tank																					
Tank Volume, MG			0.3				0.3			0.3				0.3			0.3				0.3
Denite Filters																					
Required Area, SF			400				400			400				400			400				400
Methanol, gpd			20				20			15				15			10				10
Tertiary Filters																					
Filter Area (ft2) (From Capdet)					550		550					550		550					550		550
Chemical Addition																					
Alum Dosage, gpd				15	65	15	65				17	66	17	66				33	67	33	67
Magnesium Hydroxide Dosage, gpd	40	40	40	20	80	20	60	40	30	30	20	80	10	50	25	30	30	30	60	20	40
Effluent																					
BOD, mg/L	4.5	2.8	2.8	4.5	4.5	2.8	2.8	3.5	2.3	2.3	3.5	3.5	2.3	2.3	2.5	1.5	1.5	2.5	2.5	1.5	1.5
TSS, mg/L	16.0	10.0	10.0	16.0	16.0	10.0	10.0	10.5	7.3	7.3	10.5	10.5	7.3	7.3	6.6	5.0	5.0	6.6	6.6	5.0	5.0
Phosphorous (from Biowin), mg/L	0.875	0.65	0.65	1	0.1	0.65	0.65	0.61	0.5	0.5	0.61	0.61	0.5	0.5	0.4	3	3	0.4	0.4	3	3
Phosphorous (assumed), mg/L	2	2	2	1	0.1	1	0.1	2.67	2.67	2.67	1	0.1	1	0.1	4	4	4	1	0.1	1	0.1
Ammonia N, mg/L	5.2	2	2	5.2	5.2	2	2	6.5	2.2	2.2	6.5	6.5	2.2	2.2	0.5	0.2	0.2	0.5	0.5	0.2	0.2
TIN, mg/L	9.4	6.9	3	9.4	9.4	6.9	3	11.8	7.9	3	11.8	11.8	7.9	3	9	7.4	3	9	9	7.4	3
pH	6.4	6.4	6.4	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.6	6.6	6.5	6.5	6.6	6.6

TABLE 6-15.
SEQUENCING BATCH REACTORS BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

	PROCESS DESIGN - MMDW FLOWS							DRY SEASON - ADW FLOWS						
		Upgraded Plant							Upgraded Plant					
Description	Existing SBR	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F	Existing SBR	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Nutrient Removal Goals														
TIN (mg/L)		< 8	< 3			< 8	< 3		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature														
Influent + Recycle Flow, mgd	1.021	1.021	1.021	1.021	1.021	1.021	1.021	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Temp, ^{o}C	10	10	10	10	10	10	10	15	15	15	15	15	15	15
Influent with Recycle Loads														
BOD	240	240	240	240	240	240	240	326	326	326	326	326	326	326
TSS	329	329	329	329	329	329	329	449	449	449	449	449	449	449
VSS	219	219	219	219	219	219	219	258	258	258	258	258	258	258
TKN	40	40	40	40	40	40	40	54.41	54.41	54.41	54.41	54.41	54.41	54.41
TP	9.9	12.21	12.5	11.73	10.98	12.95	10.98	13.52	17.99	17.72	16.08	14.97	16.48	14.94
Alkalinity	2.92	2.92	2.92	2.92	2.92	2.92	2.92	4	4	4	4	4	4	4
pH	7	7	7	7	7	7	7	7	7	7	7	7	7	7
SBR Tank														
No of Tanks	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Each Tank Volume, MG	0.50	0.65	0.65	0.50	0.50	0.65	0.65	0.50	0.65	0.65	0.50	0.50	0.65	0.65
HRT, hrs	23.5	30.6	30.6	23.5	23.5	30.6	30.6	23.1	30.0	60.0	46.2	46.2	60.0	60.0
MLSS Conc., mg/L	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,500	3,300	3,300	3,500	3,500	3,300	3,300
DO Concentration, mg/L	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Air Supply Rate, ft3/min	1,020	1,120	1,120	1,020	1,020	1,120	1,120	1,050	1,180	1,180	1,050	1,050	1,180	1,180
Cycle Time, hrs	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SRT, days	16	20.8	20.8	16	16	20.8	20.8	16	20.8	20.8	16	16	20.8	20.8
Equalization Tank														
Tank Volume, MG			0.3				0.3			0.3				0.3
Denite Filters														
Required Area, SF			276				276			276				276
Methanol, gpd			15				15			10				10
Tertiary Filters														
Filter Area (ft2) (to be filled)					380		380					380		380
Chemical Addition														
Alum Dosage, gpd				20	66	20	66				33	67	33	67
Magnesium Hydroxide Dosage, gpd	40	30	30	30	70	20	50	25	30	30	30	60	20	40
Effluent														
BOD, mg/L	4.5	1.5	1.5	4.5	4.5	1.5	1.5	2.5	1.5	1.5	2.5	2.5	1.5	1.5
TSS, mg/L	9.5	6.0	6.0	9.5	9.5	6.0	6.0	6.6	5.0	5.0	6.6	6.6	5.0	5.0
Phosphorous (from Biowin), mg/L	0.52	3.75	3.75	0.52	0.52	3.75	3.75	0.4	3	3	0.4	0.4	3	3
Phosphorous (assumed), mg/L	3	3	3	1	0.1	1	0.1	4	4	4	1	0.1	1	0.1
Ammonia N, mg/L	0.5	0.3	0.3	0.5	0.5	0.3	0.3	0.5	0.2	0.2	0.5	0.5	0.2	0.2
TIN, mg/L	8	6.8	3	8	8	6.8	3	9	7.4	3	9	9	7.4	3
pH	6.3	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.6	6.6	6.5	6.5	6.6	6.6

CHAPTER 7.
TECHNOLOGICAL EVALUATION FOR TRICKLING FILTER, TRICKLING FILTER/SOLIDS CONTACT AND ROTATING BIOLOGICAL CONTACTOR PLANTS

7.1 BASE CASE/EXISTING SYSTEM

It is assumed that the base case for this category is a plant that consists of the following:

- A headworks with coarse screening system
- Primary clarifiers
- Secondary treatment system consisting of trickling filters (TF), rotating biological contactors (RBC) or trickling filters with solids contact (TF/SC)
- Secondary clarifiers.

Biowin cannot model trickling filter or RBC plants. For the purposes of this report, the existing and upgraded plant data for this category are assumed to be the same as for the conventional activated sludge plants discussed in Chapter 5, except as noted in this chapter.

Cost models for the base case were developed using CapdetWorks. Primary and secondary treatment facility sizing for a 1.0-mgd existing plant were modeled as follows:

- Trickling Filter—Based on the CapdetWorks cost model, a 1.0-mgd trickling filter plant consists of two primary clarifiers, each 26 feet in diameter, one trickling filter 34.3 feet in diameter, and two secondary clarifiers, each 36 feet in diameter.
- Rotating Biological Contactor—Based on the CapdetWorks cost model, a 1.0-mgd RBC plant consists of two primary clarifiers, each 26 feet in diameter, and two secondary clarifiers, each 36 feet in diameter. The RBC size was not listed in the CapdetWorks Model. A detention time of 1.44 hours was used for the RBC tank per Metcalf & Eddy.
- Trickling Filter/Solids Contact—Based on the CapdetWorks cost model, a 1.0-mgd trickling filter/solids contact plant consists of two primary clarifiers, each 26 feet in diameter, one trickling filter 34.3 feet in diameter, two 215-square-foot aeration tanks, and two secondary clarifiers, each 21 feet in diameter.

Table 7-1 shows the secondary footprint area for existing TF, RBC and TF/SC plants for the three generic plant capacities. The existing secondary area for TF and TF/SC plants includes the trickling filters and the secondary clarifiers. The existing secondary area for RBC plants includes the RBC tanks and the secondary clarifiers..

7.2 YEAR-ROUND NUTRIENT REMOVAL

Improvements required to provide year-round nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 5-2, which is attached at the end of Chapter 5.

TABLE 7-1. FOOTPRINT COMPARISON FOR EXISTING TRICKLING FILTER, ROTATING BIOLOGICAL CONTACTOR, AND TRICKLING FILTER/SOLIDS CONTACT SYSTEMS			
Plant Design	Existing Secondary Area (square feet)		
Capacity (mgd)	TF	RBC	TF/SC
1	6,750	10,190	4,120
10	60,550	80,590	33,980
150	897,340	1,180,480	500,940

7.2.1 Objective A

Process Description

The upgrade evaluated to achieve Objective A (TIN <8 mg/L) includes demolition of the existing secondary treatment process facilities (RBC, trickling filters, solids contact tanks and clarifiers) and construction of new aeration, anoxic tanks and membrane tanks. The existing headworks coarse screen would be replaced with a fine screen system in order to protect the downstream membranes. The aeration treatment process would be an MLE-MBR process, as described for the CAS system in Section 5.2.1. The new tanks to be constructed include a 0.2-MG aeration tank, a 0.1-MG anoxic tank, and a 20,000-gallon MBR tank. The existing aeration tank volume should also be added to the total tank volume for the upgrade. Figure 5-2 shows the process flow schematic for the upgraded plant.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective A year-round treatment for a conventional activated sludge system, as described in Section 5.2.1 and listed in Table 5-3.

Sludge Production

Sludge production would be the same as estimated for Objective A year-round treatment for a conventional activated sludge system, as described in Section 5.2.1.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective A year-round would change the plant energy requirements as shown in Table 7-2, 7-3 or 7-4, respectively.

Chemical Usage

Chemical use would be the same as estimated for Objective A year-round treatment for a conventional activated sludge system, as described in Section 5.2.1.

Footprint Requirements

The proposed secondary footprint includes a new anoxic tank, aeration tank, MBR tank, aeration blower building, MBR blower building and RAS pump building. Table 7-5 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective A year-round for the three generic plant capacities. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems.

**TABLE 7-2.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective A Year-Round	674,600 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	468,800 kW-hours/year
Percent	228%
Increase per Volume of Plant Flow	2,055 kW-hours/MG

**TABLE 7-3.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective A Year-Round	656,100 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	514,400 kW-hours/year
Percent	363%
Increase per Volume of Plant Flow	2,295 kW-hours/MG

**TABLE 7-4.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective A Year-Round	704,100 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	391,300 kW-hours/year
Percent	125%
Increase per Volume of Plant Flow	1,715 kW-hours/MG

**TABLE 7-5.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE A YEAR-ROUND**

	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	1,089	(2,352)	3,724
10	3,049	(16,988)	29,621
150	(27,443)	(310,583)	368,953

7.2.2 Objective B

Process Description

The upgrade evaluated for achieving Objective B (TIN <3 mg/L) is to demolish the existing secondary treatment process facilities and construct new aeration, anoxic tanks and membrane tanks. The headworks coarse screen would be replaced with fine screen system in order to protect the downstream membranes. The aeration treatment process would be a 4-stage Bardenpho-MBR process as described for the CAS system in Section 5.2.2. The new tanks to be constructed include a 0.2-MG aeration tank, a 0.1-MG anoxic tank, a 0.05-MG post-anoxic tank, and a 20,000-gallon MBR tank. The existing aeration tank volume should also be added to the total tank volume for the upgrade. Figure 5-3 shows the upgraded process flow schematic.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective B year-round treatment for a conventional activated sludge system, as described in Section 5.2.2 and listed in Table 5-6.

Sludge Production

Sludge production would be the same as estimated for Objective B year-round treatment for a conventional activated sludge system, as described in Section 5.2.2.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective B year-round would change the plant energy requirements as shown in Table 7-6, 7-7 or 7-8, respectively.

Chemical Usage

Chemical use would be the same as estimated for Objective B year-round treatment for a conventional activated sludge system, as described in Section 5.2.2.

Footprint Requirements

The proposed secondary footprint includes new anoxic tank, aeration tank, post anoxic tank, MBR tank, aeration blower building, MBR blower building, RAS pump building, and methanol containment tank. Table 7-9 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective B year-round for the three generic plant capacities. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems.

TABLE 7-6.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective B Year-Round	779,100 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	573,300 kW-hours/year
Percent	279%
Increase per Volume of Plant Flow	2,513 kW-hours/MG

TABLE 7-7.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective B Year-Round	760,600 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	618,900 kW-hours/year
Percent	437%
Increase per Volume of Plant Flow	2,713 kW-hours/MG

TABLE 7-8.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective B Year-Round	808,600 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	495,800 kW-hours/year
Percent	159%
Increase per Volume of Plant Flow	2,174 kW-hours/MG

TABLE 7-9.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE B YEAR-ROUND

	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	2,396	(1,045)	5,031
10	11,761	(8,276)	38,333
150	(56,192)	(339,332)	340,204

7.2.3 Objective C

Process Description

Objective C (TP <1.0 mg/L) can be achieved by adding new alum storage tanks and feed system for phosphorus removal and magnesium hydroxide for pH control. Biowin cannot model TF/RBC plants, so alum and magnesium hydroxide dosages are assumed to be same as for the CAS system Objective C upgrade described in Section 5.2.3. No modifications to the solids treatment process are proposed.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective C year-round treatment for a conventional activated sludge system, as described in Section 5.2.3 and listed in Table 5-9.

Sludge Production

Sludge production would be the same as estimated for Objective C year-round treatment for a conventional activated sludge system, as described in Section 5.2.3.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective C year-round would change the plant energy requirements as shown in Table 7-10, 7-11 or 7-12, respectively.

TABLE 7-10.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective C Year-Round	220,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	14,300 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	62 kW-hours/MG

TABLE 7-11.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective C Year-Round	168,700 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	27,000 kW-hours/year
Percent	19%
Increase per Volume of Plant Flow	118 kW-hours/MG

TABLE 7-12.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective C Year-Round	326,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	13,700 kW-hours/year
Percent	4%
Increase per Volume of Plant Flow	60 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective C year-round treatment for a conventional activated sludge system, as described in Section 5.2.3.

Footprint Requirements

The total additional area required for alum and magnesium hydroxide containment tanks to achieve Objective C year-round is 186 square feet for a 1.0-mgd plant. Refer to Appendix B for detailed storage tank calculations.

7.2.4 Objective D

Process Description

Objective D (TP <0.1 mg/L) can be achieved by adding tertiary filters in addition to a chemical precipitation process using alum and magnesium hydroxide. Alum and magnesium hydroxide dosages are assumed to be same as for the CAS system Objective D upgrade described in Section 5.2.4. No modifications to the solids treatment process are proposed.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective D year-round treatment for a conventional activated sludge system, as described in Section 5.2.4 and listed in Table 5-12.

Sludge Production

Sludge production would be the same as estimated for Objective D year-round treatment for a conventional activated sludge system, as described in Section 5.2.4.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective D year-round would change the plant energy requirements as shown in Table 7-13, 7-14 or 7-15, respectively.

Chemical Usage

Chemical use would be the same as estimated for Objective D year-round treatment for a conventional activated sludge system, as described in Section 5.2.4.

Footprint Requirements

The total additional area required for the tertiary filters and the alum and magnesium hydroxide containment tanks is 762 square feet for a 1.0-mgd plant. Refer to Appendix B for detailed storage tank calculations and Appendix C for tertiary filter footprint requirements.

TABLE 7-13. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND	
Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective D Year-Round	234,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	28,600 kW-hours/year
Percent	14%
Increase per Volume of Plant Flow	125 kW-hours/MG

TABLE 7-14. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND	
Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective D Year-Round	177,900 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	36,200 kW-hours/year
Percent	26%
Increase per Volume of Plant Flow	159 kW-hours/MG

TABLE 7-15. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND	
Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective D Year-Round	335,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	22,700 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	100 kW-hours/MG

7.2.5 Objective E

Process Description

Objective E (TIN <8 mg/L and TP <1.0 mg/L) can be achieved by converting the existing plant to an MLE-MBR process and by adding alum and magnesium hydroxide feed systems and storage tanks for phosphorus removal, as described in Section 5.2.5.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective E year-round treatment for a conventional activated sludge system, as described in Section 5.2.5 and listed in Table 5-15.

Sludge Production

Sludge production would be the same as estimated for Objective E year-round treatment for a conventional activated sludge system, as described in Section 5.2.5.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective E year-round would change the plant energy requirements as shown in Table 7-16, 7-7 or 7-18, respectively.

TABLE 7-16.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective E Year-Round	690,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	484,700 kW-hours/year
Percent	236%
Increase per Volume of Plant Flow	2,125 kW-hours/MG

TABLE 7-17.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective E Year-Round	690,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	548,800 kW-hours/year
Percent	387%
Increase per Volume of Plant Flow	2,046 kW-hours/MG

TABLE 7-18.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective E Year-Round	690,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	377,700 kW-hours/year
Percent	121%
Increase per Volume of Plant Flow	1,656 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective E year-round treatment for a conventional activated sludge system, as described in Section 5.2.5.

Footprint Requirements

The proposed secondary footprint includes new anoxic tank, aeration tank, MBR tank, aeration blower building, MBR blower building, RAS pump building and containment tanks for alum and magnesium hydroxide storage. Table 7-19 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective E year-round for the three generic plant capacities. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems.

TABLE 7-19.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE E YEAR-ROUND

	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	1,089	(2,352)	3,724
10	3,485	(16,553)	30,056
150	(26,136)	(309,276)	370,260

7.2.6 Objective F

Process Description

Objective F (TIN <3 mg/L and TP <0.1 mg/L) can be achieved by converting the existing plant to a 4-stage Bardenpho process and by adding alum and magnesium hydroxide feed systems and storage tanks for phosphorus removal, as described in Section 5.2.6.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective F year-round treatment for a conventional activated sludge system, as described in Section 5.2.6 and listed in Table 5-18.

Sludge Production

Sludge production would be the same as estimated for Objective F year-round treatment for a conventional activated sludge system, as described in Section 5.2.6.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective F year-round would change the plant energy requirements as shown in Table 7-20, 7-21 or 7-22, respectively.

Chemical Usage

Chemical use would be the same as estimated for Objective F year-round treatment for a conventional activated sludge system, as described in Section 5.2.6.

**TABLE 7-20.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective F Year-Round	820,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	614,500 kW-hours/year
Percent	300%
Increase per Volume of Plant Flow	2,694 kW-hours/MG

**TABLE 7-21.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective F Year-Round	820,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	678,600 kW-hours/year
Percent	479%
Increase per Volume of Plant Flow	2,975 kW-hours/MG

**TABLE 7-22.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective F Year-Round	820,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	507,500 kW-hours/year
Percent	162%
Increase per Volume of Plant Flow	2,225 kW-hours/MG

Footprint Requirements

The proposed secondary footprint includes new anoxic tank, aeration tank, post anoxic tank, MBR tank, aeration blower building, MBR blower building, RAS pump building and alum, magnesium hydroxide and methanol containment tanks. Table 7-23 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective F year-round for the three generic plant capacities. Refer to Appendix C for a detailed footprint summary of the existing and upgraded systems.

TABLE 7-23. ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE F YEAR-ROUND			
	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	3,703	261	6,338
10	23,522	3,485	50,094
150	120,661	(162,479)	517,057

7.3 SEASONAL NUTRIENT REMOVAL

Improvements required to provide seasonal nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 5-21, which is attached at the end of Chapter 5.

7.3.1 Objective A

Process Description

The Objective A (TIN <8 mg/L) treatment process for seasonal nutrient removal would be an MLE system. The improvements would be essentially the same as described for CAS seasonal treatment in Section 5.3.1.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective A seasonal treatment for a conventional activated sludge system, as described in Section 5.3.1 and listed in Table 5-22.

Sludge Production

Sludge production would be the same as estimated for Objective A seasonal treatment for a conventional activated sludge system, as described in Section 5.3.1.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective A seasonally would change the plant energy requirements as shown in Table 7-24, 7-25 or 7-26, respectively.

TABLE 7-24. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE A SEASONALLY	
Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective A Seasonal	370,250 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	164,500 kW-hours/year
Percent	80%
Increase per Volume of Plant Flow	721 kW-hours/MG

TABLE 7-25.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

Yearly Energy Required	
Existing RBC Plant	205,900 kW-hours/year
Objective A Seasonal	351,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	210,100 kW-hours/year
Percent	148%
Increase per Volume of Plant Flow	921 kW-hours/MG

TABLE 7-26.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective A Seasonal	399,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	87,000 kW-hours/year
Percent	28%
Increase per Volume of Plant Flow	381 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective A seasonal treatment for a conventional activated sludge system, as described in Section 5.3.1.

Footprint Requirements

Table 7-27 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective A seasonally for the three generic plant capacities. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 7-27.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE A SEASONALLY

	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	3,267	(174)	5,902
10	27,878	7,841	54,450
150	352,836	69,696	749,232

7.3.2 Objective B

Process Description

The Objective B (TIN <3 mg/L) treatment processes for seasonal nutrient removal would be to upgrade to a four-stage Bardenpho process with the addition of methanol. The improvements would be essentially the same as described for CAS seasonal treatment in Section 5.3.2.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective B seasonal treatment for a conventional activated sludge system, as described in Section 5.3.2 and listed in Table 5-25.

Sludge Production

Sludge production would be the same as estimated for Objective B seasonal treatment for a conventional activated sludge system, as described in Section 5.3.2.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective B seasonally would change the plant energy requirements as shown in Table 7-28, 7-29 or 7-30, respectively.

TABLE 7-28.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective B Seasonal	384,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	178,500 kW-hours/year
Percent	87%
Increase per Volume of Plant Flow	782 kW-hours/MG

TABLE 7-29.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective B Seasonal	365,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	224,100 kW-hours/year
Percent	158%
Increase per Volume of Plant Flow	982 kW-hours/MG

TABLE 7-30.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective B Seasonal	413,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	101,000 kW-hours/year
Percent	32%
Increase per Volume of Plant Flow	443 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective B seasonal treatment for a conventional activated sludge system, as described in Section 5.3.2.

Footprint Requirements

Table 7-31 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective B seasonally for the three generic plant capacities. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 7-31.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE B SEASONALLY

	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	4,574	1,133	7,209
10	37,462	17,424	64,033
150	349,787	66,647	746,183

7.3.3 Objective C

Process Description

For Objective C (TP <1 mg/L), the only difference between the year-round and the seasonal nutrient removal is that the capital facilities would be sized for either MMDWF or ADWF instead of the MMWWF. The improvements would be essentially the same as for year-round treatment.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective C seasonal treatment for a conventional activated sludge system, as described in Section 5.3.3 and listed in Table 5-28.

Sludge Production

Sludge production would be the same as estimated for Objective C seasonal treatment for a conventional activated sludge system, as described in Section 5.3.3.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective C seasonally would change the plant energy requirements as shown in Table 7-32, 7-33 or 7-34, respectively.

TABLE 7-32.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective C Seasonal	220,400 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	14,600 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	64 kW-hours/MG

TABLE 7-33.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective C Seasonal	166,900 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	25,500 kW-hours/year
Percent	18%
Increase per Volume of Plant Flow	110 kW-hours/MG

TABLE 7-34.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective C Seasonal	327,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	14,400 kW-hours/year
Percent	5%
Increase per Volume of Plant Flow	63 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective C seasonal treatment for a conventional activated sludge system, as described in Section 5.3.3.

Footprint Requirements

The total additional area required for alum and magnesium hydroxide containment tanks to achieve Objective C seasonally is 186 square feet for a 1.0-mgd plant (the same as for Objective C year-round treatment). Refer to Appendix B for detailed storage tank calculations.

7.3.4 Objective D

Process Description

For Objective D (TP <0.1 mg/L), the only difference between the year-round and the seasonal nutrient removal is that the capital facilities would be sized for either MMDWF or ADWF instead of the MMWWF. The improvements would be essentially the same as for year-round treatment.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective D seasonal treatment for a conventional activated sludge system, as described in Section 5.3.4 and listed in Table 5-30.

Sludge Production

Sludge production would be the same as estimated for Objective D seasonal treatment for a conventional activated sludge system, as described in Section 5.3.4.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective D seasonally would change the plant energy requirements as shown in Table 7-35, 7-36 or 7-37, respectively.

TABLE 7-35.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective D Seasonal	223,100 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	17,300 kW-hours/year
Percent	8%
Increase per Volume of Plant Flow	76 kW-hours/MG

TABLE 7-36. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE D SEASONALLY	
Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective D Seasonal	166,900 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	25,200 kW-hours/year
Percent	18%
Increase per Volume of Plant Flow	110 kW-hours/MG

TABLE 7-37. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE D SEASONALLY	
Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective D Seasonal	327,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	14,400 kW-hours/year
Percent	5%
Increase per Volume of Plant Flow	63 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective D seasonal treatment for a conventional activated sludge system, as described in Section 5.3.4.

Footprint Requirements

Additional footprint area required for Objective D is the same as for Objective D seasonal treatment for a CAS plant, as listed in Table 5-32. This footprint includes alum, magnesium hydroxide containment tanks and tertiary filters.

7.3.5 Objective E

Process Description

The Objective E (TIN <8 mg/L and TP <1 mg/L) treatment process for seasonal nutrient removal would be essentially the same as described for CAS seasonal treatment in Section 5.3.5.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective E seasonal treatment for a conventional activated sludge system, as described in Section 5.3.5 and listed in Table 5-33.

Sludge Production

Sludge production would be the same as estimated for Objective E seasonal treatment for a conventional activated sludge system, as described in Section 5.3.5.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective E seasonally would change the plant energy requirements as shown in Table 7-38, 7-39 or 7-40, respectively.

**TABLE 7-38.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective E Seasonal	390,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	184,400 kW-hours/year
Percent	90%
Increase per Volume of Plant Flow	808 kW-hours/MG

**TABLE 7-39.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective E Seasonal	390,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	248,500 kW-hours/year
Percent	175%
Increase per Volume of Plant Flow	1,089 kW-hours/MG

**TABLE 7-40.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective E Seasonal	390,200 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	77,400 kW-hours/year
Percent	25%
Increase per Volume of Plant Flow	339 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective E seasonal treatment for a conventional activated sludge system, as described in Section 5.3.5.

Footprint Requirements

Table 7-41 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective E seasonally for the three generic plant capacities. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 7-41.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE E SEASONALLY

	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	3,267	(174)	5,902
10	29,621	9,583	56,192
150	375,487	92,347	771,883

7.3.6 Objective F

Process Description

The Objective F (TIN <3 mg/L and TP <0.1 mg/L) treatment process for seasonal nutrient removal would be essentially the same as described for CAS seasonal treatment in Section 5.3.6.

Recycled Loads

Recycled nutrient loads would be the same as estimated for Objective F seasonal treatment for a conventional activated sludge system, as described in Section 5.3.6 and listed in Table 5-36.

Sludge Production

Sludge production would be the same as estimated for Objective F seasonal treatment for a conventional activated sludge system, as described in Section 5.3.6.

Energy Consumption

Upgrading a TF plant, RBC plant or TF/SC plant to achieve Objective F seasonally would change the plant energy requirements as shown in Table 7-42, 7-43 or 7-44, respectively.

TABLE 7-42.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing TF Plant	205,800 kW-hours/year
Objective F Seasonal	414,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	208,600 kW-hours/year
Percent	101%
Increase per Volume of Plant Flow	914 kW-hours/MG

TABLE 7-43.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing RBC Plant	141,700 kW-hours/year
Objective F Seasonal	414,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	272,600 kW-hours/year
Percent	192%
Increase per Volume of Plant Flow	1,195 kW-hours/MG

TABLE 7-44.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing TF/SC Plant	312,800 kW-hours/year
Objective F Seasonal	414,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	101,500 kW-hours/year
Percent	32%
Increase per Volume of Plant Flow	445 kW-hours/MG

Chemical Usage

Chemical use would be the same as estimated for Objective F seasonal treatment for a conventional activated sludge system, as described in Section 5.3.6.

Footprint Requirements

Table 7-45 compares the additional site area requirements for upgrading existing TF, RBC and TF/SC plants to achieve Objective F seasonally for the three generic plant capacities. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 7-45.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING TF, RBC AND TF/SC PLANTS TO ACHIEVE OBJECTIVE F SEASONALLY

	Additional Area Required for Upgrade (square feet)		
Plant Design Capacity (mgd)	TF Plants	RBC Plants	TF/SC Plants
1	5,445	2,004	8,080
10	45,738	25,700	72,310
150	468,706	185,566	865,102

CHAPTER 8.
TECHNOLOGICAL EVALUATION FOR MEMBRANE BIOLOGICAL REACTOR PLANTS

8.1 BASE CASE/EXISTING SYSTEM

A base case model was developed in Biowin representing a membrane biological reactor (MBR) plant with a capacity of 1.0 mgd (MMWWF). Figure 8-1 depicts the process flow schematic for the modeled MBR plant. The plant features a pre-anoxic tank, an aeration tank, a post-anoxic tank and a membrane bioreactor. Waste sludge is mechanically thickened and then stabilized in an aerobic digester.

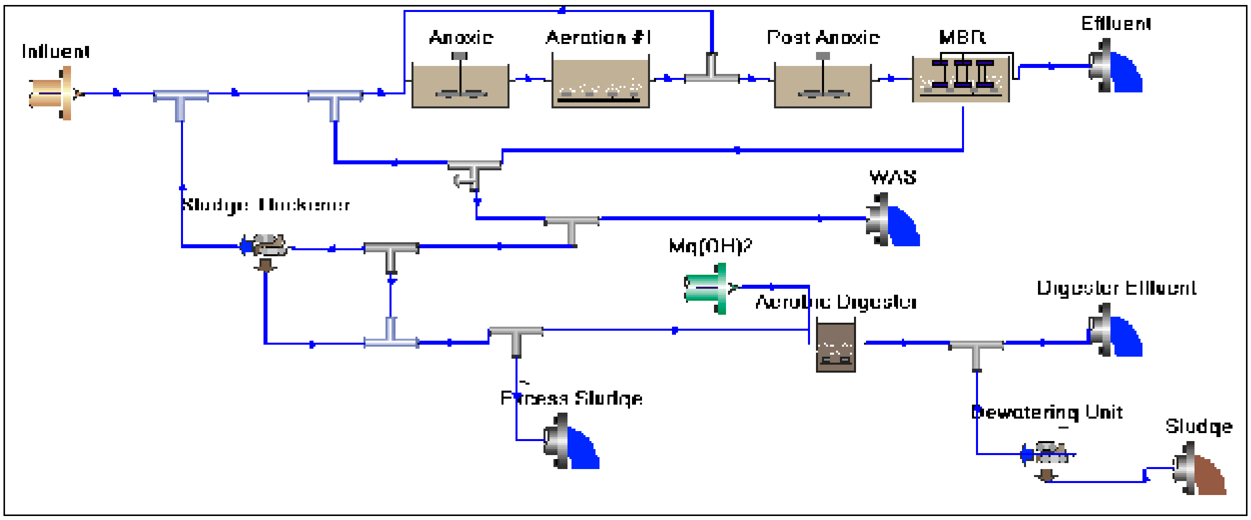


Figure 8-1. Process Flow Schematic for an Existing MBR Plant

Table 8-1 summarizes the assumed number of aeration tank trains and number of aerators per train, based on annual average plant capacity. According to the design criteria, the average annual flow for a plant with MMWWF of 1.0 mgd is 0.63 mgd. Therefore, the modeled 1.0-mgd plant has two aeration tank trains; it is assumed that each train will have two membrane tanks, for a total of four membrane tanks. One tank is assumed to be redundant, so the flow handled by each tank is calculated as the total flow divided by 3. The membranes were sized to achieve a peak-day flux of 20 gpd/ft^2. Table 8-2 shows the sizing and flux rate calculations for the 1.0-mgd plant and corresponding calculations for plants with capacities of 10 mgd and 100 mgd.

Using a packing density of 8.0 ft^2/ft^3, the volume of each membrane tank was determined to be 20,000 gallons. The total volume of the three firm membrane units is 60,000 gallons. This volume was used in the MBR Biowin model. The total tank volume of the modeled MBR process is 0.66 MG; the pre- and post-anoxic tanks each account for 18 percent of the total volume, the aerobic tank for 55 percent, and the MBR tanks for 9 percent.

Table 8-3 summarizes the existing MBR tank design data at MMWWF conditions. The Biowin model results indicate that the modeled MBR plant would produce a final effluent with a TIN concentration of 1.7 mg/L; however, to be conservative, it was assumed that the TIN in the effluent is just less than 8 mg/L.

TABLE 8-1.
NUMBER OF AERATION TANK TRAINS BASED ON TREATMENT PLANT AVERAGE ANNUAL FLOW

AAF (mgd)	No. of Aeration Tank Trains	No. of Tanks per Train
0.5 – 2	2	1
2 – 4	3	1
4 – 10	4	1
10 – 20	6	2
20 – 30	8	2
30 – 40	10	3
40 – 50	12	3
50 – 70	14	3
70 – 100	16	4

TABLE 8-2.
NUMBER OF TANKS TRAINS BASED ON PEAK PLANT CAPACITY

	MMWWF = 1 mgd	MMWWF = 10 mgd	MMWWF = 100 mgd
Average Annual Flow (mgd)	0.63	6.3	63
No. of Aeration Trains	2	4	16
No. of Membrane Tanks (N)	4	8	32
Peak Day Flow (mgd)	1.72	17.2	172
Peak Day Flux (gpd/ft^2)	20	20	20
Membrane Area (ft^2)	86,000	860,000	8,600,000
Area per Tank	21,500	107,500	268,750
No. of Membranes in operation (N-1)	3	7	31
MMWWF per train (mgd)	0.33	1.43	3.23
MMWWF Flux Rate (gpd/ft^2)	15.5	13.29	12

8.2 YEAR-ROUND NUTRIENT REMOVAL

Improvements required to provide year-round nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 8-4, which is attached at the end of this chapter.

8.2.1 Objective A

Because the existing system achieves Objective A (TIN <8 mg/L), no upgrades are required for this alternative. Operational changes should be performed if required to improve existing plant performance. Because no upgrade is required, the process flow schematic, process design data, recycled loads, sludge production, energy consumption, chemical usage and footprint requirements are all the same as for the existing MBR plant.

TABLE 8-3.
BASE CASE/EXISTING SYSTEM FOR MBR PLANT

Biowin Input Flow	1.0 mgd
Temperature	10 ºC
Aeration Tank	
Tank Volume	0.36 MG
HRT	8.64 hours
MLSS Concentration	5,073 mg/L
DO Concentration	2 mg/L
Aeration Tank Airflow Rate	697 cfm
SRT	23.01 days
RAS Recycle Rate	1.5 Q
Pre-Anoxic Tank	
Tank Volume	0.12 MG
HRT	2.88 hours
Internal Recycle Rate	4Q
Post-Anoxic Tank	
Tank Volume	0.12 MG
HRT	2.88 hours
Membrane Bioreactor	
Tank Volume	0.06 MG
No. of Cassettes	4.0
Area of each Cassette	16,320 ft^2
HRT	1.44 hours
MLSS Concentration	8,433 mg/L
DO Concentration	6.0 mg/L
Air Supply Rate	941 cfm
Membrane Flux	15.31 gpd/ft^2
Sludge Production	
Daily Sludge Production	930 ppd
Effluent	
BOD	0.87 mg/L
TSS	0.0 mg/L
Phosphorus	4.31 mg/L
Ammonia N	0.58 mg/L
TIN	1.71 mg/L (assumed to be <8 mg/L, to be conservative)
pH	6.53

8.2.2 Objective B

Process Description

The upgrade evaluated for achieving Objective B (TIN <3 mg/L) is to add methanol to the post-anoxic tank to drive the denitrification process. Figure 8-2 shows the upgraded process flow schematic. Except for the methanol storage tanks, the required facilities are same as the existing system.

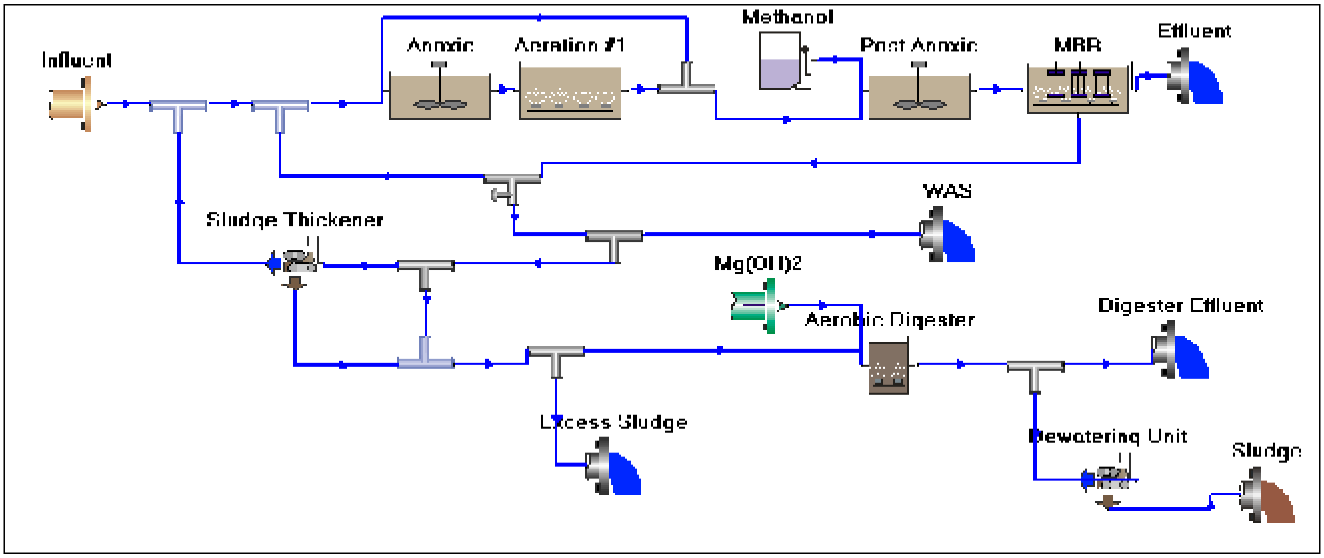


Figure 8-2. Process Schematic of MBR Plant Upgraded for Objective B Year-Round

The methanol dosage required to reduce TIN from 8 mg/L to 3 mg/L was calculated according to the dosage calculations described for extended aeration plants in Section 4.2.2. Methanol storage tanks were sized based on the methanol dosage required for the MMWWF. Table 8-4 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Waste sludge will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. The upgrades to achieve Objective B year-round will not change the estimated recycle loads.

Sludge Production

Based on modeling for Objective B upgrades to CAS and extended aeration systems, it is assumed that adding methanol will not change the sludge production compared to the existing plant.

Energy Consumption

Upgrading the MBR plant to achieve Objective B year-round would not change the plant energy requirements, as shown in Table 8-5.

TABLE 8-5.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing MBR Plant	1,213,800 kW-hours/year
Objective B Year-Round	1,213,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	0 kW-hours/year
Percent	0%
Increase per Volume of Plant Flow	0 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective B year-round would require 4,563 gallons of methanol per year for carbon supplementation to drive the denitrification process, or 20 gallons of methanol per million gallons of wastewater treated.

Footprint Requirements

Table 8-6 presents the additional site area that would be required for the three generic plant capacities. The additional footprint required for plant upgrades to achieve Objective B would be for a new methanol containment tank. Refer to detailed storage tank calculations in Appendix B.

TABLE 8-6.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING MBR PLANTS TO ACHIEVE OBJECTIVE B YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	600
10	1,000
100	3,300

8.2.3 Objective C

Process Description

The upgrade evaluated to achieve Objective C (TP <1 mg/L) is to provide addition of alum and magnesium hydroxide to the influent. Except for the addition of chemicals, the processes are the same as for the existing plant. Alum and magnesium hydroxide storage tanks were sized for the dosage required for MMWWF. Figure 8-3 depicts the upgraded process flow schematic. Table 8-4 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

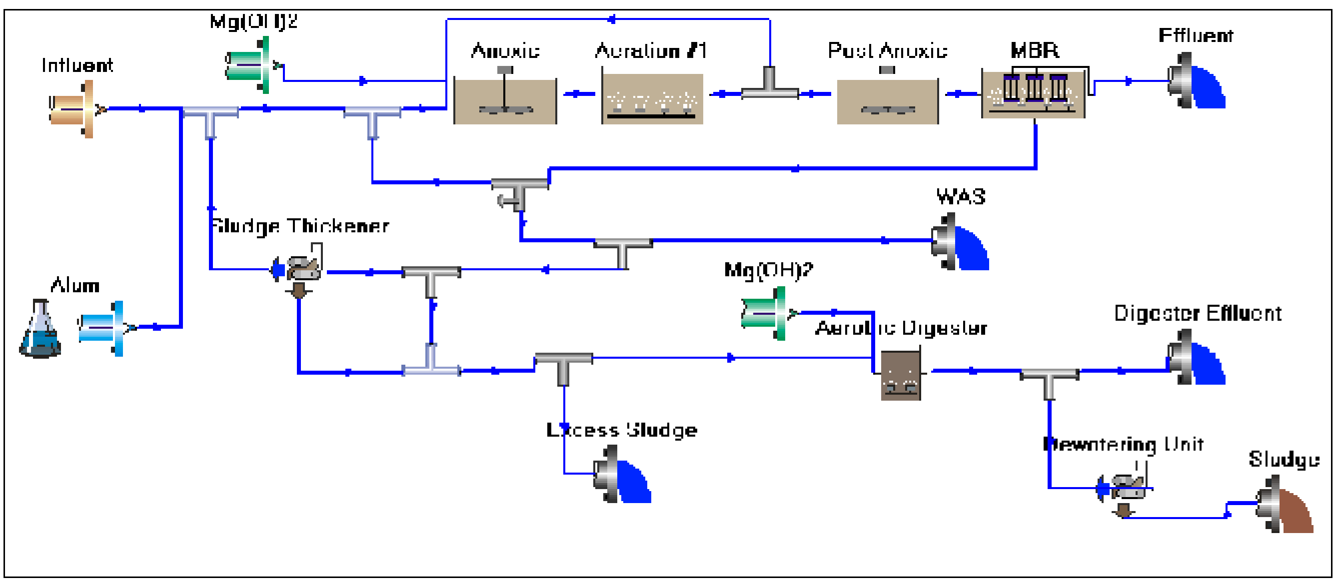


Figure 8-3. Process Schematic of MBR Plant Upgraded for Objective C Year-Round

Recycled Loads

Waste sludge will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 8-7 summarizes the results.

**TABLE 8-7.
NUTRIENT RECYCLING COMPARISON FOR MEMBRANE BIOLOGICAL REACTOR SYSTEMS, OBJECTIVE C YEAR-ROUND NUTRIENT REMOVAL**

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	15.0%	14.2%	29.7%	39.1%
Objective C Year-Round	16.3%	15.4%	47.3%	52.0%

Sludge Production

The average sludge produced with the Objective C upgrades would be 1,160 ppd (212 dry tons per year), 23 percent higher than the existing plant average of 940 ppd (172 dry tons per year).

Energy Consumption

Upgrading the MBR plant to achieve Objective C year-round would increase the plant energy requirements by 6,500 kW-hours/year, or about 0.5 percent, as shown in Table 8-8. There would be a net energy savings of 7,500 kW-hours/year associated with liquids treatment process and an additional energy requirement for the operation of solids processes of 14,000 kW-hours/year. The net increase amounts to about 29 kW-hours per million gallons of influent wastewater treated.

**TABLE 8-8.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND**

Yearly Energy Required	
Existing MBR Plant	1,213,800 kW-hours/year
Objective C Year-Round	1,220,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	6,500 kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	29 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective C year-round would require approximately 36,500 gallons of alum per year to precipitate phosphorus and approximately 7,300 gallons of magnesium hydroxide for pH control. These chemical usage rates equate to 159 gallons of alum per million gallons of wastewater treated and 32 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

Table 8-9 presents the additional site area that would be required for the three generic plant capacities. The additional footprint required for plant upgrades to achieve Objective C would be for containment tanks for alum and for magnesium hydroxide. Refer to detailed storage tank calculations in Appendix B.

TABLE 8-9.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING MBR PLANTS TO ACHIEVE OBJECTIVE C YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	500
10	2,000
100	11,000

8.2.4 Objective D

Process Description

The upgrade evaluated to achieve Objective D (TP <0.1 mg/L) is to provide addition of alum and magnesium hydroxide to the influent. Except for the addition of chemicals, the processes are the same as for the existing plant. Alum storage tanks were sized for the dosage required for ADWF and magnesium hydroxide storage tanks were sized for the dosage required for MMWWF. The process flow schematic is the same as for Objective C (Figure 8-3). Table 8-4 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Waste sludge will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 8-10 summarizes the results.

TABLE 8-10.
NUTRIENT RECYCLING COMPARISON FOR MEMBRANE BIOLOGICAL REACTOR SYSTEMS, OBJECTIVE D YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	15.0%	14.2%	29.7%	39.1%
Objective D	16.6%	15.5%	36.6%	48.2%

Sludge Production

The average sludge produced with the Objective D upgrades would be 1,240 ppd (226 dry tons per year), 32 percent higher than the existing plant average of 940 ppd (172 dry tons per year).

Energy Consumption

Upgrading the MBR plant to achieve Objective D year-round would reduce the plant energy requirements by 1,000 kW-hours/year, or <1 percent, as shown in Table 8-11. There would be a net energy savings of 10,000 kW-hours/year associated with liquids treatment process and an additional energy requirement for the operation of solids processes of 9,000 kW-hours/year. The net decrease amounts to about 4 kW-hours per million gallons of influent wastewater treated.

TABLE 8-11.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

Yearly Energy Required	
Existing MBR Plant	1,213,800 kW-hours/year
Objective D Year-Round	1,212,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(1000) kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	(4) kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective D year-round would require approximately 54,750 gallons of alum per year to precipitate phosphorus and approximately 14,600 gallons of magnesium hydroxide for pH control. These chemical usage rates equate to 238 gallons of alum per million gallons of wastewater treated and 63 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

Table 8-12 presents the additional site area that would be required for the three generic plant capacities. The additional footprint required for plant upgrades to achieve Objective D would be for containment tanks for alum and for magnesium hydroxide. Refer to detailed storage tank calculations in Appendix B.

TABLE 8-12.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING MBR PLANTS TO ACHIEVE OBJECTIVE D YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	500
10	2,000
100	11,000

8.2.5 Objective E

Because the existing system already achieves the Objective E TIN target (<8 mg/L), year-round treatment to achieve Objective E requires upgrade only to achieve the TP target (<1 mg/L) and is the same as the upgrade for Objective C year-round treatment. The process flow schematic is the same as for Objective C (Figure 8-3). Table 8-4 summarizes the process design data. Detailed Biowin model reports are in

Appendix A. The process flow schematic, process design data, recycled loads, sludge production, energy consumption, chemical usage and footprint requirements are all the same as for the year-round Objective C upgrade, as described in Section 8.2.3.

8.2.6 Objective F

Process Description

Objective F (TIN <3 mg/L and TP <0.1 mg/L) can be achieved by adding methanol to reduce TIN and adding alum and magnesium hydroxide to reduce TP. The process flow schematic for this alternative is combination of the schematics for Objectives B and D. Table 8-4 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Waste sludge will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 8-13 summarizes the results.

TABLE 8-13.
NUTRIENT RECYCLING COMPARISON FOR MEMBRANE BIOLOGICAL REACTOR SYSTEMS, OBJECTIVE F YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	15.0%	14.2%	29.7%	39.1%
Objective F Year-Round	16.6%	15.5%	36.6%	48.2%

Sludge Production

The average sludge produced with the Objective F upgrades would be 1,240 ppd (226 dry tons per year), 32 percent higher than the existing plant average of 940 ppd (172 dry tons per year).

Energy Consumption

Upgrading the MBR plant to achieve Objective F year-round would reduce the plant energy requirements by 1,000 kW-hours/year, or <1 percent, as shown in Table 8-11. There would be a net energy savings of 10,000 kW-hours/year associated with liquids treatment process and an additional energy requirement for the operation of solids processes of 9,000 kW-hours/year. The net decrease amounts to about 4 kW-hours per million gallons of influent wastewater treated.

Chemical Usage

The upgraded plant to achieve Objective F year-round would require about 54,750 gallons of alum per year to precipitate phosphorus, 14,600 gallons of magnesium hydroxide for pH control, and 4,562 gallons of methanol per year for nitrogen reduction. These chemical usage rates equate to 238 gallons of alum per million gallons of wastewater treated, 63 gallons of magnesium hydroxide per million gallons of wastewater treated, and 20 gallons of methanol per million gallons of wastewater treated.

TABLE 8-14.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

Yearly Energy Required	
Existing MBR Plant	1,213,800 kW-hours/year
Objective F Year-Round	1,212,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(1,000) kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	(4) kW-hours/MG

Footprint Requirements

Table 8-15 presents the additional site area that would be required for the three generic plant capacities. The additional footprint required for plant upgrades to achieve Objective F would be for containment tanks for alum, magnesium hydroxide and methanol. Refer to detailed storage tank calculations in Appendix B.

TABLE 8-15.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING MBR PLANTS TO ACHIEVE OBJECTIVE F YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
1	700
10	2,300
100	17,000

8.3 SEASONAL NUTRIENT REMOVAL

Improvements required to provide seasonal nutrient removal to achieve each treatment objective are described below. Process design data for all objectives are included in Table 8-16, which is attached at the end of this chapter.

8.3.1 Objective A

No upgrades are required to achieve Objective A (TIN <8 mg/L), as the existing system already meets the effluent target for TIN. Operational changes should be performed if required to improve existing plant performance. Because no upgrade is required, the process flow schematic, process design data, recycled loads, sludge production, energy consumption, chemical usage and footprint requirements are all the same as for the existing MBR plant.

8.3.2 Objective B

Process Description

The Objective B (TIN <3 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round Objective B nutrient removal (add methanol to the post-anoxic tank to drive the denitrification process) except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. Refer to Section 8.2.2 for detailed process description. Process design data are included in Table 8-16.

Recycled Loads

Seasonal treatment to achieve Objective B would not cause any change in recycled loads for an MBR plant.

Sludge Production

Seasonal treatment to achieve Objective B would not cause any change in sludge production for an MBR plant.

Energy Consumption

Seasonal treatment to achieve Objective B would not cause any change in energy consumption for an MBR plant.

Chemical Usage

The upgraded plant to achieve Objective B year-round would require 3,650 gallons of methanol per year for carbon supplementation to drive the denitrification process, or 16 gallons of methanol per million gallons of wastewater treated.

Footprint Requirements

The additional footprint requirements for achieving Objective B seasonally would be the same as for achieving this objective year-round.

8.3.3 Objective C

Process Description

The Objective C (TP <1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round Objective C nutrient removal (adding alum and magnesium hydroxide to reduce TP) except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. Refer to Section 8.2.3 for detailed process description. Process design data are included in Table 8-16.

Recycled Loads

Waste sludge will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 8-17 summarizes the results.

TABLE 8-17.
NUTRIENT RECYCLING COMPARISON FOR MEMBRANE BIOLOGICAL REACTOR SYSTEMS, OBJECTIVE C SEASONAL NUTRIENT REMOVAL

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	14.2%	39.1%
Objective C, Seasonal	15.4%	52.0%

Sludge Production

The average sludge produced with the Objective C seasonal upgrades would be 1,060 ppd (193 dry tons per year), 13 percent higher than the existing plant average of 940 ppd (172 dry tons per year).

Energy Consumption

Upgrading the MBR plant to achieve Objective C seasonally would increase the plant energy requirements by 2,000 kW-hours/year, or about <1%, as shown in Table 8-18. The annual energy consumption for the upgraded plant would increase by about 9 kW-hours per million gallons of influent wastewater treated.

TABLE 8-18.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing MBR Plant	1,213,800 kW-hours/year
Objective C Seasonal	1,215,800 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	2,000 kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	9 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective C seasonally would require chemical dosages during the dry season of 115 gpd of alum to precipitate phosphorus and 20 gpd of magnesium hydroxide for pH control. These rates equate to 20,990 gallons per year (91 gallons per million gallons of wastewater treated) of alum and 3,650 gallons per year (16 gallons per million gallons of wastewater treated) of magnesium hydroxide.

Footprint Requirements

The additional footprint requirements for achieving Objective C seasonally would be the same as for achieving this objective year-round.

Objective D

Process Description

The Objective D (TP <0.1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round Objective D nutrient removal (adding alum and magnesium hydroxide to reduce TP) except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs will be based on ADWF instead of AWWF. Refer to Section 8.2.4 for detailed process description. Process design data are included in Table 8-16.

Recycled Loads

Waste sludge will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 8-19 summarizes the results.

TABLE 8-19.
NUTRIENT RECYCLING COMPARISON FOR MEMBRANE BIOLOGICAL REACTOR SYSTEMS, OBJECTIVE D SEASONAL NUTRIENT REMOVAL

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	14.2%	39.1%
Objective D, Seasonal	15.5%	48.2%

Sludge Production

The average sludge produced with the Objective D seasonal upgrades would be 1,087 ppd (198 dry tons per year), 16 percent higher than the existing plant average of 940 ppd (172 dry tons per year).

Energy Consumption

Upgrading the MBR plant to achieve Objective D seasonally would slightly decrease the plant energy requirements as shown in Table 8-20. Although there would be a net decrease in energy requirements for the plant as a whole, the energy requirements of the solids treatment process would increase 2,500 kW-hour/year. The annual energy consumption for the upgraded plant would decrease by about 7 kW-hours per million gallons of influent wastewater treated.

TABLE 8-20.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing MBR Plant	1,213,800 kW-hours/year
Objective D Seasonal	1,212,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(1,500) kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	(7) kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective D seasonally would require chemical dosages during the dry season of 150 gpd of alum to precipitate phosphorus and 30 gpd of magnesium hydroxide for pH control. These rates equate to 27,380 gallons per year (119 gallons per million gallons of wastewater treated) of alum and 5,475 gallons per year (24 gallons per million gallons of wastewater treated) of magnesium hydroxide.

Footprint Requirements

The additional footprint requirements for achieving Objective D seasonally would be the same as for achieving this objective year-round.

8.3.5 Objective E

Because the existing system already achieves the Objective E TIN target (<8 mg/L), seasonal treatment to achieve Objective E requires upgrade only to achieve the TP target (<1 mg/L) and is the same as the upgrade for Objective C seasonal treatment. The process flow schematic, process design data, recycled loads, sludge production, energy consumption, chemical usage and footprint requirements are all the same as for the year-round Objective C upgrade, as described in Section 8.3.3. Process design data are included in Table 8-16.

8.3.6 Objective F

Process Description

The Objective F (TIN <3 mg/L and TP <0.1 mg/L) treatment processes for seasonal nutrient removal would be the same as for year-round Objective F nutrient removal (adding methanol to reduce TIN and adding alum and magnesium hydroxide to reduce TP) except that the capital facilities would be designed based on MMDWF instead of MMWWF and O&M costs would be based on ADWF instead of AWWF. Process design data are included in Table 8-16.

Recycled Loads

Waste sludge will be thickened in a sludge thickener and digested in an aerobic digester. The percentage of TN and TP returning from these sludge treatment processes was calculated using Biowin model outputs. Table 8-21 summarizes the results.

TABLE 8-21.
NUTRIENT RECYCLING COMPARISON FOR MEMBRANE BIOLOGICAL REACTOR SYSTEMS, OBJECTIVE F SEASONAL NUTRIENT REMOVAL

	% of TN Recycled (ADWF)	% of TP Recycled (ADWF)
Existing Plant	14.2%	39.1%
Objective F, Seasonal	15.5%	48.2%

Sludge Production

The average sludge produced with the Objective F seasonal upgrades would be 1,087 ppd (198 dry tons per year), 16 percent higher than the existing plant average of 940 ppd (172 dry tons per year).

Energy Consumption

Upgrading the 1-mgd modeled MBR plant to achieve Objective F year-round would reduce the plant energy requirements by 1,500 kW-hours/year, or <1 percent, as shown in Table 8-22. There would be a net energy savings of 4,000 kW-hours/year associated with liquids treatment process and an additional energy requirement for the operation of solids processes of 2,500 kW-hours/year. The annual energy consumption for the upgraded plant would decrease by about 7 kW-hours per million gallons of influent wastewater treated.

Chemical Usage

The upgraded plant to achieve Objective F seasonally would require chemical dosages during the dry season of 150 gpd of alum to precipitate phosphorus, 30 gpd of magnesium hydroxide for pH control and 10 gpd of methanol for nitrogen removal. These rates equate to 27,380 gallons per year (119 gallons per million gallons of wastewater treated) of alum, 5,475 gallons per year (24 gallons per million gallons of wastewater treated) of magnesium hydroxide, and 1,825 gallons per year (8 gallons per million gallons of wastewater treated) of methanol.

TABLE 8-22.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing MBR Plant	1,213,800 kW-hours/year
Objective F Seasonal	1,212,300 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(1,500) kW-hours/year
Percent	<1%
Increase per Volume of Plant Flow	(7) kW-hours/MG

Footprint Requirements

The additional footprint requirements for achieving Objective F seasonally would be the same as for achieving this objective year-round.

TABLE 8-4.
MEMBRANE BIOREACTOR PLANT BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

Description	PROCESS DESIGN - MMWW							WET SEASON - AWW FLOWS							DRY SEASON - ADW FLOWS						
		Upgraded Plant							Upgraded Plant							Upgraded Plant					
	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F
Nutrient Removal Goals																					
TIN (mg/L)		< 8	< 3			< 8	< 3		< 8	< 3			< 8	< 3		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1				< 1	< 0.1	< 1	< 0.1				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature																					
Influent Flow, mgd	1.0		1.0	1.0	1.0		1.0	0.75		0.75	0.75	0.75		0.75	0.50		0.50	0.50	0.50		0.50
Temp, ^{o}C	10		10	10	10		10	10		10	10	10		10	15		15	15	15		15
Influent																					
BOD	165		165	165	165		165	221		221	221	221		221	331		331	331	331		331
TSS	188		188	188	188		188	251		251	251	251		251	376		376	376	376		376
VSS	132		132	132	132		132	176		176	176	176		176	263		263	263	263		263
TKN	24		24	24	24		24	32		32	32	32		32	48		48	48	48		48
TP	5.7		5.7	5.7	5.7		5.7	7.6		7.6	7.6	7.6		7.6	11.4		11.4	11.4	11.4		11.4
Alkalinity	2.01		2.01	2.01	2.01		2.01	2.68		2.68	2.68	2.68		2.68	4		4	4	4		4
pH	6.8		6.8	6.8	6.8		6.8	6.8		6.8	6.8	6.8		6.8	7		7	7	7		7
Aeration Tank																					
Tank Volume, MG	0.36		0.36	0.36	0.36		0.36	0.36		0.36	0.36	0.36		0.36	0.36		0.36	0.36	0.36		0.36
HRT, hrs	8.64		8.64	8.64	8.64		8.64	11.52		11.52	11.52	11.52		11.52	17.28		17.28	17.28	17.28		17.28
MLSS Conc., mg/L	5,073		5,073	5,000	5,138		5,138	5,158		5,158	5,086	5,166		5,166	5,123		5,123	5,195	5,097		5,097
DO Concentration, mg/L	2		2	2	2		2	2		2	2	2		2	2		2	2	2		2
Aeration Tank Airflow rate ft3/min	697		697	670	654		654	708		708	681	668		668	769		769	748	746		746
BioWin SRT, days	23.01		23.01	19	18		18	23.01		23.01	19.01	18.01		18.01	23.01		23.01	19.02	18.02		18.02
RAS Recyle Rate	1.5 Q		1.5 Q	1.5 Q	1.5 Q		1.5 Q	1.5 Q		1.5 Q	1.5 Q	1.5 Q		1.5 Q	1.5 Q		1.5 Q	1.5 Q	1.5 Q		1.5 Q
Pre - Anoxic Tank																					
Tank Volume, MG	0.12		0.12	0.12	0.12		0.12	0.12		0.12	0.12	0.12		0.12	0.12		0.12	0.12	0.12		0.12
HRT, hrs	2.88		2.88	2.88	2.88		2.88	3.84		3.84	3.84	3.84		3.84	5.76		5.76	5.76	5.76		5.76
Internal Recycle Rate	4Q		4Q	4Q	4Q		4Q	4Q		4Q	4Q	4Q		4Q	4Q		4Q	4Q	4Q		4Q
Post - Anoxic Tank																					
Tank Volume, MG	0.12		0.12	0.12	0.12		0.12	0.12		0.12	0.12	0.12		0.12	0.12		0.12	0.12	0.12		0.12
HRT, hrs	2.88		2.88	2.88	2.88		2.88	3.84		3.84	3.84	3.84		3.84	5.76		5.76	5.76	5.76		5.76
Methanol, gpd			20				20			15				15			10				10
Membrane Bioreactor																					
Tank Volume, MG	0.06		0.06	0.06	0.06		0.06	0.06		0.06	0.06	0.06		0.06	0.06		0.06	0.06	0.06		0.06
No. of Cassettes	4.0		4.0	4.0	4.0		4.0	4.0		4.0	4.0	4.0		4.0	4.0		4.0	4.0	4.0		4.0
Area of each Cassette, ft^2	16,320		16,320	16,320	16,320		16,320	16,320		16,320	16,320	16,320		16,320	16,320		16,320	16,320	16,320		16,320
HRT, hrs	1.44		1.44	1.44	1.44		1.44	1.92		1.92	1.92	1.92		1.92	2.88		2.88	2.88	2.88		2.88
MLSS Conc., mg/L	8,433		8,433	8,313	8,534		8,534	8,568		8,568	8,449	8,585		8,585	8,499		8,499	8,620	8,458		8,458
DO Concentration, mg/L	6		6	6	6		6	6		6	6	6		6	6		6	6	6		6
Air Supply Rate, ft^3/min	941		941	933	942		942	853		853	854	876		876	839		839	832	874		874
Membrane Flux, gpd/ft2	15.31		15.31	15.31	15.31		15.31	11.48		11.48	11.48	11.48		11.48	7.65		7.65	7.65	7.65		7.65

TABLE 8-4.
MEMBRANE BIOREACTOR PLANT BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

	PROCESS DESIGN - MMWW							WET SEASON - AWW FLOWS							DRY SEASON - ADW FLOWS						
		Upgraded Plant							Upgraded Plant							Upgraded Plant					
Description	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F
Chemical Addition																					
Alum Dosage, gpd				80	150		150				85	150		150				115	150		150
Magnesium Hydroxide Dosage, gpd				25	50		50				20	50		50				20	30		30
Magnesium Hydroxide Conc., meq/L				14,500	14,500		14,500				14,500	14,500		14,500				14,500	14,500		14,500
Aerobic Digester																					
Solids % from Clarifier	0.80%		0.80%	0.83%	0.85%		0.85%	0.85%		0.85%	0.84%	0.85%		0.85%	0.84%		0.84%	0.86%	0.84%		0.84%
Solids % from Thickener	6.00%		6.00%	5.90%	6.10%		6.10%	6.10%		6.10%	6.00%	6.10%		6.10%	6.00%		6.00%	6.10%	6.00%		6.00%
Combined Solids % to Aerobic Digester	3.90%		3.90%	3.90%	4.00%		4.00%	4.00%		4.00%	3.90%	4.00%		4.00%	3.90%		3.90%	4.02%	3.90%		3.90%
VSS loading to Digester,ppd	693		693	722	729		729	695		695	722	728		728	677		677	702	699		699
Total loading to Digester, ppd	1,282		1,282	1,529	1,659		1,659	1,303		1,303	1,555	1,668		1,668	1,293		1,293	1,587	1,645		1,645
Volume, MG	0.25		0.25	0.25	0.25		0.25	0.25		0.25	0.25	0.25		0.25	0.25		0.25	0.25	0.25		0.25
Hydraulic Residence Time, hrs	1,532		1,532	1,266	1,200		1,200	1,531		1,531	1,266	1,200		1,200	1,530		1,530	1,265	1,198		1,198
Digester Sludge Age, days	63.83		63.83	52.75	50.00		50.00	63.79		63.79	52.75	50.00		50.00	63.75		63.75	52.71	49.92		49.92
Total Sludge Age, days	86.84		86.84	71.75	68.00		68.00	86.80		86.80	71.76	68.01		68.01	86.76		86.76	71.73	67.94		67.94
Digester Airflow rate ft3/min	116		116	116	142		142	116		116	116	116		116	101		101	119	123		123
VSS destruction %	24.69%		24.69%	27.00%	27.60%		27.60%	24.70%		24.70%	27.00%	27.72%		27.72%	22.74%		22.74%	24.98%	25.58%		25.58%
SOUR, mg/L of O_2/hr/g TSS (< = 1.5)	0.194		0.194	0.222	0.219		0.219	0.191		0.191	0.217	0.218		0.218	0.171		0.171	0.188	0.195		0.195
Methanol addition,gpd	20.0		20.0	20.0	20.0		20.0	20.0		20.0	20.0	20.0		20.0	20.0		20.0	20.0	20.0		20.0
Sludge Production																					
Daily Sludge Production,ppd	930		930	1,119	1,238		1,238	941		941	1,140	1,246		1,246	938		938	1,180	1,233		1,233
Effluent																					
BOD, mg/L	0.87		0.87	0.9	1.06		1.06	0.81		0.81	0.86	1.07		1.07	0.71		0.71	0.72	0.84		0.84
TSS, mg/L	0.0		0.0	0.0	0.0		0.0	0.0		0.0	0.0	0.0		0.0	0.0		0.0	0.0	0.0		0.0
Phosphorus, mg/L	4.31		4.31	0.81	0.01		0.01	5.64		5.64	0.75	0.01		0.01	8.22		8.22	0.86	0.05		0.05
Ammonia N, mg/L	0.58		0.58	0.71	0.99		0.99	0.5		0.5	0.62	0.86		0.86	0.23		0.23	0.27	0.32		0.32
TIN, mg/L	1.71		1.71	1.85	2.15		2.15	1.95		1.95	2.1	2.38		2.38	2.05		2.05	2.11	2.27		2.27
pH	6.53		6.53	6.53	6.51		6.51	6.65		6.65	6.61	6.63		6.63	6.85		6.85	6.71	6.68		6.68
Recycle Loads																					
TN in thickener SSM	230.12		230.12	232.52	233.47		233.47	230.32		230.32	232.87	233.58		233.58	228.72		228.72	231.08	231.31		231.31
TN in aerobic digester SSM	220.44		220.44	222.34	223		223	220.55		220.55	222.53	223.06		223.06	219.17		219.17	221	221.21		221.21
TN in Influent	200.29		200.29	200.29	200.29		200.29	200.29		200.29	200.29	200.29		200.29	200.29		200.29	200.29	200.29		200.29
TN recycled from thickener	9.68		9.68	10.18	10.47		10.47	9.77		9.77	10.34	10.52		10.52	9.55		9.55	10.08	10.1		10.1
TN recycled from Digester	20.15		20.15	22.05	22.71		22.71	20.26		20.26	22.24	22.77		22.77	18.88		18.88	20.71	20.92		20.92
Total TN recycled	14.9%		14.9%	16.1%	16.6%		16.6%	15.0%		15.0%	16.3%	16.6%		16.6%	14.2%		14.2%	15.4%	15.5%		15.5%
Phosphorus Recycle from Thickener, ppd	3.66		3.66	8.78	9.01		9.01	4.35		4.35	9.19	9.02		9.02	5.42		5.42	9.67	9.77		9.77
Phosphorus Recycle from Digester, ppd	7.39		7.39	12.7	8.38		8.38	9.78		9.78	13.3	8.39		8.39	13.19		13.19	15.08	13.16		13.16
Total Phosphorus Recycled, ppd	11.05		11.05	21.48	17.39		17.39	14.13		14.13	22.49	17.41		17.41	18.61		18.61	24.75	22.93		22.93
% TP Recycled	23.2%		23.2%	45.2%	36.6%		36.6%	29.7%		29.7%	47.3%	36.6%		36.6%	39.1%		39.1%	52.0%	48.2%		48.2%

TABLE 8-16.
MEMBRANE BIOREACTOR PLANT BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

	PROCESS DESIGN - MMDW							DRY SEASON - ADW FLOWS						
		Upgraded Plant							Upgraded Plant					
Description	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F
Nutrient Removal Goals														
TIN (mg/L)		< 8	< 3			< 8	< 3		< 8	< 3			< 8	< 3
TP (mg/L)				< 1	< 0.1	< 1	< 0.1				< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature														
Influent Flow, mgd	0.69		0.69	0.69	0.69		0.69	0.50		0.50	0.50	0.50		0.50
Temp, ^{o}C	10		10	10	10		10	15		15	15	15		15
Influent														
BOD	241		241	241	241		241	331		331	331	331		331
TSS	273		273	273	273		273	376		376	376	376		376
VSS	191		191	191	191		191	263		263	263	263		263
TKN	35		35	35	35		35	48		48	48	48		48
TP	8.3		8.3	8.3	8.3		8.3	11.4		11.4	11.4	11.4		11.4
Alkalinity	2.92		2.92	2.92	2.92		2.92	4		4	4	4		4
pH	7		7	7	7		7	7		7	7	7		7
Aeration Tank														
Tank Volume, MG	0.36		0.36	0.36	0.36		0.36	0.36		0.36	0.36	0.36		0.36
HRT, hrs	12.5		12.5	12.5	12.5		12.5	17.28		17.28	17.28	17.28		17.28
MLSS Conc., mg/L	5,064		5,064	5,161	5,064		5,064	5,123		5,123	5,195	5,097		5,097
DO Concentration, mg/L	2		2	2	2		2	2		2	2	2		2
Aeration Tank Airflow rate ft3/min	769		769	745	736		736	769		769	748	746		746
BioWin SRT, days	23.02		23.02	19	18		18	23.01		23.01	19.02	18.02		18.02
RAS Recyle Rate	1.5 Q		1.5 Q	1.5 Q	1.5 Q		1.5 Q	1.5 Q		1.5 Q	1.5 Q	1.5 Q		1.5 Q
Pre - Anoxic Tank														
Tank Volume, MG	0.12		0.12	0.12	0.12		0.12	0.12		0.12	0.12	0.12		0.12
HRT, hrs	4		4	4	4		4	5.76		5.76	5.76	5.76		5.76
Internal Recycle Rate	4Q		4Q	4Q	4Q		4Q	4Q		4Q	4Q	4Q		4Q
Post - Anoxic Tank														
Tank Volume, MG	0.12		0.12	0.12	0.12		0.12	0.12		0.12	0.12	0.12		0.12
HRT, hrs	4		4	4	4		4	5.76		5.76	5.76	5.76		5.76
Methanol, gal/d			15				15			10				10
Membrane Bioreactor														
Tank Volume, MG	0.06		0.06	0.06	0.06		0.06	0.06		0.06	0.06	0.06		0.06
No. of Cassettes	4.0		4.0	4.0	4.0		4.0	4.0		4.0	4.0	4.0		4.0
Area of each Cassette, ft^2	16,320		16,320	16,320	16,320		16,320	16,320		16,320	16,320	16,320		16,320
HRT, hrs	2		2	2	2		2	2.88		2.88	2.88	2.88		2.88
MLSS Conc., mg/L	8400		8400	8572	8400		8400	8,499		8,499	8,620	8,458		8,458
DO Concentration, mg/L	6		6	6	6		6	6		6	6	6		6
Air Supply Rate, ft^3/min	943		943	940	970		970	839		839	832	874		874
Membrane Flux, gpd/ft^2	15.31		15.31	15.31	15.31		15.31	7.65		7.65	7.65	7.65		7.65
Chemical Addition														
Alum Dosage, gpd				115	150		150				115	150		150
Magnesium Hydroxide Dosage, gpd				20	30		30				20	30		30

TABLE 8-16.
MEMBRANE BIOREACTOR PLANT BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

Description	PROCESS DESIGN - MMDW							DRY SEASON - ADW FLOWS						
		Upgraded Plant							Upgraded Plant					
	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F	Existing MBR Plant	Obj. A (same as existing)	Obj. B	Ojb. C	Obj. D	Obj. E (same as Obj. C)	Obj. F
Magnesium Hydroxide Conc., meq/L											14,500	14,500		14,500
Aerobic Digester														
Solids % from Clarifier	0.84%		0.84%	0.85%	0.85%		0.85%	0.84%		0.84%	0.86%	0.84%		0.84%
Solids % from Thickener	6.00%		6.00%	6.10%	6.00%		6.00%	6.00%		6.00%	6.10%	6.00%		6.00%
Combined Solids % to Aerobic Digester	3.90%		3.90%	4.00%	4.00%		4.00%	3.90%		3.90%	4.02%	3.90%		3.90%
VSS loading to Digester, ppd	676		676	701	706		706	677		677	702	699		699
Total loading to Digester, ppd	1,279		1,279	1,578	1,653		1,653	1,293		1,293	1,587	1,645		1,645
Volume, MG	0.25		0.25	0.25	0.25		0.25	0.25		0.25	0.25	0.25		0.25
Hydraulic Residence Time, hrs	1,531		1,531	1,266	1,200		1,200	1,530		1,530	1,265	1,198		1,198
Digester Sludge Age, days	63.79		63.79	52.75	50.00		50.00	63.75		63.75	52.71	49.92		49.92
Total Sludge Age, days	86.81		86.81	71.75	68.00		68.00	86.76		86.76	71.73	67.94		67.94
Digester Airflow rate ft3/min	102		102	120	125		125	101		101	119	123		123
VSS destruction %	22.73%		22.73%	22.73%	25.67%		25.67%	22.74%		22.74%	24.98%	25.58%		25.58%
SOUR, mg/L of O_2/hr/g TSS (< = 1.5)	0.172		0.172	0.190	0.197		0.197	0.171		0.171	0.188	0.195		0.195
Methanol addition, gpd	20.0		20.0	20.0	20.0		20.0	20.0		20.0	20.0	20.0		20.0
Sludge Production														
Daily Sludge production, ppd	936		936	1,177	1,238		1,238	938		938	1,180	1,233		1,233
Effluent														
BOD, mg/L	0.76		0.76	0.76	0.88		0.88	0.71		0.71	0.72	0.84		0.84
TSS, mg/L	0.0		0.0	0.0	0.0		0.0	0.0		0.0	0.0	0.0		0.0
Phosphorous, mg/L	6.18		6.18	0.82	0.06		0.06	8.22		8.22	0.86	0.05		0.05
Ammonia N, mg/L	0.26		0.26	0.26	0.36		0.36	0.23		0.23	0.27	0.32		0.32
TIN, mg/L	1.66		1.66	1.74	1.85		1.85	2.05		2.05	2.11	2.27		2.27
pH	6.72		6.72	6.72	6.54		6.54	6.85		6.85	6.71	6.68		6.68
Recycle Loads														
Total TN in thickener SSM	**229.79**		**229.79**	**231.54**	**232.78**		**232.78**	**228.72**		**228.72**	**231.08**	**231.31**		**231.31**
Total TN in aerobic digester SSM	220.35		220.35	221.72	222.69		222.69	219.17		219.17	221	221.21		221.21
TN in Influent	200.29		200.29	200.29	200.29		200.29	200.29		200.29	200.29	200.29		200.29
TN recycled from thickener	9.44		9.44	9.82	10.09		10.09	9.55		9.55	10.08	10.1		10.1
TN recycled from Digester	20.06		20.06	21.43	22.4		22.4	18.88		18.88	20.71	20.92		20.92
% TN Recycled	14.7%		14.7%	15.6%	16.2%		16.2%	14.2%		14.2%	15.4%	15.5%		15.5%
Phosphorus Recycle from Thickener, ppd	4.35		4.35	9.19	9.8		9.8	5.42		5.42	9.67	9.77		9.77
Phosphorus Recycle from Digester, ppd	9.38		9.38	13.06	13.24		13.24	13.19		13.19	15.08	13.16		13.16
Total Phosphorus Recycled, ppd	13.73		13.73	22.25	23.04		23.04	18.61		18.61	24.75	22.93		22.93
% TP Recycled	28.9%		28.9%	46.8%	48.4%		48.4%	39.1%		39.1%	52.0%	48.2%		48.2%

CHAPTER 9.
TECHNOLOGICAL EVALUATION FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE PLANTS

9.1 BASE CASE/EXISTING SYSTEM

As there are few high-purity oxygen activated sludge (HPO) treatment plants in Washington, a base case model was developed based on process design data for the West Point Treatment Plant, which has a MMWWF of 215 mgd. The plant has six treatment trains, with a total mixed liquor tankage volume of 14.1 MG. Each train has four mixed liquor tank; under normal operating conditions the plant is operated contact sludge reoxygenation process where three tanks are operated in series as an oxygenated plug flow contact reactor with the fourth tank used for re-oxygenation of return activated sludge. The design recycle ratio for the plant is 0.3Q.

For a 1.0-mgd plant, the total mixed liquor tank volume would be 0.066 MG. Figure 9-1 depicts the process flow schematic for a 1.0-mgd HPO plant with anaerobic digestion for solids treatment. The system uses a series of well-mixed reactors employing concurrent gas-liquid contact in covered oxygenated mixed liquor tanks. Oxygenation Tanks 1, 2 and 3 operate in series (75 percent contact) as plug flow reactors and oxygenation Tank 4 is operated in line with the secondary clarifier. RAS from the clarifier is conveyed to sludge re-oxygenation tank(i.e. Tank 4) to partially stabilize the biological solids prior to combining the RAS with the primary clarifier effluent in oxygenation Tank 1. . The DO concentration in the mixed liquor oxygenation tanks is maintained at 7.0 mg/L. Table 9-1 summarizes the process design data for the 1.0-mgd base case HPO activated sludge treatment plant.

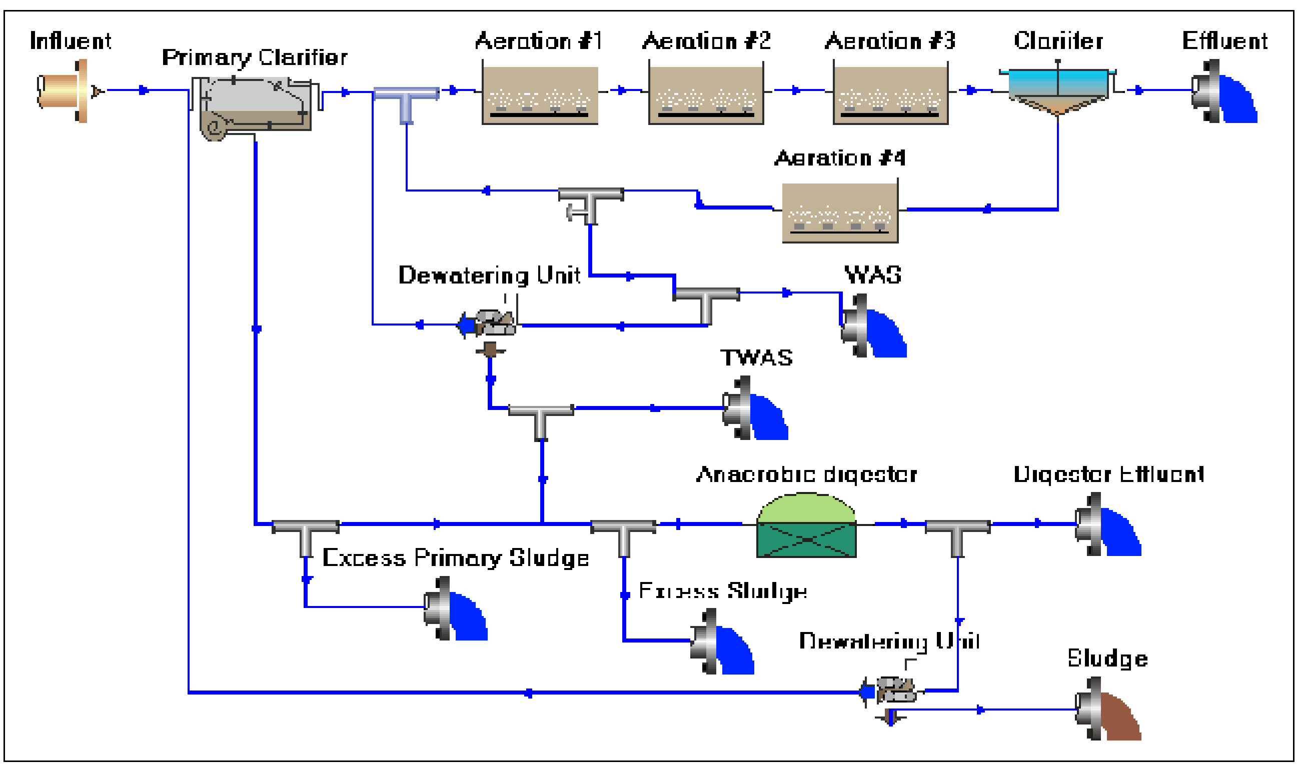


Figure 9-1. Process Flow Schematic for an Existing HPO Plant

TABLE 9-1. BASE CASE/EXISTING SYSTEM FOR HPO ACTIVATED SLUDGE PLANT	
Biowin Input Flow	1.0 mgd
Temperature	10ºC
Aeration Tank	
No of Stages	4
Mode of Operation	75%/25%
Total Oxygen Supply	52 cfm
SRT	1.5 days
RAS Recycle Rate	0.3Q
Stage #1	
Operation	ML Oxygenation
Volume	0.017 MG
HRT	0.40 hours
MLSS Concentration	1,142 mg/L
Oxygen Supply	16.1 cfm
Stage #2	
Operation	ML Oxygenation
Volume	0.017 MG
HRT	0.40 hours
MLSS Concentration	1,151 mg/L
Oxygen Supply	8.26 cfm
Stage #3	
Operation	ML Oxygenation
Volume	0.017 MG
HRT	0.40 hours
MLSS Concentration	1,153 mg/L
Oxygen Supply	6.5 cfm
Stage #4	
Operation	ML Oxygenation
Volume	0.017 MG
HRT	0.40 hours
MLSS Concentration	4,899 mg/L
Oxygen Supply	21 cfm
DO Concentration	7 mg/L
Sludge Production	
Total Sludge Produced	932 ppd
Effluent	
BOD	14.83 mg/L
TSS	18.8 mg/L
Phosphorous	4.26 mg/L
Ammonia N	15.95 mg/L
TIN	19.61 mg/L
pH	6.45

9.2 YEAR-ROUND NUTRIENT REMOVAL

Improvements required to provide year-round nutrient removal to achieve Objectives A and B are described below. The other treatment objectives were not evaluated for the HPO plant model. Process design data for year-round treatment to achieve these two objectives are included in Table 9-2, which is attached at the end of this chapter.

9.2.1 Objective A

Process Description

The upgrade evaluated for achieving Objective A (TIN <8 mg/L) included converting the existing HPO system to an oxygen activated MLE process coupled with a MBR (MLE-MBR). The upgraded system would consist of a 0.12-MG anoxic tank for denitrification, followed by three 0.04-MG aeration tanks in series for nitrification. The existing clarifier would be replaced with a 0.02-MG MBR tank. The existing mix liquor tank volume of 0.066 MG would be increased to 0.26 MG; this represents approximately a 300% increase in tankage that would need to be constructed.

The SRT of the upgraded system would be 16.3 days. Magnesium hydroxide would be added to the influent to maintain pH in the effluent at or above 6.5. Figure 9-2 shows the upgraded process flow schematic. Table 9-2 summarizes process design data. Detailed Biowin model reports are in Appendix A.

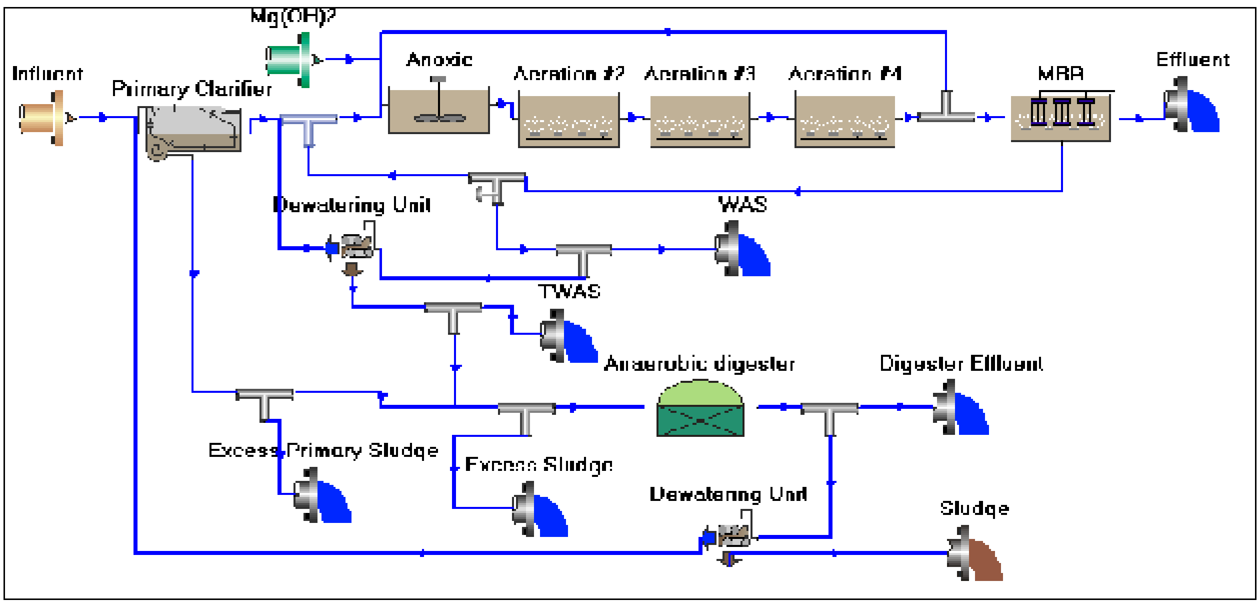


Figure 9-2. Process Schematic of HPO Plant Upgraded for Objective A Year-Round

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. Table 9-3 summarizes the results.

TABLE 9-3. NUTRIENT RECYCLING COMPARISON FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE SYSTEMS, OBJECTIVE A YEAR-ROUND NUTRIENT REMOVAL				
	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	27.4%	28.1%	45.6%	50.2%
Objective A Year-Round	16.9%	16.1%	30.4%	31.1%

Sludge Production

The quantity sludge produced with the Objective A upgrades would be 938 ppd (171 dry tons per year), 1.6 percent higher than the existing plant average of 923 ppd (168 dry tons per year).

Energy Consumption

Upgrading a 20 mgd (MM) HPO plant to achieve Objective A year-round would increase the plant energy requirements by 2,726,991 kW-hours/year, or about 63 percent, as shown in Table 9-4. None of this increase in energy demand would be attributable to the operation of solids processes associated with achieving Objective A. The annual energy consumption for the upgraded plant would increase by about 598 kW-hours per million gallons of influent wastewater treated.

TABLE 9-4. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND	
Yearly Energy Required	
Existing HPO Plant	5,080,000 kW-hours/year
Objective A Year-Round	7,807,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	2,727,000 kW-hours/year
Percent	54%
Increase per Volume of Plant Flow	598 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective A year-round would require approximately 18,250 gallons of magnesium hydroxide per year for pH control. This equates to 79 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

Table 9-5 presents the additional site area that would be required for the two generic plant capacities. The additional footprint required for plant upgrades to achieve Objective A would be for containment tanks for magnesium hydroxide. Refer to detailed storage tank calculations in Appendix B.

TABLE 9-5.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING HPO PLANTS TO ACHIEVE OBJECTIVE A YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
20	50,000
220	473,000

9.2.2 Objective B

Process Description

The upgrade evaluated for achieving Objective B (TIN <3 mg/L) is to convert the HPO system to a oxygen activated sludge system using a 4BDP-MBR process. The upgraded system would consist of a 0.12-MG anoxic tank for denitrification, followed by three 0.04-MG aeration tanks in series for nitrification and a 0.1-MG post-anoxic tank for post-denitrification. The existing clarifier would be replaced with a 0.02-MG MBR. The existing mixed liquor oxygenation tank volume of 0.066 MG would be increased to 0.36 MG; this represents approximately a 450% increase in the mixed-liquor tankage relative to the existing plant.

The SRT of the upgraded system would be 22.15 days. Magnesium hydroxide would be added to the influent to maintain pH in the effluent at or above 6.5. Methanol would be added to the post-anoxic tank to drive the denitrification process. Figure 9-3 shows the upgraded process flow schematic. Table 9-2 summarizes process design data. Detailed Biowin model reports are in Appendix A.

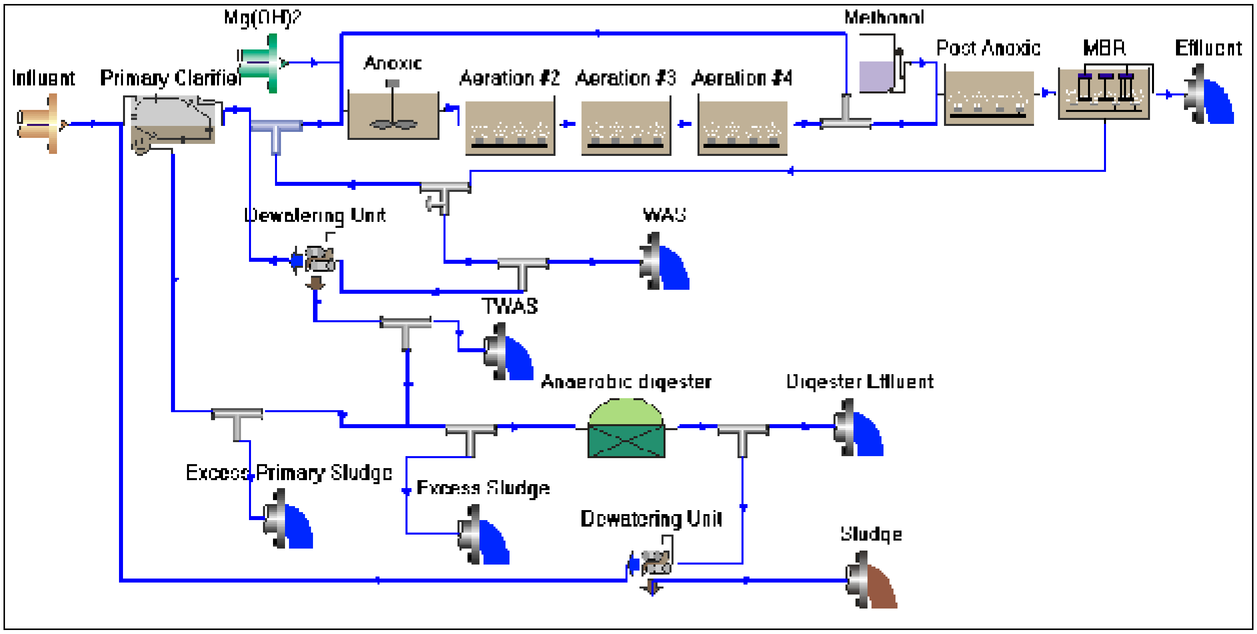


Figure 9-3. Process Schematic of HPO Plant Upgraded for Objective B Year-Round

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. Table 9-6 summarizes the results.

TABLE 9-6.
NUTRIENT RECYCLING COMPARISON FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE SYSTEMS, OBJECTIVE B YEAR-ROUND NUTRIENT REMOVAL

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Existing Plant	27.4%	28.1%	45.6%	50.2%
Objective B Year-Round	16.3%	15.6%	51.6%	47.2%

Sludge Production

The average sludge produced with the Objective B upgrades would be 971 ppd (177 dry tons per year), 5.2 percent higher than the existing plant average of 923 ppd (168 dry tons per year).

Energy Consumption

Upgrading the HPO plant to achieve Objective B year-round would increase the 20 mgd-plant energy requirements by 6,637,000 kW-hours/year, or about 133 percent, as shown in Table 9-7. None of this increase in energy would be attributable to the operation of solids processes associated with achieving Objective B. The annual energy consumption for the upgraded plant would increase by about 1,455 kW-hours per million gallons of influent wastewater treated.

TABLE 9-7.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

Yearly Energy Required	
Existing HPO Plant	5,080,000 kW-hours/year
Objective B Year-Round	11,717,000.kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	6,637,000 kW-hours/year
Percent	133%
Increase per Volume of Plant Flow	1,455 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective B year-round would require approximately 5,475 gallons of methanol per year for nitrogen removal and 14,600 gallons of magnesium hydroxide per year for pH control. This equates to 24 gallons of methanol and 63 gallons of magnesium hydroxide per million gallons of wastewater treated.

Footprint Requirements

Table 9-8 presents the additional site area that would be required for the two generic plant capacities. The additional footprint required for plant upgrades to achieve Objective B would be for containment tanks for methanol and magnesium hydroxide. Refer to detailed storage tank calculations in Appendix B.

TABLE 9-8.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING HPO PLANTS TO ACHIEVE OBJECTIVE B YEAR-ROUND

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
20	114,100
220	1,161,700

9.3 SEASONAL NUTRIENT REMOVAL

Improvements required to provide seasonal nutrient removal to achieve Objectives A and B are described below. Process design data for the two objectives are included in Table 9-9, which is attached at the end of this chapter.

9.3.1 Objective A

Process Description

The upgrade evaluated for achieving seasonal treatment for Objective A (TIN <8 mg/L) seasonally is to convert the HPO system to an oxygen activated sludge system using the MLE process using the existing clarifiers. The mix liquor tankage would be the same as that described for the year around system to achieve objective A. The SRT of the upgraded system would be 13.5 days. Magnesium hydroxide would be added to the influent to maintain the pH in the effluent at or above 6.5. Figure 9-4 shows the upgraded process flow schematic. Table 9-9 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. Table 9-10 summarizes the results.

Sludge Production

The annual average sludge produced with the Objective A seasonal upgrades would be 912 ppd (166 dry tons per year), 1 percent less than the existing plant average of 922 ppd (168 dry tons per year).

Energy Consumption

Upgrading the HPO plant to achieve Objective A seasonally would increase the plant energy requirements by 210,000 kW-hours/year, or about 4 percent, as shown in Table 9-11. The annual energy consumption for the upgraded plant would increase only 46 kW-hours per million gallons of influent wastewater treated. By comparison the energy required to achieve Objective A on a seasonal basis would be about 8 percent of the incremental energy requirements to achieve Objective A year around.

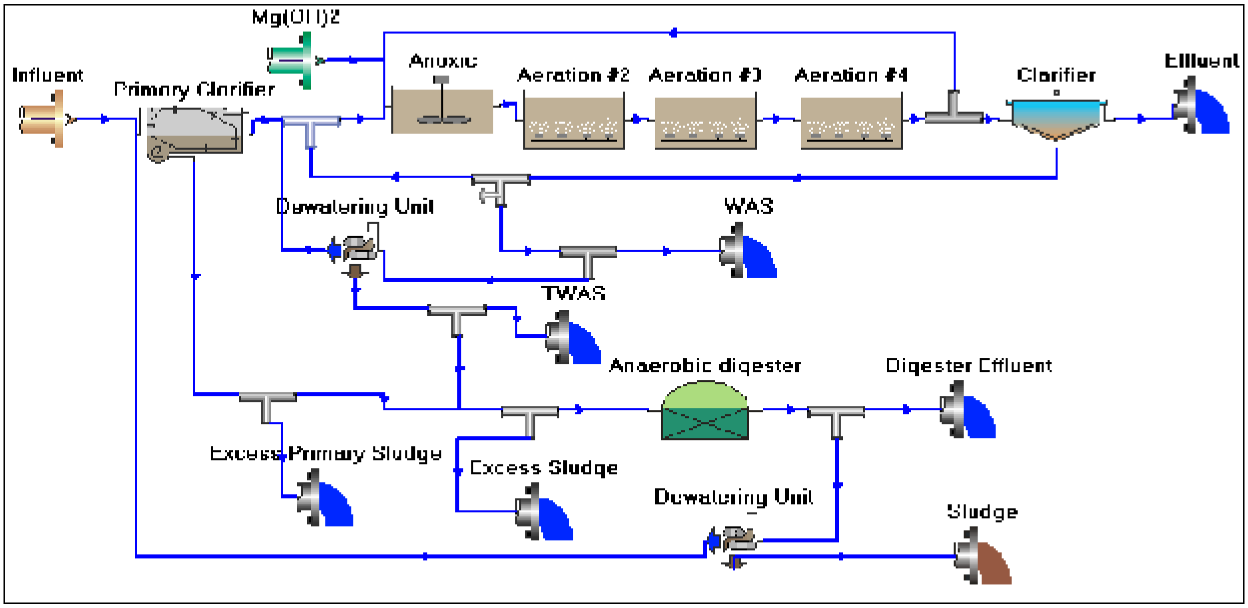


Figure 9-4. Process Schematic of HPO Plant Upgraded for Objective A Seasonal

TABLE 9-10.
NUTRIENT RECYCLING COMPARISON FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE SYSTEMS, OBJECTIVE A SEASONAL NUTRIENT REMOVAL

	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	28.1%	50.2%
Objective A, Seasonal	16.6%	38.4%

TABLE 9-11.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

Yearly Energy Required	
Existing HPO Plant	5,080,000 kW-hours/year
Objective A Seasonal	5,290,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	210,000 kW-hours/year
Percent	4%
Increase per Volume of Plant Flow	46 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective A seasonally would require chemical dosages during the dry season of 70 gpd of magnesium hydroxide for pH control. This equates to 12,775 gallons of magnesium hydroxide per year (56 gallons per million gallons of wastewater treated).

Footprint Requirements

Table 9-12 presents the additional site area that would be required for the two generic plant capacities. The additional footprint required for plant upgrades to achieve Objective A would be for containment tanks for magnesium hydroxide. Refer to detailed storage tank calculations in Appendix B.

TABLE 9-12.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING HPO PLANTS TO ACHIEVE OBJECTIVE A SEASONALLY

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
20	88,900
220	971,400

9.3.2 Objective B

Process Description

The upgrade evaluated for achieving seasonal treatment for Objective B (TIN <3 mg/L) seasonally is to convert the HPO system to an oxygen activated sludge system using 4BDP using the existing clarifiers. An additional 0.224 MG of mixed liquor tankage would need to be constructed per mgd of maximum month plant capacity. The SRT of the upgraded system would be 13.5 days. Magnesium hydroxide would be added to the influent to maintain the pH in the effluent at or above 6.5. Methanol would be added as a carbon source to the post-anoxic tank to drive the denitrification process. Figure 9-5 shows the upgraded process flow schematic. Table 9-9 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

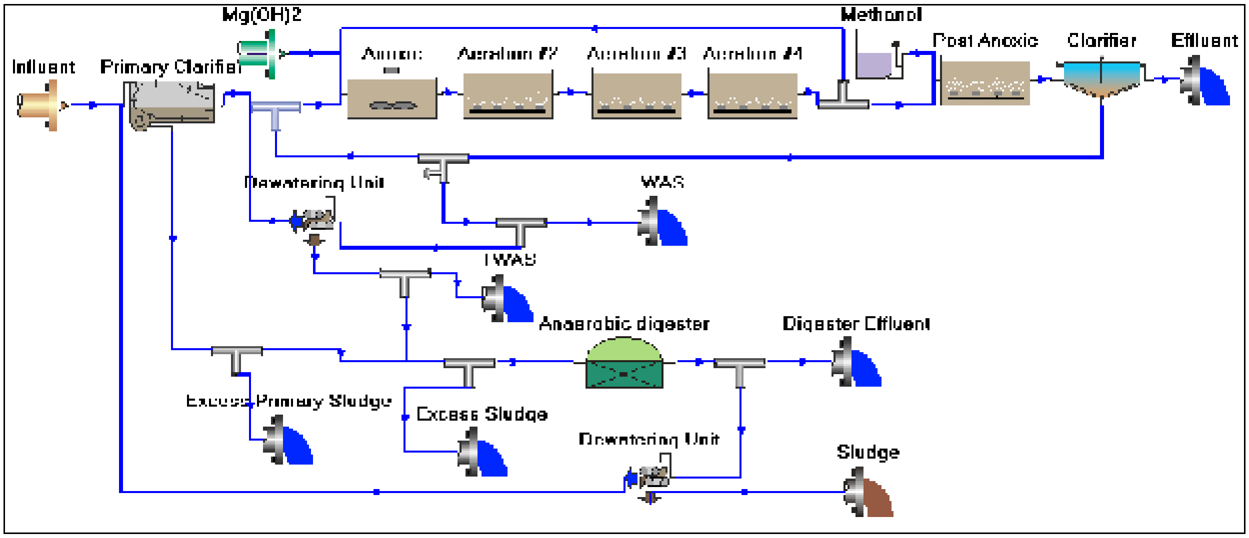


Figure 9-5. Process Schematic of HPO Plant Upgraded for Objective B Seasonal

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. Table 9-13 summarizes the results.

TABLE 9-13. NUTRIENT RECYCLING COMPARISON FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE SYSTEMS, OBJECTIVE B SEASONAL NUTRIENT REMOVAL		
	% of TN Recycled	% of TP Recycled
	ADWF	ADWF
Existing Plant	28.1%	50.2%
Objective B	17.2%	50.1%

Sludge Production

The annual average sludge produced with the Objective B seasonal upgrades would be 918 ppd (168 dry tons per year), a negligible difference from the existing plant average of 922 ppd (168 dry tons per year).

Energy Consumption

Upgrading the HPO plant to achieve Objective B seasonally would increase the plant energy requirements by 1,425,000 kW-hours/year, or about 28 percent, as shown in Table 9-14. The annual energy consumption for the upgraded plant would increase by about 312 kW-hours per million gallons of influent wastewater treated. By comparison the energy required to achieve Objective B on a seasonal basis would be about 21 percent of the incremental energy requirements to achieve Objective B year around.

TABLE 9-14. ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE B SEASONALLY	
Yearly Energy Required	
Existing HPO Plant	5.080,000 kW-hours/year
Objective B Seasonal	11,717,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	1,425,000 kW-hours/year
Percent	28%
Increase per Volume of Plant Flow	312 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective B seasonally would require chemical dosages during the dry season of 60 gpd of magnesium hydroxide for pH control and 10 gpd of methanol for nitrogen reduction. This equates to 10,950 gallons of magnesium hydroxide per year (48 gallons per million gallons of wastewater treated) and 1,825 gallons of methanol per year (8 gallons per million gallons of wastewater treated)

Footprint Requirements

Table 9-15 presents the additional site area that would be required for the two generic plant capacities. The additional footprint required for plant upgrades to achieve Objective B would be for containment tanks for methanol and magnesium hydroxide. Refer to detailed storage tank calculations in Appendix B.

**TABLE 9-15.
ADDITIONAL FOOTPRINT REQUIRED FOR UPGRADING HPO PLANTS TO ACHIEVE OBJECTIVE B SEASONALLY**

Plant Design Capacity (mgd)	Additional Area Required for Upgrade (square feet)
20	149,000
220	1,624,800

TABLE 9-2.
HIGH PURITY OXYGEN PLANTS BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

	PROCESS DESIGN - MMWW			WET SEASON - AWW FLOWS			DRY SEASON - ADW FLOWS		
	Existing	Upgraded Plant		Existing	Upgraded Plant		Existing	Upgraded Plant	
Description	HPO Plant	Obj. A	Obj. B	HPO Plant	Obj. A	Obj. B	HPO Plant	Obj. A	Obj. B
Nutrient Removal Goals									
TIN (mg/L)		< 8	< 3		< 8	< 3		< 8	< 3
TP (mg/L)		—	—		—	—		—	—
Plant Size, Average Temperature									
Influent Flow, mgd	1.0	1.0	1.0	0.75	0.75	0.75	0.5	0.5	0.75
Temp, ^{o}C	10	10	10	10	10	10	15	15	10
Influent									
BOD	165	165	165	221	221	221	331	331	331
TSS	188	188	188	251	251	251	376	376	376
VSS	132	132	132	176	176	176	263	263	263
TKN	24	24	24	32	32	32	48	48	48
TP	5.7	5.7	5.7	7.6	7.6	7.6	11.4	11.4	11.4
Alkalinity	2.01	2.01	2.01	2.68	2.68	2.68	4	4	4
pH	6.8	6.8	6.8	6.8	6.8	6.8	7	7	7
Aeration Tank									
No of Stages	4	4	4	4	4	4	4	4	4
Mode of Operation	75% / 25%	Complete Mix	Complete Mix	75% / 25%	Complete Mix	Complete Mix	75% / 25%	Complete Mix	Complete Mix
Stage #1									
Operation	Aeration	Anoxic	Anoxic	Aeration	Anoxic	Anoxic	Aeration	Anoxic	Anoxic
Volume	0.017	0.12	0.12	0.02	0.12	0.12	0.02	0.12	0.12
HRT	0.40	2.88	2.88	0.53	3.84	3.84	0.79	5.76	3.84
MLSS	1,142	4,216	4,539	1,262	4,254	4,413	1,301	4,093	4,193
Oxygen Supply, ft^3/min	16.1			16.1			21.9		
Stage #2									
Operation	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration
Volume	0.017	0.04	0.04	0.017	0.04	0.04	0.017	0.04	0.04
HRT	0.40	0.96	0.96	0.53	1.28	1.28	0.79	1.92	1.28
MLSS	1,151	4,215	4,539	1,272	4,252	4,414	1,311	4,090	4,194
Oxygen Supply, ft^3/min	8.26	66.21	54.00	8.26	60.03	56.00	11.63	71.00	66.00
Stage #3									
Operation	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration
Volume	0.017	0.04	0.04	0.017	0.04	0.04	0.017	0.04	0.04
HRT	0.40	0.96	0.96	0.53	1.28	1.28	0.79	1.92	1.28
MLSS	1,153	4,214	4,063	1,273	4,250	4,413	1,308	4,087	4,193
Oxygen Supply, ft^3/min	6.5	29.2	25.5	6.5	31.1	26.0	7.9	42.0	37.0
Stage #4									
Operation	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration
Volume	0.017	0.04	0.04	0.017	0.04	0.04	0.017	0.04	0.04
HRT	0.40	0.96	0.96	0.53	1.28	1.28	0.79	1.92	1.28
MLSS	4,899	4,212	4,061	5,415	4,248	4,413	5,540	4,084	4,193
Oxygen Supply, ft^3/min	21	27.4	23.5	20.7	29.0	24.0	31.0	34.0	31.4
Total Oxygen Supply, ft^3/min	52	123	103	52	120	106	72	147	134
DO Concentration, mg/L	7	7	7	7	7	7	7	7	7
BioWin SRT, days	1.5	16.28	22.15	1.5	16.29	22.19	1.5	16.31	22.15
RAS Recyle Rate	0.3Q	1Q	1Q	0.3Q	1Q	1Q	0.3Q	1Q	1Q
Preanoxic Internal Recycle Rate		4Q	4Q		4Q	4Q		4Q	4Q
Post - Anoxic Tank									
Tank Volume, MG			0.10			0.10			0.10
HRT, hrs			2.40			3.20			3.20
Methanol, gpd			20			15			15

TABLE 9-2.
HIGH PURITY OXYGEN PLANTS BIOWIN RESULTS FOR YEAR-ROUND NUTRIENT REMOVAL

	PROCESS DESIGN - MMWW			WET SEASON - AWW FLOWS			DRY SEASON - ADW FLOWS		
	Existing	Upgraded Plant		Existing	Upgraded Plant		Existing	Upgraded Plant	
Description	HPO Plant	Obj. A	Obj. B	HPO Plant	Obj. A	Obj. B	HPO Plant	Obj. A	Obj. B
Clarifier									
Area, ft^2	1,000			1,000			1,000		
Surface Overflow Rate, gal/ft^2	1,000			750			500		
Membrane Bioreactor									
Tank Volume, MG		0.02	0.02		0.02	0.02		0.02	0.02
No. of Cassettes		4.0	4.0		4.0	4.0		4.0	4.0
Area of each Cassette, ft^2		16,320	16,320		16,320	16,320		16,320	16,320
HRT, hrs		0.48	0.48		0.64	0.64		0.96	0.64
MLSS Conc., mg/L		8,416	9,073		8,485	8,795		8,151	8,347
DO Concentration, mg/L		6	6		6	6		6	6
Air Supply Rate, ft^3/min		415	668		420	606		390	546
Membrane Flux, gpd/ft2		15.31	15.31		11.48	11.48		7.65	7.65
Tank Volumes									
Total Tankage Volume, MG	0.066	0.260	0.360	0.066	0.260	0.260	0.066	0.260	0.360
Total Additional Volume, MG		0.194	0.294		0.194	0.194		0.194	0.294
Available onsite volume, MG		0.130	0.130		0.130	0.130		0.130	0.130
Additional Volume needed, MG		0.064	0.164		0.064	0.064		0.064	0.164
Chemical Addition									
Magnesium Hydroxide Dosage, gpd		65	50		50	40			
Magnesium Hydroxide Conc., meq/L		14,500	14,500		14,500	14,500			
Anaerobic Digester									
TSS wasted from Aerobic Tank, ppd	765	597	643	845	602	624	865	578	580
Total loading to Digester, ppd	1,891	1,729	1,779	1,974	1,733	1,757	1,989	1,703	1,712
Volume, MG	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Hydraulic Residence Time, hrs	19.7	19.9	19.9	26.1	26.4	26.4	39.1	39.4	26.4
Sludge Production									
Total Sludge Produced, ppd	932	984	1,005	938	959	973	907	916	969
Effluent									
BOD, mg/L	14.83	0.86	0.87	10.13	0.86	0.83	6.23	0.86	0.75
TSS, mg/L	18.8	0.0	0.0	12.9	0.0	0.0	7.8	0.0	0.0
Phosphorous, mg/L	4.26	4.25	3.85	5.7	5.77	5.44	4.26	4.25	8.51
Ammonia N, mg/L	15.95	0.39	0.98	22.05	0.34	0.9	33.79	0.39	0.22
TIN, mg/L	15.95	6.59	2.49	22.05	6.29	2.87	33.84	6.59	1.97
pH	6.45	6.51	6.61	6.48	6.59	6.67	6.63	6.5	6.63
Recycle Loads									
TN in the influent	200.29	200.29	202.33	200.29	200.29	200.29	200.29	200.29	200.29
TN from Thickener and Digester	219.1	203.46	219.1	224.84	204.52	202.95	227.03	203.24	201.86
% TN Recycled to Aeration Tank	9%	2%	8%	12%	2%	1%	13%	1%	1%
TP from Thickener and Digester	53.55	48.23	62.66	56.24	49.06	58.93	58.51	49.51	56.98
TN from Thickener	10.57	6.1	6.12	12.58	6.13	5.99	14.97	5.79	5.61
TN from Digester	38.5	26.91	26.26	42.21	27.75	26.62	41.3	26.45	25.71
% TN Recycled	24.5%	16.5%	16.0%	27.4%	16.9%	16.3%	28.1%	16.1%	15.6%
Phosphorus Recycle from Thickener, ppd	3.11	2.22	4.85	3.68	2.35	4.12	4.37	2.5	3.82
Phosphorus Recycle from Digester, ppd	15.89	11.48	23.64	17.99	12.1	20.42	19.5	12.3	18.61
Total Phosphorus Recycled, ppd	19	13.7	28.49	21.67	14.45	24.54	23.87	14.8	22.43
% TP Recycled	39.9%	28.8%	59.9%	45.6%	30.4%	51.6%	50.2%	31.1%	47.2%

TABLE 9-9.
HIGH PURITY OXYGEN PLANTS BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL

Description	PROCESS DESIGN - MMDW			DRY SEASON - ADW FLOWS		
	Existing	Upgraded Plant		Existing	Upgraded Plant	
	HPO Plant	Obj. A	Obj. B	HPO Plant	Obj. A	Obj. B
Nutrient Removal Goals						
TIN (mg/L)						
TP (mg/L)						
Plant Size, Average Temperature						
Influent Flow, mgd	0.7	0.7	0.7	0.5	0.5	0.5
Temp, ^{o}C	15	15	15	15	15	15
Influent						
BOD	241	241	241	331	331	331
TSS	273	273	273	376	376	376
VSS	191	191	191	263	263	263
TKN	35	35	35	48	48	48
TP	8.3	8.3	8.3	11.4	11.4	11.4
Alkalinity	2.92	2.92	2.92	4	4	4
pH	7	7	7	7	7	7
Aeration Tank						
No of Stages	4	4	4	4	4	4
Mode of Operation	75% / 25%	Complete Mix	Complete Mix	75% / 25%	Complete Mix	Complete Mix
Stage #1						
Operation	Aeration	Anoxic	Anoxic	Aeration	Anoxic	Anoxic
Volume	0.017	0.12	0.12	0.02	0.12	0.12
HRT	0.57	4.17	4.17	0.79	5.76	5.76
MLSS	1,259	3,588	3,030	1,301	3,880	3,597
Oxygen Supply, ft^3/min	22.0			21.9		
Stage #2						
Operation	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration
Volume	0.017	0.04	0.04	0.017	0.04	0.04
HRT	0.57	1.39	1.39	0.79	1.92	1.92
MLSS	1,268	3,586	3,027	1,311	3,878	3,597
Oxygen Supply, ft^3/min	11.44	78.00	74.00	11.63	77.00	72.00
Stage #3						
Operation	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration
Volume	0.017	0.04	0.04	0.017	0.04	0.04
HRT	0.57	1.39	1.39	0.79	1.92	1.92
MLSS	1,266	3,584	3,024	1,308	3,875	3,598
Oxygen Supply, ft^3/min	7.9	43.0	39.0	7.9	46.0	43.0
Stage #4						
Operation	Aeration	Aeration	Aeration	Aeration	Aeration	Aeration
Volume	0.017	0.04	0.04	0.017	0.04	0.04
HRT	0.57	1.39	1.39	0.79	1.92	1.92
MLSS	5,379	3,581	3,020	5,540	3,872	3,596
Oxygen Supply, ft^3/min	30.5	34.0	35.0	31.0	33.0	35.0
Total Oxygen Supply, ft^3/min	72	155	148	72	156	150
DO Concentration, mg/L	7	7	7	7	7	7
BioWin SRT, days	1.5	13.5	14.26	1.5	13.5	14.26
RAS Recyle Rate	0.3Q	0.5Q	0.5Q	0.3Q	0.5Q	0.5Q
Preanoxic Internal Recycle Rate		4Q	4Q		4Q	4Q
Post - Anoxic Tank						

TABLE 9-9. HIGH PURITY OXYGEN PLANTS BIOWIN RESULTS FOR SEASONAL NUTRIENT REMOVAL						
	PROCESS DESIGN - MMDW			DRY SEASON - ADW FLOWS		
	Existing	Upgraded Plant		Existing	Upgraded Plant	
Description	HPO Plant	Obj. A	Obj. B	HPO Plant	Obj. A	Obj. B
Tank Volume, MG			0.05			0.05
HRT, hrs			1.74			2.40
Methanol, gpd			15			10
Clarifier						
Area, ft^2	1,000	1,000	1,000	1,000	1,000	1,000
Surface Overflow Rate, gal/ft^2	690	690	690	500	500	500
Tank Volumes						
Total Tankage Volume, MG	0.066	0.240	0.290	0.066	0.240	0.290
Total Additional Volume, MG		0.174	0.224		0.174	0.224
Available Volume onsite, MG		0.0	0.0		0.0	0.0
Additional Volume needed, MG		0.174	0.224		0.174	0.224
Chemical Addition						
Magnesium Hydroxide Dosage, gpd		95	90		70	60
Magnesium Hydroxide Conc., meq/L		14,500	14,500		14,500	14,500
Anaerobic Digester						
TSS wasted from Aerobic Tank, ppd	839	576	582	865	576	610
Total loading to Digester, ppd	1,968	1,700	1,707	1,989	1,698	1,734
Volume, MG	0.15	0.15	0.15	0.15	0.15	0.15
Hydraulic Residence Time, hrs	28.3	28.8	28.7	39.1	39.4	39.4
Sludge Production						
Sludge Produced, ppd						
Effluent						
BOD, mg/L	8.29	5.28	8.29	6.23	3.55	4.37
TSS, mg/L	11.5	14.8	14.6	7.8	9.4	9.8
Phosphorous, mg/L	6.24	6.5	6.17	4.26	8.86	8.58
Ammonia N, mg/L	24.3	0.48	1.13	33.79	0.35	0.97
TIN, mg/L	24.33	5.07	1.38	33.84	6.85	2.01
pH	6.56	6.51	6.55	6.63	6.51	6.51
Recycle Loads						
Nitrogen Recycle from Thickener, ppd	13.2	5.51	5.87	14.97	5.79	6.11
Nitrogen Recycle from Digester, ppd	42.66	27.28	28.2	41.3	27.47	28.35
Total Nitrogen Recycled, ppd	55.86	32.79	34.07	56.27	33.26	34.46
% TN Recycled	27.9%	16.4%	17.0%	28.1%	16.6%	17.2%
Phosphorus Recycle from Thickener, ppd	3.86	2.06	3.71	4.37	2.83	3.86
Phosphorus Recycle from Digester, ppd	18.38	12.1	19.71	19.5	15.43	19.98
Total Phosphorus Recycled, ppd	22.24	14.16	23.42	23.87	18.26	23.84
% TP Recycled	46.8%	29.8%	49.2%	50.2%	38.4%	50.1%

CHAPTER 10.
TECHNOLOGICAL EVALUATION FOR AERATED OR FACULTATIVE LAGOON PLANTS

10.1 BASE CASE/EXISTING SYSTEM

Biowin cannot model lagoon plants, so CapdetWorks was used to develop the following lagoon models for base case cost estimating:

- A 1.0-mgd facultative lagoon system consisting of a bar screen for preliminary treatment followed by 68-acres facultative lagoons
- A 1.0-mgd aerated lagoon and facultative lagoon system consisting of a bar screen for preliminary treatment followed by 2-acres of complete mix aerated lagoon(s) and 34 acres of facultative lagoons.

Table 10-1 summarizes the concentrations assumed for the lagoon effluent.

TABLE 10-1.
LAGOON EFFLUENT CONCENTRATIONS

	AWWF	ADWF
BOD (mg/L)	30	30
TSS (mg/L)	30	45
VSS (mg/L)	21	32
TKN (mg/L)	13.3	20
TP (mg/L)	5.3	8
Alkalinity (meq/L)	3.35	5
pH	7	8.5

The evaluation assumed that aerated lagoons would be dredged every 10 years of operation and the facultative lagoons would be dredged every 20 years. The dredged solids from the lagoons was assumed to meet the Class B biosolids requirements. Sludge production for facultative lagoon treatment plants and treatment plants using aerated lagoons in conjunction with facultative lagoons were assumed to have a sludge production rate of 0.42 pounds of dry sludge solids per pound of BOD5 applied or 0.46 tons dry solids per million gallons of wastewater treated.

10.2 YEAR-ROUND NUTRIENT REMOVAL

To achieve year-round nitrogen-removal Objectives for A, B, E and F, the existing lagoon plant would need to be replaced with a new mechanical plant.. The elements included in the replacement plant would depend on the size of the original plant:

- For plants up to 5 mgd, the replacement plant would be the same as the upgraded plant for existing extended aeration treatment plants, as described in Chapter 4; process design data for these plants are presented in Table 4-2.

- For plants larger than 5 mgd, the proposed new plant is similar to, though not exactly the same as, the upgraded plant for existing CAS treatment plants, as described in Chapter 5. Process design data for these plants are presented in Table 10-2. In order to provide a consistent comparison with other upgrades discussed in this report, the modeled size of these plants is 1.0-mgd; tank sizes would be scaled linearly to obtain sizes for plants rated up to 50 mgd.

The phosphorus removal objectives associated with Objectives C and D can be achieved by upgrading the lagoon plant . Process design data for these plants are presented in Table 10-3.

10.2.1 Objective A

Process Description

To achieve Objective A (TIN <8 mg/L) year-round for lagoons rated up to 5.0 mgd, the existing lagoons would be decommissioned and new liquid and solids treatment facilities would be constructed on-site. The new plant would include the same process elements as the year-round Objective A upgrade for extended aeration plants. The process flow schematic for this new plant would be as shown in Figure 4-3. Table 4-2 summarizes the process design data.

To achieve Objective A year-round for lagoons rated greater than 5.0 mgd, the existing lagoons would be decommissioned and replace with new liquid and solids treatment facilities. The new treatment plant process elements would consist of the same process elements that are included in the upgraded conventional activated sludge plant upgrade to achieve this Objective on a dry season basis presented in Chapter 5. The new process elements would include, a new influent pump station, a headworks with a fine screen system, primary clarifiers a conventional MLE activated sludge process with secondary clarifiers,. The new plant would also include solids handling facility to thicken the waste activated sludge prior to digestion, an anaerobic digester, and digested solids dewatering system with a belt filter press. The process flow schematic for this objective is similar to the CAS seasonal process flow schematic shown in Figure 5-6. Table 10-2 summarizes the process design data; detailed Biowin model reports are in Appendix A.

Recycled Loads

Table 10-4 summarizes the recycled-load modeling results for the upgrades to achieve Objective A year-round at existing lagoon plants.

TABLE 10-4.
NUTRIENT RECYCLING ESTIMATES FOR LAGOON PLANTS UPGRADED TO ACHIEVE OBJECTIVE A YEAR-ROUND

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Plants Up to 5.0 mgd	16.3%	15.5%	48.7%	64.1%
Plants > 5.0 mgd	15.9%	15.5%	47.3%	42.4%

Sludge Production

The sludge produced from a 1-mgd plant with the Objective A year-round upgrades would be as follows:

- With upgrades proposed for plants up to 5.0 mgd:
  - Annual average of 939 ppd
  - 171 dry tons per year
  - 0.75 dry tons per million gallons of wastewater treated
  - This represents 63% increase in the quantity of biosolids by the plant
- With upgrades proposed for plants greater than 5.0 mgd
  - Annual average of 916 ppd
  - 167 dry tons per year
  - 0.73 dry tons per million gallons of wastewater treated
  - This represents a 59% increase in the quantity of biosolids generated by the plant

Energy Consumption

Upgrading an existing 1-mgd(MM) aerated or facultative lagoon plant to achieve Objective A year-round would change the plant energy requirements as shown in Table 10-5 or 10-6, respectively. These rates can be extrapolated and applied to plants up to a rated maximum month capacity of 5 mgd.

TABLE 10-5.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING A 1-MGD AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective A Year-Round	1,010,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	38,000 kW-hours/year
Percent	4%
Increase per Volume of Plant Flow	167 kW-hours/MG

TABLE 10-6.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING A 1- MGD FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective A Year-Round	1,010,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	874,000 kW-hours/year
Percent	642%
Increase per Volume of Plant Flow	3831 kW-hours/MG

Chemical Usage

For plants up to 5.0 mgd, the chemical usage for an upgraded plant to achieve Objective A year-round would be the same as for extended aeration plants upgraded to achieve Objective A year-round, as described in Section 4.2.1.

For plants larger than 5.0 mgd, no additional use of chemicals would be required the upgraded plant to achieve Objective A year-round.

Footprint Requirements

Table 10-7 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective A for the three generic plant capacities. For plants up to 5 mgd in capacity, the upgrade footprint includes preliminary treatment, an influent pump station, an aeration tank, an anoxic tank, secondary clarifiers, an aerobic digester and a belt filer press. For plants larger than 5 mgd, the upgrade footprint includes preliminary treatment, an influent pump station, primary clarifiers, an aeration tank, an anoxic tank, secondary clarifiers, an anaerobic digester and a belt filer press. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 10-7.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE A YEAR-ROUND

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(304,900)	(348,500)
5	(6,708,200)	(7,143,800)
50	(72,004,700)	(76,360,700)

10.2.2 Objective B

Process Description

To achieve Objective B (TIN <3 mg/L) year-round for lagoons rated up to 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the year-round Objective B upgrade for extended aeration plants. The process flow schematic for this upgrade is shown in Figure 4-4, and Table 4-2 summarizes the process design data.

To achieve Objective B year-round for lagoons rated greater than 5.0 mgd, the existing lagoons would be abandoned in place and new liquids and solids handling treatment facilities would be constructed. A new influent pump station, a headworks with a fine screen system and a new 1,020-square-foot primary clarifier should be constructed. The new liquids treatment system would use the 4-stage Bardenpho activated sludge process and secondary clarifiers, requiring the construction of a new 0.25-MG aeration tank, a 0.10-MG pre-anoxic tank, a 0.05-MG post-anoxic tank and a 2,200-square-foot secondary clarifier. Methanol would be added as an additional carbon source to the post-anoxic tank to increase the denitrification process, requiring a methanol storage and dosing system. The process flow schematic for this objective is similar to the CAS seasonal process flow schematic shown in Figure 5-7. Table 10-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Table 10-8 summarizes the recycled-load modeling results for the upgrades to achieve Objective B year-round at lagoon plants. For lagoon plants with capacities up to 5.0 mgd, the recycled loads are the same as those calculated for the year-round Objective B upgrade for extended aeration systems.

TABLE 10-8.
NUTRIENT RECYCLING ESTIMATES FOR LAGOON PLANTS UPGRADED TO ACHIEVE OBJECTIVE B YEAR-ROUND

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Plants Up to 5.0 mgd	17.2%	15.9%	55.7%	61.7%
Plants > 5.0 mgd	14.5%	15.5%	33.5%	29.7%

Sludge Production

The sludge produced from a 1-mgd plant with the Objective B year-round upgrades would be as follows:

- With upgrades proposed for plants up to 5.0 mgd:
  - Annual average of 951 ppd
  - 174 dry tons per year
  - 0.75 dry tons per million gallons of wastewater treated
  - This represents 63% increase in the quantity of biosolids by the plant
- With upgrades proposed for plants greater than 5.0 mgd
  - Annual average of 924 ppd
  - 169 dry tons per year
  - 0.73 dry tons per million gallons of wastewater treated
  - This represents 59% increase in the quantity of biosolids by the plant

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective B year-round would change the plant energy requirements as shown in Table 10-9 or 10-10, respectively.

Chemical Usage

For plants up to 5.0 mgd, the chemical usage for an upgraded plant to achieve Objective B year-round would be the same as for extended aeration plants upgraded to achieve Objective B year-round, as described in Section 4.2.2.

For plants larger than 5.0 mgd, the upgraded plant to achieve Objective B year-round would require 4,563 gallons of methanol per year for carbon supplementation to drive the denitrification process, or 20 gallons of methanol per million gallons of wastewater treated.

**TABLE 10-9.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND**

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective B Year-Round	1,292,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	320,000 kW-hours/year
Percent	33%
Increase per Volume of Plant Flow	1403 kW-hours/MG

**TABLE 10-10.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND**

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective B Year-Round	1,292,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	1,156,000 kW-hours/year
Percent	850%
Increase per Volume of Plant Flow	5068 kW-hours/MG

Footprint Requirements

Table 10-11 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective B for the three generic plant capacities. For plants up to 5 mgd in capacity, the upgrade footprint includes preliminary treatment, an influent pump station, an aeration tank, pre- and post-anoxic tanks, methanol containment, secondary clarifiers, an aerobic digester and a belt filer press. For plants larger than 5 mgd, the upgrade footprint includes preliminary treatment, an influent pump station, primary clarifiers, an aeration tank, pre- and post-anoxic tanks, methanol containment, secondary clarifiers, an anaerobic digester and a belt filer press. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

**TABLE 10-11.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE B YEAR-ROUND**

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(304,900)	(348,500)
5	(6,708,200)	(7,143,800)
50	(72,004,700)	(76,360,700)

10.2.3 Objective C

Process Description

Objective C (TP <1.0 mg/L) can be achieved year-round by adding a new chemical clarifier to the existing lagoon system. The effluent from the lagoon would be sent to the clarifier, where alum would be added for precipitation of phosphorus. The clarifier would be designed for an overflow rate of 500 gpd/ft^2, so the required clarifier area for a MMWWF of 1.0 mgd would be 2,000 square feet. A simple Biowin model was developed consisting of an influent equal to the lagoon effluent and a chemical clarifier as shown in Figure 10-1. Table 10-3 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

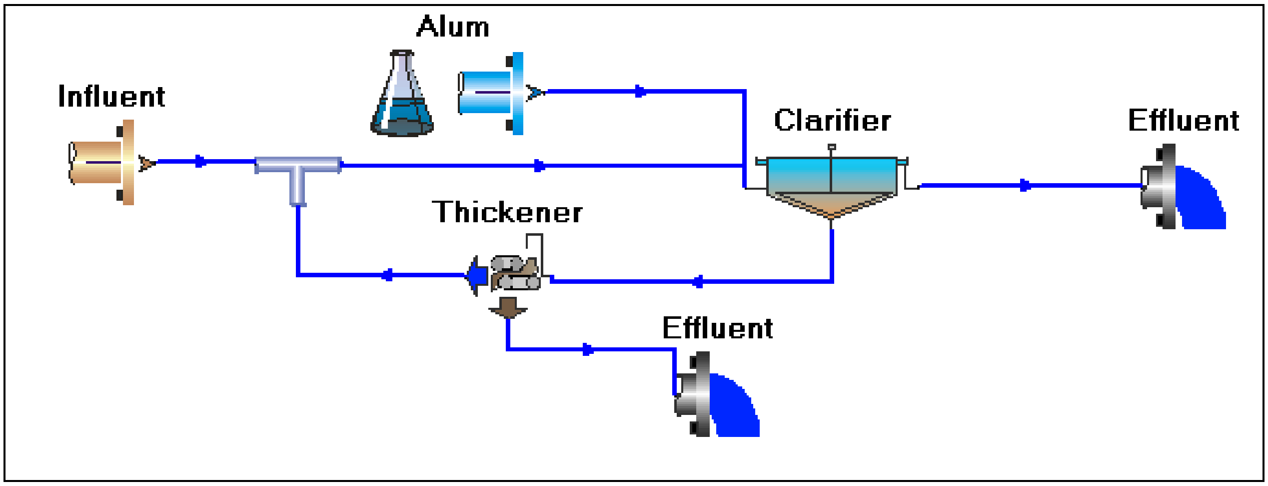


Figure 10-1. Process Schematic of Clarifier Used to Upgrade Lagoon Plant for Objective C Year-Round

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. Table 10-12 summarizes the results.

**TABLE 10-12.
NUTRIENT RECYCLING FOR AERATED OR FACULTATIVE LAGOON SYSTEMS,
OBJECTIVE C YEAR-ROUND NUTRIENT REMOVAL**

	AWWF	ADWF
% of TN Recycled	4.4%	4.4%
% of TP Recycled	1.1%	1.3%

Sludge Production

Addition of alum will result in higher sludge production rates which will increase the quantity of sludge that would need to be dredged from the lagoons. The additional sludge produced would be equivalent to 0.15 tons per million gallons of wastewater treated.. This represent approximately a 33% increase in the sludge production by the treatment plant.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective C year-round would change the plant energy requirements as shown in Table 10-13 or 10-14, respectively.

**TABLE 10-13.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND**

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective C Year-Round	1,038,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	66,000 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	105,600 kW-hours/MG

**TABLE 10-14.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND**

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective C Year-Round	202,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	66,000 kW-hours/year
Percent	49%
Increase per Volume of Plant Flow	105,600 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective C year-round would require 22,995 gallons of alum per year for phosphorus removal, or 100 gallons of alum per million gallons of wastewater treated.

Footprint Requirements

Table 10-15 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective C for the three generic plant capacities. The upgraded footprint area includes a new chemical clarifier, a chemical containment tank and a pump station. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 10-15.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE C YEAR-ROUND

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	3,900	3,900
5	30,000	30,000
50	233,000	233,000

10.2.4 Objective D

Process Description

Objective D (TP <0.1 mg/L) can be achieved year-round by adding a new chemical clarifier and tertiary filters to the existing lagoon system. The effluent from the lagoon would be sent to the clarifier, where alum would be added for precipitation of phosphorus. The clarifier would be designed for an overflow rate of 500 gpd/ft^2, so the required clarifier area for an MMWWF of 1.0 mgd would be 2,000 square feet. A process schematic for this upgrade is shown in Figure 10-2. Table 10-3 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

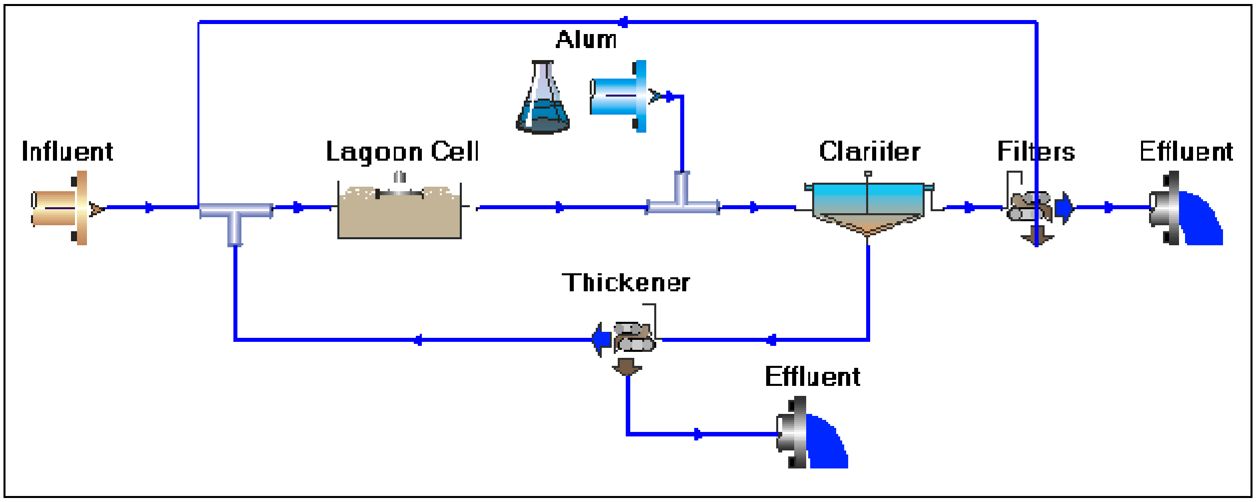


Figure 10-2. Process Schematic of Upgraded Lagoon Plant for Objective D Year-Round

The sludge produced from the chemical clarifier and the backwash from the filters would be sent back to the existing lagoon. Part of the lagoon would be partitioned to store the sludge from the chemical clarifier by constructing a 10-foot earthen berm with 3:1 side slopes. The size of this lagoon cell is assumed to be 1.0 acre for a 1.0-mgd lagoon plant. Sludge from the chemical clarifier will be accumulated in this lagoon cell and decanted. The accumulated sludge will be dredged out every 5 to 7 years. A new pump station should be constructed to transfer the lagoon effluent to the physical/chemical treatment process.

Recycled Loads

The percentage of TN and TP returning from the sludge treatment processes was calculated using Biowin model outputs. Table 10-16 summarizes the results.

TABLE 10-16.
NUTRIENT RECYCLING FOR AERATED OR FACULTATIVE LAGOON SYSTEMS, OBJECTIVE D YEAR-ROUND NUTRIENT REMOVAL

	AWWF	ADWF
% of TN Recycled	9.5%	8.7%
% of TP Recycled	5.9%	3.4%

Sludge Production

Addition of alum will result in higher sludge production rates which will increase the quantity of sludge that would need to be dredged from the lagoons. The additional sludge produced would be equivalent to 0.19 tons per million gallons of wastewater treated.. This represent approximately a 41% increase in the sludge production by the treatment plant.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective D year-round would change the plant energy requirements as shown in Table 10-17 or 10-18, respectively.

Chemical Usage

The upgraded plant to achieve Objective D year-round would require 51,100 gallons of alum per year for phosphorus removal, or 222 gallons of alum per million gallons of wastewater treated.

Footprint Requirements

Table 10-19 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective D for the three generic plant capacities. The upgraded footprint area includes a new chemical clarifier, a chemical containment tank, tertiary filters, and a pump station. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 10-17.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective D Year-Round	1,042,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	71,000 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	113,600 kW-hours/MG

**TABLE 10-18.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND**

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective D Year-Round	207,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	71,000 kW-hours/year
Percent	52%
Increase per Volume of Plant Flow	113,600 kW-hours/MG

**TABLE 10-19.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE D YEAR-ROUND**

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	4,800	4,800
5	37,000	37,000
50	285,800	285,800

10.2.5 Objective E

Process Description

To achieve Objective E (TIN <8 mg/L and TP <1.0 mg/L) year-round for lagoons rated up to 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the year-round Objective E upgrade for extended aeration plants. Table 4-2 summarizes the process design data.

To achieve Objective E year-round for lagoons rated greater than 5.0 mgd, the existing lagoon plant would be upgraded as described for Objective A, with the additional upgrades of constructing an alum tank for precipitation of phosphorus and a magnesium hydroxide tank for pH control. Tanks would be sized based on maximum chemical usage during MMWWF, AWWF or ADWF (whichever is higher). The process flow schematics are similar to those for Objective A, with the addition of alum and magnesium hydroxide to the secondary process. A mechanical dewatering system would be constructed to concentrate biosolids to a minimum of 16 percent dry solids content. Table 10-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Table 10-20 summarizes the recycled-load modeling results for the upgrades to achieve Objective E year-round at lagoon plants. For lagoon plants with capacities up to 5.0 mgd, the recycled loads are the same as those calculated for the year-round Objective E upgrade for extended aeration systems.

**TABLE 10-20.
NUTRIENT RECYCLING ESTIMATES FOR LAGOON PLANTS UPGRADED TO ACHIEVE OBJECTIVE E YEAR-ROUND**

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Plants Up to 5.0 mgd	18.0%	15.2%	35.9%	50.4%
Plants > 5.0 mgd	2.2%	15.4%	45.5%	46.4%

Sludge Production

The sludge produced from a 1-mgd plant with the Objective E year-round upgrades would be as follows:

- With upgrades proposed for plants up to 5.0 mgd:
  - Annual average of 1,177 ppd
  - 214 dry tons per year
  - 0.93 dry tons per million gallons of wastewater treated
  - Sludge production would therefore increase 102%
- With upgrades proposed for plants greater than 5.0 mgd
  - Annual average of 1,175 ppd
  - 214 dry tons per year
  - 0.93 dry tons per million gallons of wastewater treated
  - Sludge production would therefore increase 102%

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective E year-round would change the plant energy requirements as shown in Table 10-21 or 10-22, respectively.

**TABLE 10-21.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND**

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective E Year-Round	1,022,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	50,000 kW-hours/year
Percent	5%
Increase per Volume of Plant Flow	219 kW-hours/MG

TABLE 10-22.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective E Year-Round	1,022,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	886,000 kW-hours/year
Percent	651%
Increase per Volume of Plant Flow	3883 kW-hours/MG

Chemical Usage

For plants up to 5.0 mgd, the chemical usage for an upgraded plant to achieve Objective E year-round would be the same as for extended aeration plants upgraded to achieve Objective E year-round, as described in Section 4.2.5.

For plants larger than 5.0 mgd, the upgraded plant to achieve Objective E year-round would require 44,530 gallons of alum per year (194 gallons per million gallons of wastewater treated) for phosphorus reduction and 32,850 gallons of magnesium hydroxide per year (143 gallons per million gallons of wastewater treated) for pH control.

Footprint Requirements

Table 10-23 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective E for the three generic plant capacities. For plants up to 5 mgd in capacity, the upgrade footprint includes preliminary treatment, an influent pump station, an aeration tank, an anoxic tank, alum and magnesium hydroxide containment, secondary clarifiers, an aerobic digester and a belt filer press. For plants larger than 5 mgd, the upgrade footprint includes preliminary treatment, an influent pump station, primary clarifiers, an aeration tank, an anoxic tank, alum and magnesium hydroxide containment, secondary clarifiers, an anaerobic digester and a belt filer press. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 10-23.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE E YEAR-ROUND

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(304,900)	(348,500)
5	(6,708,200)	(7,143,800)
50	(72,004,700)	(76,360,700)

10.2.6 Objective F

Process Description

To achieve Objective F (TIN <3 mg/L and TP <0.1 mg/L) year-round for lagoons rated up to 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the year-round Objective F upgrade for extended aeration plants. Table 4-2 summarizes the process design data.

To achieve Objective F year-round for lagoons rated greater than 5.0 mgd, the existing lagoon plant would be upgraded as described for Objective B, with the additional upgrades of constructing an alum tank for precipitation of phosphorus, a magnesium hydroxide tank for pH control, and new conventional gravity filters. Tanks would be sized based on maximum chemical usage during MMWWF, AWWF or ADWF (whichever is higher). The process flow schematics are similar to those for Objective B, with the addition of alum and magnesium hydroxide to the secondary process. A mechanical dewatering system would be constructed to concentrate biosolids to a minimum of 16 percent dry solids content. Table 10-2 summarizes the process design data. Detailed Biowin model reports are in Appendix A.

Recycled Loads

Table 10-24 summarizes the recycled-load modeling results for the upgrades to achieve Objective F year-round at lagoon plants. For lagoon plants with capacities up to 5.0 mgd, the recycled loads are the same as those calculated for the year-round Objective F upgrade for extended aeration systems.

**TABLE 10-24.
NUTRIENT RECYCLING ESTIMATES FOR LAGOON PLANTS UPGRADED TO ACHIEVE OBJECTIVE F YEAR-ROUND**

	% of TN Recycled		% of TP Recycled	
	AWWF	ADWF	AWWF	ADWF
Plants Up to 5.0 mgd	16.5%	15.3%	36.5%	36.6%
Plants > 5.0 mgd	16.1%	15.5%	24.5%	24.7%

Sludge Production

The sludge produced from a 1-mgd plant with the Objective F year-round upgrades would be as follows:

- With upgrades proposed for plants up to 5.0 mgd:
  - Annual average of 1,228 ppd
  - 224 dry tons per year
  - 0.97 dry tons per million gallons of wastewater treated
  - Sludge production would therefore increase 111%
- With upgrades proposed for plants greater than 5.0 mgd
  - Annual average of 1,264 ppd
  - 231 dry tons per year
  - 1.00 dry tons per million gallons of wastewater treated

– Sludge production would therefore increase 117%

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective F year-round would change the plant energy requirements as shown in Table 10-25 or 10-26, respectively.

**TABLE 10-25.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective F Year-Round	1,317,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	345,500 kW-hours/year
Percent	35.5%
Increase per Volume of Plant Flow	1515 kW-hours/MG

**TABLE 10-26.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND**

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective F Year-Round	1,317,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	1,181,500 kW-hours/year
Percent	869%
Increase per Volume of Plant Flow	5179 kW-hours/MG

Chemical Usage

For plants up to 5.0 mgd, the chemical usage for an upgraded plant to achieve Objective F year-round would be the same as for extended aeration plants upgraded to achieve Objective F year-round, as described in Section 4.2.6.

For plants larger than 5.0 mgd, the upgraded plant to achieve Objective F year-round would require 63,875 gallons of alum per year (278 gallons per million gallons of wastewater treated) for phosphorus reduction, 43,800 gallons of magnesium hydroxide per year (190 gallons per million gallons of wastewater treated) for pH control, and 5,475 gallons of methanol per year (24 gallons per million gallons of wastewater treated) for nitrogen removal.

Footprint Requirements

Table 10-27 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective F for the three generic plant capacities. For plants up to 5 mgd in capacity, the upgrade footprint includes preliminary treatment; an influent pump station; an aeration tank; pre- and post-anoxic tanks; alum, magnesium hydroxide and methanol containment; tertiary filters; secondary clarifiers; an aerobic digester; and a belt filer press. For plants larger than 5 mgd, the upgrade footprint includes preliminary treatment; an influent pump station; primary clarifiers; an aeration tank; pre- and post-anoxic tanks; alum, magnesium hydroxide and methanol containment; tertiary filters; secondary clarifiers; an anaerobic digester; and a belt filer press. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 10-27.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE F YEAR-ROUND

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(304,900)	(348,500)
5	(6,708,200)	(7,143,800)
50	(72,004,700)	(76,360,700)

10.3 SEASONAL NUTRIENT REMOVAL

To achieve seasonal nitrogen-removal objectives (A, B, E and F) a lagoon plant would need to be abandoned and a new plant constructed in its place. The elements included in the replacement plant would depend on the size of the original plant:

- For plants up to 5 mgd, the replacement plant would be the same as the upgraded plant for existing extended aeration treatment plants, as described in Chapter 4; process design data for these plants are presented in Table 4-31.
- For plants larger than 5 mgd, the proposed new plant is the same as the upgraded plant for existing CAS treatment plants, as described in Chapter 5. Process design data for these plants are presented in Table 5-21. In order to provide a consistent comparison with other upgrades discussed in this report, the modeled size of these plants is 1.0-mgd; tank sizes would be scaled linearly to obtain sizes for plants rated up to 50 mgd.

To achieve objectives to remove only phosphorus seasonally (Objectives C and D), a lagoon plant could be upgraded rather than abandoned and replaced. Process design data for these plants are presented in Table 10-3.

10.3.1 Objective A

Process Description

To achieve Objective A seasonally for lagoons rated up to 5.0 mgd, the existing lagoons would be replaced by a new mechanical liquid and solids treatment plant. The new plant would be feature the same processes as described for the upgraded extended aeration plant to achieve Objective A seasonally. Table 4-31 summarizes the process design data.

For existing lagoon plants greater than 5 mgd would require construction of a new mechanical liquid and solids treatment plant conforming with the processes described for upgraded CAS plants that are to achieve Objective A during the dry weather season. The process flow schematic for this upgrade is shown in Figure 5-6, and Table 5-21 summarizes the process design data.

Recycled Loads

For plants rated up to 5.0 mgd, recycled loads for upgrades to achieve Objective A seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.1. For plants rated greater than 5.0 mgd, recycled loads would be the same as given for upgraded CAS plants in Section 5.3.1.

Sludge Production

For plants rated up to 5.0 mgd, sludge production for upgrades to achieve Objective A seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.1. For plants rated greater than 5.0 mgd, sludge production would be the same as given for upgraded CAS plants in Section 5.3.1.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective A seasonally would change the plant energy requirements as shown in Table 10-28 or 10-29, respectively.

TABLE 10-28.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING 1 MGD AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective A, Seasonal	938,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(33,500), kW-hours/year
Percent	(3%)%
Increase per Volume of Plant Flow	(147) kW-hours/MG

TABLE 10-29.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING 1 MGD FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective A, Seasonal	938,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	802,500 kW-hours/year
Percent	590%
Increase per Volume of Plant Flow	3,518 kW-hours/MG

Chemical Usage

For plants rated up to 5.0 mgd, chemical usage for upgrades to achieve Objective A seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.1. For plants rated greater than 5.0 mgd, chemical usage would be the same as given for upgraded CAS plants in Section 5.3.1.

Footprint Requirements

Table 10-30 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective A seasonally for the three generic plant capacities.

TABLE 10-30.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE A SEASONALLY

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(348,500)	(392,000)
5	(6,795,400)	(7,231,000)
50	(72,440,300)	(76,796,300)

10.3.2 Objective B

Process Description

To achieve Objective B seasonally for lagoons rated up to 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the seasonal Objective B upgrade for extended aeration plants. Table 4-31 summarizes the process design data.

To achieve Objective B seasonally for lagoons rated greater than 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the seasonal Objective B upgrade for CAS plants. The process flow schematic for this upgrade is shown in Figure 5-7, and Table 5-21 summarizes the process design data.

Recycled Loads

For plants rated up to 5.0 mgd, recycled loads for upgrades to achieve Objective B seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.2. For plants rated greater than 5.0 mgd, recycled loads would be the same as given for upgraded CAS plants in Section 5.3.2.

Sludge Production

For plants rated up to 5.0 mgd, sludge production for upgrades to achieve Objective B seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.2. For plants rated greater than 5.0 mgd, sludge production would be the same as given for upgraded CAS plants in Section 5.3.2.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective B seasonally would change the plant energy requirements as shown in Table 10-31 or 10-32, respectively.

TABLE 10-31.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective B, Seasonal	1,042,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	70,500 kW-hours/year
Percent	7%
Increase per Volume of Plant Flow	309 kW-hours/MG

TABLE 10-32.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective B, Seasonal	1,042,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	906,500 kW-hours/year
Percent	767%
Increase per Volume of Plant Flow	3,974 kW-hours/MG

Chemical Usage

For plants rated up to 5.0 mgd, chemical usage for upgrades to achieve Objective B seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.2. For plants rated greater than 5.0 mgd, chemical usage would be the same as given for upgraded CAS plants in Section 5.3.2.

Footprint Requirements

Table 10-33 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective B seasonally for the three generic plant capacities.

TABLE 10-33.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE B SEASONALLY

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(348,500)	(392,000)
5	(6,795,400)	(7,231,000)
50	(72,440,300)	(76,796,300)

10.3.3 Objective C

Process Description

Objective C can be achieved seasonally with the same upgrades as described for the year-round Objective C upgrade. Table 10-3 summarizes the process design data.

Recycled Loads

Average dry-weather recycled load percentages for upgrades to achieve Objective C seasonally would be the same as for upgrades to achieve Objective C year-round.

Sludge Production

Addition of alum will result in higher sludge production rates which will increase the quantity of sludge that would need to be dredged from the lagoons. The additional sludge produced would be equivalent to 0.084 tons per million gallons of wastewater treated.. This represent approximately a 18% increase in the sludge production by the treatment plant.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective C seasonally would change the plant energy requirements as shown in Table 10-34 or 10-35, respectively.

TABLE 10-34.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective C, Seasonal	853,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	118,500 kW-hours/year
Percent	12%
Increase per Volume of Plant Flow	519 kW-hours/MG

TABLE 10-35.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective C, Seasonal	254,500 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	118,500 kW-hours/year
Percent	87%
Increase per Volume of Plant Flow	3,145 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective C seasonally would require 12,775 gallons of alum per year for phosphorus removal, or 56 gallons of alum per million gallons of wastewater treated.

Footprint Requirements

Table 10-36 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective C seasonally for the three generic plant capacities. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 10-36.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE C SEASONALLY

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	4,400	4,400
5	30,500	30,500
50	230,900	230,900

10.3.4 Objective D

Process Description

Objective D can be achieved seasonally with the same upgrades as described for the year-round Objective D upgrade. Table 10-3 summarizes the process design data.

Recycled Loads

Average dry-weather recycled load percentages for upgrades to achieve Objective D seasonally would be the same as for upgrades to achieve Objective D year-round.

Sludge Production

Addition of alum will result in higher sludge production rates which will increase the quantity of sludge that would need to be dredged from the lagoons. The additional sludge produced would be equivalent to 0.095 tons per million gallons of wastewater treated.. This represent approximately a 21% increase in the sludge production by the treatment plant.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective D seasonally would change the plant energy requirements as shown in Table 10-37 or 10-38, respectively.

TABLE 10-37.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective D, Seasonal	870,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(102,000) kW-hours/year
Percent	(10)%
Increase per Volume of Plant Flow	(447) kW-hours/MG

TABLE 10-38.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective D, Seasonal	870,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	734,000 kW-hours/year
Percent	539%
Increase per Volume of Plant Flow	3,217 kW-hours/MG

Chemical Usage

The upgraded plant to achieve Objective D year-round would require 25,550 gallons of alum per year for phosphorus removal, or 111 gallons of alum per million gallons of wastewater treated.

Footprint Requirements

Table 10-39 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective D seasonally for the three generic plant capacities. Refer to Appendix C for detailed footprint areas of the existing system and the proposed system.

TABLE 10-39.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE D SEASONALLY

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	4,400	4,400
5	39,200	39,200
50	270,100	270,100

10.3.5 Objective E

Process Description

To achieve Objective E seasonally for lagoons rated up to 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the seasonal Objective E upgrade for extended aeration plants. Table 4-31 summarizes the process design data.

To achieve Objective E seasonally for lagoons rated greater than 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the seasonal Objective E upgrade for CAS plants. Table 5-21 summarizes the process design data.

Recycled Loads

For plants rated up to 5.0 mgd, recycled loads for upgrades to achieve Objective E seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.5. For plants rated greater than 5.0 mgd, recycled loads would be the same as given for upgraded CAS plants in Section 5.3.5.

Sludge Production

For plants rated up to 5.0 mgd, sludge production for upgrades to achieve Objective E seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.5. For plants rated greater than 5.0 mgd, sludge production would be the same as given for upgraded CAS plants in Section 5.3.5.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective E seasonally would change the plant energy requirements as shown in Table 10-40 or 10-41, respectively.

Chemical Usage

For plants rated up to 5.0 mgd, chemical usage for upgrades to achieve Objective E seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.5. For plants rated greater than 5.0 mgd, chemical usage would be the same as given for upgraded CAS plants in Section 5.3.5.

Footprint Requirements

Table 10-42 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective E seasonally for the three generic plant capacities.

TABLE 10-40.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective E, Seasonal	940,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	(32,000) kW-hours/year
Percent	(3)%
Increase per Volume of Plant Flow	(140) kW-hours/MG

**TABLE 10-41.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective E, Seasonal	940,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	804,000 kW-hours/year
Percent	591%
Increase per Volume of Plant Flow	3,524 kW-hours/MG

**TABLE 10-42.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE E SEASONALLY**

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(348,500)	(392,000)
5	(6,791,000)	(7,226,600)
50	(72,435,900)	(76,791,900)

10.3.6 Objective F

Process Description

To achieve Objective F seasonally for lagoons rated up to 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the seasonal Objective F upgrade for extended aeration plants. Table 4-31 summarizes the process design data.

To achieve Objective F seasonally for lagoons rated greater than 5.0 mgd, the existing lagoons would be abandoned in place and new liquid and solids treatment facilities would be constructed the same as for the seasonal Objective F upgrade for CAS plants. Table 5-21 summarizes the process design data.

Recycled Loads

For plants rated up to 5.0 mgd, recycled loads for upgrades to achieve Objective F seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.6. For plants rated greater than 5.0 mgd, recycled loads would be the same as given for upgraded CAS plants in Section 5.3.6.

Sludge Production

For plants rated up to 5.0 mgd, sludge production for upgrades to achieve Objective F seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.6. For plants rated greater than 5.0 mgd, sludge production would be the same as given for upgraded CAS plants in Section 5.3.6.

Energy Consumption

Upgrading an aerated or facultative lagoon plant to achieve Objective B seasonally would change the plant energy requirements as shown in Table 10-43 or 10-44, respectively.

TABLE 10-43.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing Aerated Lagoon Plant	972,000 kW-hours/year
Objective F, Seasonal	1,045,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	73,000 kW-hours/year
Percent	8%
Increase per Volume of Plant Flow	320 kW-hours/MG

TABLE 10-44.
ADDITIONAL ENERGY CONSUMPTION FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

Yearly Energy Required	
Existing Facultative Lagoon Plant	136,000 kW-hours/year
Objective F, Seasonal	1,045,000 kW-hours/year
Energy Increase for Upgrade	
Annual Quantity	909,000 kW-hours/year
Percent	668%
Increase per Volume of Plant Flow	3,984 kW-hours/MG

Chemical Usage

For plants rated up to 5.0 mgd, chemical usage for upgrades to achieve Objective F seasonally would be the same as given for upgraded extended aeration plants in Section 4.3.6. For plants rated greater than 5.0 mgd, chemical usage would be the same as given for upgraded CAS plants in Section 5.3.6.

Footprint Requirements

Table 10-45 compares the additional footprint area for upgrading existing lagoon plants to achieve Objective B seasonally for the three generic plant capacities.

TABLE 10-45.
ADDITIONAL FOOTPRINT REQUIREMENTS FOR UPGRADING AERATED LAGOON AND FACULTATIVE LAGOON PLANTS TO ACHIEVE OBJECTIVE F SEASONALLY

	Additional Area Required for Upgrade (square feet)	
Plant Design Capacity (mgd)	Aerated Lagoon Plants	Facultative Lagoon Plants
0.5	(348,500)	(392,000)
5	(6,786,600)	(7,222,200)
50	(72,435,000)	(76,791,000)

TABLE 10-2.
BIOWIN RESULTS FOR AERATED OR FACULTATIVE LAGOONS > 5.0 MGD, FOR OBJECTIVES A, B, E AND F YEAR-ROUND

	PROCESS DESIGN - MMWW				AWW				ADW			
Description	Obj. A	Obj. B	Obj. E	Obj. F	Obj. A	Obj. B	Obj. E	Obj. F	Obj. A	Obj. B	Obj. E	Obj. F
Nutrient Removal Goals												
TIN (mg/L)	< 8	< 3	< 8	< 3	< 8	< 3	< 8	< 3	< 8	< 3	< 8	< 3
TP (mg/L)			< 1	< 0.1			< 1	< 0.1			< 1	< 0.1
Plant Size, Average Temperature												
Influent Flow, mgd	1.0	1.0	1.0	1.0	0.75	0.75	0.75	0.75	0.50	0.50	0.50	0.50
Temp, ^{o}C	10	10	10	10	10	10	10	10	15	15	15	15
Influent												
BOD	165	165	165	165	221	221	221	221	331	331	331	331
TSS	188	188	188	188	251	251	251	251	376	376	376	376
VSS	132	132	132	132	176	176	176	176	263	263	263	263
TKN	24	24	24	24	32	32	32	32	48	48	48	48
TP	5.7	5.7	5.7	5.7	7.6	7.6	7.6	7.6	11.4	11.4	11.4	11.4
Alkalinity	2.01	2.01	2.01	2.01	2.68	2.68	2.68	2.68	4	4	4	4
pH	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	7	7	7	7
Aerobic Tank												
Tank Volume, MG	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
HRT, hrs	6.0	4.8	6.0	4.8	8.0	6.4	8.0	6.4	12	9.6	12	9.6
MLSS Conc., mg/L	3,182	3,372	3,602	3,989	3,334	3,372	3,869	3,339	3,264	3,334	3,889	4,117
DO Concentration, mg/L	2, 0.5	2, 0.5, 2	2, 0.5	2, 0.5, 2	2, 0.5	2, 0.5, 2	2, 0.5	2, 0.5, 2	2, 0.5	2, 0.5, 2	2, 0.5	2, 0.5, 2
Air Supply Rate, ft^3/min	592	672	617	684	618	672	628	724	680	720	689	733
BioWin SRT, days	18.45	20.14	17.6	19.13	18.45	20.14	18.45	15.32	18.47	20.19	18.81	19.16
RAS Recyle Rate	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q	0.5Q
Pre - Anoxic Tank												
Tank Volume, MG	0.15	0.1	0.15	0.1	0.15	0.1	0.15	0.1	0.15	0.1	0.15	0.1
HRT, hrs	3.6	2.4	3.6	2.4	4.8	3.2	4.8	3.2	7.2	4.8	7.2	4.8
Internal Recycle Rate	5Q	5Q	5Q	5Q	5Q	5Q	5Q	5Q	5Q	5Q	5Q	5Q
Post - Anoxic Tank												
Tank Volume, MG		0.05		0.05		0.05		0.05		0.05		0.05
HRT, hrs		1.2		1.2		1.6		1.6		2.4		2.4
Methanol, gpd		15		15		15		15		10		15
Clarifier												
Area, ft^2	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200	2,200
Surface Overflow Rate, gal/ft^2	454	454	454	454	341	341	341	357	227	227	227	227

TABLE 10-2.
BIOWIN RESULTS FOR AERATED OR FACULTATIVE LAGOONS > 5.0 MGD, FOR OBJECTIVES A, B, E AND F YEAR-ROUND

	PROCESS DESIGN - MMWW				AWW				ADW			
Description	Obj. A	Obj. B	Obj. E	Obj. F	Obj. A	Obj. B	Obj. E	Obj. F	Obj. A	Obj. B	Obj. E	Obj. F
Tertiary Filters												
Filter Area (ft2)				552				552				552
Chemical Addition												
Alum Dosage, gpd			90	200			105	175			130	175
Magnesium Hydroxide Dosage, gpd			100	170			120	120			60	120
Magnesium Hydroxide Conc., meq/L											14,500	14,500
Anaerobic Digester												
TSS wasted from Aerobic Tank, ppd	540	536	612	682	567	536	658	698	555	557	661	687
Total loading to Digester, ppd	1,668	1,663	1,898	2,073	1,695	1,663	1,972	2,082	1,678	1,682	1,990	2,054
Volume, MG	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Hydraulic Residence Time, hrs	19.8	19.8	19.8	19.8	26.5	26.5	26.5	26.5	39.5	39.5	39.5	37.5
Sludge Production												
Sludge Production, ppd	934	937	1,137	1,325	931	937	1,176	1,282	902	911	1,173	1,246
Effluent												
BOD, mg/L	2.96	3	2.78	1.53	2.31	3	2.13	1.36	1.66	1.61	1.57	1.12
TSS, mg/L	8.0	8.1	8.2	4.5	5.7	8.1	5.8	4.4	3.6	3,6	3.6	5.5
Phosphorous, mg/L	4.11	4.27	0.48	0.06	5.6	4.27	0.68	0.05	8.7	8.8	0.45	0.03
Ammonia N, mg/L	1.41	0.54	0.86	0.64	1.26	0.54	0.9	0.17	0.34	0.09	0.37	0.09
TIN, mg/L	4.06	2.08	5.51	2.17	5.03	2.08	4.68	2.09	6.4	1.44	4.8	1.4
pH	6.31	6.33	6.58	6.52	6.27	6.33	6.6	6.54	6.4	6.53	6.55	6.57
Recycle Loads												
Nitrogen Recycle from Thickener, ppd	5.29	5.35	5.36	5.57	5.54	5.35	5.51	6.04	5.35	5.51	5.39	5.73
Nitrogen Recycle from Digester, ppd	23.7	23.73	23.77	25.39	26.33	23.7	23.79	26.22	25.66	25.51	25.35	25.35
Total Nitrogen Recycled, ppd	28.99	29.08	29.13	30.96	31.87	29.05	4.33	32.26	31.01	31.02	30.74	31.08
Phosphorus Recycle from Thickener, ppd	3.06	2.45	4.14	3.18	3	2.45	3.52	3.32	2.67	2.24	4.25	3.39
Phosphorus Recycle from Digester, ppd	19.78	13.5	17.48	8.13	19.49	13.5	18.13	8.34	17.5	11.9	17.84	8.37
Total Phosphorus Recycled, ppd	22.84	15.95	21.62	11.31	22.49	15.95	21.65	11.66	20.17	14.14	22.09	11.76
% TN Recycled	14.5%	14.5%	14.6%	15.5%	15.9%	14.5%	2.2%	16.1%	15.5%	15.5%	15.4%	15.5%
% TP Recycled	48.0%	33.5%	45.4%	23.8%	47.3%	33.5%	45.5%	24.5%	42.4%	29.7%	46.4%	24.7%

TABLE 10-3.
BIOWIN RESULTS FOR AERATED OR FACULTATIVE LAGOONS FOR OBJECTIVES C AND D

	Year-Round Nutrient Removal						Seasonal Nutrient Removal			
	MMWW		AWW		ADW		MMDW		ADW	
Description	Obj. C	Obj. D	Obj. C	Obj. D	Obj. C	Obj. D	Obj. C	Obj. D	Obj. C	Obj. D
Nutrient Removal Goals										
TIN (mg/L)	—	—	—	—	—	—	—	—	—	—
TP (mg/L)	< 1	< 0.1	< 1	< 0.1	< 1	< 0.1	< 1	< 0.1	< 1	< 0.1
Plant Size, Average Temperature										
Influent Flow, mgd	1.00	1.00	0.75	0.75	0.50	0.50	0.69	0.69	0.50	0.50
Temp, ^{o}C	10	10	10	10	15	15	15	15	15	15
Influent										
BOD	22.5	22.5	30	30	45	45	32.6	32.6	45	45
TSS	22.5	22.5	30	30	45	45	32.6	32.6	45	45
VSS	16	16	21	21	32	32	23	23	32	32
TKN	10	10	13.3	13.3	20	20	14.5	14.5	20	20
TP	4	4	5.3	5.3	8	8	5.8	5.8	8	8
Alkalinity	2.5	2.5	3.35	3.35	5	5	3.6	3.6	5	5
pH	7	7	7	7	8.5	8.5	8.5	8.5	8.5	8.5
Existing Lagoon Partition										
Area of the partition		43,560		43,560		43,560		43,560		43,560
Volume		1.3		1.3		1.3		1.3		1.3
Clarifier										
Area, ft^2	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Surface Overflow Rate, gal/ft^2	525	525	375	375	250	250	345	345	250	250
Thickener / Dewatering Unit										
% Removal Efficiency	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
Tertiary Filters										
Filter Area (ft2)		555		555		555		380		380
Chemical Addition										
Alum Dosage, gpd	55	160	55	140	70	140	70	140	70	140
Effluent										
BOD, mg/L	13.47	9.07	17.43	4.16	25.24	2.38	18.58	3.11	25.24	2.38
TSS, mg/L	5.1	1.2	4.0	0.9	2.8	0.6	3.8	0.9	2.8	0.6
Phosphorous, mg/L	0.63	0.09	0.52	0.07	0.67	0.05	0.65	0.07	0.67	0.05
Ammonia N, mg/L	6.6	6.34	8.78	8.48	13.2	12.34	9.57	9.16	13.2	12.34
TIN, mg/L	6.6	6.35	8.78	8.48	13.2	13.08	9.57	13.08	13.2	13.08
pH	6.81	6.66	6.81	6.78	7.29	6.79	7.29	6.79	7.29	6.79
TN returned from thickener, ppd	87.04	91.2	86.83	91.1	87.05	90.62	87.09	91.08	87.05	90.62
TP Returned from Thickener, ppd	33.71	36.48	33.51	35.12	33.78	34.48	33.78	35.13	33.78	34.48
% TN Recycled	4.36%	9.35%	4.37%	9.51%	4.38%	8.66%	4.37%	9.15%	4.38%	8.66%
% TP Recycled	1.05%	9.35%	1.08%	5.94%	1.26%	3.36%	1.21%	5.25%	1.26%	3.36%

CHAPTER 11.
COST EVALUATION, OBJECTIVE A

11.1 YEAR-ROUND NUTRIENT REMOVAL

11.1.1 Extended Aeration Plants

Table 11-1 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A year-round for an extended aeration plant using mechanical aeration. Figures 11-1 and 11-2 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-2 and Figures 11-3 and 11-4 summarize these costs for an extended aeration plant using diffuser aeration. Tables 11-3 and 11-4 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 11-1.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.78	$2.26	$2.20
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.21	$0.01	($0.02)

TABLE 11-2.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.07	$0.75	$0.31
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.02	($0.05)	($0.05)

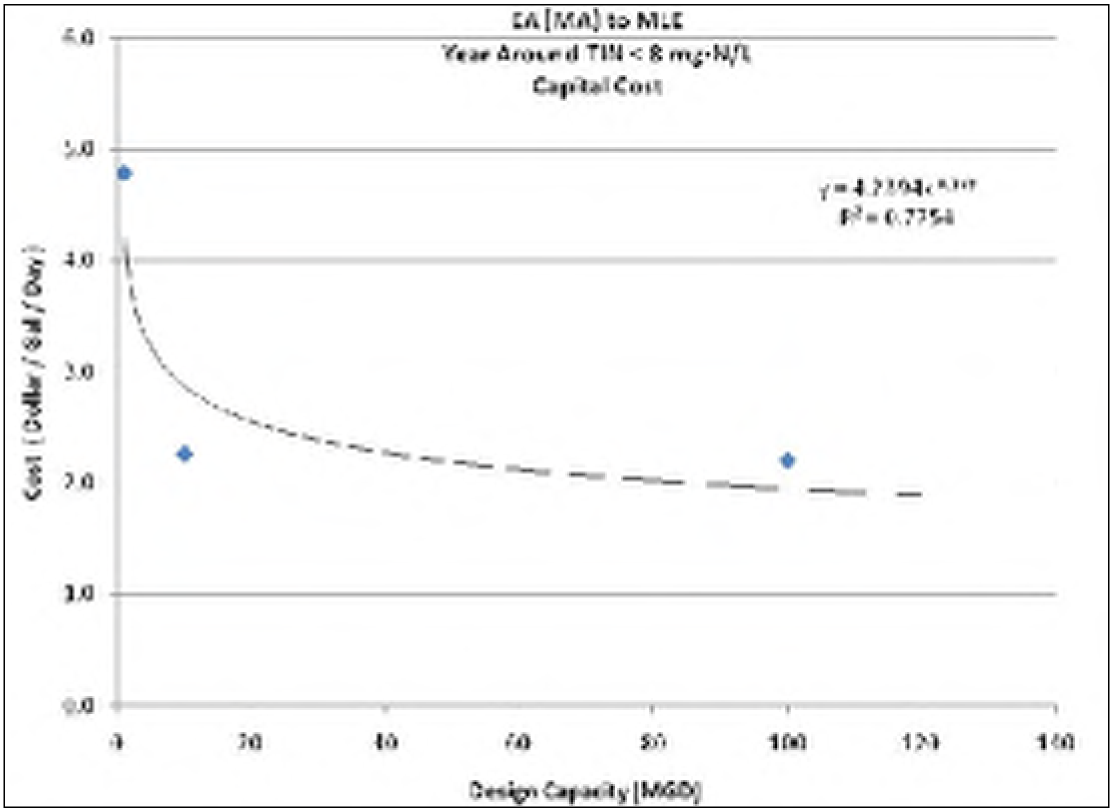


Figure 11-1. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective A Year-Round

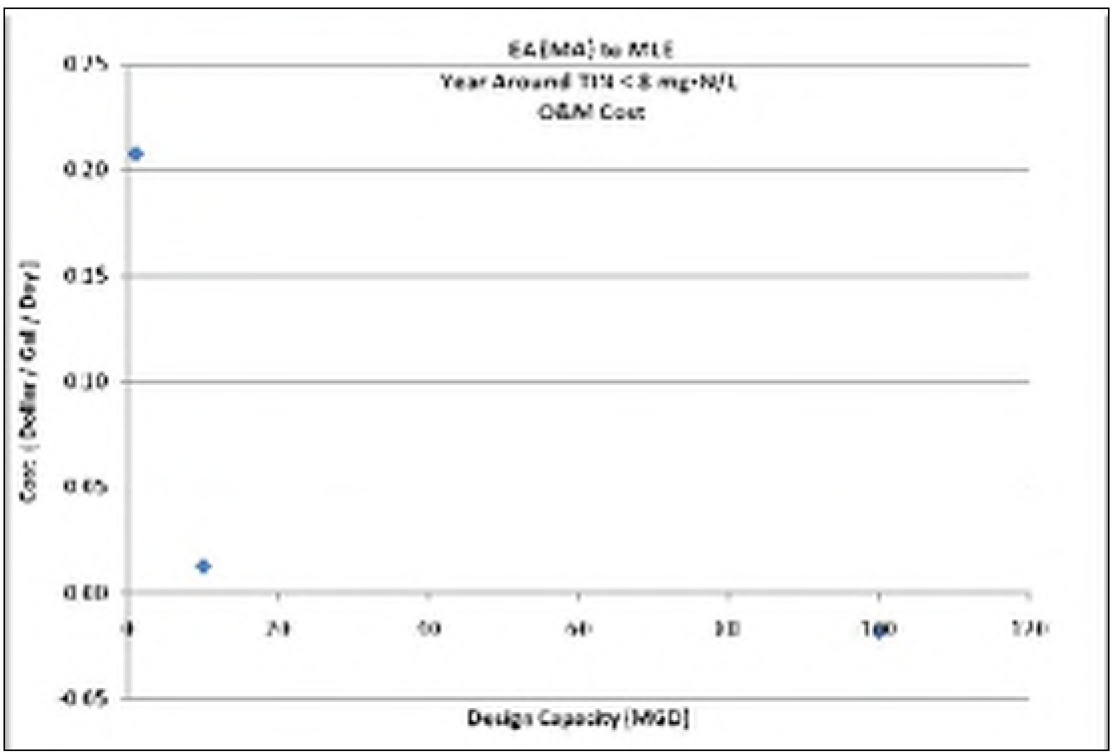


Figure 11-2. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective A Year-Round

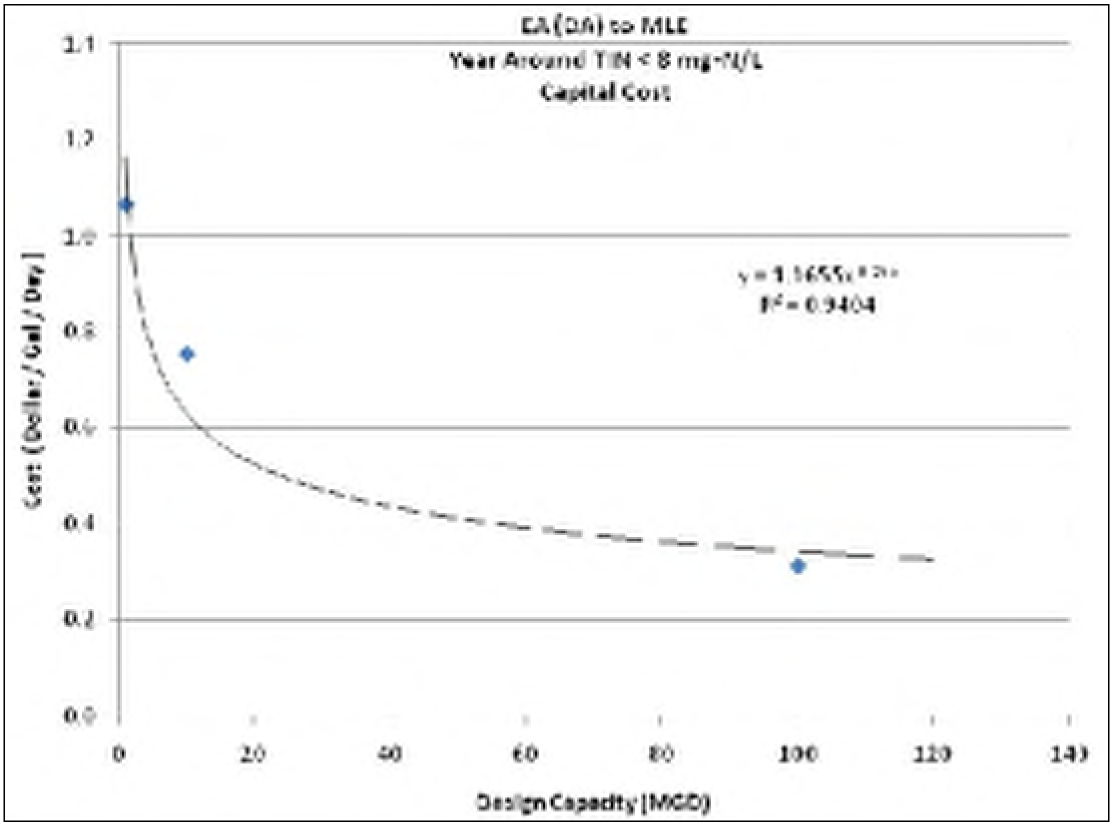


Figure 11-3. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective A Year-Round

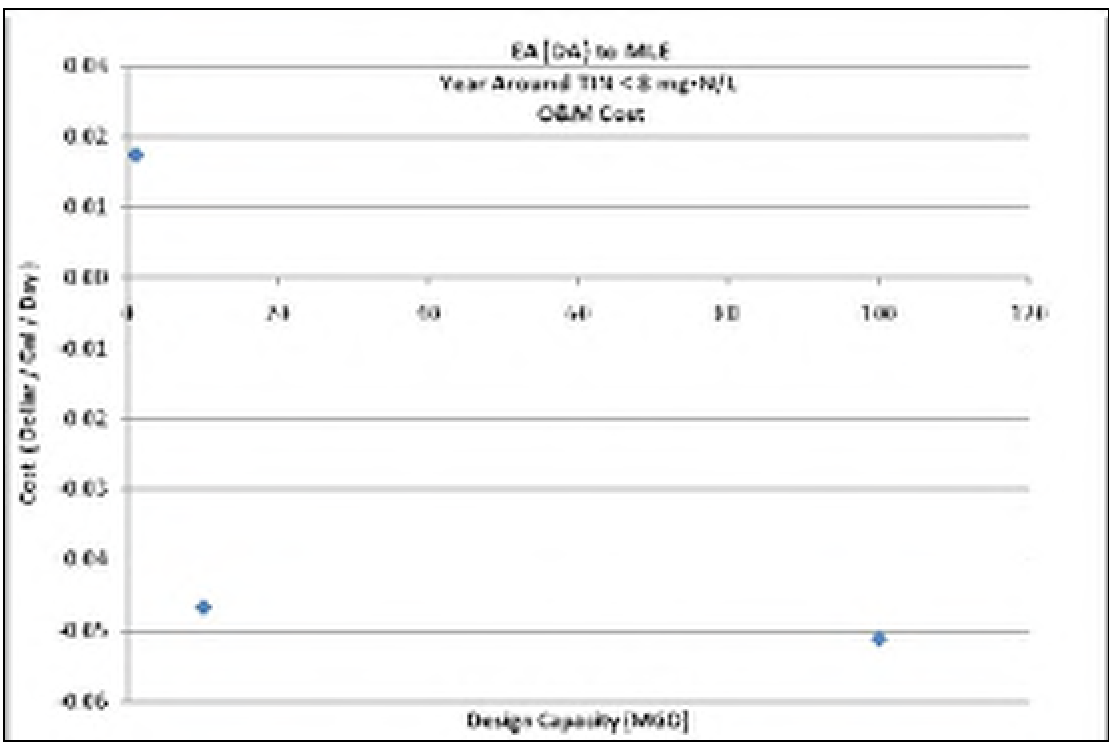


Figure 11-4. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective A Year-Round

**TABLE 11-3.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$351,414	$1,656,556	$16,134,708
2014 Incremental O&M Cost	$234,218	$142,715	-$2,068,685
Total Annual Cost	**$585,632**	**$1,799,270**	**$14,066,023**
Annual TIN Load Reduction (lb/yr)	35,259	352,590	3,525,900
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$16.61	$5.10	$3.99
Equation:[a]	$y = 363.87x^{-0.31}$		
R-Square Value:	0.8746		

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

**TABLE 11-4.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$78,303	$554,242	$2,298,201
2014 Incremental O&M Cost	$19,584	-$526,175	-$5,747,411
Total Annual Cost	**$97,887**	**$28,066**	**-$3,449,210**
Annual TIN Load Reduction (lb/yr)	35,223	352,225	3,522,250
Estimated Cost for TIN Reduction ($/lb TIN removed)	$2.78	$0.08	-$0.98
Equation and R-Square Value[a]		—	

a. Equation and R-square value not determined because annual cost estimates are below the level of precision that can be achieved using the CapdetWorks cost model.

11.1.2 Conventional Activated Sludge Plants

Table 11-5 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A year-round for a conventional activated sludge plant. Figures 11-5 and 11-6 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-6 presents the annualized unit costs for reducing nutrient loads.

TABLE 11-5.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$6.63	$4.55	$3.32
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.23	$0.13	$0.08

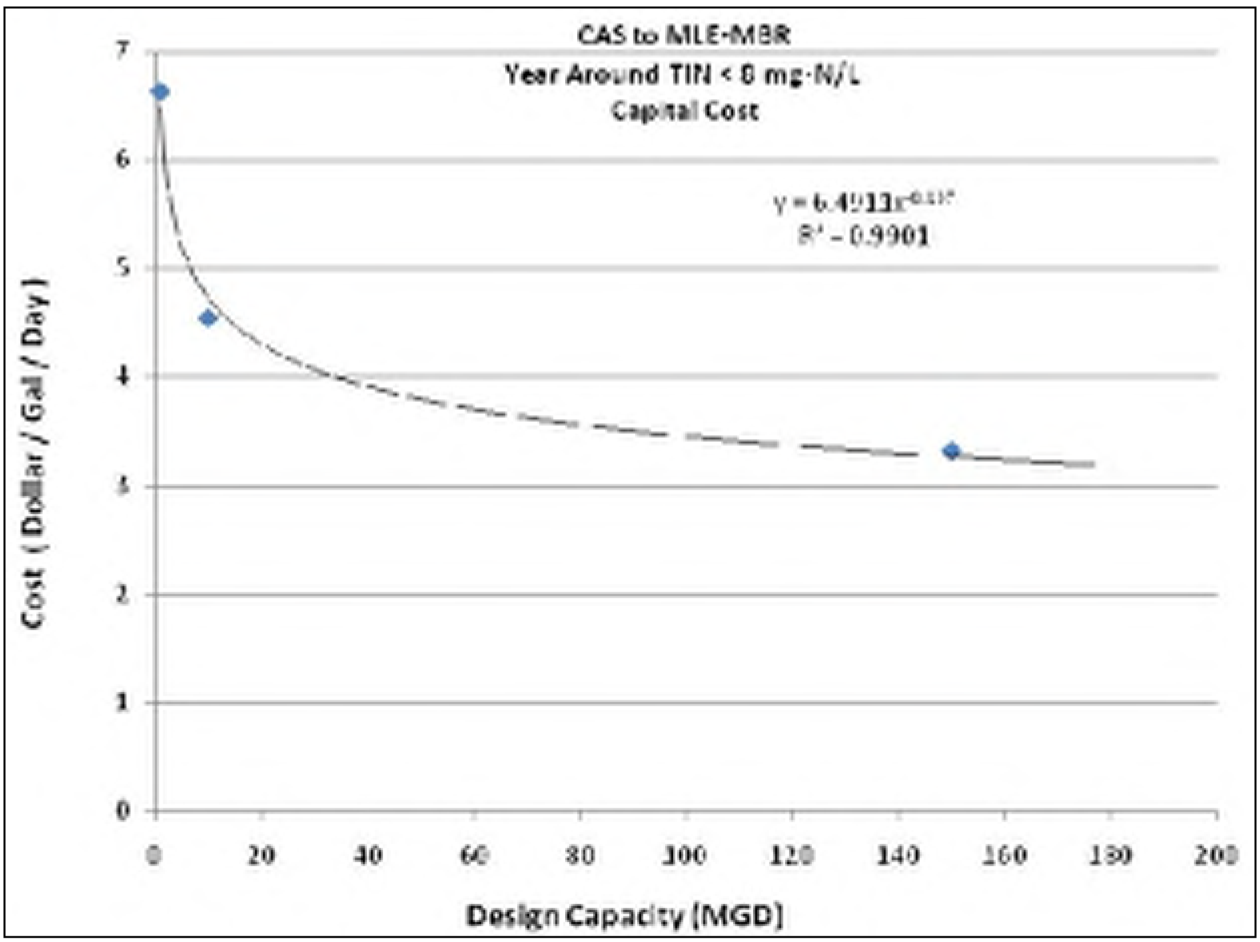


Figure 11-5. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective A Year-Round

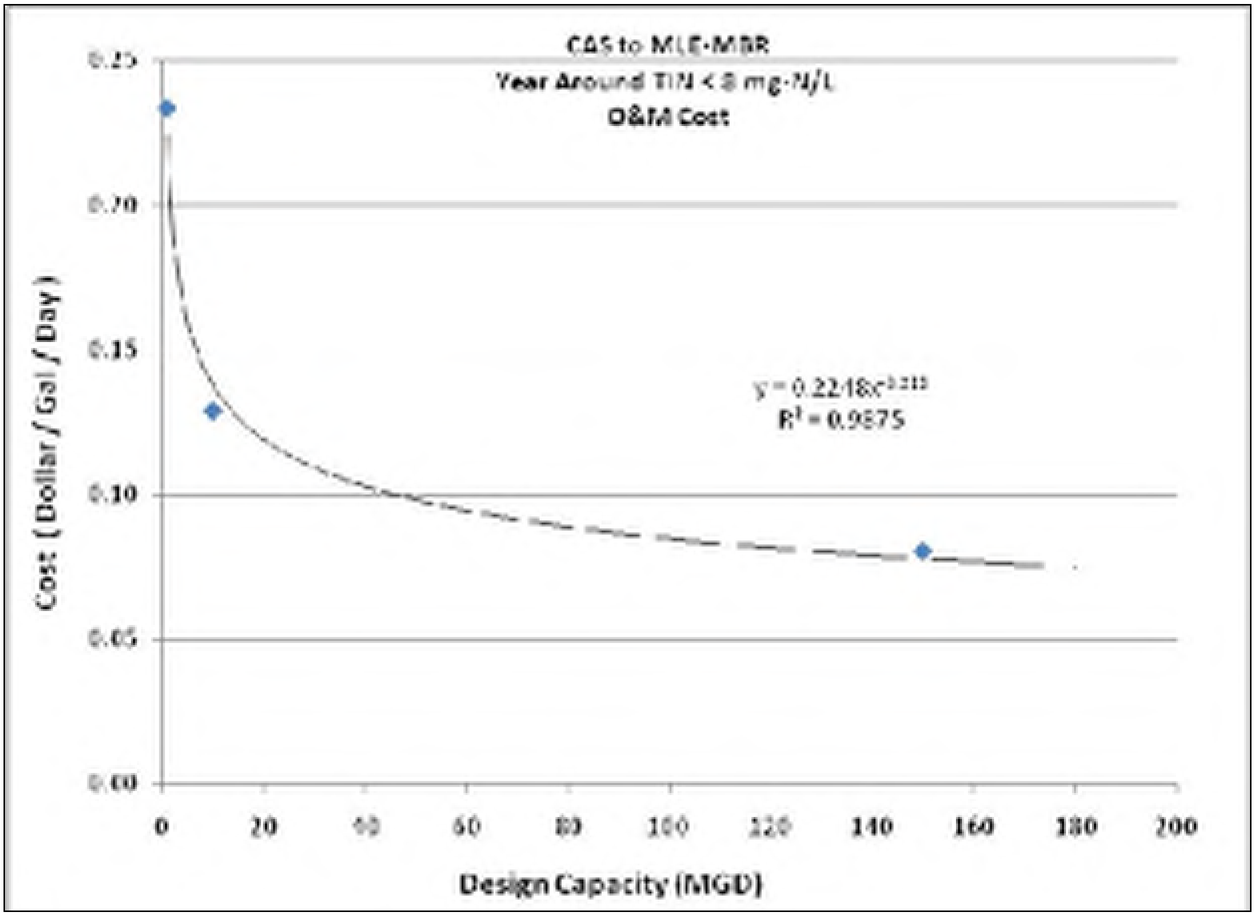


Figure 11-6. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective A Year-Round

TABLE 11-6.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	\$487,073	\$3,341,694	\$36,630,838
2014 O&M Cost	\$262,642	\$1,451,579	\$13,597.004
Total Annual Cost	**\$749,715**	**\$4,793,273**	**\$50,209,841**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Estimated Cost for TIN Reduction (\$/lb TIN removed)	\$21.09	\$13.48	\$9.42
Equation:[a]			$y = 109.71x^{-0.16}$
R-Square Value:			$R^2 = 0.9878$

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction (\$/lb TIN removed)

11.1.3 Sequencing Batch Reactor Plants

Table 11-7 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A year-round for an SBR plant. Figures 11-7 and 11-8 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-8 presents the annualized unit costs for reducing nutrient loads.

TABLE 11-7.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$0.45	$0.24	$0.18
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.01	$0.01	$0.004

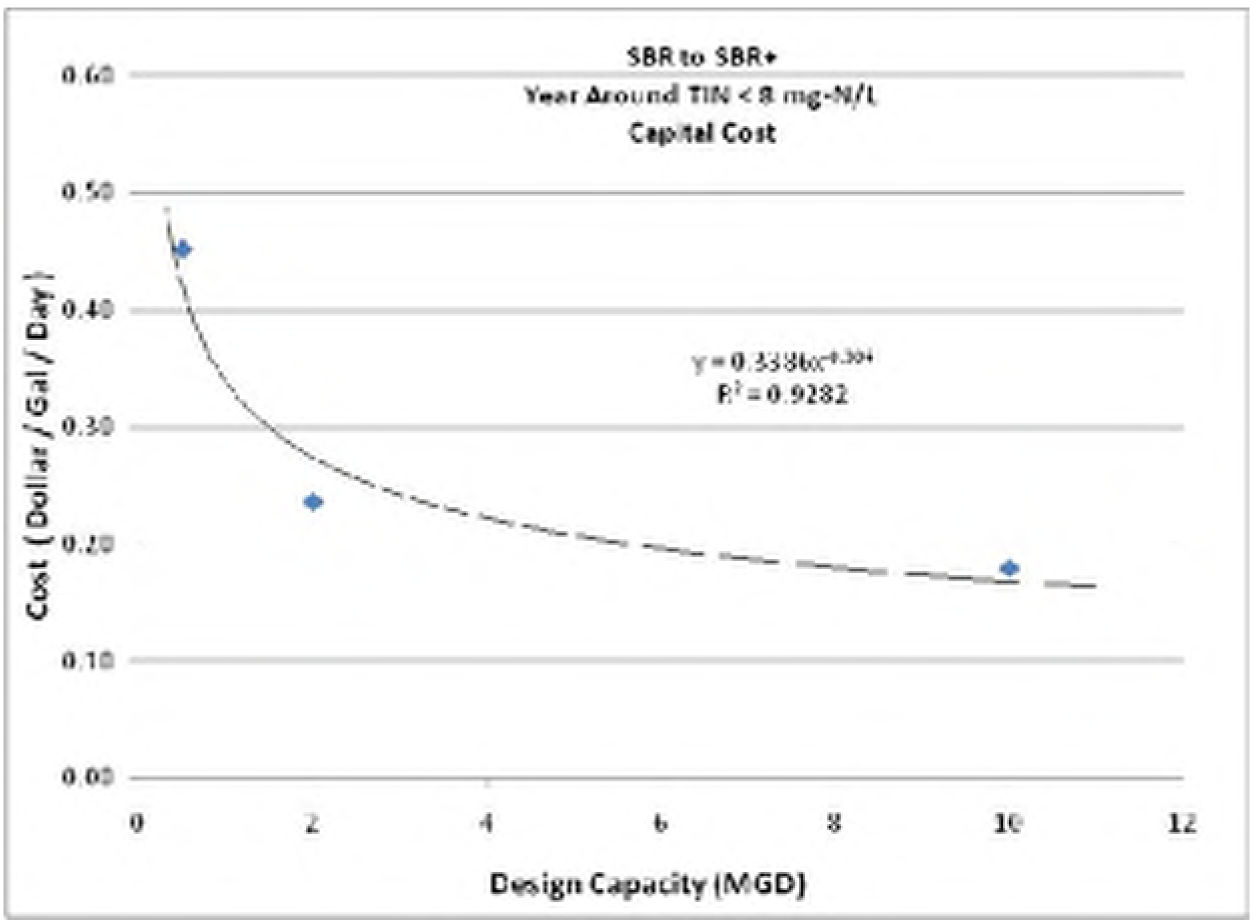


Figure 11-7. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective A Year-Round

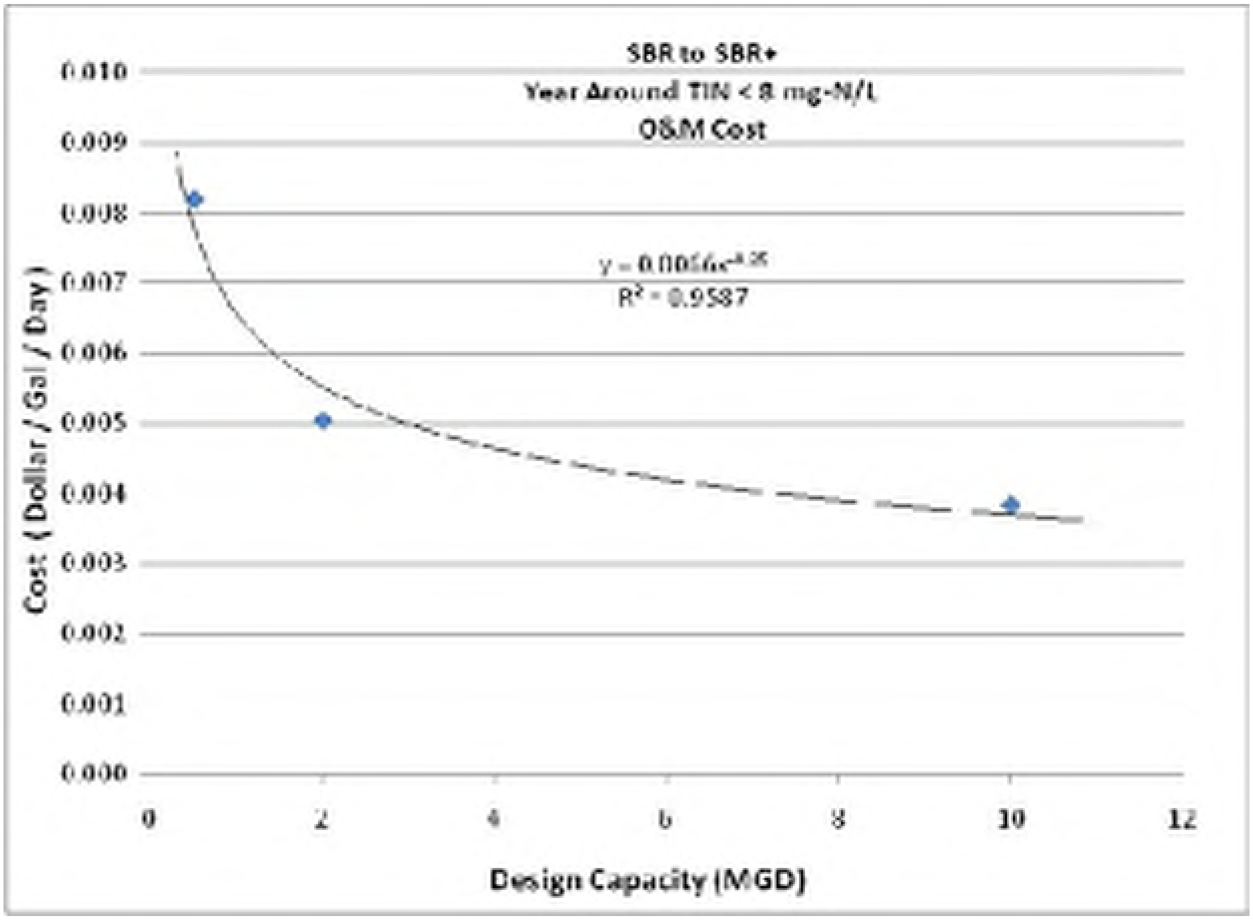


Figure 11-8. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective A Year-Round

TABLE 11-8.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$16,607	$34,807	$132,134
2014 O&M Cost	$4,615	$11,368	$43,332
Total Annual Cost	**$21,221**	**$46,175**	**$175,466**
Annual TIN Load Reduction (lb/yr)	2,245	8,979	44,895
Estimated Cost for TIN Reduction ($/lb TIN removed)	$9.45	$5.14	$3.91
Equation:[a]		$y = 83.25x^{-0.291}$	
R-Square Value:		$R^2 = 0.9344$	

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.1.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 11-9 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A year-round for a trickling filter plant. Figures 11-9 and 11-10 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-10 and Figures 11-11 and 11-12 summarize these costs for a trickling filter/solids contact plant. Table 11-11 and Figures 11-13 and 11-14 summarize these costs for an RBC plant. Tables 11-12, 11-13 and 11-14 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 11-9.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$8.19	$5.83	$3.82
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.29	$0.15	$0.08

TABLE 11-10.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$6.91	$5.27	$3.50
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.18	$0.13	$0.07

TABLE 11-11.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$8.19	$5.85	$3.87
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.35	$0.16	$0.09

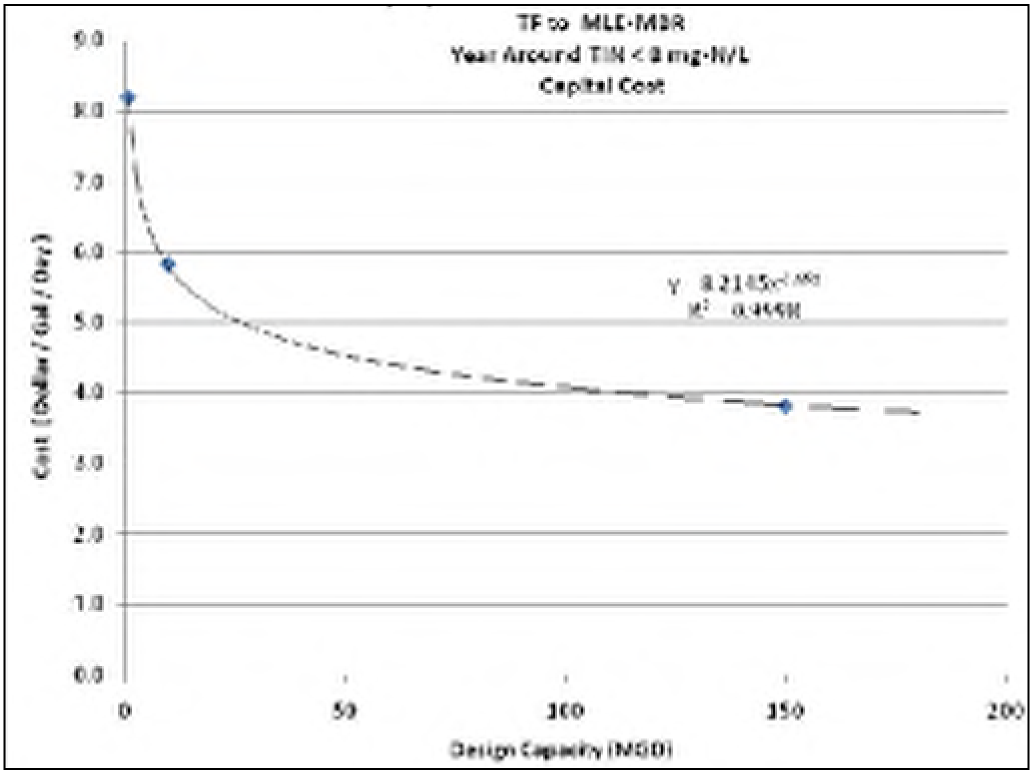


Figure 11-9. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective A Year-Round

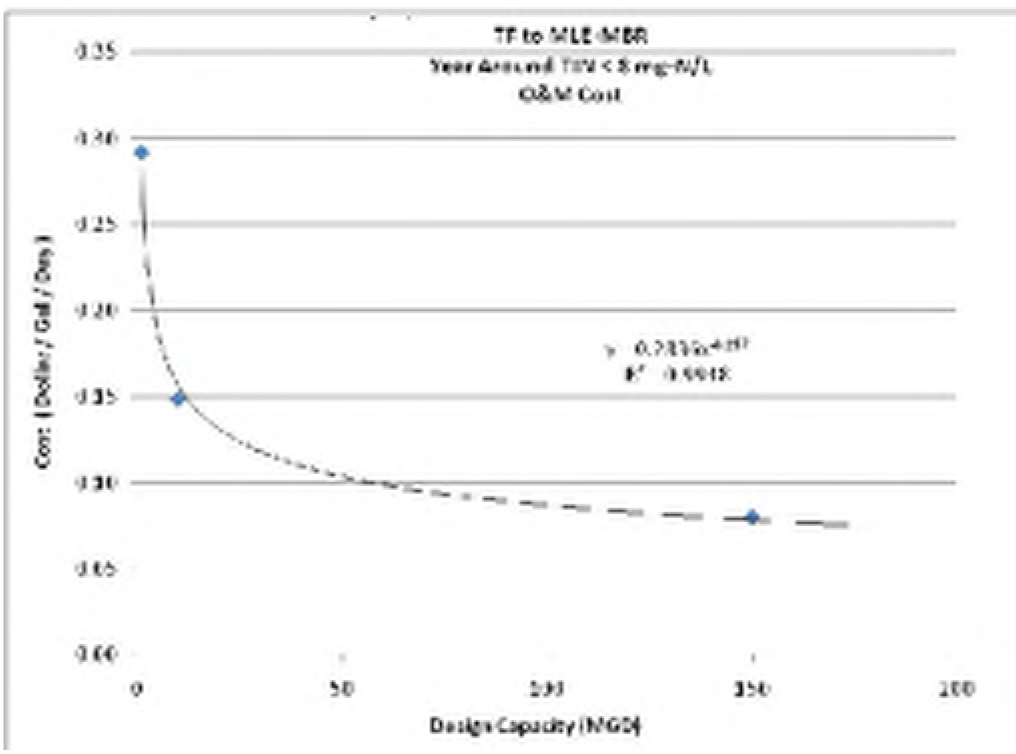


Figure 11-10. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective A Year-Round

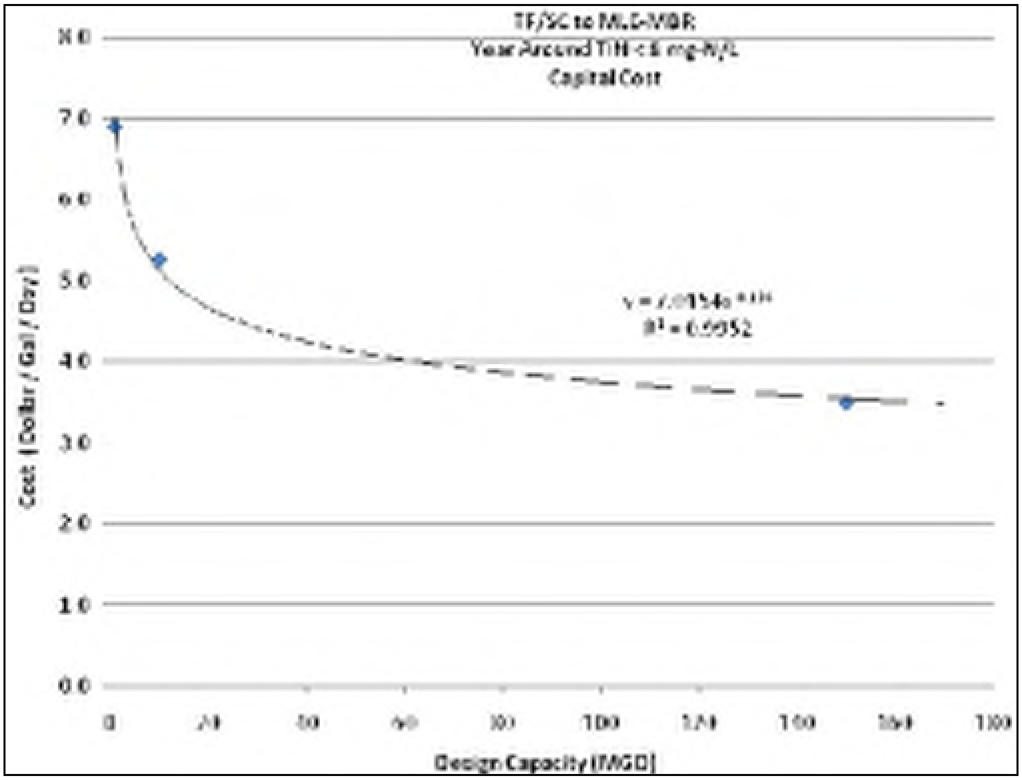


Figure 11-11. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective A Year-Round

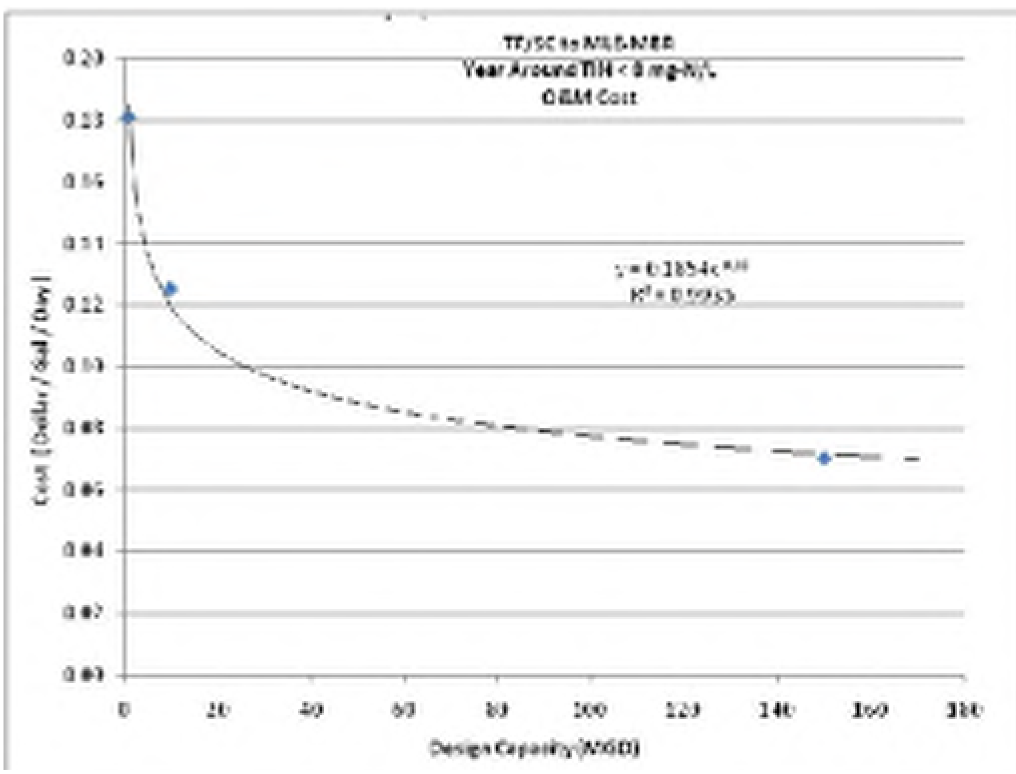


Figure 11-12. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective A Year-Round

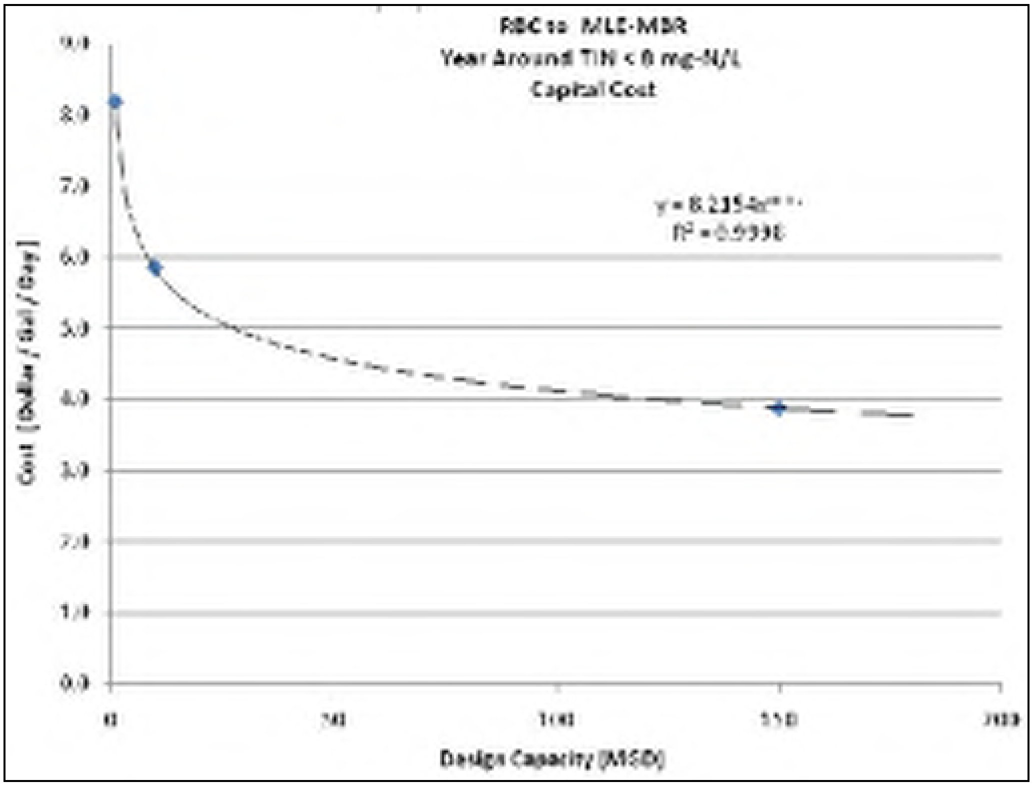


Figure 11-13. Capital Cost per Plant Capacity for RBC Upgraded for Objective A Year-Round

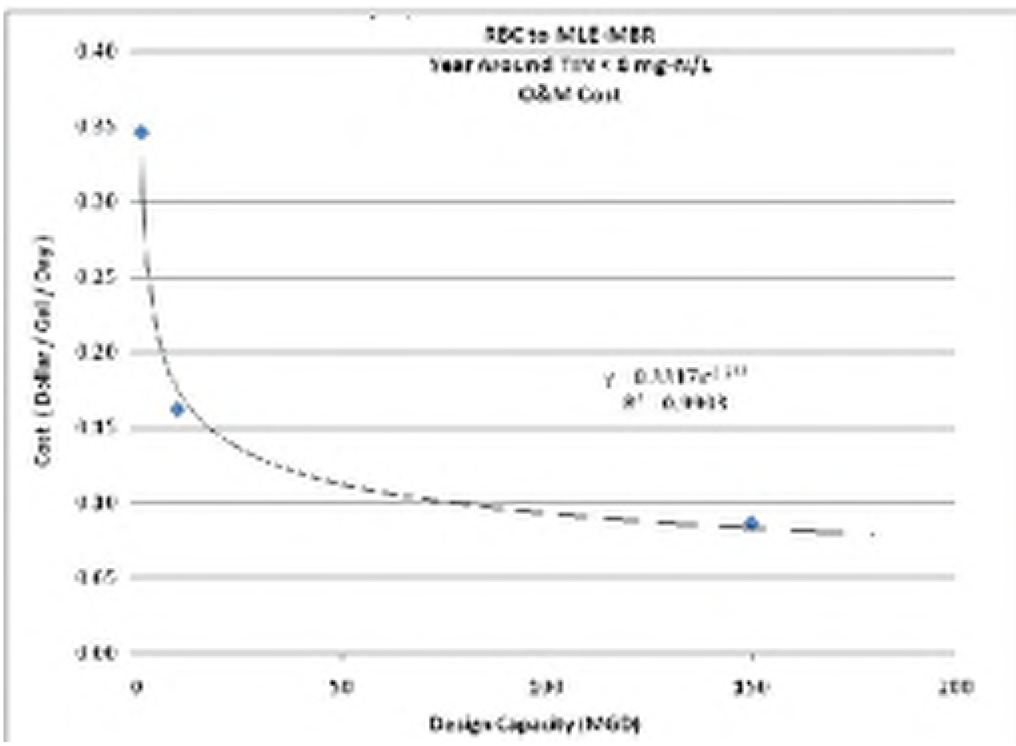


Figure 11-14. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective A Year-Round

TABLE 11-12.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$601,194	$4,278,563	$42,098,874
2014 O&M Cost	$328,594	$1,672,797	$13,518,789
Total Annual Cost	**$929,791**	**$5,951,361**	**$55,617,663**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Estimated Cost for TIN Reduction ($/lb TIN removed)	$26.15	$16.74	$10.43
Equation:[a]	$y = 176.78x^{-0.183}$		
R-Square Value:	0.9991		

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 11-13.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$507,744	$3,870,296	$38,592,858
2014 O&M Cost	$203,721	$1,409,147	$11,856,412
Total Annual Cost	**$711,465**	**$5,279,443**	**$50,449,270**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Estimated Cost for TIN Reduction ($/lb TIN removed)	$20.01	$14.85	$9.46
Equation:[a]	$y = 97.972x^{-0.15}$		
R-Square Value:	0.995		

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 11-14.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$601,523	$4,298,964	$42,622,884
2014 O&M Cost	$389,616	$1,824,178	$14,526,119
Total Annual Cost	**$991,139**	**$6,123,143**	**$57,149,004**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Estimated Cost for TIN Reduction ($/lb TIN removed)	$27.88	$17.22	$10.72
Equation:[a]	$y = 201.67x^{-0.19}$		
R-Square Value:	0.9974		

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.1.5 Membrane Biological Reactor Plants

No new facilities or activities are required to achieve Objective A for MBR plants, so there are no associated capital or O&M costs.

11.1.6 High-Purity Oxygen Activated Sludge Plants

Table 11-15 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A year-round for an HPO activated sludge plant. Figures 11-15 and 11-16 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-16 presents the annualized unit costs for reducing nutrient loads.

**TABLE 11-15.
ESTIMATED COST PER CAPACITY FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

	20-mgd Plant	220-mgd Plant
Capital Cost per gpd of Plant Capacity	$3.91	$3.03
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.14

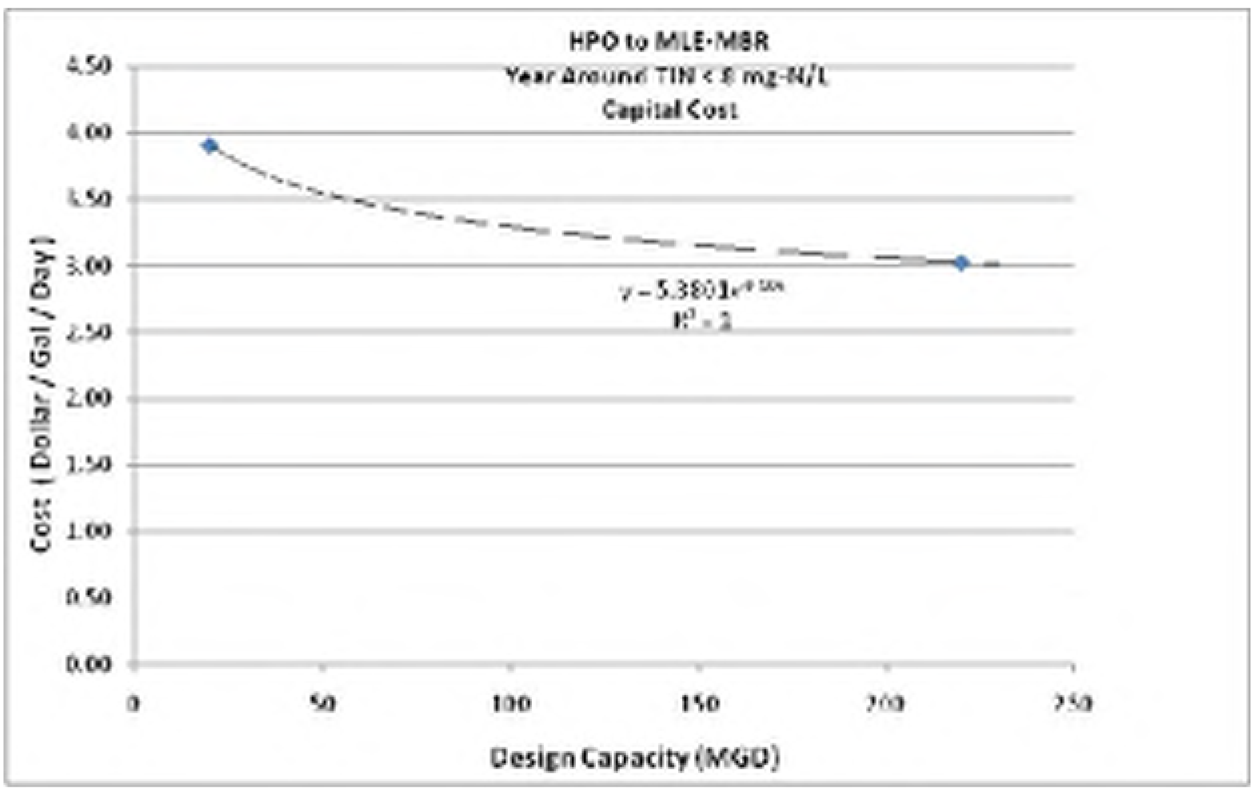


Figure 11-15. Capital Cost per Plant Capacity for HPO Plant Upgraded for Objective A Year-Round

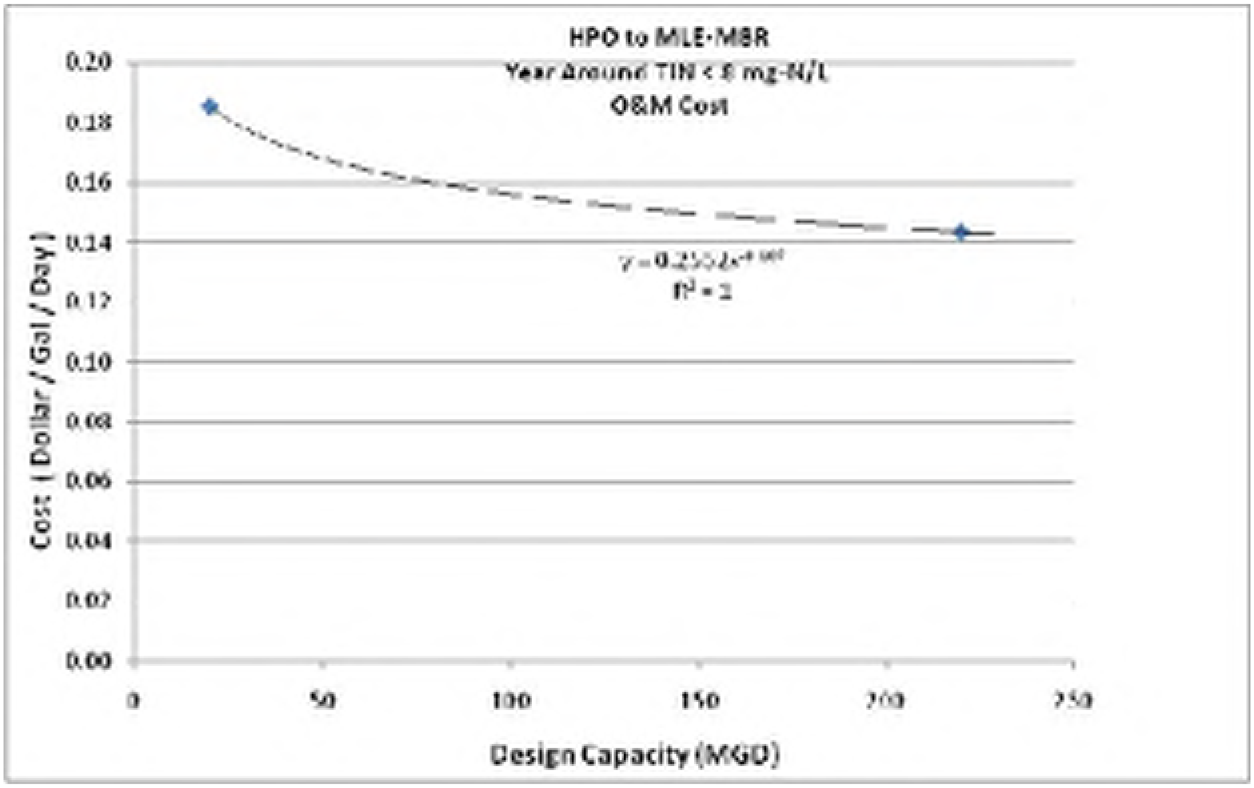


Figure 11-16. O&M Cost per Plant Capacity for HPO Plant Upgraded for Objective A Year-Round

TABLE 11-16.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	20-mgd Plant	220-mgd Plant
Annualized Capital Cost	$5,745,000	$48,960,000
2014 O&M Cost	$4,172,000	$35,520,000
Total Annual Cost	**$9,917,000**	**$87,480,000**
Annual TIN Load Reduction (lb/yr)	761,390	8,375,290
Estimated Cost for TIN Reduction ($/lb TIN removed)	$13.00	$10.10

Equation:[a] .... $y = 54.946x^{-0.106}$
R-Square Value: 1

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.1.7 Aerated or Facultative Lagoon Plants

Table 11-17 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A year-round for an aerated lagoon plant. Figures 11-17 and 11-18 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-18 and Figures 11-19 and 11-20 summarize these costs for a facultative lagoon plant. Tables 11-19 and 11-20 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 11-17.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$22.33	$17.04	$11.18	$6.58
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.91	$0.53	$0.23	$0.11

TABLE 11-18.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$22.19	$16.92	$11.09	$6.53
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.18	$0.77	$0.40	$0.14

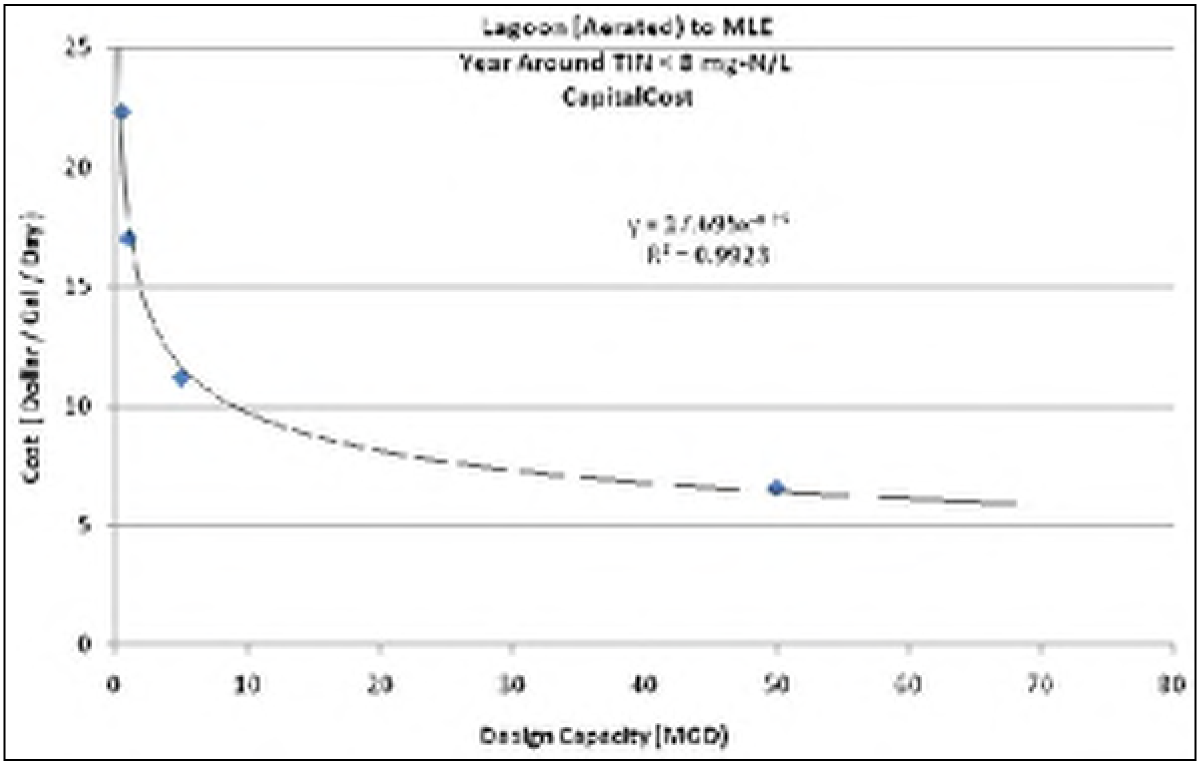


Figure 11-17. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective A Year-Round

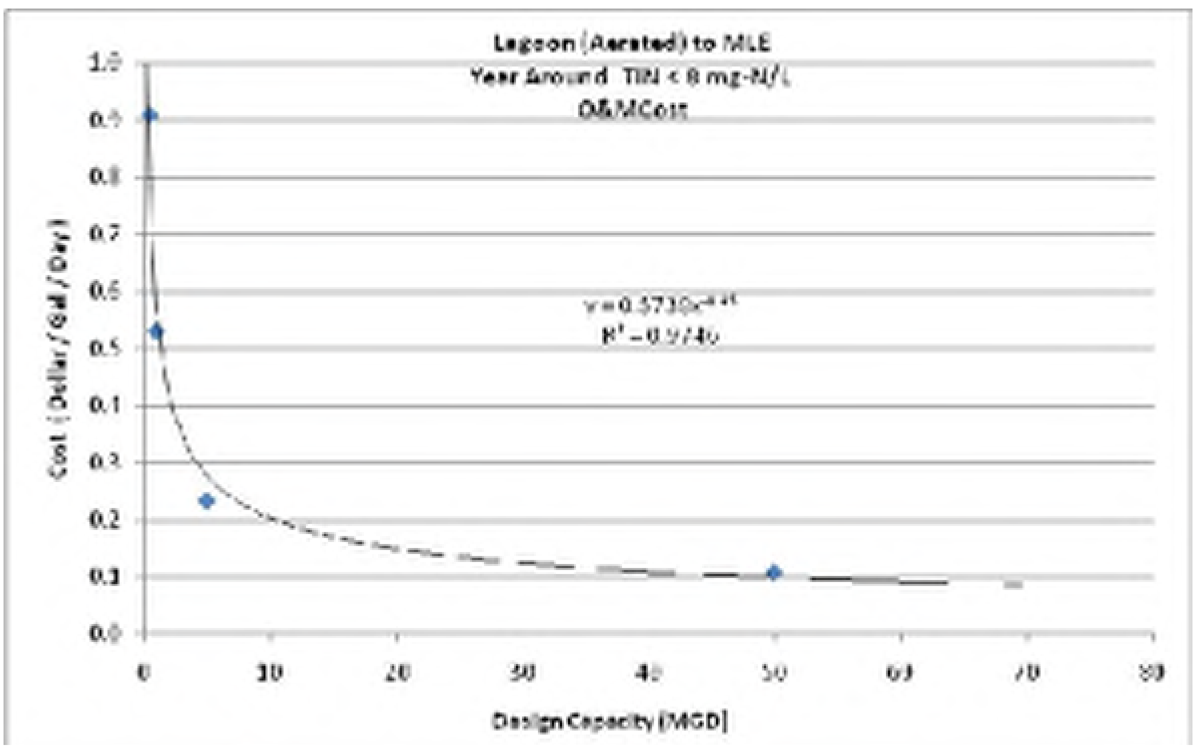


Figure 11-18. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective A Year-Round

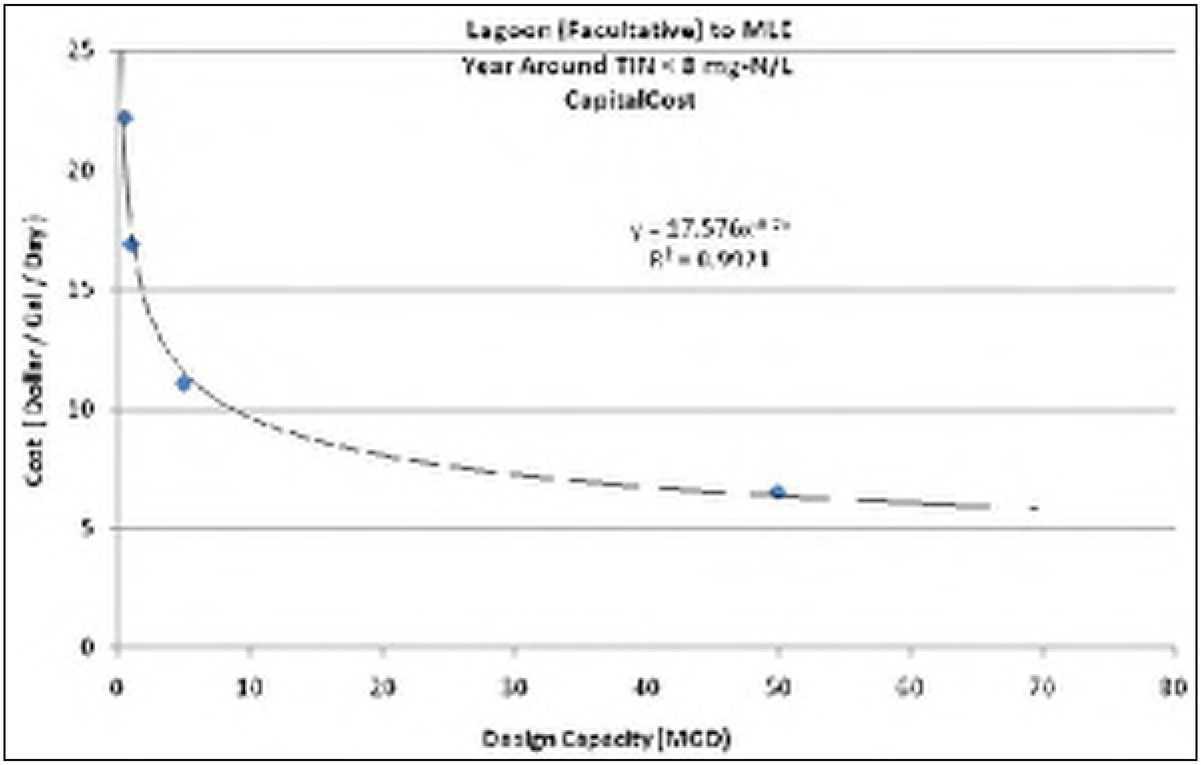


Figure 11-19. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective A Year-Round

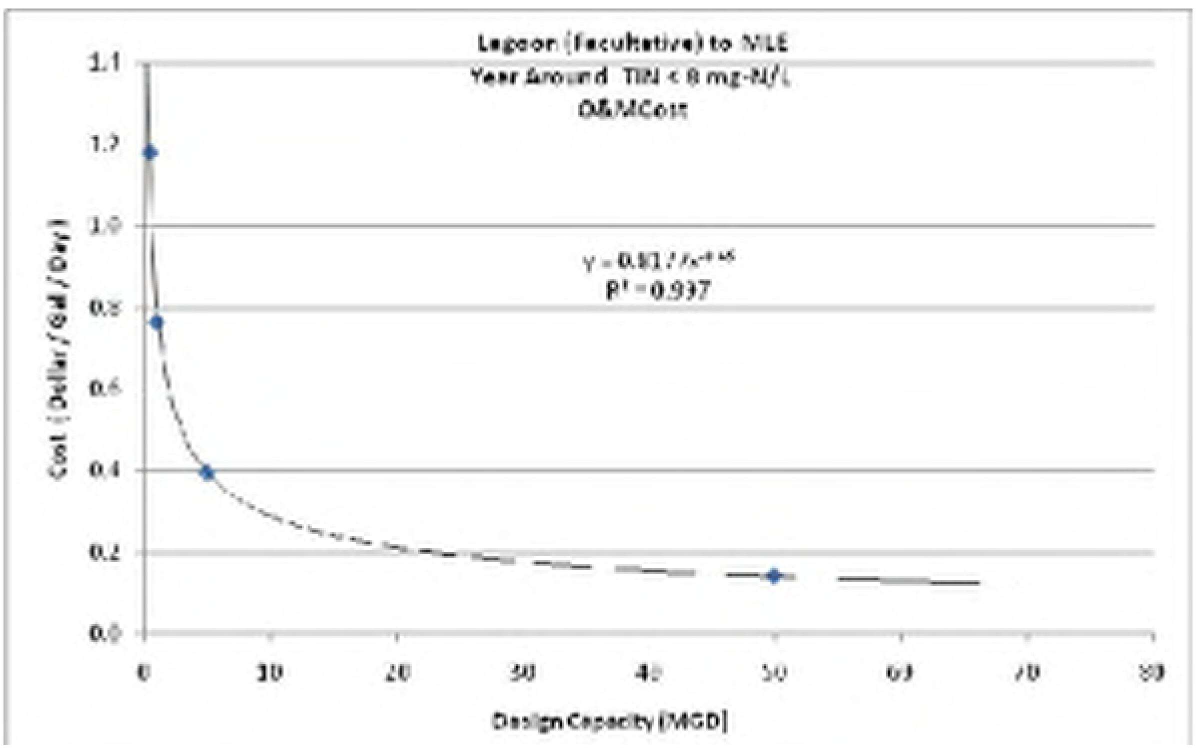


Figure 11-20. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective A Year-Round

**TABLE 11-19.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$82,0052	$1,251,455	$4,106,942	$24,168,643
2014 O&M Cost	$512,439	$598,073	$1,321,179	$6,109,993
Total Annual Cost	**$1,332,490**	**$1,849,528**	**$5,428,120**	**$30,278,636**
Annual TIN Load Reduction (lb/yr)	17,593	35,186	175,930	1,755,650
Estimated Cost for TIN Reduction ($/lb TIN removed)	$75.74	$52.26	$30.85	$17.25

Equation:[a] .... $y = 1458.7x^{-0.312}$
R-Square Value:........ 0.982

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

**TABLE 11-20.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE A YEAR-ROUND**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$815,034	$1,242,982	$4,073,790	$23,994,247
2014 O&M Cost	$665,608	$861,751	$2,224,005	$7,997,263
Total Annual Cost	**$1,480,641**	**$2,104,734**	**$6,297,796**	**$31,991,510**
Annual TIN Load Reduction (lb/yr)	17,593	35,186	175,930	1,755,650
Estimated Cost for TIN Reduction ($/lb TIN removed)	$63.89	$44.77	$35.80	$18.22

Equation:[a] .... $y = 725.24x^{-0.255}$
R-Square Value:........ 0.9728

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.2 SEASONAL NUTRIENT REMOVAL

11.2.1 Extended Aeration Plants

Table 11-21 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A seasonally for an extended aeration plant using mechanical aeration. Figures 11-21 and 11-22 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-22 and Figures 11-23 and 11-24 summarize these costs for an extended aeration plant using diffuser aeration. Tables 11-23 and 11-24 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 11-21.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.37	$2.28	$2.27
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.04	$0.01

TABLE 11-22.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$0.64	$0.79	$0.40
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.03	($0.02)	($0.02)

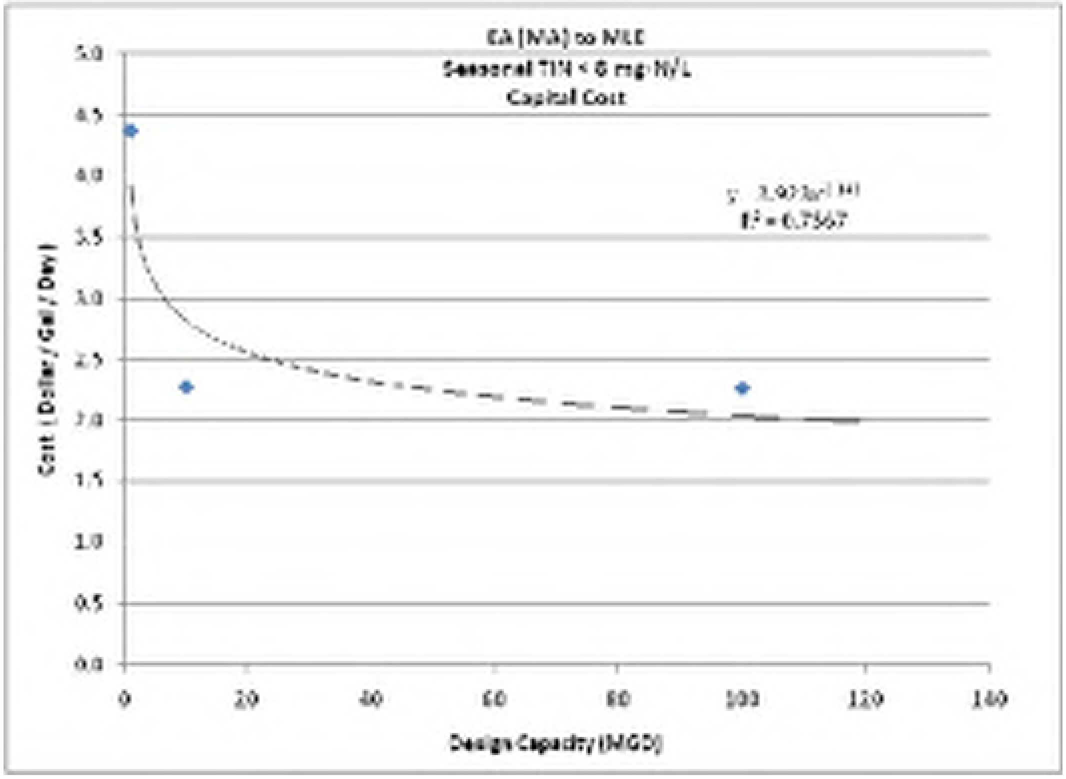


Figure 11-21. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective A Seasonally

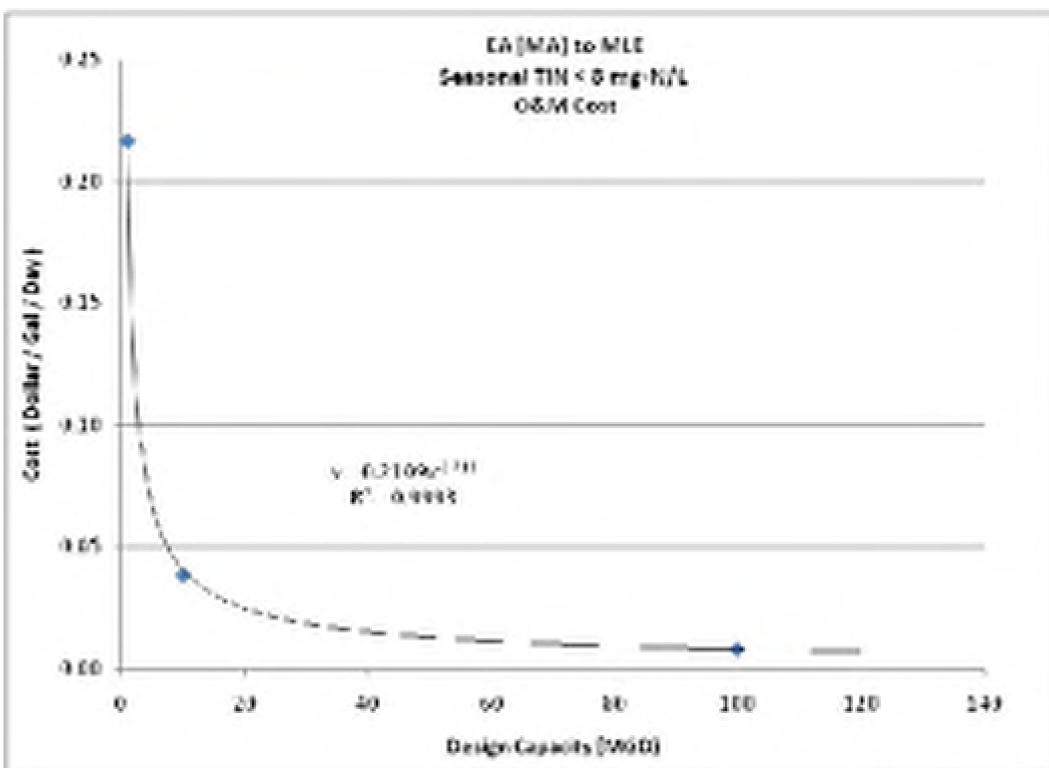


Figure 11-22. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective A Seasonal

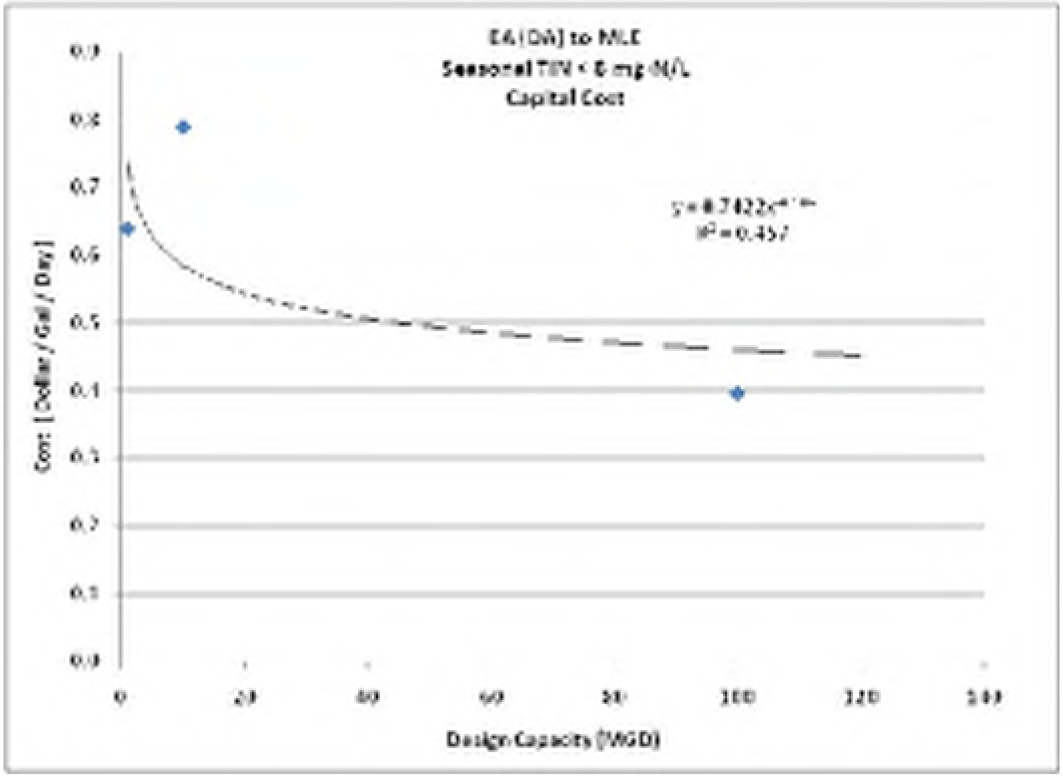


Figure 11-23. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective A Seasonally

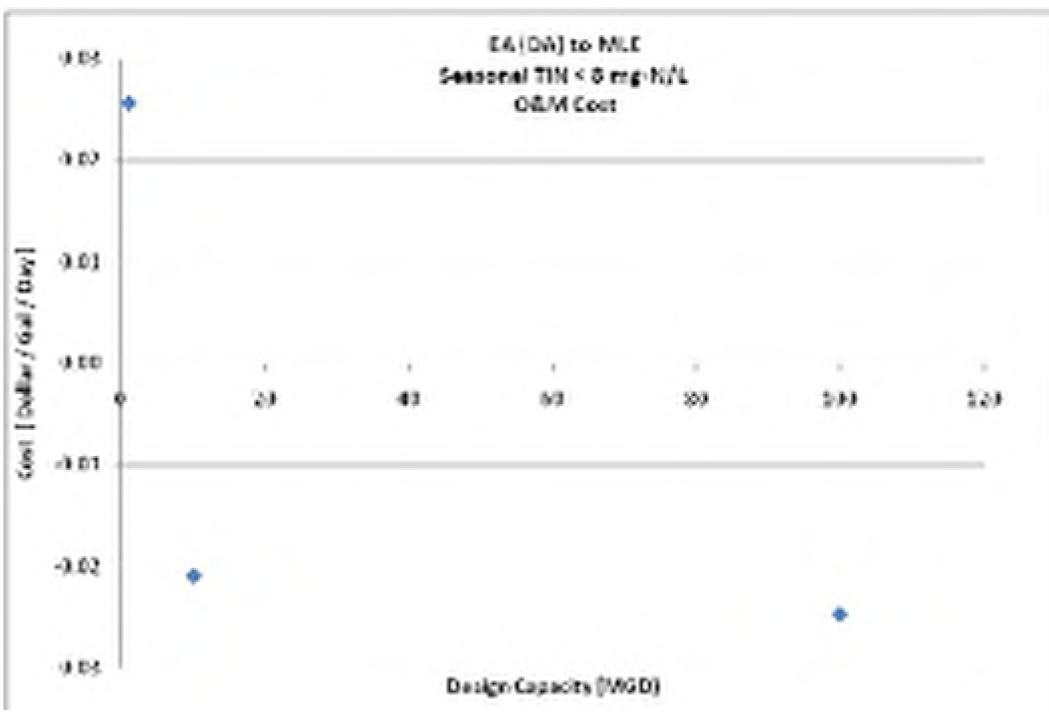


Figure 11-24. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective A Seasonal

TABLE 11-23.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$320,823	$1,674,036	$16,642,677
2014 O&M Cost	$243,560	$433,659	$901,533
Total Annual Cost	**$564,383**	**$2,107,695**	**$17,544,210**
Annual TIN Load Reduction (lb/yr)	19,418	194,180	1,941,800
Estimated Cost for TIN Reduction ($/lb TIN removed)	$29.06	$10.85	$9.04

Equation:[a] .... $y = 310.83x^{-0.254}$
R-Square Value: 0.8639

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 11-24.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$46,889	$579,949	$2,904,885
2014 O&M Cost	$28,926	-$235,231	-$2,777,193
Total Annual Cost	**$75,815**	**$344,717**	**$127,692**
Annual TIN Load Reduction (lb/yr)	19,400	193,998	1,939,975
Estimated Cost for TIN Reduction ($/lb TIN removed)	$3.91	$1.78	$0.07

Equation:[a] .... $y = 32735x^{-0.874}$
R-Square Value: 0.8901

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.2.2 Conventional Activated Sludge Plants

Table 11-25 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A seasonally for a conventional activated sludge plant. Figures 11-25 and 11-26 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-26 presents the annualized unit costs for reducing nutrient loads.

TABLE 11-25.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.35	$1.18	$1.40
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.16	$0.04	$0.02

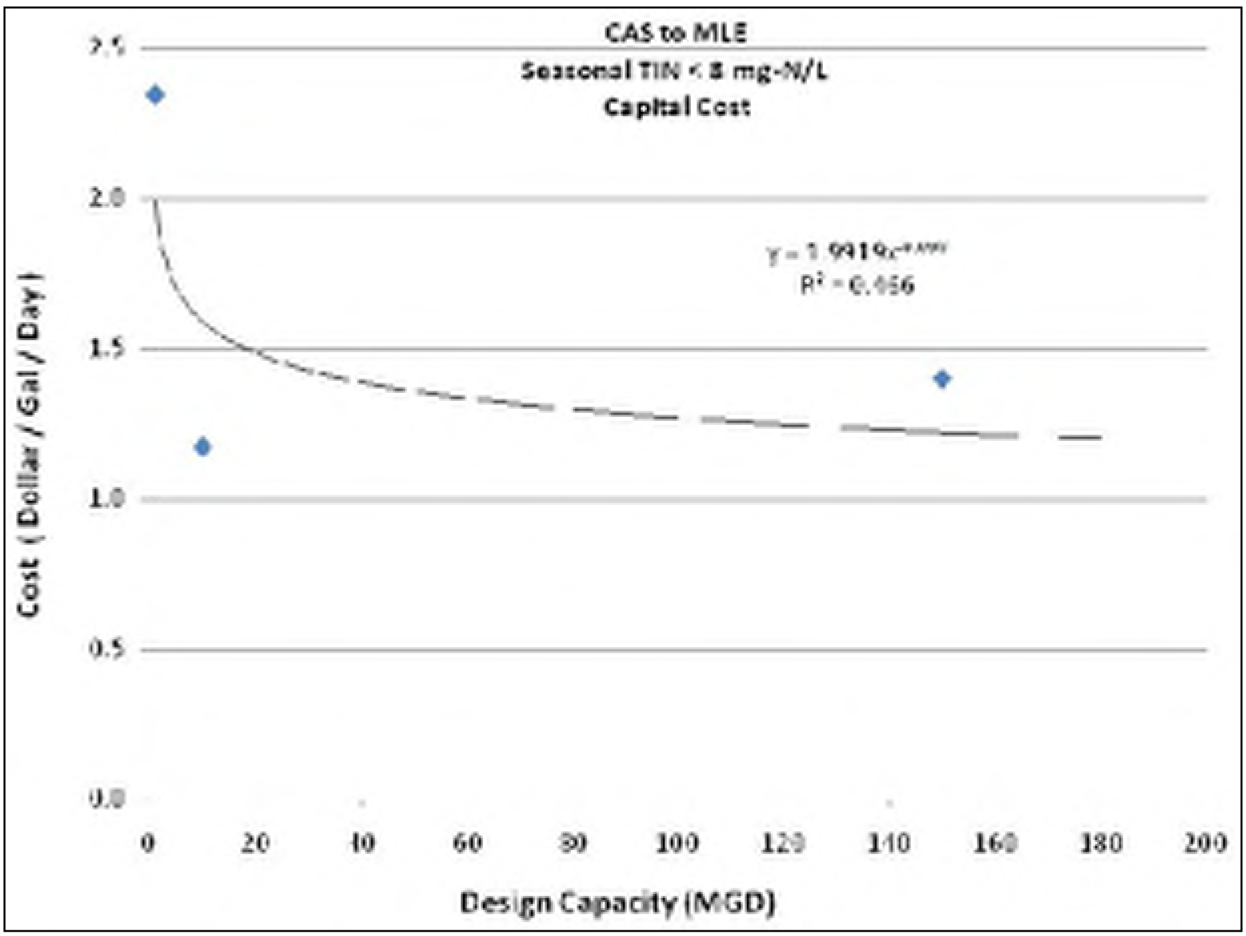


Figure 11-25. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective A Seasonally

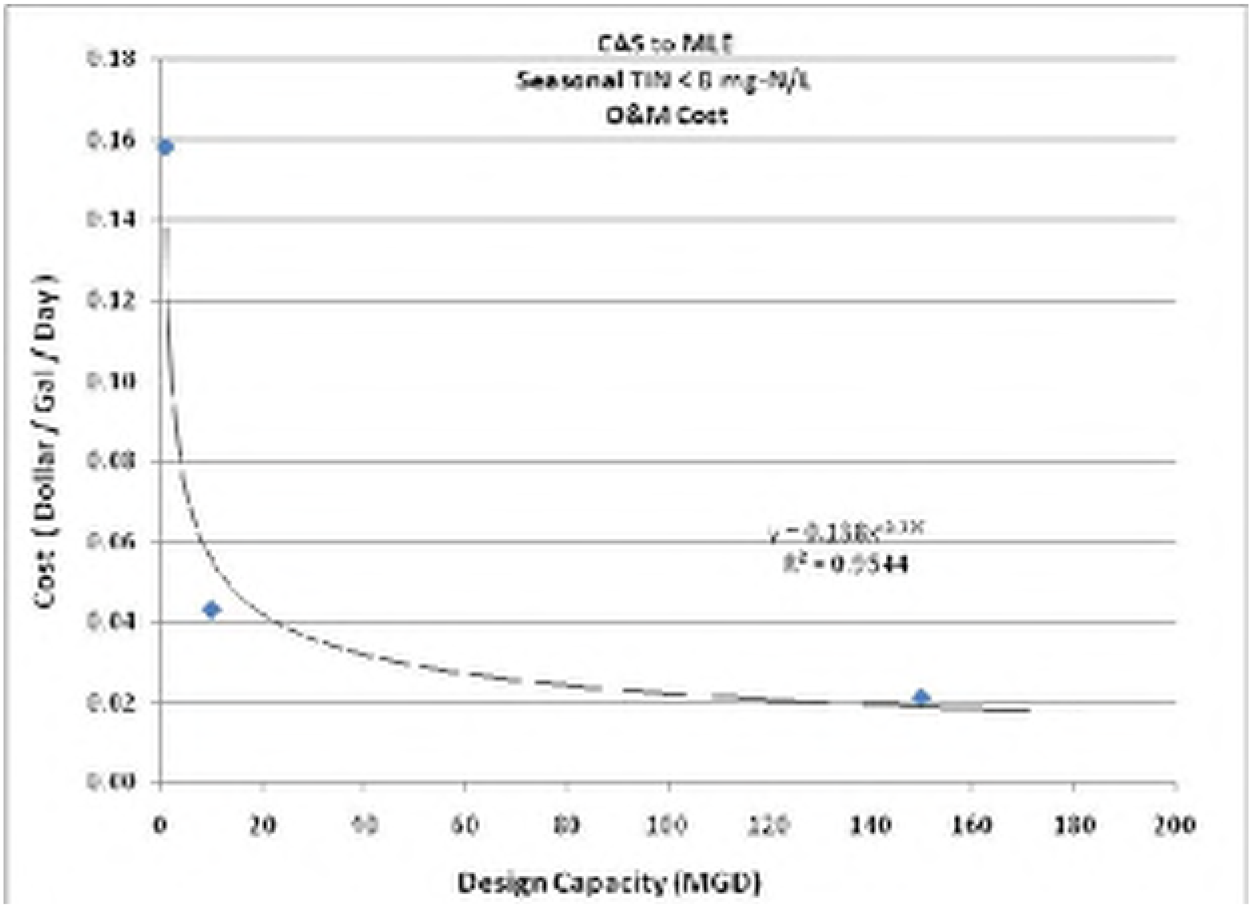


Figure 11-26. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective A Seasonal

TABLE 11-26.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$172,242	$864,178	$15,467,709
2014 O&M Cost	$177,887	$486,220	$3,598,252
Total Annual Cost	**$350,129**	**$1,350,397**	**$19,065,961**
Annual TIN Load Reduction (lb/yr)	19,455	194,545	2,918,175
Estimated Cost for TIN Reduction ($/lb TIN removed)	$18.00	$6.94	$6.53

Equation:[a] .... $y = 105.86x^{-0.197}$
R-Square Value: 0.7559

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.2.3 Sequencing Batch Reactor Plants

Table 11-27 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A seasonally for an SBR plant. Figures 11-27 and 11-28 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-28 presents the annualized unit costs for reducing nutrient loads.

TABLE 11-27.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$0.42	$0.22	$0.16
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.00	($0.00)	$0.0004

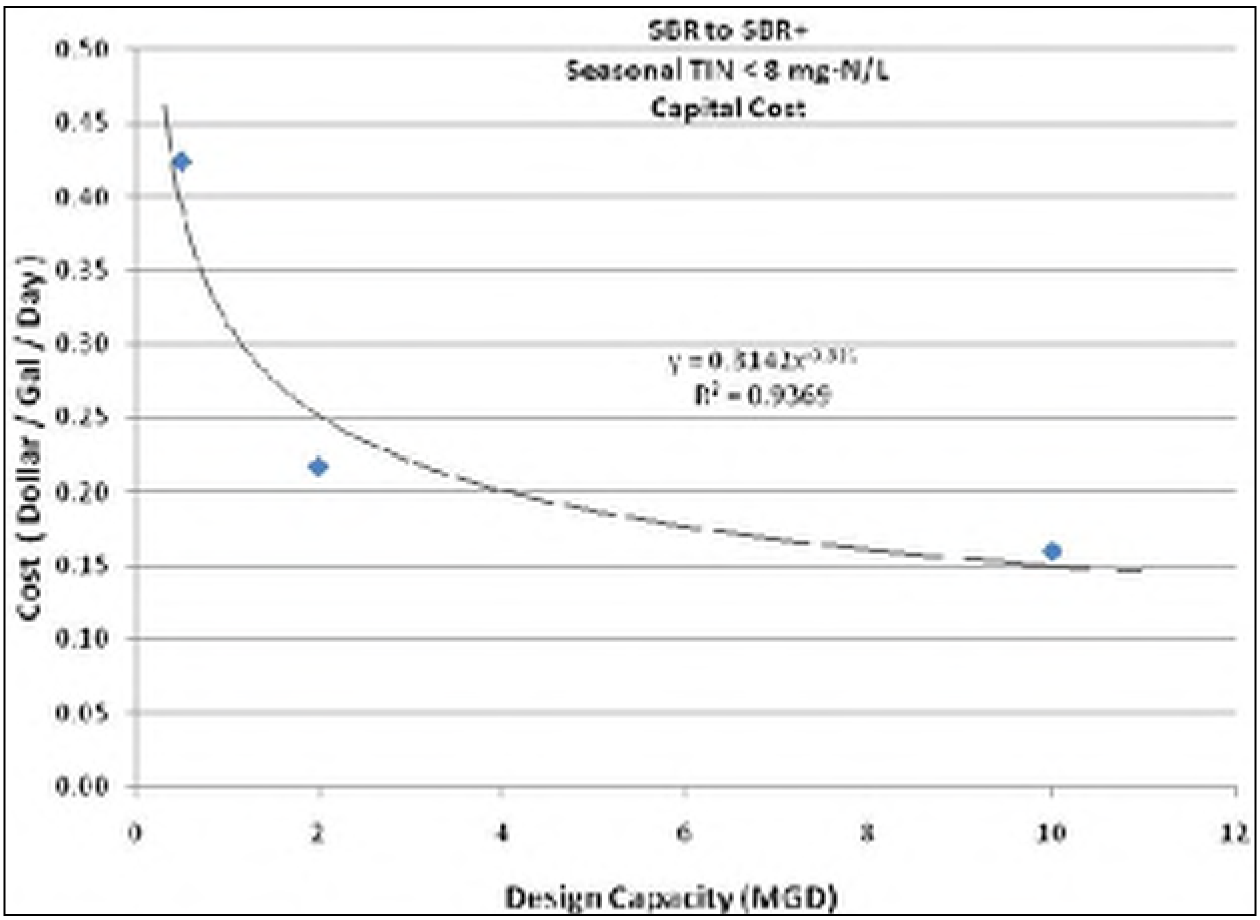


Figure 11-27. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective A Seasonally

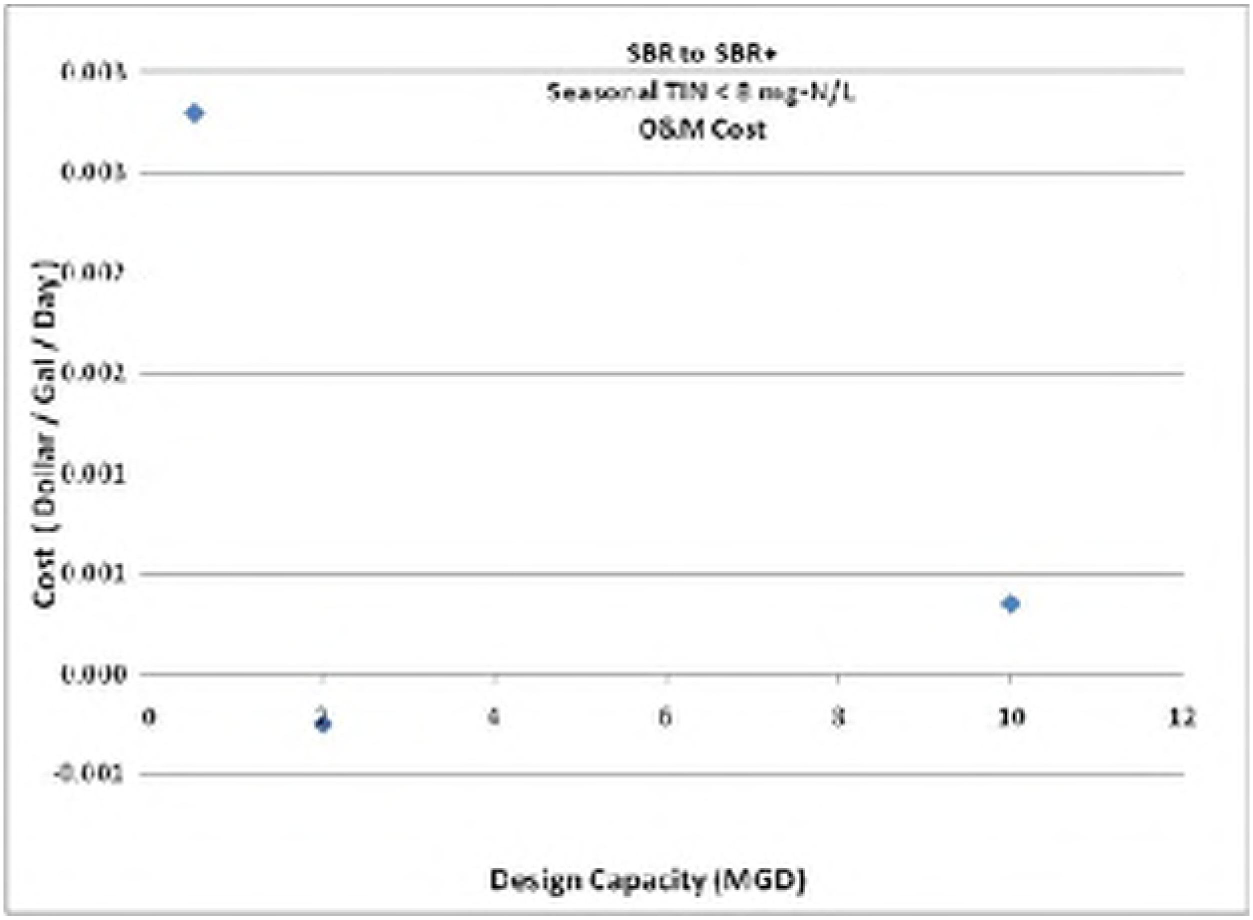


Figure 11-28. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective A Seasonal

TABLE 11-28.
UNIT NUTRIENT REMOVAL COSTS FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$15,578	$31,979	$117,738
2014 O&M Cost	$1,576	-$563	$3,939
Total Annual Cost	**$17,154**	**$31,417**	**$121,677**
Annual TIN Load Reduction (lb/yr)	246	986	4,928
Estimated Cost for TIN Reduction ($/lb TIN removed)	$69.63	$31.88	$24.69

Equation:[a] .... $y = 408.67x^{-0.341}$
R-Square Value: 0.8967

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.2.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 11-29 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A seasonally for a trickling filter plant. Figures 11-29 and 11-30 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-30 and Figures 11-31 and 11-32 summarize these costs for a trickling filter/solids contact plant. Table 11-31 and Figures 11-33 and 11-34 summarize these costs for an RBC plant. Tables 11-32, 11-33 and 11-34 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 11-29.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.68	$2.80	$2.18
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.06	$0.02

TABLE 11-30.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.94	$2.11	$1.77
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.11	$0.04	$0.01

TABLE 11-31.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.71	$2.83	$2.22
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.27	$0.08	$0.03

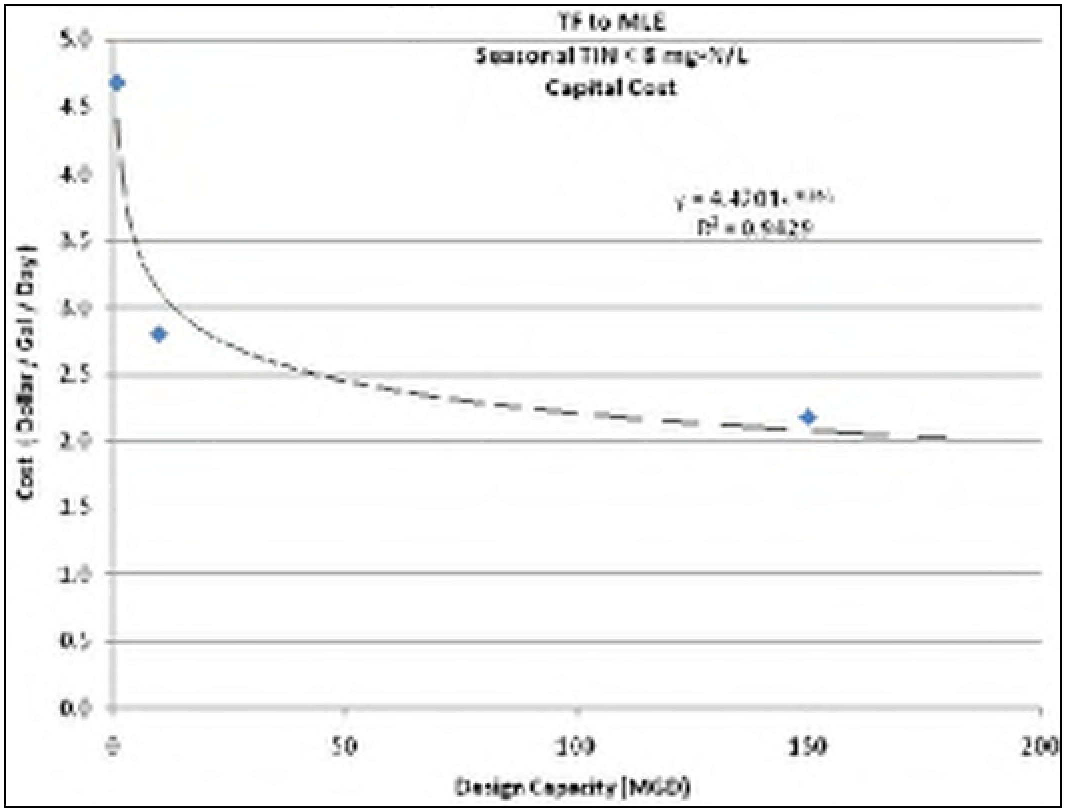


Figure 11-29. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective A Seasonally

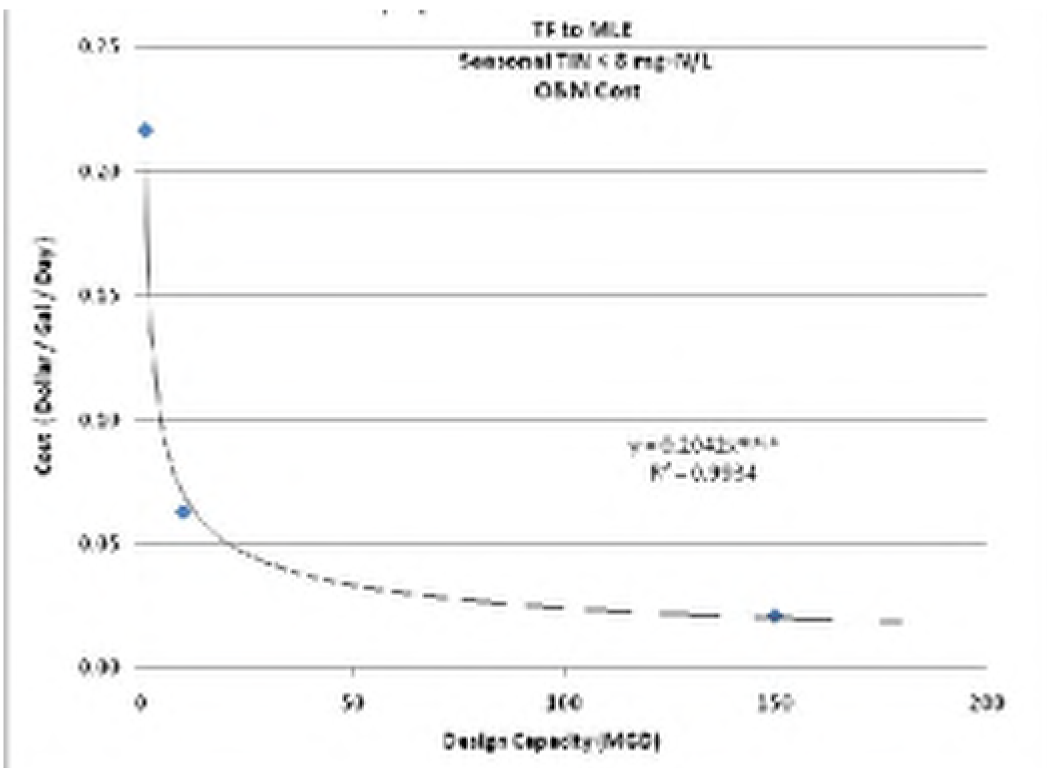


Figure 11-30. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective A Seasonal

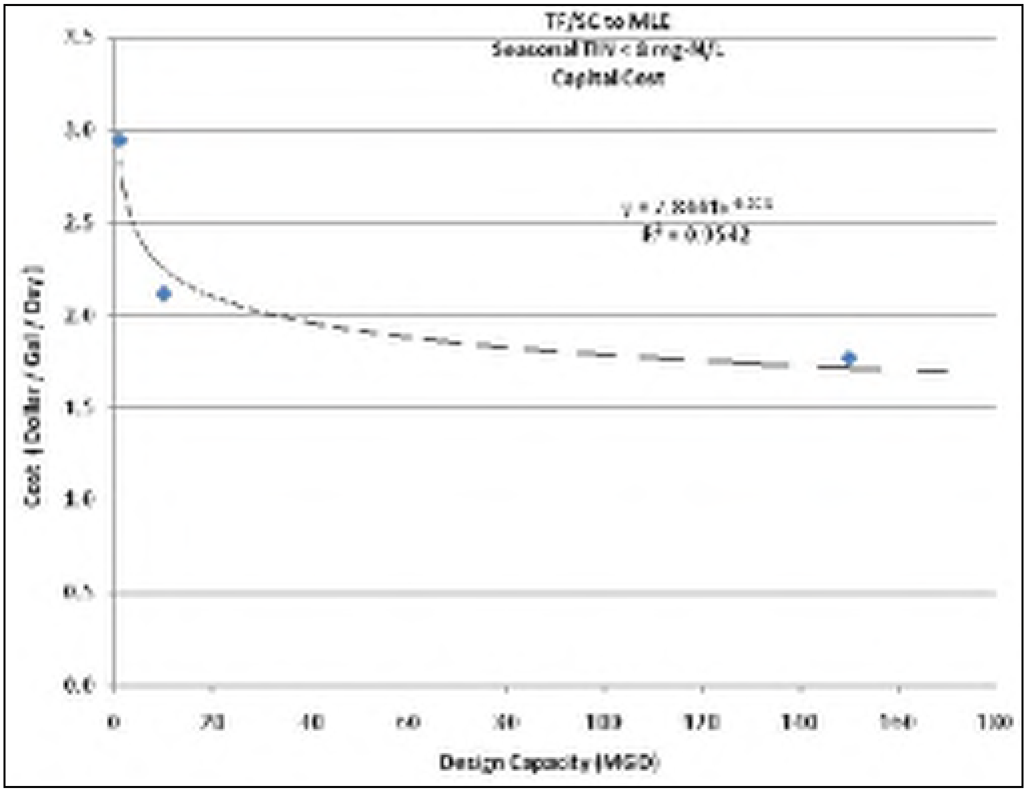


Figure 11-31. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective A Seasonally

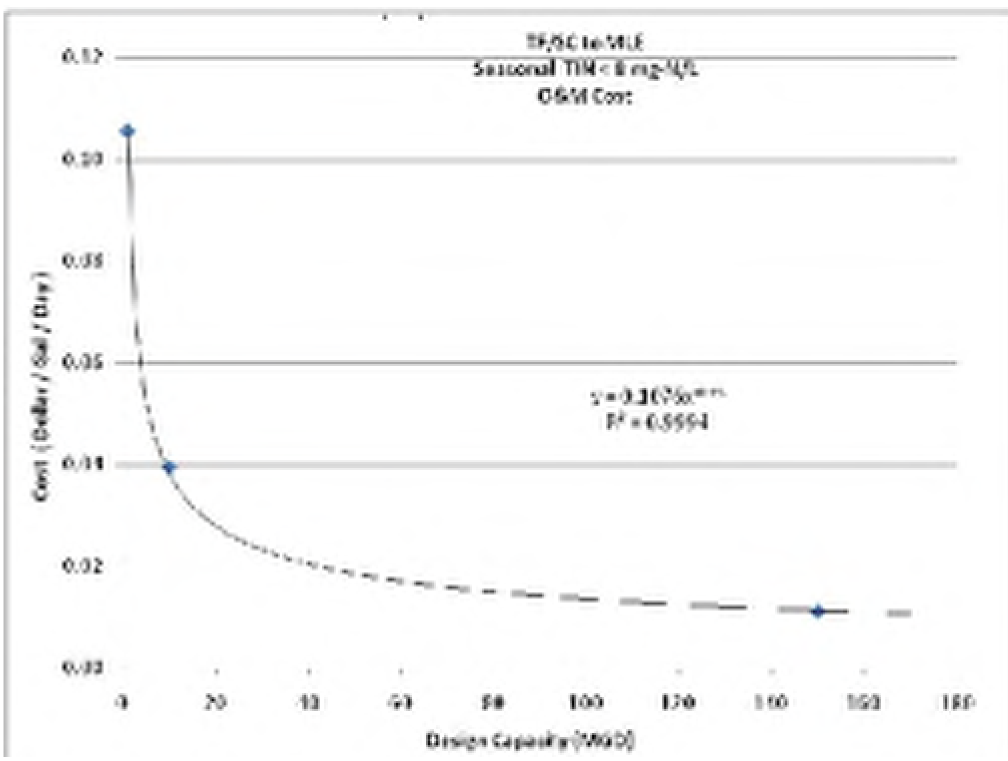


Figure 11-32. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective A Seasonal

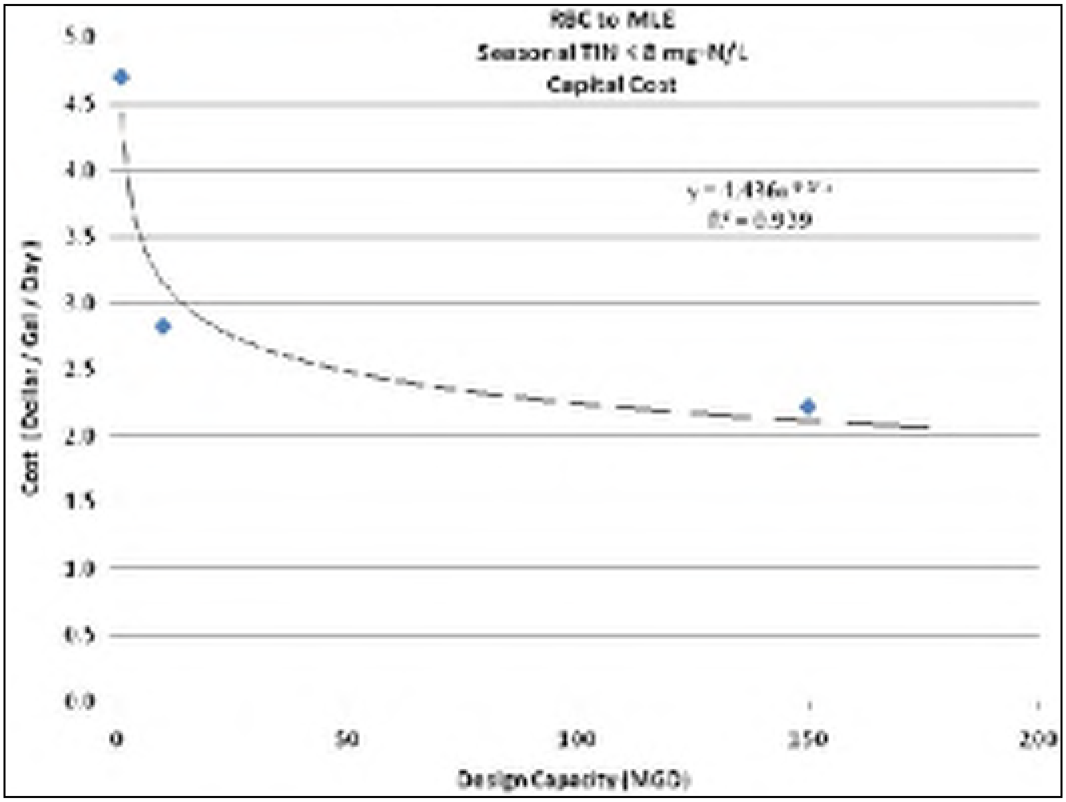


Figure 11-33. Capital Cost per Plant Capacity for RBC Plant Upgraded for Objective A Seasonally

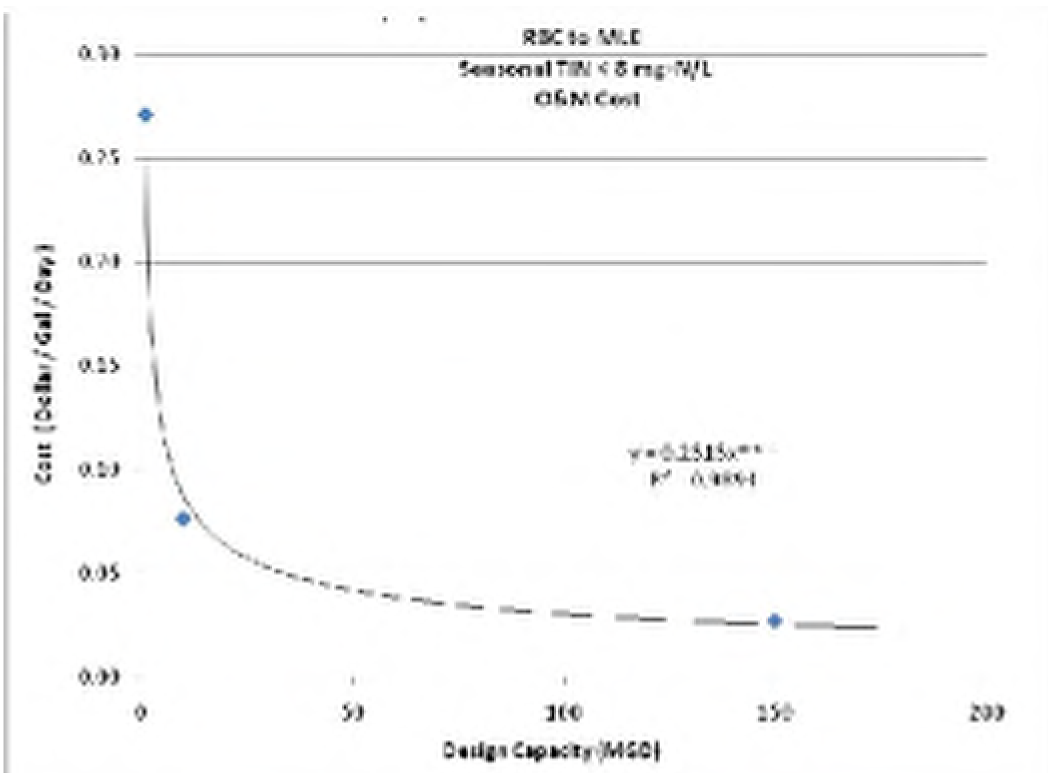


Figure 11-34. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective A Seasonal

TABLE 11-32.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$344,062	$2,059,887	$24,020,776
2014 O&M Cost	$243,841	$707,439	$3,538,037
Total Annual Cost	**$587,903**	**$2,767,326**	**$27,558,813**
Annual TIN Load Reduction (lb/yr)	19,455	194,545	2,918,175
Estimated Cost for TIN Reduction ($/lb TIN removed)	$30.22	$14.22	$9.44

Equation:[a] .... $y = 270.37x^{-0.23}$
R-Square Value: 0.9541

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 11-33.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$216,251	$1,552,823	$19,453,578
2014 O&M Cost	$118,966	$443,788	$1,875,660
Total Annual Cost	**$335,217**	**$1,996,611**	**$21,329,238**
Annual TIN Load Reduction (lb/yr)	19,455	194,545	2,918,175
Estimated Cost for TIN Reduction ($/lb TIN removed)	$17.23	$10.26	$7.31

Equation:[a] .... $y = 88.118x^{-0.17}$
R-Square Value: 0.9724

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 11-34.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$345,625	$2,077,327	$24,474,041
2014 O&M Cost	$304,861	$858,819	$4,545,367
Total Annual Cost	**$650,486**	**$2,936,146**	**$29,019,409**
Annual TIN Load Reduction (lb/yr)	19,455	194,545	2,918,175
Estimated Cost for TIN Reduction ($/lb TIN removed)	$33.44	$15.09	$9.94

Equation:[a] .... $y = 327.02x^{-0.24}$
R-Square Value: 0.9503

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.2.5 Membrane Biological Reactor Plants

No new facilities or activities are required to achieve Objective A for MBR plants, so there are no associated capital or O&M costs.

11.2.6 High-Purity Oxygen Activated Sludge Plants

Table 11-35 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A seasonally for an HPO plant. Figures 11-35 and 11-36 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-36 presents the annualized unit costs for reducing nutrient loads.

TABLE 11-35.
ESTIMATED COST PER CAPACITY FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	20-mgd Plant	220-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.22	$1.24
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.11	$0.09

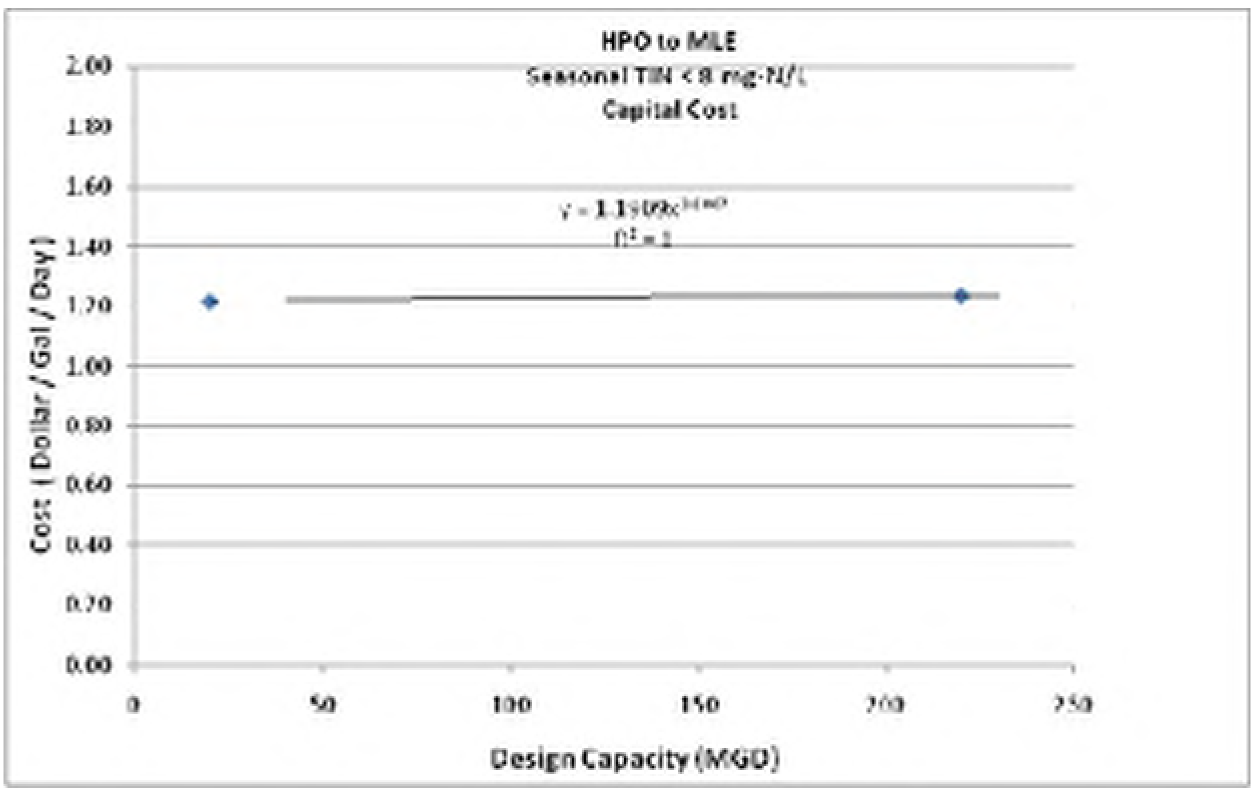


Figure 11-35. Capital Cost per Plant Capacity for HPO Plant Upgraded for Objective A Seasonal

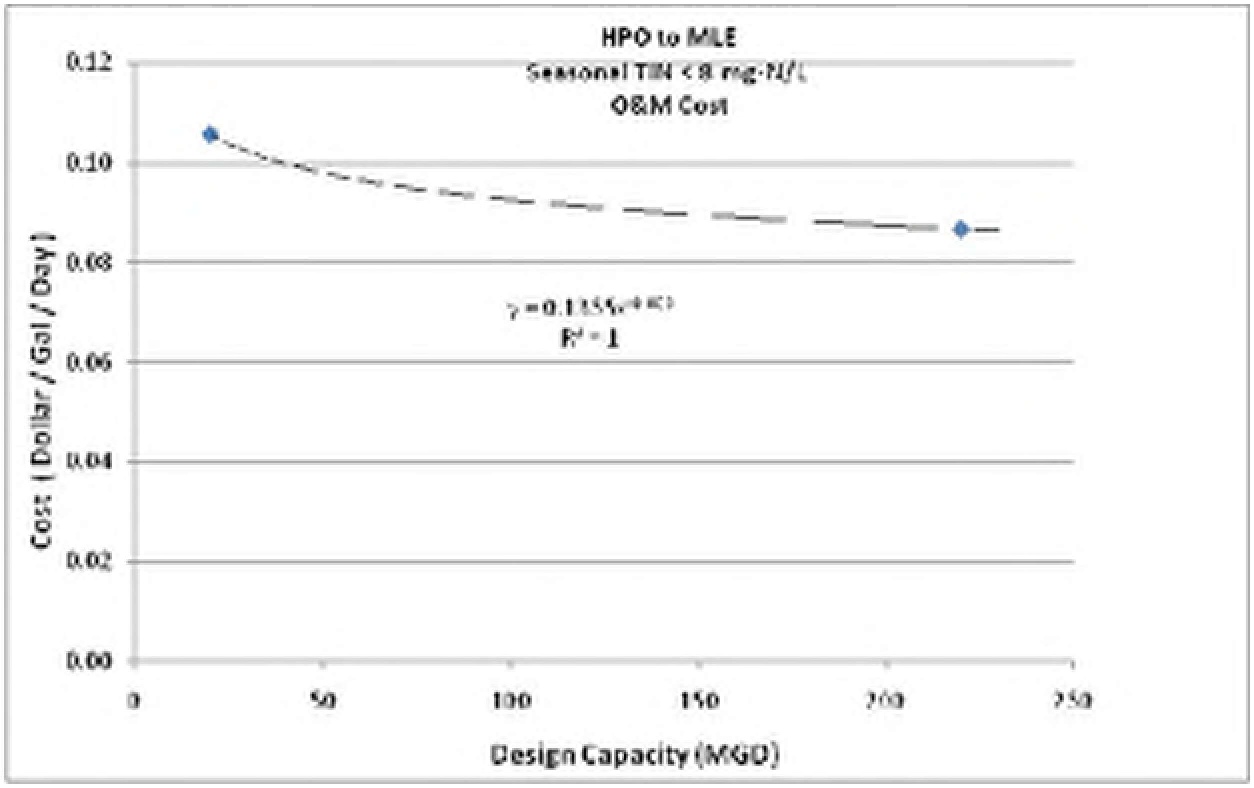


Figure 11-36. O&M Cost per Plant Capacity for HPO Plant Upgraded for Objective A Seasonal

TABLE 11-36.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	20-mgd Plant	220-mgd Plant
Annualized Capital Cost	$1,785,000	$19,957,000
2014 O&M Cost	$2,381,000	$21,479,000
Total Annual Cost	**$4,166,000**	**$41,436,000**
Annual TIN Load Reduction (lb/yr)	401,500	4,416,500
Estimated Cost for TIN Reduction ($/lb TIN removed)	$10.40	$9.40

Equation:[a] .... $y = 17.903x^{-0.042}$
R-Square Value: 1

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

11.2.7 Aerated or Facultative Lagoon Plants

Table 11-37 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective A seasonally for an aerated lagoon plan. Figures 11-37 and 11-38 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 11-38 and Figures 11-39 and 11-40 summarize these costs for a facultative lagoon plant. Tables 11-39 and 11-40 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 11-37.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$21.49	$16.16	$10.54	$6.78
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.87	$0.51	$0.22	$0.08

TABLE 11-38.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$21.35	$16.04	$10.45	$6.74
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.14	$0.74	$0.38	$0.11

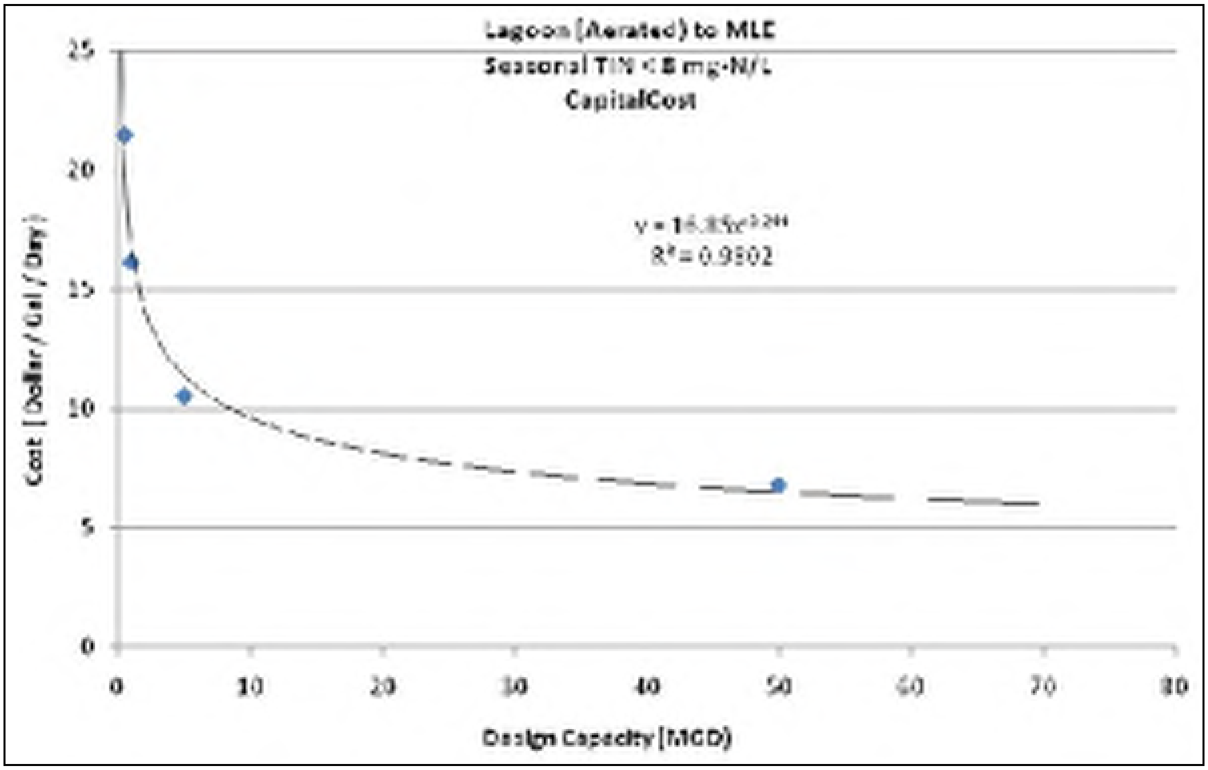


Figure 11-37. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective A Seasonally

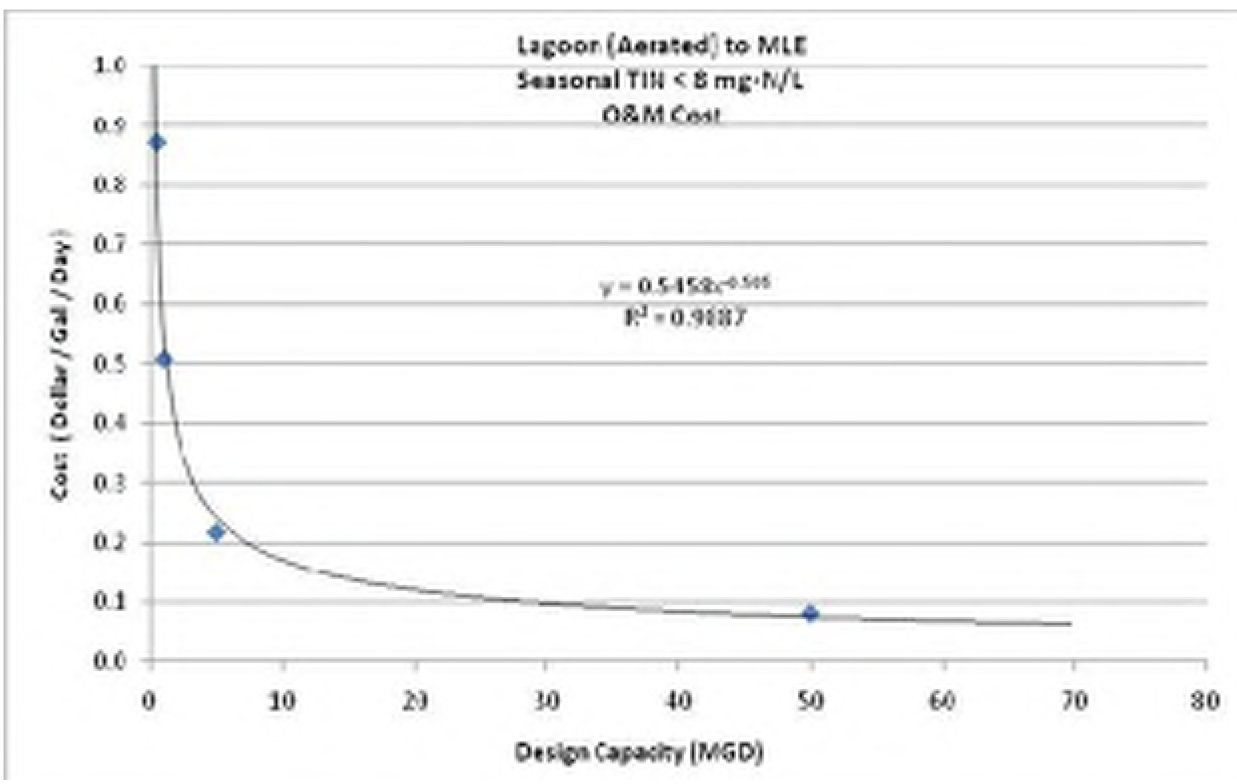


Figure 11-38. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective A Seasonal

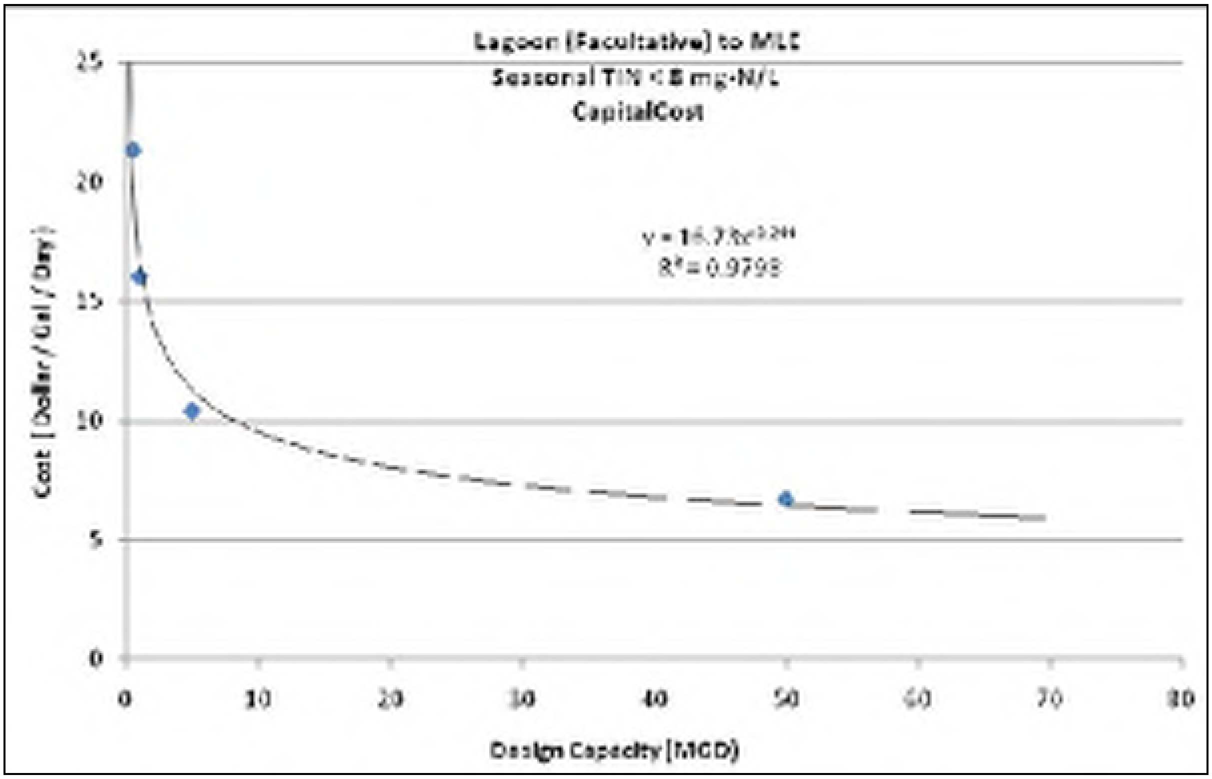


Figure 11-39. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective A Seasonally

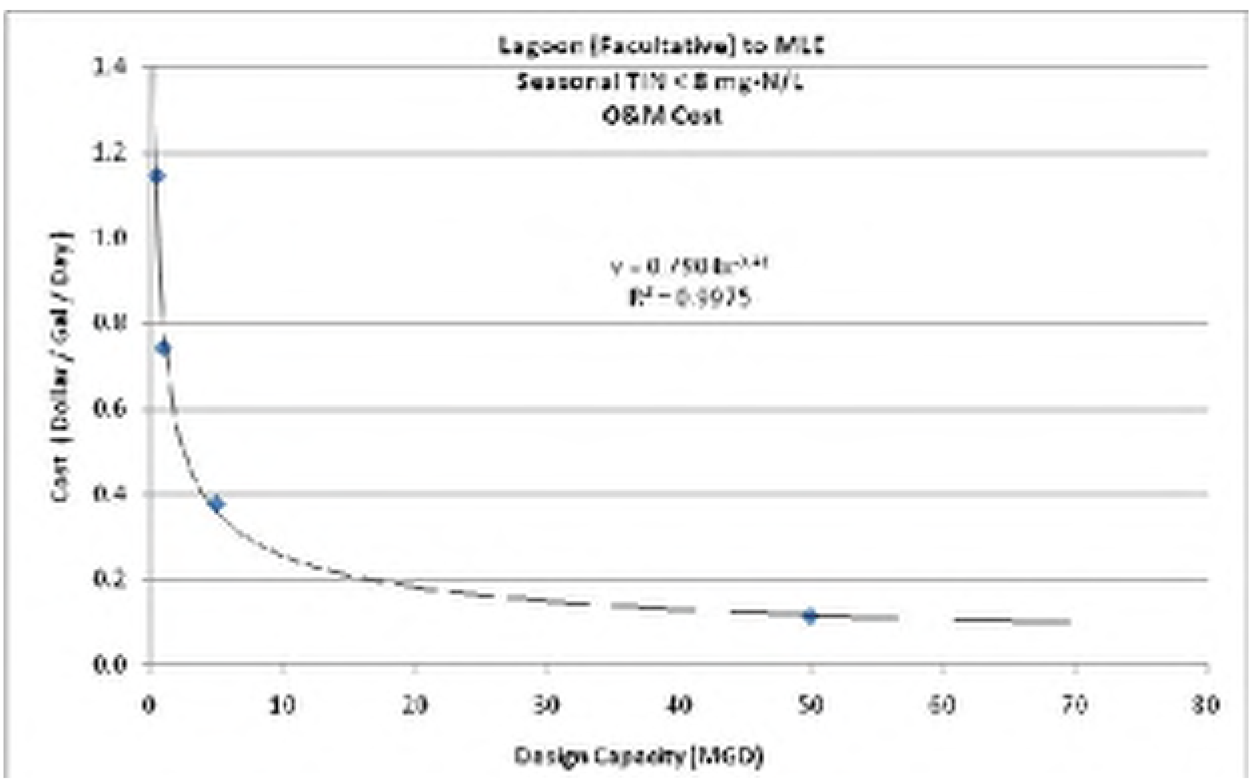


Figure 11-40. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective A Seasonal

TABLE 11-39.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$789,070	$1,186,818	$3,870,397	$24,915,789
2014 O&M Cost	$490,941	$570,779	$1,212,069	$4,519,475
Total Annual Cost	$1,280,011	$1,757,597	$5,087,466	$29,465,265
Annual TIN Load Reduction (lb/yr)	10,476	20,951	104,755	972,725
Estimated Cost for TIN Reduction ($/lb TIN removed)	$122.19	$83.89	$48.57	$30.29

Equation:[a] .... $y = 1747.8x^{-0.299}$
R-Square Value: 0.9681

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 11-40.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE A SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$783,969	$1,178,345	$3,837,246	$24,741,394
2014 O&M Cost	$644,111	$834,458	$2,119,896	$6,436,745
Total Annual Cost	$1,428,080	$2,012,803	$5,957,141	$31,178,139
Annual TIN Load Reduction (lb/yr)	10,476	20,951	104,755	972,725
Estimated Cost for TIN Reduction ($/lb TIN removed)	$136.33	$96.07	$56.87	$32.05

Equation:[a] .... $y = 2251.9x^{-0.312}$
R-Square Value: 0.9857

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

CHAPTER 12.
COST EVALUATION, OBJECTIVE B

12.1 YEAR-ROUND NUTRIENT REMOVAL

12.1.1 Extended Aeration Plants

Table 12-1 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B year-round for an extended aeration plant using mechanical aeration. Figures 12-1 and 12-2 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-2 and Figures 12-3 and 12-4 summarize these costs for an extended aeration plant using diffuser aeration. Tables 12-3 and 12-4 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 12-1.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.57	$2.65	$2.38
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.34	$0.07	$0.02

TABLE 12-2.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.85	$1.15	$0.49
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.15	$0.02	($0.01)

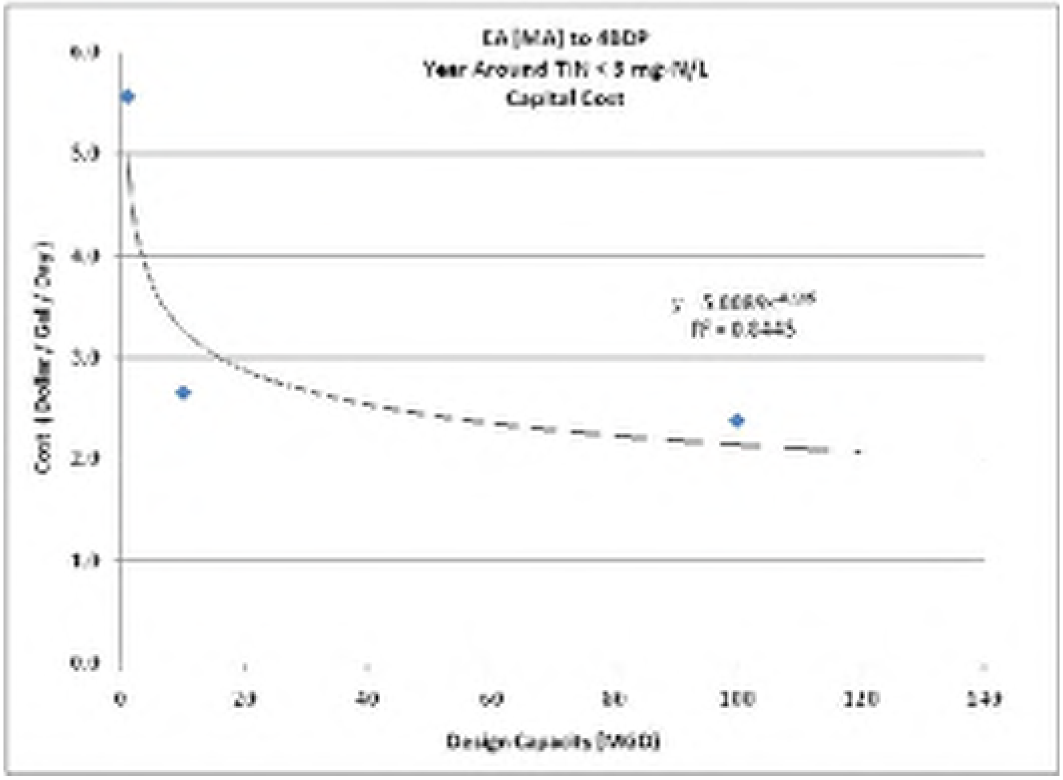


Figure 12-1. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective B Year-Round

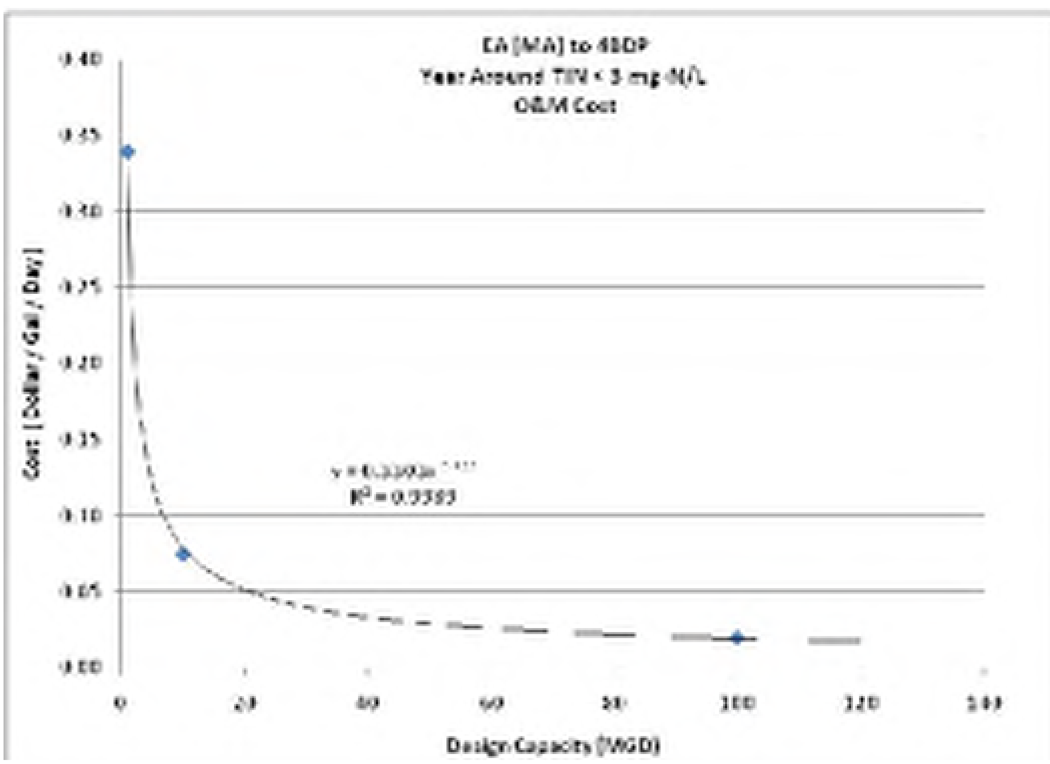


Figure 12-2. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective B Year-Round

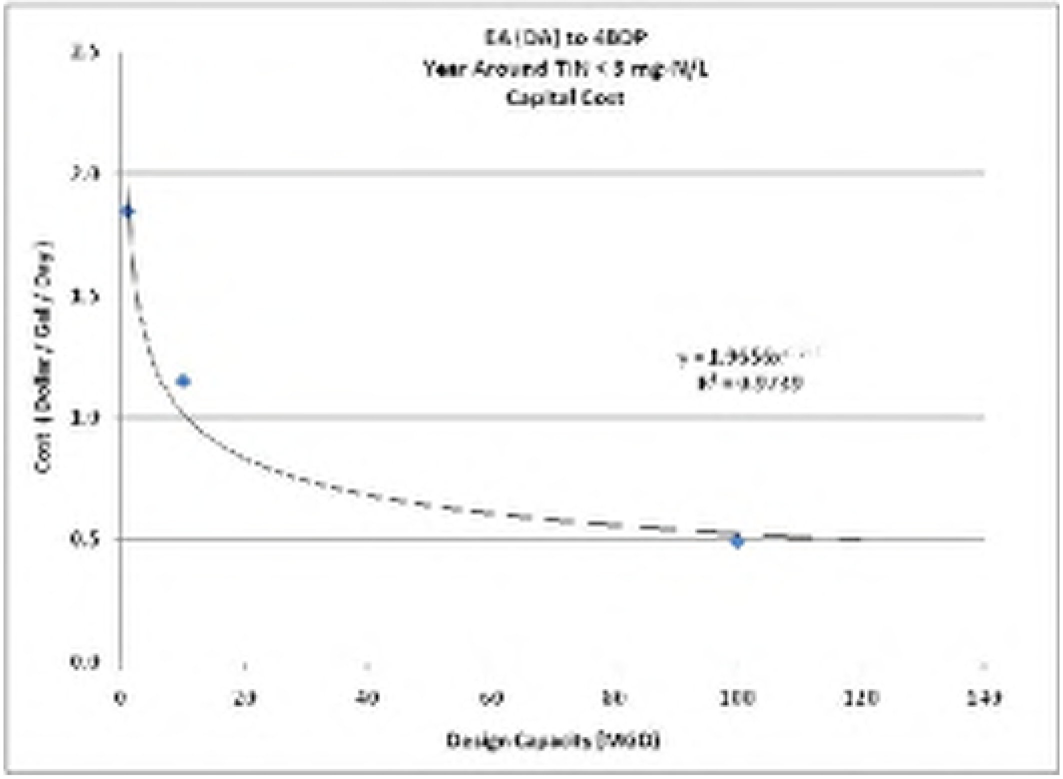


Figure 12-3. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective B Year-Round

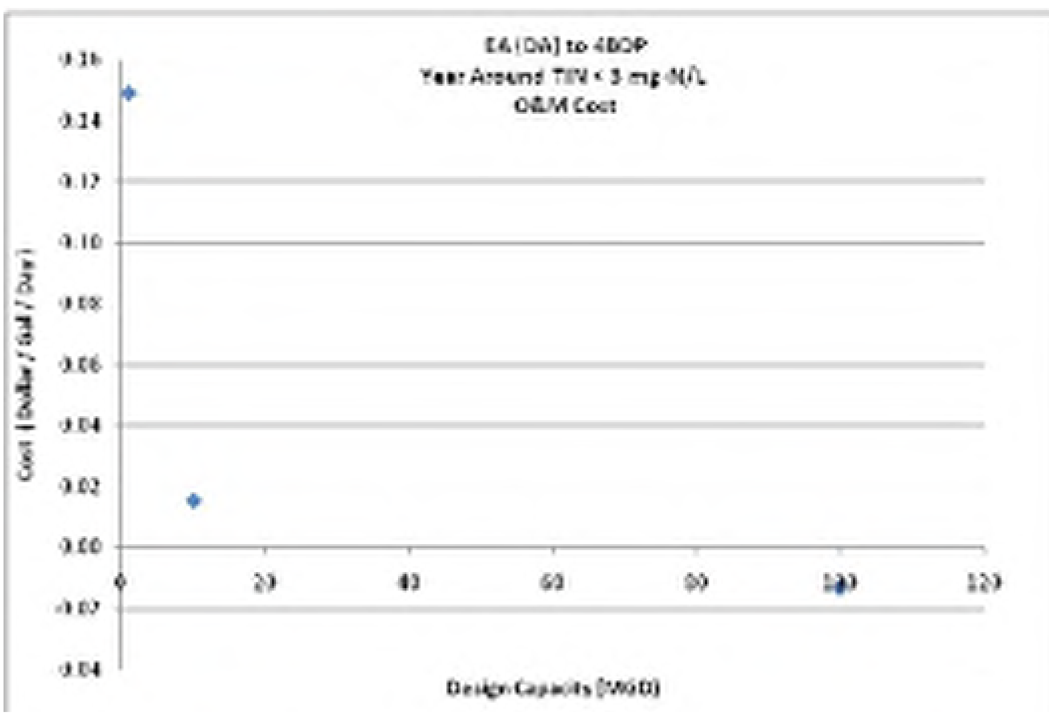


Figure 12-4. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective B Year-Round

TABLE 12-3.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$408,762	$1,947,903	$17,463,507
2014 Incremental O&M Cost	$382,230	$840,600	$2,183,065
Total Annual Cost	**$790,992**	**$2,788,504**	**$19,646,572**
Annual TIN Load Reduction (lb/yr)	44,932	449,315	4,493,150
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$17.60	$6.21	$4.37

Equation:[a] .... $y = 400.88x^{-0.303}$
R-Square Value: 0.9243

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 12-4.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$135,652	$845,590	$3,627,000
2014 Incremental O&M Cost	$167,595	$171,710	-$1,495,661
Total Annual Cost	**$303,247**	**$1,017,300**	**$2,131,340**
Annual TIN Load Reduction (lb/yr)	44,932	449,315	4,493,150
Estimated Cost for TIN Reduction ($/lb TIN removed)	$6.75	$2.26	$0.47

Equation:[a] .... $y = 3595.5x^{-0.579}$
R-Square Value: 0.9895

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.1.2 Conventional Activated Sludge Plants

Table 12-5 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B year-round for a conventional activated sludge plant. Figures 12-5 and 12-6 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-6 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-5.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$7.63	$5.15	$3.44
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.32	$0.16	$0.10

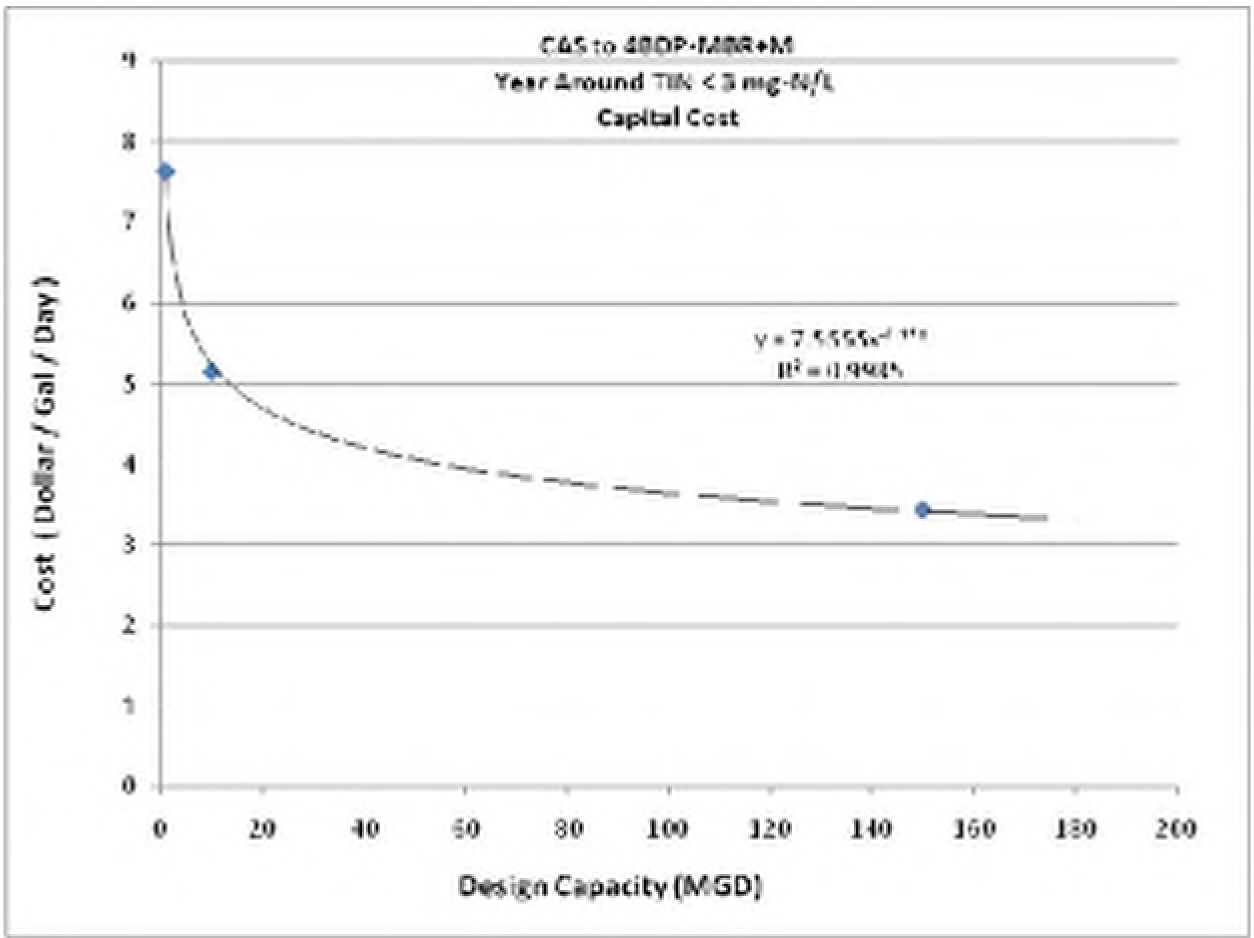


Figure 12-5. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective B Year-Round

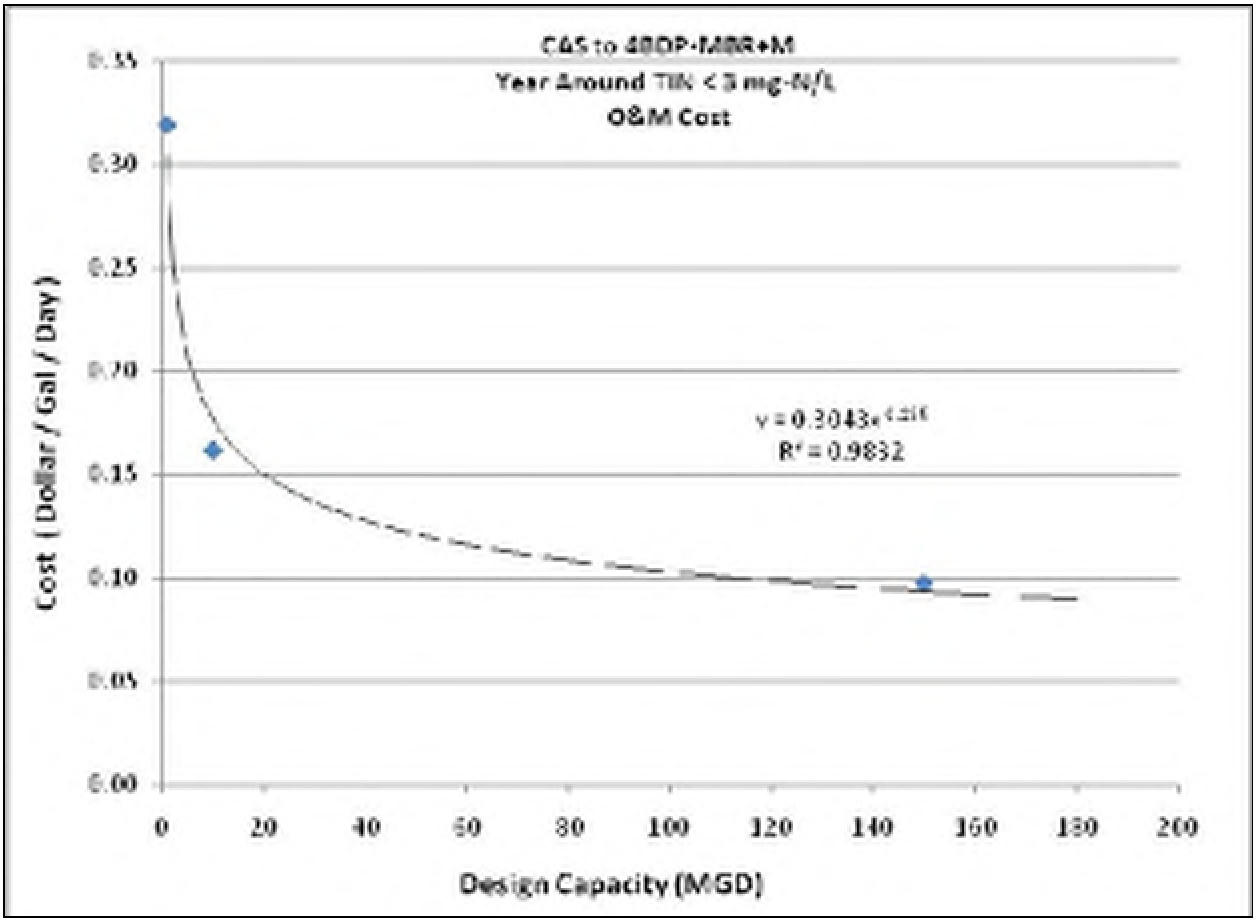


Figure 12-6. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective B Year-Round

TABLE 12-6.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$560,269	$3,785,071	$37,928,146
2014 O&M Cost	$359,351	$1,824,403	$16,486,747
Total Annual Cost	**$919,620**	**$5,6094,74**	**$54,414,620**
Annual TIN Load Reduction (lb/yr)	45,443	454,425	6,816,375
Estimated Cost for TIN Reduction ($/lb TIN removed)	$20.24	$12.34	$7.98

Equation:[a] .... $y = 143.71x^{-0.185}$

R-Square Value: 0.9931

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.1.3 Sequencing Batch Reactor Plants

Table 12-7 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B year-round for an SBR plant. Figures 12-7 and 12-8 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-8 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-7.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.98	$0.96	$0.59
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.70	$0.31	$0.14

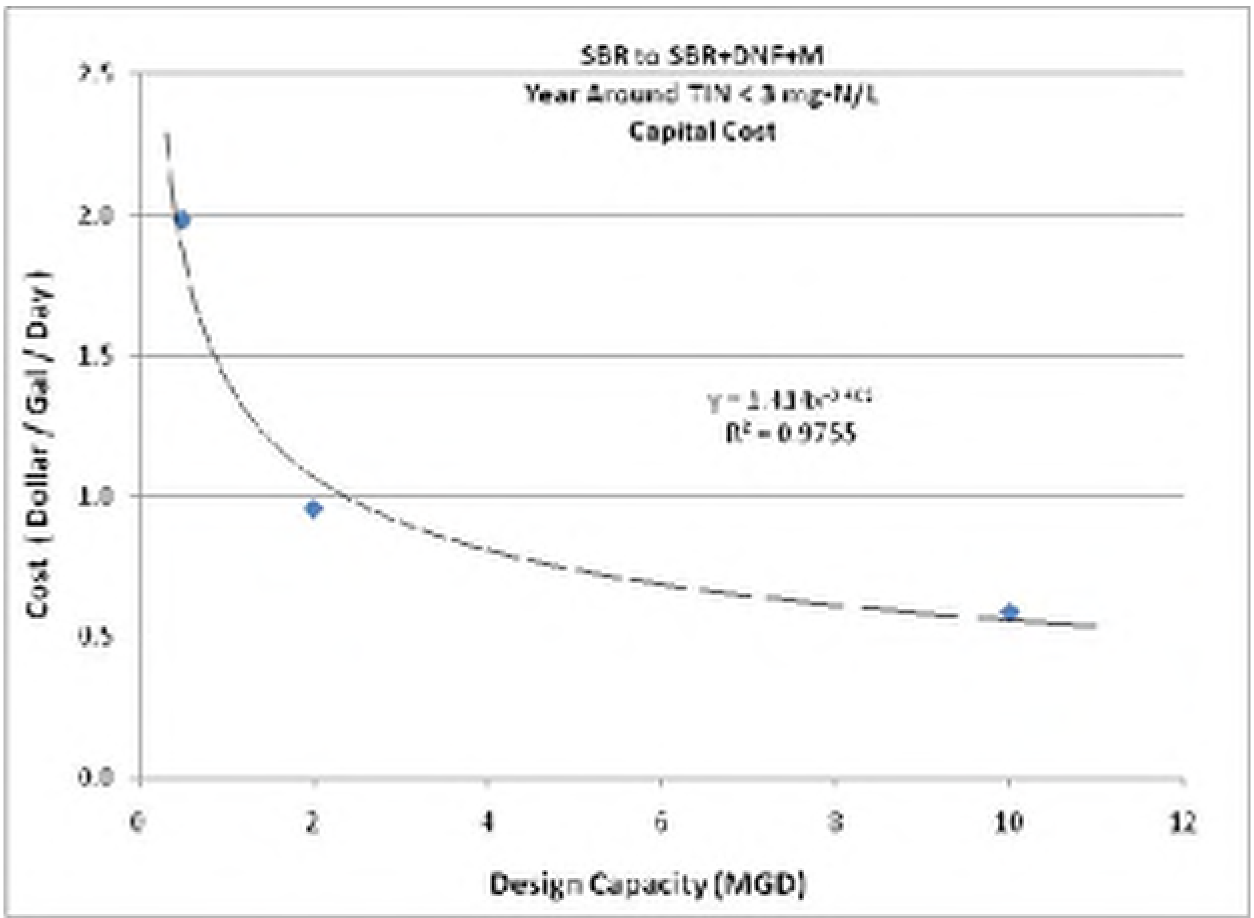


Figure 12-7. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective B Year-Round

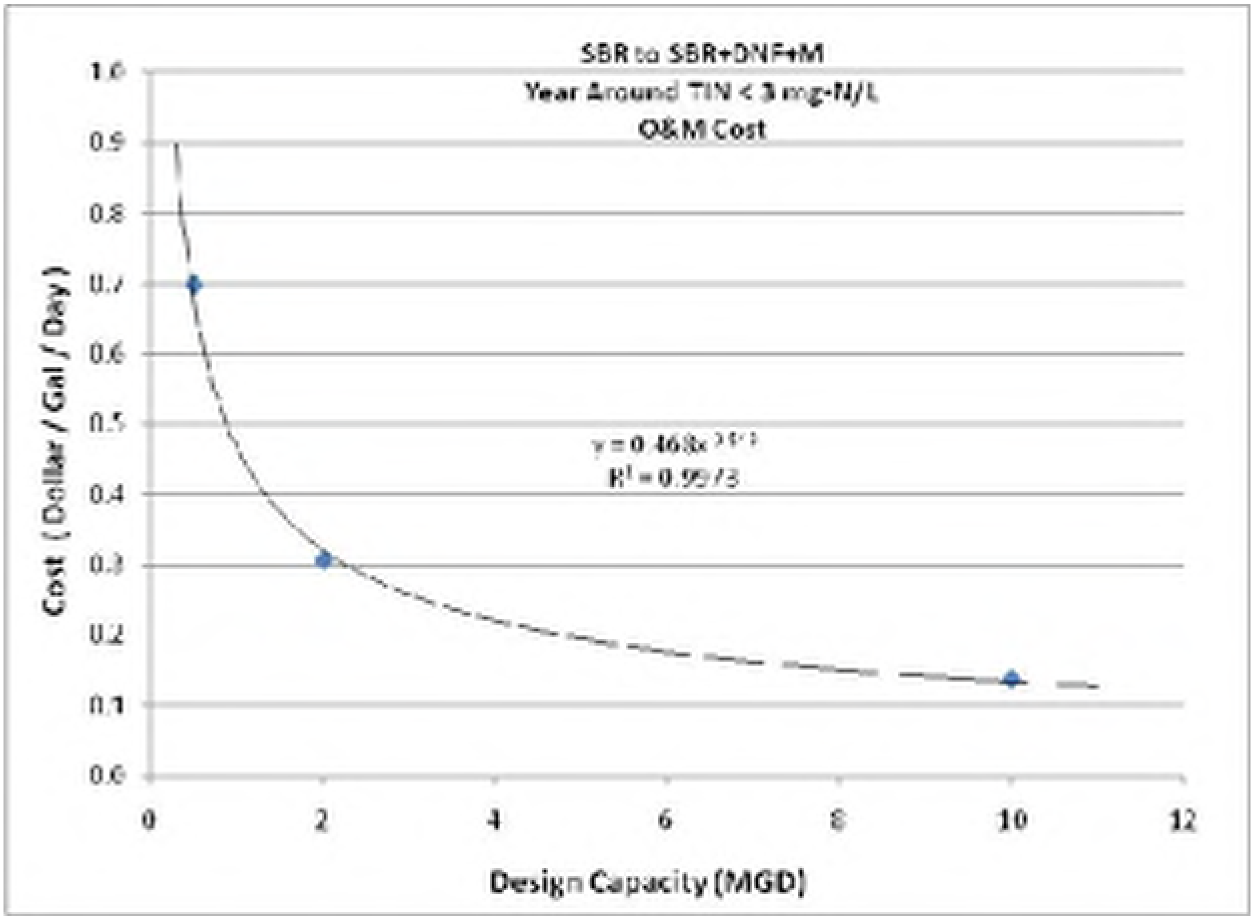


Figure 12-8. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective B Year-Round

TABLE 12-8.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$72,824	$140,735	$432,604
2014 O&M Cost	$393,776	$688,910	$1,543,846
Total Annual Cost	**$466,600**	**$829,644**	**$1,976,450**
Annual TIN Load Reduction (lb/yr)	2,537	10,147	50,735
Estimated Cost for TIN Reduction ($/lb TIN removed)	$183.94	$81.76	$38.96

Equation:[a] .... $y = 10207x^{-0.517}$

R-Square Value: .... $R^2 = 0.9953$

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.1.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 12-9 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B year-round for a trickling filter plant. Figures 12-9 and 12-10 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-10 and Figures 12-11 and 12-12 summarize these costs for a trickling filter/solids contact plant. Table 12-11 and Figures 12-13 and 12-14 summarize these costs for an RBC plant. Tables 12-12, 12-13 and 12-14 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 12-9.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$9.18	$6.43	$3.94
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.38	$0.18	$0.10

TABLE 12-10.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$7.91	$5.87	$3.62
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.27	$0.16	$0.09

TABLE 12-11.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$9.19	$6.46	$3.99
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.43	$0.20	$0.10

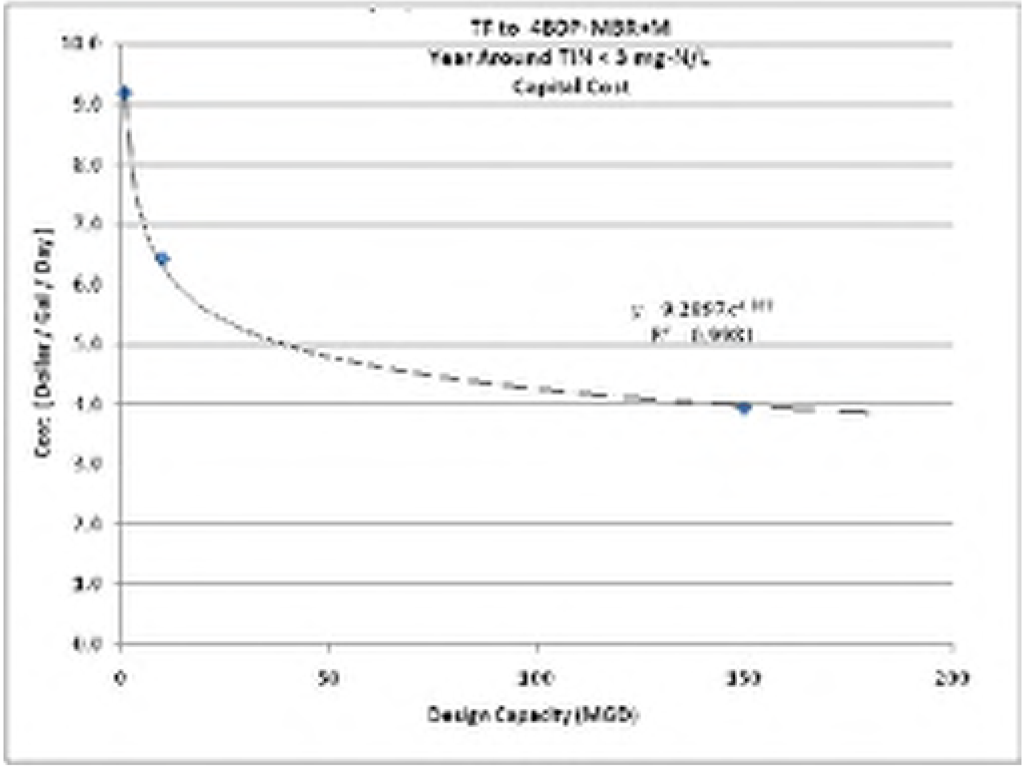


Figure 12-9. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective B Year-Round

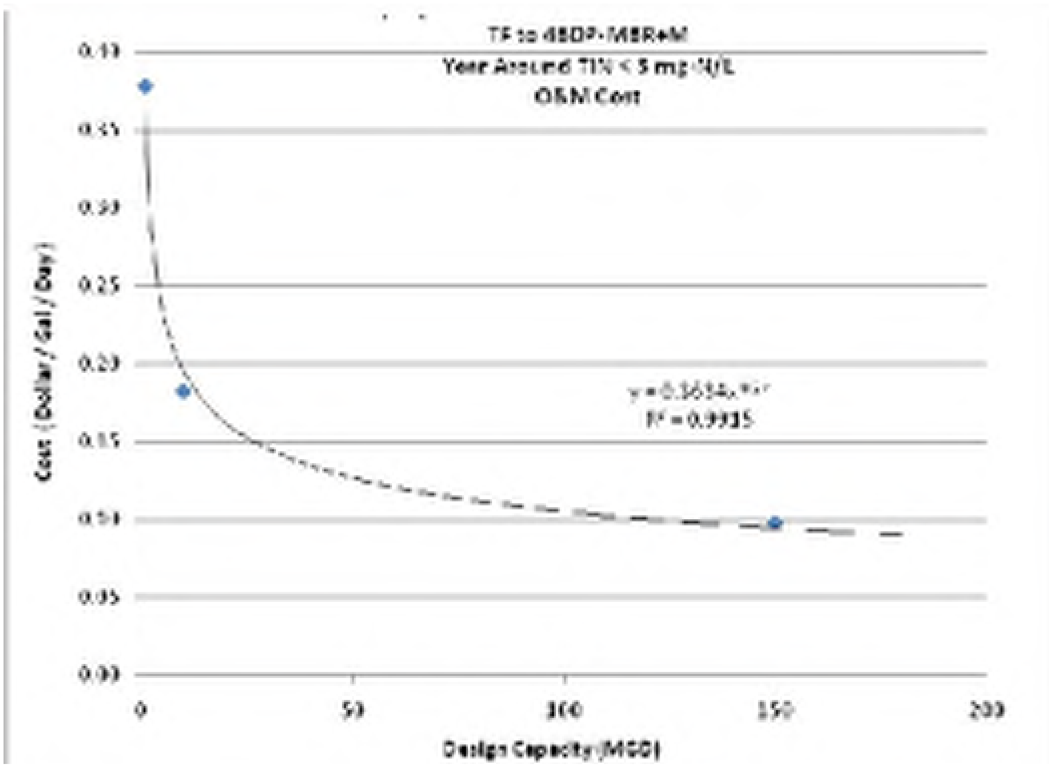


Figure 12-10. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective B Year-Round

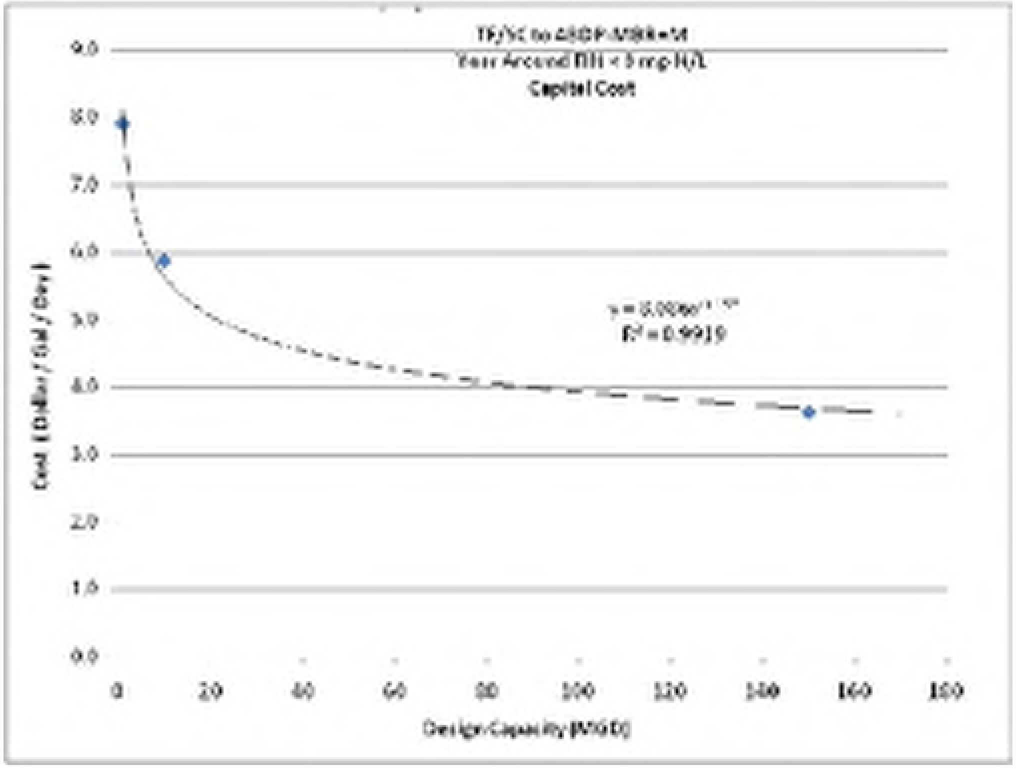


Figure 12-11. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective B Year-Round

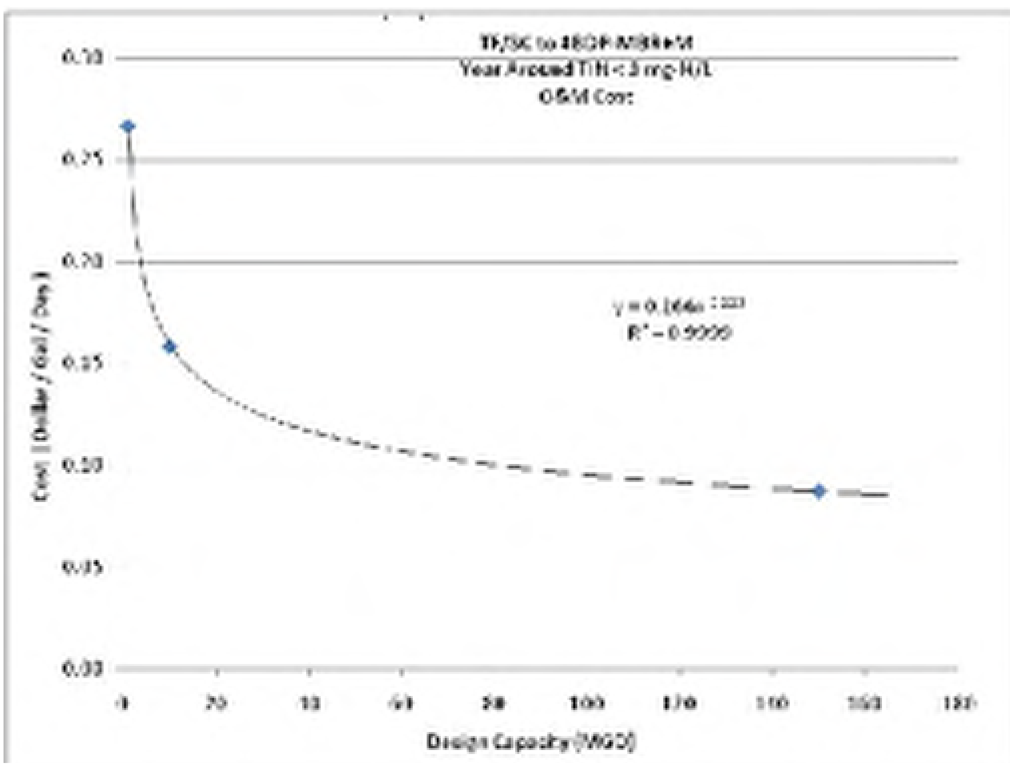


Figure 12-12. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective B Year-Round

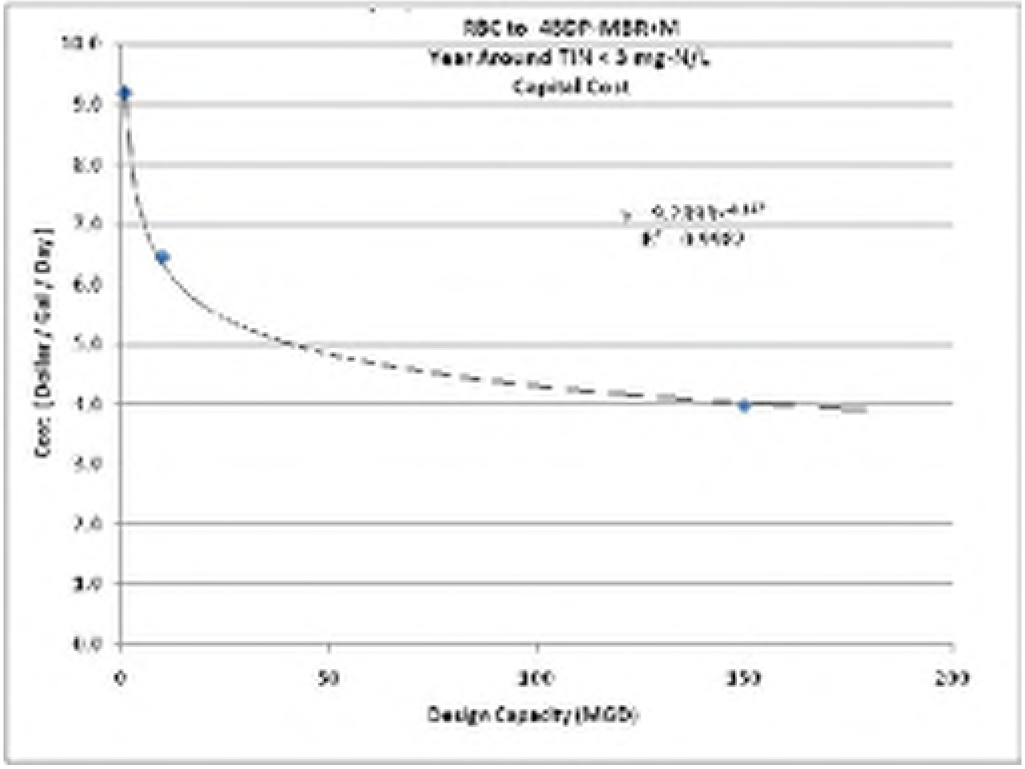


Figure 12-13. Capital Cost per Plant Capacity for RBC Upgraded for Objective B Year-Round

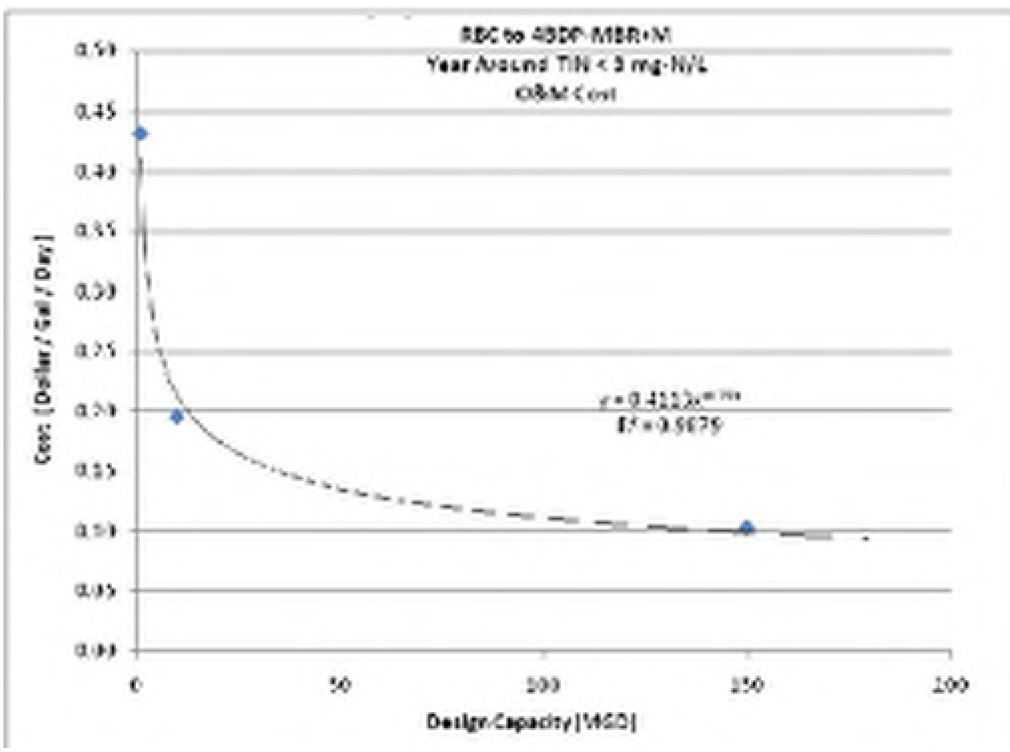


Figure 12-14. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective B Year-Round

TABLE 12-12.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$674,390	$4,721,940	$43,396,182
2014 O&M Cost	$425,306	$2,045,622	$16,426,259
Total Annual Cost	**$1,099,696**	**$6,767,562**	**$59,822,441**
Annual TIN Load Reduction (lb/yr)	45,443	454,425	6,816,375
Estimated Cost for TIN Reduction ($/lb TIN removed)	$24.20	$14.89	$8.78

Equation:[a] .... $y = 209.97x^{-0.202}$
R-Square Value: 0.9995

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 12-13.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	580,940	4,313,673	39,890,166
2014 O&M Cost	300,431	1,781,972	14,763,883
Total Annual Cost	**881,371**	**6,095,644**	**54,654,049**
Annual TIN Load Reduction (lb/yr)	45,443	454,425	6,816,375
Estimated Cost for TIN Reduction ($/lb TIN removed)	19.40	13.41	8.02

Equation:[a] .... $y = 130.75x^{-0.177}$
R-Square Value: 0.9977

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 12-14.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$674,719	$4,742,341	$43,920,192
2014 O&M Cost	$486,325	$2,197,003	$17,433,590
Total Annual Cost	**$1,161,044**	**$6,939,344**	**$61,353,782**
Annual TIN Load Reduction (lb/yr)	45,443	454,425	6,816,375
Estimated Cost for TIN Reduction ($/lb TIN removed)	$25.55	$15.27	$9.00

Equation:[a] .... $y = 234.42x^{-0.208}$
R-Square Value: 0.9985

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.1.5 Membrane Biological Reactor Plants

Table 12-15 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B year-round for an MBR plant. Figures 12-15 and 12-16 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-16 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-15.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$0.031	$0.004	$0.002
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.016	$0.016	$0.016

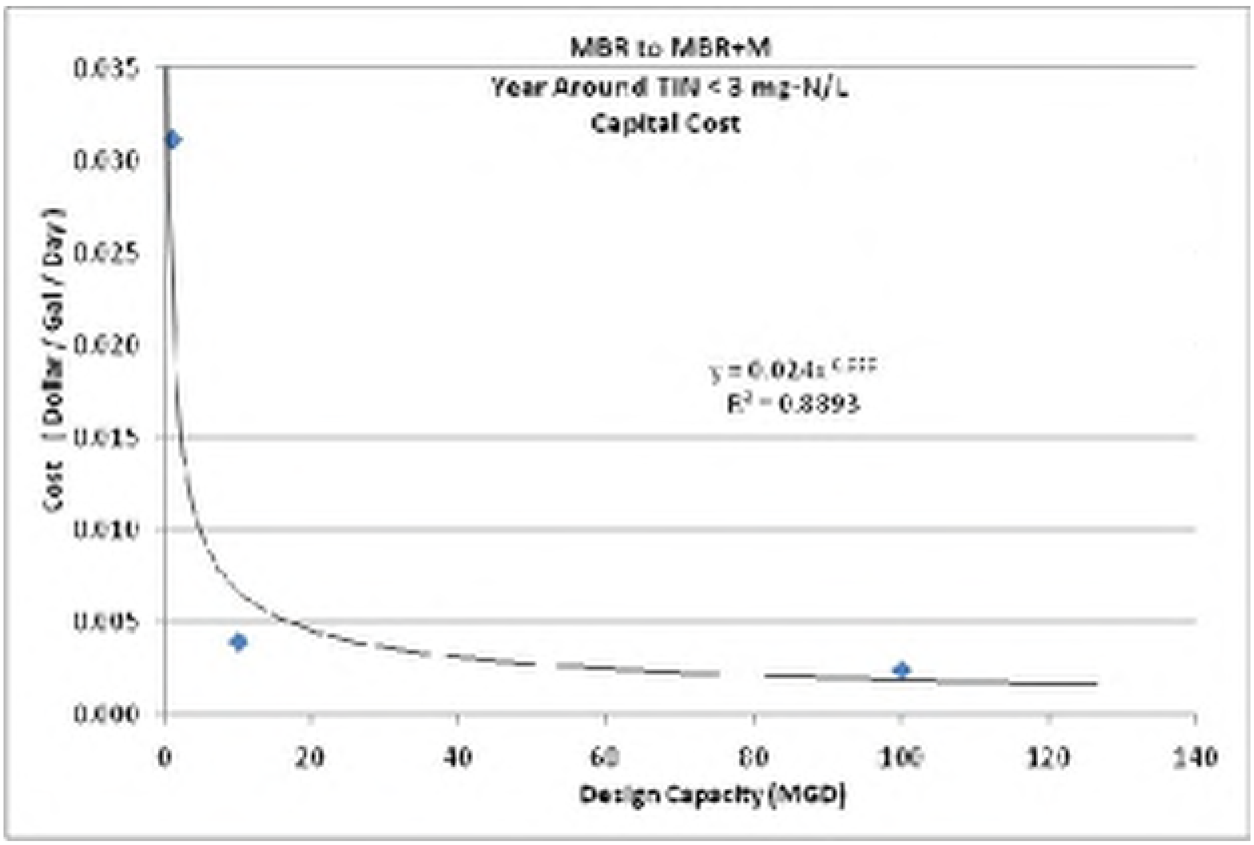


Figure 12-15. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective B Year-Round

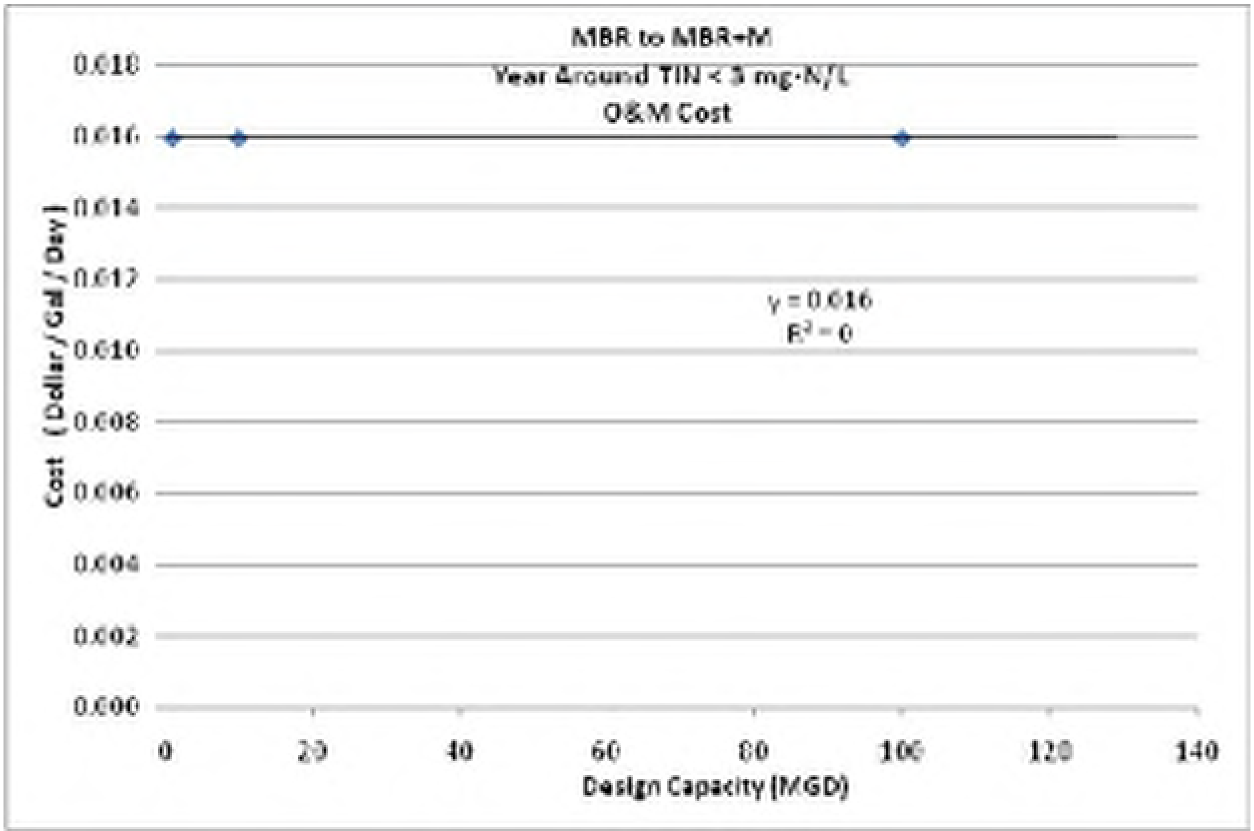


Figure 12-16. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective B Year-Round

TABLE 12-16.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$2,284	$2,916	$17,745
2014 O&M Cost	$17,973	$179,730	$1,797,297
Total Annual Cost	**$20,257**	**$182,646**	**$1,815,042**
Annual TIN Load Reduction (lb/yr)	9,527	95,265	952,650
Estimated Cost for TIN Reduction ($/lb TIN removed)	$2.13	$1.92	$1.91
Equation:[a]		$y = 2.6028x^{-0.024}$	
R-Square Value:		0.7858	

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.1.6 High-Purity Oxygen Activated Sludge Plants

Table 12-17 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B year-round for an HPO activated sludge plant. Figures 12-17 and 12-18 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-18 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-17.
ESTIMATED COST PER CAPACITY FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	20-mgd Plant	220-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.60	$3.67
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.17

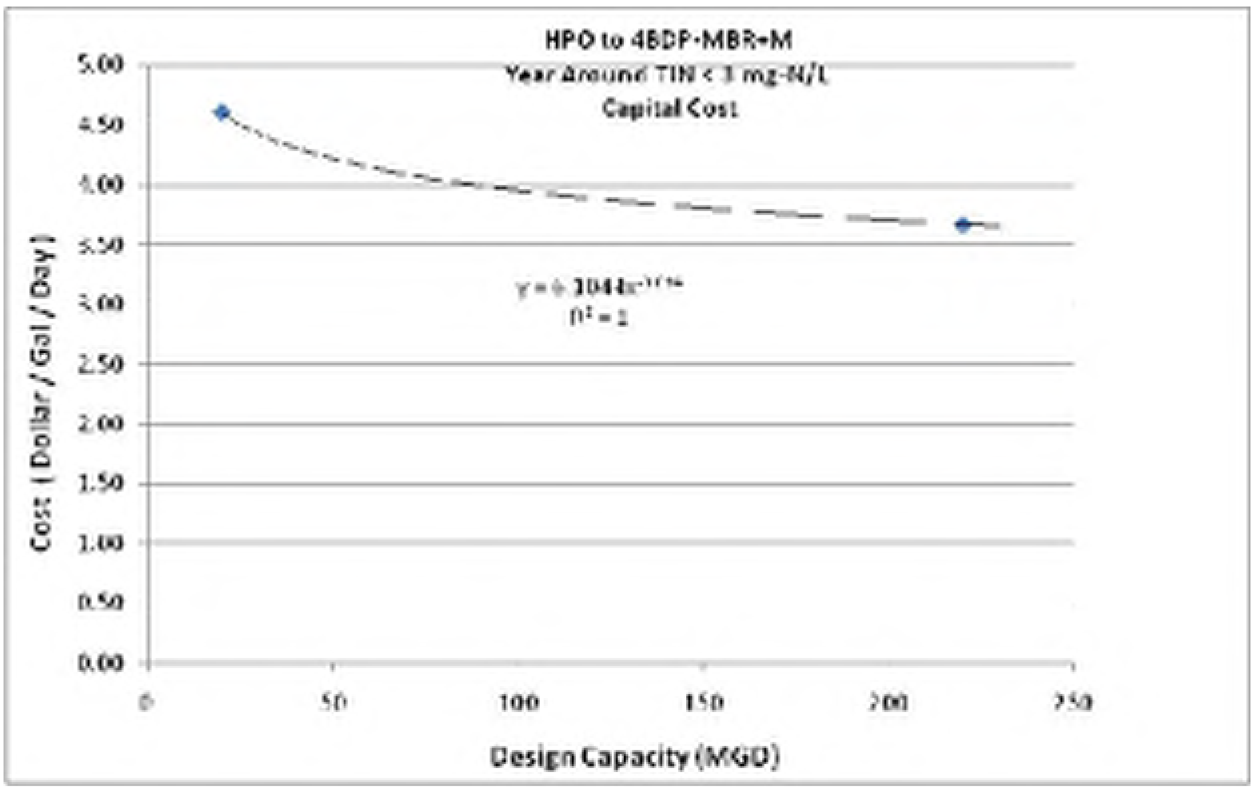


Figure 12-17. Capital Cost per Plant Capacity for HPO Plant Upgraded for Objective B Year-Round

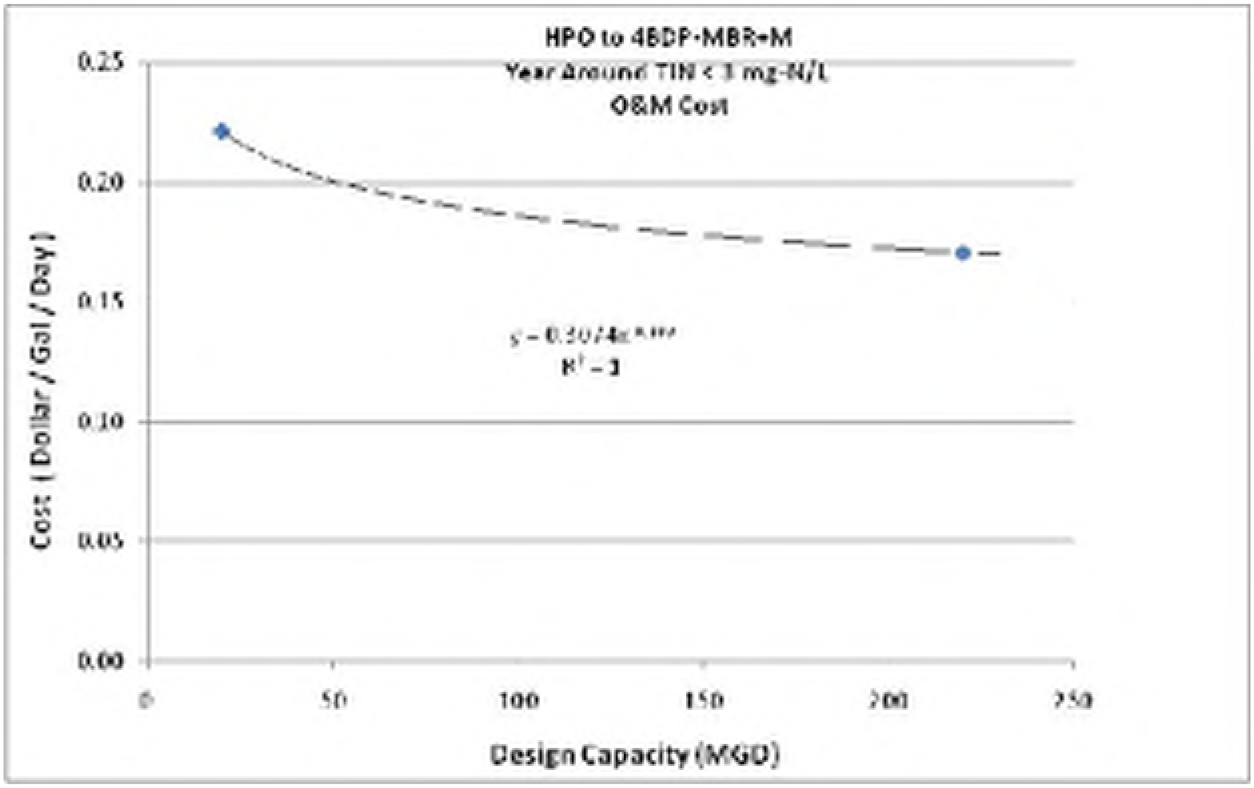


Figure 12-18. O&M Cost per Plant Capacity for HPO Upgraded for Objective B Year-Round

TABLE 12-18.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	20-mgd Plant	220-mgd Plant
Annualized Capital Cost	\$6,760,000	\$59,304,000
2014 O&M Cost	\$4,991,000	\$42,269,000
Total Annual Cost	**\$11,751,000**	**\$101,573,000**
Annual TIN Load Reduction (lb/yr)	962,870	10,591,570
Estimated Cost for TIN Reduction (\$/lb TIN removed)	\$12.20	\$9.60
Equation:[a]		$y = 48.664x^{-0.100}$
R-Square Value:	1	

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction (\$/lb TIN removed)

12.1.7 Aerated or Facultative Lagoon Plants

Table 12-19 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B year-round for an aerated lagoon plant. Figures 12-19 and 12-20 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-20 and Figures 12-21 and 12-22 summarize these costs for a facultative lagoon plant. Tables 12-21 and 12-22 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 12-19.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$23.46	$17.78	$11.93	$7.75
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.10	$0.67	$0.30	$0.14

TABLE 12-20.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$23.32	$17.67	$11.84	$7.70
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.37	$0.90	$0.46	$0.17

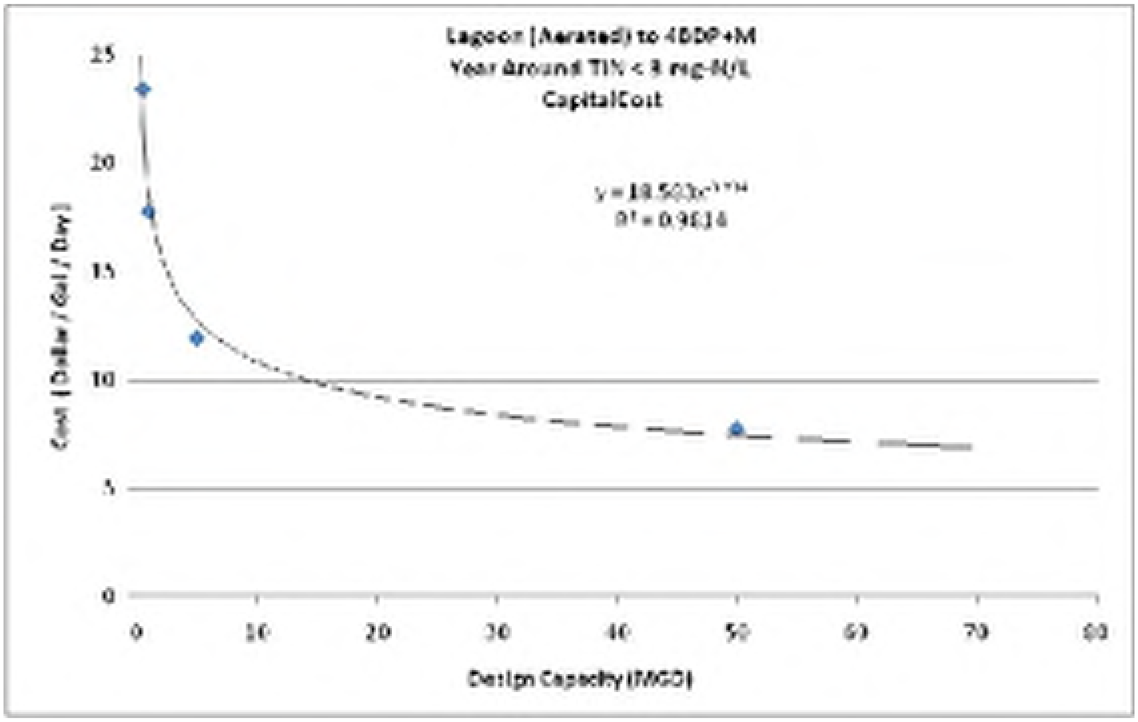


Figure 12-19. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective B Year-Round

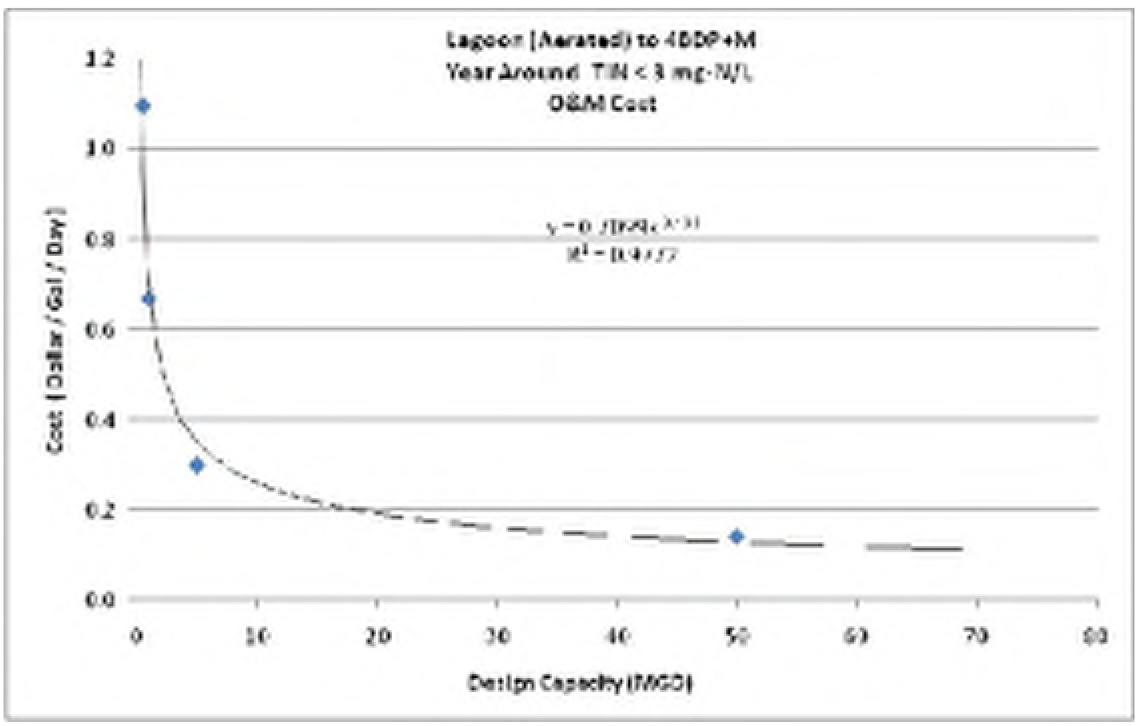


Figure 12-20. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective B Year-Round

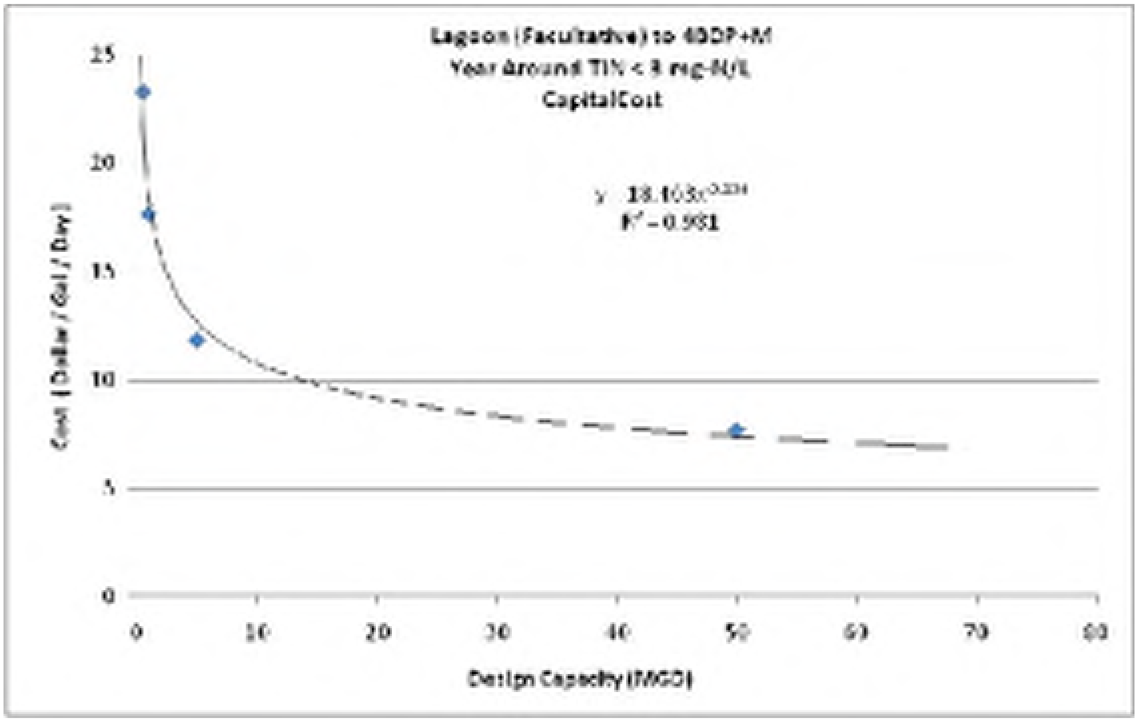


Figure 12-21. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective B Year-Round

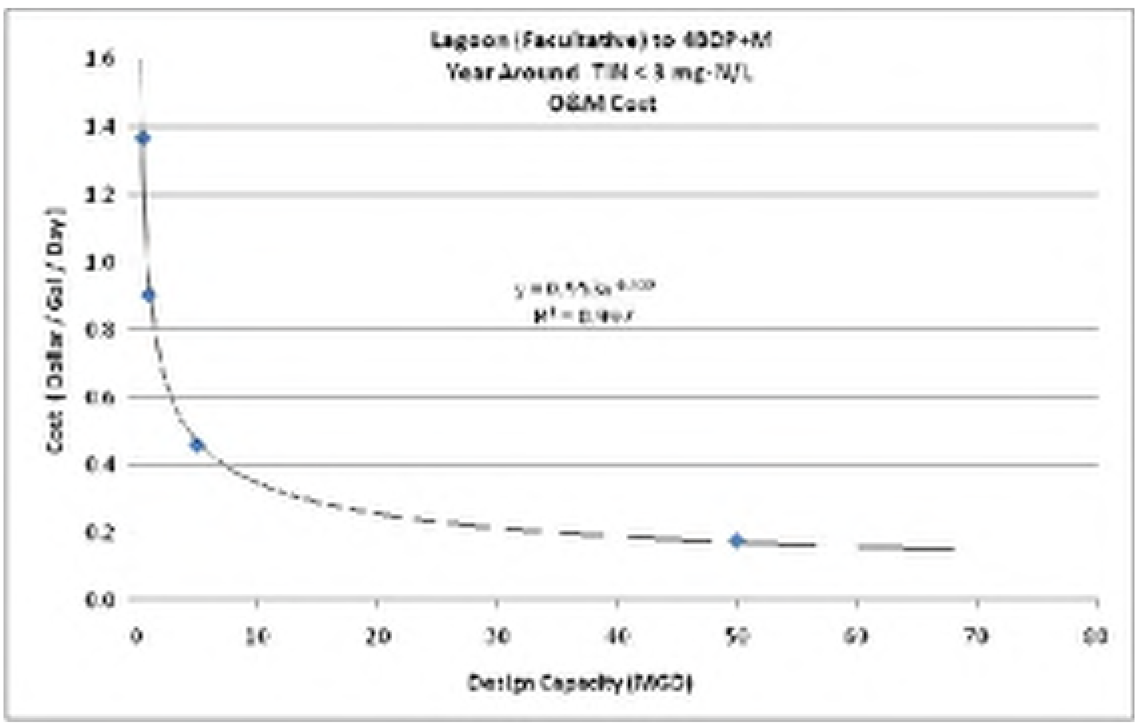


Figure 12-22. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective B Year-Round

**TABLE 12-21.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$861,410	$1,306,182	$4,380,684	$28,454,843
2014 O&M Cost	$616,861	$752,106	$1,685,034	$7,948,371
Total Annual Cost	**$1,478,272**	**$2,058,287**	**$6,065,718**	**$36,403,214**
Annual TIN Load Reduction (lb/yr)	22,429	44,859	224,293	2,224,675
Estimated Cost for TIN Reduction ($/lb TIN removed)	$65.91	$45.88	$27.04	$16.36

Equation:[a] .... $y = 1139.5x^{-0.295}$
R-Square Value: 0.9733

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

**TABLE 12-22.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE B YEAR-ROUND**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$856,392	$1,297,709	$4,347,532	$28,280,447
2014 O&M Cost	$770,030	$1,015,784	$2,587,861	$9,835,641
Total Annual Cost	**$1,626,423**	**$2,313,496**	**$6,935,394**	**$38,116,088**
Annual TIN Load Reduction (lb/yr)	22,429	44,859	224,293	2,224,675
Estimated Cost for TIN Reduction ($/lb TIN removed)	$72.51	$51.57	$30.92	$17.13

Equation:[a] .... $y = 1441.6x^{-0.306}$
R-Square Value: 0.9871

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.2 SEASONAL NUTRIENT REMOVAL

12.2.1 Extended Aeration Plants

Table 12-23 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B seasonally for an extended aeration plant using mechanical aeration. Figures 12-23 and 12-24 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-24 and Figures 12-25 and 12-26 summarize these costs for an extended aeration plant using diffuser aeration. Tables 12-25 and 12-26 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 12-23.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.96	$2.54	$2.30
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.32	$0.07	$0.02

TABLE 12-24.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.23	$1.06	$0.43
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.13	$0.01	($0.01)

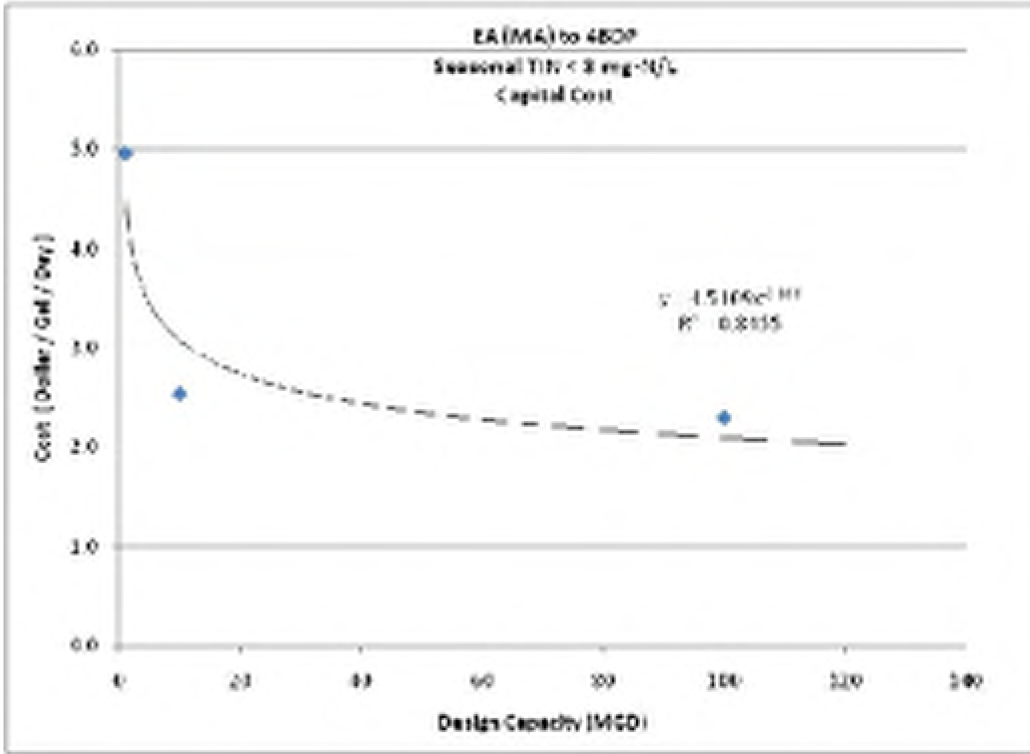


Figure 12-23. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective B Seasonally

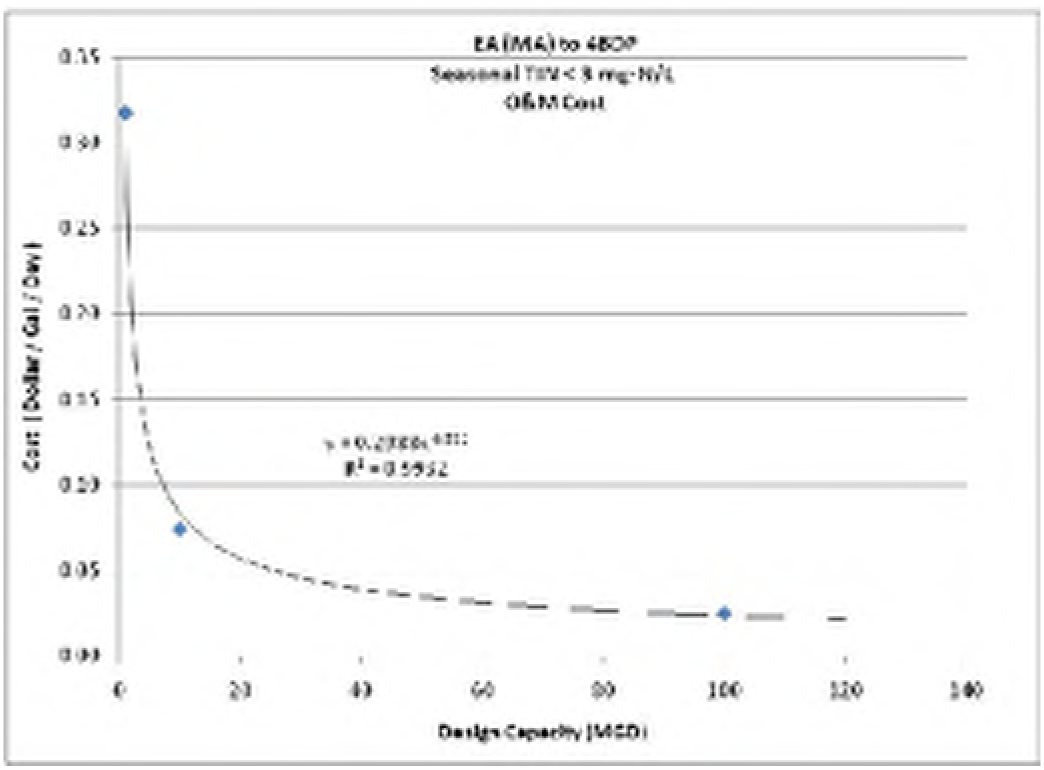


Figure 12-24. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective B Seasonal

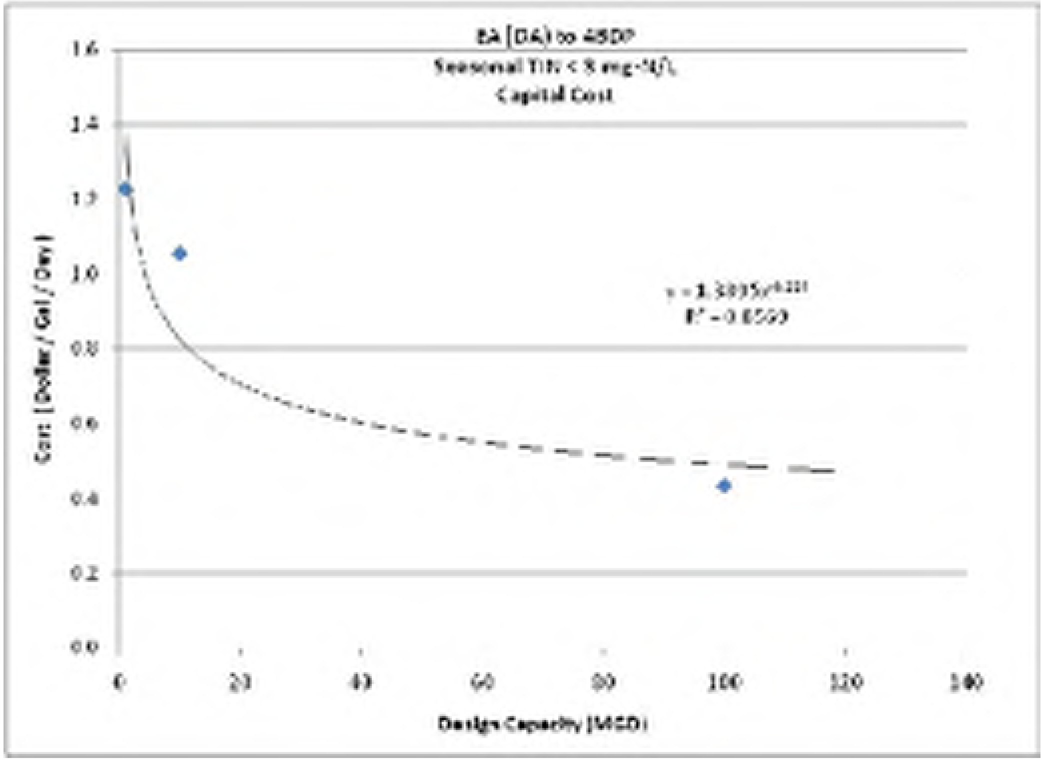


Figure 12-25. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective B Seasonally

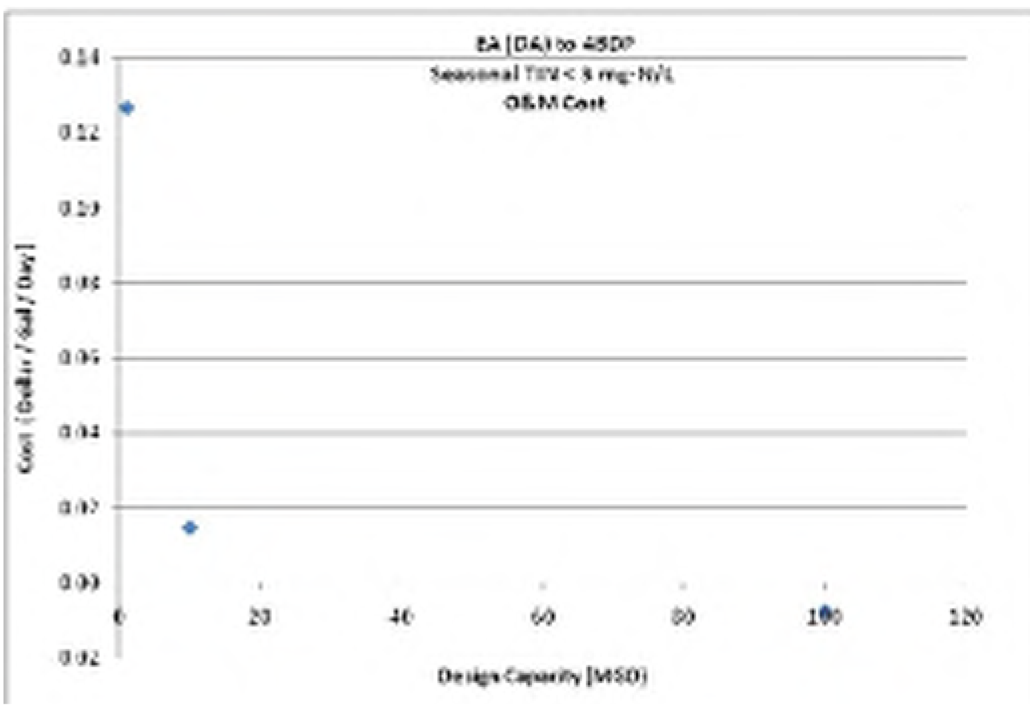


Figure 12-26. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective B Seasonal

TABLE 12-25.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$364,187	$1,869,240	$16,922,633
2014 O&M Cost	$357,321	$835,184	$2,809,833
Total Annual Cost	**$721,508**	**$2,704,424**	**$19,732,466**
Annual TIN Load Reduction (lb/yr)	23,305	233,053	2,330,525
Estimated Cost for TIN Reduction ($/lb TIN removed)	$30.96	$11.60	$8.47

Equation:[a] .... $y = 469.64x^{-0.281}$
R-Square Value: 0.9188

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 12-26.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA ((DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$90,253	$775,153	$3,184,841
2014 O&M Cost	$142,686	$166,294	-$868,893
Total Annual Cost	**$232,940**	**$941,447**	**$2,315,948**
Annual TIN Load Reduction (lb/yr)	23,287	232,870	2,328,700
Estimated Cost for TIN Reduction ($/lb TIN removed)	$10.00	$4.04	$0.99

Equation:[a] .... $y = 262.5x^{-0.331}$
R-Square Value: 0.9957

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.2.2 Conventional Activated Sludge Plants

Table 12-27 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B seasonally for a conventional activated sludge plant. Figures 12-27 and 12-28 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-28 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-27.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.83	$1.62	$1.30
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.06	$0.03

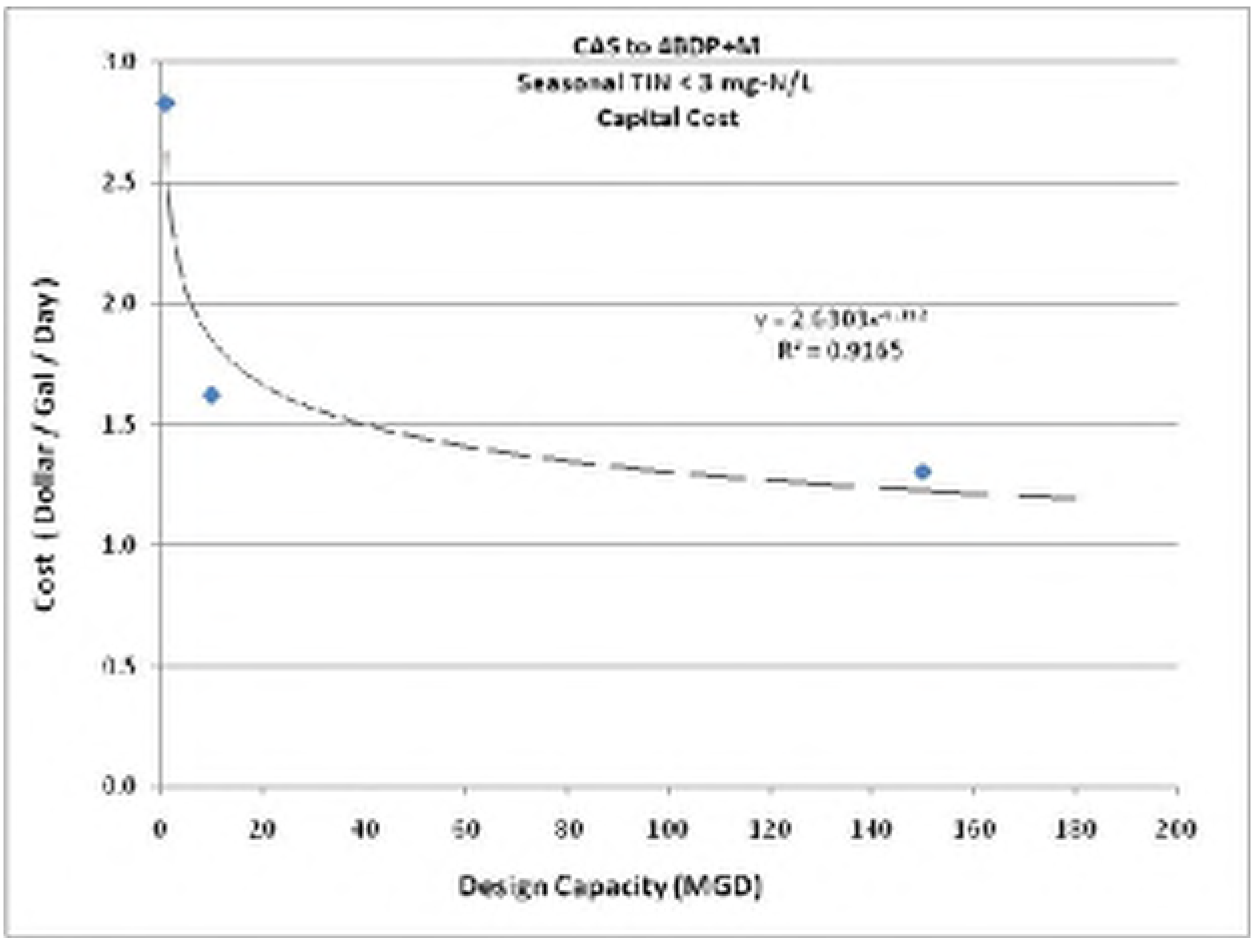


Figure 12-27. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective B Seasonally

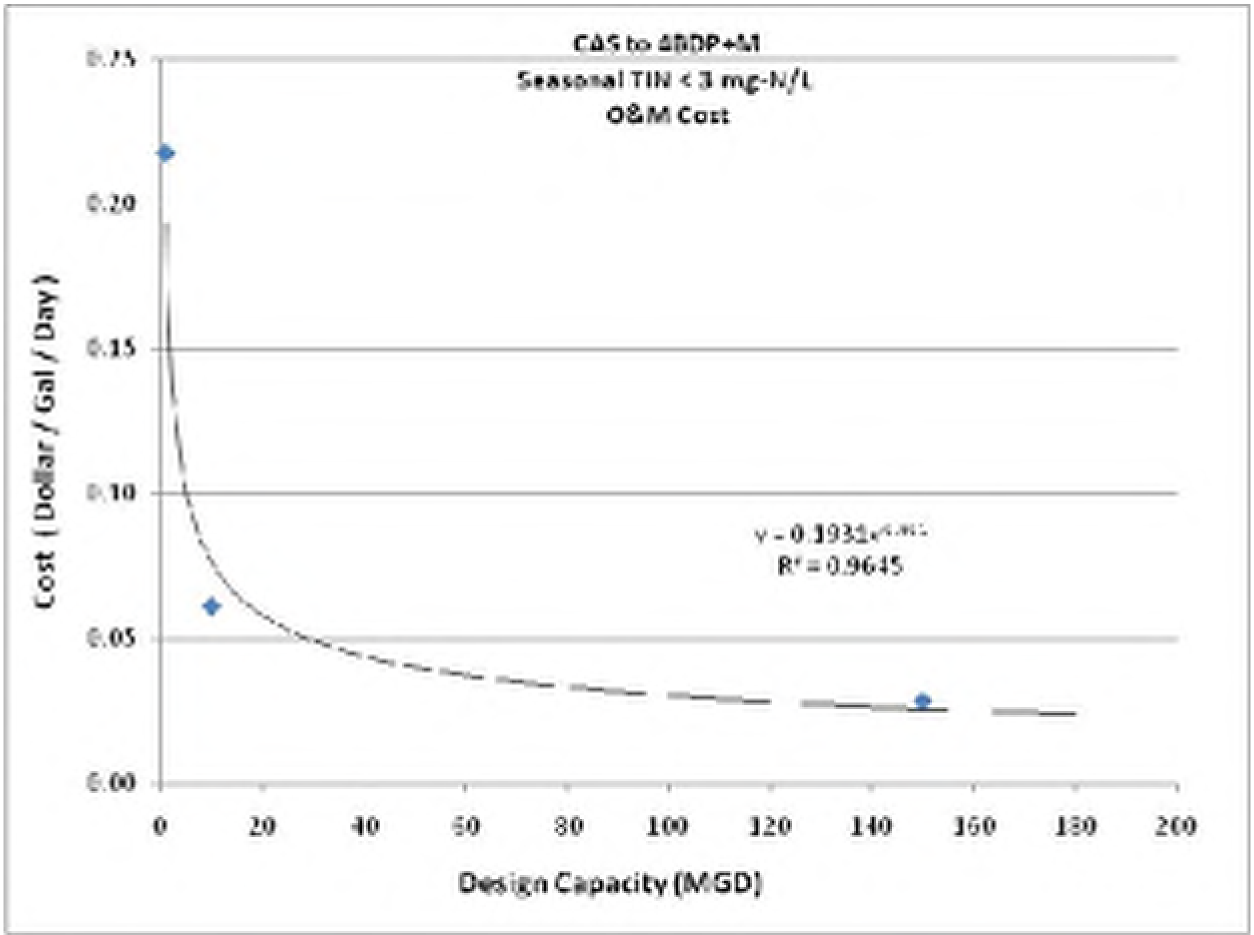


Figure 12-28. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective B Seasonal

TABLE 12-28.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$207,608	$1,190,435	$14,350,478
2014 O&M Cost	$245,065	$691,484	$4,846,582
Total Annual Cost	**$452,673**	**$1,881,920**	**$19,197,060**
Annual TIN Load Reduction (lb/yr)	22,685	226,848	3,402,713
Estimated Cost for TIN Reduction ($/lb TIN removed)	$19.95	$8.30	$5.64

Equation:[a] .... $y = 217.78x^{-0.249}$
R-Square Value: 0.9303

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.2.3 Sequencing Batch Reactor Plants

Table 12-29 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B seasonally for an SBR plant. Figures 12-29 and 12-30 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-30 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-29.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.81	$0.85	$0.50
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.59	$0.24	$0.10

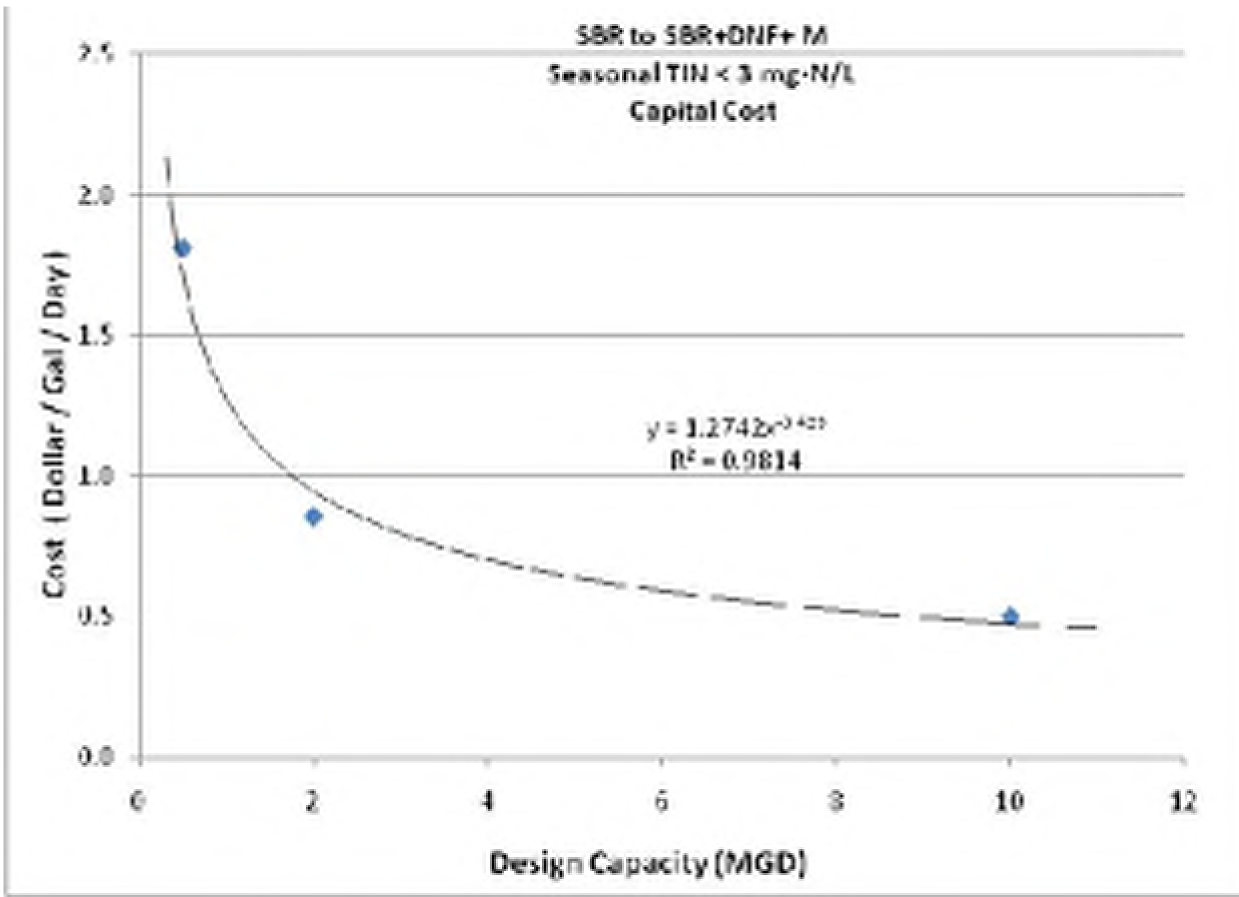


Figure 12-29. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective B Seasonally

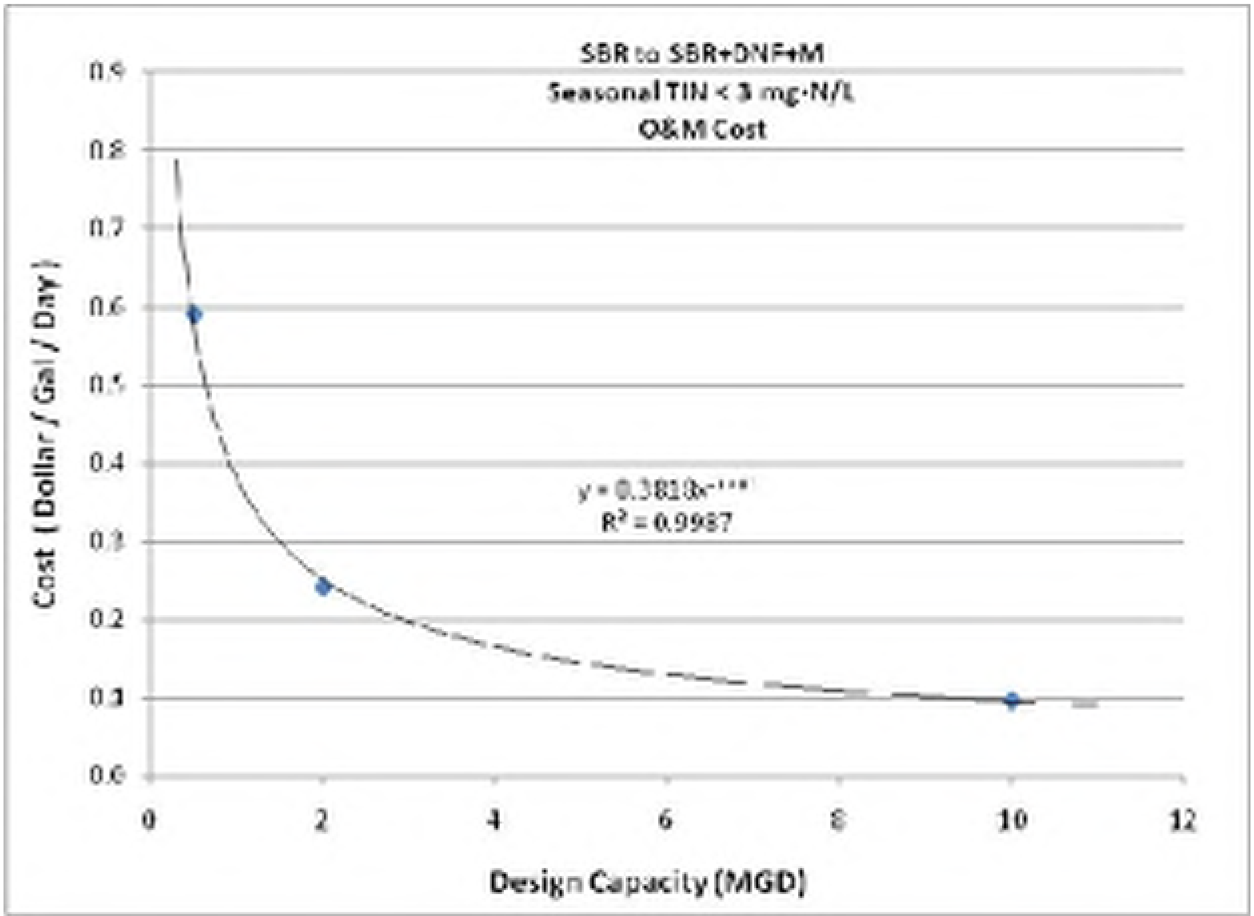


Figure 12-30. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective B Seasonal

TABLE 12-30.
UNIT NUTRIENT REMOVAL COSTS FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$66,552	$125,538	$365,384
2014 O&M Cost	$332,581	$545,450	$1,098,542
Total Annual Cost	**$399,132**	**$670,988**	**$1,460,926**
Annual TIN Load Reduction (lb/yr)	475	1,898	9,490
Estimated Cost for TIN Reduction ($/lb TIN removed)	$841.16	$353.52	$153.94

Equation:[a] .... $y = 26701x^{-0.566}$

R-Square Value: 0.997

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.2.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 12-31 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B seasonally for a trickling filter plant. Figures 12-31 and 12-32 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-32 and Figures 12-33 and 12-34 summarize these costs for a trickling filter/solids contact plant. Table 12-33 and Figures 12-35 and 12-36 summarize these costs for an RBC plant. Tables 12-34, 12-35 and 12-36 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 12-31.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.17	$3.25	$2.08
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.28	$0.08	$0.03

TABLE 12-32.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$3.43	$2.56	$1.66
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.17	$0.06	$0.02

TABLE 12-33.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.19	$3.27	$2.12
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.33	$0.09	$0.03

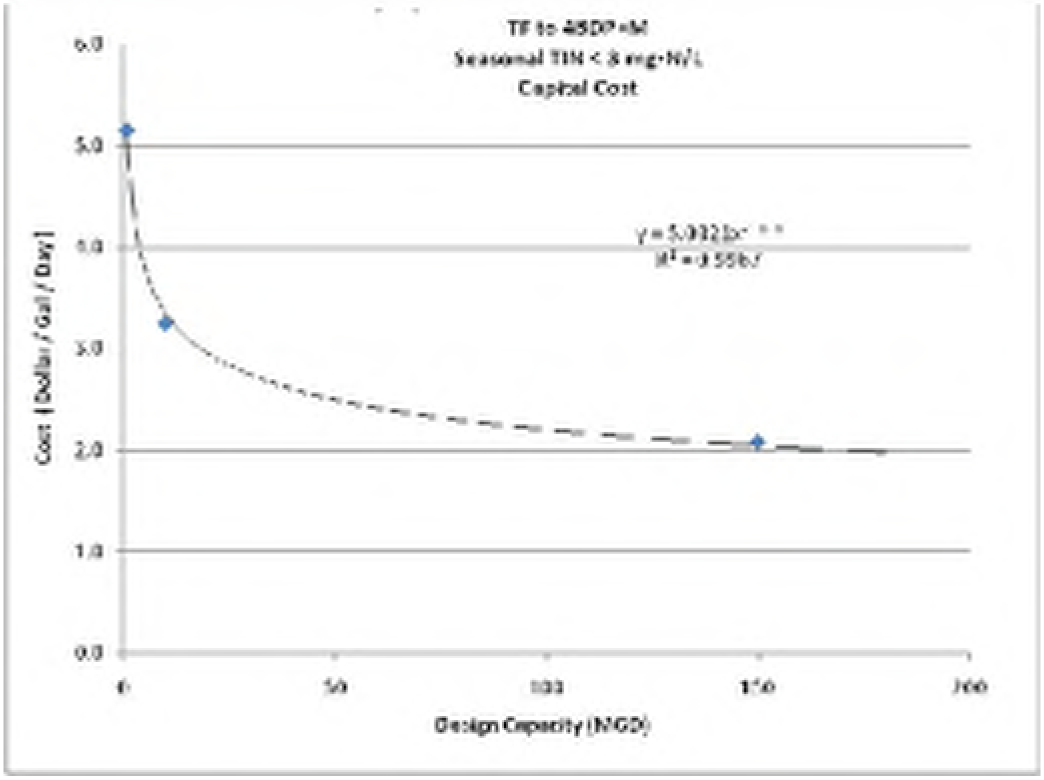


Figure 12-31. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective B Seasonally

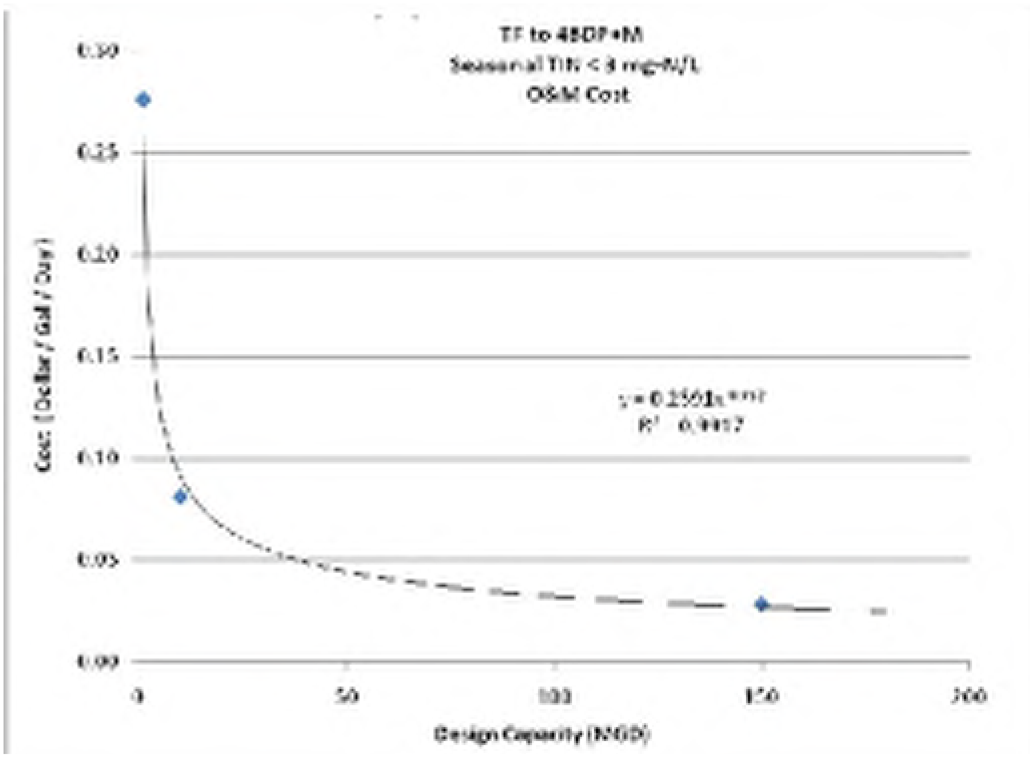


Figure 12-32. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective B Seasonal

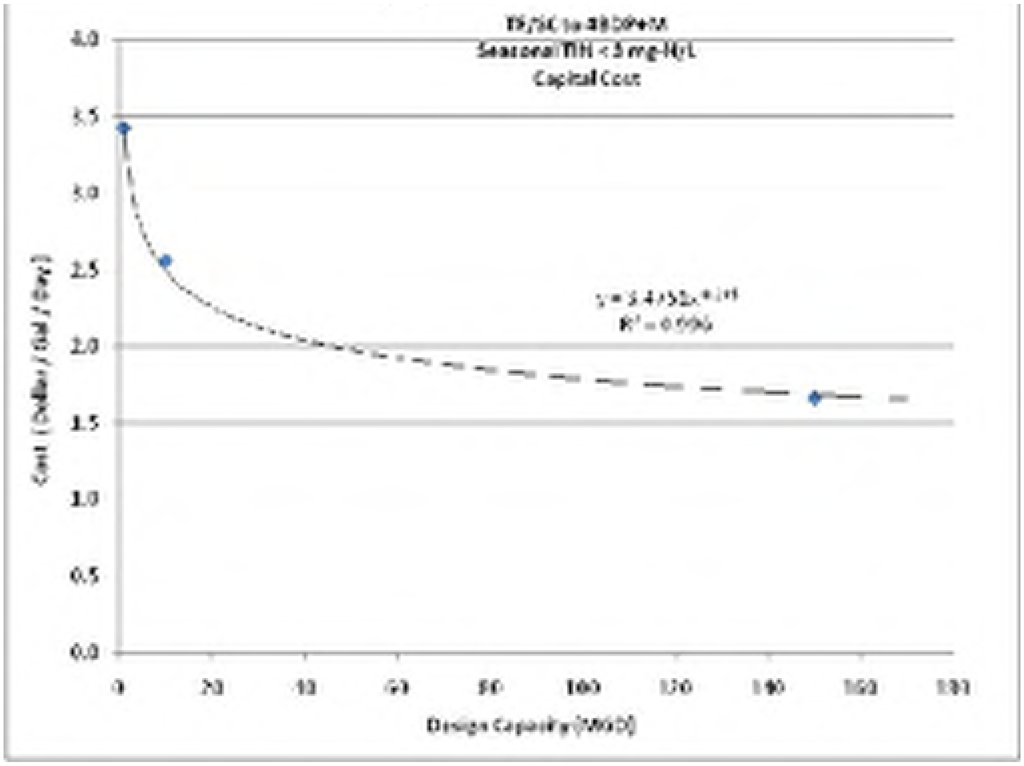


Figure 12-33. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective B Seasonally

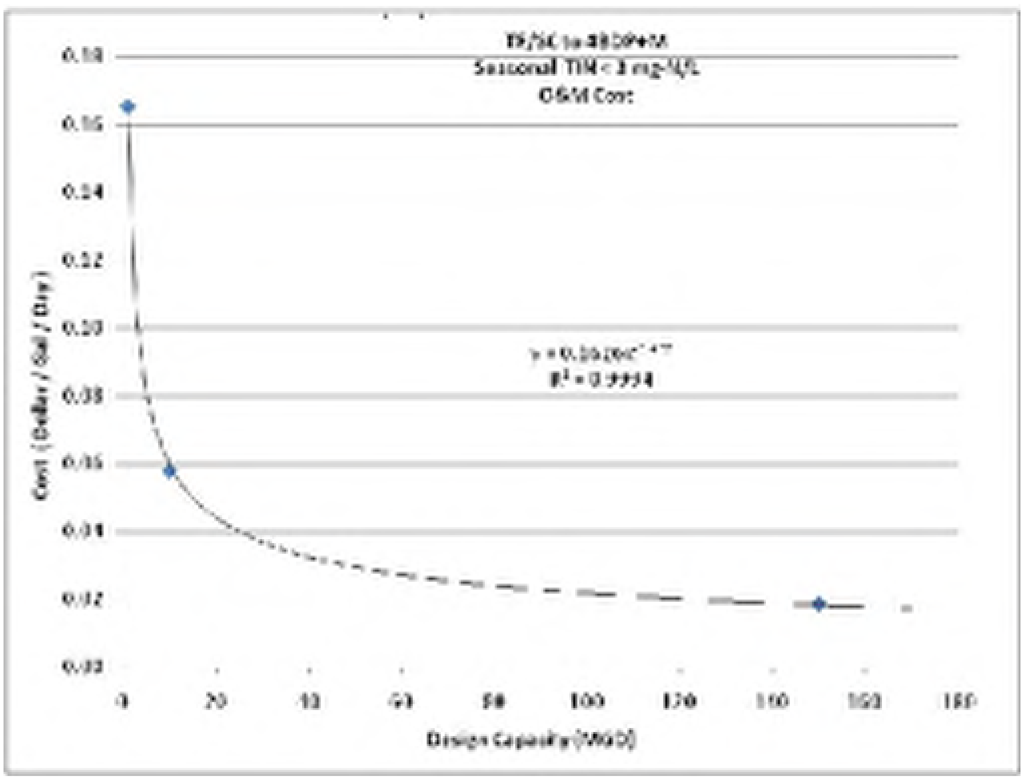


Figure 12-34. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective B Seasonal

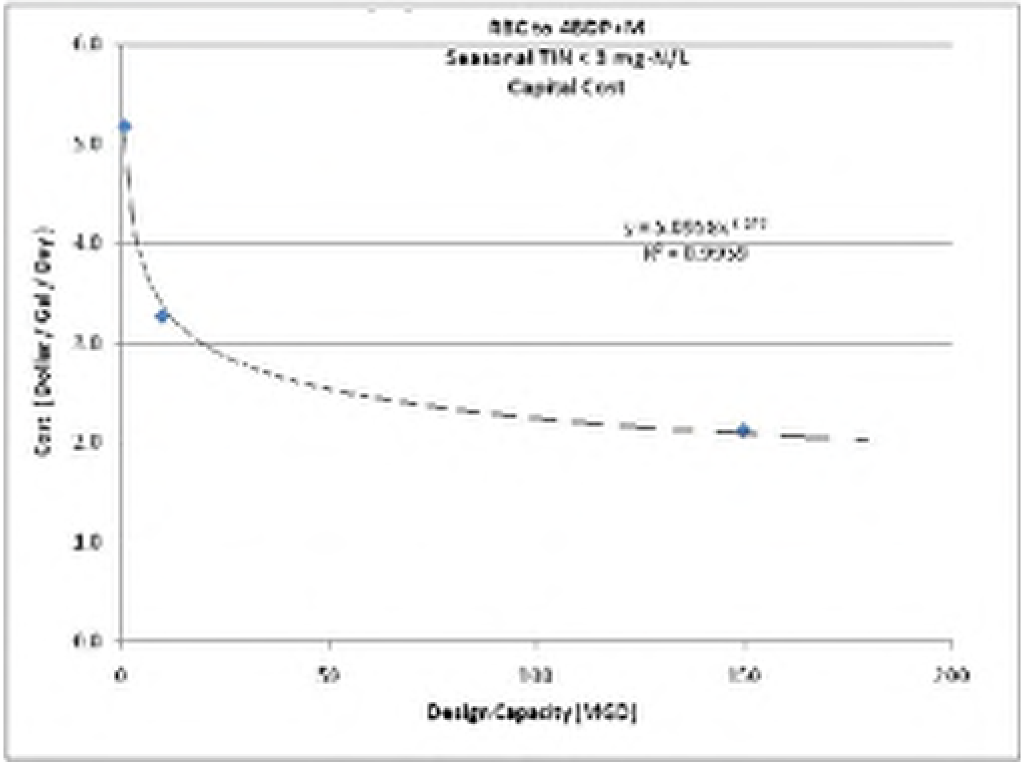


Figure 12-35. Capital Cost per Plant Capacity for RBC Plant Upgraded for Objective B Seasonally

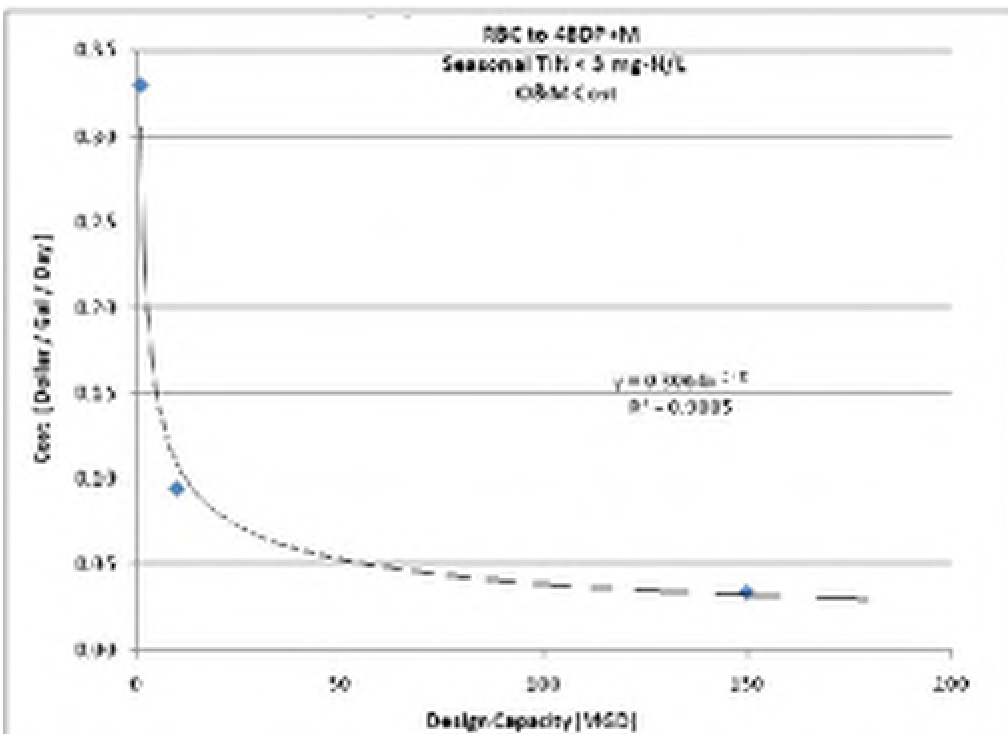


Figure 12-36. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective B Seasonal

**TABLE 12-34.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE B SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$379,427	$2,386,145	$22,903,545
2014 O&M Cost	$311,020	$912,703	$4,786,367
Total Annual Cost	**$690,447**	**$3,298,848**	**$27,689,912**
Annual TIN Load Reduction (lb/yr)	22,685	226,848	3,402,713
Estimated Cost for TIN Reduction ($/lb TIN removed)	$30.44	$14.54	$8.14

Equation:[a] .... $y = 400.95x^{-0.262}$
R-Square Value: 0.9866

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

**TABLE 12-35.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE B SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$251,616	$1,879,081	$8,336,346
2014 O&M Cost	$186,145	$649,053	$3,123,990
Total Annual Cost	**$437,761**	**$2,528,134**	**$21,460,337**
Annual TIN Load Reduction (lb/yr)	22,685	226,848	3,402,713
Estimated Cost for TIN Reduction ($/lb TIN removed)	$19.30	$11.14	$6.31

Equation:[a] .... $y = 177.89x^{-0.223}$
R-Square Value: 0.9986

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

**TABLE 12-36.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE B SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$380,990	$2,403,585	$23,356,810
2014 O&M Cost	$372,040	$1,064,084	$5,793,697
Total Annual Cost	**$753,030**	**$3,467,669**	**$29,150,507**
Annual TIN Load Reduction (lb/yr)	22,685	226,848	3,402,713
Estimated Cost for TIN Reduction ($/lb TIN removed)	$33.20	$15.29	$8.57

Equation:[a] .... $y = 464.91x^{-0.269}$
R-Square Value: 0.9831

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.2.5 Membrane Biological Reactor Plants

Table 12-37 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B seasonally for an MBR plant. Figures 12-37 and 12-38 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-38 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-37.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$0.029	$0.004	$0.002
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.013	$0.013	$0.013

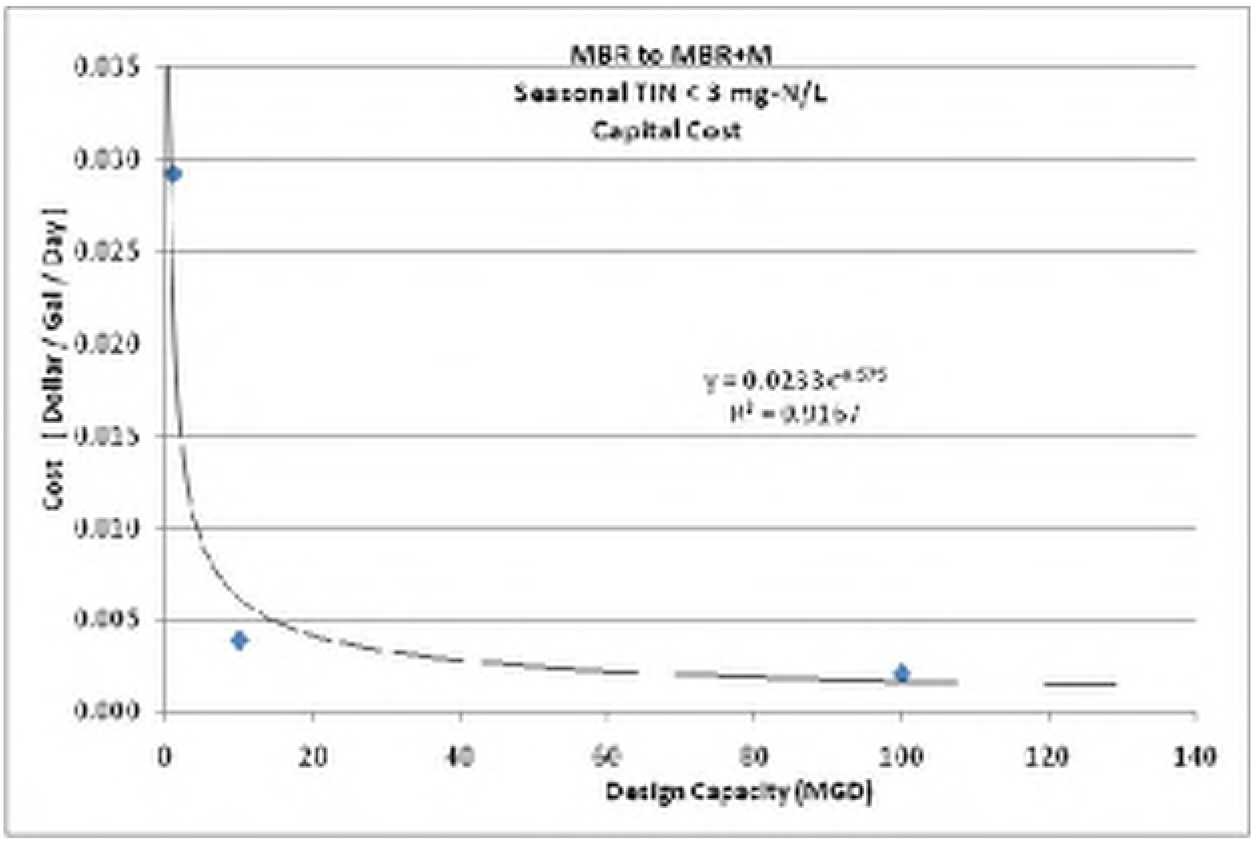


Figure 12-37. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective B Seasonally

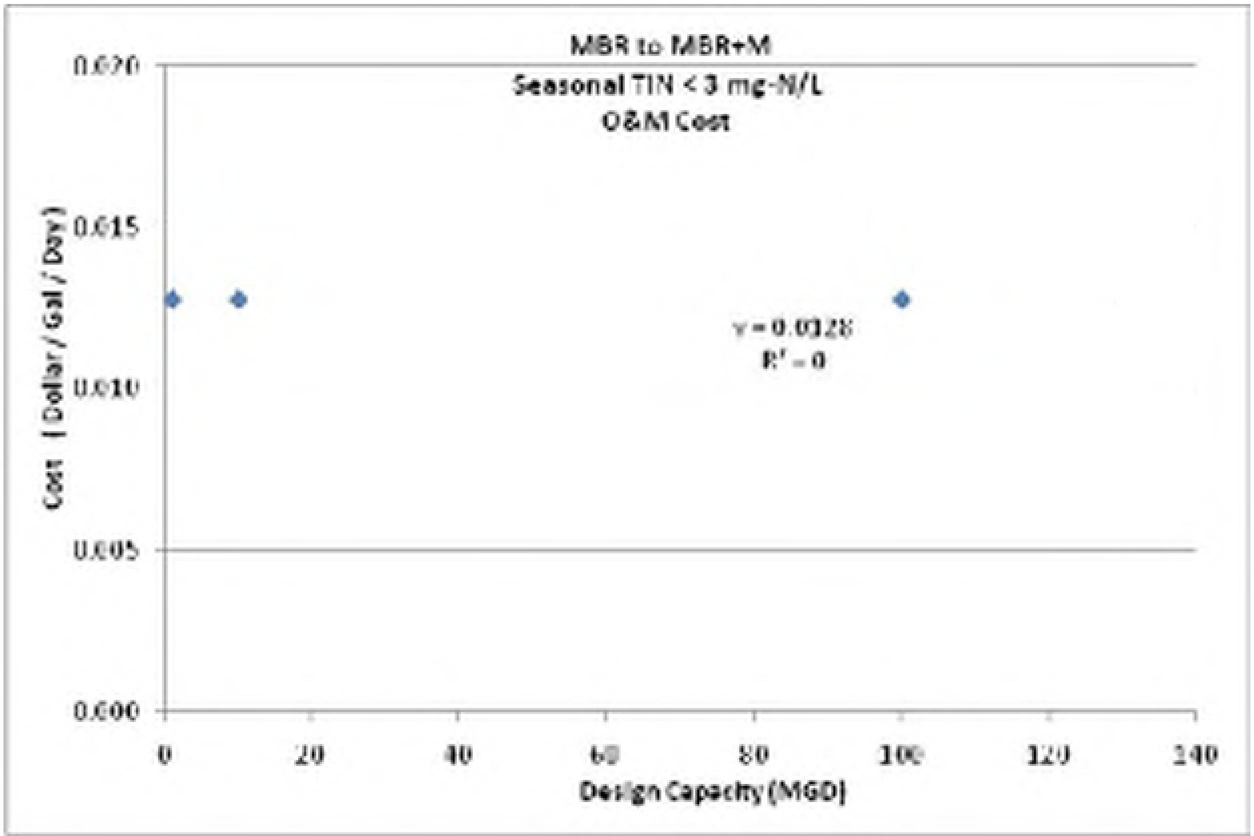


Figure 12-38. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective B Seasonal

TABLE 12-38.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$2,512	$2,864	$15,211
2014 O&M Cost	$14,378	$143,784	$1,437,838
Total Annual Cost	**$16,530**	**$146,648**	**$1,453,049**
Annual TIN Load Reduction (lb/yr)	3,814	38,143	381,425
Estimated Cost for TIN Reduction ($/lb TIN removed)	$4.33	$3.84	$3.81

Equation:[a] .... $y = 5.3439x^{-0.028}$
R-Square Value:.................... 0.7958

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

12.2.6 High-Purity Oxygen Activated Sludge Plants

Table 12-39 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B seasonally for an HPO plant. Figures 12-39 and 12-40 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-40 presents the annualized unit costs for reducing nutrient loads.

TABLE 12-39.
ESTIMATED COST PER CAPACITY FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	20-mgd Plant	220-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.71	$1.60
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.13	$0.10

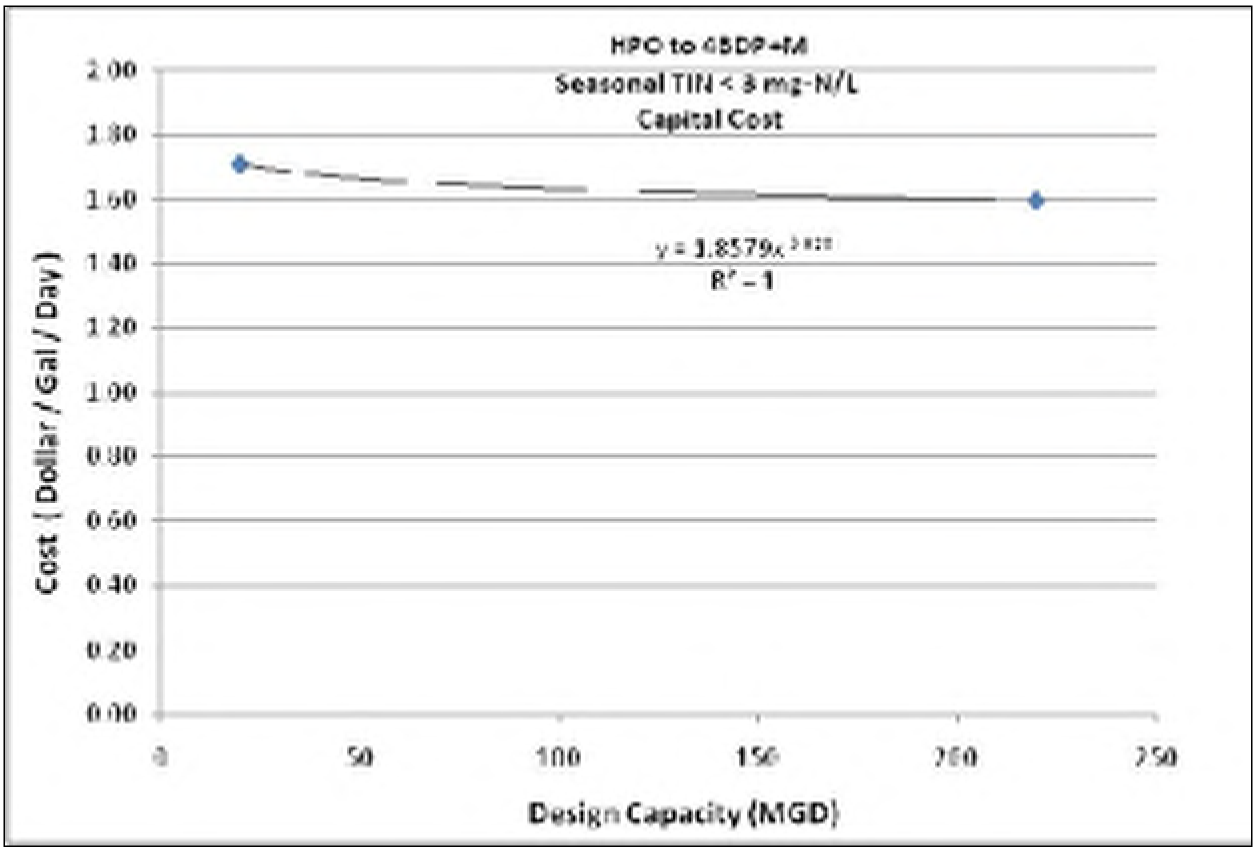


Figure 12-39. Capital Cost per Plant Capacity for HPO Plant Upgraded for Objective B Seasonal

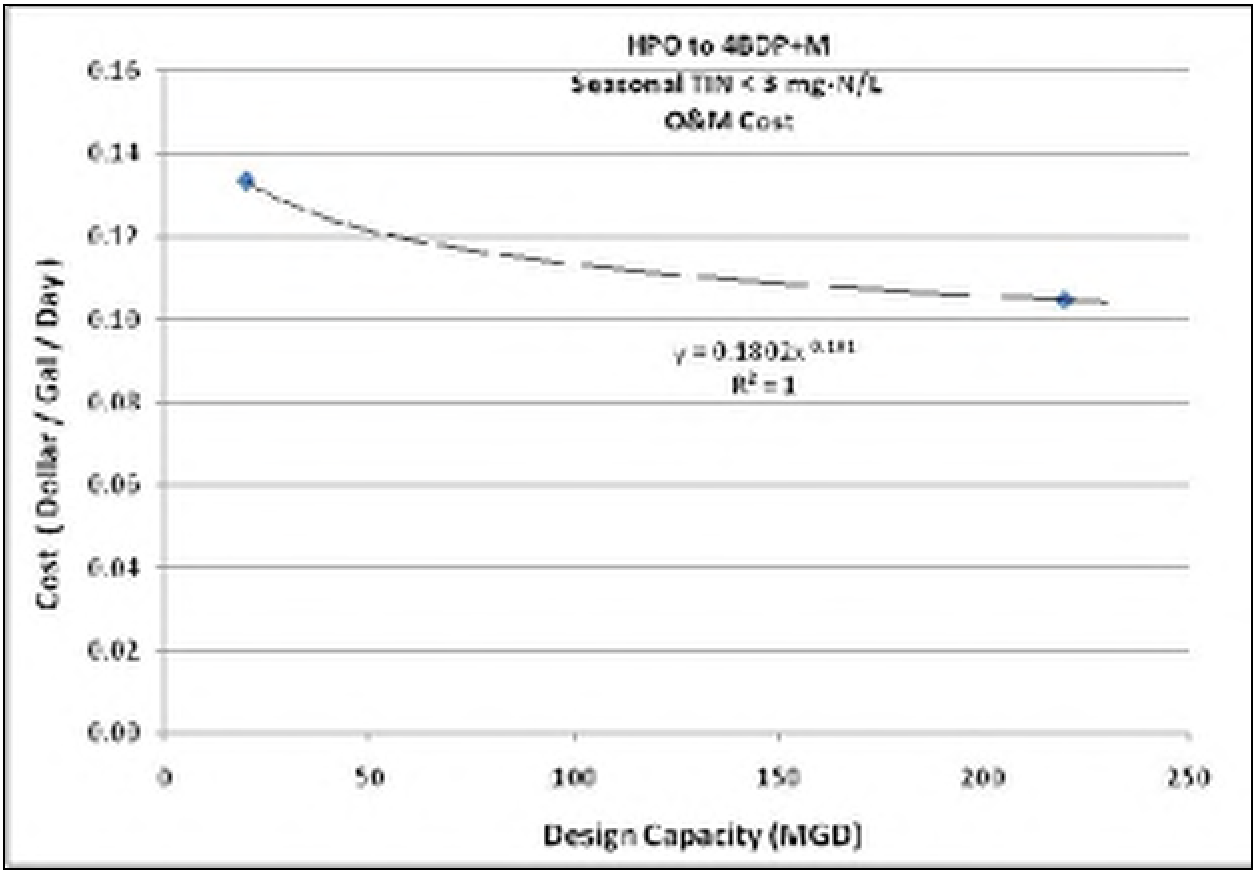


Figure 12-40. O&M Cost per Plant Capacity for HPO Upgraded for Objective B Seasonal

TABLE 12-40.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING HPO PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	20-mgd Plant	220-mgd Plant
Annualized Capital Cost	\$2,508,000	\$25,791,880
2014 O&M Cost	\$3,002,000	\$25,942,000
Total Annual Cost	**\$5,510,185**	**\$51,734,000**
Annual TIN Load Reduction (lb/yr)	479,975	5,279,725
Estimated Cost for TIN Reduction (\$/lb TIN removed)	\$11.50	\$9.80
Equation:[a]		$y = 27.215x^{-0.066}$
R-Square Value:		1

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction (\$/lb TIN removed)

12.2.7 Aerated or Facultative Lagoon Plants

Table 12-41 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective B seasonally for an aerated lagoon plan. Figures 12-41 and 12-42 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 12-42 and Figures 12-43 and 12-44 summarize these costs for a facultative lagoon plant. Tables 12-43 and 12-44 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 12-41.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$22.30	$16.67	$11.02	$6.65
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.02	$0.61	$0.26	$0.11

TABLE 12-42.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$22.16	$16.55	$10.93	$6.60
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.29	$0.84	$0.42	$0.14

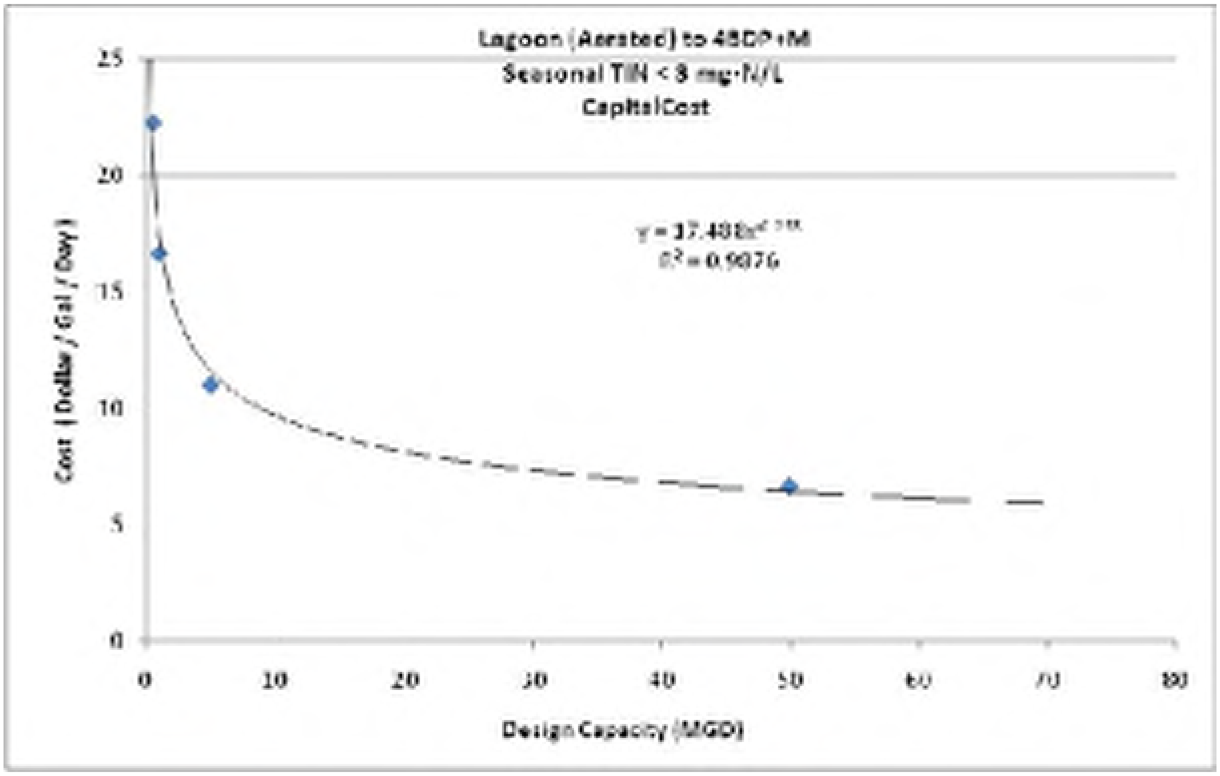


Figure 12-41. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective B Seasonally

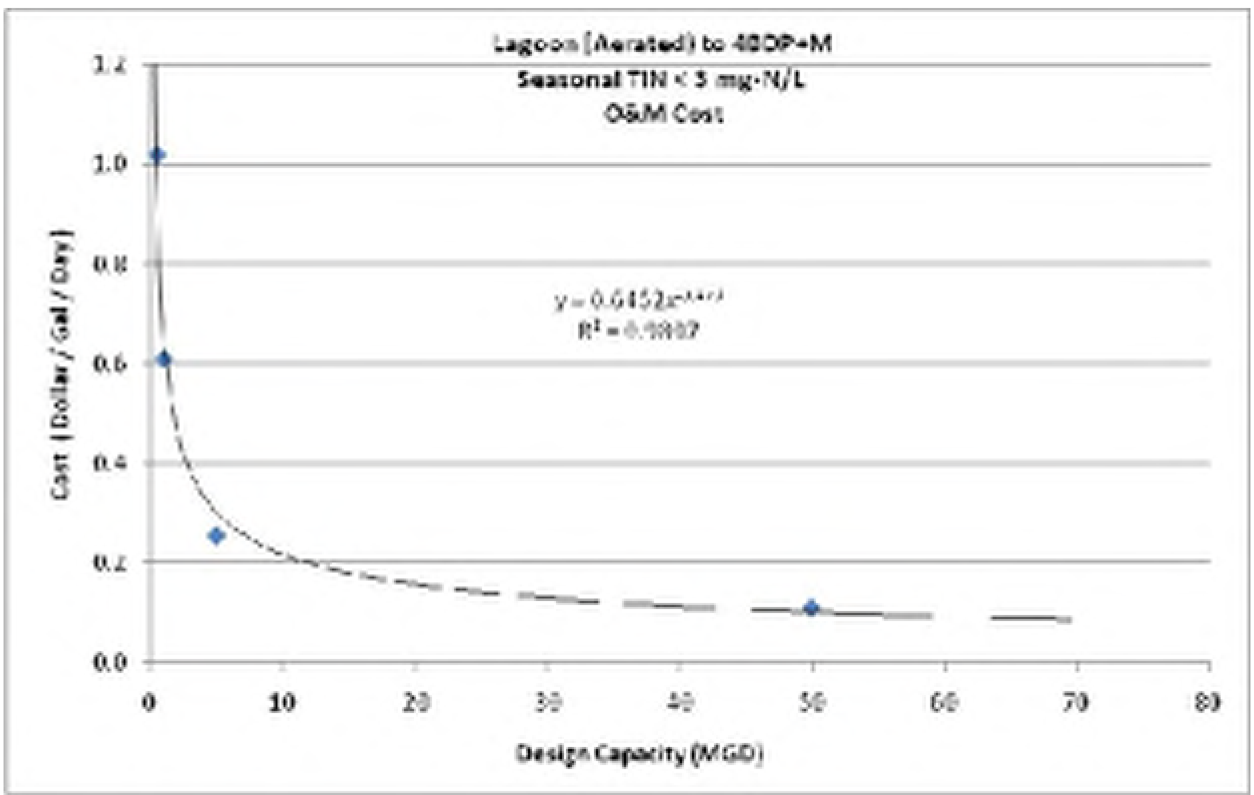


Figure 12-42. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective B Seasonal

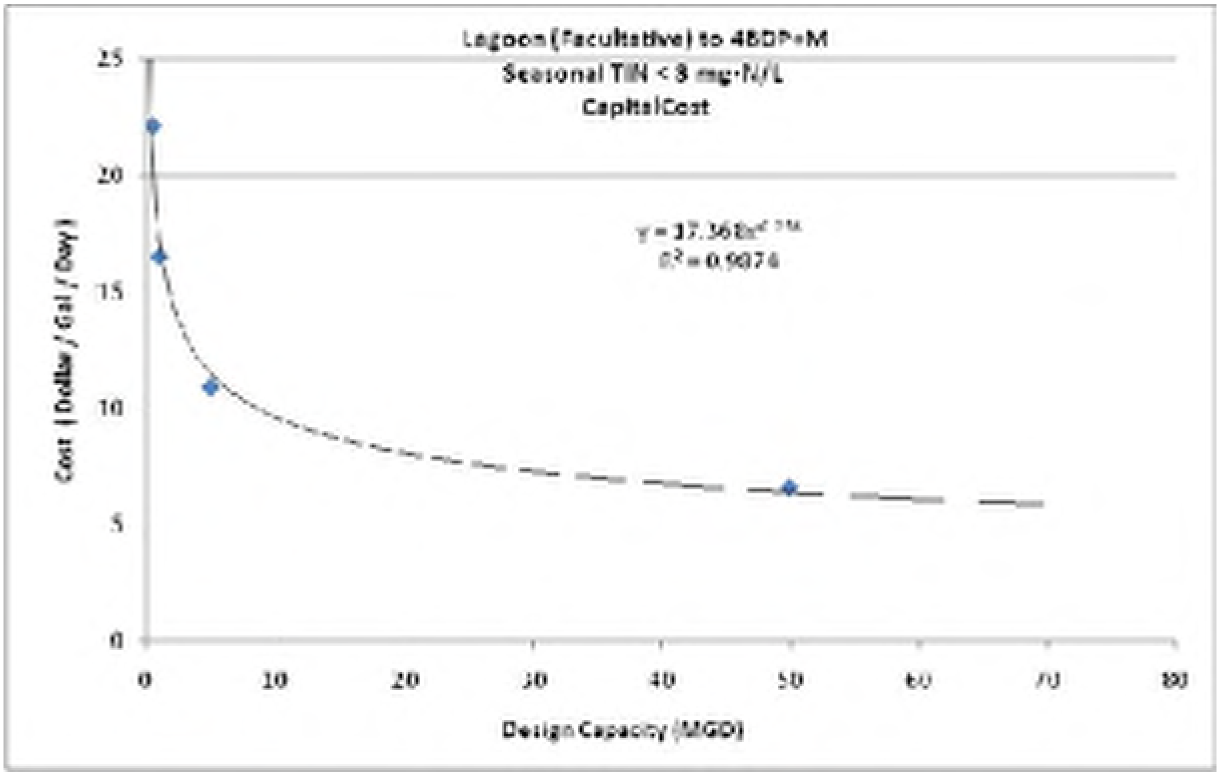


Figure 12-43. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective B Seasonally

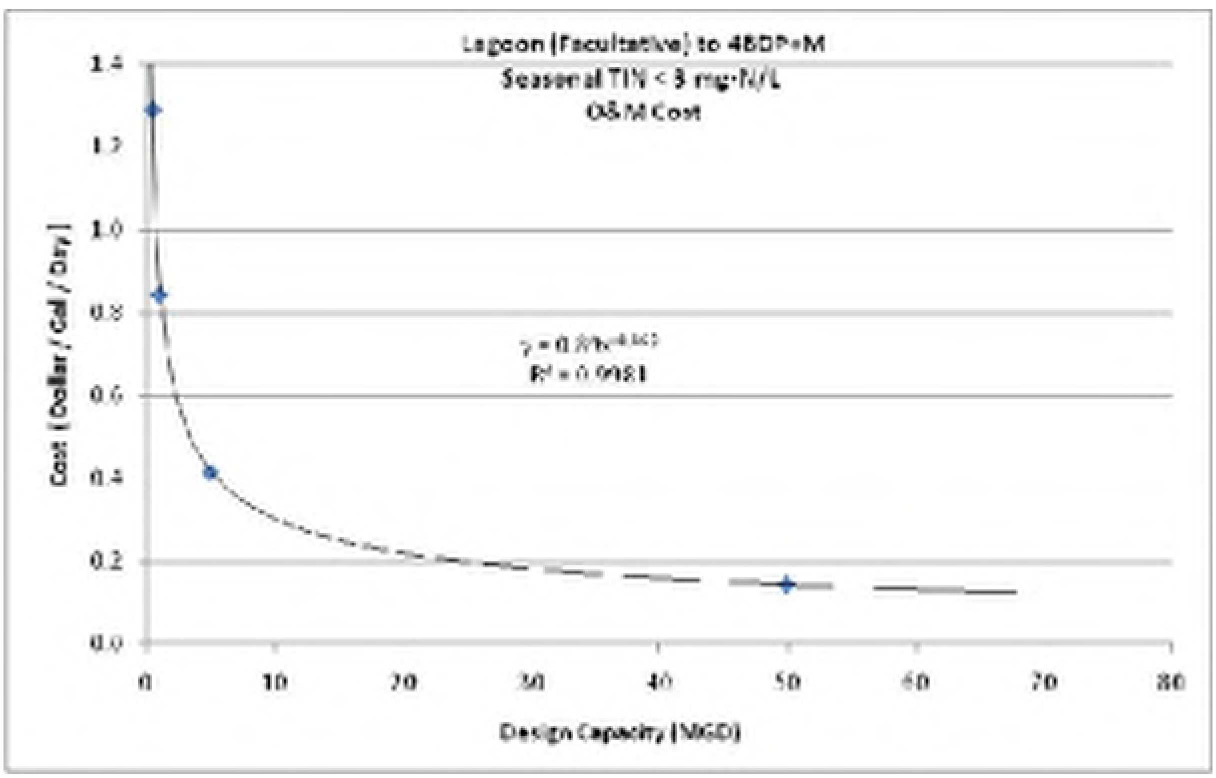


Figure 12-44. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective B Seasonal

TABLE 12-43.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$819,066	$1,224,063	$4,047,995	$24,419,256
2014 O&M Cost	$573,765	$687,016	$1,437,528	$6,243,366
Total Annual Cost	**$1,392,831**	**$1,991,080**	**$5,485,523**	**$30,662,622**
Annual TIN Load Reduction (lb/yr)	11,534	23,068	115,340	1,134,238
Estimated Cost for TIN Reduction ($/lb TIN removed)	$120.76	$82.85	$47.56	$27.03

Equation:[a] .... $y = 2132.1x^{-0.318}$
R-Square Value: 0.979

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

TABLE 12-44.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE B SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$813,966	$1,215,590	$4,014,843	$24,244,860
2014 O&M Cost	$726,934	$950,695	$2,340,355	$8,130,636
Total Annual Cost	**$1,540,900**	**$2,166,285**	**$6,355,198**	**$32,375,496**
Annual TIN Load Reduction (lb/yr)	11,534	23,068	115,340	1,134,238
Estimated Cost for TIN Reduction ($/lb TIN removed)	$133.60	$93.91	$55.10	$28.54

Equation:[a] .... $y = 2798.3x^{-0.332}$
R-Square Value: 0.9928

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)

CHAPTER 13.
COST EVALUATION, OBJECTIVE C

13.1 YEAR-ROUND NUTRIENT REMOVAL

13.1.1 Extended Aeration Plants

Table 13-1 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C year-round for an extended aeration plant using mechanical aeration. Figures 13-1 and 13-2 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-2 and Figures 13-3 and 12-4 summarize these costs for an extended aeration plant using diffuser aeration. Tables 13-3 and 13-4 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 13-1.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$0.78	$0.23	$0.24
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.14	$0.13

TABLE 13-2.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.00	$0.46	$0.29
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.14	$0.10	$0.09

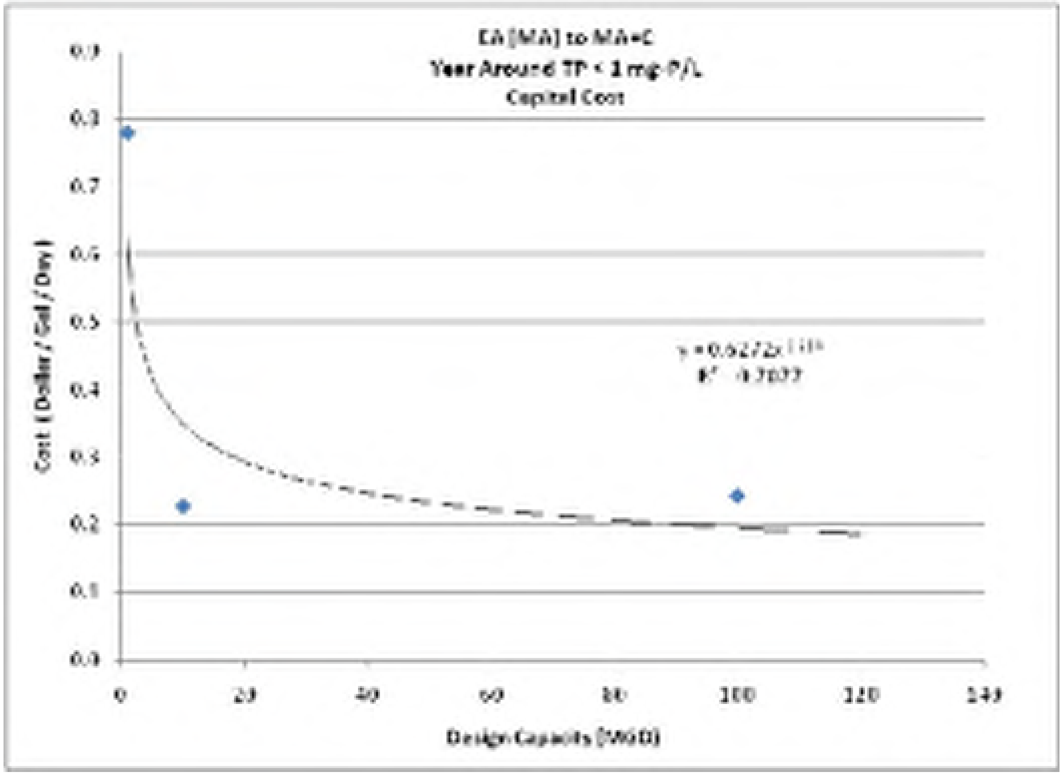


Figure 13-1. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective C Year-Round

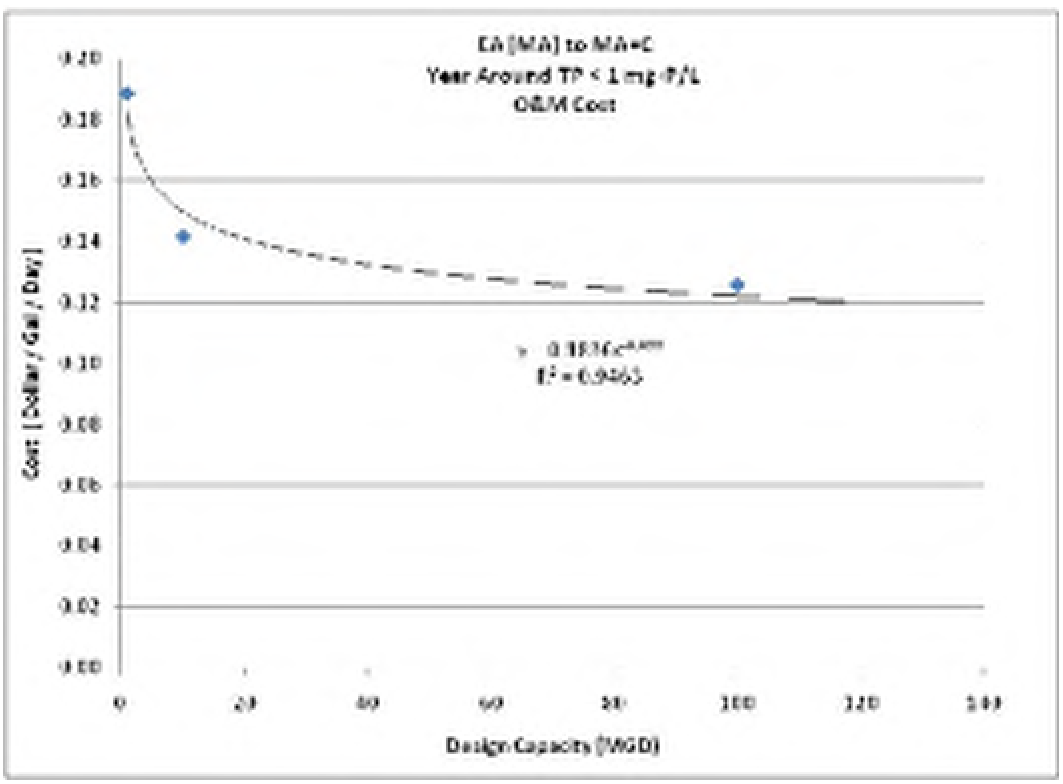


Figure 13-2. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective C Year-Round

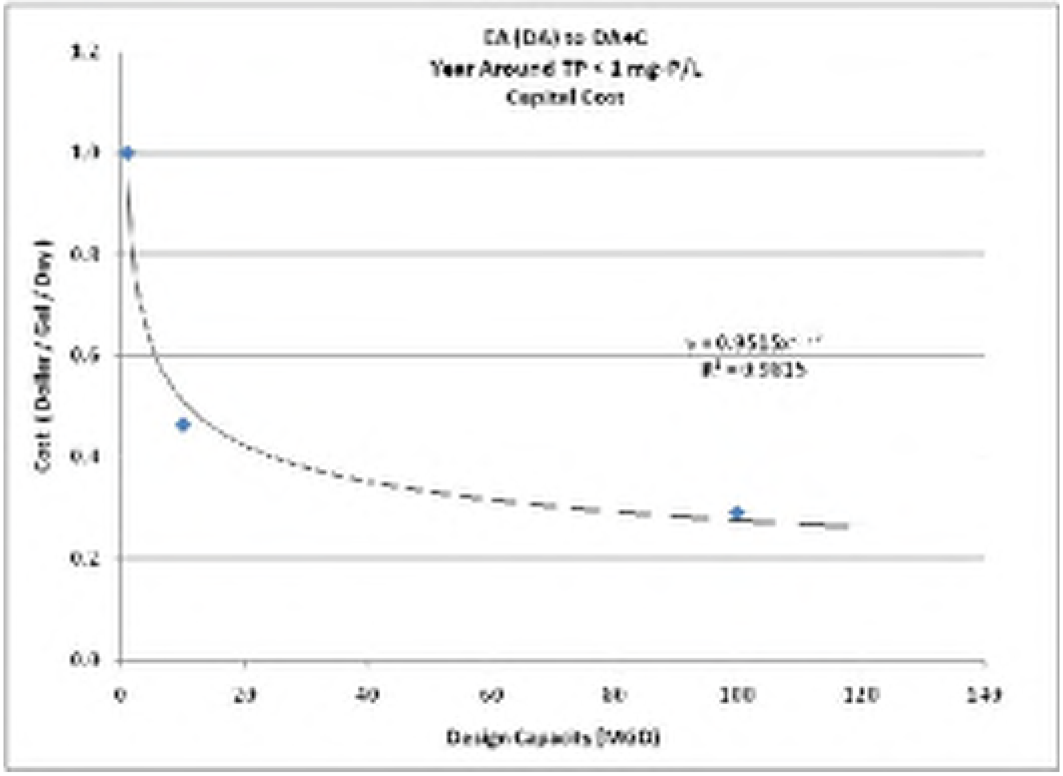


Figure 13-3. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective C Year-Round

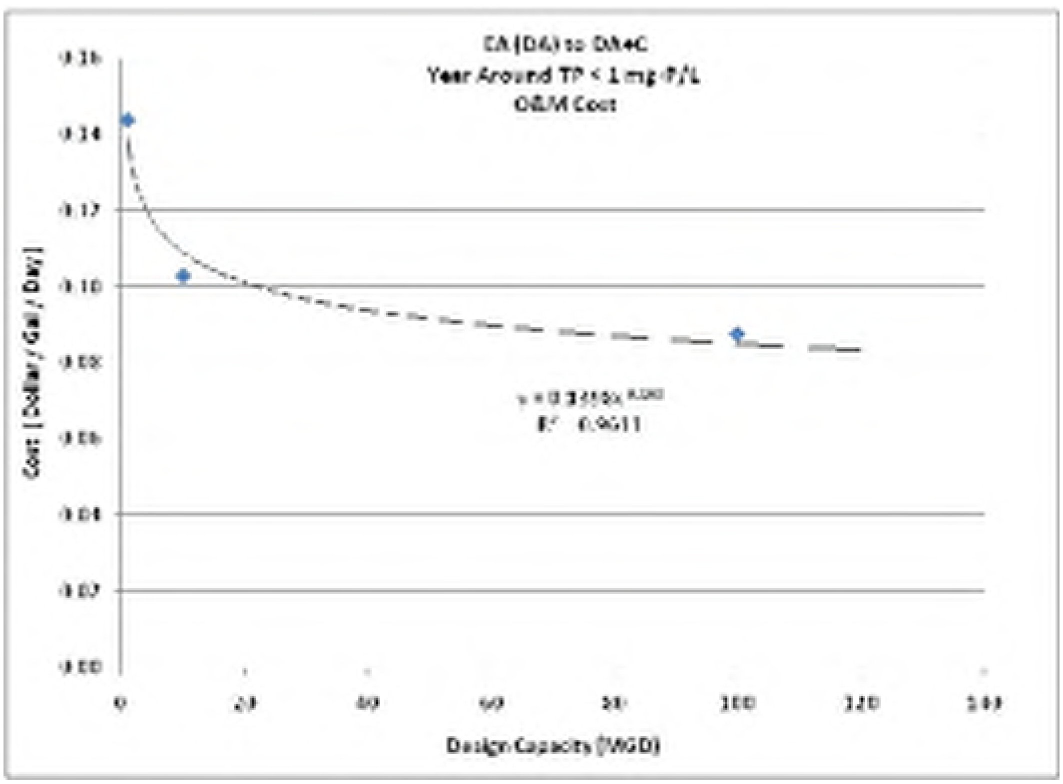


Figure 13-4. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective C Year-Round

TABLE 13-3.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$57,213	$166,499	$1,778,664
2014 Incremental O&M Cost	$212,440	$1,594,852	$14,156,762
Total Annual Cost	**$269,653**	**$1,761,350**	**$15,935,426**
Annual TP Load Reduction (lb/yr)	11,060	110,595	1,105,950
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$24.38	$15.93	$14.41

Equation:[a] .... $y = 66.869x^{-0.114}$
R-Square Value: 0.8869

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-4.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$73,409	$340,278	$2,119,024
2014 Incremental O&M Cost	$161,961	$1,157,141	$9,837,060
Total Annual Cost	**$235,369**	**$1,497,419**	**$11,956,083**
Annual TP Load Reduction (lb/yr)	11,023	110,230	1,102,300
Estimated Cost for TP Reduction ($/lb TP removed)	$21.35	$13.58	$10.85

Equation:[a] .... $y = 80.732x^{-0.147}$
R-Square Value: .... $R^2 = 0.9636$

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.1.2 Conventional Activated Sludge Plants

Table 13-5 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C year-round for a conventional activated sludge plant. Figures 13-5 and 13-6 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-6 presents the annualized unit costs for reducing nutrient loads.

**TABLE 13-5.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.22	$0.25	$0.27
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.14	$0.12

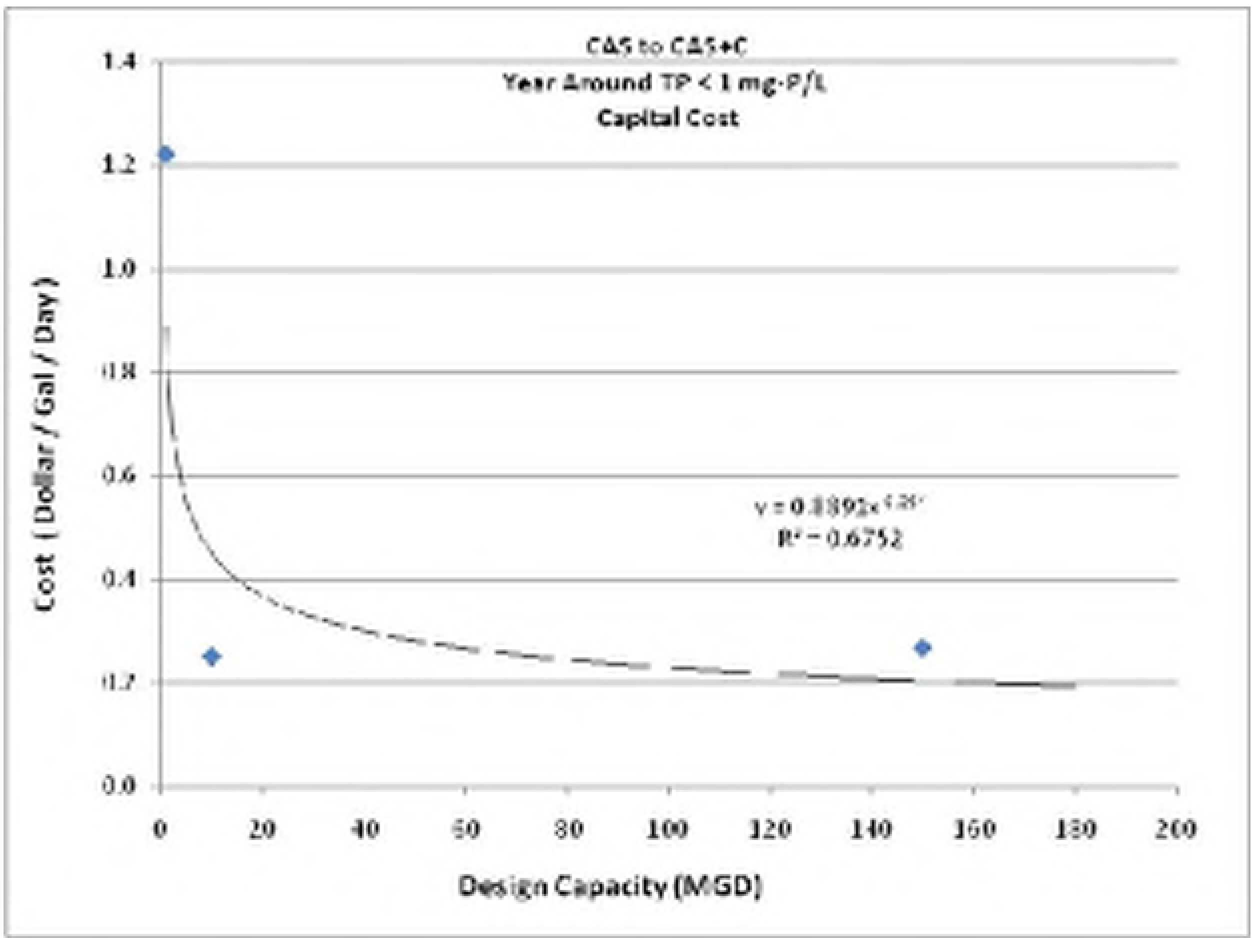


Figure 13-5. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective C Year-Round

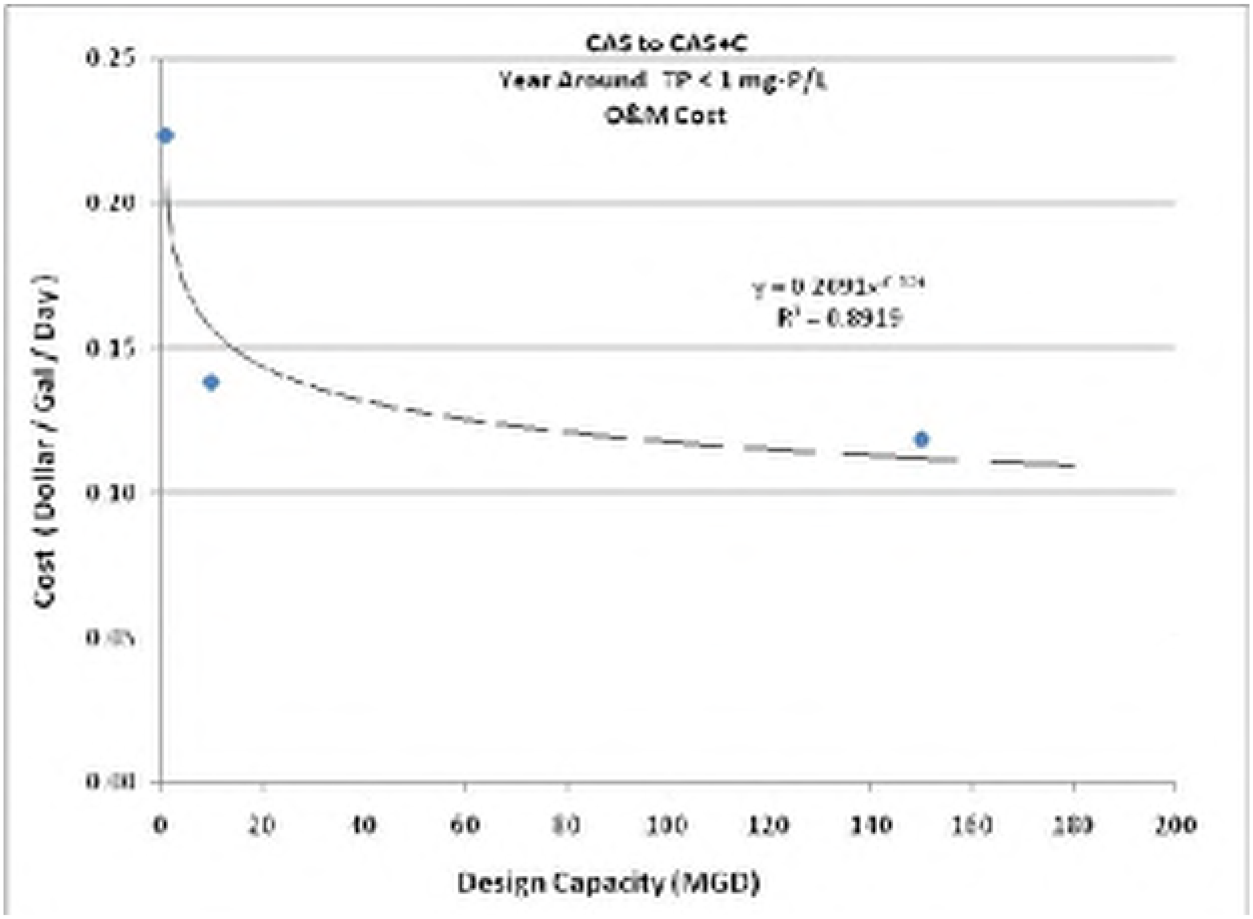


Figure 13-6. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective C Year-Round

TABLE 13-6.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$89,810	$184,134	$2,946,787
2014 O&M Cost	$251,872	$1,558,830	$20,042,160
Total Annual Cost	**$341,682**	**$1,742,963**	**$22,988,948**
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Cost for TP Reduction ($/lb TP removed)	$29.91	$15.26	$13.41
Equation:[a]	$y = 116.06x^{-0.157}$		
R-Square Value:	0.834		

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.1.3 Sequencing Batch Reactor Plants

Table 13-7 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C year-round for an SBR plant. Figures 13-7 and 13-8 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-8 presents the annualized unit costs for reducing nutrient loads.

TABLE 13-7.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.44	$0.47	$0.20
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.10	$0.02	$0.01

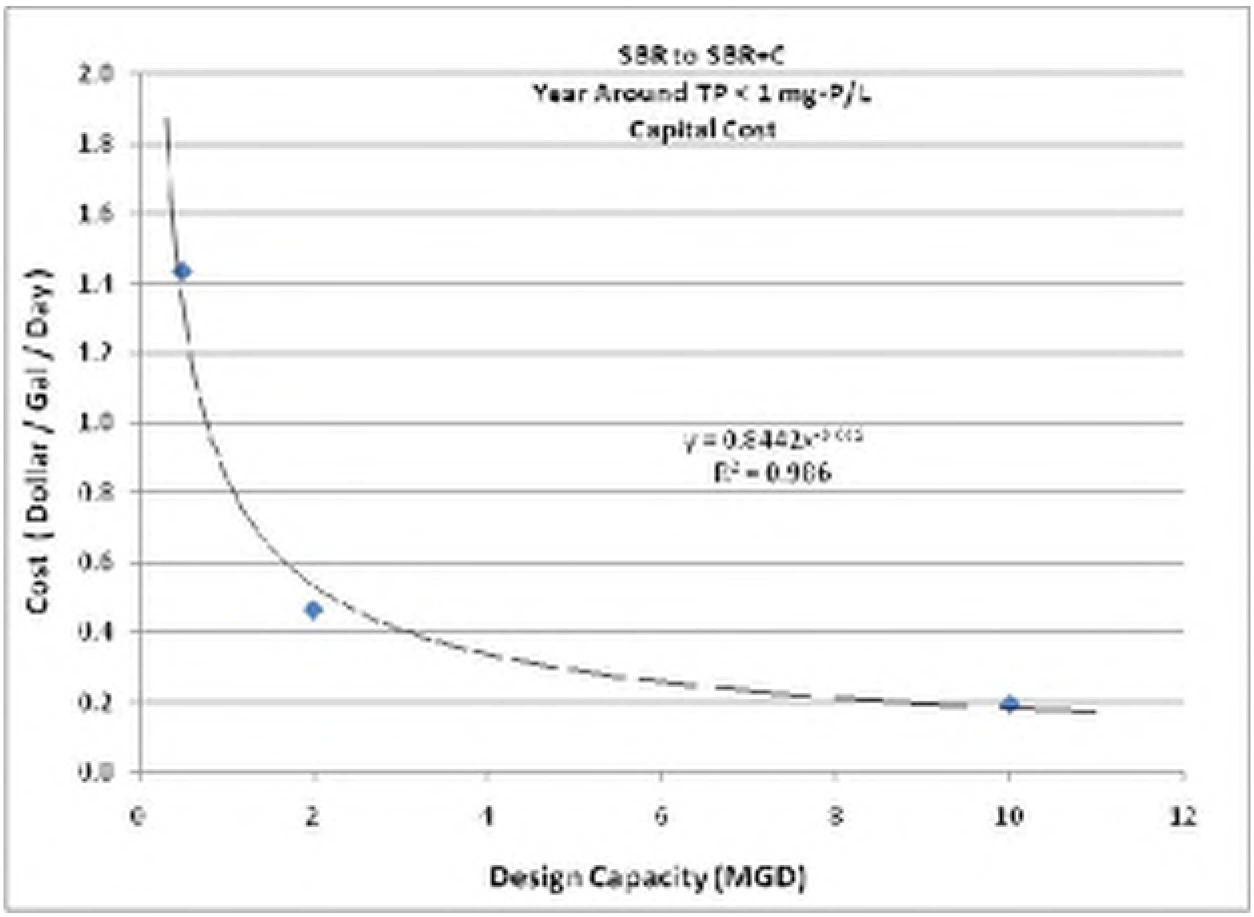


Figure 13-7. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective C Year-Round

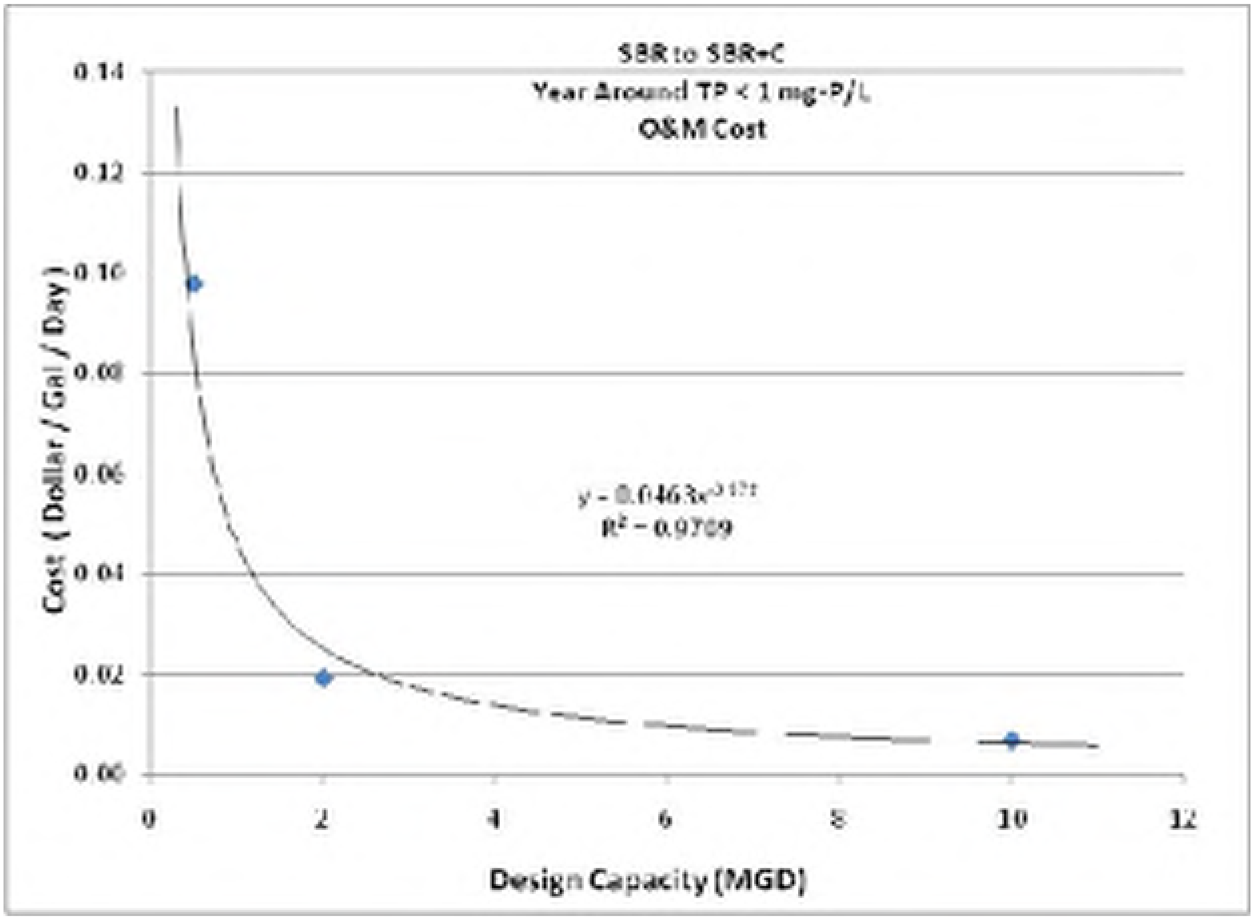


Figure 13-8. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective C Year-Round

TABLE 13-8.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$52,792	$68,370	$143,846
2014 O&M Cost	$55,144	$43,585	$77,885
Total Annual Cost	**$107,936**	**$1,11,956**	**$221,731**
Annual TP Load Reduction (lb/yr)	2,099	8,395	41,975
Estimated Cost for TP Reduction ($/lb TP removed)	$51.43	$13.34	$5.28

Equation:[a] .... $y = 14903x^{-0.755}$
R-Square Value: 0.9777

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.1.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 13-9 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C year-round for a trickling filter plant. Figures 13-9 and 13-10 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-10 and Figures 13-11 and 13-12 summarize these costs for a trickling filter/solids contact plant. Table 13-11 and Figures 13-13 and 13-14 summarize these costs for an RBC plant. Tables 13-12, 13-13 and 13-14 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 13-9.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.22	$0.25	$0.27
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.21	$0.13	$0.11

TABLE 13-10.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.22	$0.25	$0.27
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.13	$0.11

TABLE 13-11.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.22	$0.25	$0.27
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.13	$0.11

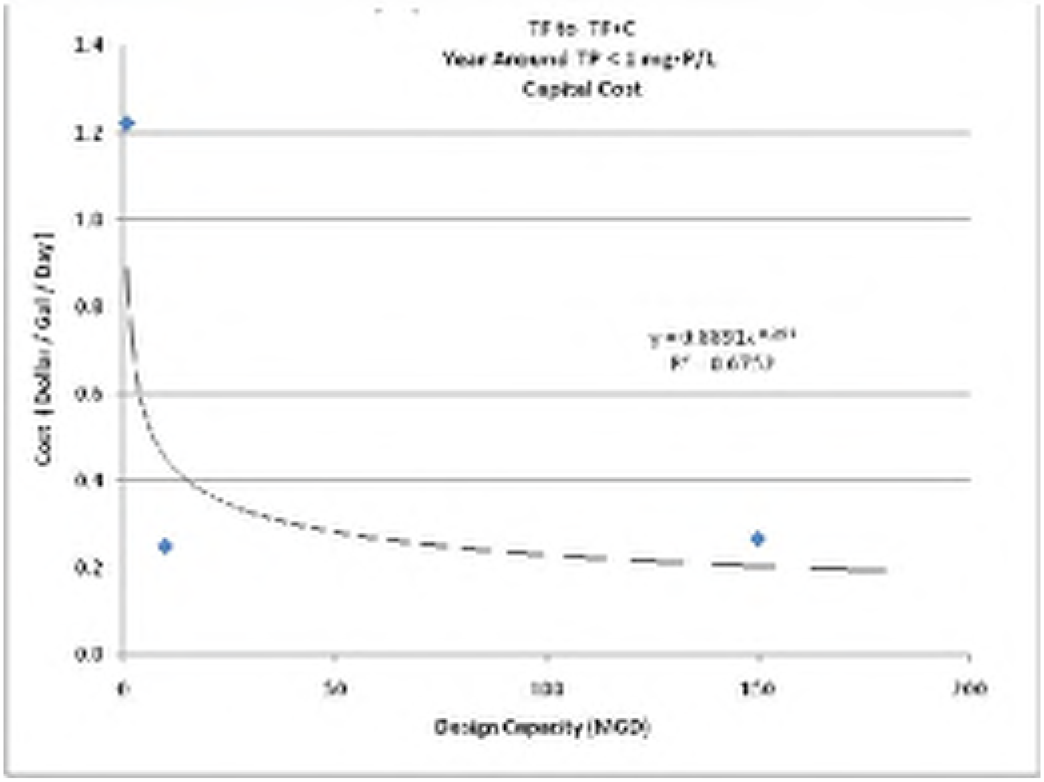


Figure 13-9. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective C Year-Round

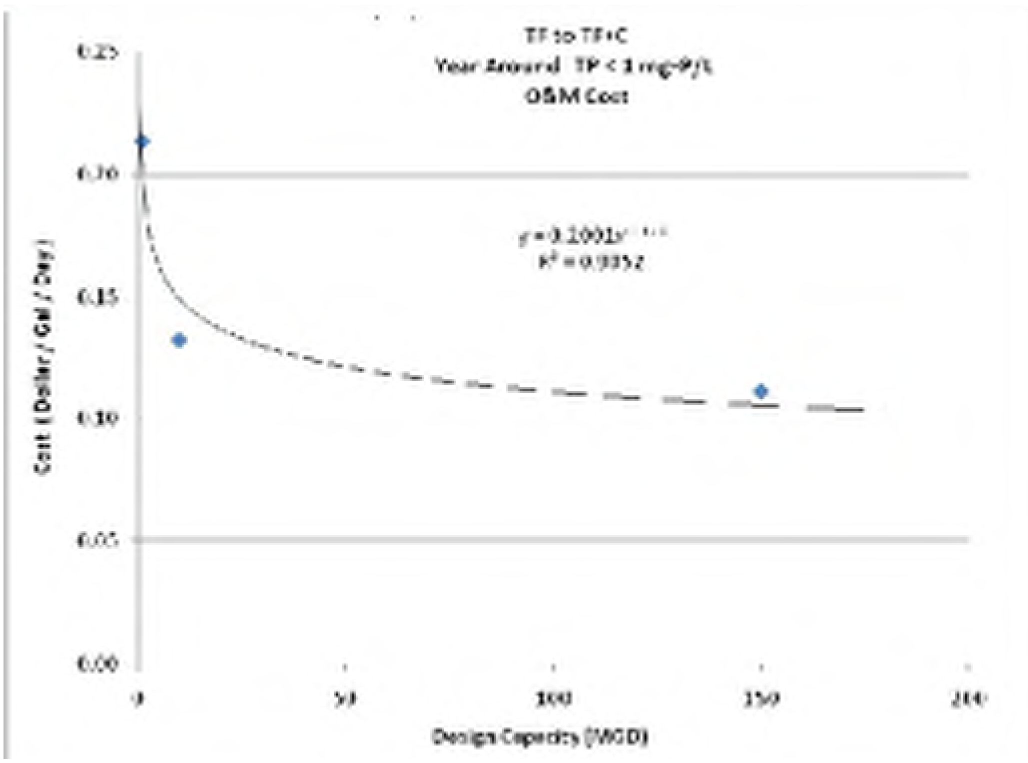


Figure 13-10. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective C Year-Round

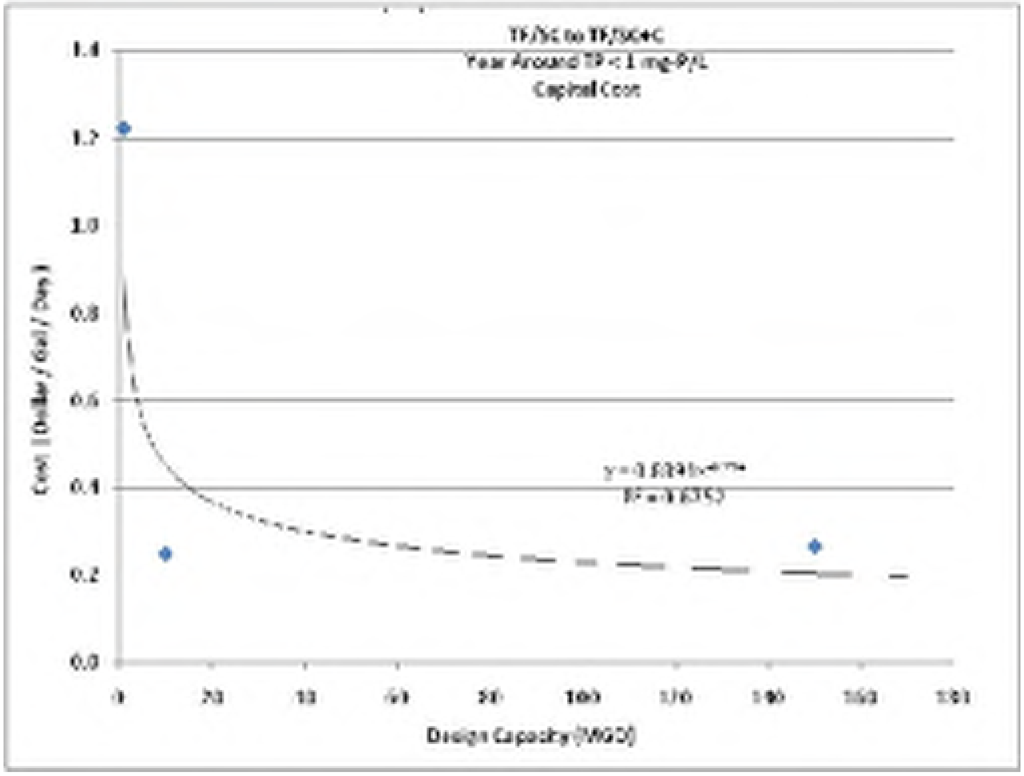


Figure 13-11. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective C Year-Round

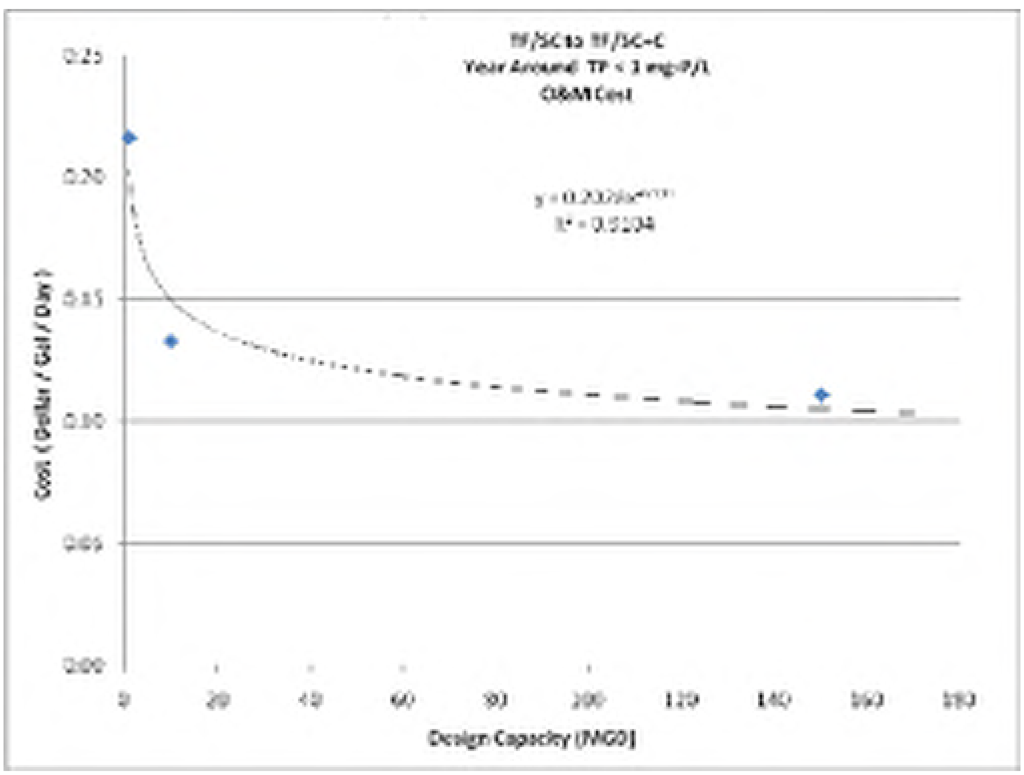


Figure 13-12. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective C Year-Round

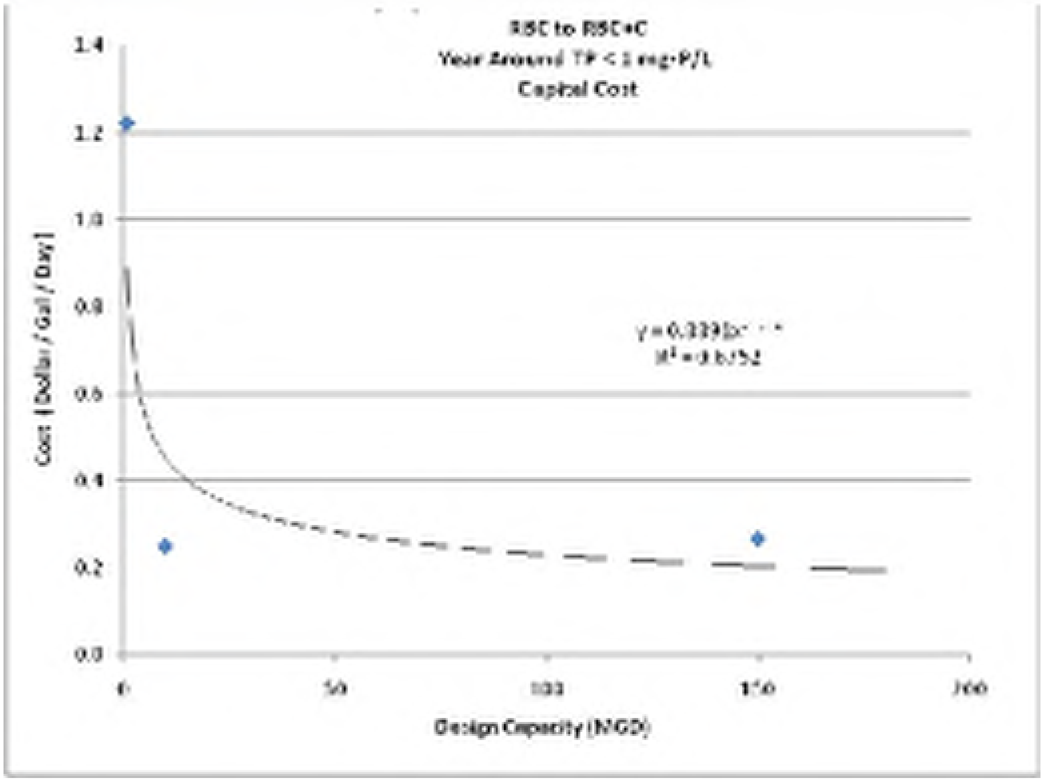


Figure 13-13. Capital Cost per Plant Capacity for RBC Upgraded for Objective C Year-Round

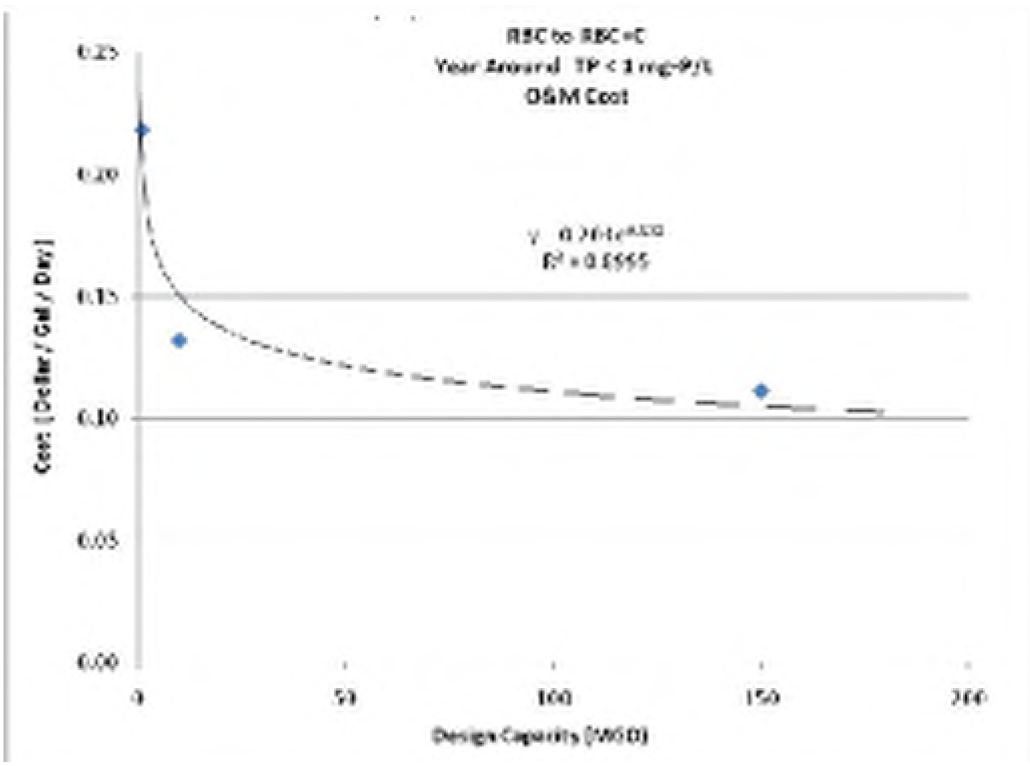


Figure 13-14. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective C Year-Round

TABLE 13-12.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$89,810	$184,134	$2,946,787
2014 O&M Cost	$240,206	$1,489,273	$18,823,234
Total Annual Cost	**$330,016**	**$1,673,407**	**$21,770,022**
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Cost for TP Reduction ($/lb TP removed)	$28.89	$14.65	$12.70

Equation:[a] .... $y = 62.964x^{-0.116}$
R-Square Value:........ 0.9558

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-13.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$89,810	$184,134	$2,946,787
2014 O&M Cost	$243,470	$1,497,940	$18,738,821
Total Annual Cost	**$333,280**	**$1,682,073**	**$21,685,609**
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Cost for TP Reduction ($/lb TP removed)	$29.17	$14.72	$12.65

Equation:[a] .... $y = 120.68x^{-0.164}$
R-Square Value:........ 0.8489

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-14.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$89,810	$184,134	$2,946,787
2014 O&M Cost	$246,053	$1,490,793	$18,841,805
Total Annual Cost	**$335,863**	**$1,674,926**	**$21,788,593**
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Cost for TP Reduction ($/lb TP removed)	$29.40	$14.66	$12.71

Equation:[a] .... $y = 65.083x^{-0.119}$
R-Square Value:........ 0.9543

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.1.5 Membrane Biological Reactor Plants

Table 13-15 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C year-round for an MBR plant. Figures 13-15 and 13-16 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-16 presents the annualized unit costs for reducing nutrient loads.

TABLE 13-15.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.32	$0.33	$0.23
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.16	$0.08	$0.06

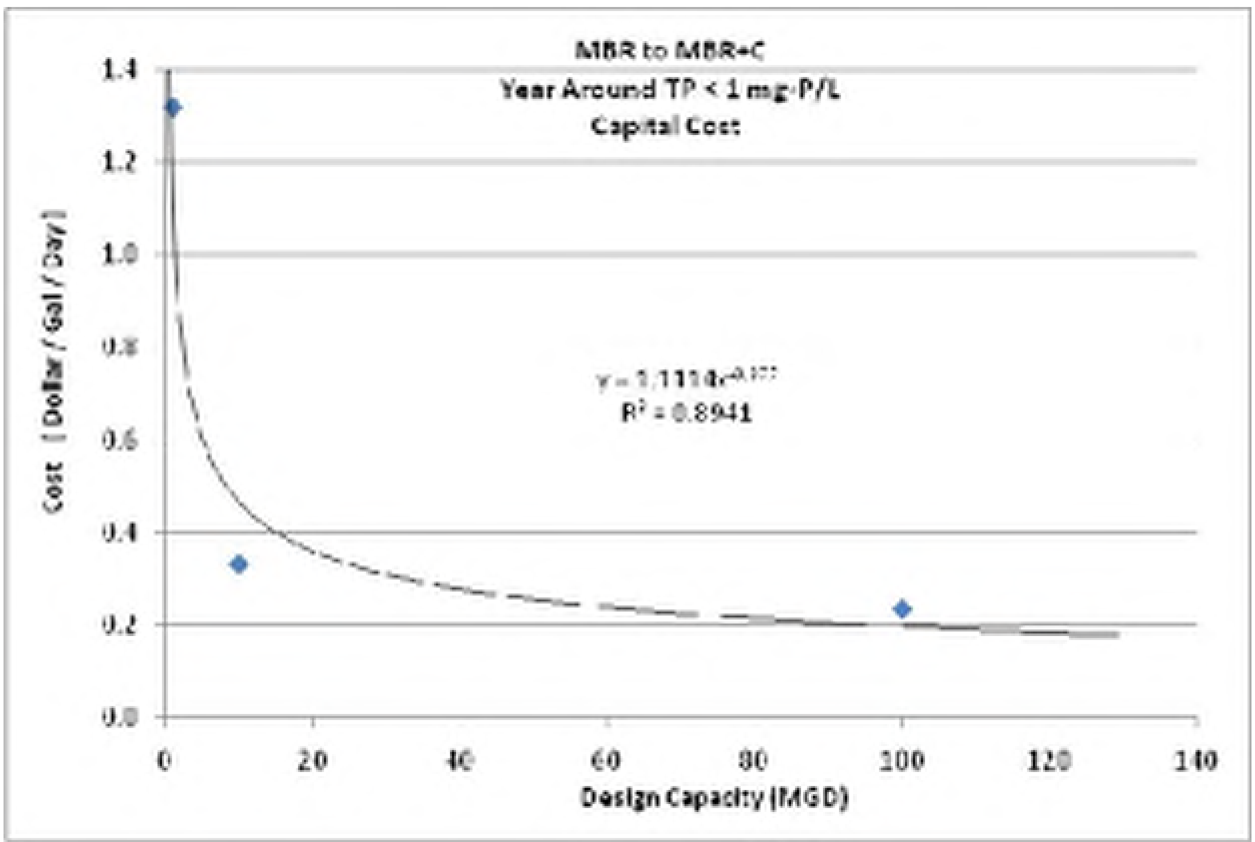


Figure 13-15. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective C Year-Round

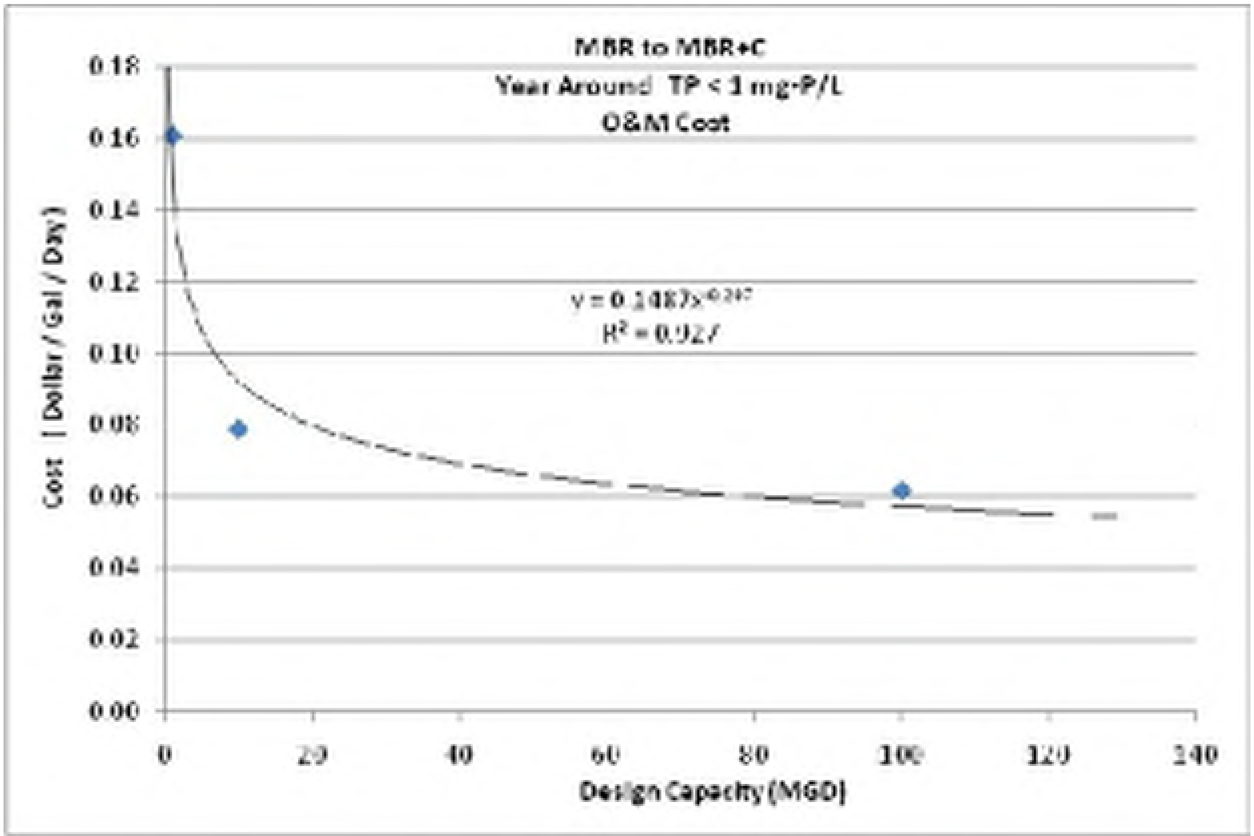


Figure 13-16. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective C Year-Round

TABLE 13-16.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$97,008	$242,560	$1,707,918
2014 O&M Cost	$180,864	$889,546	$6,960,248
Total Annual Cost	**$277,871**	**$1,132,106**	**$8,668,166**
Annual TP Load Reduction (lb/yr)	10,768	107,675	1,076,750
Estimated Cost for TP Reduction ($/lb TP removed)	$25.81	$10.51	$8.05

Equation:[a] .... $y = 243.32x^{-0.253}$
R-Square Value:.. 0.9107

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.1.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective C were developed for these plants.

13.1.7 Aerated or Facultative Lagoon Plants

Table 13-17 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C year-round for an aerated lagoon plant. Figures 13-17 and 13-18 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-18 and Figures 13-19 and 13-20 summarize these costs for a facultative lagoon plant. Tables 13-19 and 13-20 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 13-17.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.76	$3.87	$2.22	$2.45
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.34	$0.20	$0.08	$0.04

TABLE 13-18.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.76	$3.87	$2.22	$2.45
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.34	$0.20	$0.08	$0.04

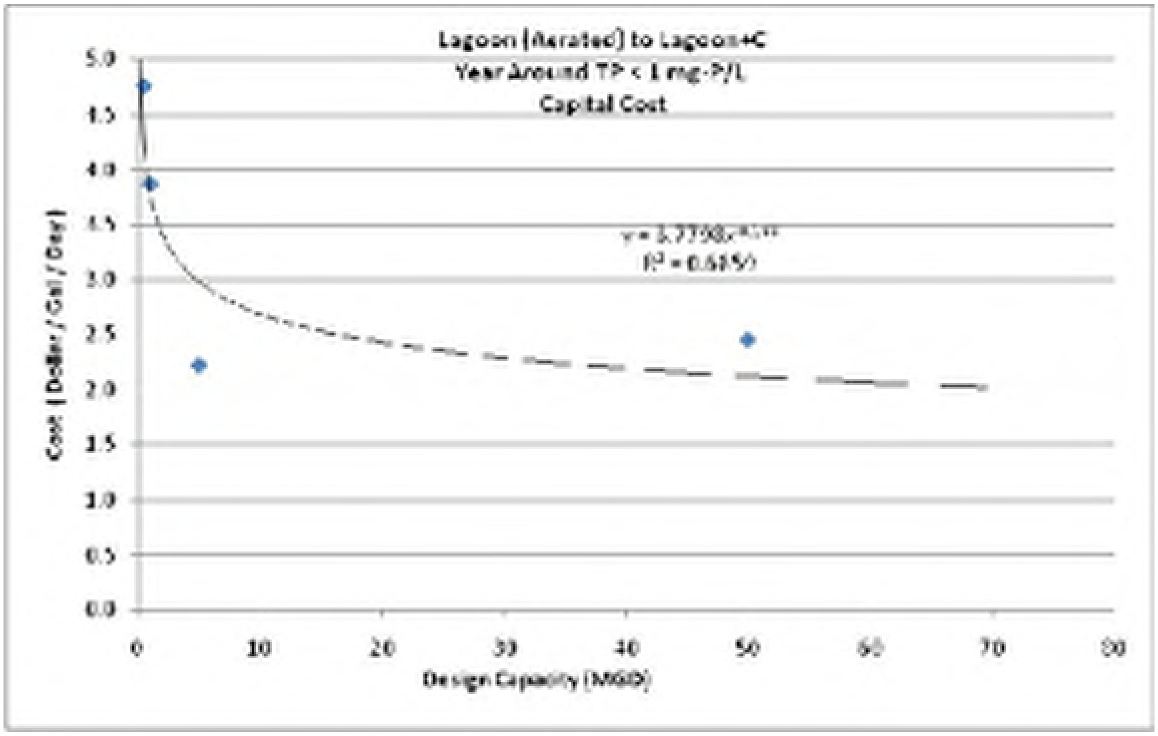


Figure 13-17. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective C Year-Round

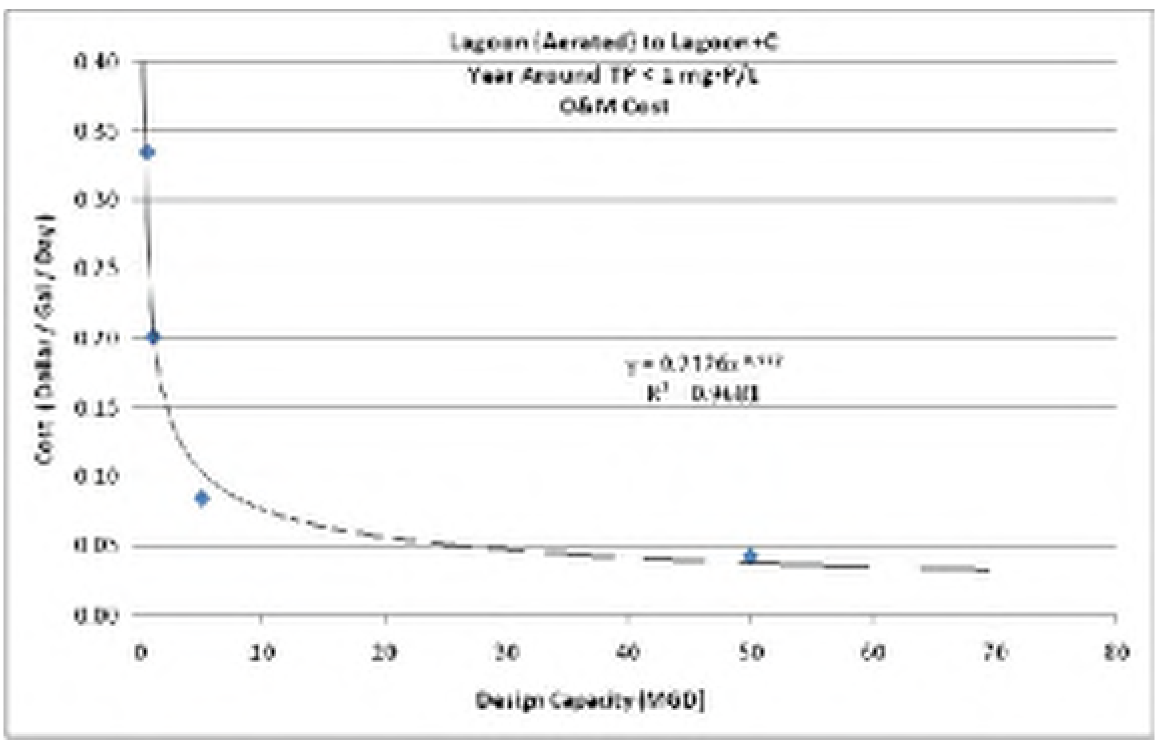


Figure 13-18. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective C Year-Round

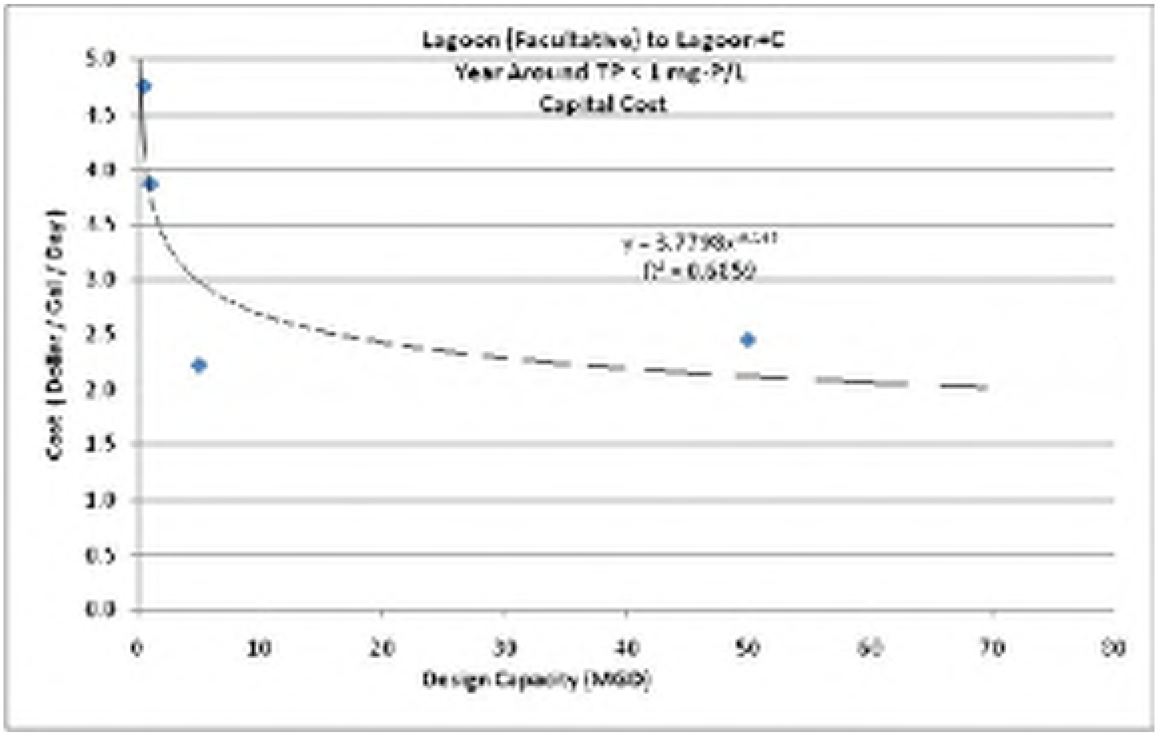


Figure 13-19. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective C Year-Round

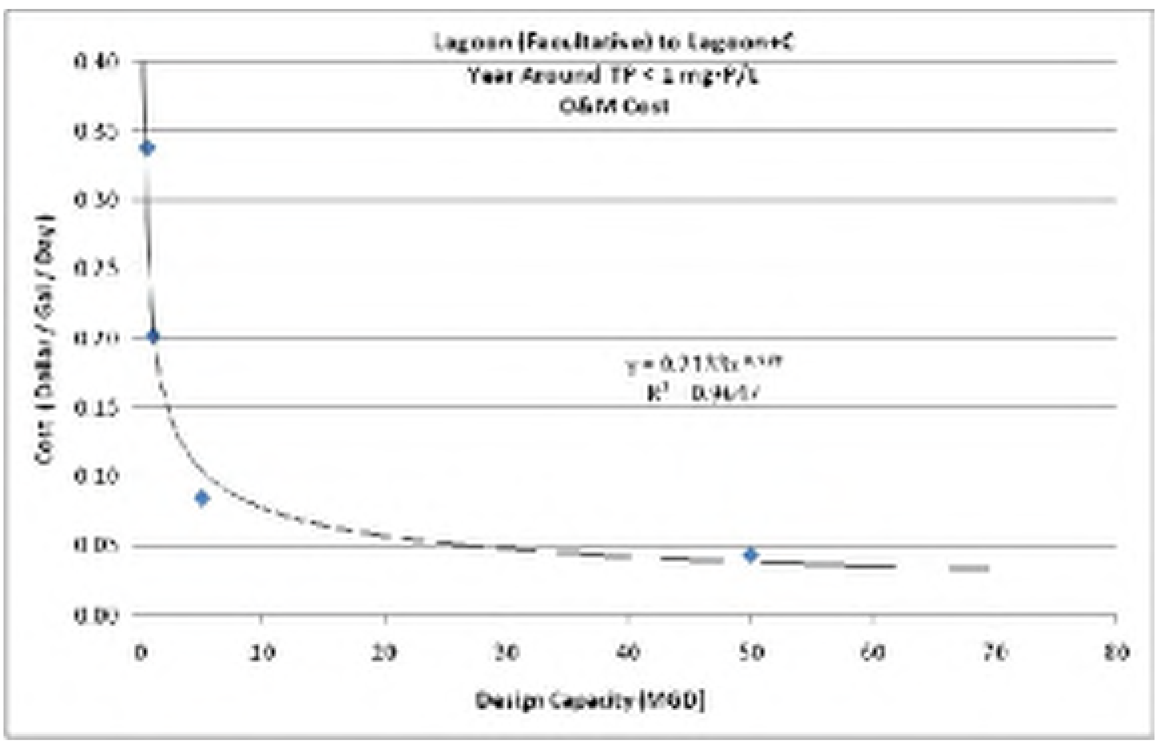


Figure 13-20. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective C Year-Round

TABLE 13-19.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$174,807	$284,062	$814,602	$9,002,573
2014 O&M Cost	$188,787	$226,632	$476,934	$2,370,547
Total Annual Cost	**$363,594**	**$510,694**	**$1,291,536**	**$11,373,119**
Annual TP Load Reduction (lb/yr)	5,712	11,425	57,123	571,225
Estimated Cost for TP Reduction ($/lb TP removed)	$63.65	$44.70	$22.61	$19.91

Equation:[a] .... $y = 469.06x^{-0.25}$
R-Square Value: 0.8503

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-20.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE C YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$174,807	$284,062	$814,602	$9,002,573
2014 O&M Cost	$190,143	$227,358	$475,753	$2,419,844
Total Annual Cost	**$364,951**	**$511,420**	**$1,290,354**	**$11,422,417**
Annual TP Load Reduction (lb/yr)	5,712	11,425	57,123	571,225
Estimated Cost for TP Reduction ($/lb TP removed)	$63.89	$44.77	$22.59	$20.00

Equation:[a] .... $y = 469x^{-0.25}$
R-Square Value: 0.8472

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.2 SEASONAL NUTRIENT REMOVAL

13.2.1 Extended Aeration Plants

Table 13-21 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C seasonally for an extended aeration plant using mechanical aeration. Figures 13-21 and 13-22 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-22 and Figures 13-23 and 13-24 summarize these costs for an extended aeration plant using diffuser aeration. Tables 13-23 and 13-24 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 13-21.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$0.77	$0.20	$0.21
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.12	$0.08	$0.07

TABLE 13-22.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.01	$0.47	$0.30
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.11	$0.06	$0.05

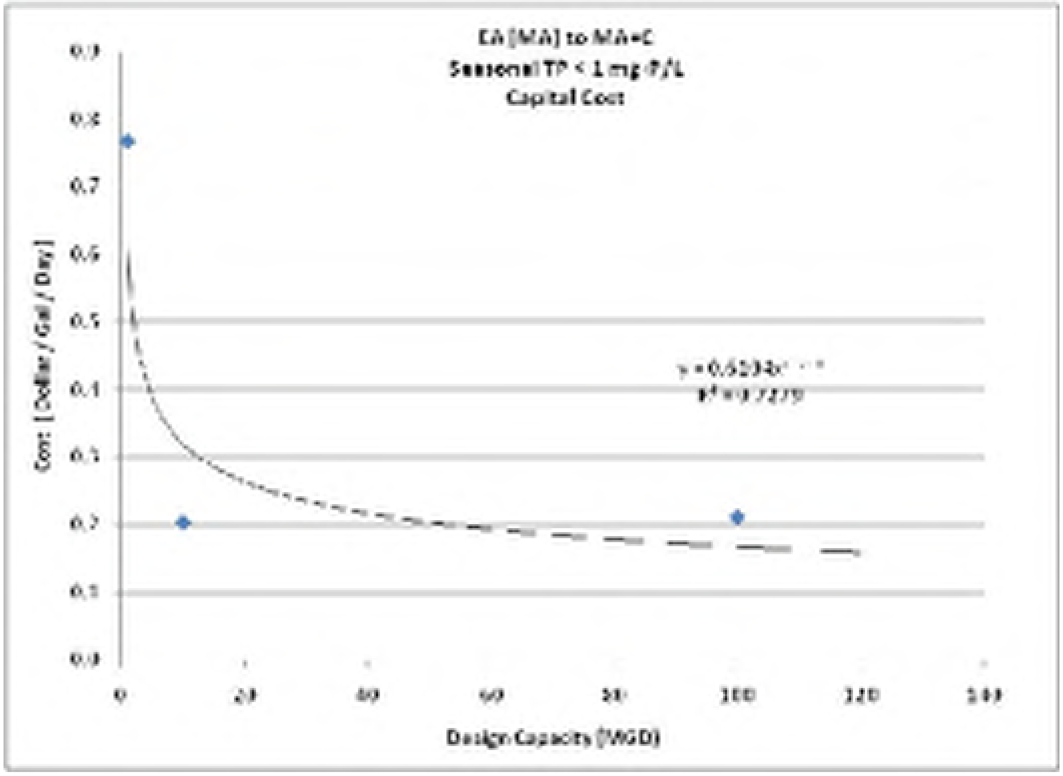


Figure 13-21. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective C Seasonally

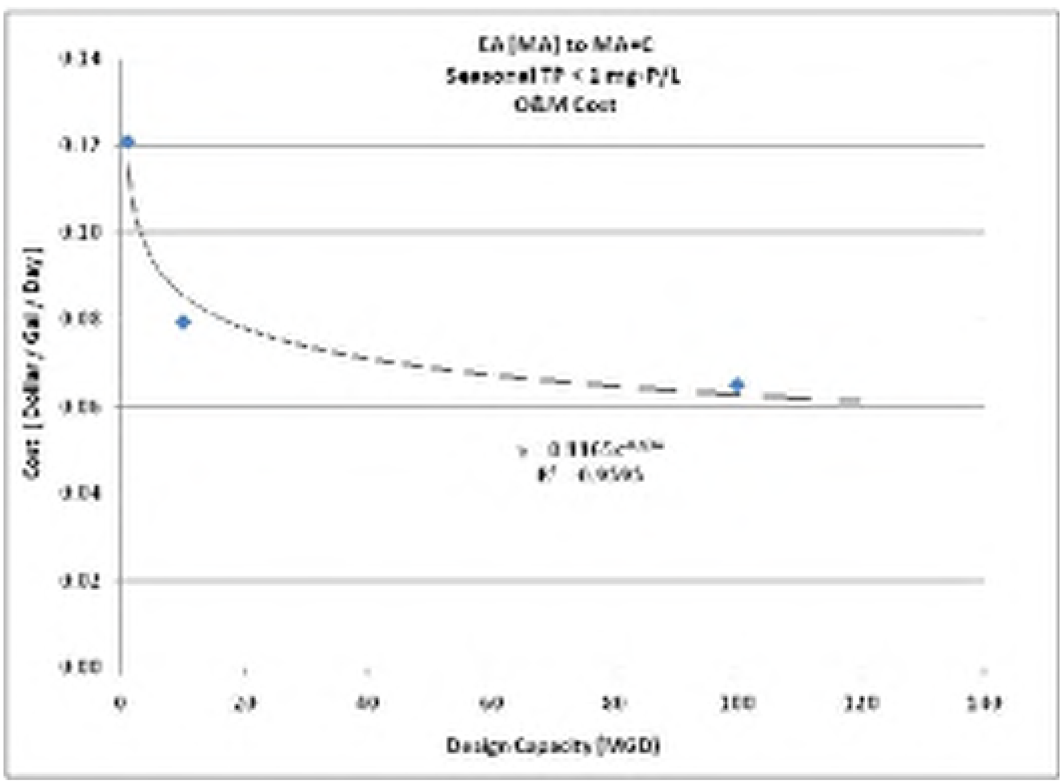


Figure 13-22. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective C Seasonal

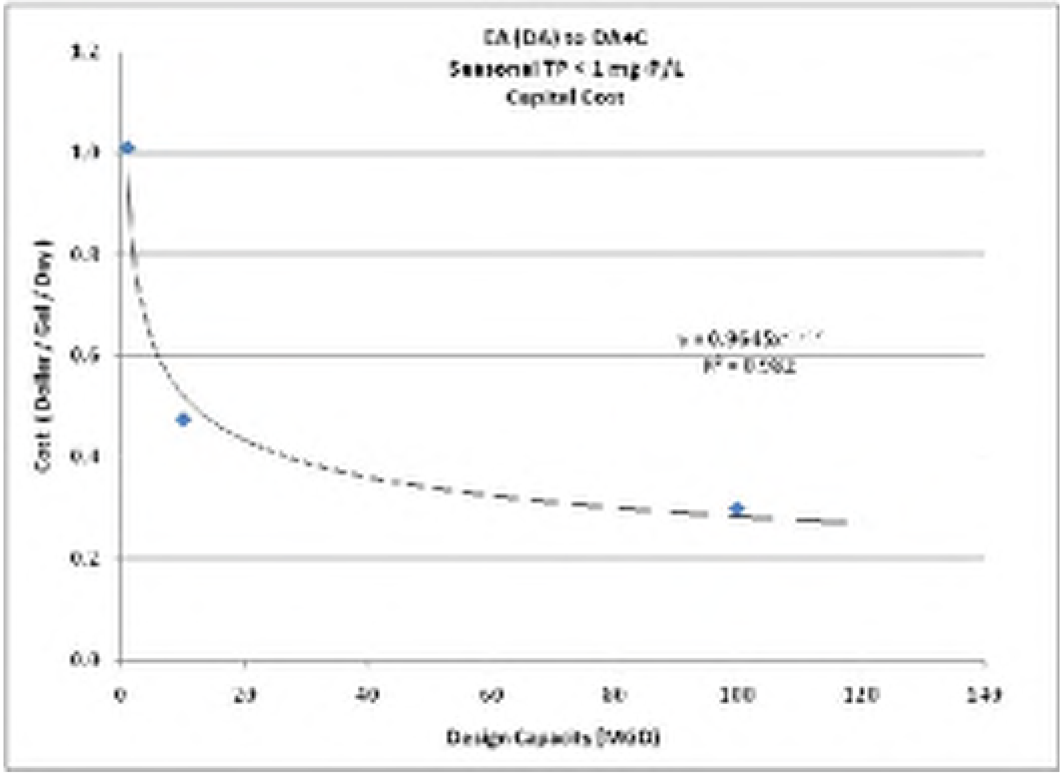


Figure 13-23. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective C Seasonally

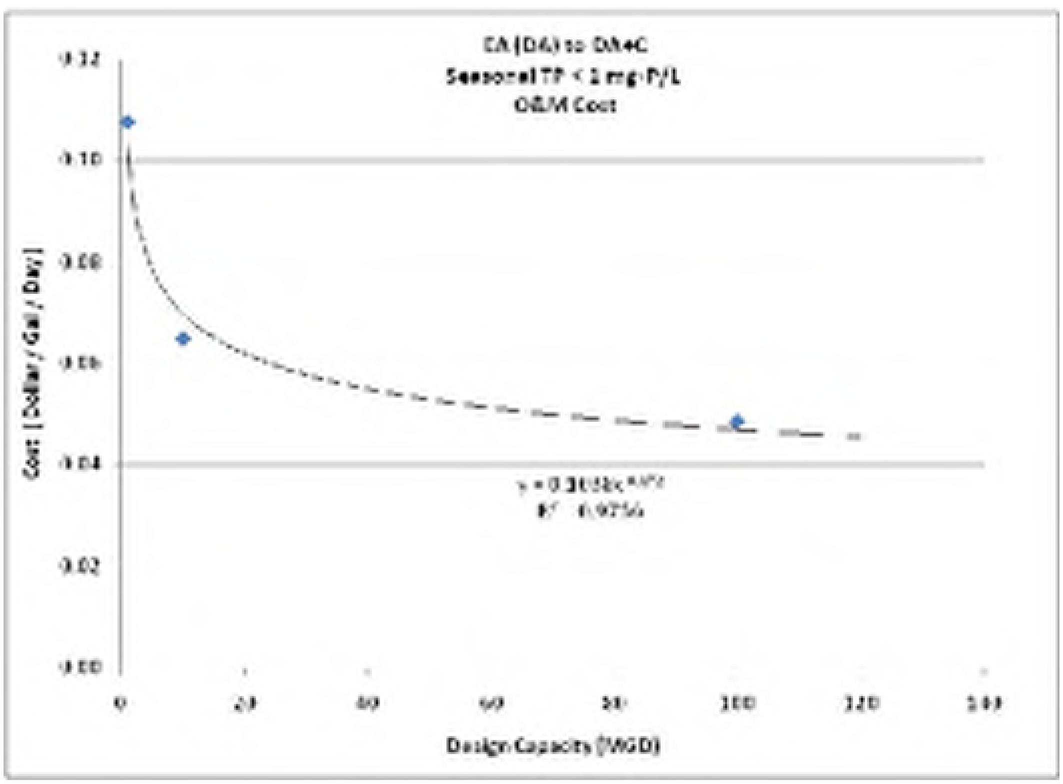


Figure 13-24. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective C Seasonal

TABLE 13-23.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$56,339	$148,668	$1,544,576
2014 O&M Cost	$136,074	$894,341	$7,326,837
Total Annual Cost	**$192,416**	**$1,043,009**	**$8,871,413**
Annual TP Load Reduction (lb/yr)	5,694	56940	569,400
Estimated Cost for TP Reduction ($/lb TP removed)	$33.79	$18.32	$15.58
Equation:[a]		$y = 134.13x^{-0.168}$	
R-Square Value:		0.8987	

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-24.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA ((DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$74,334	$348,154	$2,175,939
2014 O&M Cost	$121,105	$730,579	$5,478,189
Total Annual Cost	**$195,439**	**$1,078,733**	**$7,654,128**
Annual TP Load Reduction (lb/yr)	5,694	56940	569400
Estimated Cost for TP Reduction ($/lb TP removed)	$34.32	$18.95	$13.44
Equation:[a]		$y = 191.4x^{-0.204}$	
R-Square Value:		0.9768	

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.2.2 Conventional Activated Sludge Plants

Table 13-25 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C seasonally for a conventional activated sludge plant. Figures 13-25 and 13-26 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-26 presents the annualized unit costs for reducing nutrient loads.

TABLE 13-25.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.28	$0.32	$0.42
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.20	$0.10	$0.08

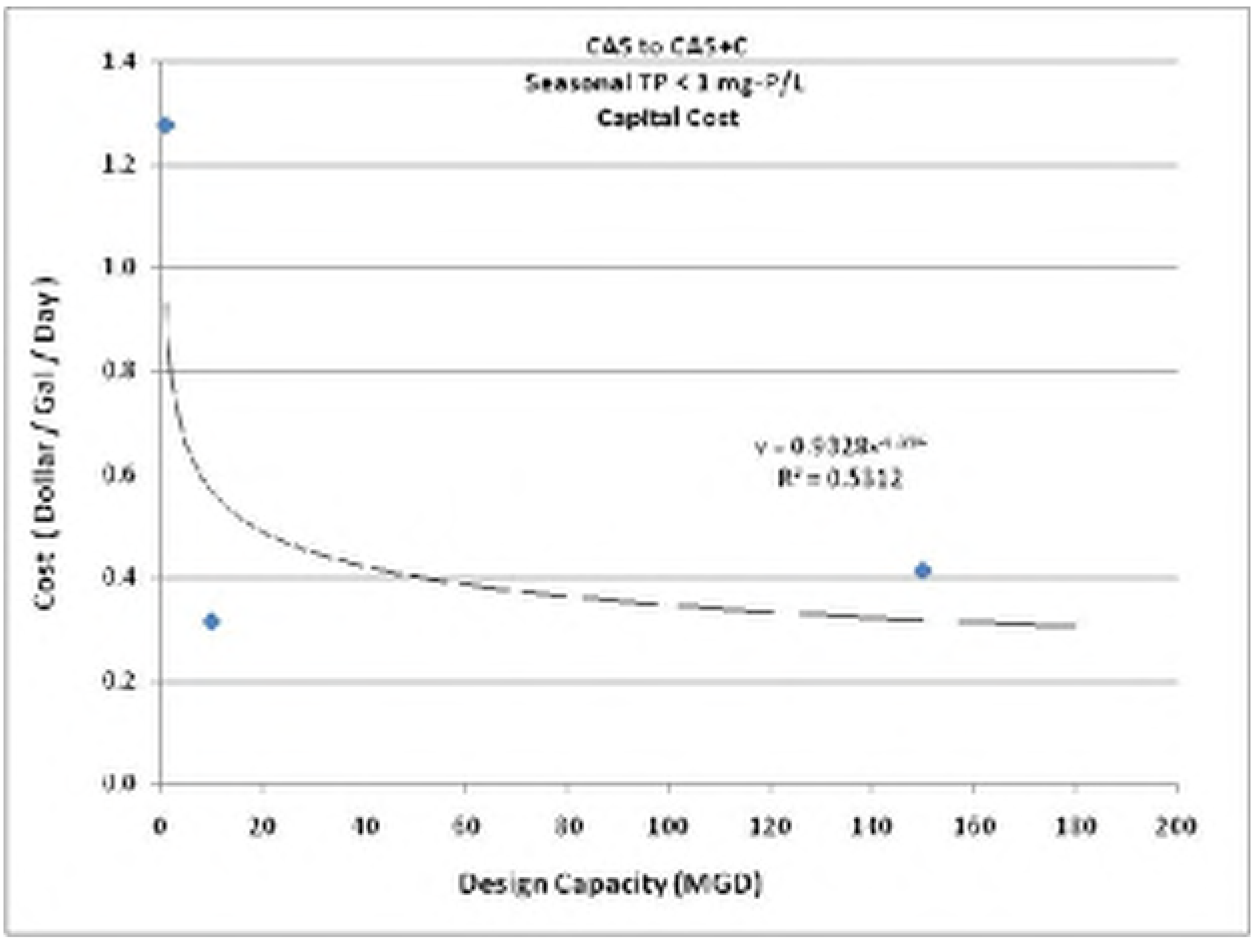


Figure 13-25. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective C Seasonally

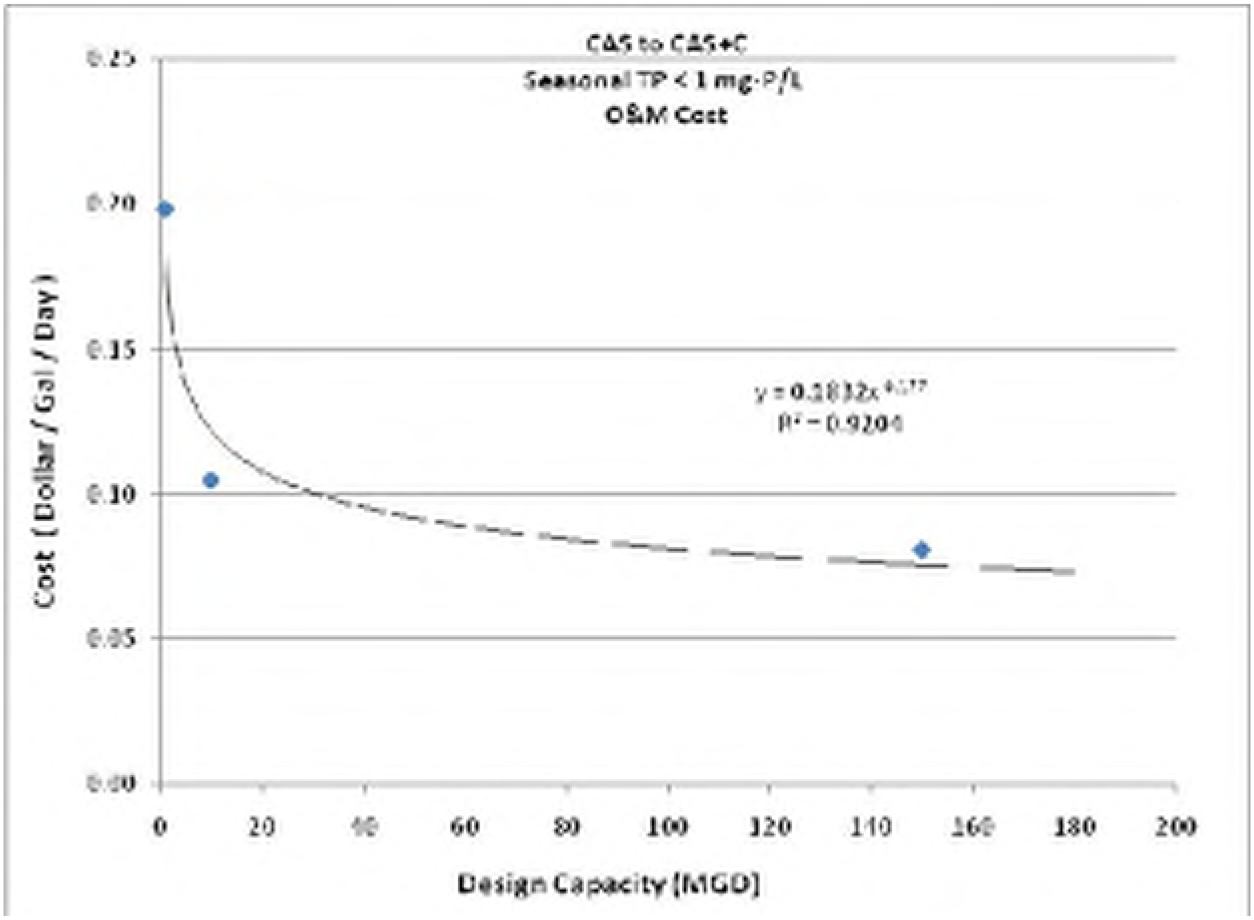


Figure 13-26. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective C Seasonal

TABLE 13-26.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$93,871	$233,501	$4,587,148
2014 O&M Cost	$223,605	$1,181,638	$13,681,122
Total Annual Cost	**$317,476**	**$1,415,139**	**$18,268,270**
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Cost for TP Reduction ($/lb TP removed)	$53.86	$24.01	$20.66

Equation:[a] .... $y = 239.89x^{-0.187}$
R-Square Value: 0.8308

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.2.3 Sequencing Batch Reactor Plants

Table 13-27 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C seasonally for an SBR plant. Figures 13-27 and 13-28 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-28 presents the annualized unit costs for reducing nutrient loads.

**TABLE 13-27.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE C SEASONALLY**

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.41	$0.45	$0.18
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.09	$0.03	$0.01

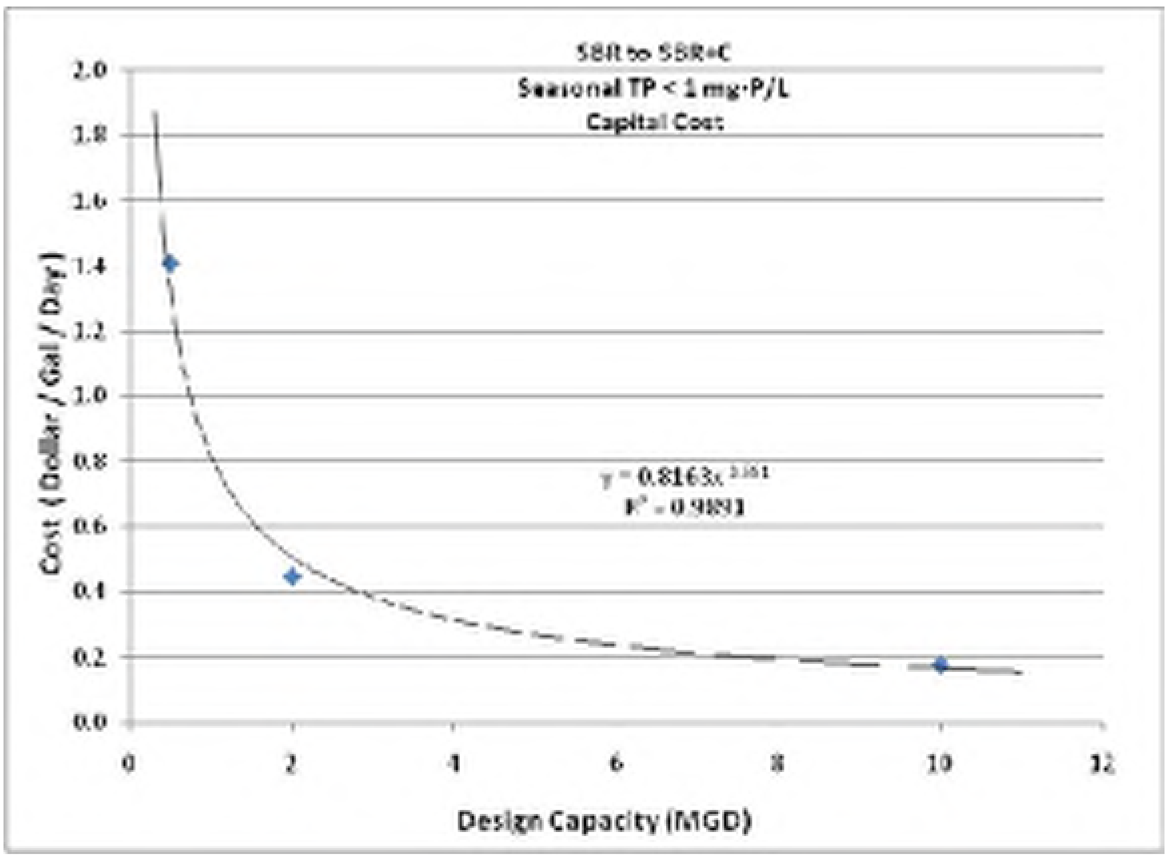


Figure 13-27. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective C Seasonally

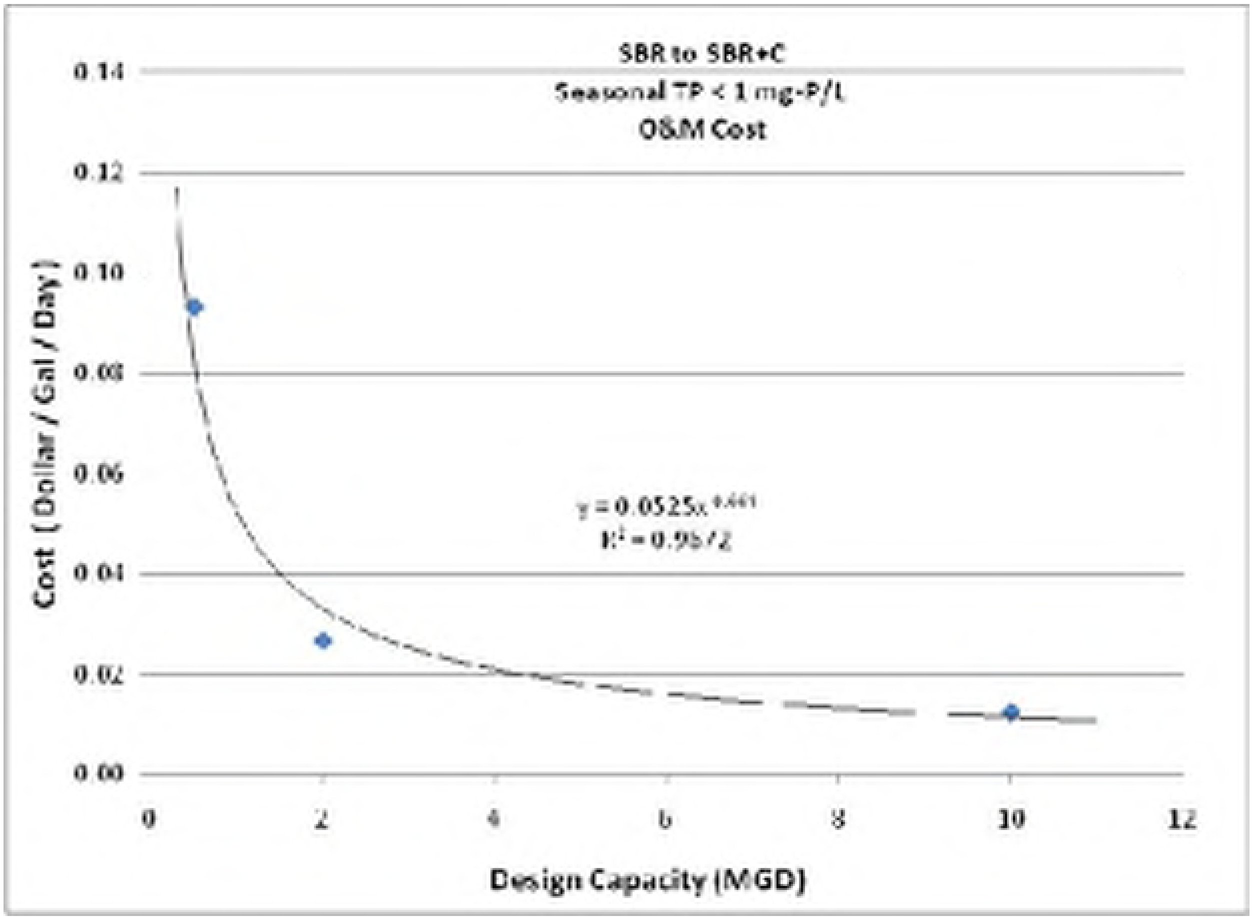


Figure 13-28. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective C Seasonal

TABLE 13-28.
UNIT NUTRIENT REMOVAL COSTS FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$51,764	$65,542	$129,450
2014 O&M Cost	$52,477	$60,384	$141,251
Total Annual Cost	**$104,240**	**$125,926**	**$270,701**
Annual TP Load Reduction (lb/yr)	1,141	4,563	22,813
Estimated Cost for TP Reduction ($/lb TP removed)	$91.39	$27.60	$11.87
Equation:[a]			$y = 9820.1x^{-0.677}$
R-Square Value:			0.9798

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.2.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 13-29 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C seasonally for a trickling filter plant. Figures 13-29 and 13-30 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-30 and Figures 13-31 and 13-32 summarize these costs for a trickling filter/solids contact plant. Table 13-31 and Figures 13-33 and 13-34 summarize these costs for an RBC plant. Tables 13-32, 13-33 and 13-34 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 13-29.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.28	$0.32	$0.42
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.10	$0.07

TABLE 13-30.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.28	$0.32	$0.42
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.10	$0.07

TABLE 13-31.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.28	$0.32	$0.42
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.10	$0.07

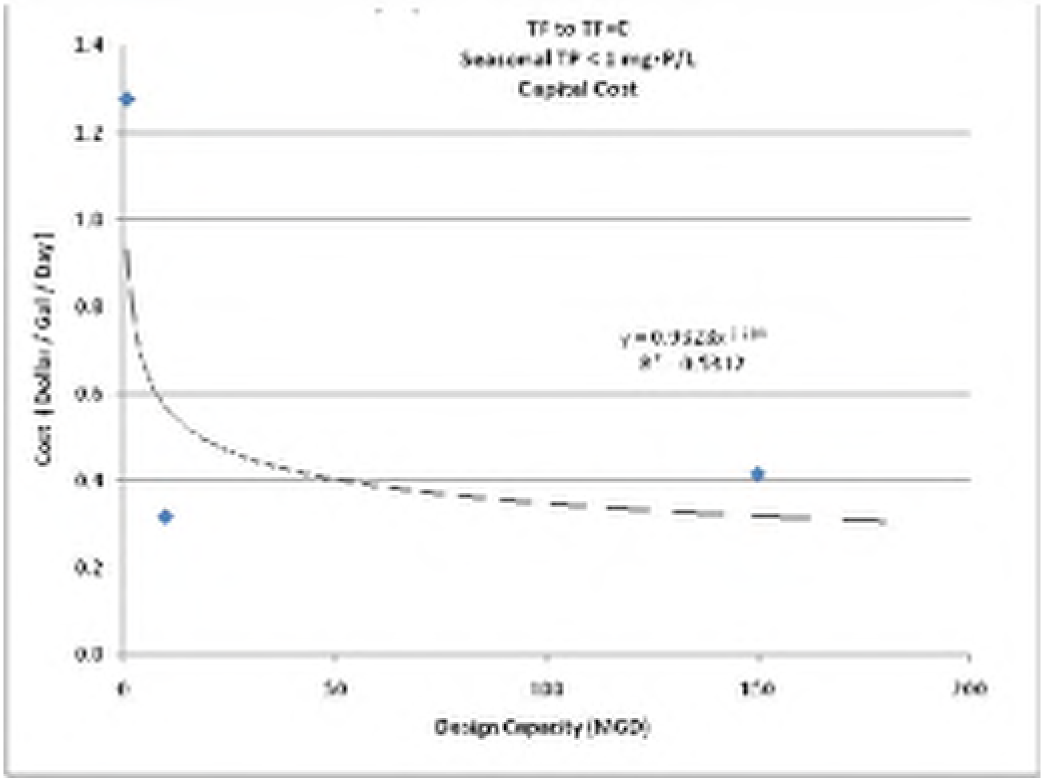


Figure 13-29. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective C Seasonally

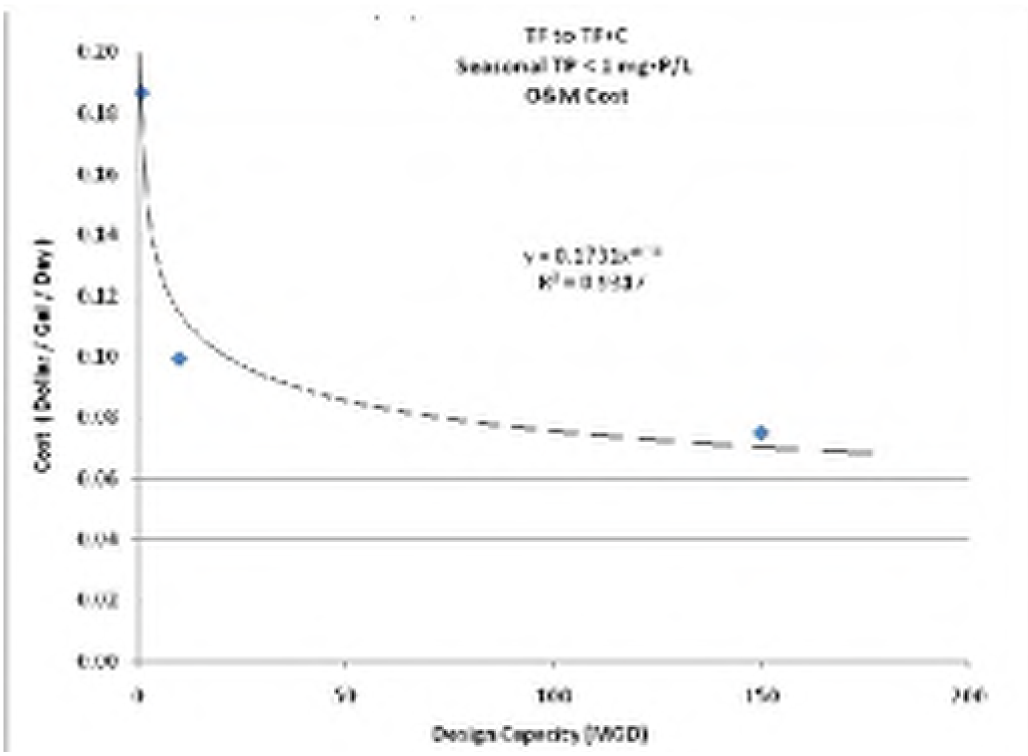


Figure 13-30. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective C Seasonal

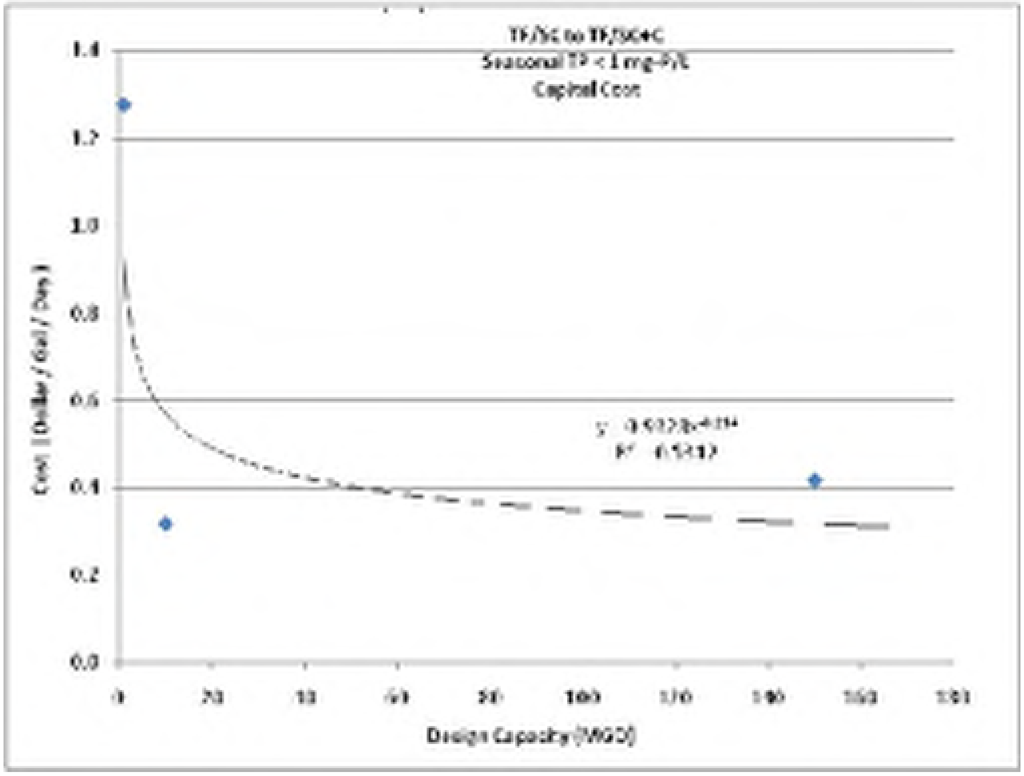


Figure 13-31. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective C Seasonally

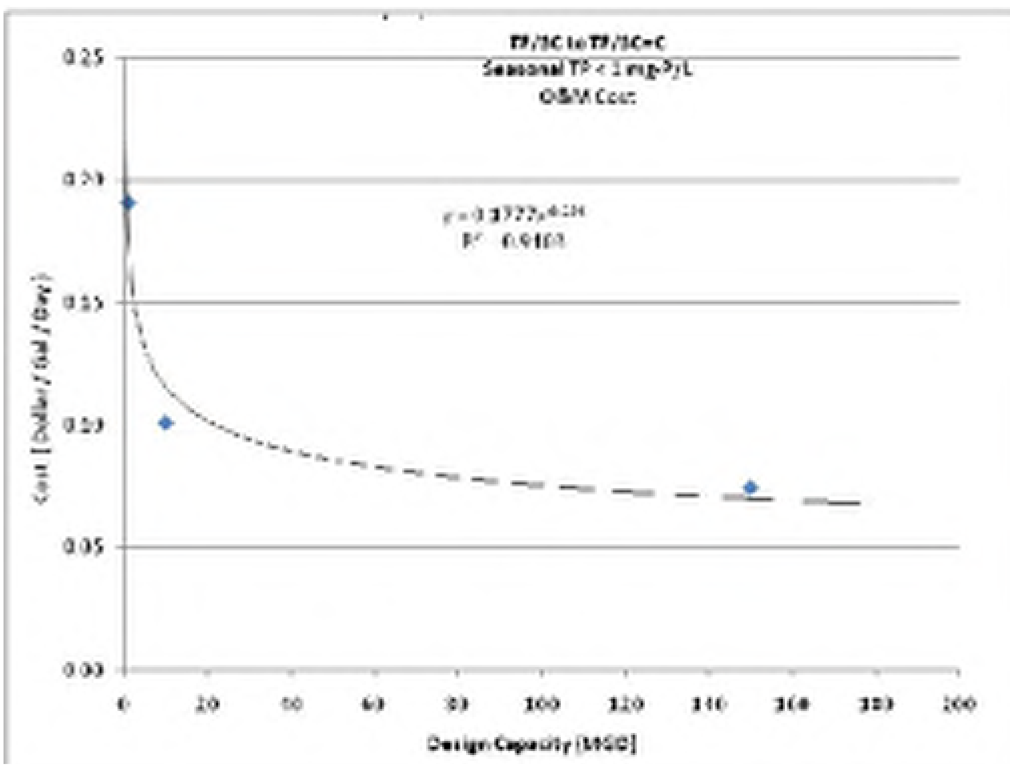


Figure 13-32. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective C Seasonal

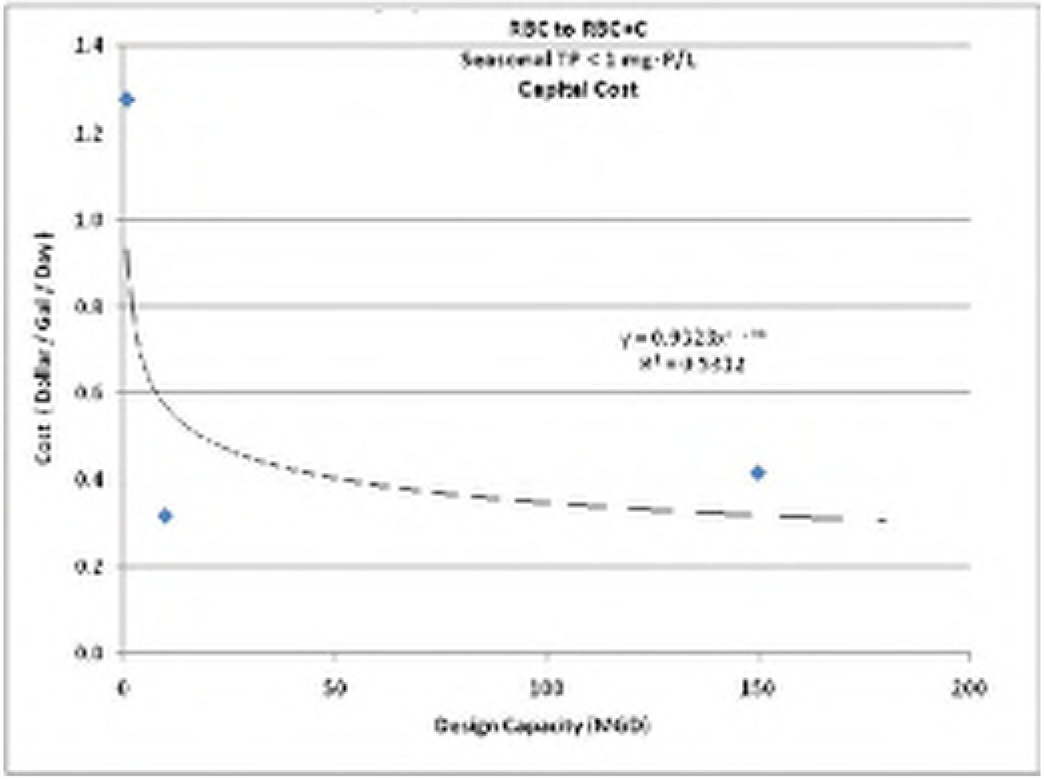


Figure 13-33. Capital Cost per Plant Capacity for RBC Plant Upgraded for Objective C Seasonally

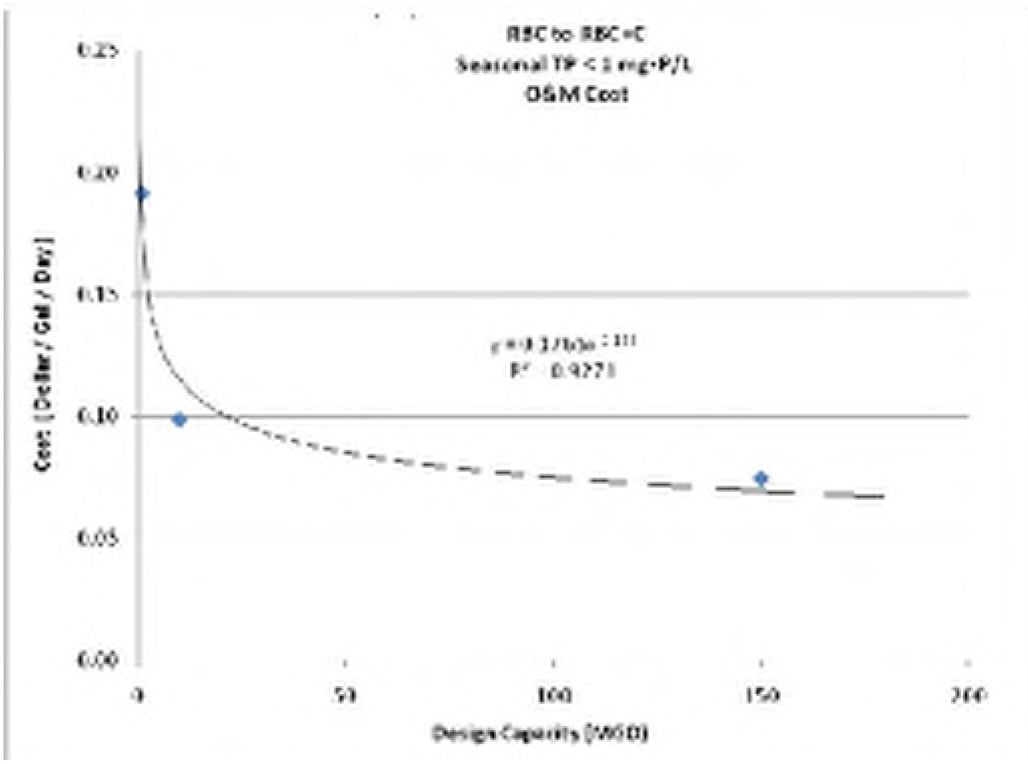


Figure 13-34. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective C Seasonal

TABLE 13-32.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$93,871	$233,501	$4,587,148
2014 O&M Cost	$210,217	$1,118,216	$12,659,160
Total Annual Cost	**$304,088**	**$1,351,717**	**$17,246,308**
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Cost for TP Reduction ($/lb TP removed)	$51.59	$22.93	$19.50

Equation:[a] .... $y = 236.13x^{-0.19}$
R-Square Value: 0.838

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-33.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$93,871	$233,501	$4,587,148
2014 O&M Cost	$215,237	$1,137,743	$12,568,557
Total Annual Cost	**$309,108**	**$1,371,244**	**$17,1557,04**
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Cost for TP Reduction ($/lb TP removed)	$43.06	$23.26	$19.40

Equation:[a] .... $y = 153.11x^{-0.156}$
R-Square Value: 0.8815

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-34.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$93,871	$233,501	$4,587,148
2014 O&M Cost	$215,614	$1,112,475	$12,562,367
Total Annual Cost	**$309,485**	**$1,345,977**	**$17,149,514**
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Cost for TP Reduction ($/lb TP removed)	$52.50	$22.83	$19.40

Equation:[a] .... $y = 225.71x^{-0.187}$
R-Square Value: 0.8407

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

13.2.5 Membrane Biological Reactor Plants

Table 13-35 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C seasonally for an MBR plant. Figures 13-35 and 13-36 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-36 presents the annualized unit costs for reducing nutrient loads.

TABLE 13-35.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.19	$0.27	$0.07
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.15	$0.07	$0.04

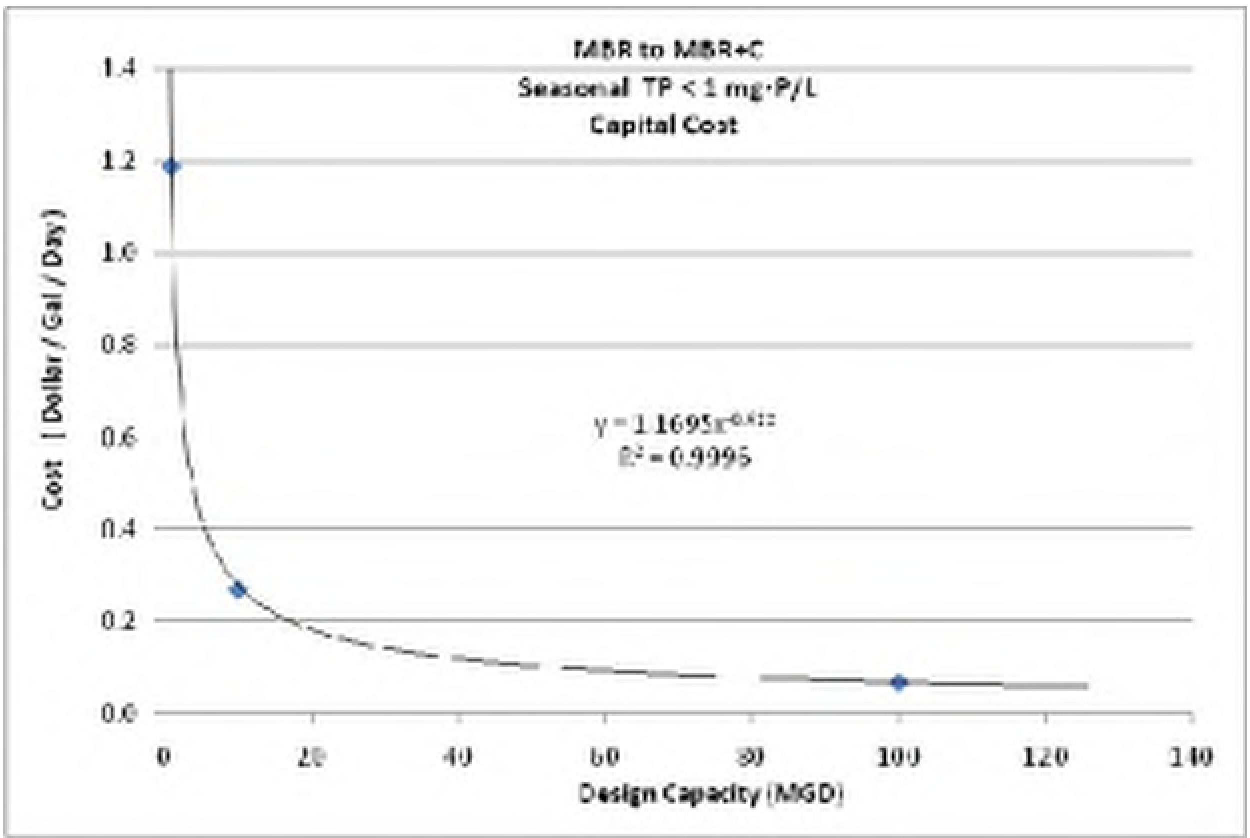


Figure 13-35. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective C Seasonally

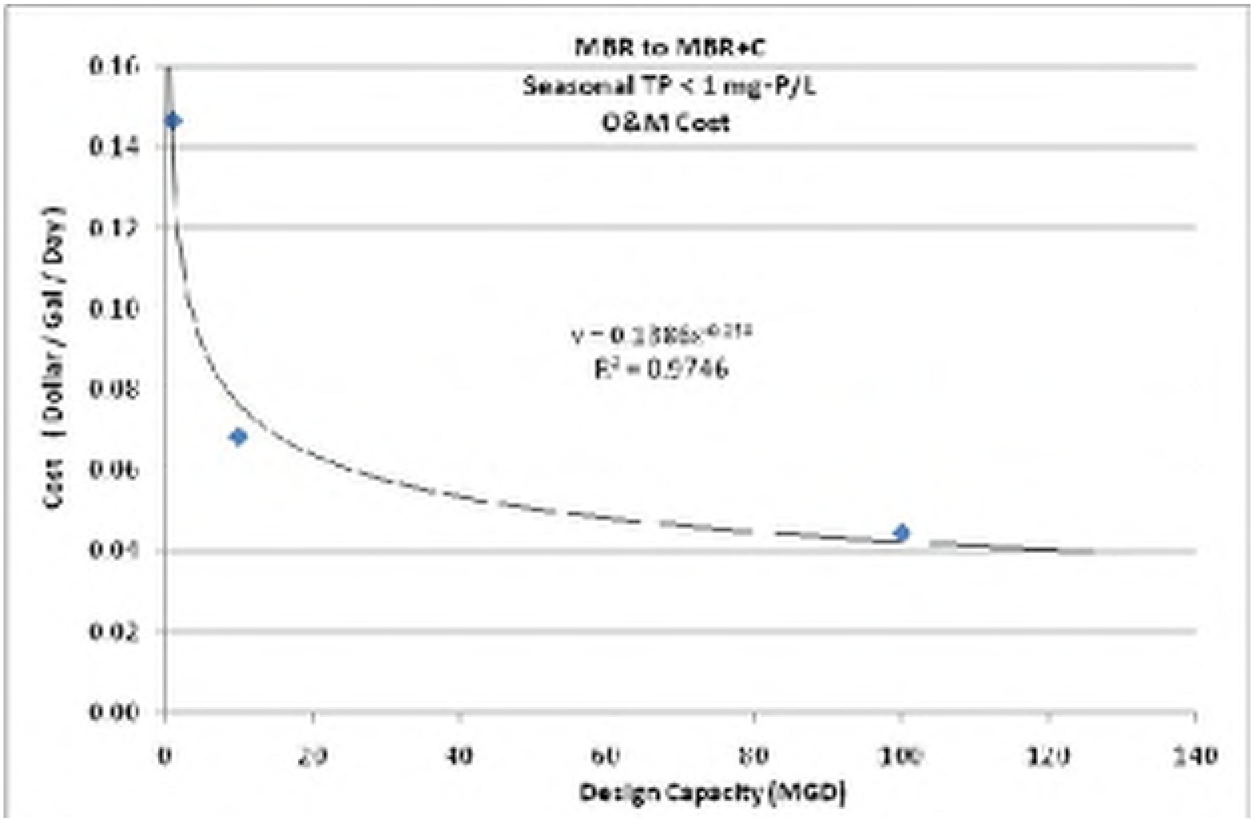


Figure 13-36. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective C Seasonal

TABLE 13-36.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	\$87,393	\$198,159	\$498,252
2014 O&M Cost	\$164,904	\$771,109	\$5,026,973
Total Annual Cost	**\$252,297**	**\$969,268**	**\$5,525,225**
Annual TP Load Reduction (lb/yr)	5,493	54,933	549,325
Estimated Cost for TP Reduction (\$/lb TP removed)	\$45.93	\$17.64	\$10.06
Equation:[a]			$y = 735.65x^{-0.33}$
R-Square Value:			0.9779

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction (\$/lb TP removed)

13.2.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective C were developed for these plants.

13.2.7 Aerated or Facultative Lagoon Plants

Table 13-37 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective C seasonally for an aerated lagoon plan. Figures 13-37 and 13-38 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 13-38 and Figures 13-39 and 13-40 summarize these costs for a facultative lagoon plant. Tables 13-39 and 13-40 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 13-37.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.55	$3.50	$1.83	$1.84
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.35	$0.22	$0.10	$0.04

TABLE 13-38.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.55	$3.50	$1.83	$1.84
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.32	$0.19	$0.07	$0.03

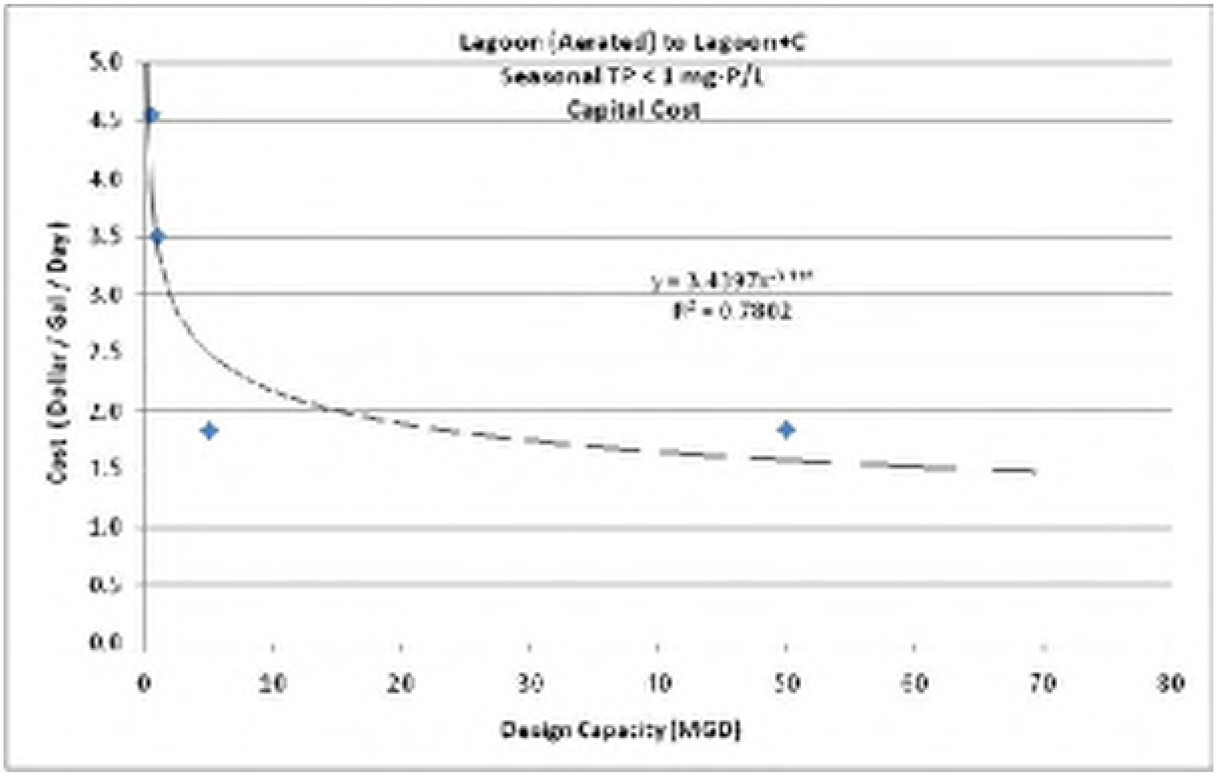


Figure 13-37. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective C Seasonally

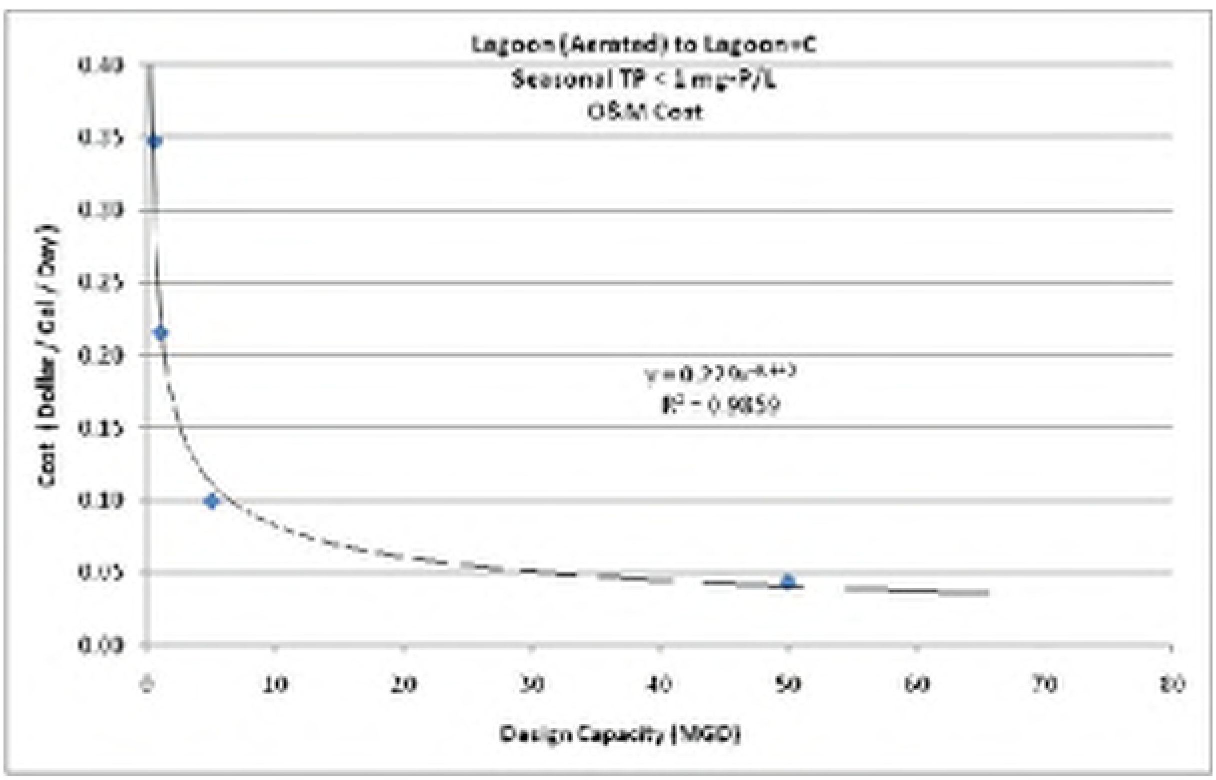


Figure 13-38. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective C Seasonal

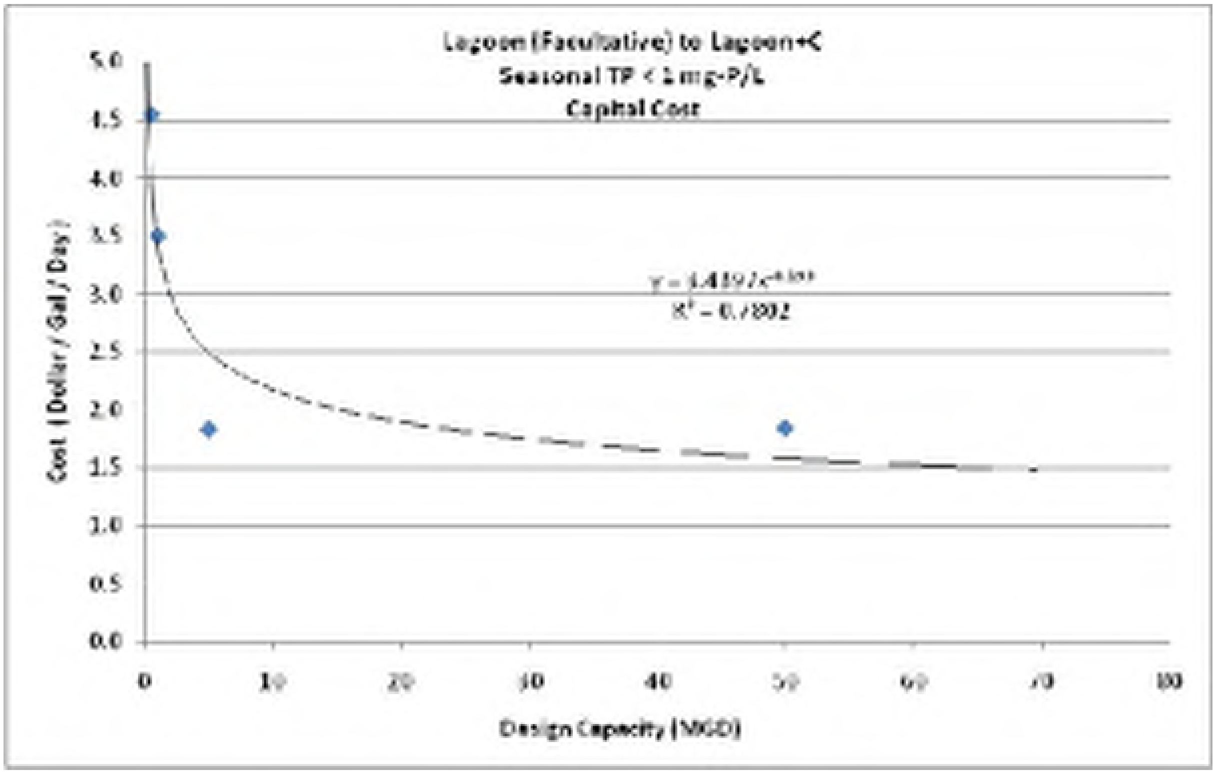


Figure 13-39. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective C Seasonally

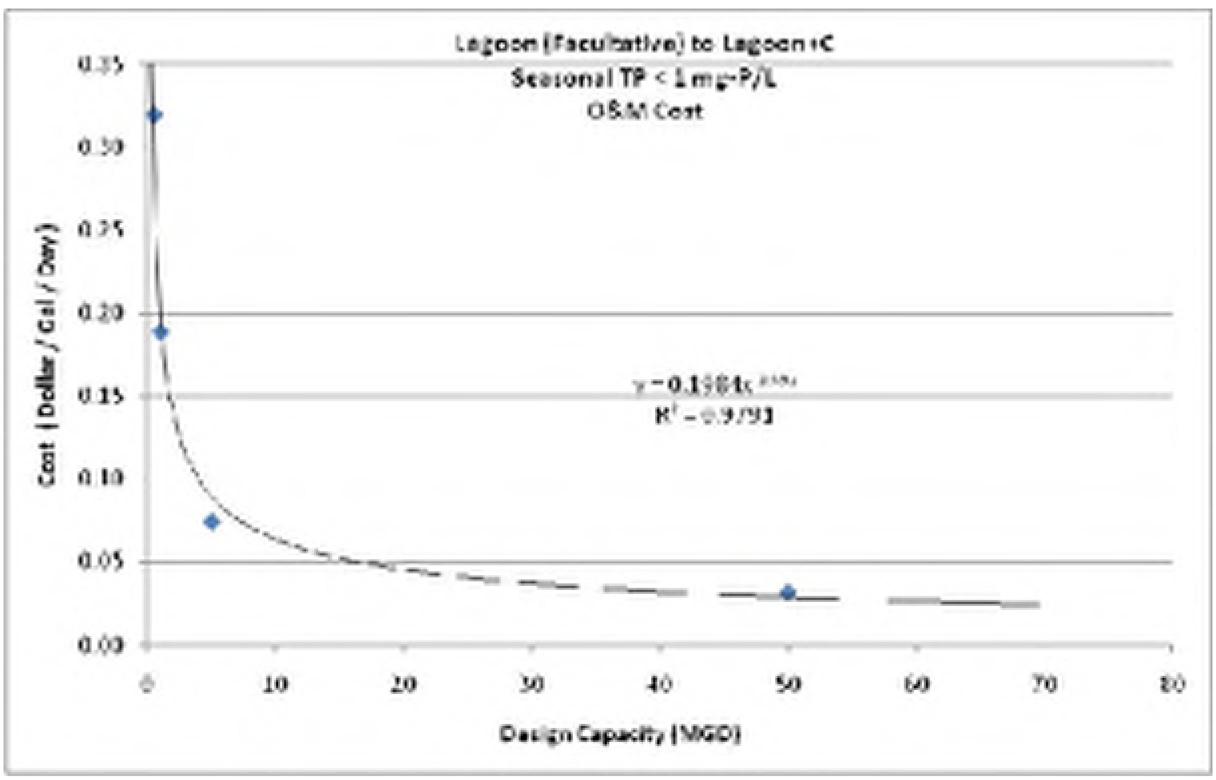


Figure 13-40. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective C Seasonal

TABLE 13-39.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$166,941	$256,967	$672,134	$6,756,300
2014 O&M Cost	$195,653	$242,885	$559,828	$2,441,060
Total Annual Cost	**$362,594**	**$499,851**	**$1,231,962**	**$9,197,359**
Annual TP Load Reduction (lb/yr)	2,947	5,895	29,474	294,738
Estimated Cost for TP Reduction ($/lb TP removed)	$123.02	$84.80	$41.80	$32.21

Equation:[a] .... $y = 1053.4x^{-0.288}$
R-Square Value: 0.9023

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 13-40.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE C SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$166,941	$256,967	$672,134	$6,756,300
2014 O&M Cost	$179,868	$212,603	$419,196	$1,792,767
Total Annual Cost	**$346,808**	**$469,570**	**$1,091,330**	**$8,549,066**
Annual TP Load Reduction (lb/yr)	2,947	5,895	29,474	294,738
Estimated Cost for TP Reduction ($/lb TP removed)	$117.67	$79.66	$37.03	$29.01

Equation:[a] .... $y = 1109.9x^{-0.301}$
R-Square Value:........................ 0.8912

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

CHAPTER 14.
COST EVALUATION, OBJECTIVE D

14.1 YEAR-ROUND NUTRIENT REMOVAL

14.1.1 Extended Aeration Plants

Table 14-1 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D year-round for an extended aeration plant using mechanical aeration. Figures 14-1 and 14-2 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-2 and Figures 14-3 and 14-4 summarize these costs for an extended aeration plant using diffuser aeration. Tables 14-3 and 14-4 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 14-1.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	\$3.14	\$1.40	\$1.01
Incremental Annual O&M Cost per gpd of Plant Capacity	\$0.29	\$0.21	\$0.19

TABLE 14-2.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	\$3.38	\$1.65	\$1.07
Incremental Annual O&M Cost per gpd of Plant Capacity	\$0.24	\$0.18	\$0.15

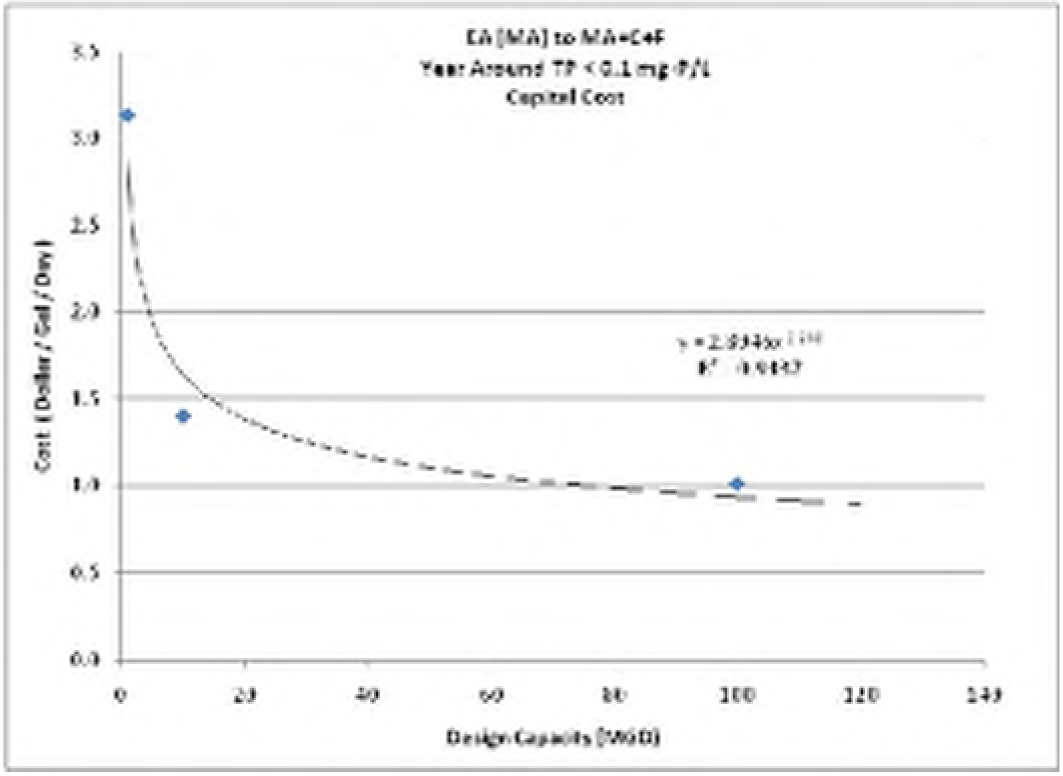


Figure 14-1. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective D Year-Round

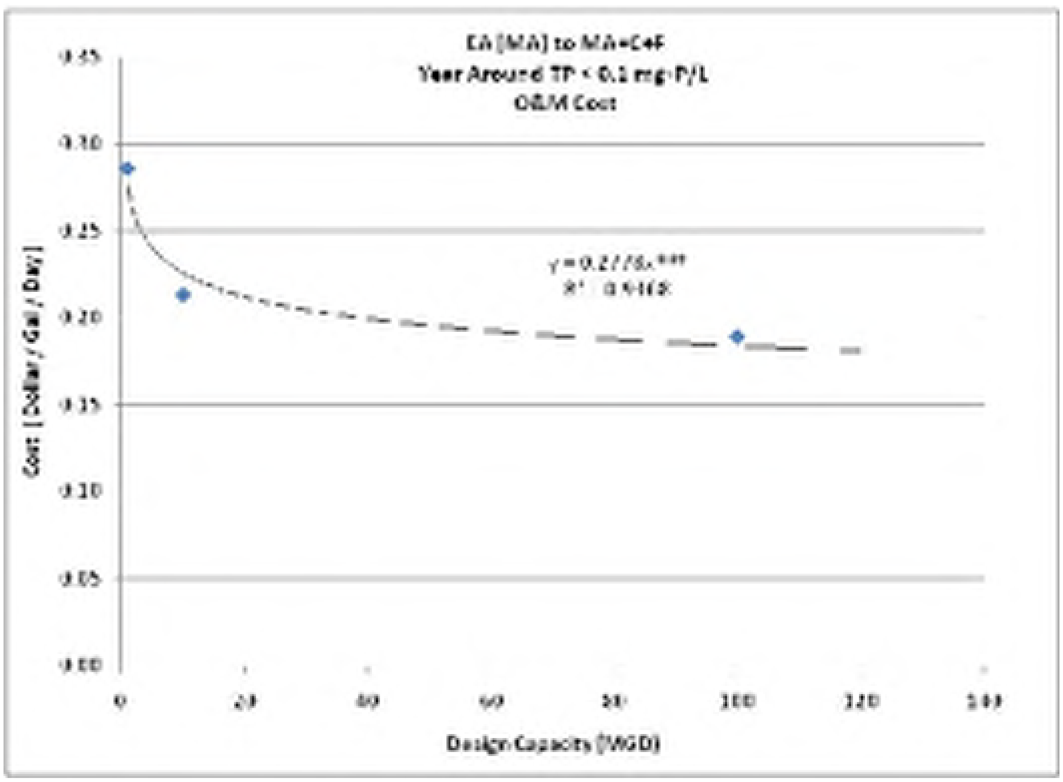


Figure 14-2. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective D Year-Round

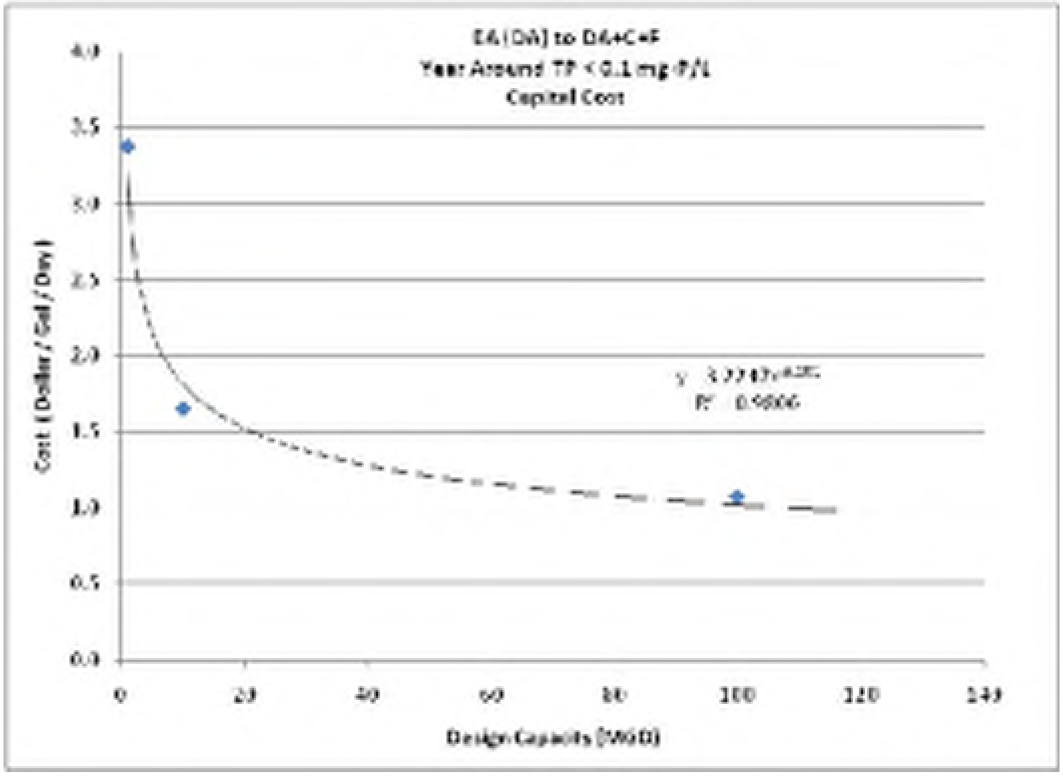


Figure 14-3. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective D Year-Round

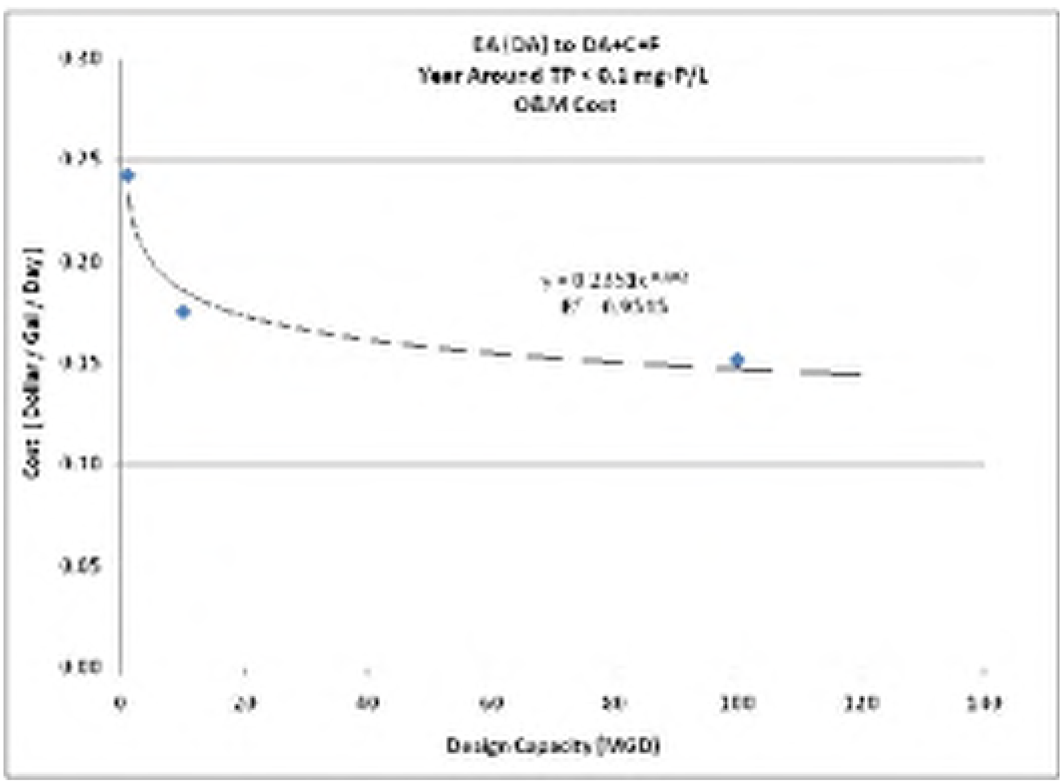


Figure 14-4. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective D Year-Round

TABLE 14-3.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$230,273	$1,028,735	$7,420,567
2014 Incremental O&M Cost	$321,614	$2,402,989	$21,274,480
Total Annual Cost	**$551,887**	**$3,431,725**	**$28,695,047**
Annual TP Load Reduction (lb/yr)	12,775	127,750	1,277,500
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$43.20	$26.86	$22.46

Equation:[a] .... $y = 157.5x^{-0.142}$
R-Square Value: 0.936

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 14-4.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$248,216	$1,211,255	$7,830,850
2014 Incremental O&M Cost	$272,598	$1,971,976	$17,039,753
Total Annual Cost	**$520,814**	**$3,183,231**	**$24,870,603**
Annual TP Load Reduction (lb/yr)	12,739	127,385	1,273,850
Estimated Cost for TP Reduction ($/lb TP removed)	$40.89	$24.99	$19.52

Equation:[a] .... $y = 179.07x^{-0.161}$
R-Square Value: 0.9646

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.1.2 Conventional Activated Sludge Plants

Table 14-5 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D year-round for a conventional activated sludge plant. Figures 14-5 and 14-6 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-6 presents the annualized unit costs for reducing nutrient loads.

TABLE 14-5.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$3.60	$1.42	$0.96
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.28	$0.18	$0.15

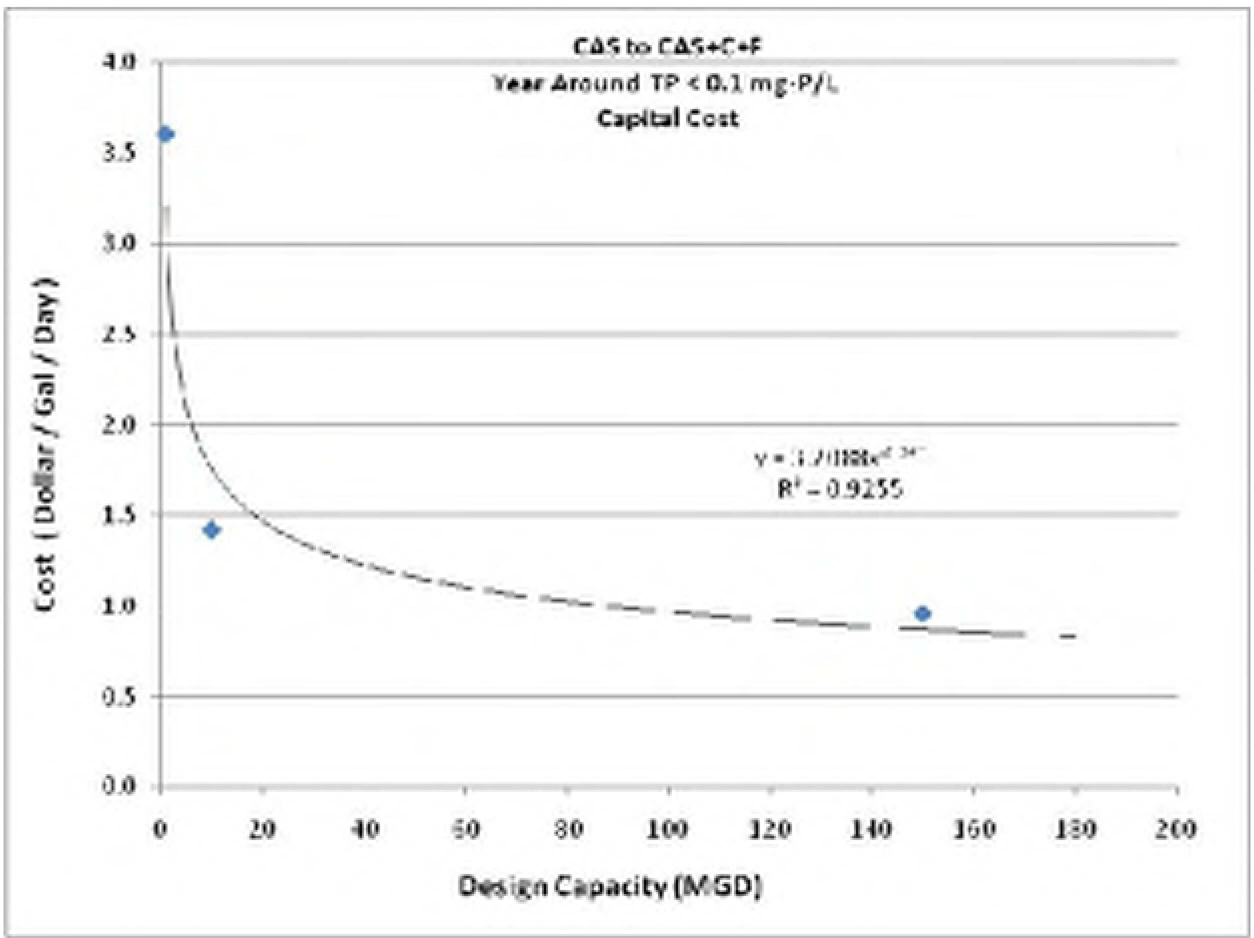


Figure 14-5. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective D Year-Round

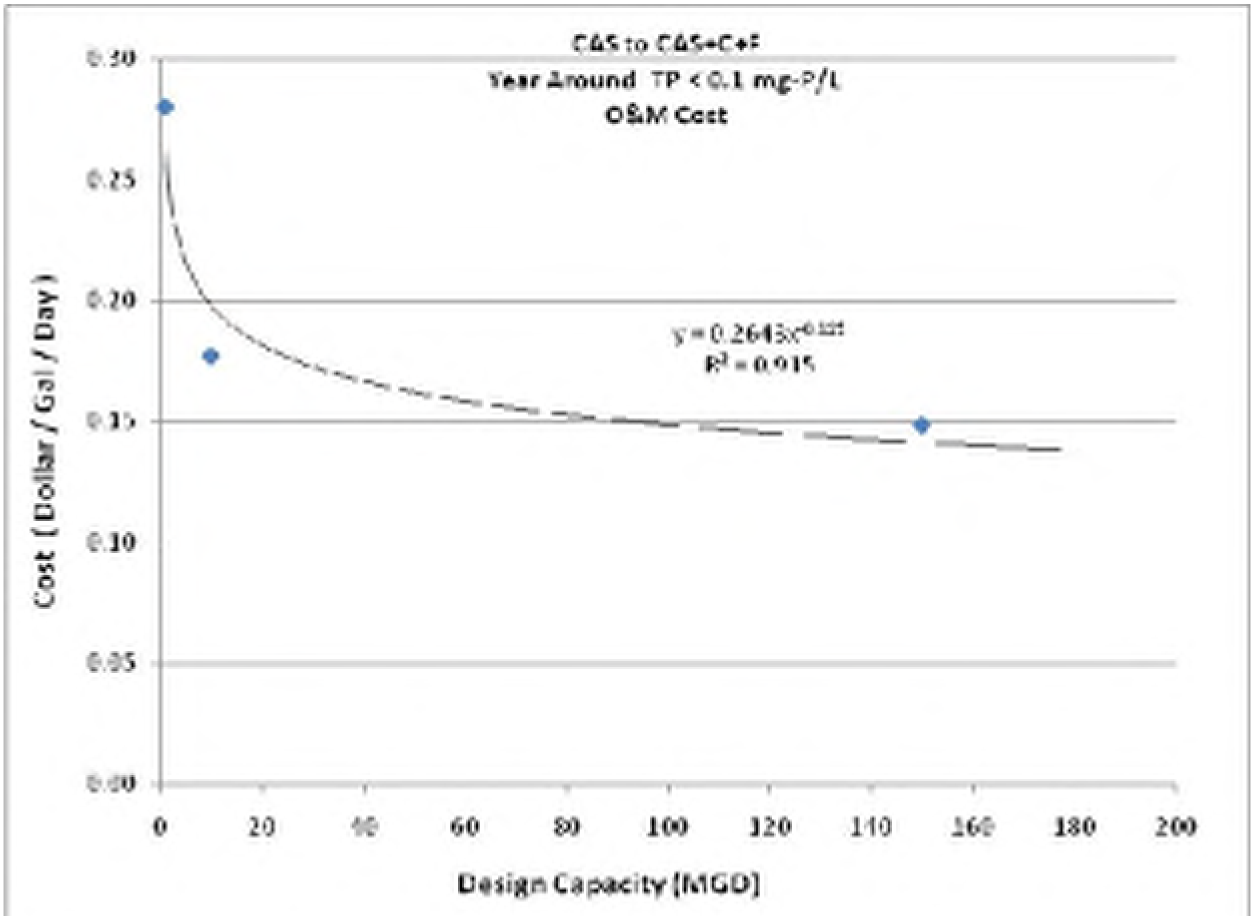


Figure 14-6. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective D Year-Round

TABLE 14-6.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$264,517	$1,043,049	$10,550,902
2014 O&M Cost	$315,750	$1,997,694	$25,088,042
Total Annual Cost	**$580,367**	**3,040,743**	**$35,638,944**
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Cost for TP Reduction ($/lb TP removed)	$44.17	$23.14	$18.08
Equation:[a]		$y = 214.81x^{-0.176}$	
R-Square Value:		0.9129	

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.1.3 Sequencing Batch Reactor Plants

Table 14-7 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D year-round for an SBR plant. Figures 14-7 and 14-8 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-8 presents the annualized unit costs for reducing nutrient loads.

**TABLE 14-7.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND**

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$3.27	$2.21	$1.36
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.12	$0.09

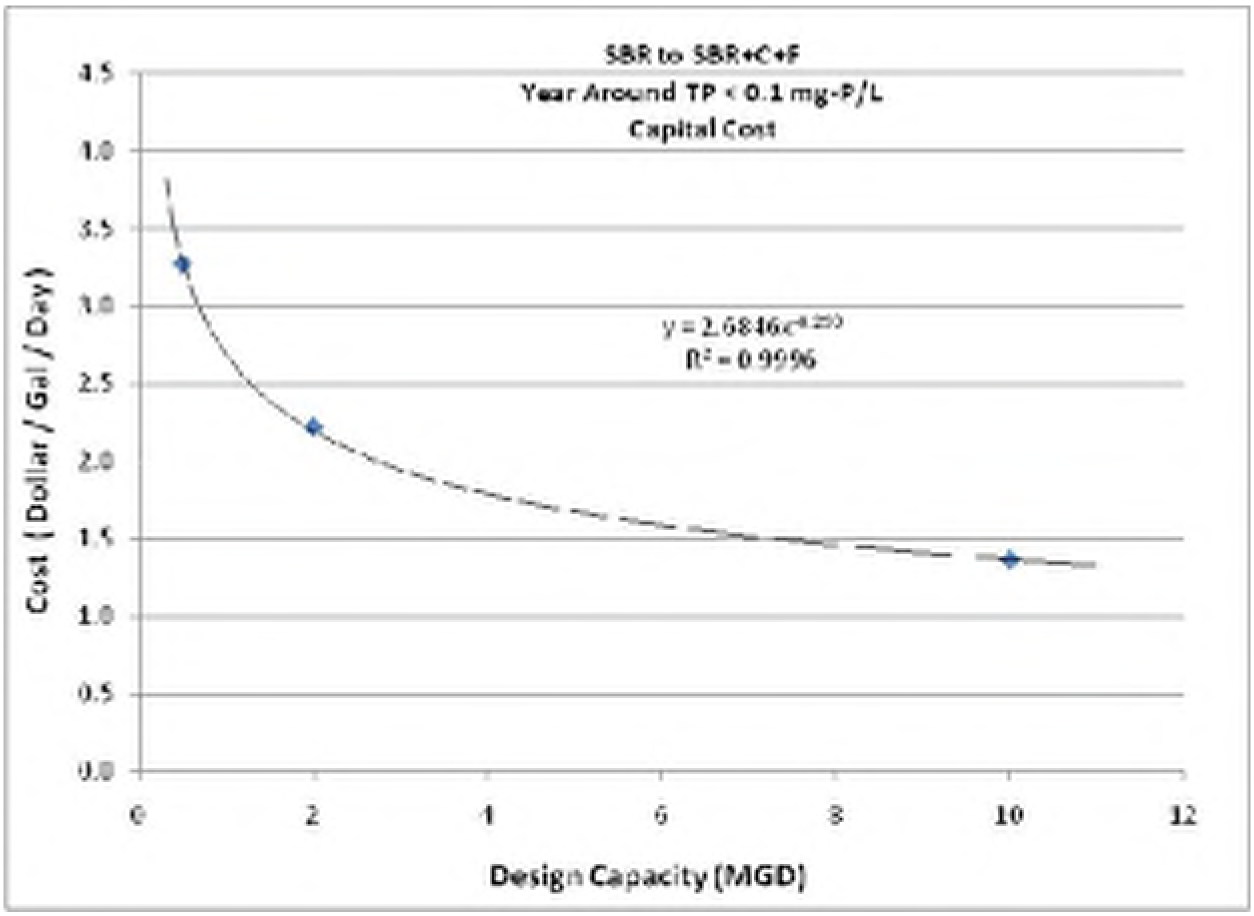


Figure 14-7. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective D Year-Round

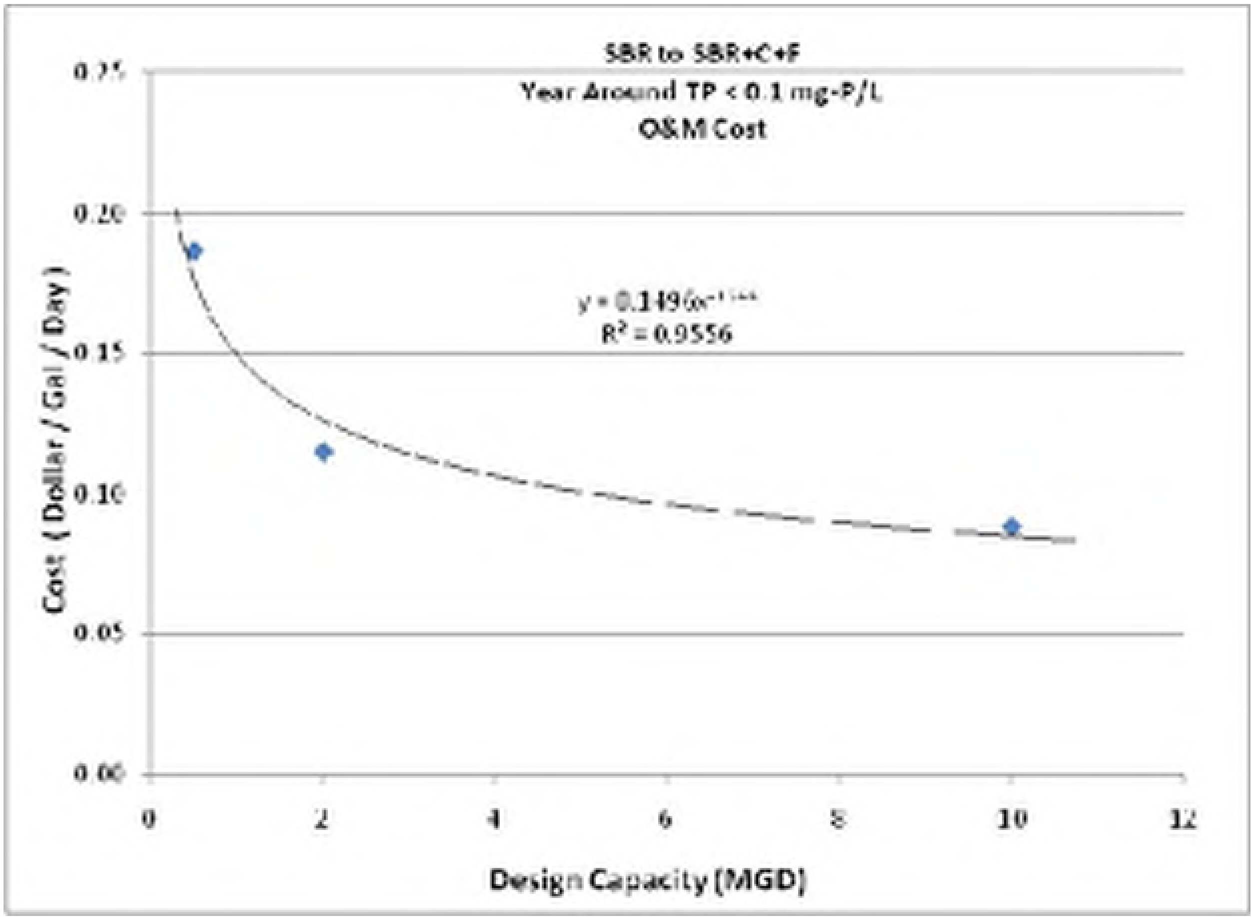


Figure 14-8. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective D Year-Round

TABLE 14-8.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	\$120,093	\$325,337	\$999,877
2014 O&M Cost	\$104,836	\$259,036	\$996,931
Total Annual Cost	**\$224,928**	**\$584,373**	**\$1,996,808**
Annual TP Load Reduction (lb/yr)	2,957	11,826	59,130
Estimated Cost for TP Reduction (\$/lb TP removed)	\$76.08	\$49.41	\$33.77
Equation:[a]	$y = 646.37x^{-0.27}$		
R-Square Value:	0.9937		

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction (\$/lb TP removed)

14.1.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 14-9 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D year-round for a trickling filter plant. Figures 14-9 and 14-10 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-10 and Figurse 14-11 and 14-12 summarize these costs for a trickling filter/solids contact plant. Table 14-11 and Figures 14-13 and 14-14 summarize these costs for an RBC plant. Tables 14-12, 14-13 and 14-14 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 14-9.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	\$3.60	\$1.42	\$0.96
Incremental Annual O&M Cost per gpd of Plant Capacity	\$0.26	\$0.17	\$0.14

TABLE 14-10.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	\$3.60	\$1.42	\$0.96
Incremental Annual O&M Cost per gpd of Plant Capacity	\$0.27	\$0.17	\$0.14

TABLE 14-11.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	\$3.60	\$1.42	\$0.96
Incremental Annual O&M Cost per gpd of Plant Capacity	\$0.27	\$0.17	\$0.14

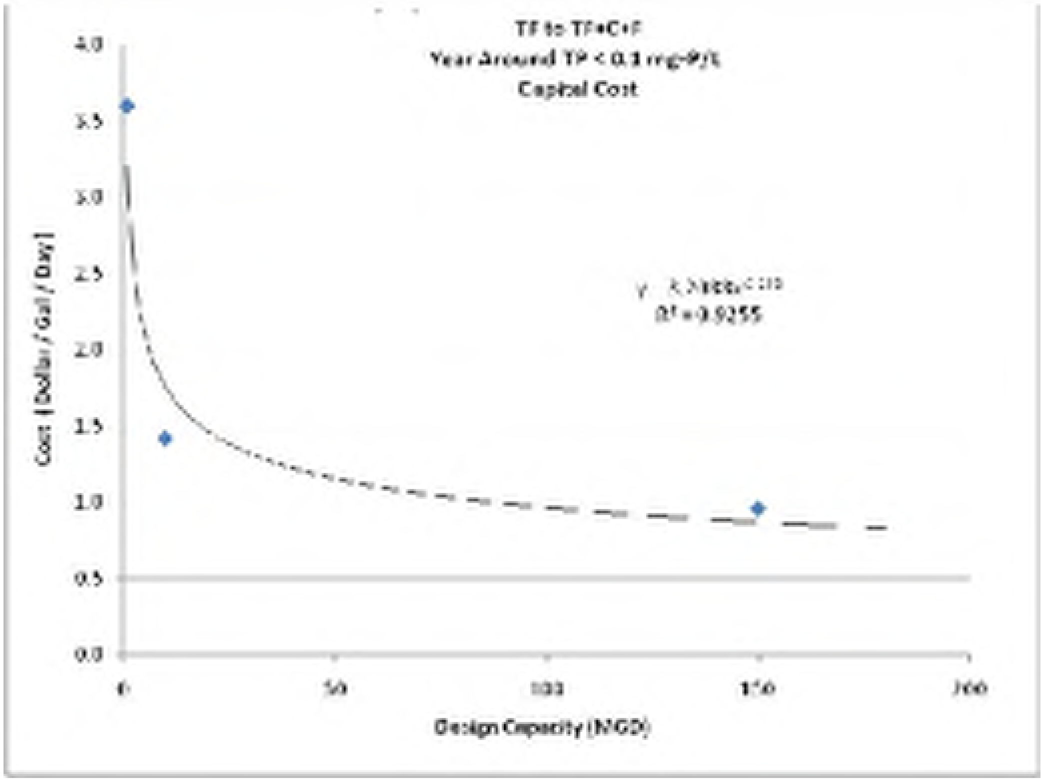


Figure 14-9. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective D Year-Round

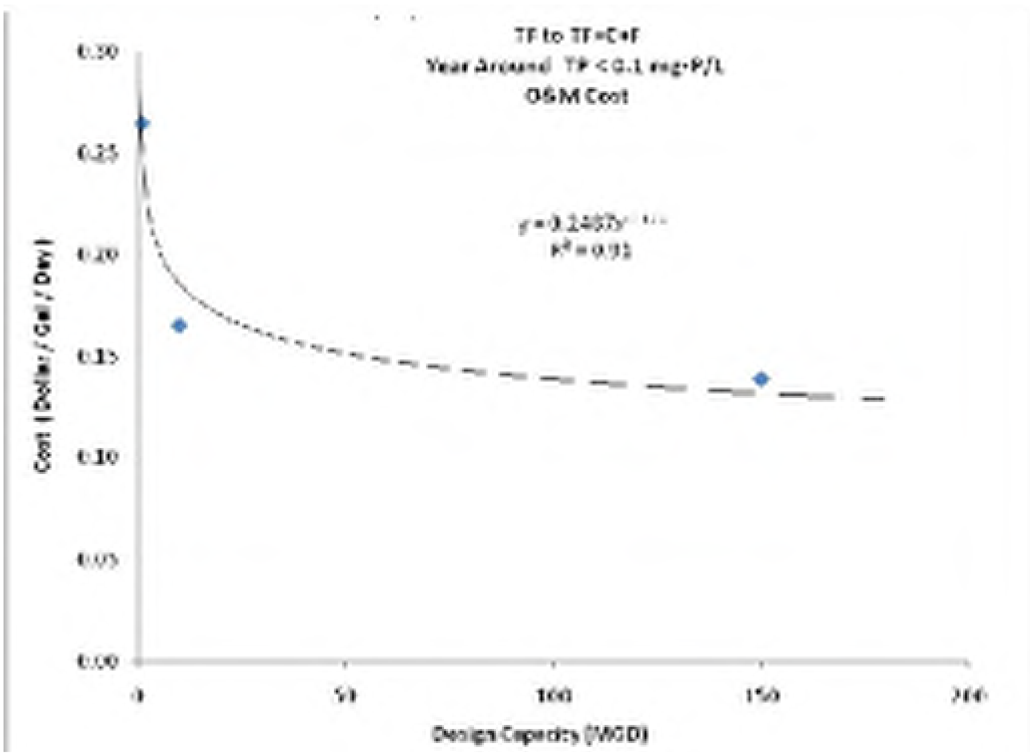


Figure 14-10. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective D Year-Round

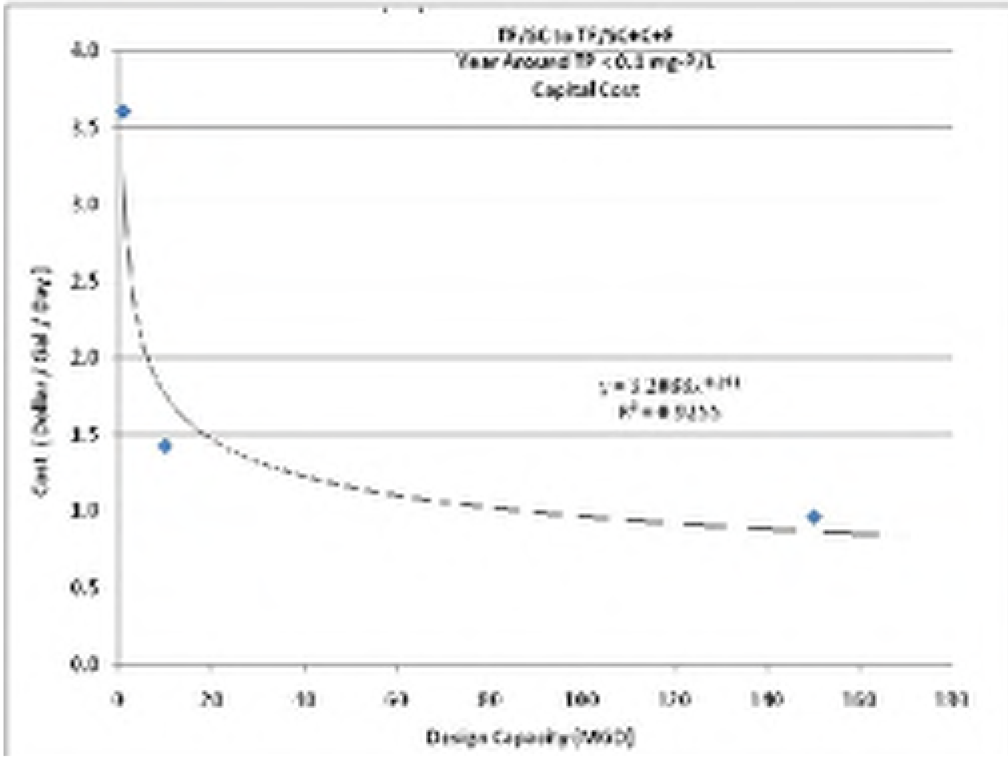


Figure 14-11. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective D Year-Round

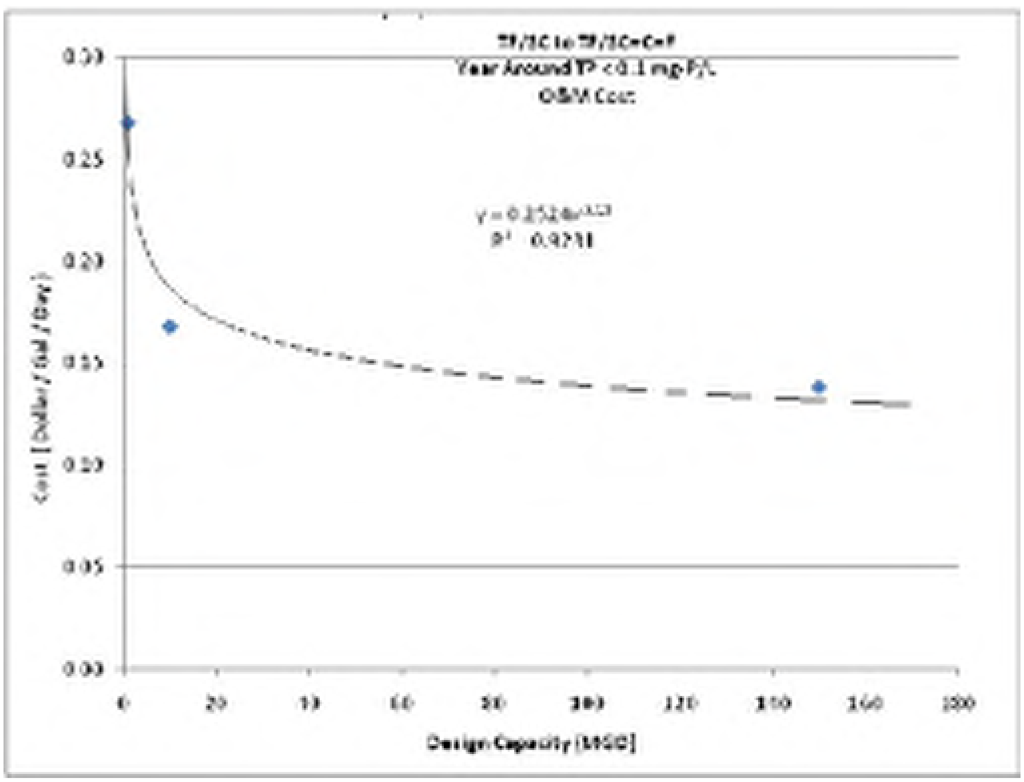


Figure 14-12. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective D Year-Round

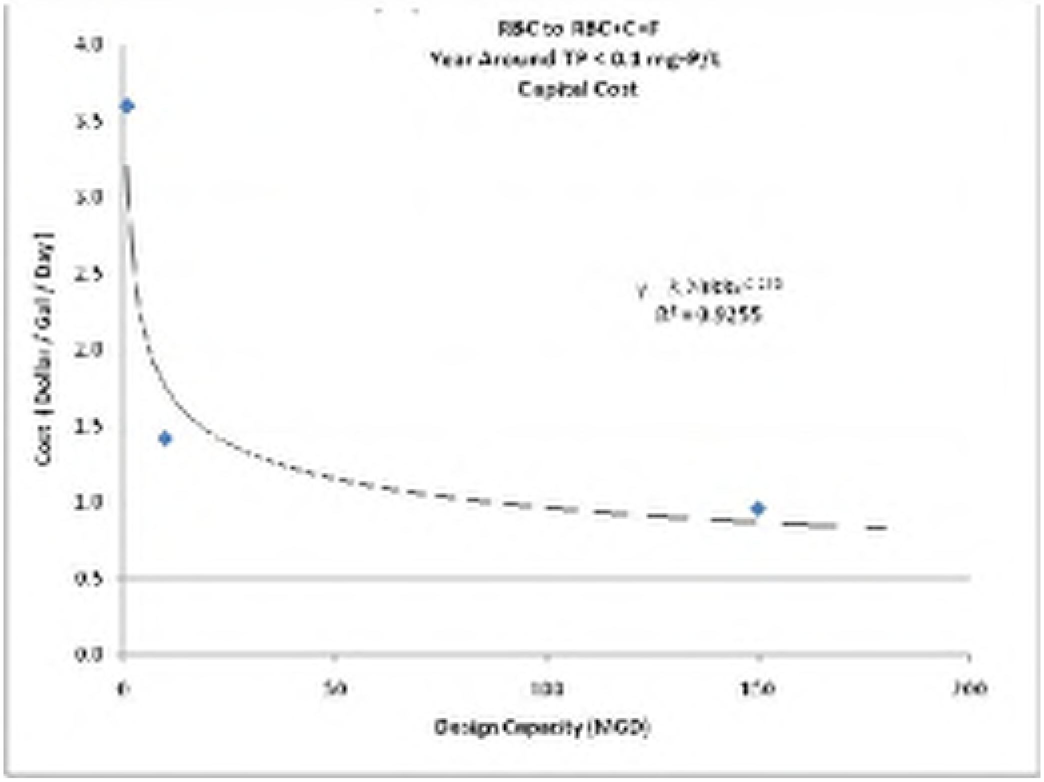


Figure 14-13. Capital Cost per Plant Capacity for RBC Upgraded for Objective D Year-Round

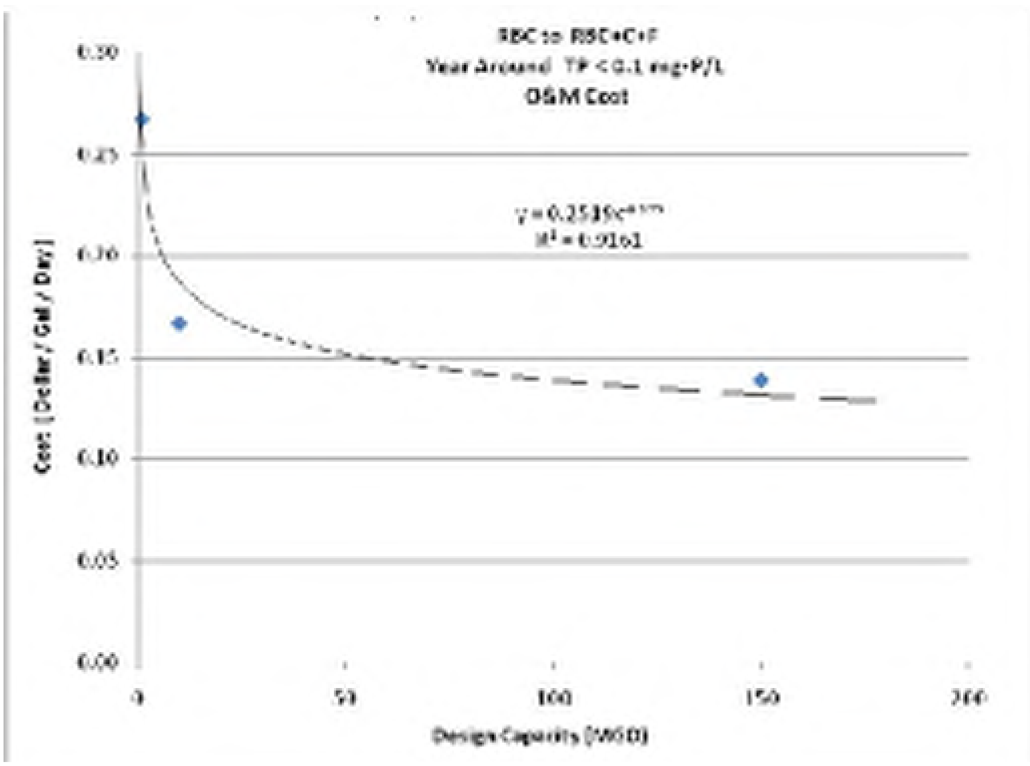


Figure 14-14. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective D Year-Round

TABLE 14-12.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$264,617	$1,043,049	$10,550,902
2014 O&M Cost	$297,872	$1,864,659	$23,490,382
Total Annual Cost	**$562,489**	**$2,907,708**	**$34,041,284**
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Cost for TP Reduction ($/lb TP removed)	$42.81	$22.13	$17.27

Equation:[a] .... $y = 213.36x^{-0.179}$
R-Square Value:.......... 0.911

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 14-13.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$264,617	$1,043,049	$10,550,902
2014 O&M Cost	$301,209	$1,891,108	$23,384,021
Total Annual Cost	**$565,826**	**$2,934,157**	**$33,934,923**
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Cost for TP Reduction ($/lb TP removed)	$43.06	$22.33	$17.22

Equation:[a] .... $y = 218.9x^{-0.18}$
R-Square Value:.......... 0.9173

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 14-14.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$264,617	$1,043,049	$10,550,902
2014 O&M Cost	$301,383	$1,878,840	$23,420,038
Total Annual Cost	**$566,000**	**$2,921,889**	**$33,970,940**
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Cost for TP Reduction ($/lb TP removed)	$43.07	$22.24	$17.24

Equation:[a] .... $y = 218.09x^{-0.18}$
R-Square Value:.......... 0.9141

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.1.5 Membrane Biological Reactor Plants

Table 14-15 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D year-round for an MBR plant. Figures 14-15 and 14-16 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-16 presents the annualized unit costs for reducing nutrient loads.

TABLE 14-15.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.32	$0.34	$0.28
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.11	$0.09

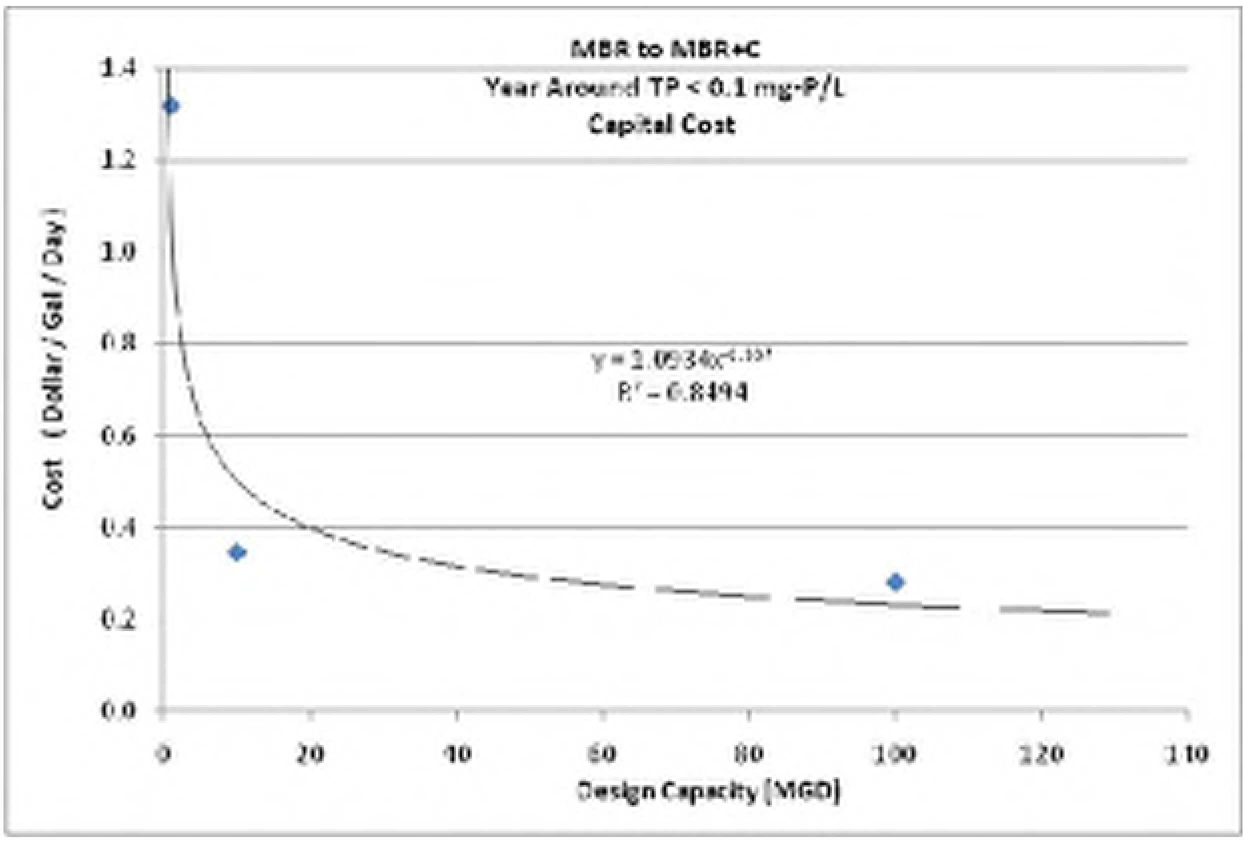


Figure 14-15. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective D Year-Round

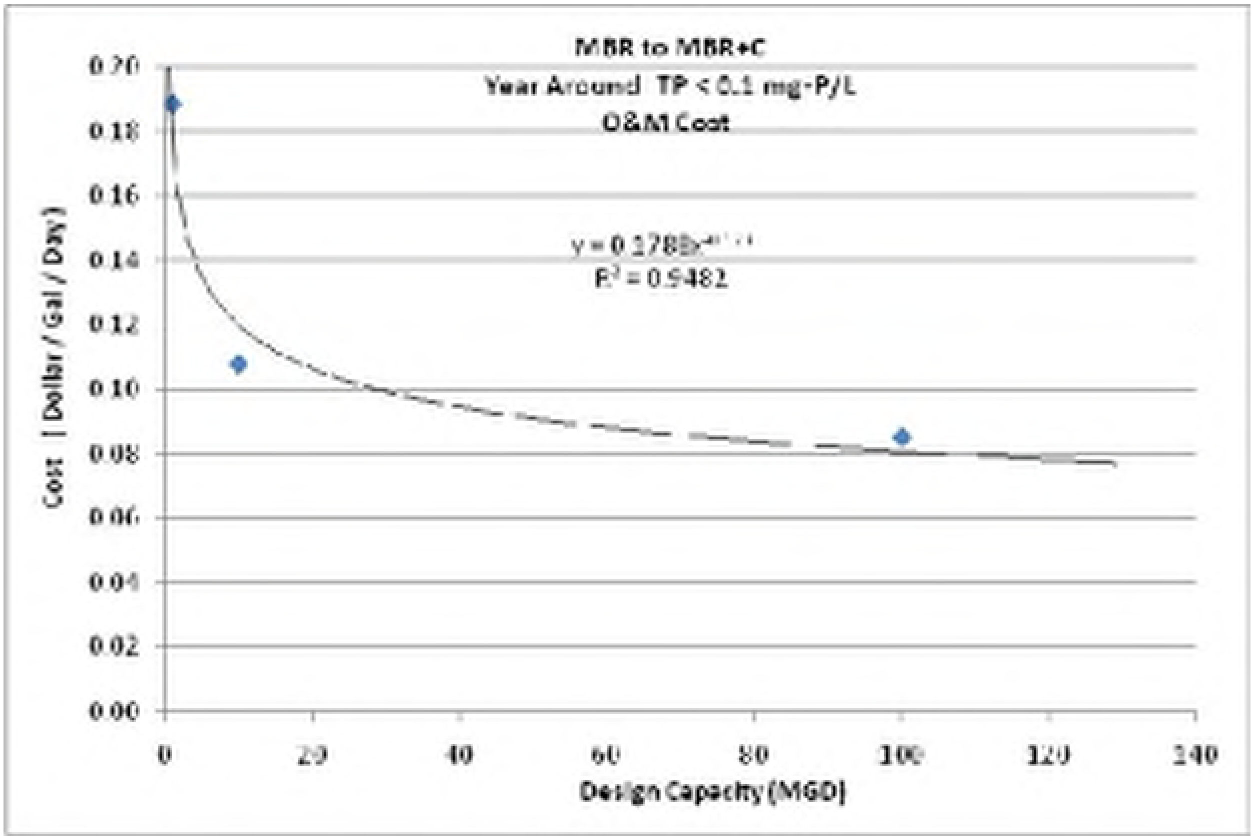


Figure 14-16. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective D Year-Round

TABLE 14-16.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$97,008	$253,136	$20,51,414
2014 O&M Cost	$212,293	$1,213,732	$9,578,080
Total Annual Cost	**$309,301**	**$1,466,868**	**$11,629,494**
Annual TP Load Reduction (lb/yr)	12,483	124,830	1,248,300
Estimated Cost for TP Reduction ($/lb TP removed)	$24.78	$11.75	$9.32

Equation:[a] .... $y = 168.53x^{-0.212}$
R-Square Value: 0.9155

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.1.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective D were developed for these plants.

14.1.7 Aerated or Facultative Lagoon Plants

Table 14-17 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D year-round for an aerated lagoon plant. Figures 14-17 and 14-18 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-18 and Figures 14-19 and 14-20 summarize these costs for a facultative lagoon plant. Tables 14-19 and 14-20 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

**TABLE 14-17.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$6.85	$6.37	$3.72	$3.41
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.39	$0.25	$0.12	$0.07

**TABLE 14-18.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$6.85	$6.37	$3.72	$3.41
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.39	$0.25	$0.12	$0.07

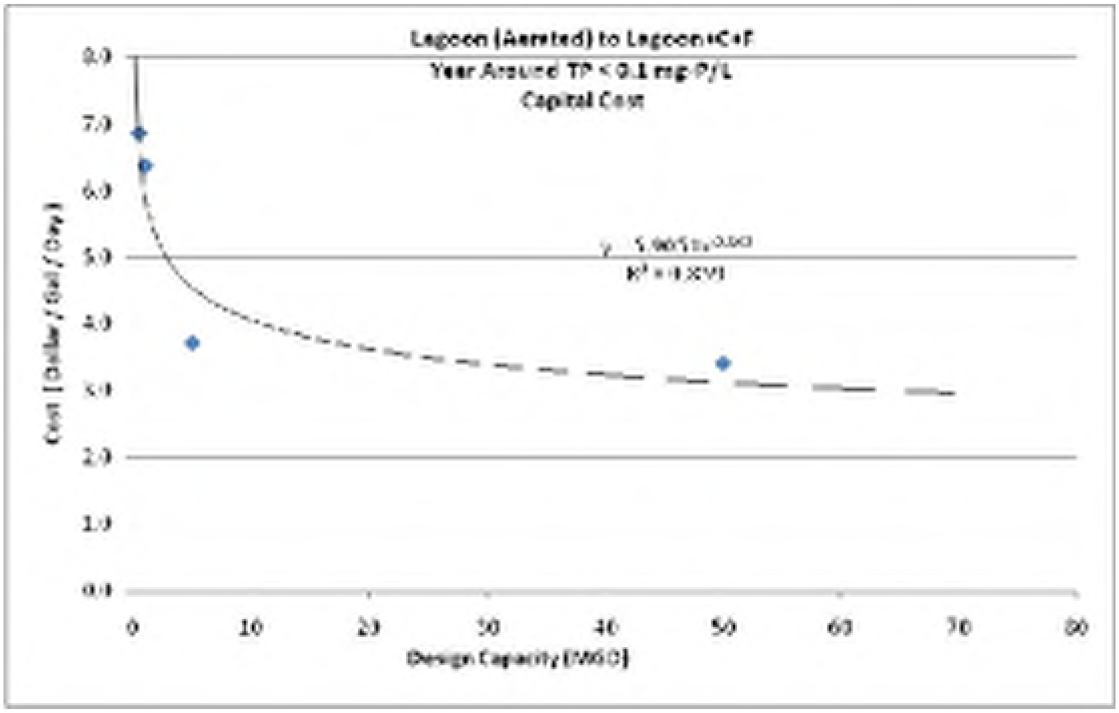


Figure 14-17. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective D Year-Round

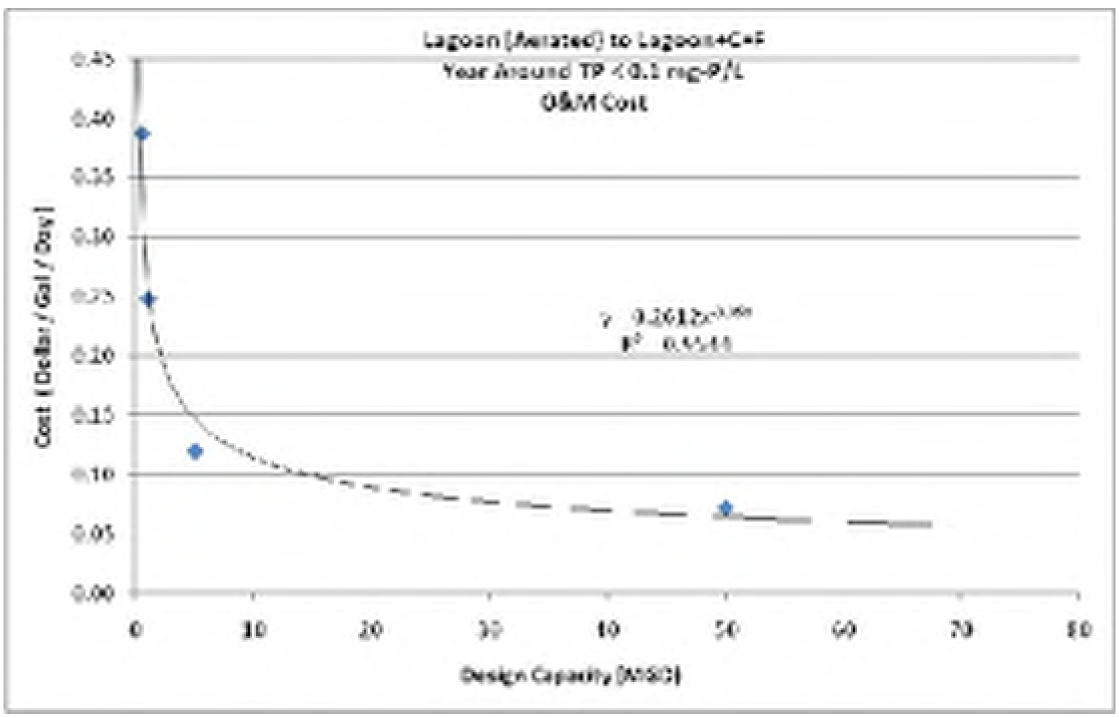


Figure 14-18. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective D Year-Round

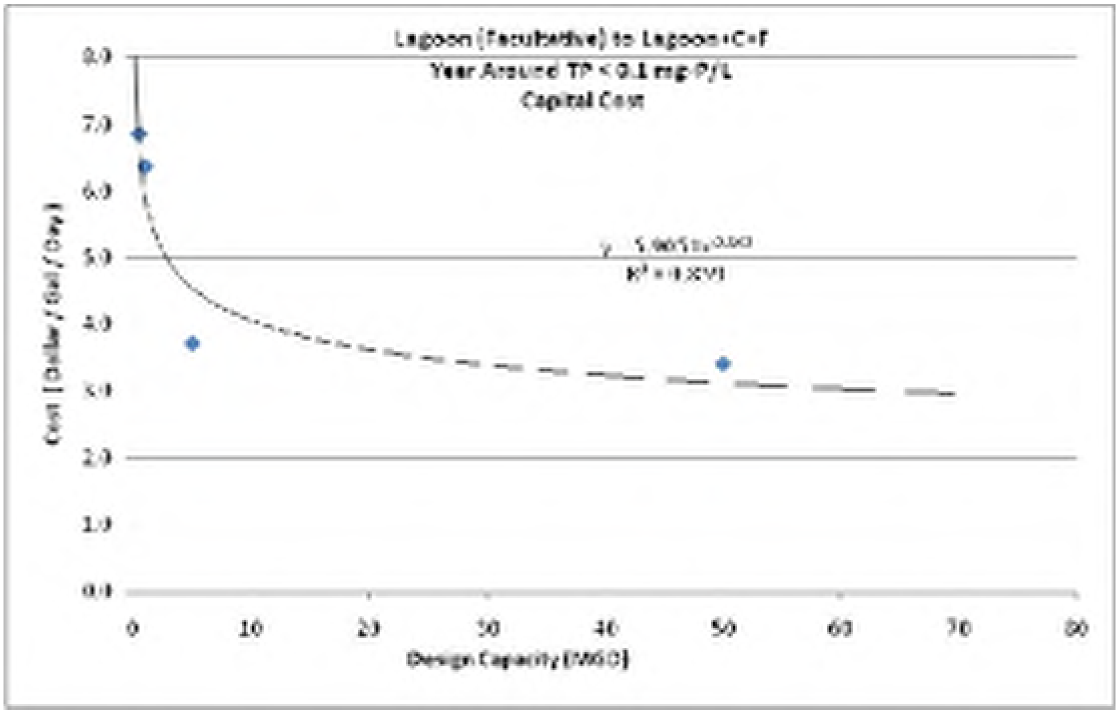


Figure 14-19. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective D Year-Round

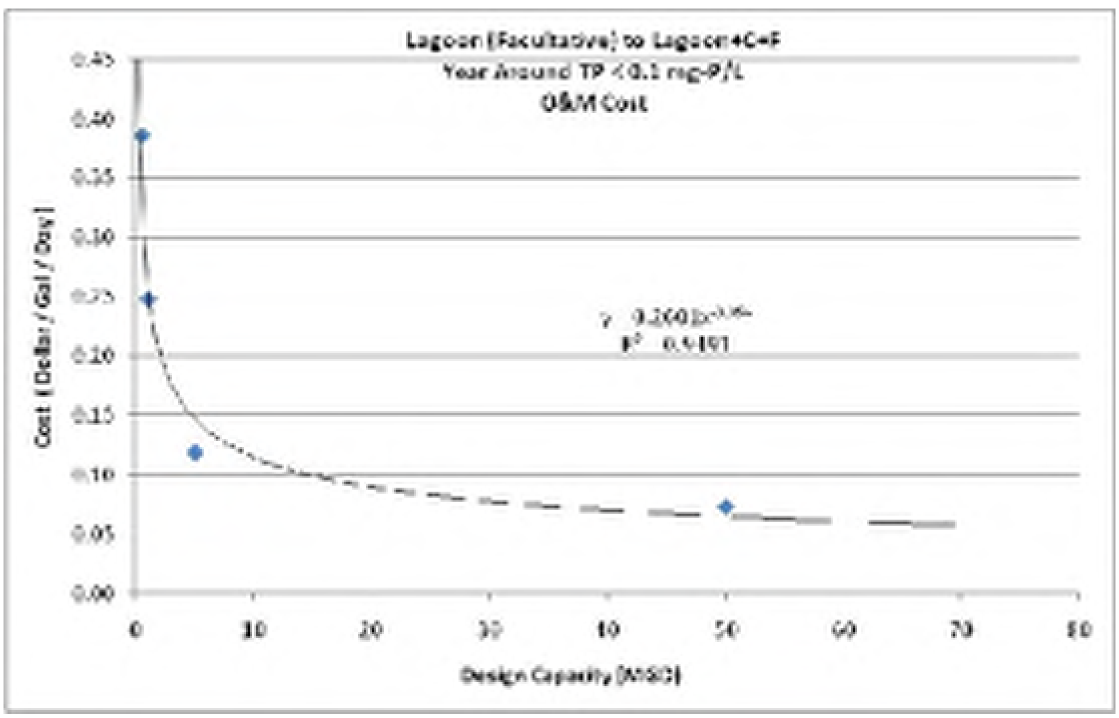


Figure 14-20. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective D Year-Round

TABLE 14-19.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$251,627	$467,514	$1,367,389	$12,537,645
2014 O&M Cost	$217,989	$279,379	$672,379	$4,047,892
Total Annual Cost	**$469,615**	**$746,893**	**$2,039,768**	**$16,585,537**
Annual TP Load Reduction (lb/yr)	6,570	13,140	65,700	657,000
Estimated Cost for TP Reduction ($/lb TP removed)	$71.48	$56.84	$31.05	$25.24

Equation:[a] .... $y = 489.23x^{-0.229}$
R-Square Value: 0.9088

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 14-20.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE D YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$251,627	$467,514	$1,367,389	$12,537,645
2014 O&M Cost	$217,144	$278,985	$666,583	$4,106,982
Total Annual Cost	**$468,771**	**$746,499**	**$2,033,972**	**$16,644,627**
Annual TP Load Reduction (lb/yr)	6,570	13,140	65,700	657,000
Estimated Cost for TP Reduction ($/lb TP removed)	$71.35	$56.81	$30.96	$25.33

Equation:[a] .... $y = 483.82x^{-0.228}$
R-Square Value: 0.906

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.2 SEASONAL NUTRIENT REMOVAL

14.2.1 Extended Aeration Plants

Table 14-21 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D seasonally for an extended aeration plant using mechanical aeration. Figures 14-21 and 14-22 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-22 and Figures 14-23 and 14-24 summarize these costs for an extended aeration plant using diffuser aeration. Tables 14-23 and 14-24 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 14-21.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.80	$1.11	$0.81
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.18	$0.12	$0.10

TABLE 14-22.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.06	$1.38	$0.89
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.17	$0.11	$0.08

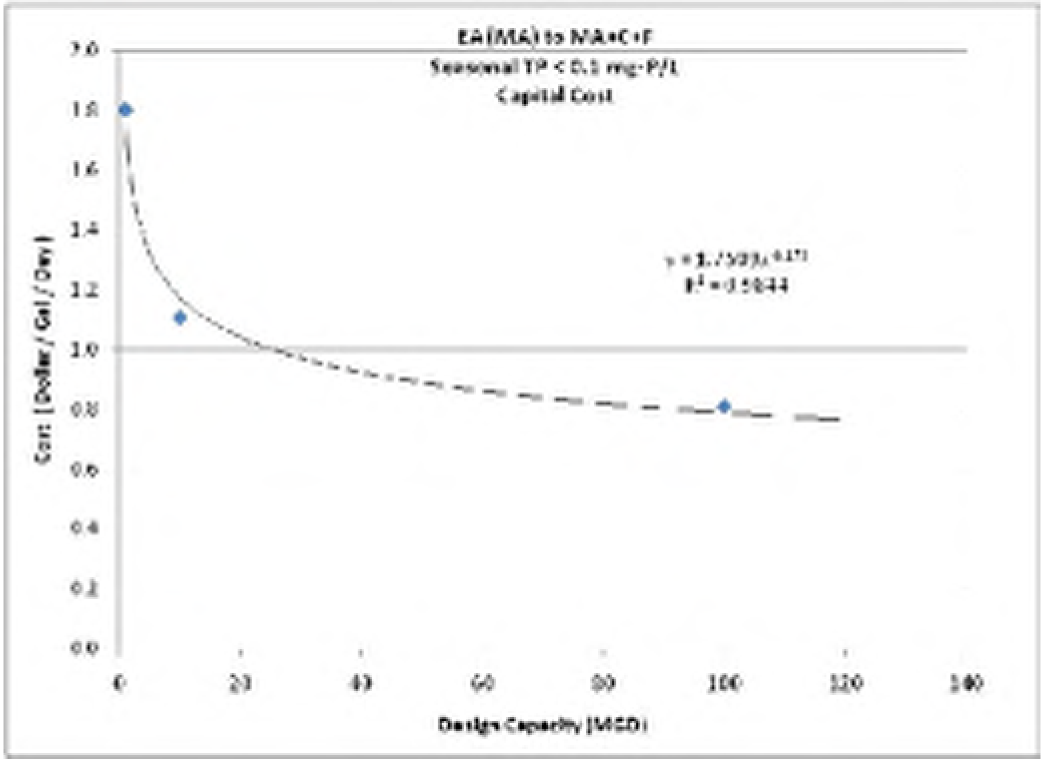


Figure 14-21. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective D Seasonally

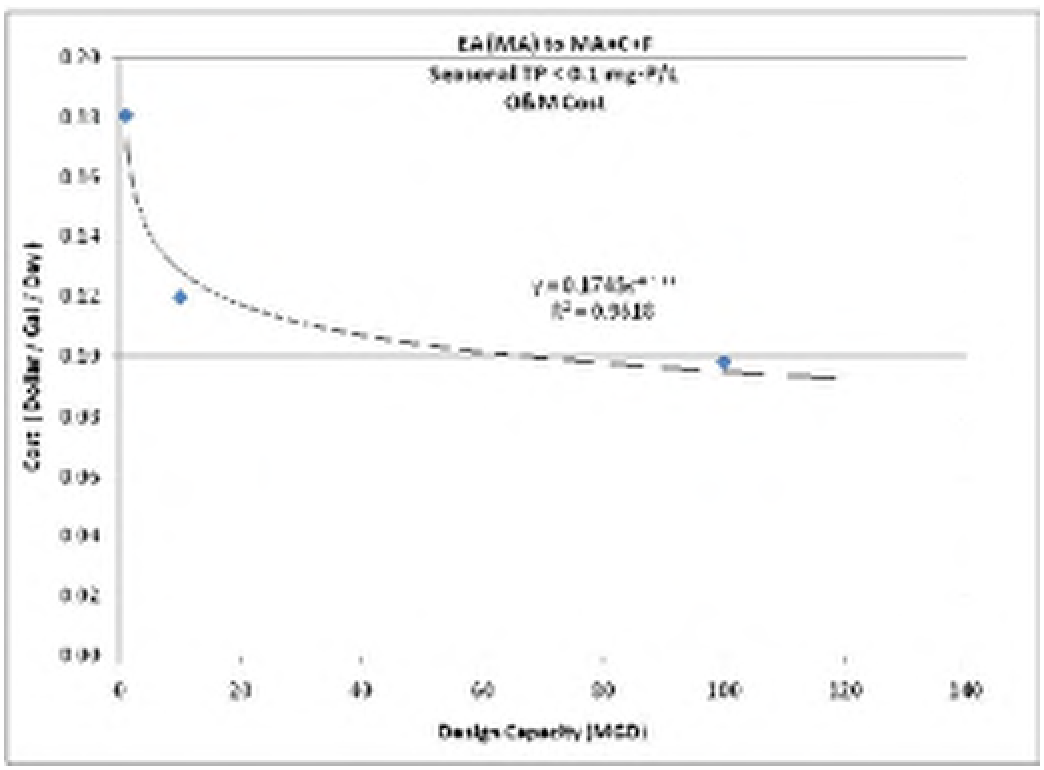


Figure 14-22. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective D Seasonal

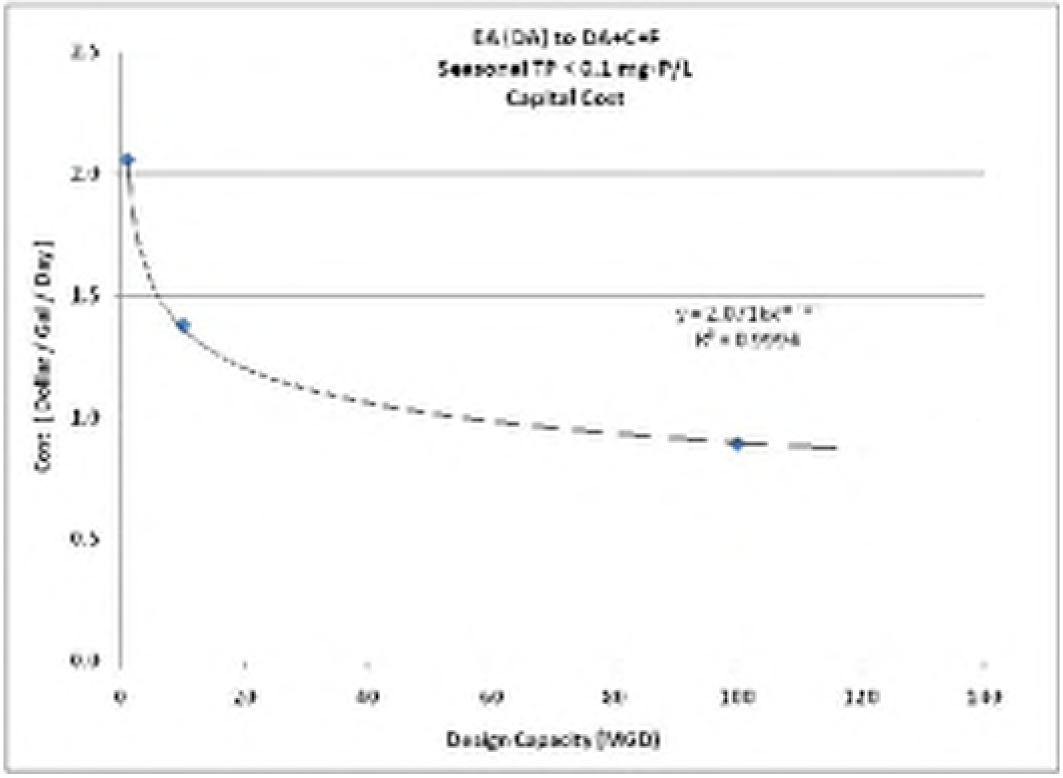


Figure 14-23. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective D Seasonally

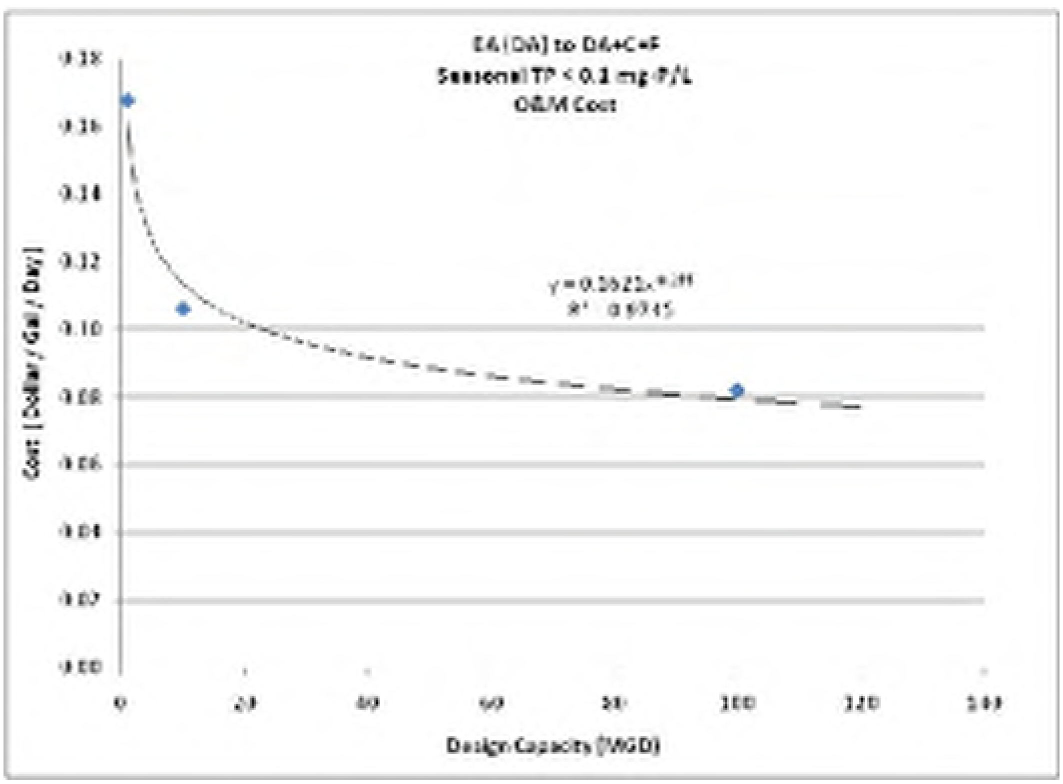


Figure 14-24. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective D Seasonal

TABLE 14-23.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$132,380	$814,509	$5,961,955
2014 O&M Cost	$203,379	$1,349,147	$11,047,094
Total Annual Cost	**$335,760**	**$2,163,657**	**$17,009,049**
Annual TP Load Reduction (lb/yr)	6,388	63,875	638,750
Estimated Cost for TP Reduction ($/lb TP removed)	$52.57	$33.87	$26.63

Equation:[a] .... $y = 185.49x^{-0.148}$
R-Square Value: 0.9722

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 14-24.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA ((DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$151,249	$1,013,995	$6,558,356
2014 O&M Cost	$188,692	$1,194,728	$9,241,215
Total Annual Cost	**$339,941**	**$2,208,723**	**$15,799,571**
Annual TP Load Reduction (lb/yr)	6,388	63,875	638,750
Estimated Cost for TP Reduction ($/lb TP removed)	$53.22	$34.58	$24.74

Equation:[a] .... $y = 224.95x^{-0.166}$
R-Square Value: 0.9948

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.2.2 Conventional Activated Sludge Plants

Table 14-25 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D seasonally for a conventional activated sludge plant. Figures 14-25 and 14-26 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-26 presents the annualized unit costs for reducing nutrient loads.

TABLE 14-25. ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.27	$1.15	$0.80
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.23	$0.13	$0.10

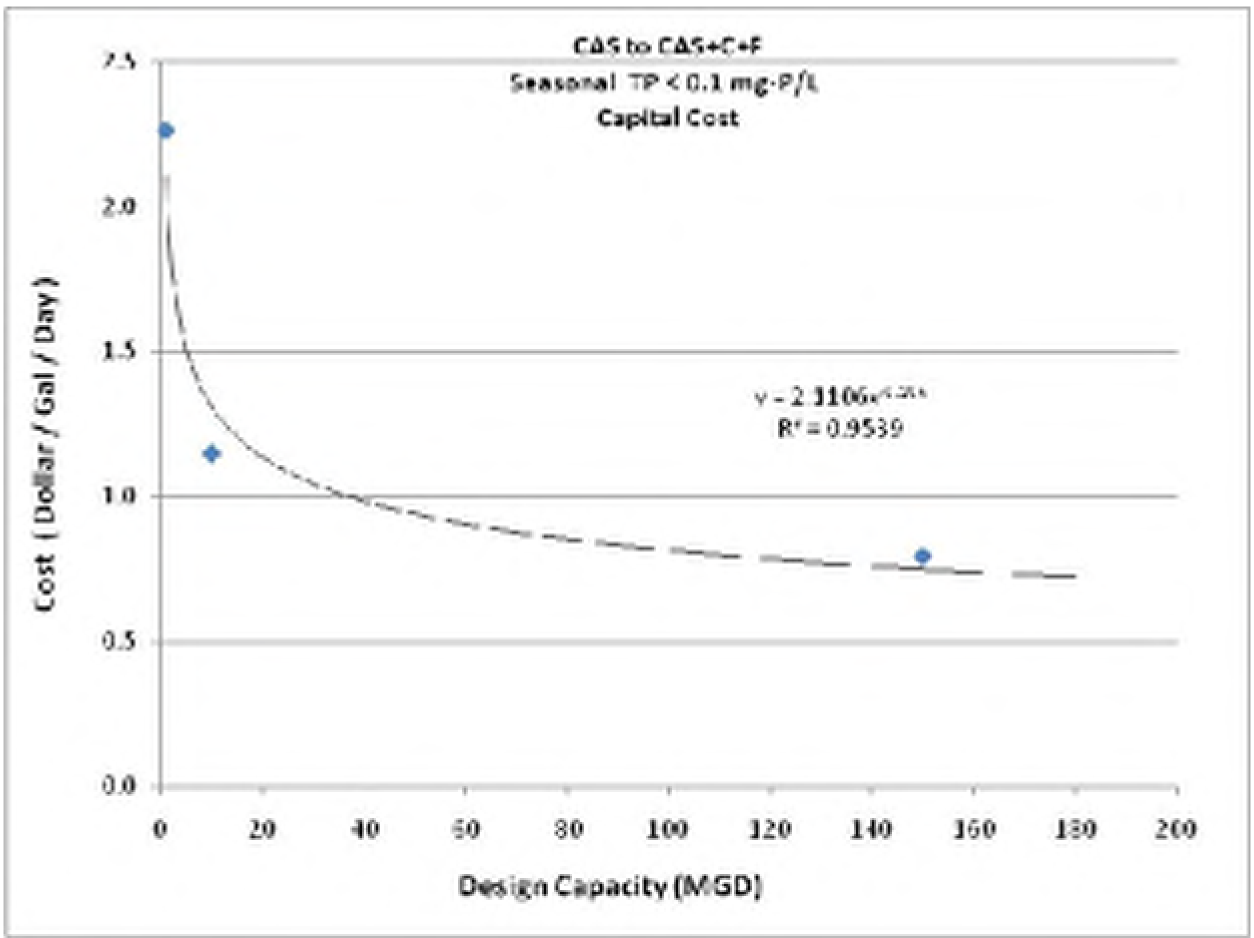


Figure 14-25. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective D Seasonally

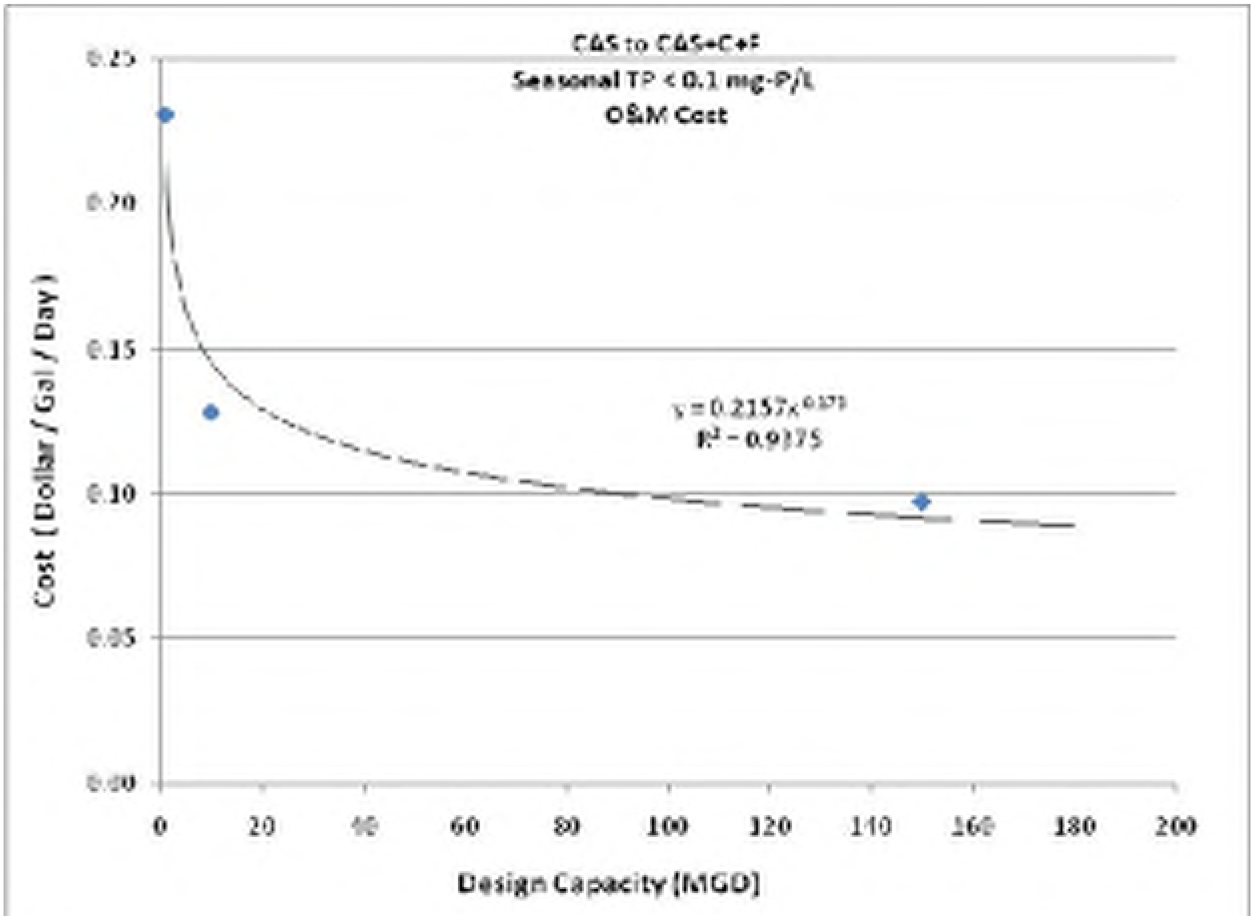


Figure 14-26. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective D Seasonal

TABLE 14-26.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$166,416	$845,327	$8,782,521
2014 O&M Cost	$260,128	$1,442,643	$16,418,247
Total Annual Cost	**$426,544**	**$2,287,970**	**$25,200,768**
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Cost for TP Reduction ($/lb TP removed)	$64.74	$34.73	$25.50

Equation:[a] .... $y = 304x^{-0.184}$
R-Square Value: 0.9441

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.2.3 Sequencing Batch Reactor Plants

Table 14-27 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D seasonally for an SBR plant. Figures 14-27 and 14-28 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-28 presents the annualized unit costs for reducing nutrient loads.

TABLE 14-27.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.98	$1.81	$1.05
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.15	$0.07	$0.05

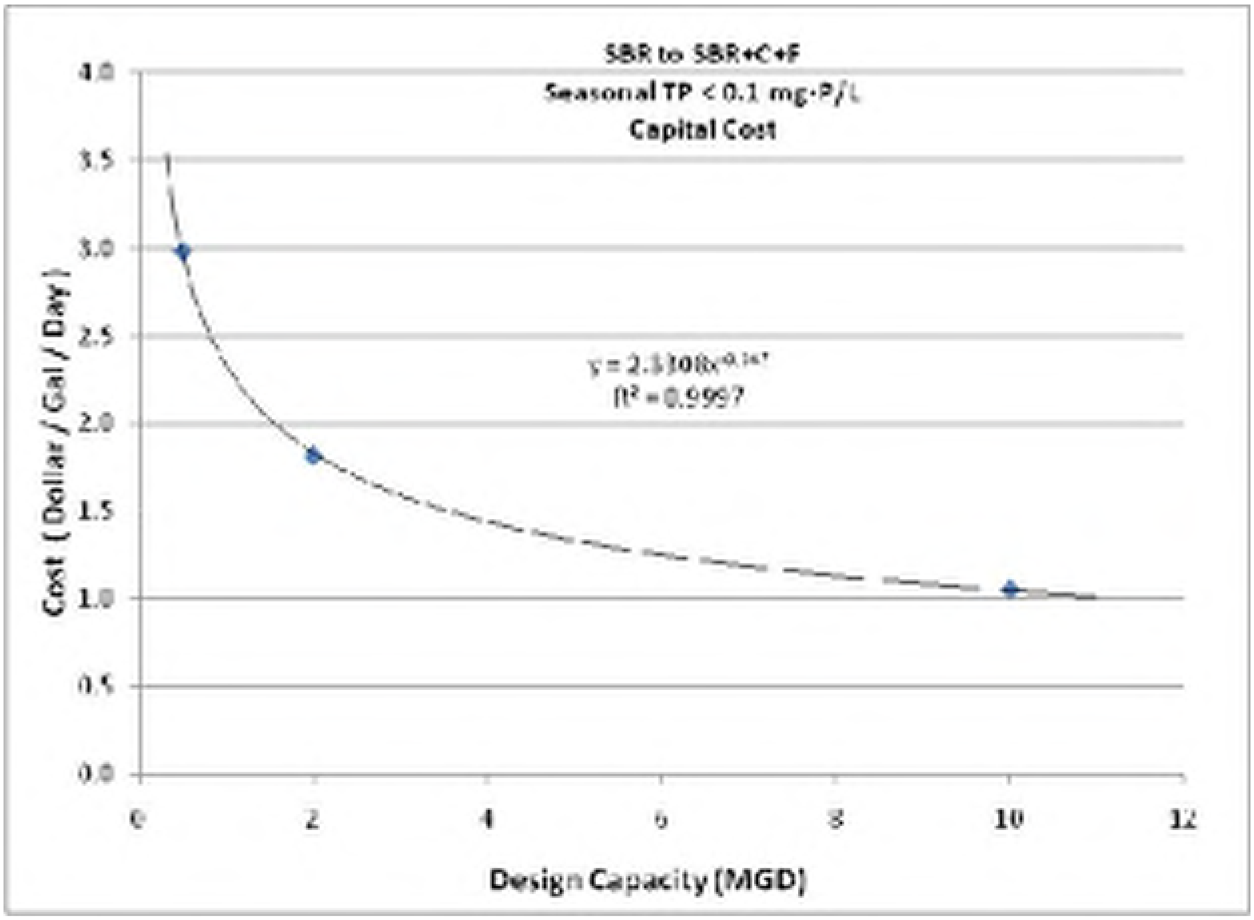


Figure 14-27. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective D Seasonally

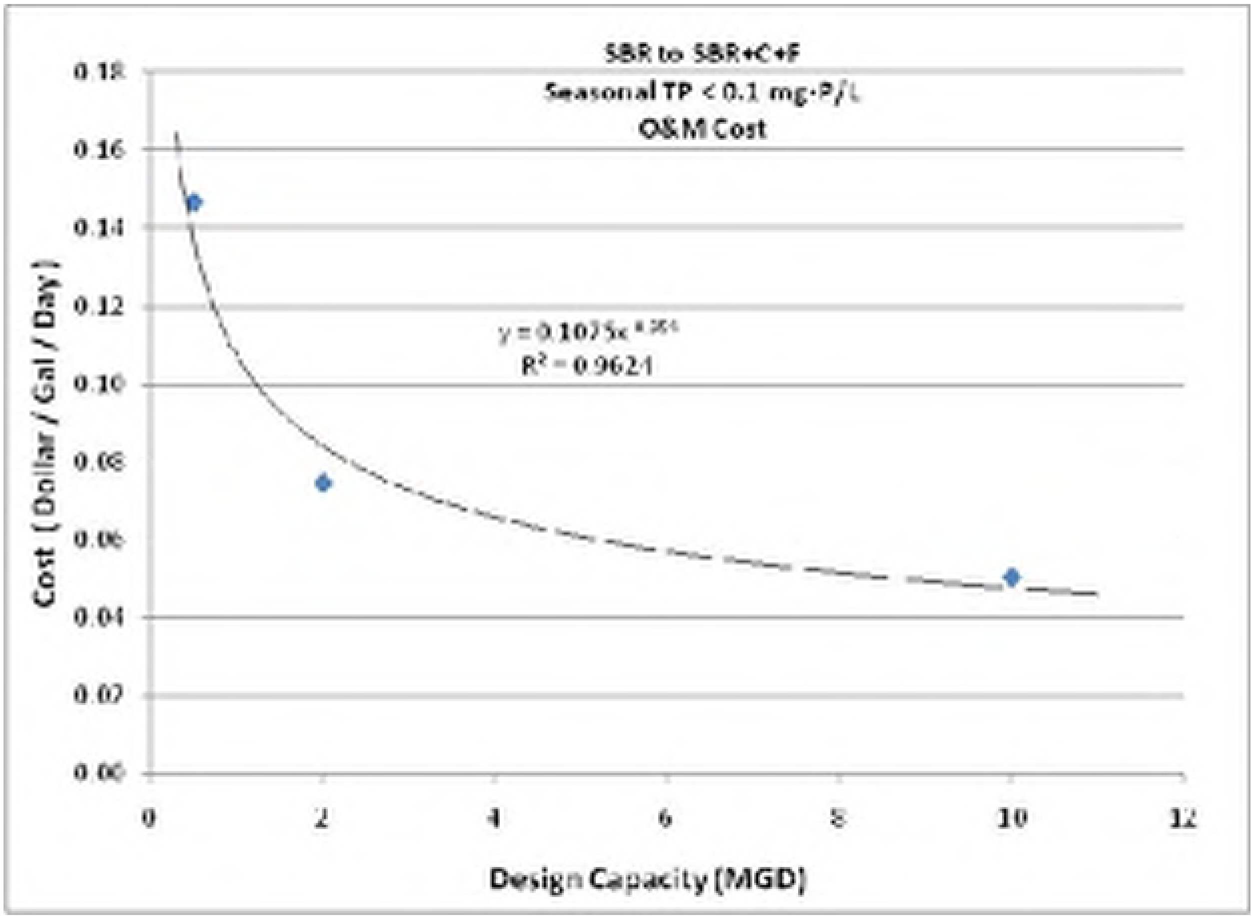


Figure 14-28. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective D Seasonal

TABLE 14-28.
UNIT NUTRIENT REMOVAL COSTS FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$109,450	$266,571	$773,265
2014 O&M Cost	$82,489	$167,701	$566,221
Total Annual Cost	**$191,938**	**$434,272**	**$1,339,486**
Annual TP Load Reduction (lb/yr)	1,487	5,950	29,748
Estimated Cost for TP Reduction ($/lb TP removed)	$129.05	$72.99	$45.03

Equation:[a] .... $y = 1616x^{-0.35}$
R-Square Value: 0.9918

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.2.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 14-29 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D seasonally for a trickling filter plant. Figures 14-29 and 14-30 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-30 and Figures 14-31 and 14-32 summarize these costs for a trickling filter/solids contact plant. Table 14-31 and Figures 14-33 and 14-34 summarize these costs for an RBC plant. Tables 14-32, 14-33 and 14-34 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 14-29.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.27	$1.15	$0.80
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.12	$0.09

TABLE 14-30.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.27	$1.15	$0.80
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.12	$0.09

TABLE 14-31.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$2.27	$1.15	$0.80
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.22	$0.12	$0.09

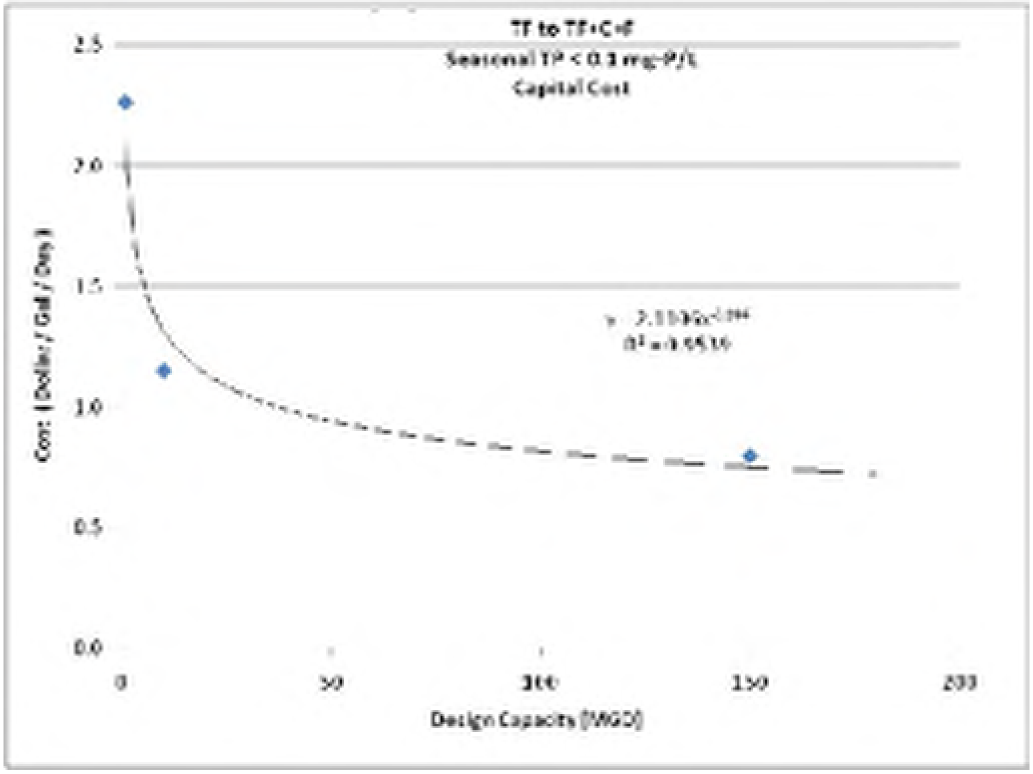


Figure 14-29. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective D Seasonally

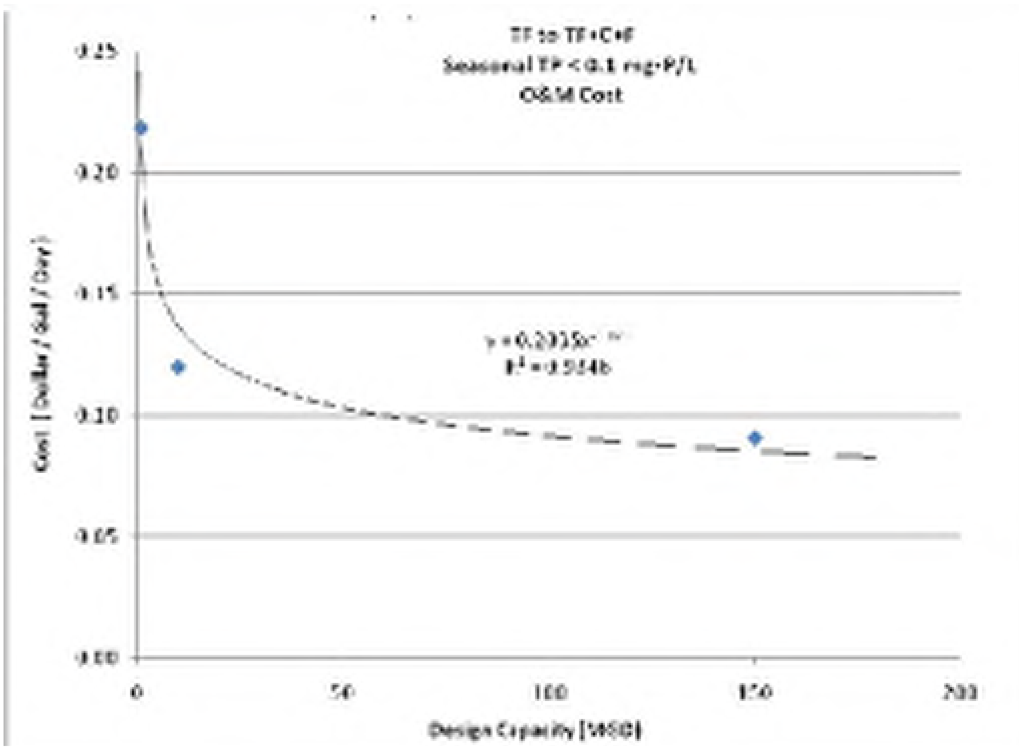


Figure 14-30. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective D Seasonal

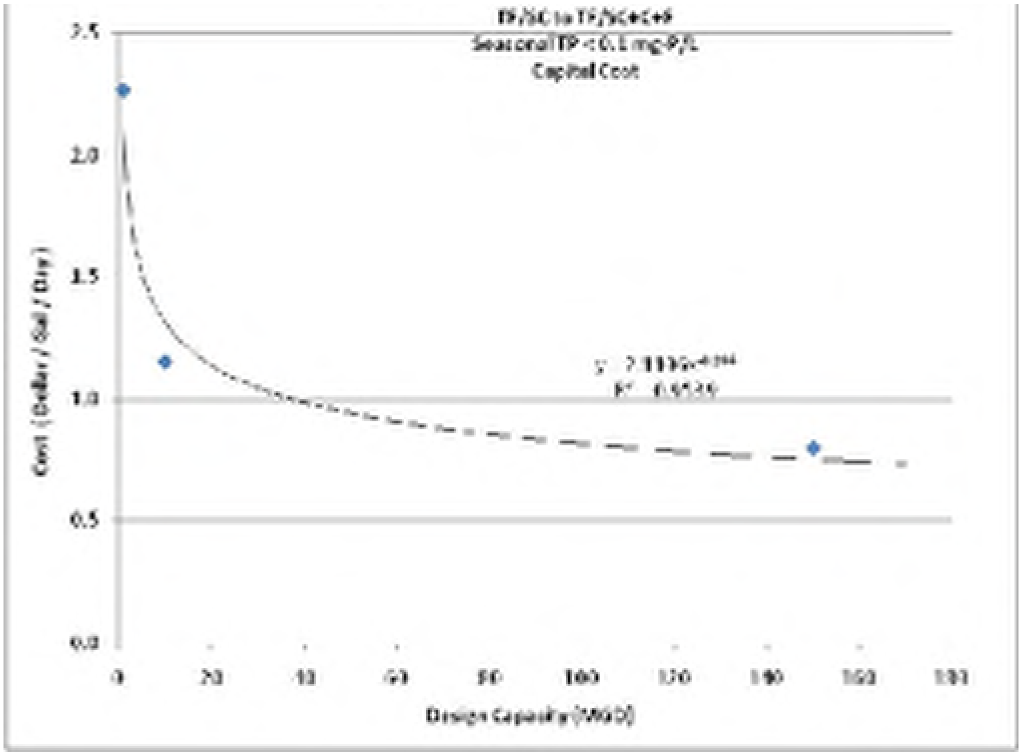


Figure 14-31. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective D Seasonally

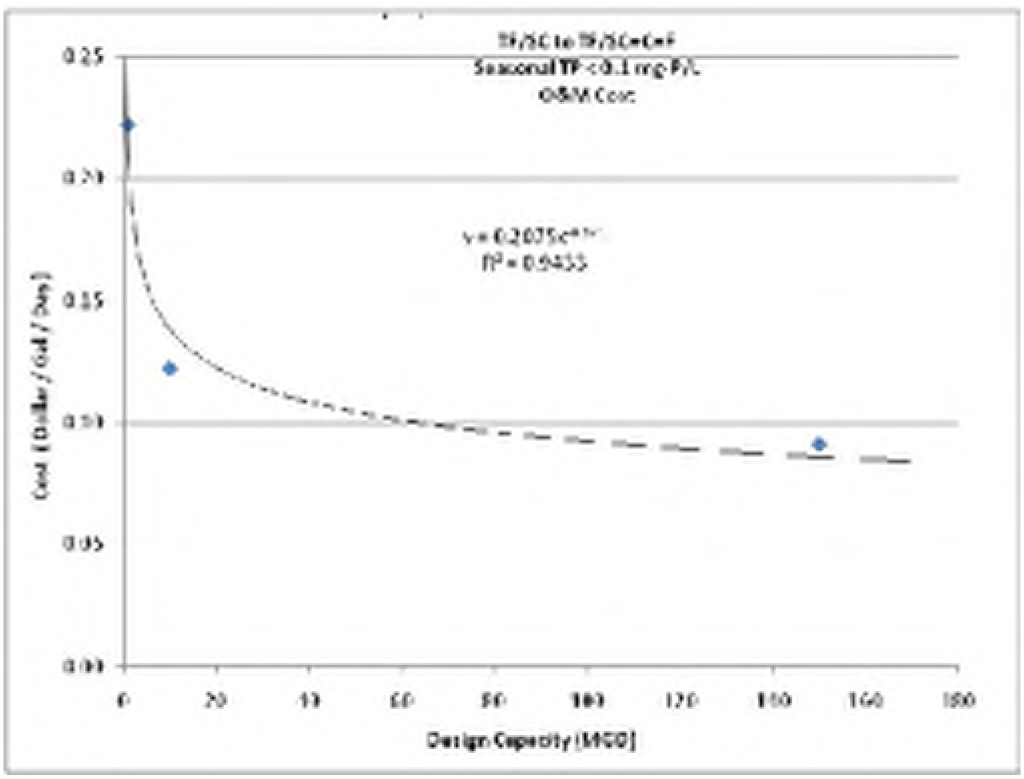


Figure 14-32. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective D Seasonal

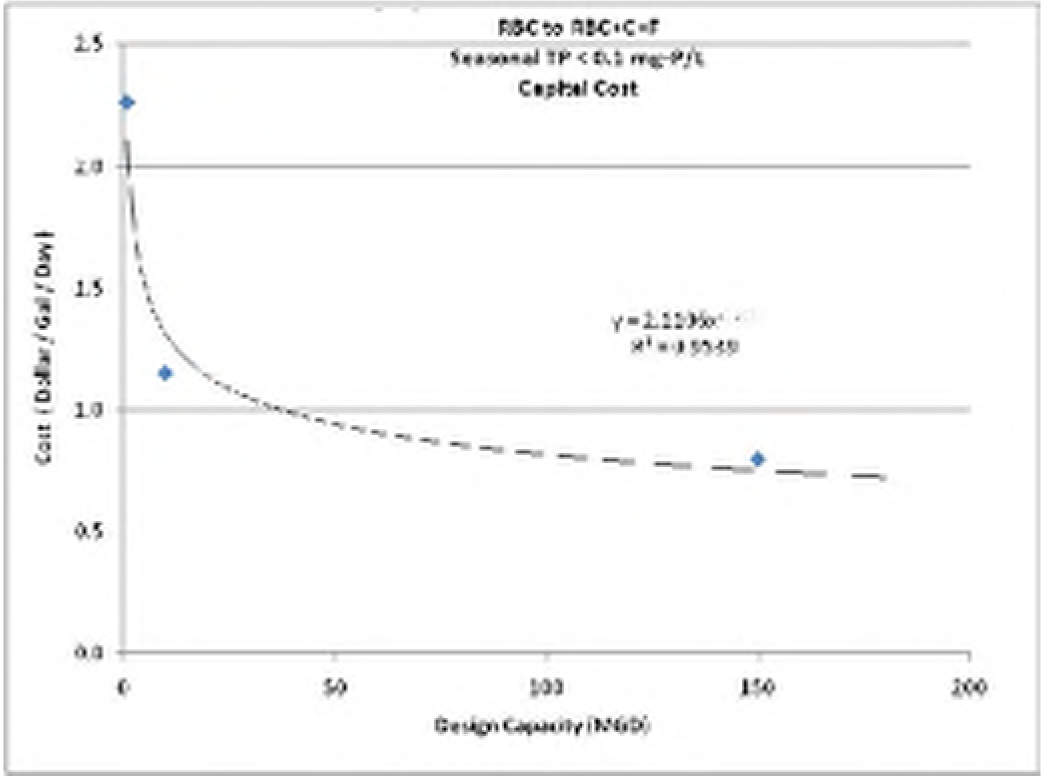


Figure 14-33. Capital Cost per Plant Capacity for RBC Plant Upgraded for Objective D Seasonally

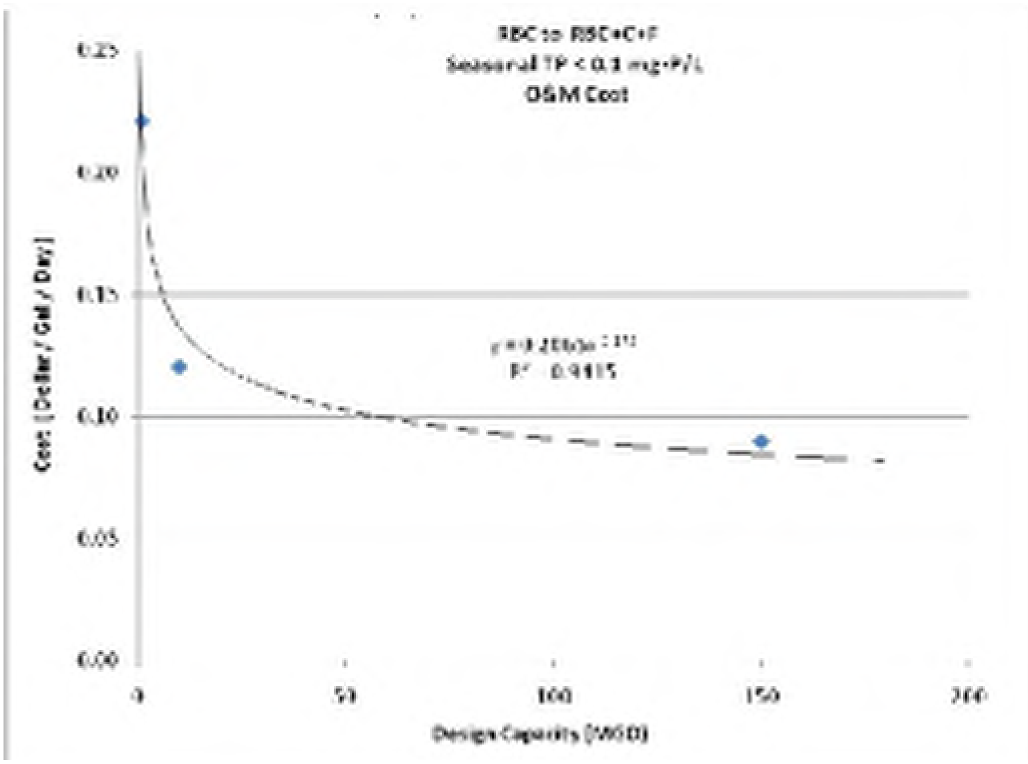


Figure 14-34. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective D Seasonal

**TABLE 14-32.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE D SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$166,416	$845,327	$8,782,521
2014 O&M Cost	$246,014	$1,346,356	$15,331,006
Total Annual Cost	**$412,430**	**$2,191,683**	**$24,113,527**
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Cost for TP Reduction ($/lb TP removed)	$62.60	$33.27	$24.40

Equation:[a] .... $y = 298.79x^{-0.186}$
R-Square Value: 0.9428

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

**TABLE 14-33.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE D SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	166,416	845,327	8,782,521
2014 O&M Cost	$249,902	$1,374,438	$15,356,892
Total Annual Cost	**$416,319**	**$2,2197,64**	**$24,139,414**
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Cost for TP Reduction ($/lb TP removed)	$63.19	$33.69	$24.43

Equation:[a] .... $y = 306.92x^{-0.188}$
R-Square Value: 0.9474

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

**TABLE 14-34.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE D SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$166,416	$845,327	$8,782,521
2014 O&M Cost	$249,188	$1,355,248	$15,128,977
Total Annual Cost	**$415,604**	**$2,200,574**	**$23,911,498**
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Cost for TP Reduction ($/lb TP removed)	$63.08	$33.40	$24.20

Equation:[a] .... $y = 310.09x^{-0.189}$
R-Square Value: 0.9465

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.2.5 Membrane Biological Reactor Plants

Table 14-35 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D seasonally for an MBR plant. Figures 14-35 and 14-36 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-36 presents the annualized unit costs for reducing nutrient loads.

TABLE 14-35.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.19	$0.27	$0.03
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.15	$0.07	$0.05

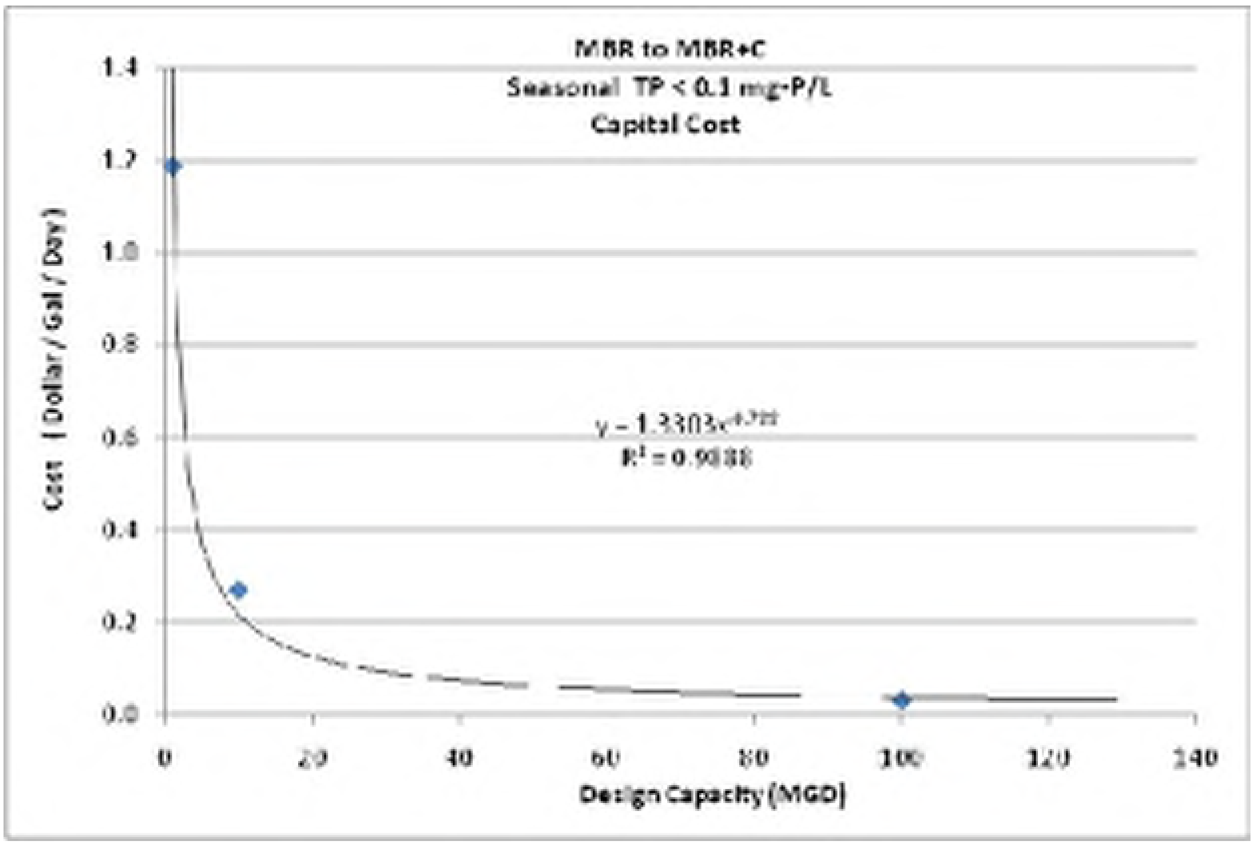


Figure 14-35. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective D Seasonally

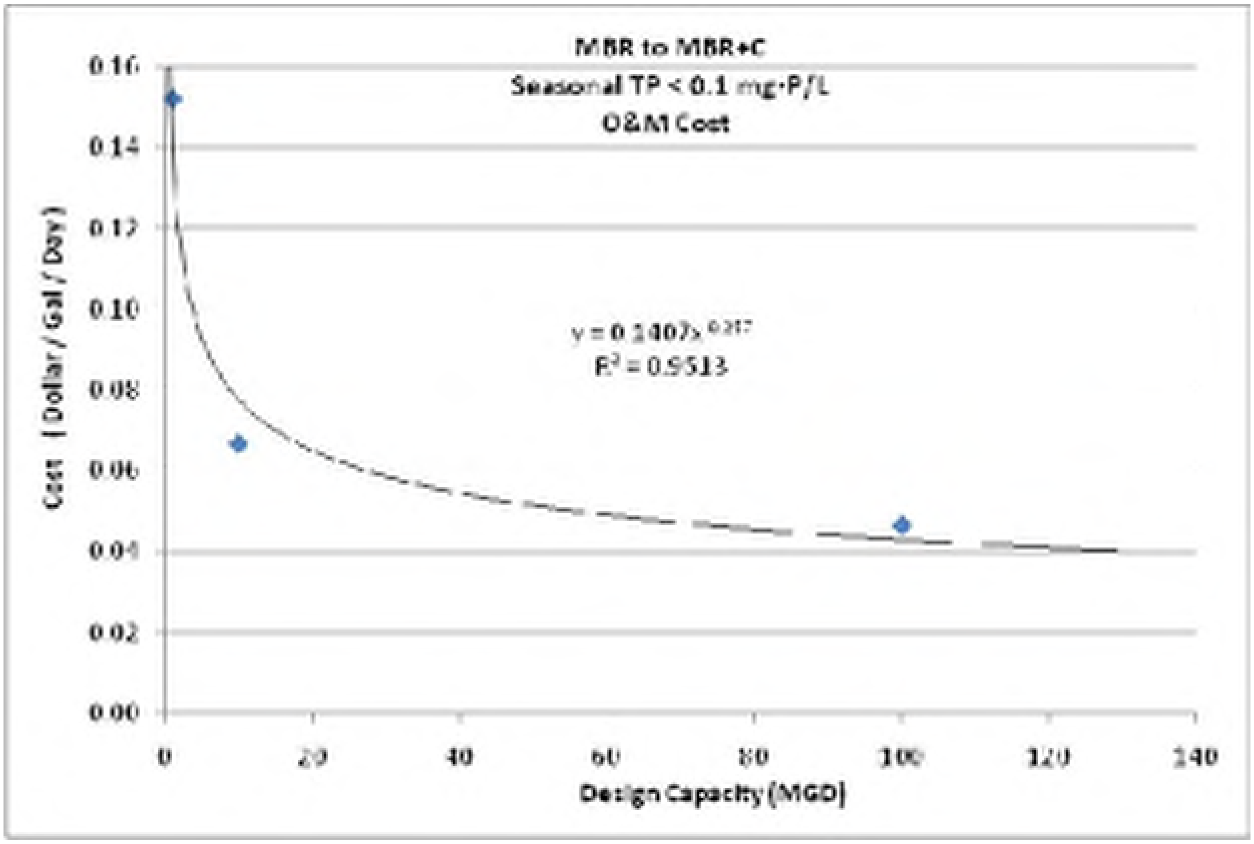


Figure 14-36. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective D Seasonal

TABLE 14-36.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$87,393	$198,859	$231,671
2014 O&M Cost	$171,139	$749,983	$5,229,902
Total Annual Cost	**$258,533**	**$948,841**	**$5,461,573**
Annual TP Load Reduction (lb/yr)	6,169	61,685	616,850
Estimated Cost for TP Reduction ($/lb TP removed)	$41.91	$15.38	$8.85

Equation:[a] .... $y = 740.77x^{-0.338}$
R-Square Value: 0.9729

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

14.2.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective D were developed for these plants.

14.2.7 Aerated or Facultative Lagoon Plants

Table 14-37 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective D seasonally for an aerated lagoon plan. Figures 14-37 and 14-38 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 14-38 and Figures 14-39 and 14-40 summarize these costs for a facultative lagoon plant. Tables 14-39 and 14-40 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 14-37.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$6.40	$4.66	$3.01	$2.60
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.40	$0.25	$0.13	$0.06

TABLE 14-38.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$6.40	$4.66	$3.01	$2.60
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.37	$0.23	$0.10	$0.05

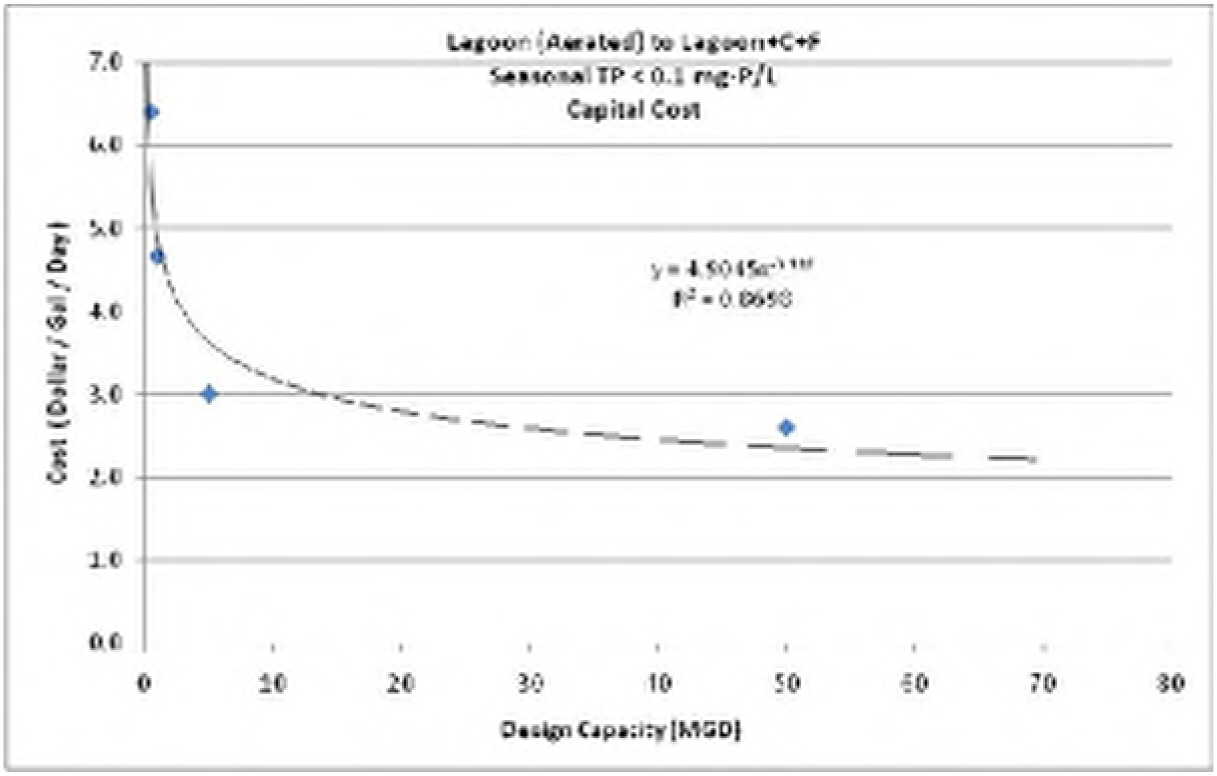


Figure 14-37. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective D Seasonally

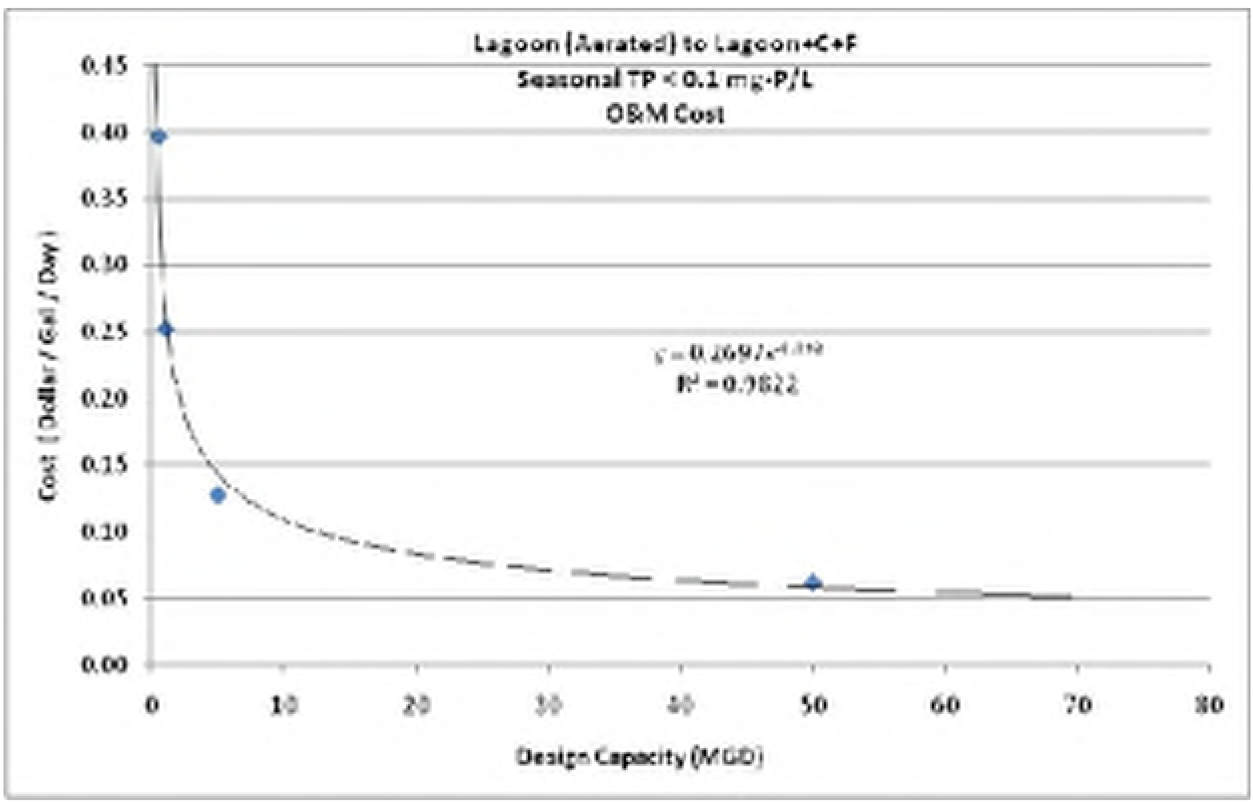


Figure 14-38. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective D Seasonal

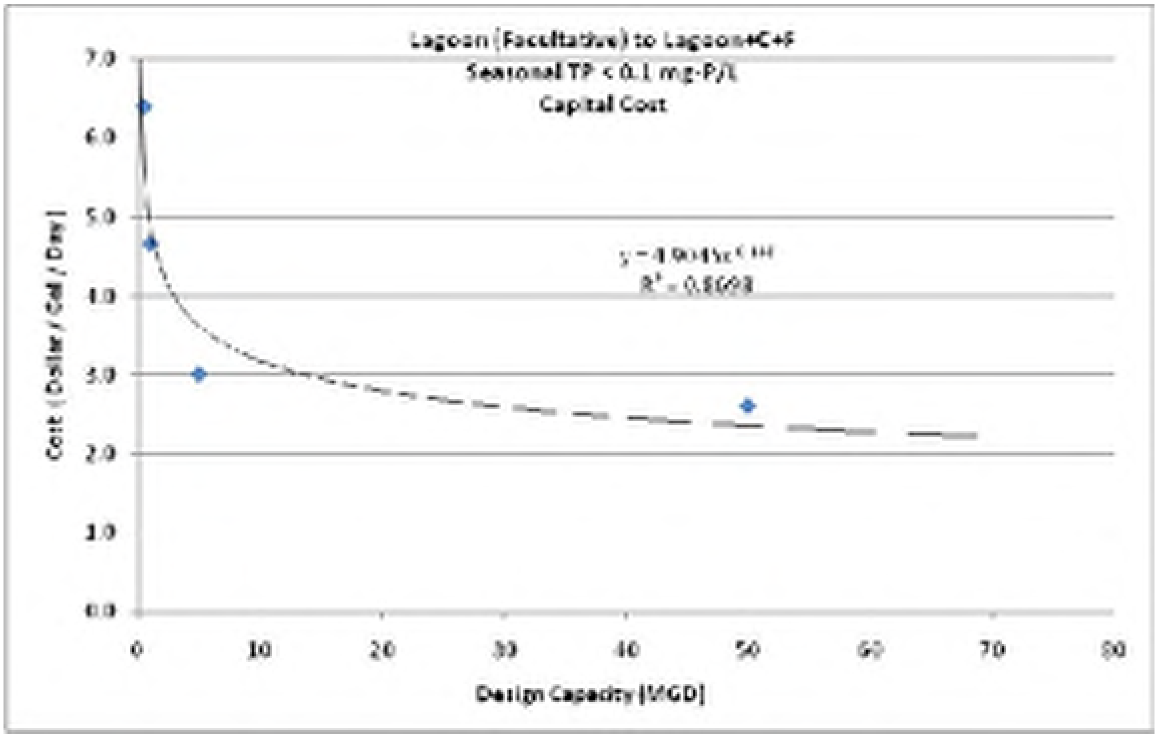


Figure 14-39. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective D Seasonally

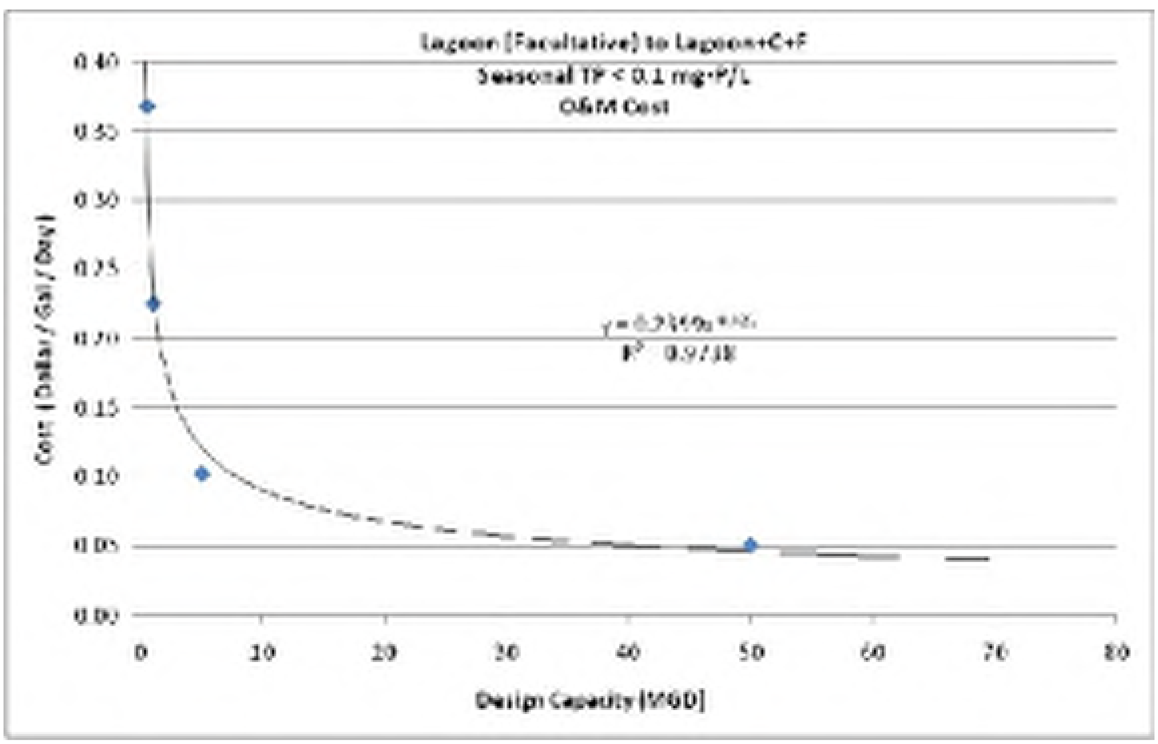


Figure 14-40. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective D Seasonal

TABLE 14-39.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$235,020	$342,527	$1,105,178	$9,565,922
2014 O&M Cost	$223,166	$284,253	$719,425	$3,500,332
Total Annual Cost	**$458,186**	**$626,780**	**$1,824,604**	**$13,066,254**
Annual TP Load Reduction (lb/yr)	3,294	6,588	32,941	329,413
Estimated Cost for TP Reduction ($/lb TP removed)	$139.09	$95.14	$55.39	$39.67

Equation:[a] .... $y = 1023.5x^{-0.263}$
R-Square Value: 0.9326

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 14-40.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE D SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$235,020	$342,527	$1,105,178	$9,562,922
2014 O&M Cost	$207,268	$253,864	$578,568	$2,851,477
Total Annual Cost	**$442,288**	**$596,391**	**$1,683,746**	**$12,417,399**
Annual TP Load Reduction (lb/yr)	3,294	6,588	32,941	329,413
Estimated Cost for TP Reduction ($/lb TP removed)	$134.27	$90.52	$51.11	$37.70

Equation:[a] .... $y = 1003.4x^{-0.267}$
R-Square Value: 0.9193

a. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

CHAPTER 15.
COST EVALUATION, OBJECTIVE E

15.1 YEAR-ROUND NUTRIENT REMOVAL

15.1.1 Extended Aeration Plants

Table 15-1 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E year-round for an extended aeration plant using mechanical aeration. Figures 15-1 and 15-2 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-2 and Figures 15-3 and 15-4 summarize these costs for an extended aeration plant using diffuser aeration. Tables 15-3 and 15-4 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

**TABLE 15-1.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.28	$2.34	$2.33
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.39	$0.14	$0.09

**TABLE 15-2.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.56	$0.84	$0.44
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.20	$0.08	$0.05

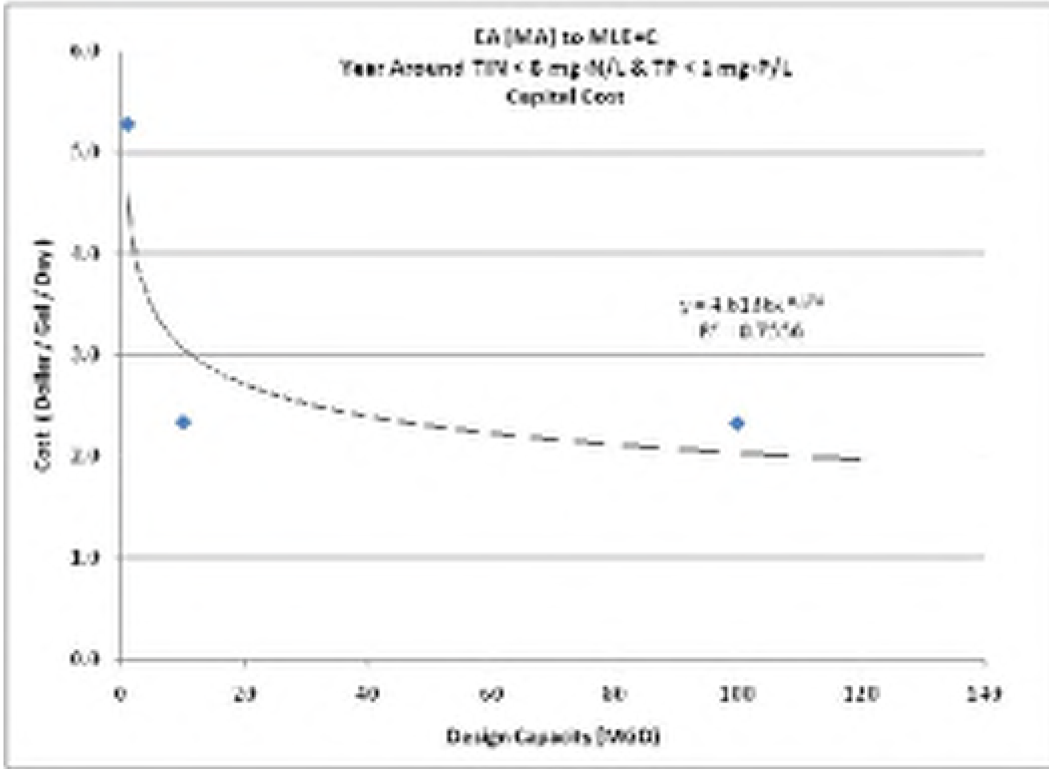


Figure 15-1. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective E Year-Round

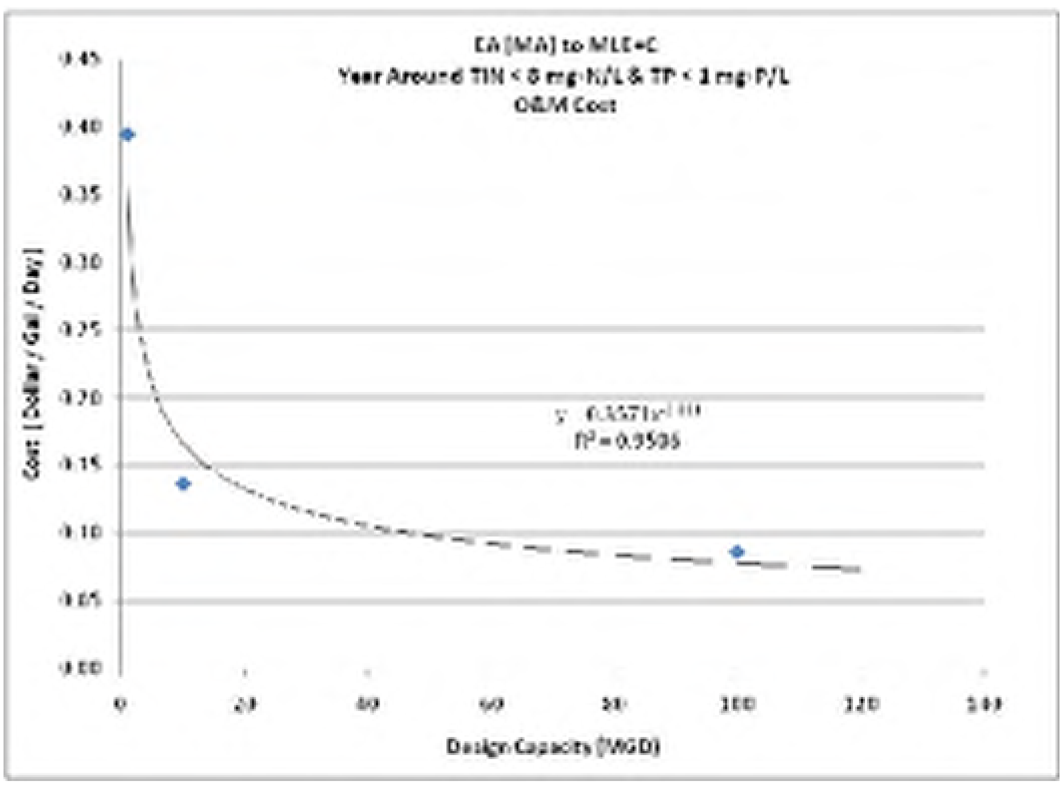


Figure 15-2. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective E Year-Round

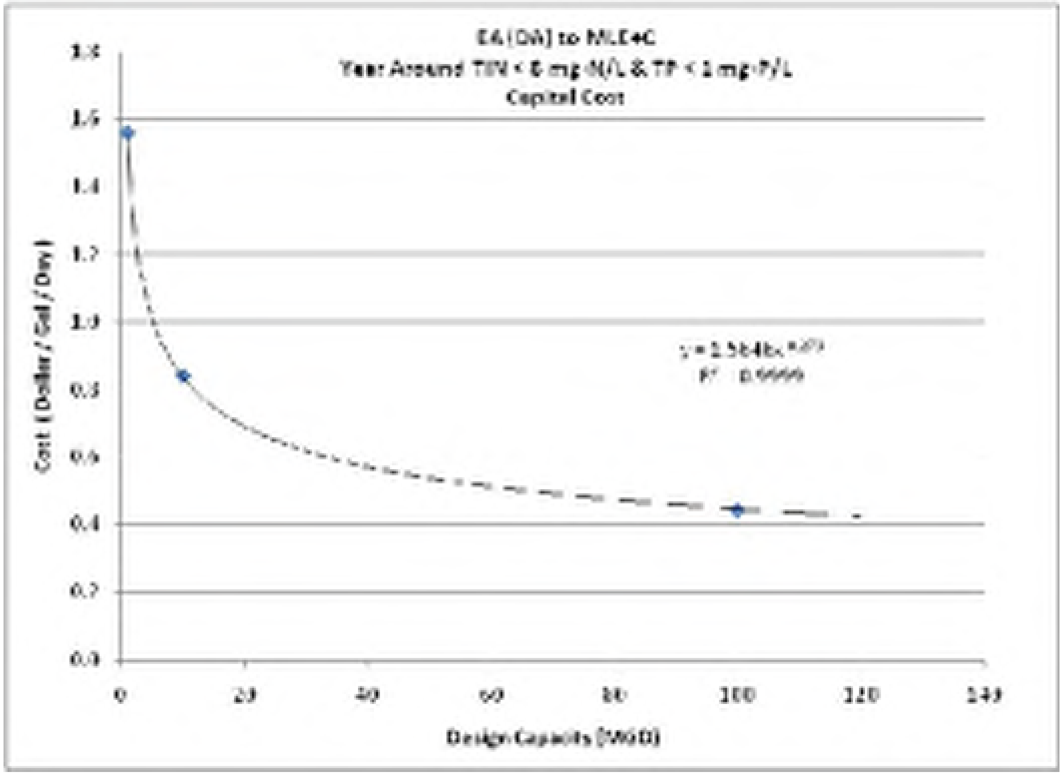


Figure 15-3. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective E Year-Round

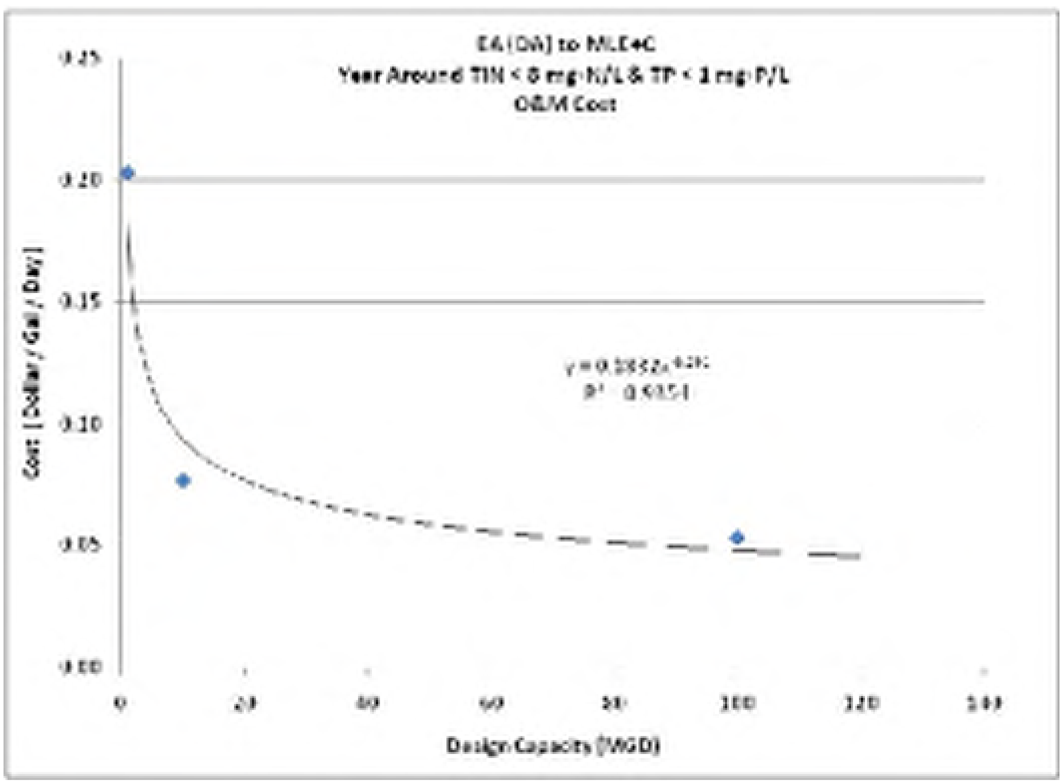


Figure 15-4. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective E Year-Round

TABLE 15-3.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$387,599	$1,720,185	$17,097,022
2014 Incremental O&M Cost	$444,351	$1,534,699	$9,678,363
Total Annual Cost	**$831,950**	**$3,254,884**	**$26,775,385**
Annual TIN Load Reduction (lb/yr)	35,442	35,4415	3,544,150
Annual TP Load Reduction (lb/yr)	11,060	110,595	1,105,950
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$15.87	$4.21	$3.06
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$24.38	$15.93	$14.41

TIN Cost Equation:[a] .... $y = 567.22x^{-0.357}$
TIN Cost R-Square Value:.......... 0.8889

TP Cost Equation:[b] .... $y = 66.869x^{-0.114}$
TP Cost R-Square Value: 0.8869

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-4.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$114,488	$617,872	$3,260,515
2014 Incremental O&M Cost	$228,309	$861,307	$5,979,378
Total Annual Cost	**$342,798**	**$1,479,178**	**$9,239,893**
Annual TIN Load Reduction (lb/yr)	35,442	354,415	3,544,150
Annual TP Load Reduction (lb/yr)	11,023	110,230	1,102,300
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$3.03	-$0.05	-$0.77
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$21.35	$13.58	$10.85

TIN Cost Equation and R-Square Value[a]

TP Cost Equation:[b] .... $y = 80.732x^{-0.147}$
TP Cost R-Square Value: 0.9636

a. Equation and R-square value for TIN not determined because annual cost estimates are below the level of precision that can be achieved using the CapdetWorks cost model.
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.1.2 Conventional Activated Sludge Plants

Table 15-5 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E year-round for a conventional activated sludge plant. Figures 15-5 and 15-6 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-6 presents the annualized unit costs for reducing nutrient loads.

TABLE 15-5.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$7.69	$4.73	$3.45
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.44	$0.25	$0.17

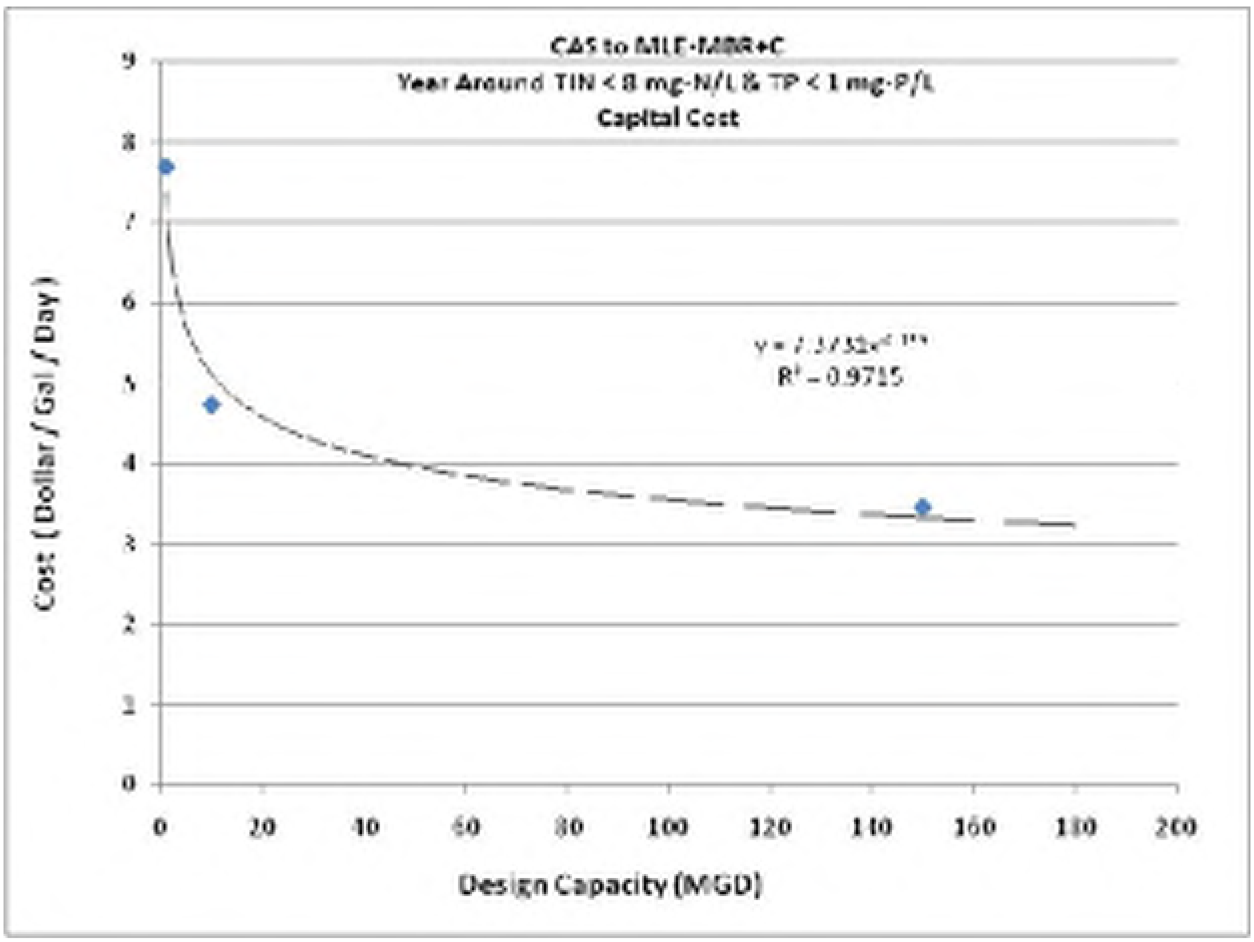


Figure 15-5. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective E Year-Round

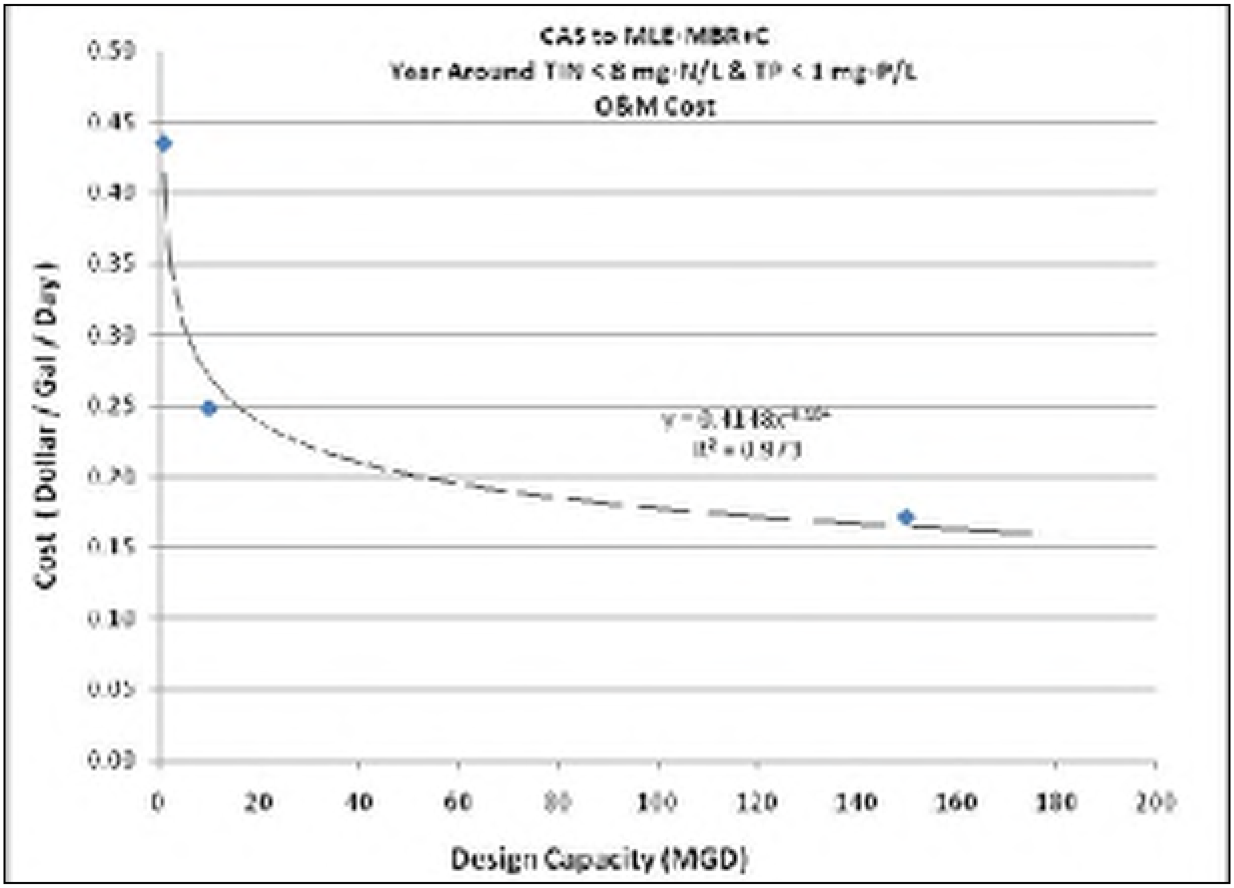


Figure 15-6. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective E Year-Round

TABLE 15-6.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$565,047	$3,472,850	$38,005,203
2014 Incremental O&M Cost	$489,775	$2,796,089	$29,003,426
Total Annual Cost	**$1,054,822**	**$6,268,939**	**$67,008,629**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$20.06	$12.73	$8.25
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$29.91	$15.26	$13.41

TIN Cost Equation:[a] .... $y = 125.83x^{-0.177}$
TIN Cost R-Square Value: 0.9964

TP Cost Equation:[b] .... $y = 116.06x^{-0.157}$
TP Cost R-Square Value: 0.834

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.1.3 Sequencing Batch Reactor Plants

Table 15-7 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E year-round for an SBR plant. Figures 15-7 and 15-8 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-8 presents the annualized unit costs for reducing nutrient loads.

TABLE 16-7.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.49	$0.50	$0.23
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.10	$0.01	($0.00)

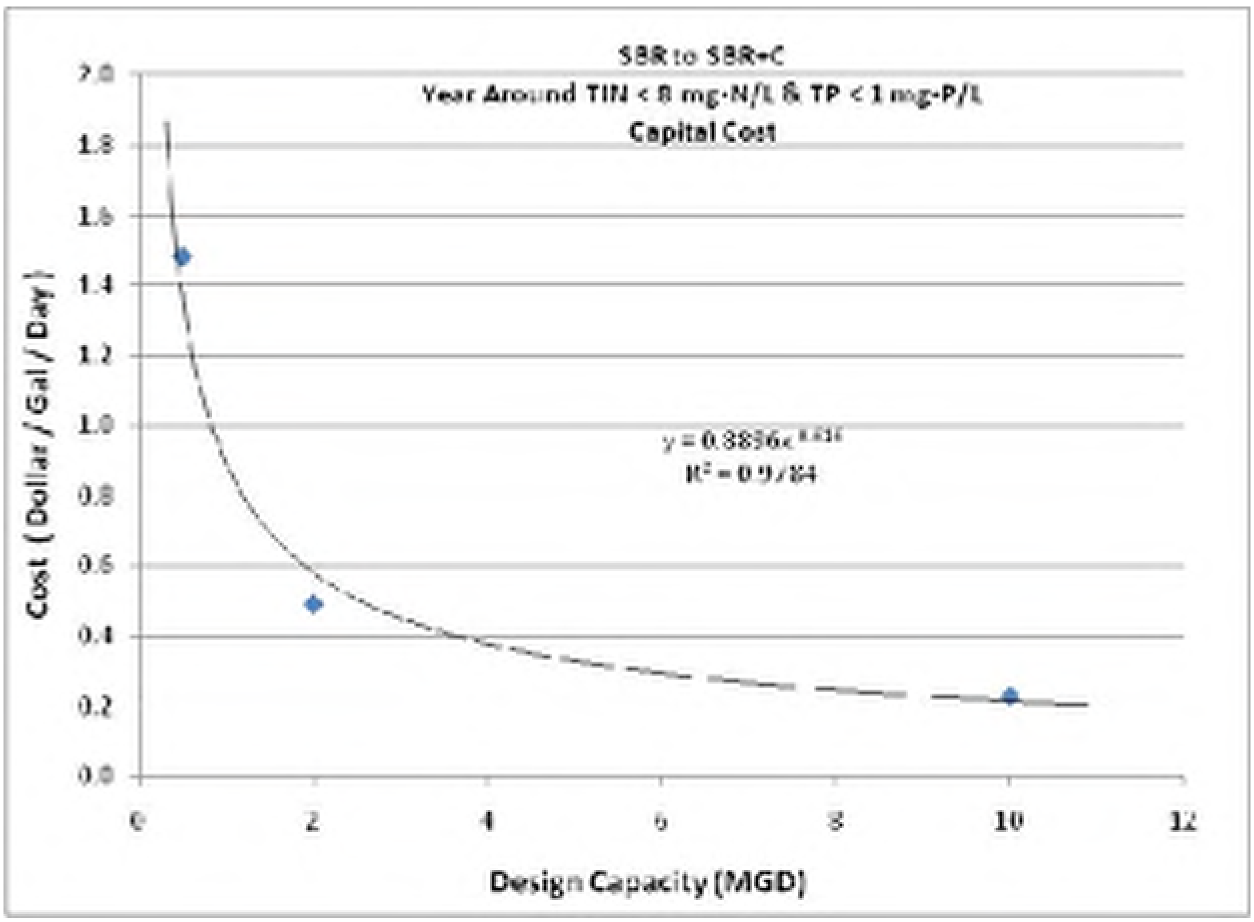


Figure 15-7. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective E Year-Round

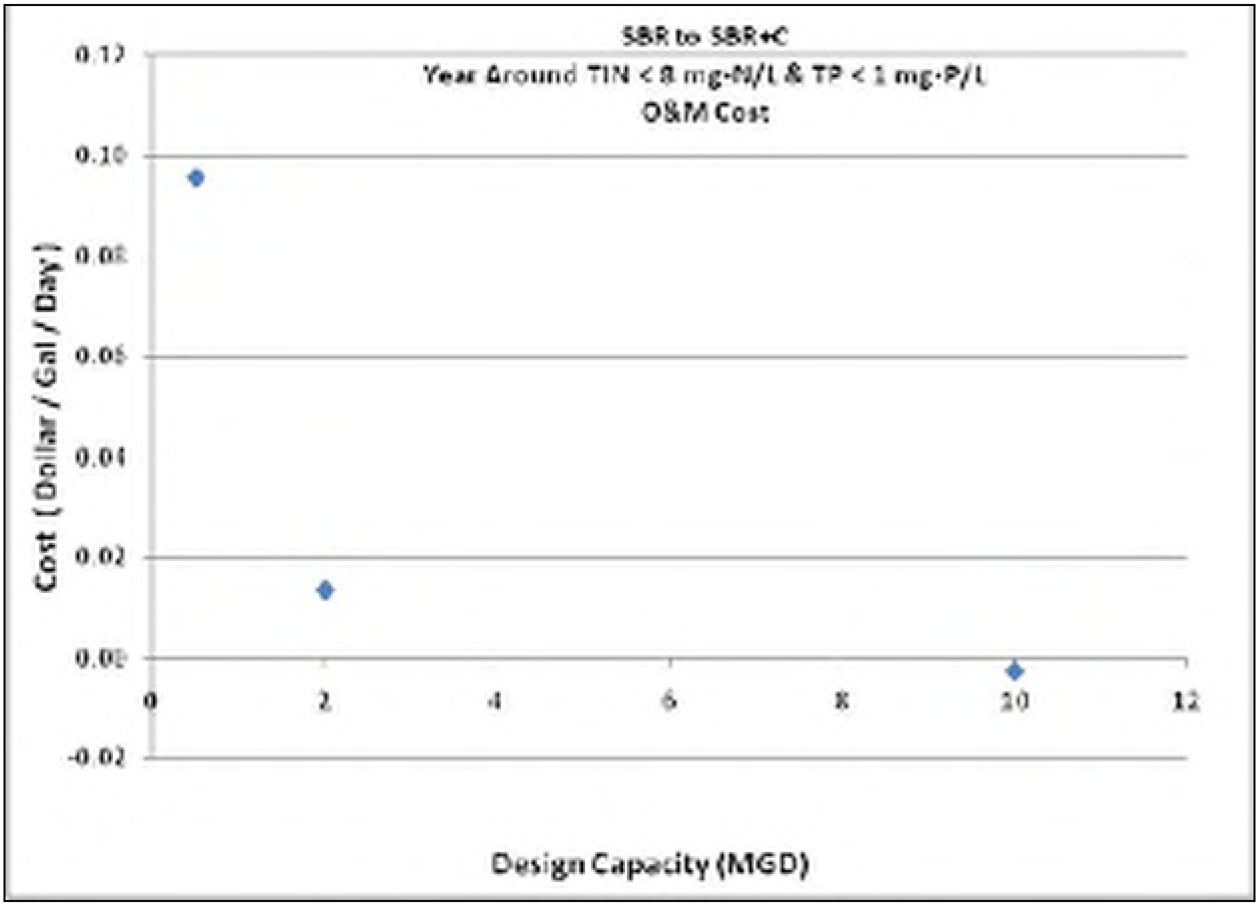


Figure 15-8. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective E Year-Round

TABLE 15-8.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$54,540	$72,740	$170,067
2014 Incremental O&M Cost	$53,878	$30,417	-$28,813
Total Annual Cost	**$1,08,418**	**$103,157**	**$141,254**
Annual TIN Load Reduction (lb/yr)	2,245	8,979	44,895
Annual TP Load Reduction (lb/yr)	2,099	8,395	41,975
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$0.21	-$0.98	-$1.79
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$51.43	$13.34	$5.28
TIN Cost Equation and R-Square Value[a]			
TP Cost Equation:[b]			$y = 14903x^{-0.755}$
TP Cost R-Square Value:			0.9777

a. Equation and R-square value for TIN not determined because annual cost estimates are below the level of precision that can be achieved using the CapdetWorks cost model.
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.1.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 15-9 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E year-round for a trickling filter plant. Figures 15-9 and 15-10 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-10 and Figures 15-11 and 15-12 summarize these costs for a trickling filter/solids contact plant. Table 15-11 and Figures 15-13 and 15-14 summarize these costs for an RBC plant. Tables 15-12, 15-13 and 15-14 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

**TABLE 15-9.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$9.09	$5.86	$3.69
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.50	$0.27	$0.18

**TABLE 15-10.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$7.82	$5.31	$3.37
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.37	$0.23	$0.15

**TABLE 15-11.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$9.10	$5.89	$3.74
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.56	$0.29	$0.19

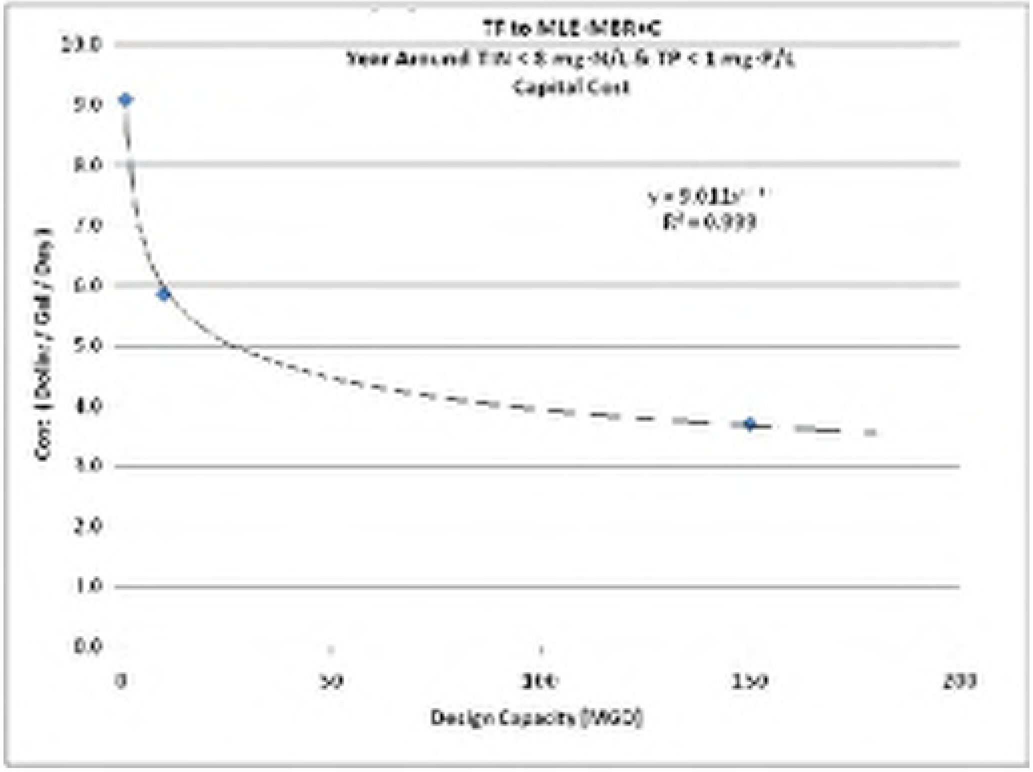


Figure 15-9. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective E Year-Round

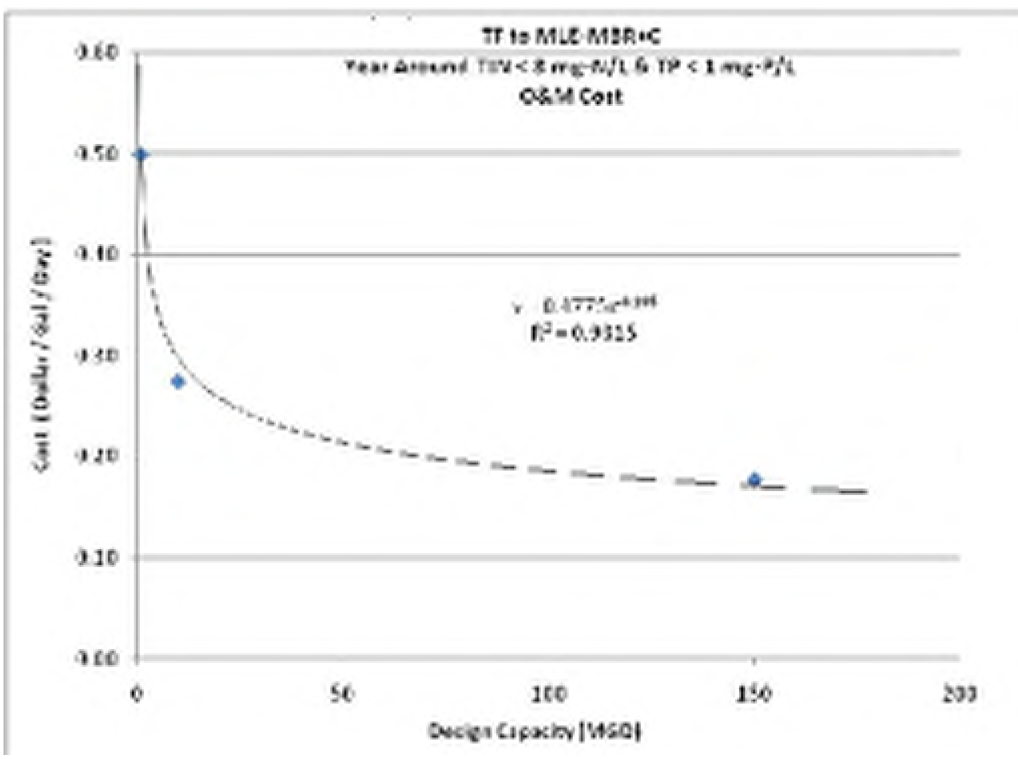


Figure 15-10. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective E Year-Round

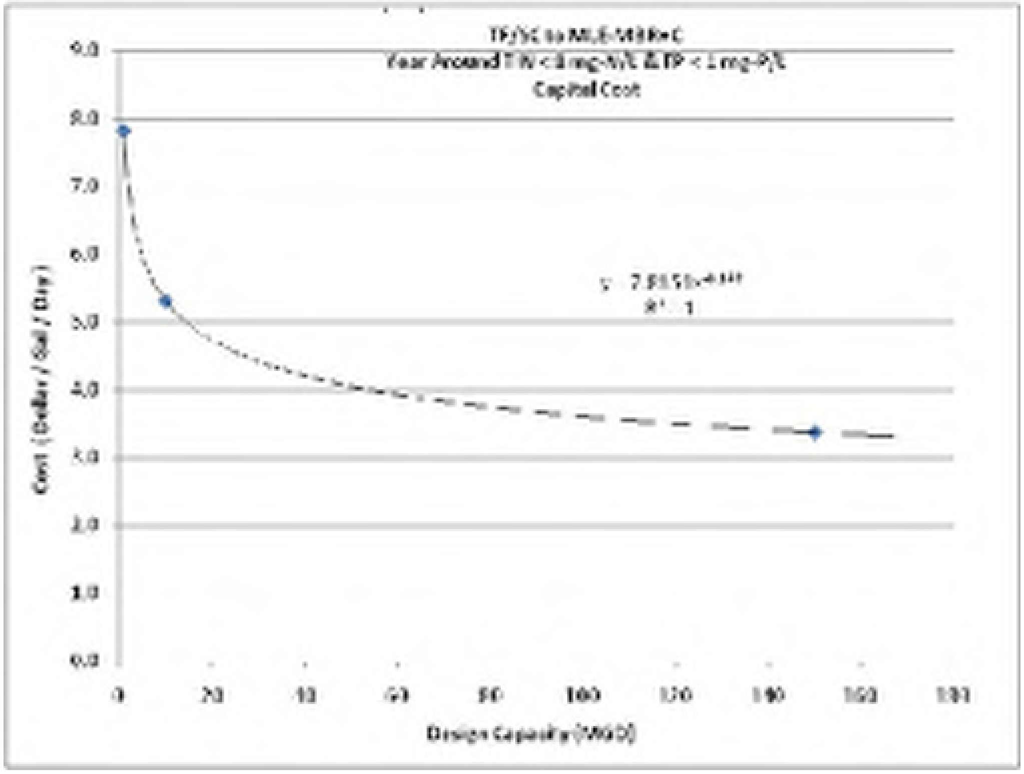


Figure 15-11. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective E Year-Round

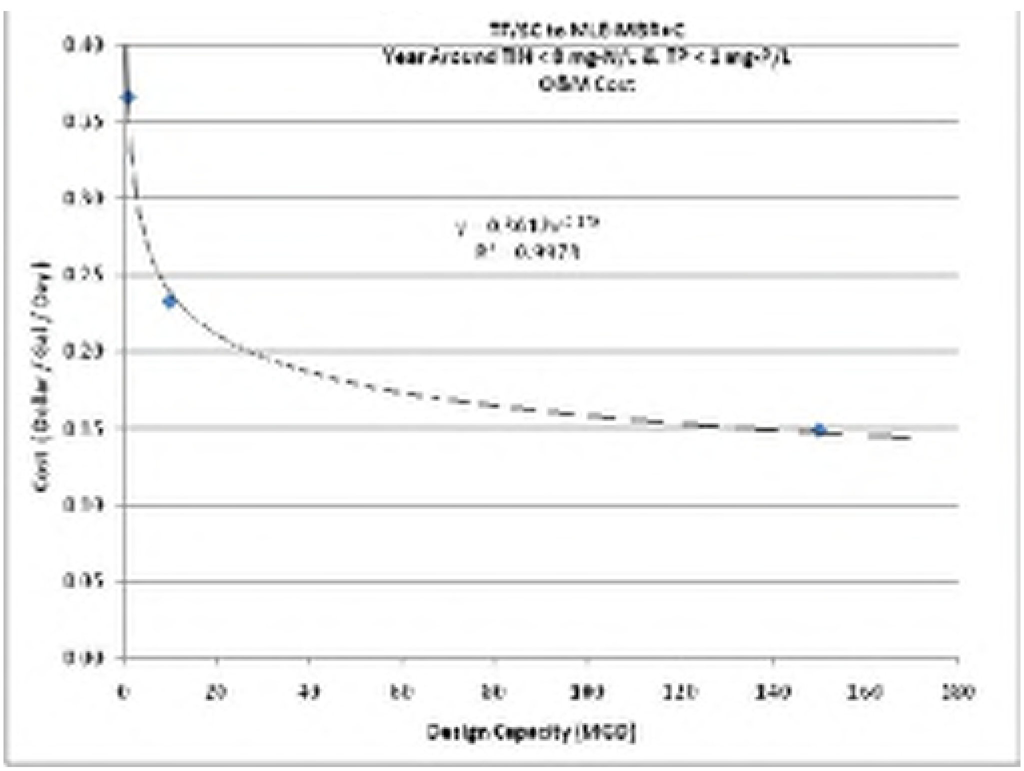


Figure 15-12. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective E Year-Round

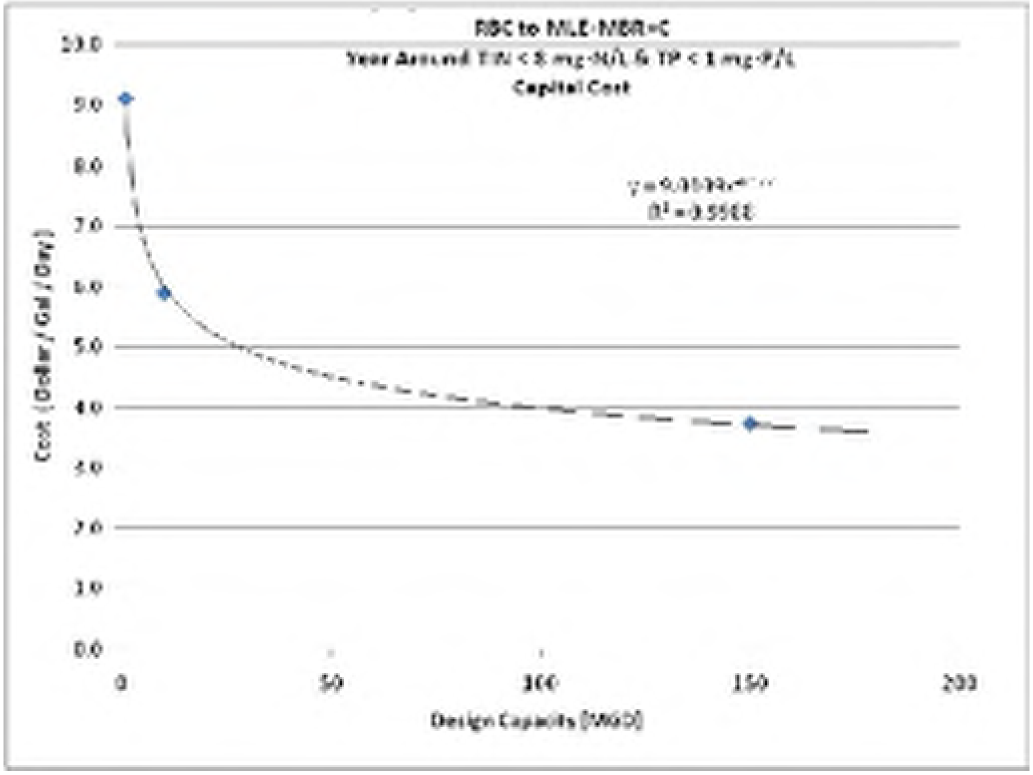


Figure 15-13. Capital Cost per Plant Capacity for RBC Upgraded for Objective E Year-Round

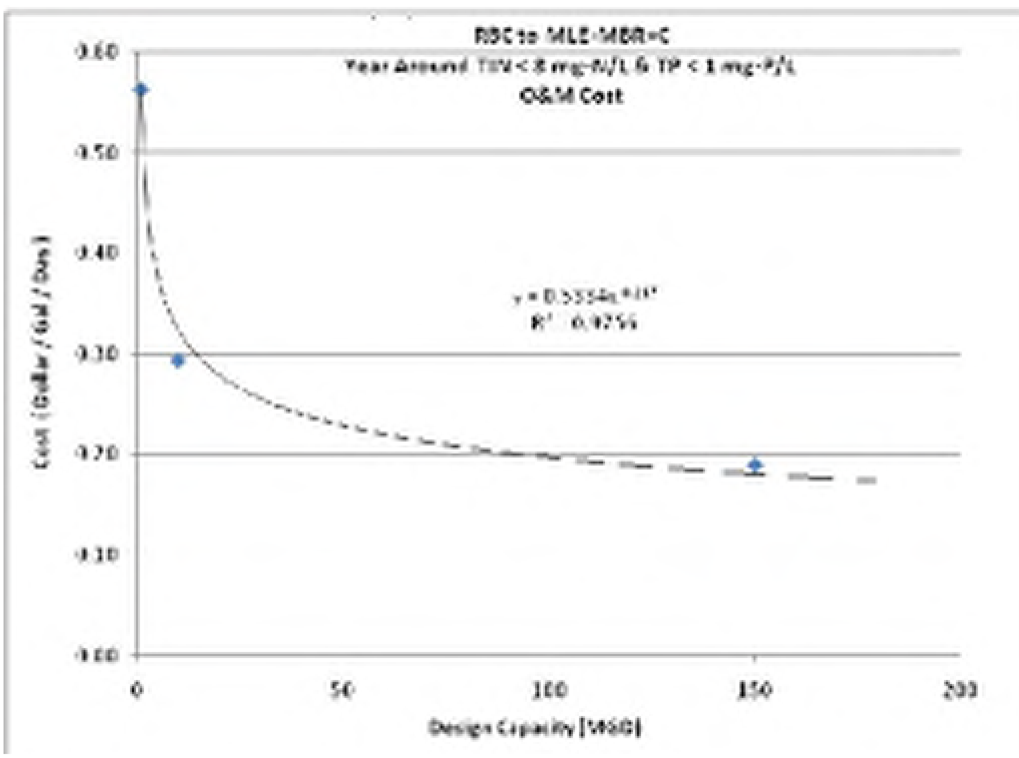


Figure 15-14. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective E Year-Round

TABLE 15-12.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$667,805	$4,305,835	$40,676,323
2014 Incremental O&M Cost	$561,622	$3,087,483	$29,924,655
Total Annual Cost	**$1,229,427**	**$7,392,318**	**$70,600,979**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$25.30	$16.09	$9.16
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$28.89	$14.65	$12.70

TIN Cost Equation:[a] .... $y = 213.2x^{-0.203}$
TIN Cost R-Square Value:........ 0.9997

TP Cost Equation:[b] .... $y = 62.964x^{-0.116}$
TP Cost R-Square Value: 0.9558

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-13.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$574,356	$3,896,568	$37,170,307
2014 Incremental O&M Cost	$238,822	$1,881,688	$17,690,375
Total Annual Cost	**$903,177**	**$5,888,255**	**$54,860,682**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$15.82	$11.89	$6.24
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$29.83	$14.56	$12.61

TIN Cost Equation:[a] .... $y = 118.37x^{-0.187}$
TIN Cost R-Square Value:........ 0.9705

TP Cost Equation:[b] .... $y = 128.15x^{-0.168}$
TP Cost R-Square Value: 0.8383

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-14.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$668,134	$4325,236	$41,200,334
2014 Incremental O&M Cost	$633,323	$3,301,949	$31,839,709
Total Annual Cost	**$1,301,457**	**$7,627,185**	**$73,040,042**
Annual TIN Load Reduction (lb/yr)	35,551	355,510	5,332,650
Annual TP Load Reduction (lb/yr)	11,425	114,245	1,713,675
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$27.16	$16.74	$9.61
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$29.40	$14.66	$12.71

TIN Cost Equation:[a] .... $y = 237.79x^{-0.207}$
TIN Cost R-Square Value:.......... 0.9999

TP Cost Equation:[b] .... $y = 65.083x^{-0.119}$
TP Cost R-Square Value: 0.9543

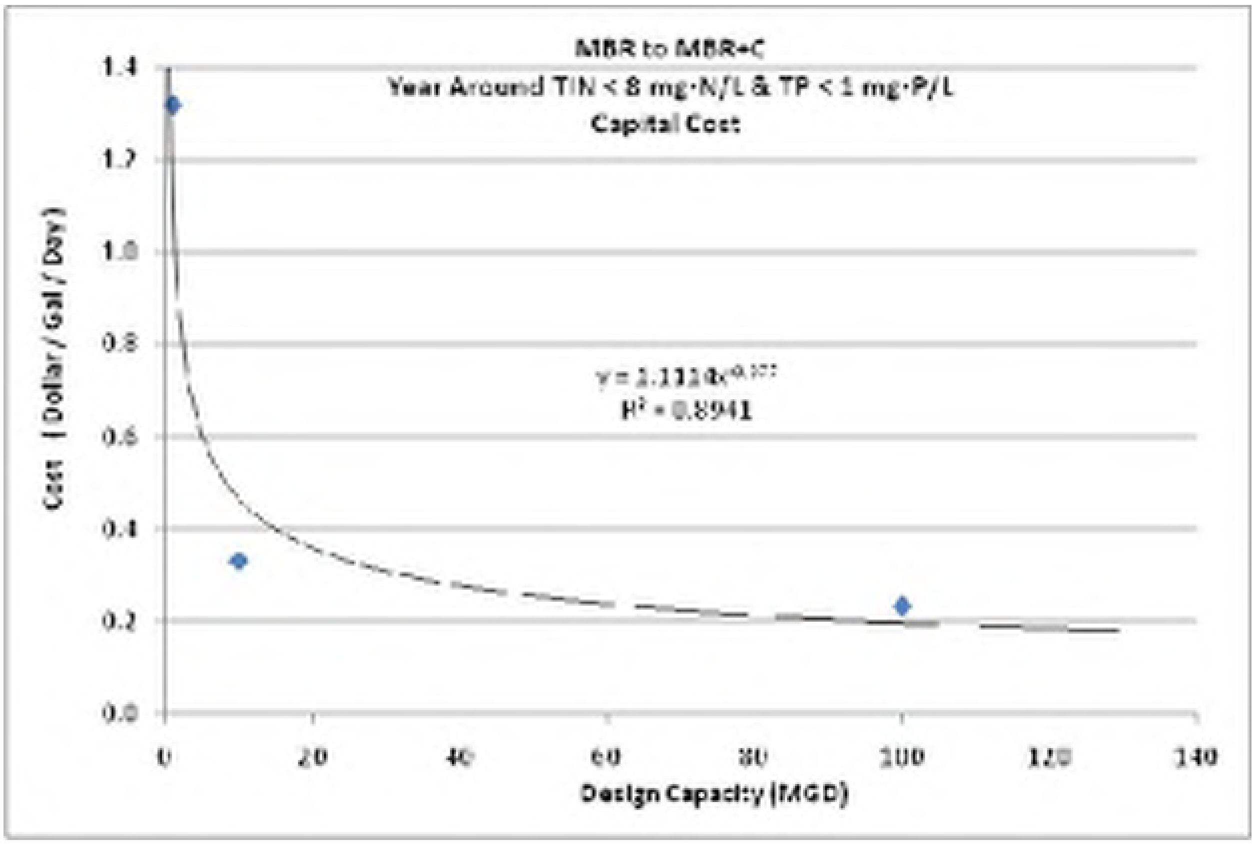
a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.1.5 Membrane Biological Reactor Plants

Table 15-15 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E year-round for an MBR plant. Figures 15-15 and 15-16 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-16 presents the annualized unit costs for reducing nutrient loads.

TABLE 15-15.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.32	$0.33	$0.23
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.16	$0.08	$0.06



15-15. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective E Year-Round

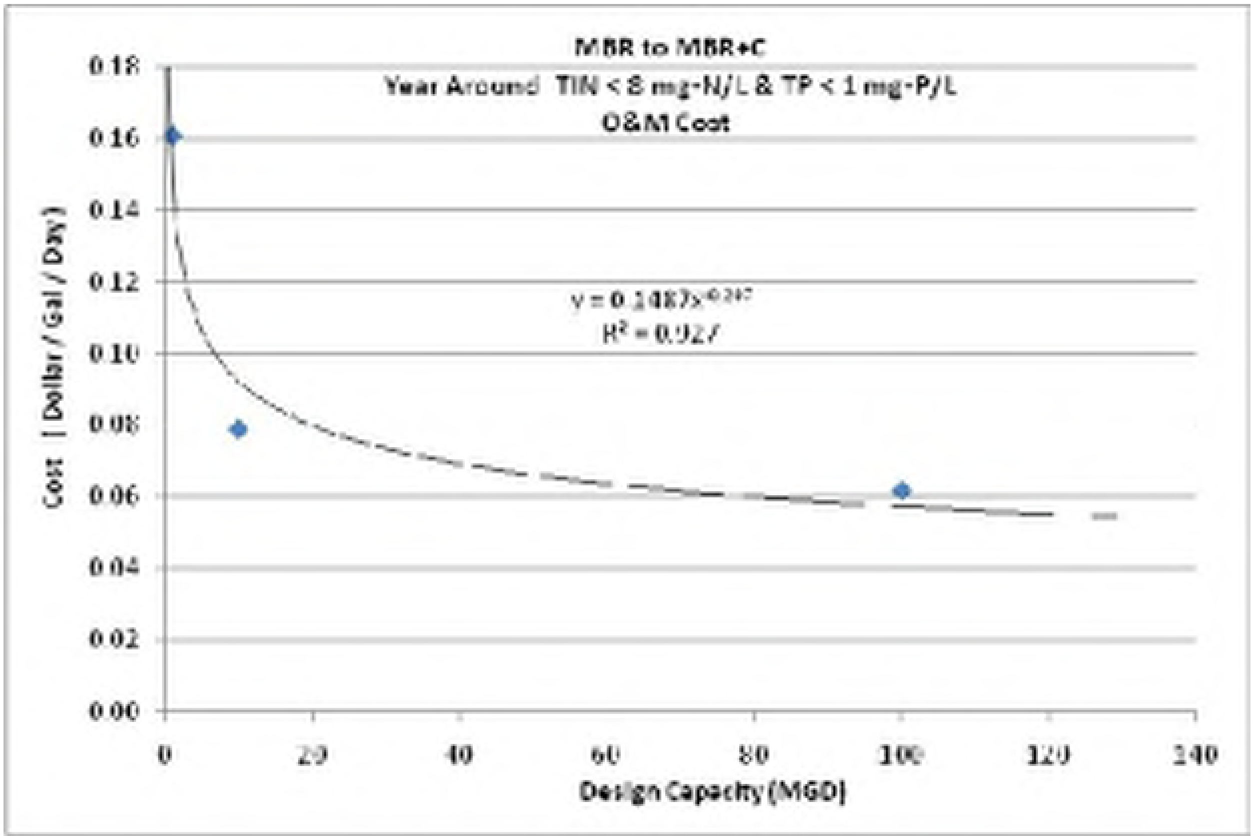


Figure 15-16. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective E Year-Round

TABLE 15-16.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$97,008	$242,560	$1,707,918
2014 Incremental O&M Cost	$180,864	$889,546	$6,960,248
Total Annual Cost	**$277,871**	**$1,132,106**	**$8,668,166**
Annual TIN Load Reduction (lb/yr)	0	0	0
Annual TP Load Reduction (lb/yr)	10,768	107,675	1,076,750
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	0	0	0
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$25.81	$10.51	$8.05
TIN Cost Equation:[a]			—
TIN Cost R-Square Value:			—
TP Cost Equation:[b]			$y = 243.32x^{-0.253}$
TP Cost R-Square Value:			0.9107

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.1.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective E were developed for these plants.

15.1.7 Aerated or Facultative Lagoon Plants

Table 15-17 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E year-round for an aerated lagoon plant. Figures 15-17 and 15-18 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-18 and Figures 15-19 and 15-20 summarize these costs for a facultative lagoon plant. Tables 15-19 and 15-20 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 15-17.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$24.70	$18.27	$11.64	$7.27
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.21	$0.75	$0.38	$0.24

TABLE 15-18.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$24.56	$18.15	$11.55	$7.22
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.49	$0.98	$0.54	$0.28

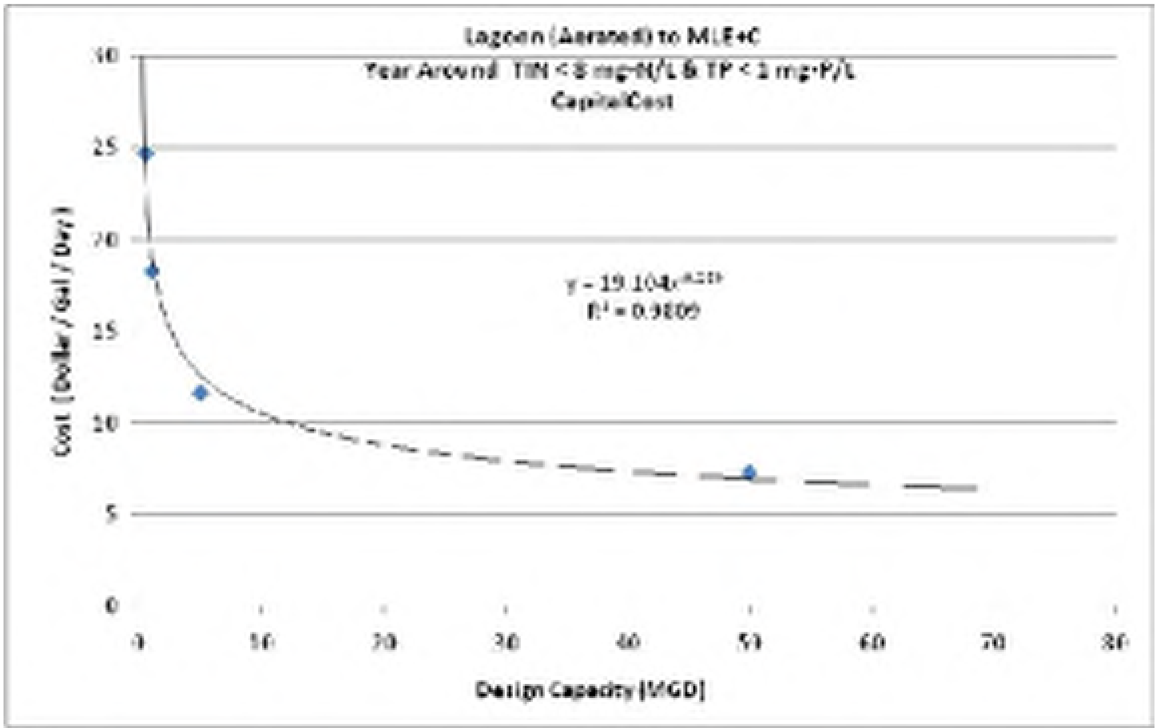


Figure 15-17. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective E Year-Round

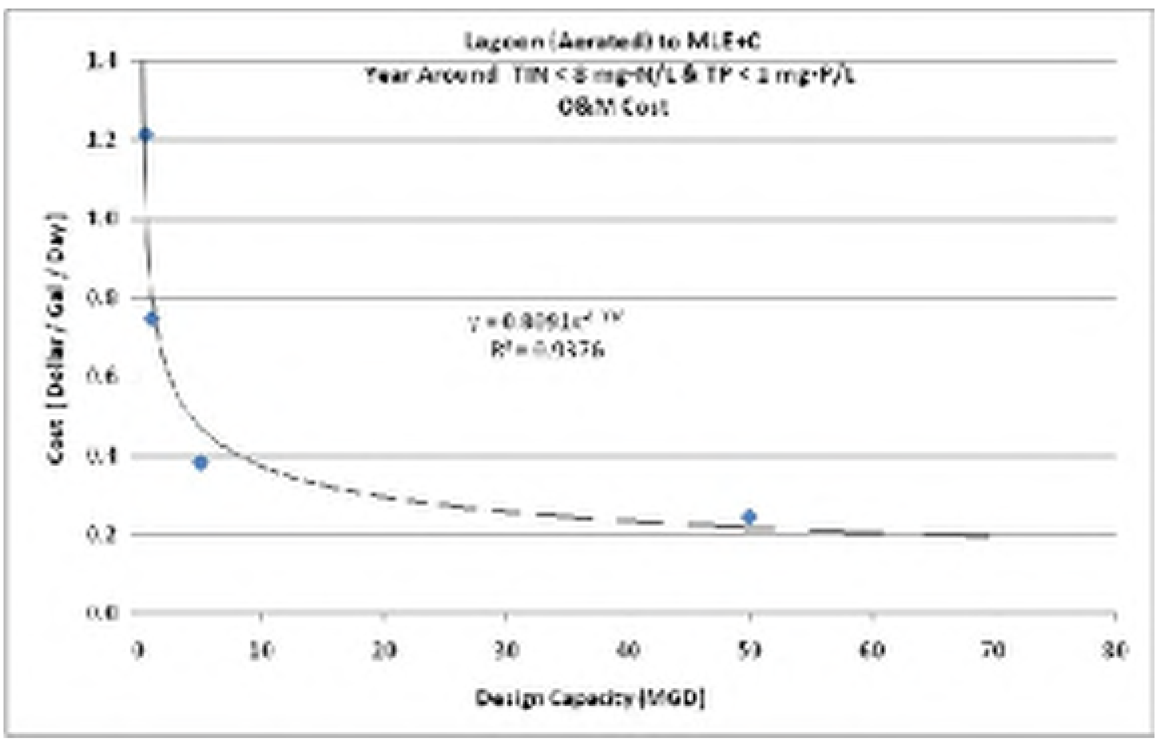


Figure 15-18. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective E Year-Round

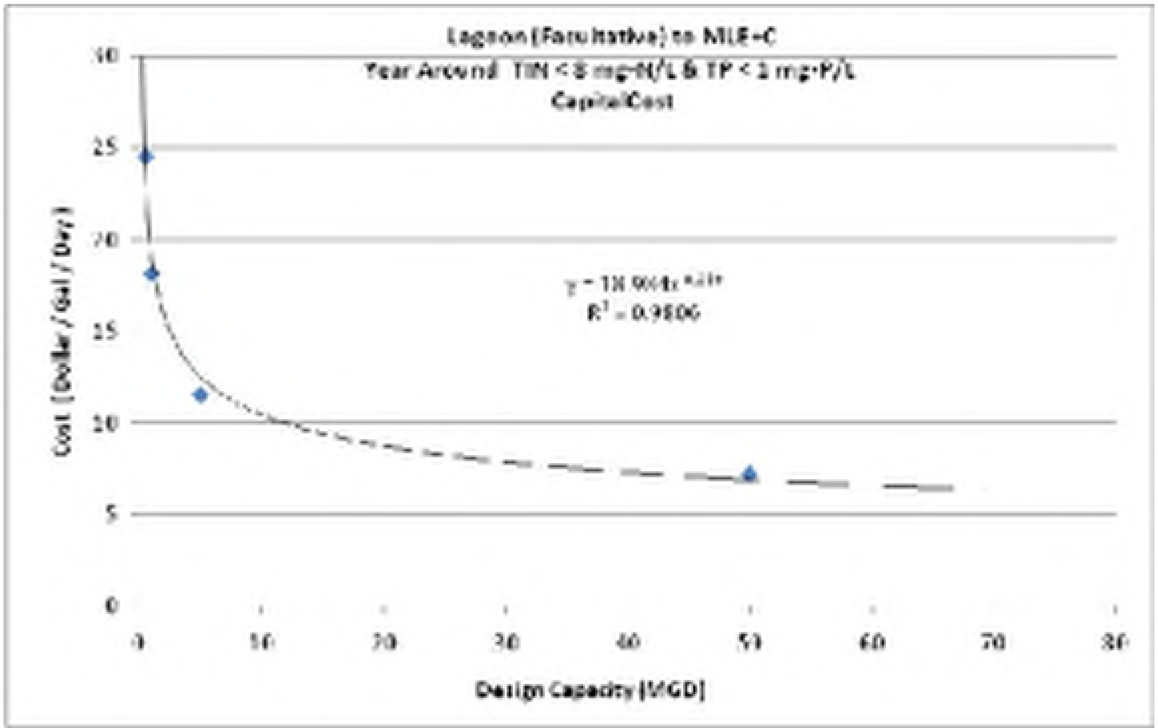


Figure 15-19. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective E Year-Round

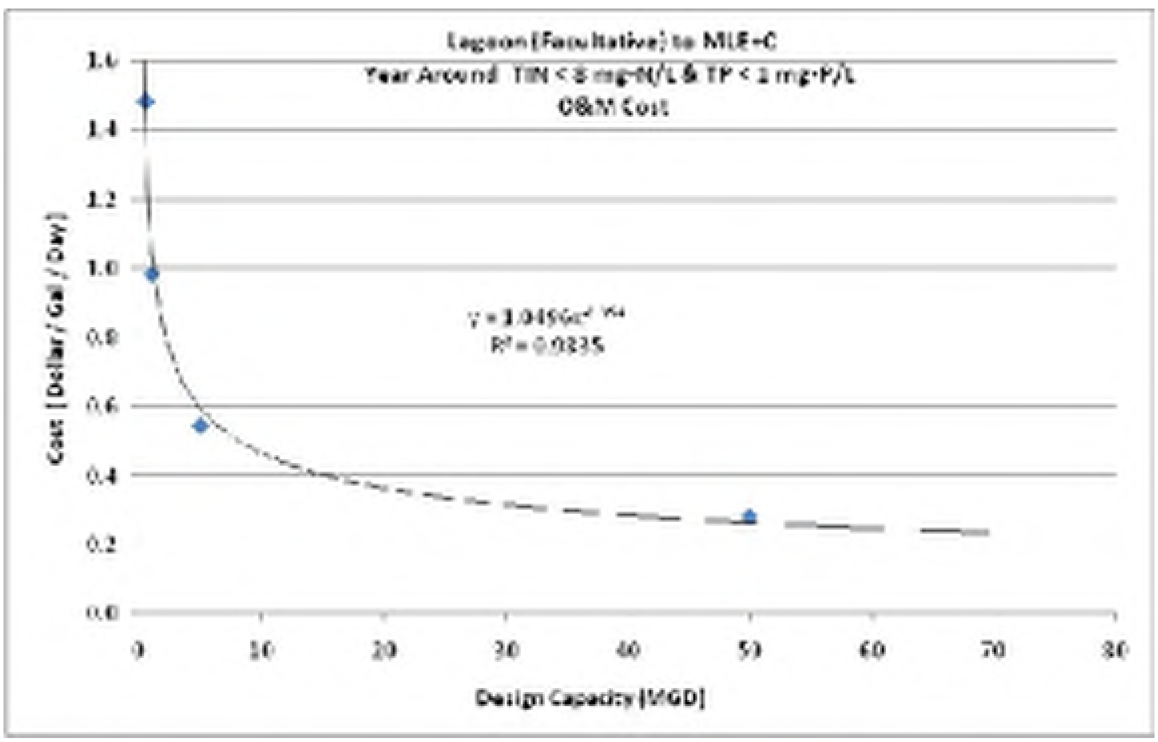


Figure 15-20. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective E Year-Round

TABLE 15-19.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$906,931	$1,341,831	$4,275,806	$26,699,852
2014 Incremental O&M Cost	$682,841	$841,183	$2,149,969	$13,773,921
Total Annual Cost	**$1,589,771**	**$2,183,013**	**$6,425,775**	**$40,473,772**
Annual TIN Load Reduction (lb/yr)	17,684	35,369	176,843	1,759,300
Annual TP Load Reduction (lb/yr)	5,712	11,425	57,123	571,225
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$69.34	$47.28	$29.03	$16.54
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$63.65	$44.70	$22.61	$19.91

TIN Cost Equation:[a] .... $y = 1183.4x^{-0.3}$
TIN Cost R-Square Value:.......... 0.9791

TP Cost Equation:[b] .... $y = 469.06x^{-0.25}$
TP Cost R-Square Value: 0.8503

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-20.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE E YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$901,913	$1,333,358	$4,242,654	$26,525,456
2014 Incremental O&M Cost	$836,010	$1,104,861	$3,052,796	$15,661,191
Total Annual Cost	**$1,737,923**	**$2,438,219**	**$7,295,450**	**$42,186,646**
Annual TIN Load Reduction (lb/yr)	17,684	35,369	176,843	1,759,300
Annual TP Load Reduction (lb/yr)	5,712	11,425	57,123	571,225
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$77.64	$54.48	$33.96	$17.49
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$63.89	$44.77	$22.59	$20.00

TIN Cost Equation:[a] .... $y = 1560.9x^{-0.314}$
TIN Cost R-Square Value:.......... 0.9911

TP Cost Equation:[b] .... $y = 469x^{-0.25}$
TP Cost R-Square Value: 0.8472

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.2 SEASONAL NUTRIENT REMOVAL

15.2.1 Extended Aeration Plants

Table 15-21 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E seasonally for an extended aeration plant using mechanical aeration. Figures 15-21 and 15-22 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-22 and Figures 15-23 and 15-24 summarize these costs for an extended aeration plant using diffuser aeration. Tables 15-23 and 15-24 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 15-21.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.41	$2.41	$2.37
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.38	$0.12	$0.07

TABLE 15-22.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.68	$0.92	$0.50
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.19	$0.06	$0.04

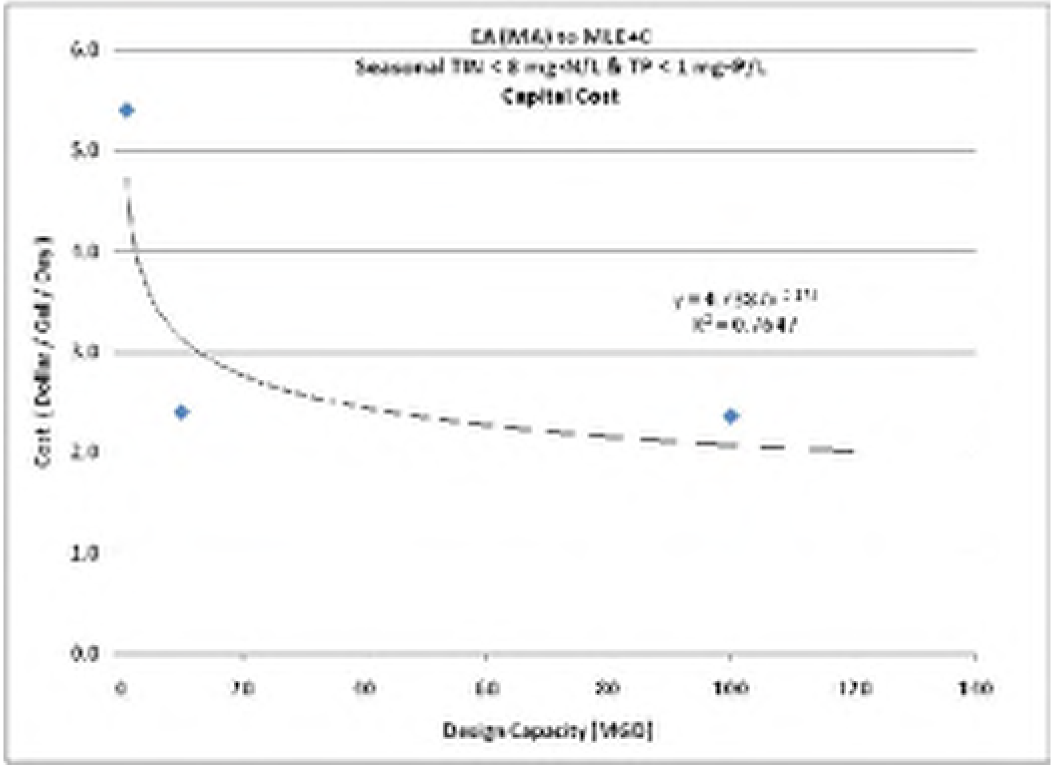


Figure 15-21. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective E Seasonally

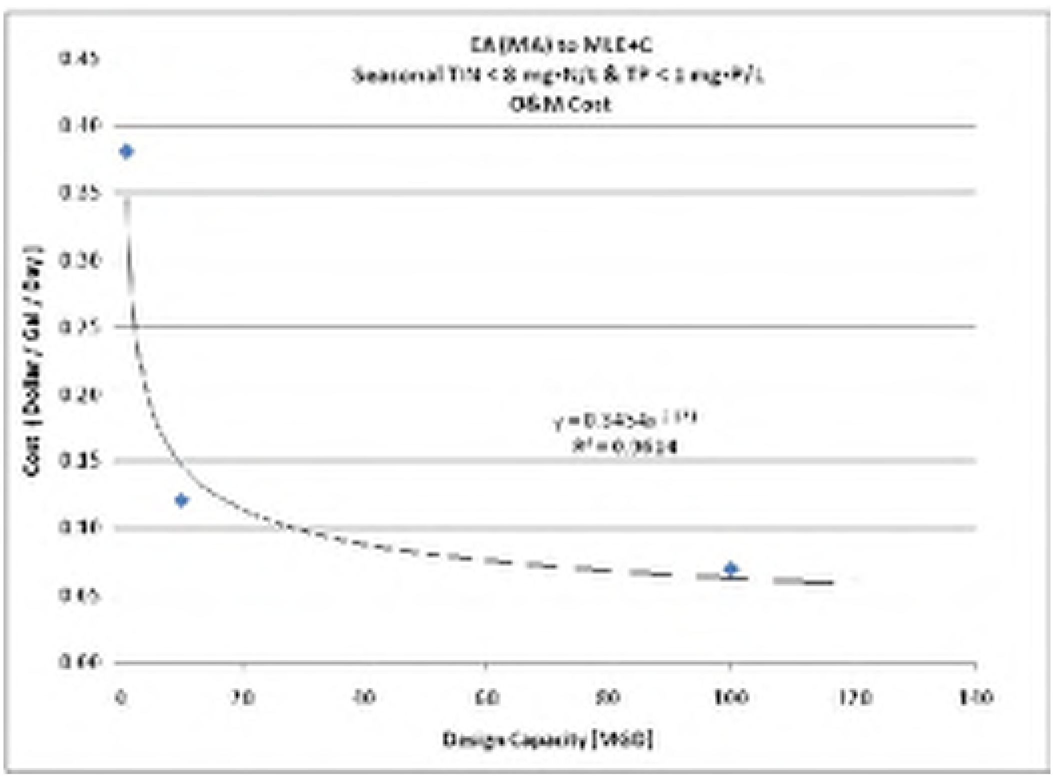


Figure 15-22. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective E Seasonal

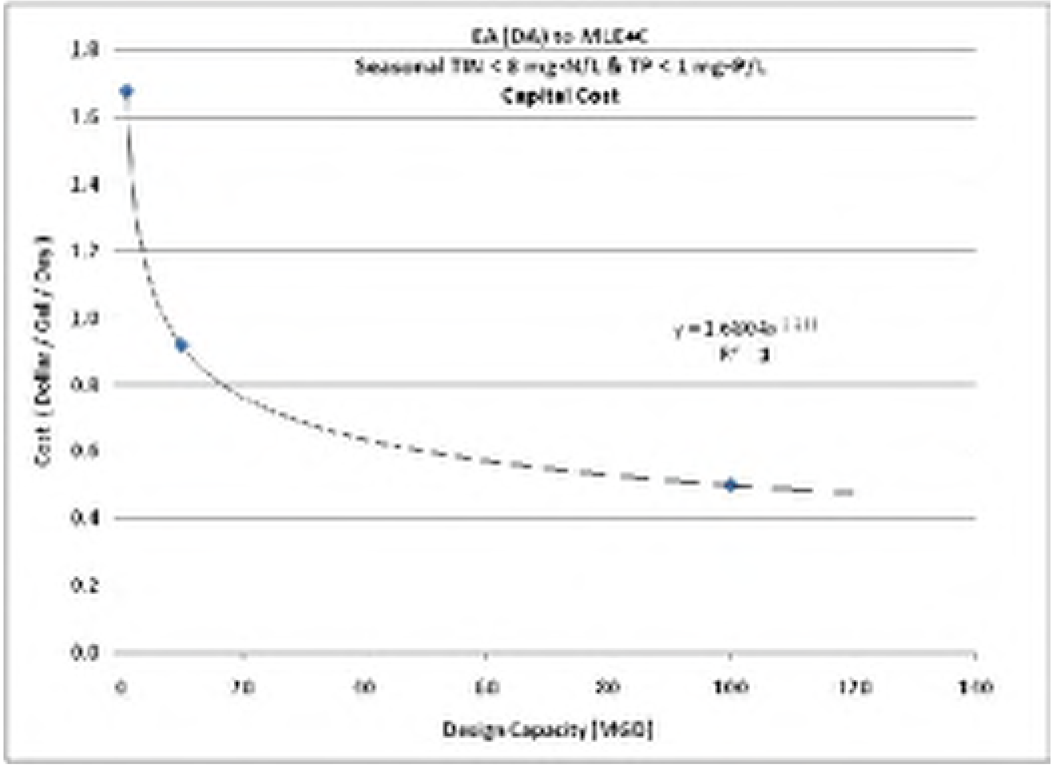


Figure 15-23. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective E Seasonally

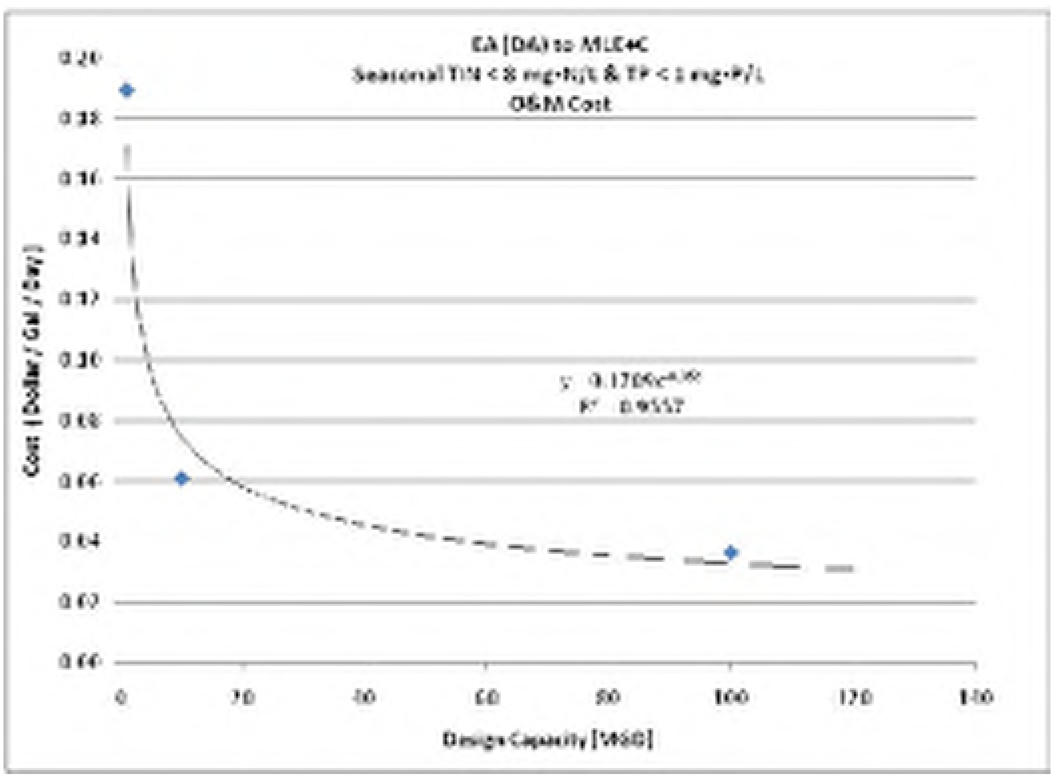


Figure 15-24. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective E Seasonal

TABLE 15-23.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$387,213	$1,769,044	$17,407,459
2014 Incremental O&M Cost	$429,157	$1,358,917	$7,782,443
Total Annual Cost	**$826,370**	**$3,127,961**	**$25,189,902**
Annual TIN Load Reduction (lb/yr)	19,564	195,640	1,956,400
Annual TP Load Reduction (lb/yr)	5,694	56940	569,400
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$32.40	$10.66	$8.34
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$33.79	$18.32	$15.58

TIN Cost Equation:[a] .... $y = 515.81x^{-0.295}$
TIN Cost R-Square Value:........ 0.8804

TP Cost Equation:[b] .... $y = 134.13x^{-0.168}$
TP Cost R-Square Value: 0.8987

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-24.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA ((DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$123,280	$674,956	$3,669,667
2014 Incremental O&M Cost	$213,115	$685,525	$4,083,459
Total Annual Cost	**$336,395**	**$1,360,481**	**$7,753,125**
Annual TIN Load Reduction (lb/yr)	19,546	195,458	1,954,575
Annual TP Load Reduction (lb/yr)	5,694	56940	569400
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$7.21	$1.44	$0.05
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$34.32	$18.95	$13.44

TIN Cost Equation:[a] .... $y = 412014x^{-1.079}$
TIN Cost R-Square Value:........ 0.9603

TP Cost Equation:[b] .... $y = 191.4x^{-0.204}$
TP Cost R-Square Value: 0.9768

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.2.2 Conventional Activated Sludge Plants

Table 15-25 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E seasonally for a conventional activated sludge plant. Figures 15-25 and 15-26 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-26 presents the annualized unit costs for reducing nutrient loads.

TABLE 15-25.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	\$3.34	\$1.35	\$1.54
Incremental Annual O&M Cost per gpd of Plant Capacity	\$0.34	\$0.14	\$0.09

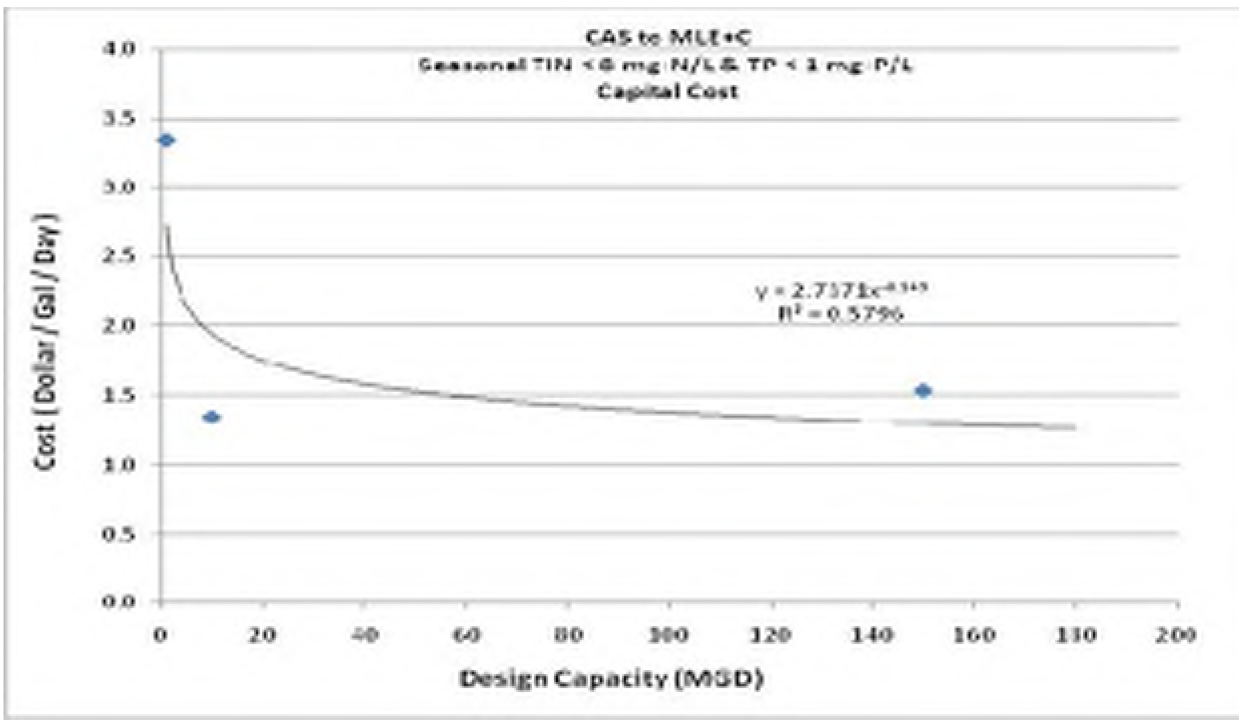


Figure 15-25. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective E Seasonally

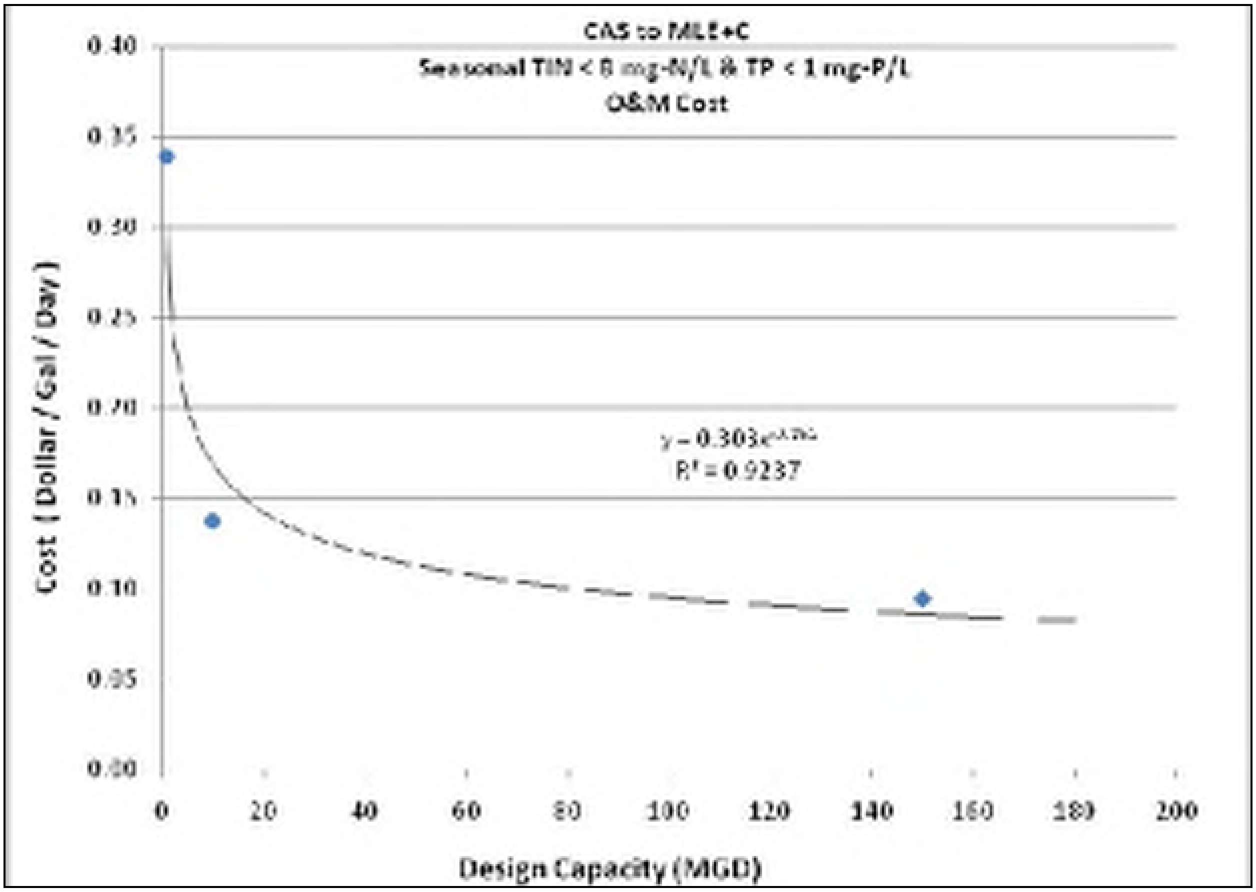


Figure 15-26. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective E Seasonal

TABLE 15-26.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$245,137	$988,465	$16,923,854
2014 Incremental O&M Cost	$381,947	$1,546,730	$15,914,019
Total Annual Cost	**$627,084**	**$2,535,196**	**$32,837,873**
Annual TIN Load Reduction (lb/yr)	19,418	194,180	2,912,700
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$15.94	$5.77	$5.00
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$53.86	$24.01	$20.66

TIN Cost Equation:[a] .... $y = 125.02x^{-0.226}$
TIN Cost R-Square Value:........ 0.8055

TP Cost Equation:[b] .... $y = 239.89x^{-0.187}$
TP Cost R-Square Value: 0.8308

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.2.3 Sequencing Batch Reactor Plants

Table 15-27 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E seasonally for an SBR plant. Figures 15-27 and 15-28 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-28 presents the annualized unit costs for reducing nutrient loads.

TABLE 15-27.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.46	$0.48	$0.21
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.09	$0.02	$0.01

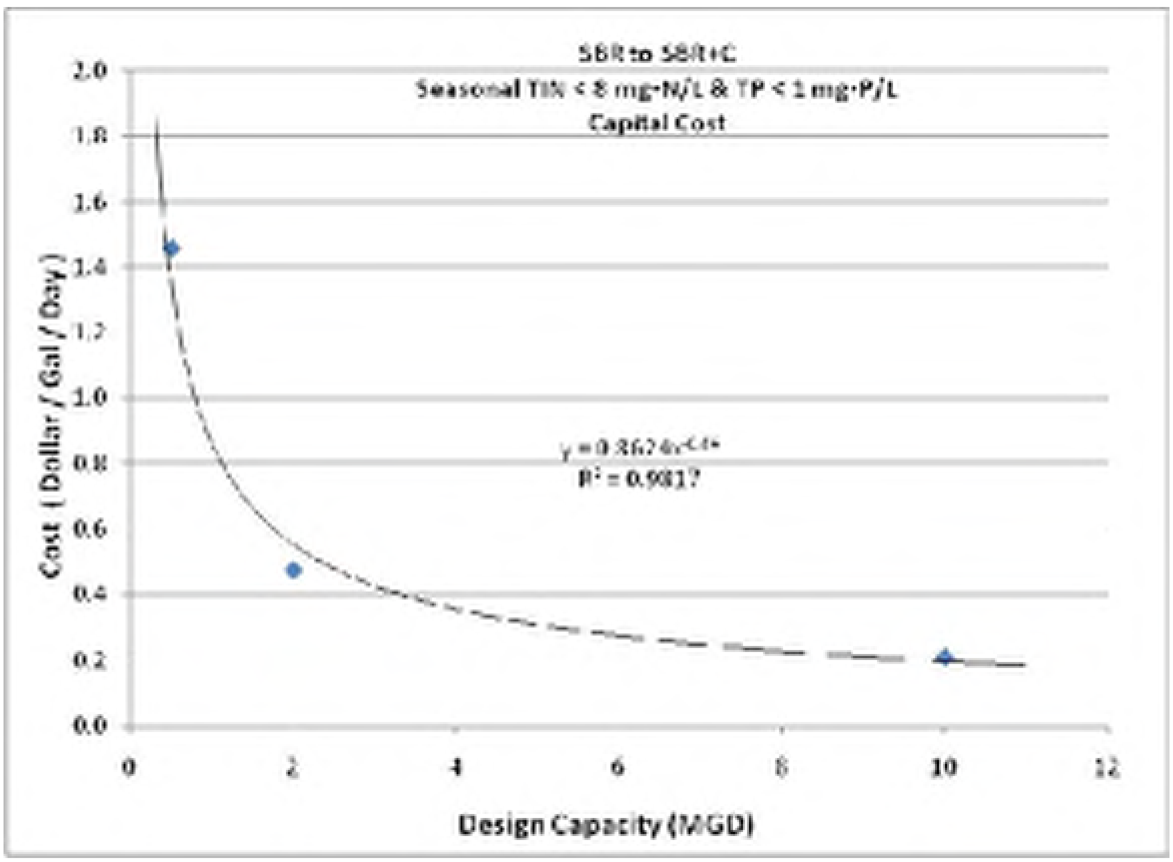


Figure 15-27. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective E Seasonally

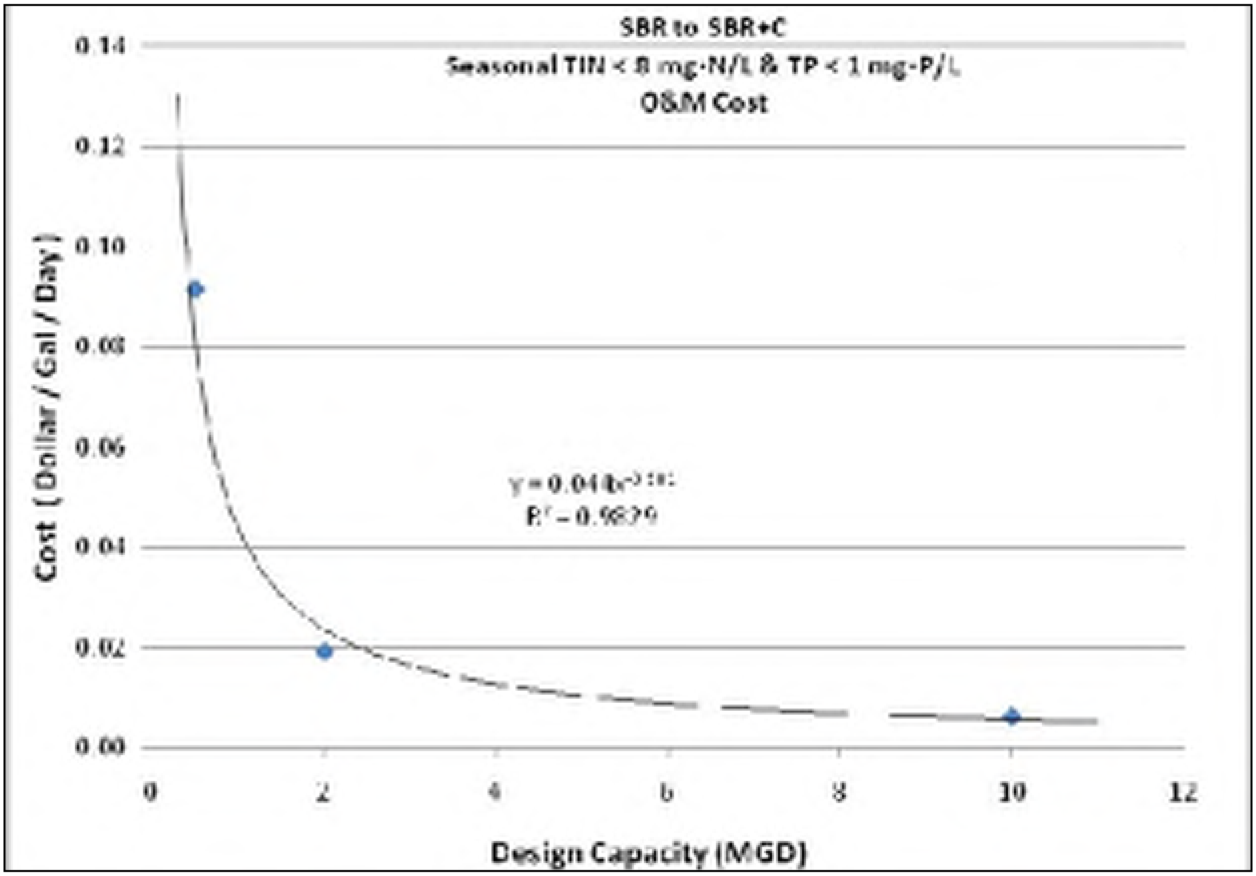


Figure 15-28. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective E Seasonal

TABLE 15-28.
UNIT NUTRIENT REMOVAL COSTS FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$53,512	$69,913	$155,671
2014 Incremental O&M Cost	$51,605	$43,163	$68,421
Total Annual Cost	**$105,116**	**$113,076**	**$224,102**
Annual TIN Load Reduction (lb/yr)	246	986	4,928
Annual TP Load Reduction (lb/yr)	1,141	4,563	22,813
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$0.21	-$13.04	-$9.46
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$91.39	$27.60	$11.87
TIN Cost Equation and R-Square Value[a]			

TP Cost Equation:[b] .... $y = 9820.1x^{-0.677}$
TP Cost R-Square Value: 0.9798

a. Equation and R-square value for TIN not determined because annual cost estimates are below the level of precision that can be achieved using the CapdetWorks cost model.
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.2.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 15-29 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E seasonally for a trickling filter plant. Figures 15-29 and 15-30 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-30 and Figures 15-31 and 15-32 summarize these costs for a trickling filter/solids contact plant. Table 15-31 and Figures 15-33 and 15-34 summarize these costs for an RBC plant. Tables 15-32, 15-33 and 15-34 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

**TABLE 15-29.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.39	$2.88	$2.03
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.40	$0.16	$0.10

**TABLE 15-30.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$3.65	$2.19	$1.62
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.27	$0.12	$0.07

**TABLE 15-31.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.41	$2.90	$2.08
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.47	$0.18	$0.11

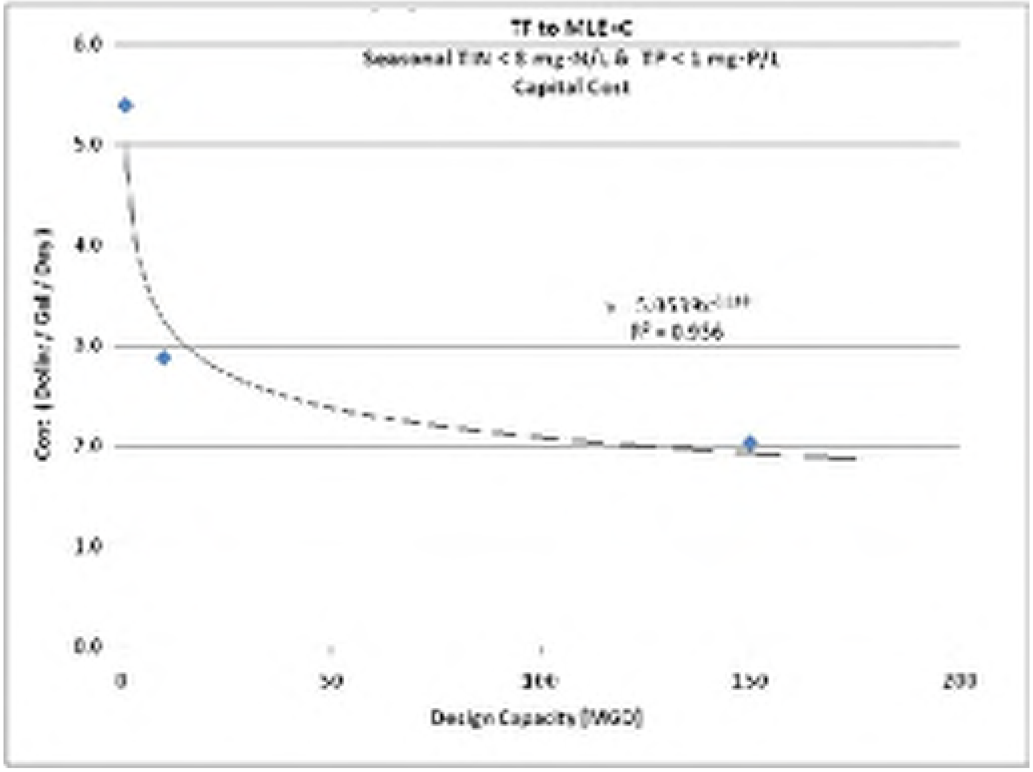


Figure 15-29. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective E Seasonally

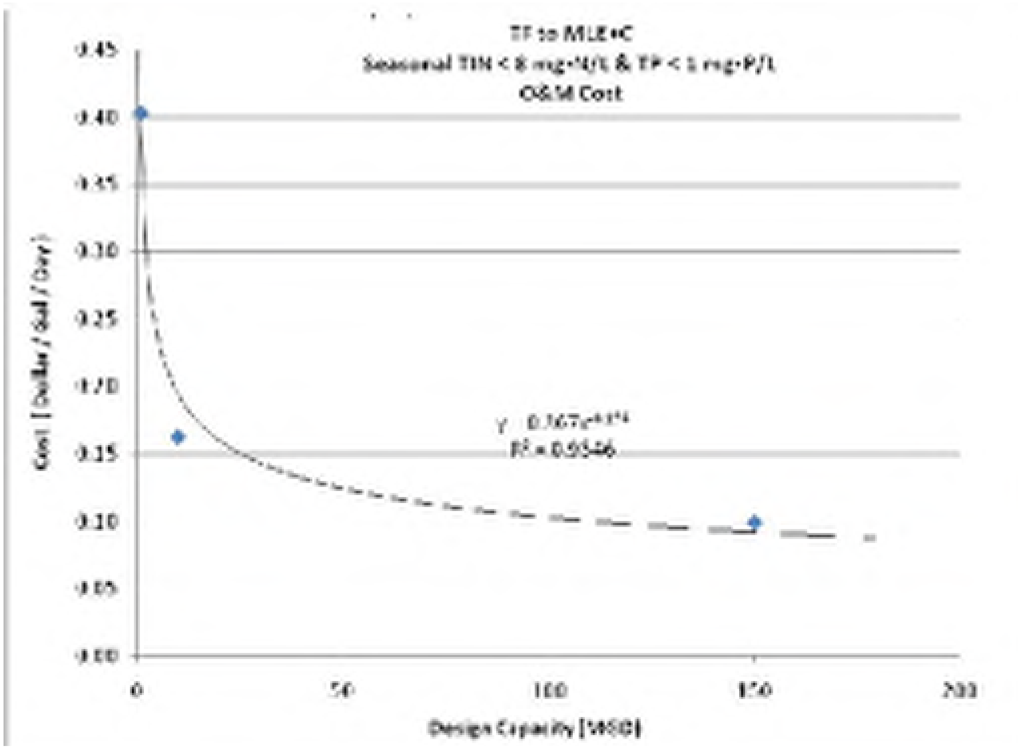


Figure 15-30. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective E Seasonal

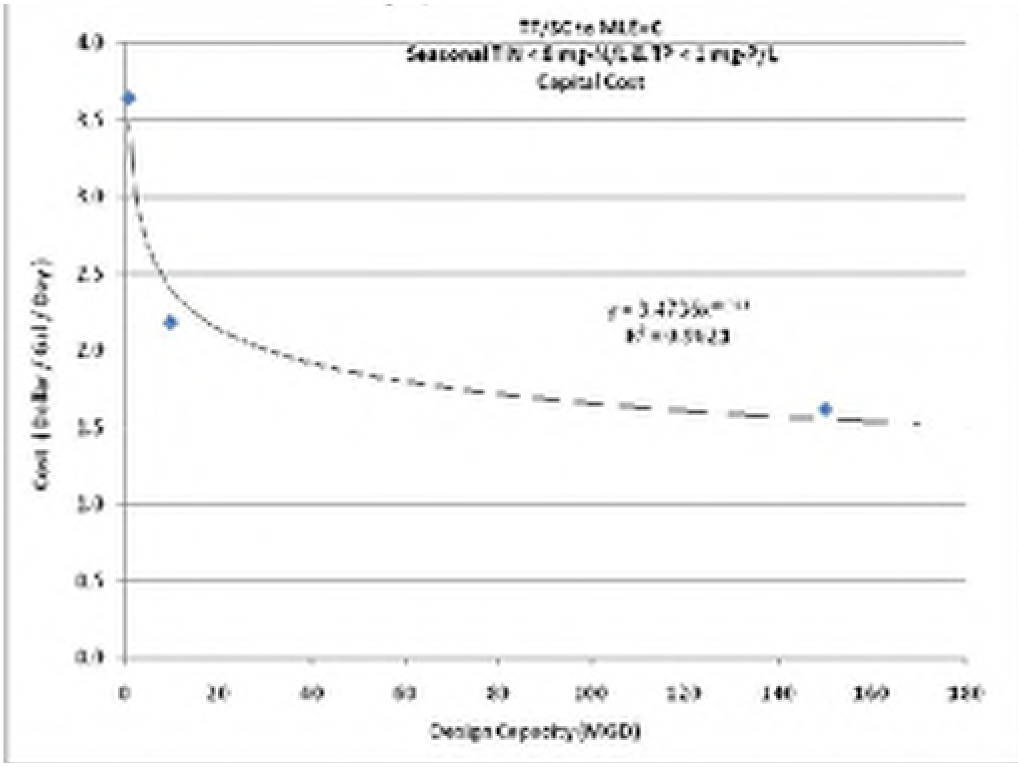


Figure 15-31. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective E Seasonally

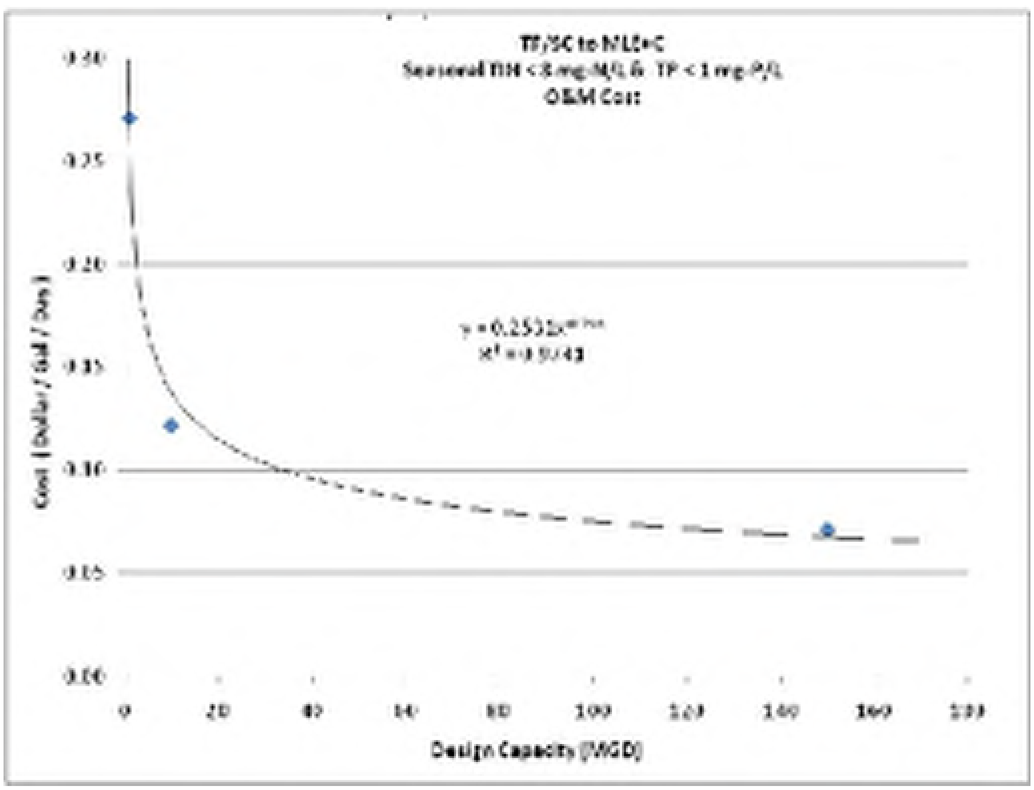


Figure 15-32. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective E Seasonal

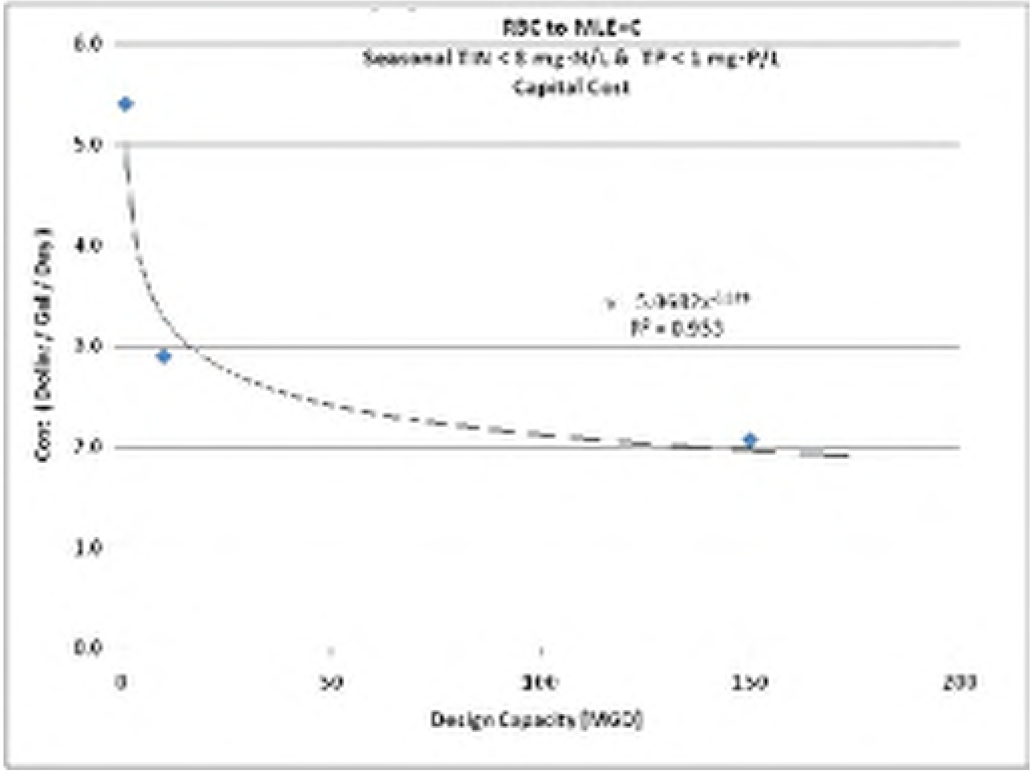


Figure 15-33. Capital Cost per Plant Capacity for RBC Plant Upgraded for Objective E Seasonally

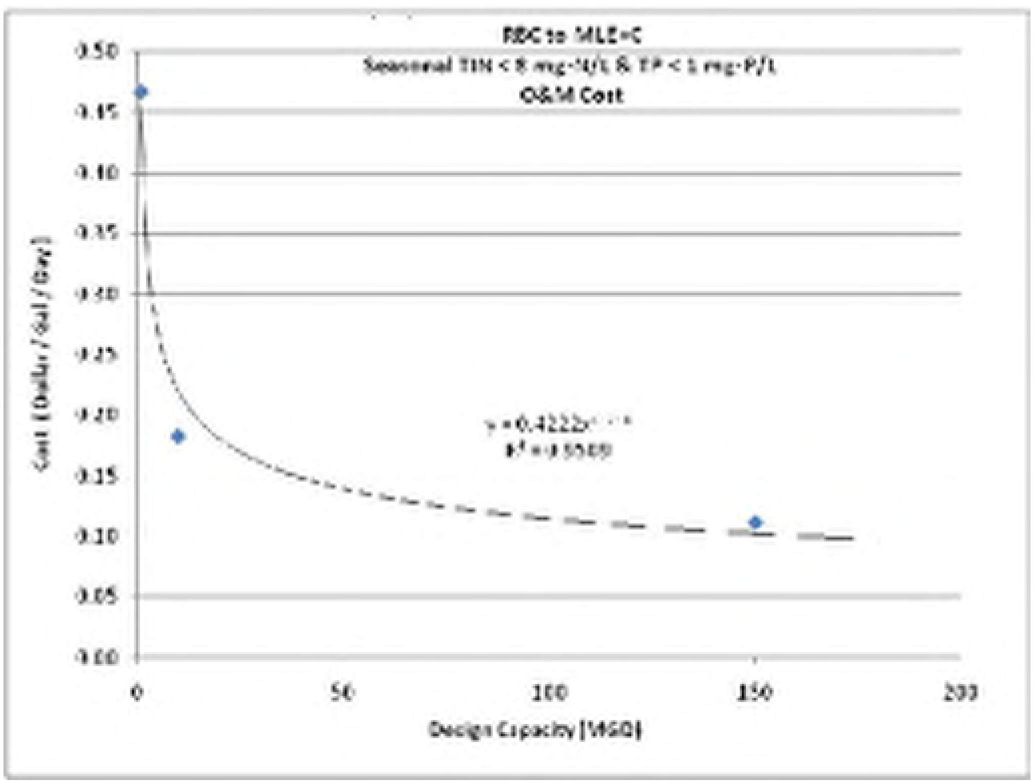


Figure 15-34. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective E Seasonal

TABLE 15-32.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$395,980	$2,114,252	$22,417,794
2014 Incremental O&M Cost	$453,794	$1,838,125	$16,835,248
Total Annual Cost	**$849,773**	**$3,952,377**	**$39,253,042**
Annual TIN Load Reduction (lb/yr)	19,418	194,180	2,912,700
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$28.10	$13.39	$7.56
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$51.59	$22.93	$19.50

TIN Cost Equation:[a] .... $y = 350.28x^{-0.261}$
TIN Cost R-Square Value: 0.9854

TP Cost Equation:[b] .... $y = 236.13x^{-0.19}$
TP Cost R-Square Value: 0.838

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-33.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$268,169	$1,607,188	$17,850,595
2014 Incremental O&M Cost	$304,715	$1,370,813	$12,075,471
Total Annual Cost	**$572,883**	**$2,978,001**	**$29,926,067**
Annual TIN Load Reduction (lb/yr)	19,418	194,180	2,912,700
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$18.42	$8.27	$4.38
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$43.06	$23.26	$19.40

TIN Cost Equation:[a] .... $y = 292.5x^{-0.285}$
TIN Cost R-Square Value: 0.9873

TP Cost Equation:[b] .... $y = 153.11x^{-0.156}$
TP Cost R-Square Value: 0.8815

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-34.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$397,543	$2,131,692	$22,871,059
2014 Incremental O&M Cost	$525,494	$2,052,590	$18,750,301
Total Annual Cost	**$923,037**	**$4,184,282**	**$41,621,360**
Annual TIN Load Reduction (lb/yr)	19,418	194,180	2,912,700
Annual TP Load Reduction (lb/yr)	5,895	58,948	884,213
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$31.60	$14.62	$8.40
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$52.50	$22.83	$19.40

TIN Cost Equation:[a] .... $y = 398.88x^{-0.263}$
TIN Cost R-Square Value:.......... 0.9803

TP Cost Equation:[b] .... $y = 225.71x^{-0.187}$
TP Cost R-Square Value: 0.8407

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.2.5 Membrane Biological Reactor Plants

Table 15-35 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E seasonally for an MBR plant. Figures 15-35 and 15-36 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-36 presents the annualized unit costs for reducing nutrient loads.

TABLE 15-35.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.19	$0.27	$0.07
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.15	$0.07	$0.04

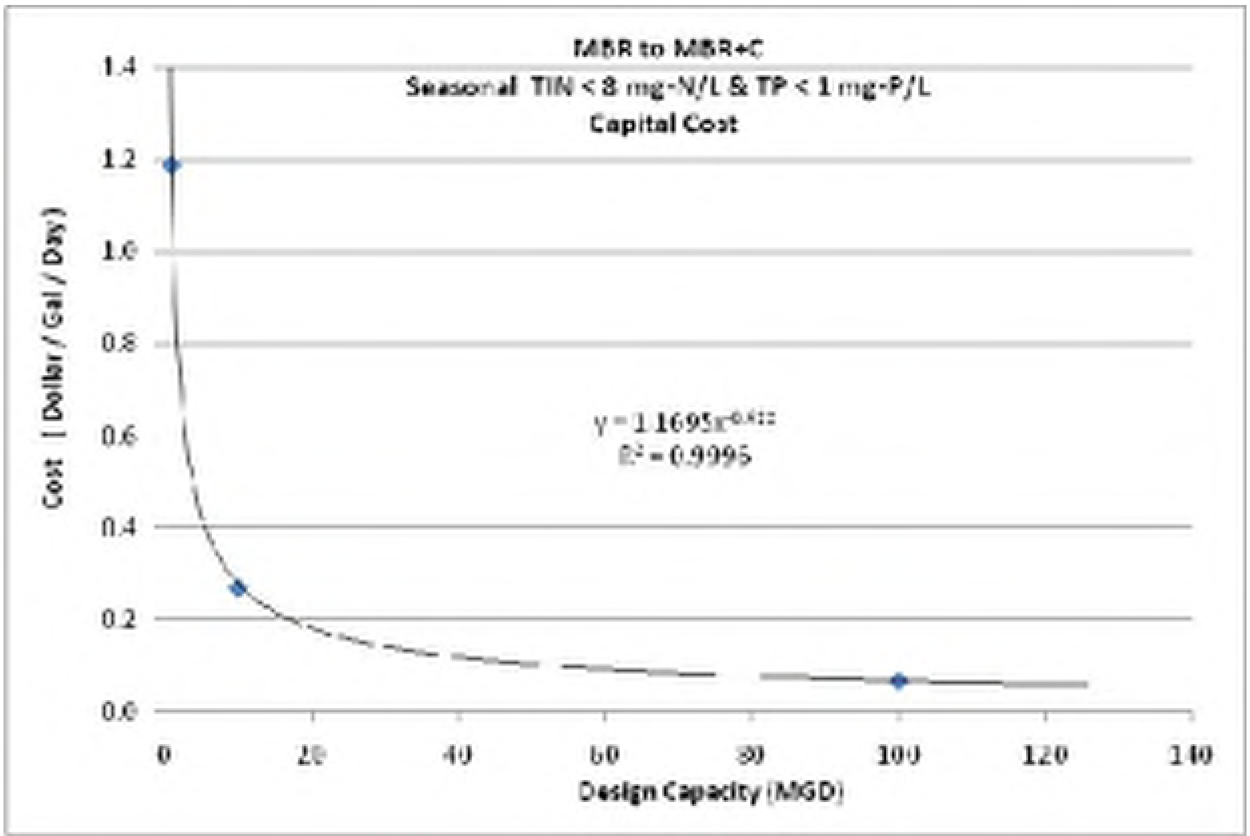


Figure 15-35. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective E Seasonally

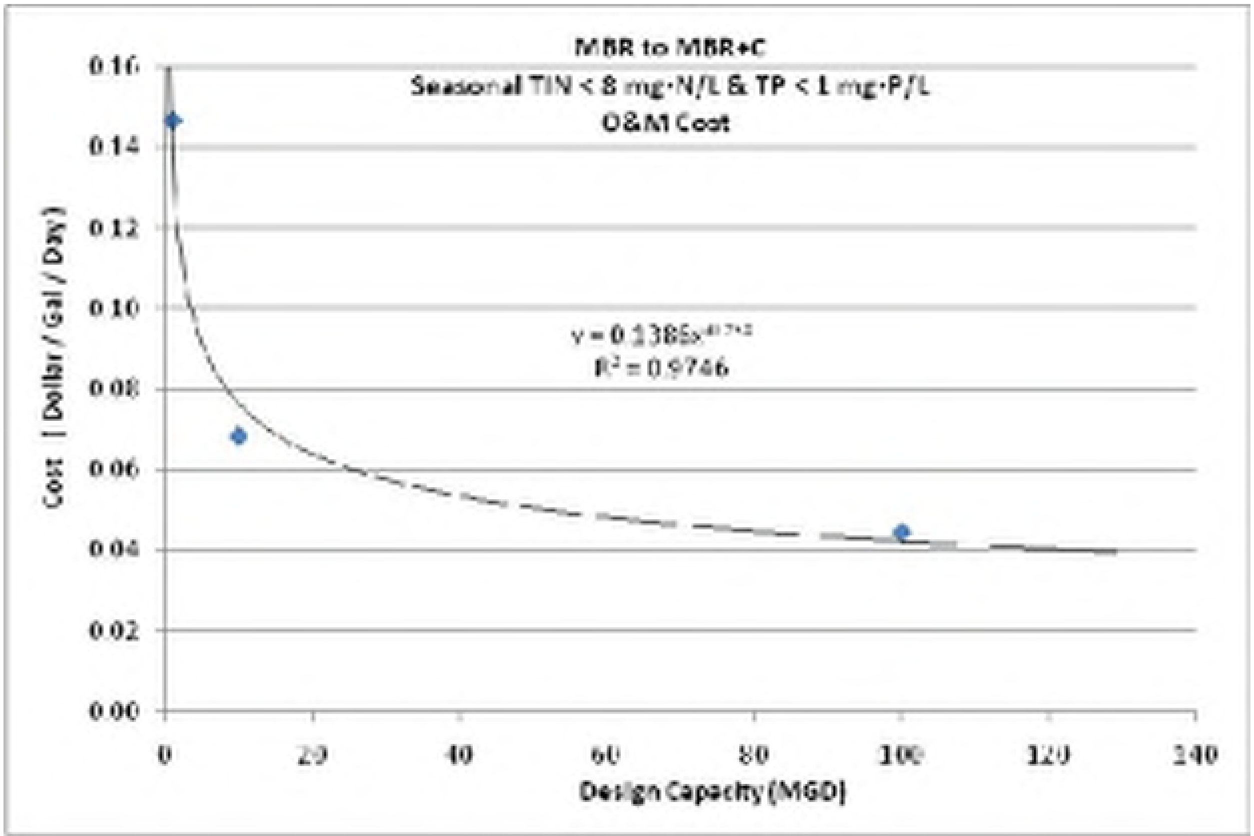


Figure 15-36. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective E Seasonal

TABLE 15-36.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	87,393	198,159	498,252
2014 Incremental O&M Cost	164,904	771,109	5,026,973
Total Annual Cost	**252,297**	**969,268**	**5,525,225**
Annual TIN Load Reduction (lb/yr)	0	0	0
Annual TP Load Reduction (lb/yr)	5,493	54,933	549,325
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	0	0	0
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$45.93	$17.64	$10.06
TIN Cost Equation and R-Square Value[a]			

TP Cost Equation:[b] .... $y = 735.65x^{-0.33}$
TP Cost R-Square Value: 0.9779

a. Equation and R-square value for TIN not determined because annual cost estimates are below the level of precision that can be achieved using the CapdetWorks cost model.
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

15.2.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective E were developed for these plants.

15.2.7 Aerated or Facultative Lagoon Plants

Table 15-37 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective E seasonally for an aerated lagoon plan. Figures 15-37 and 15-38 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 15-38 and Figures 15-39 and 15-40 summarize these costs for a facultative lagoon plant. Tables 15-39 and 15-40 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

**TABLE 15-37.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$23.90	$17.39	$11.05	$7.32
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.13	$0.67	$0.31	$0.15

**TABLE 15-38.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE E SEASONALLY**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$23.76	$17.27	$10.96	$7.27
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.40	$0.90	$0.47	$0.18

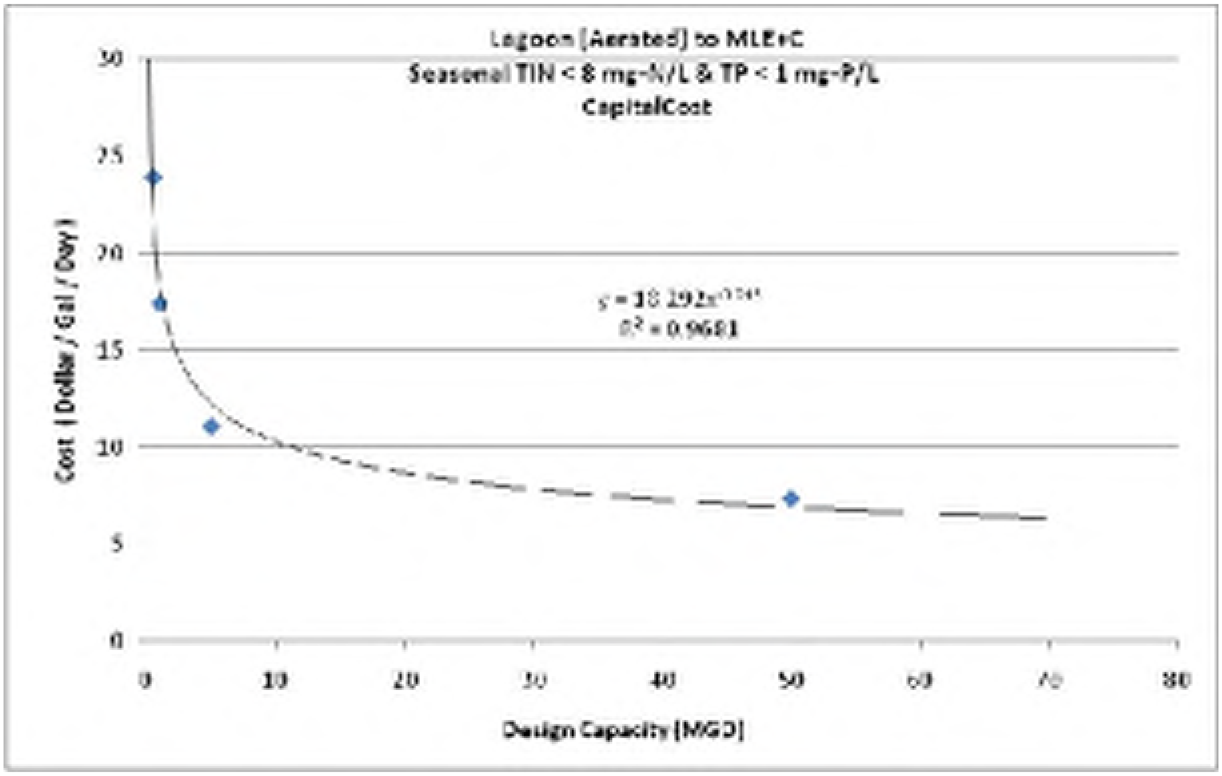


Figure 15-37. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective E Seasonally

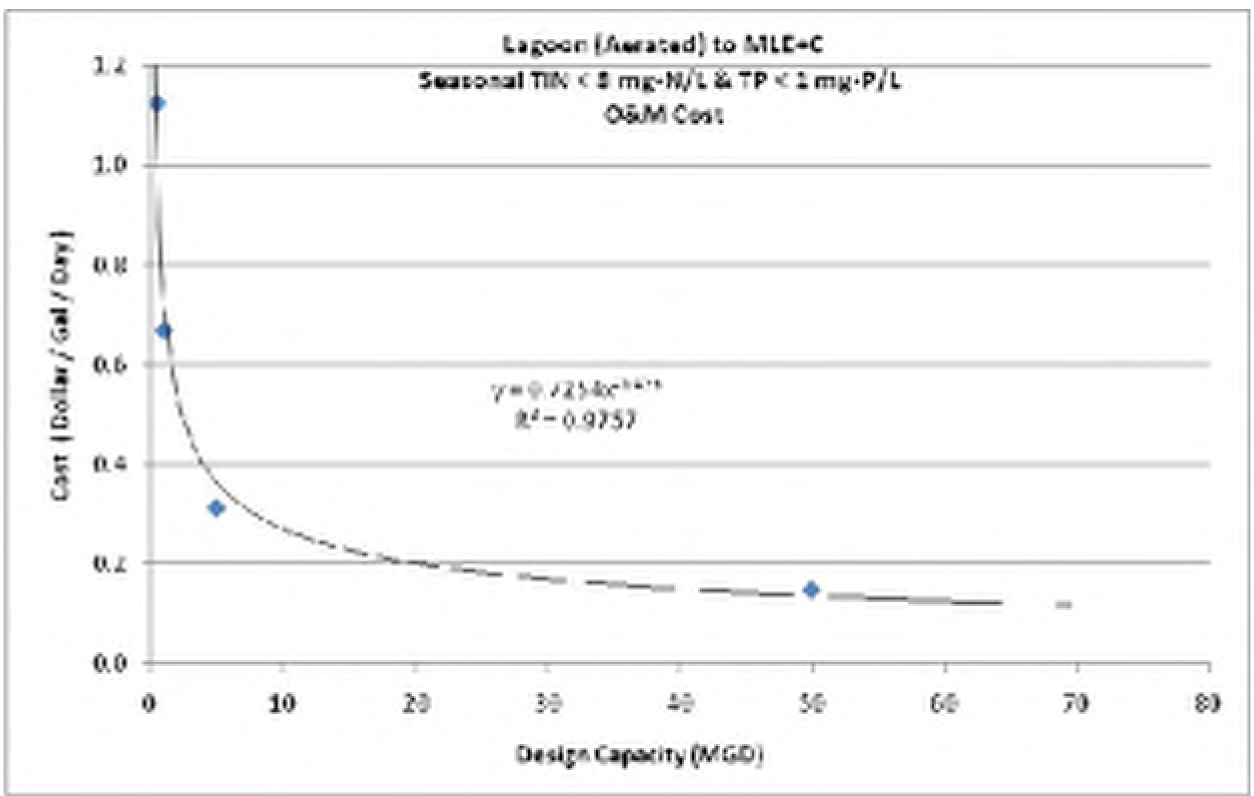


Figure 15-38. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective E Seasonal

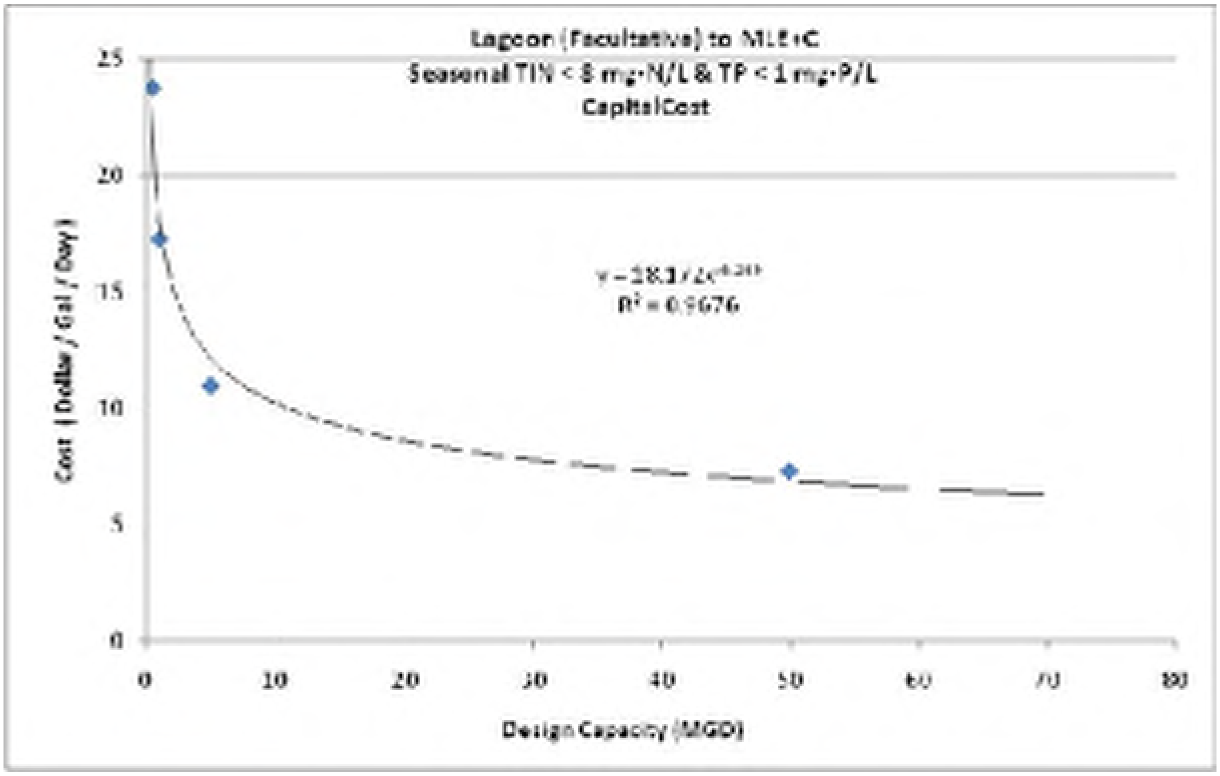


Figure 15-39. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective E Seasonally

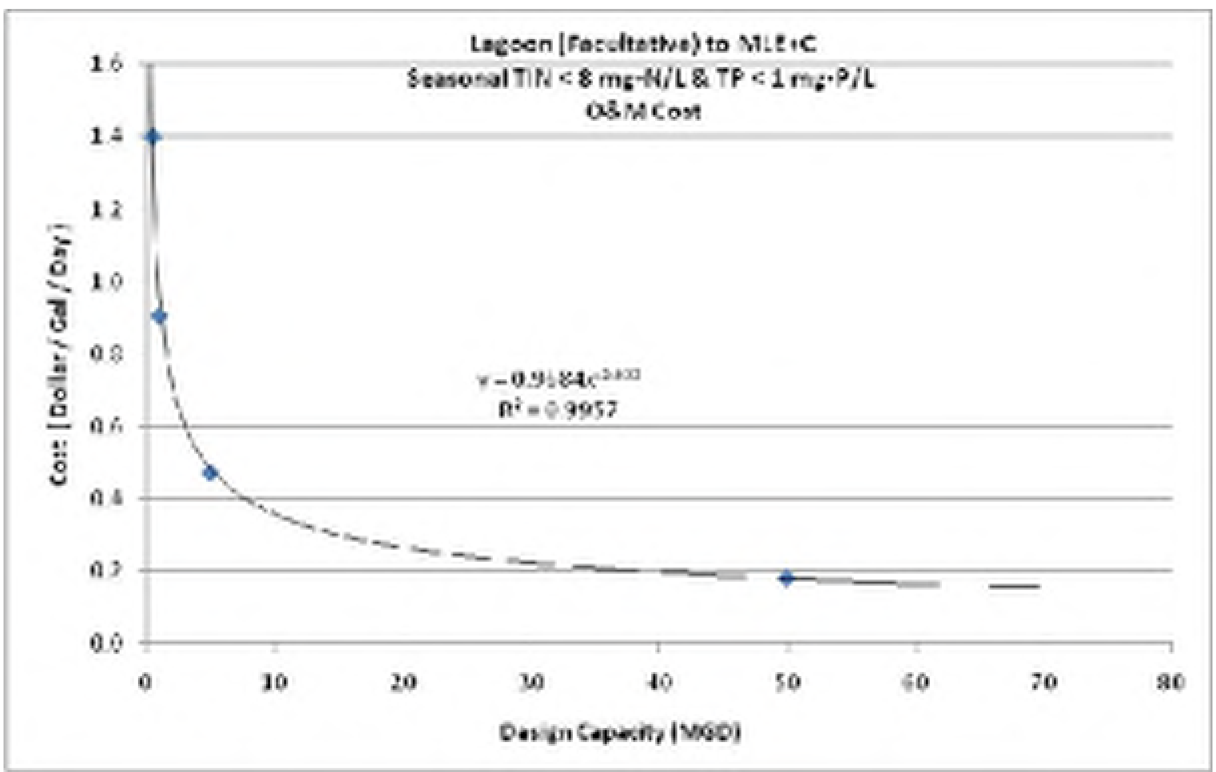


Figure 15-40. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective E Seasonal

TABLE 15-39.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$877,697	$1,277,193	$4,056,916	$26,881,497
2014 Incremental O&M Cost	$634,168	$754,125	$1,759,508	$8,327,583
Total Annual Cost	**$1,511,865**	**$2,031,318**	**$5,816,424**	**$35,209,080**
Annual TIN Load Reduction (lb/yr)	9,663	19,327	96,634	970,900
Annual TP Load Reduction (lb/yr)	2,947	5,895	29,474	294,738
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$118.93	$79.24	$47.44	$26.79
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$123.02	$84.80	$41.80	$32.21

TIN Cost Equation:[a] .... $y = 1852.5x^{-0.311}$
TIN Cost R-Square Value:........ 0.976

TP Cost Equation:[b] .... $y = 1053.4x^{-0.288}$
TP Cost R-Square Value: 0.9023

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 15-40.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE E SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$872,597	$1,268,720	$4,023,764	$26,707,101
2014 Incremental O&M Cost	$787,337	$1,017,803	$2,662,335	$10,214,853
Total Annual Cost	**$1,659,934**	**$2,286,523**	**$6,686,099**	**$36,921,954**
Annual TIN Load Reduction (lb/yr)	9,663	19,327	96,634	970,900
Annual TP Load Reduction (lb/yr)	2,947	5,895	29,474	294,738
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$135.89	$94.01	$57.90	$29.22
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$117.67	$79.66	$37.03	$29.01

TIN Cost Equation:[a] .... $y = 2439.5x^{-0.323}$
TIN Cost R-Square Value:........ 0.9907

TP Cost Equation:[b] .... $y = 1109.9x^{-0.301}$
TP Cost R-Square Value: 0.8912

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

CHAPTER 16.
COST EVALUATION, OBJECTIVE F

16.1 YEAR-ROUND NUTRIENT REMOVAL

167.1.1 Extended Aeration Plants

Table 16-1 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F year-round for an extended aeration plant using mechanical aeration. Figures 16-1 and 16-2 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-2 and Figures 16-3 a nd 16-4 summarize these costs for an extended aeration plant using diffuser aeration. Tables 16-3 and 16-4 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 16-1.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$8.44	$3.92	$3.25
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.61	$0.26	$0.18

TABLE 16-2.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.72	$2.42	$1.36
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.42	$0.20	$0.15

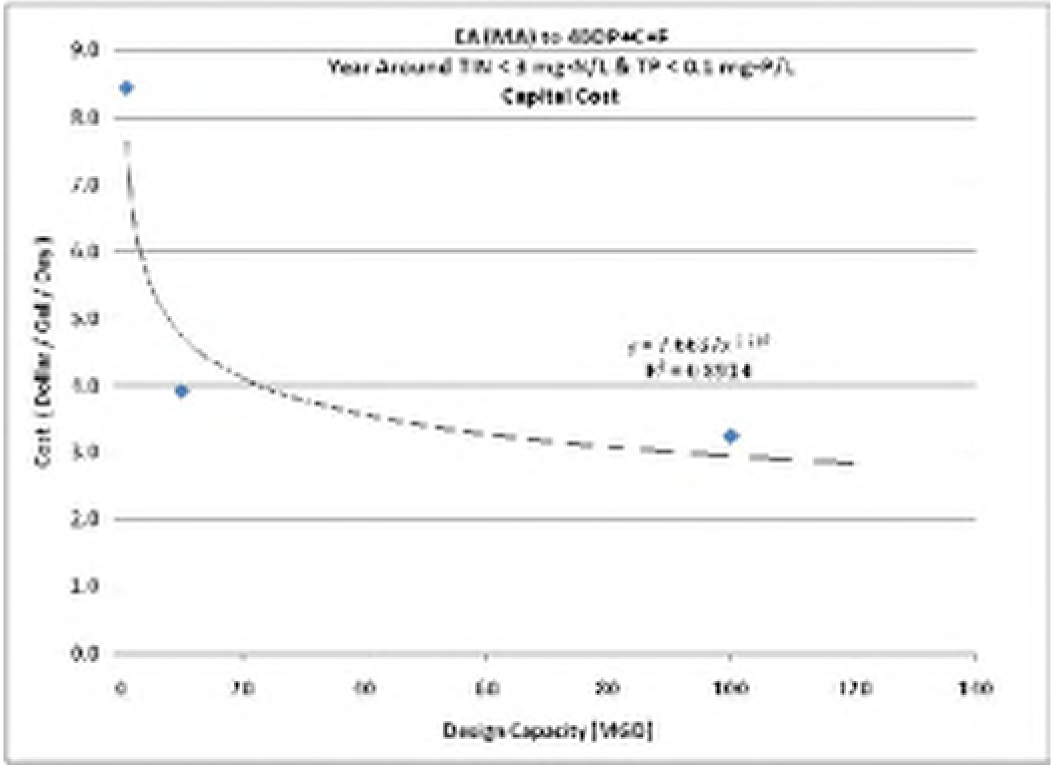


Figure 16-1. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective F Year-Round

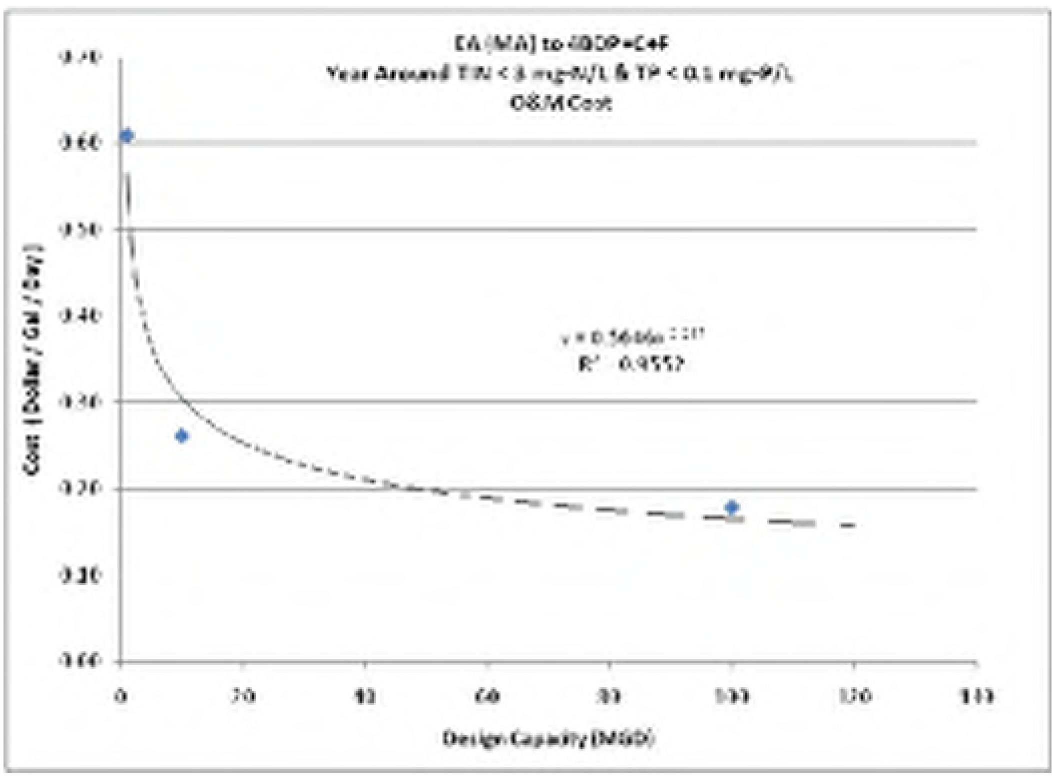


Figure 16-2. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective F Year-Round

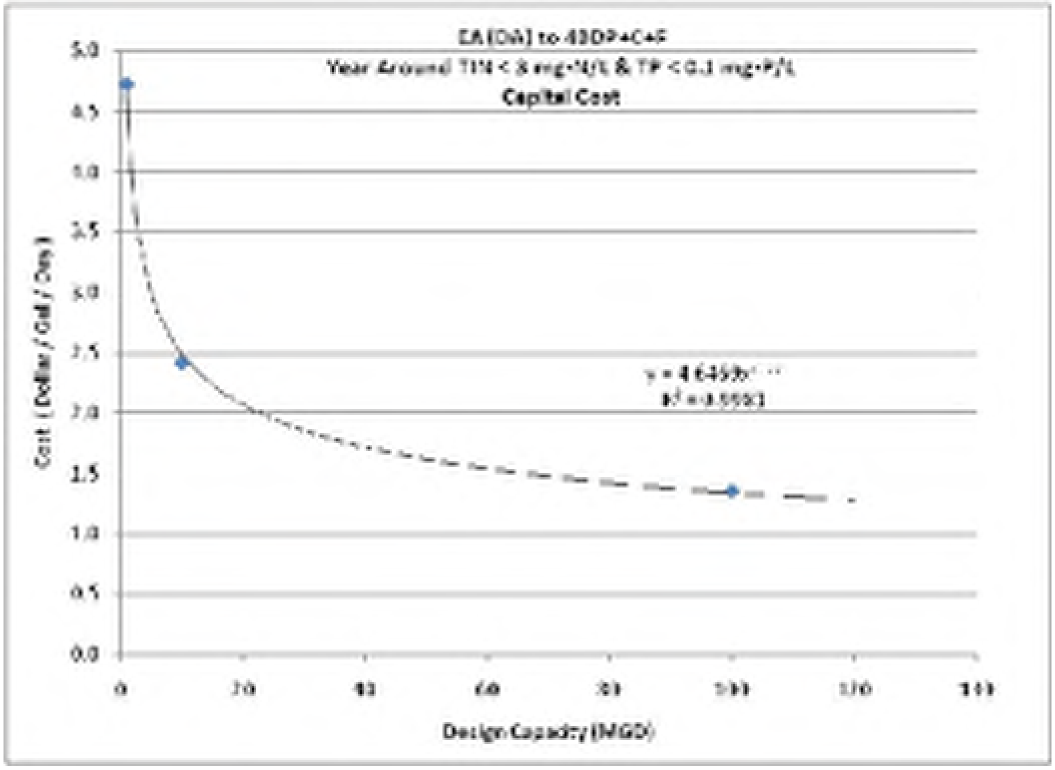


Figure 16-3. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective F Year-Round

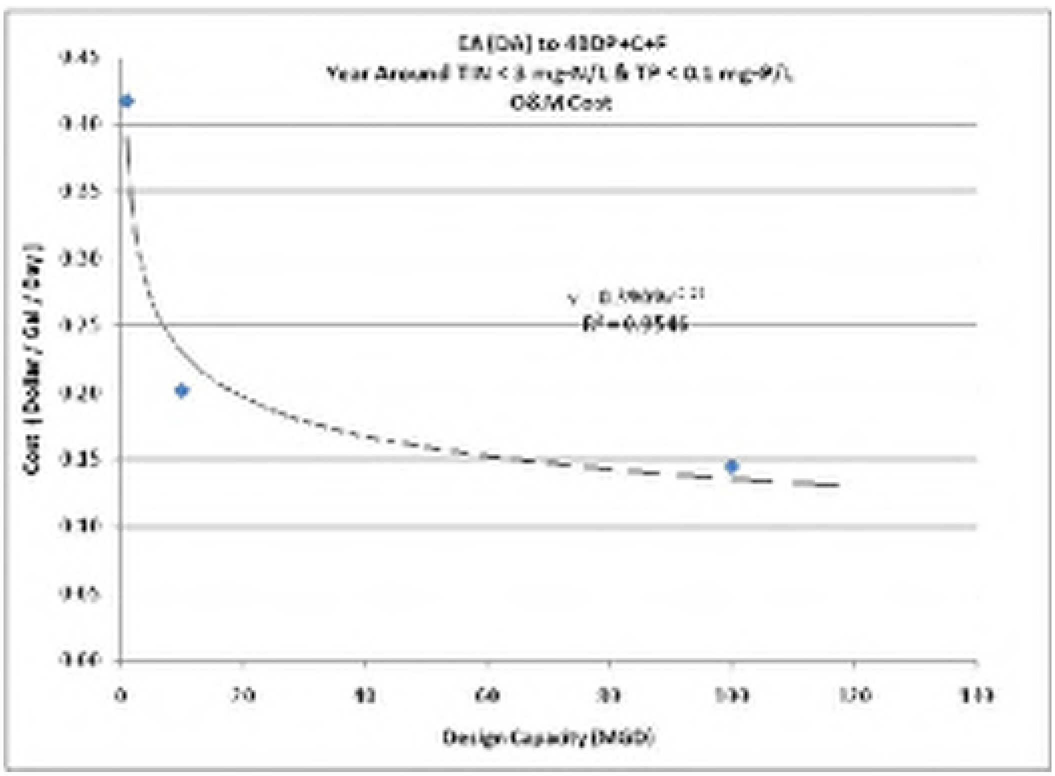


Figure 16-4. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective F Year-Round

TABLE 16-3.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$519,755	$2,879,976	$23,842,223
2014 Incremental O&M Cost	$686,335	$2,942,508	$20,025,334
Total Annual Cost	**$1,306,090**	**$5,822,483**	**$43,867,557**
Annual TIN Load Reduction (lb/yr)	45,406	454,060	4,540,600
Annual TP Load Reduction (lb/yr)	12,775	127,750	1,277,500
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$16.61	$5.27	$3.34
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$43.20	$26.86	$22.46

TIN Cost Equation:[a] .... $y = 620.03x^{-0.348}$
TIN Cost R-Square Value:........ 0.9416

TP Cost Equation:[b] .... $y = 157.5x^{-0.142}$
TP Cost R-Square Value: 0.936

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-4.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$346,644	$1,777,662	$10,005,716
2014 Incremental O&M Cost	$470,294	$2,269,116	$16,326,349
Total Annual Cost	**$816,938**	**$4,046,778**	**$26,332,066**
Annual TIN Load Reduction (lb/yr)	45,370	453,695	4,536,950
Annual TP Load Reduction (lb/yr)	12,739	127,385	1,273,850
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$6.53	$1.90	$0.32
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$40.89	$24.99	$19.52

TIN Cost Equation:[a] .... $y = 8019.1x^{-0.655}$
TIN Cost R-Square Value:........ 0.9892

TP Cost Equation:[b] .... $y = 179.07x^{-0.161}$
TP Cost R-Square Value: 0.9646

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.1.2 Conventional Activated Sludge Plants

Table 16-5 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F year-round for a conventional activated sludge plant. Figures 16-5 and 16-6 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-6 presents the annualized unit costs for reducing nutrient loads.

TABLE 16-5.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$11.00	$6.45	$4.16
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.59	$0.33	$0.24

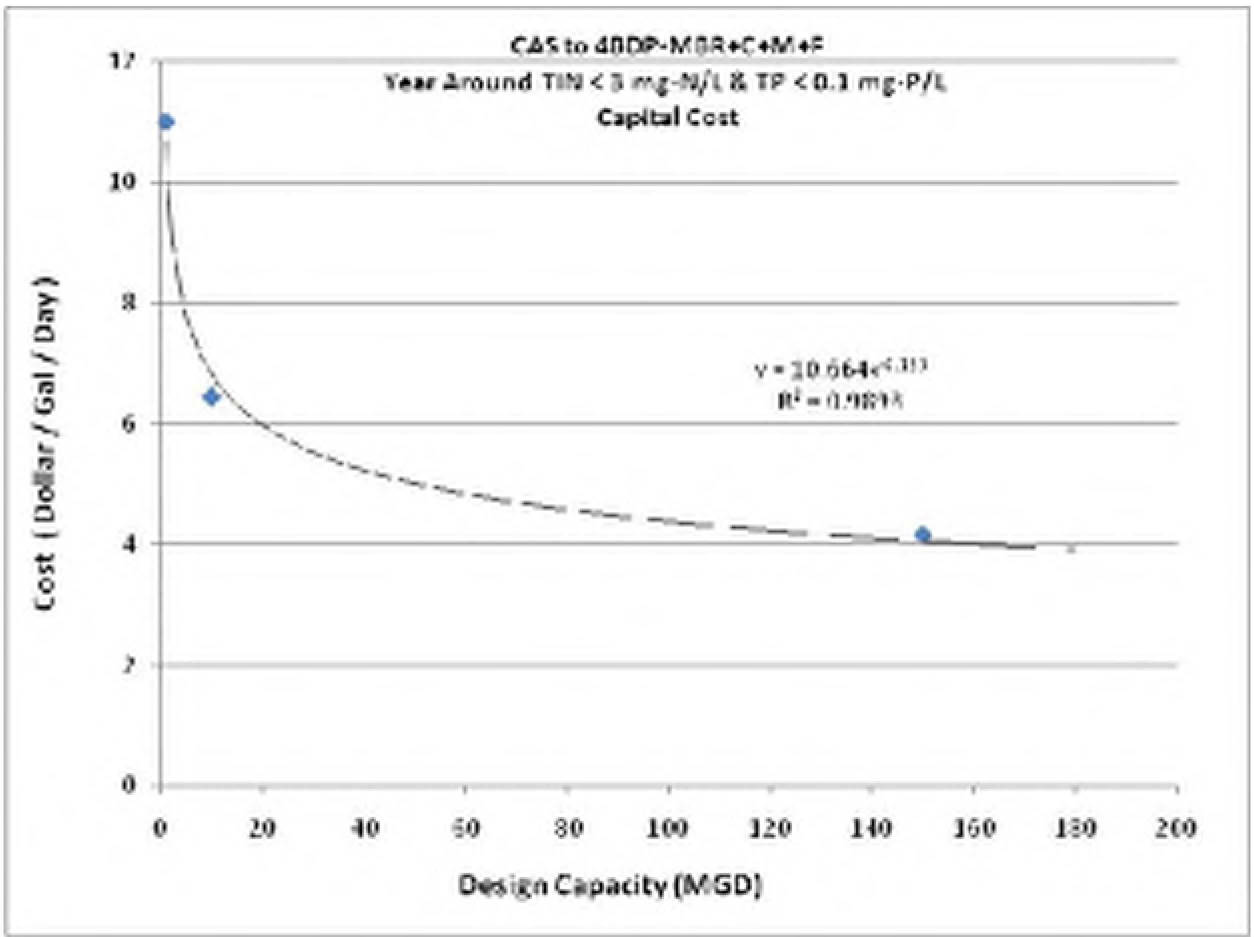


Figure 16-5. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective F Year-Round

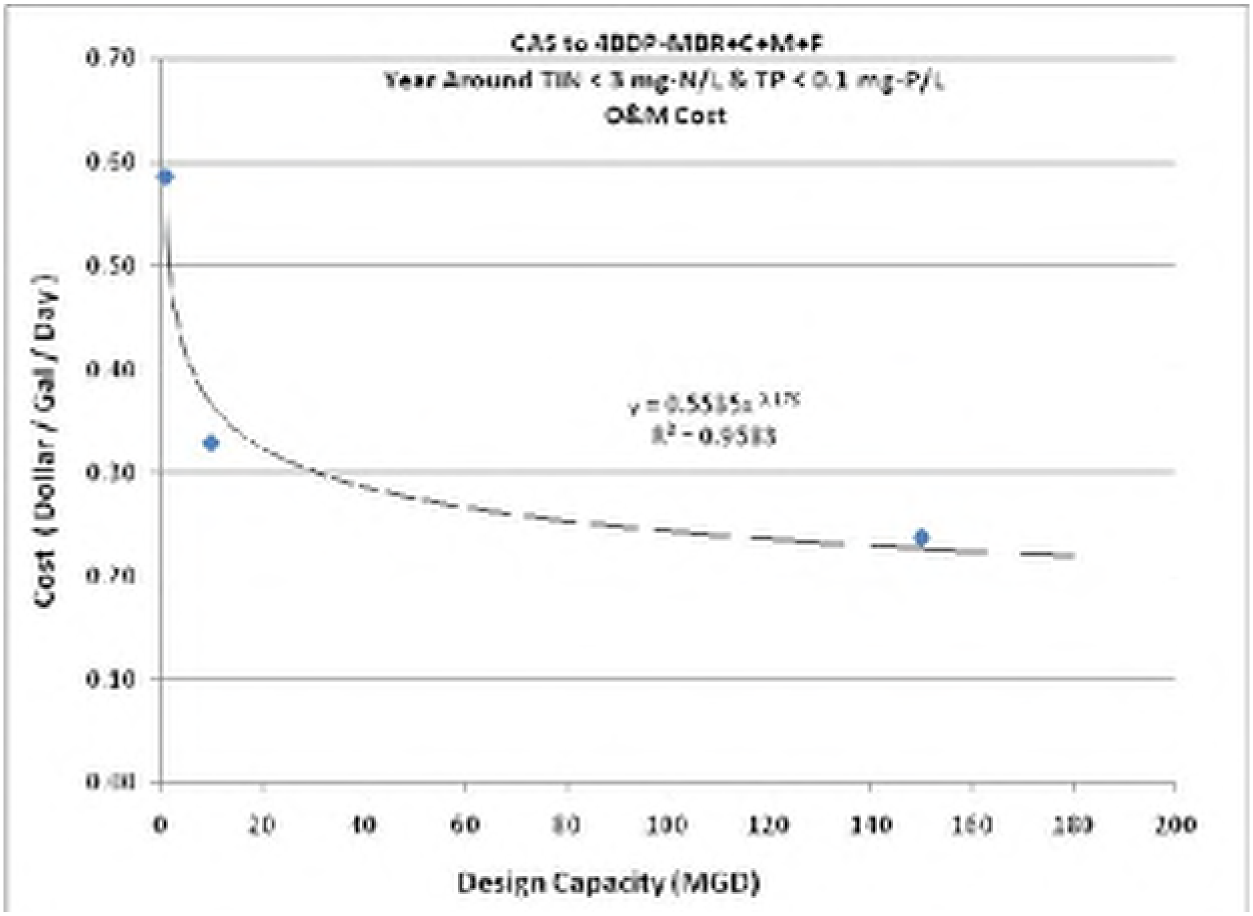


Figure 16-6. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective F Year-Round

TABLE 16-6.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$808,295	$4,735,944	$45,832,152
2014 Incremental O&M Cost	$660,329	$3,707,577	$40,125,423
Total Annual Cost	**$1,468,624**	**$8,443,521**	**$85,957,575**
Annual TIN Load Reduction (lb/yr)	45,479	454,790	6,821,850
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$19.53	$11.88	$7.38
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$44.17	$23.14	$18.08

TIN Cost Equation:[a] .... $y = 153.13x^{-0.194}$
TIN Cost R-Square Value: 0.9965

TP Cost Equation:[b] .... $y = 214.81x^{-0.176}$
TP Cost R-Square Value: 0.9129

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.1.3 Sequencing Batch Reactor Plants

Table 16-7 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F year-round for an SBR plant. Figures 16-7 and 16-8 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-8 presents the annualized unit costs for reducing nutrient loads.

TABLE 16-7.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.85	$2.97	$1.80
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.86	$0.39	$0.19

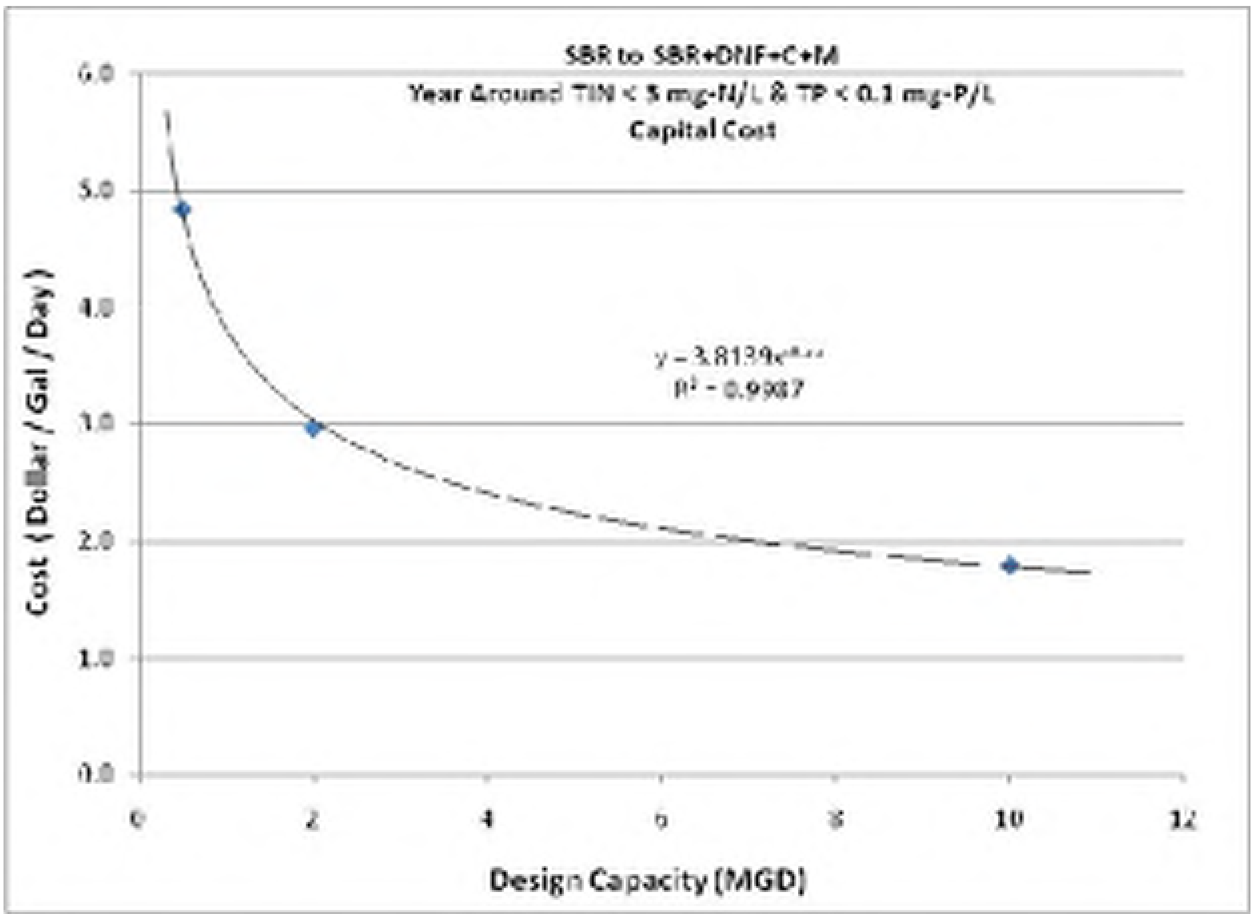


Figure 16-7. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective F Year-Round

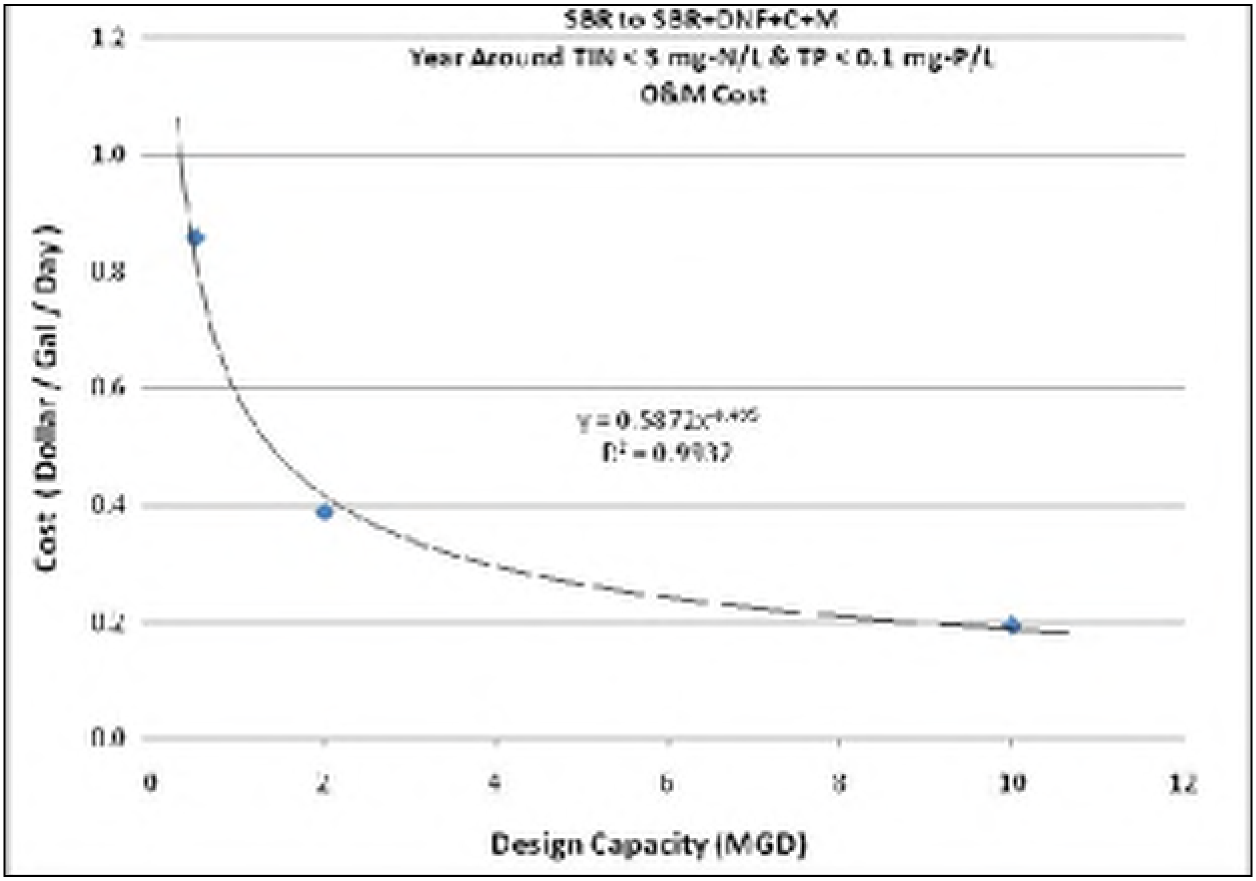


Figure 16-8. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective F Year-Round

TABLE 16-8.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$178,058	$436,508	$1,322,023
2014 Incremental O&M Cost	$483,732	$873,775	$2,184,463
Total Annual Cost	**$661,790**	**$1,310,283**	**$3,506,487**
Annual TIN Load Reduction (lb/yr)	2,537	10,147	50,735
Annual TP Load Reduction (lb/yr)	2,957	11,826	59,130
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$172.21	$71.54	$29.76
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$76.08	$49.41	$33.77

TIN Cost Equation:[a] .... $y = 16486x^{-0.585}$
TIN Cost R-Square Value:.. 0.9981

TP Cost Equation:[b] .... $y = 646.37x^{-0.27}$
TP Cost R-Square Value: 0.9937

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.1.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 16-9 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F year-round for a trickling filter plant. Figures 16-9 and 16-10 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-10 and Figures 16-1 and 16-12 summarize these costs for a trickling filter/solids contact plant. Table 16-11 and Figures 16-13 and 16-14 summarize these costs for an RBC plant. Tables 16-12, 16-13 and 16-14 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 16-9.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$12.44	$7.62	$4.53
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.65	$0.36	$0.24

TABLE 16-10.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$11.17	$7.06	$4.21
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.52	$0.31	$0.21

TABLE 16-11.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$12.44	$7.64	$4.58
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.71	$0.37	$0.25

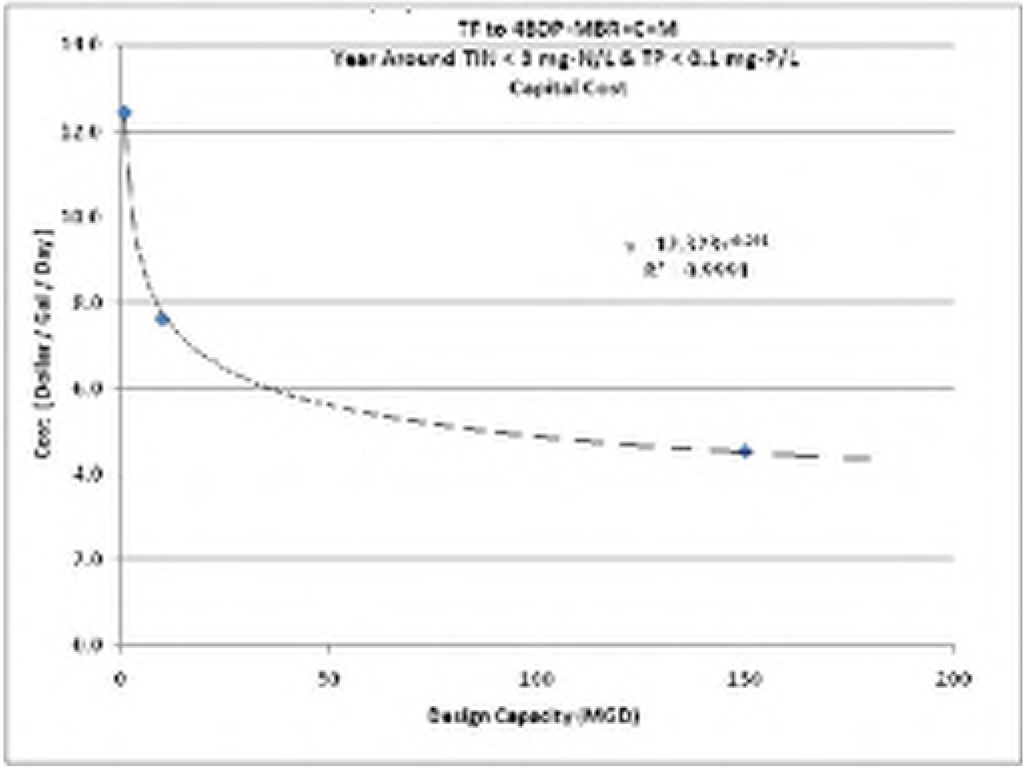


Figure 16-9. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective F Year-Round

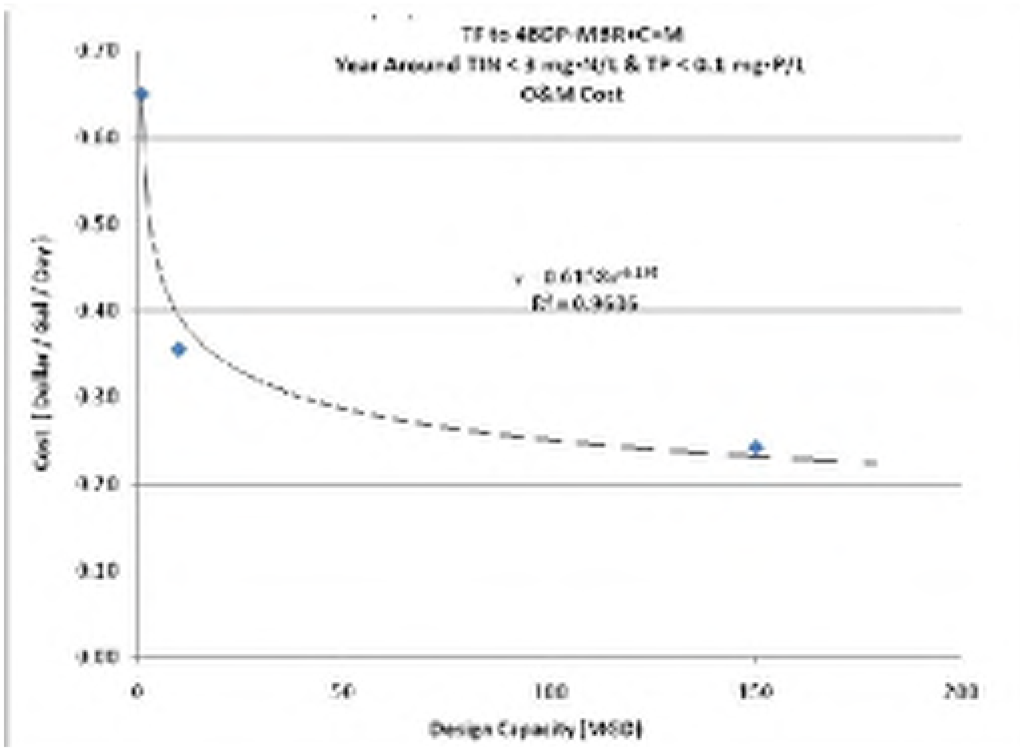


Figure 16-10. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective F Year-Round

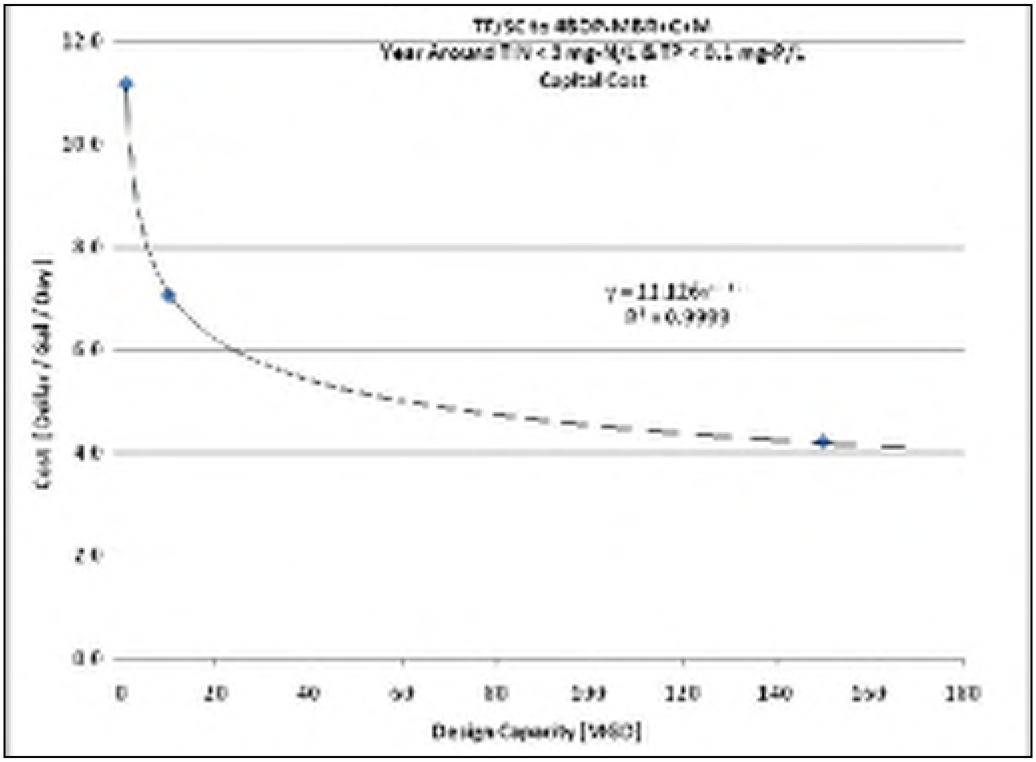


Figure 16-11. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective F Year-Round

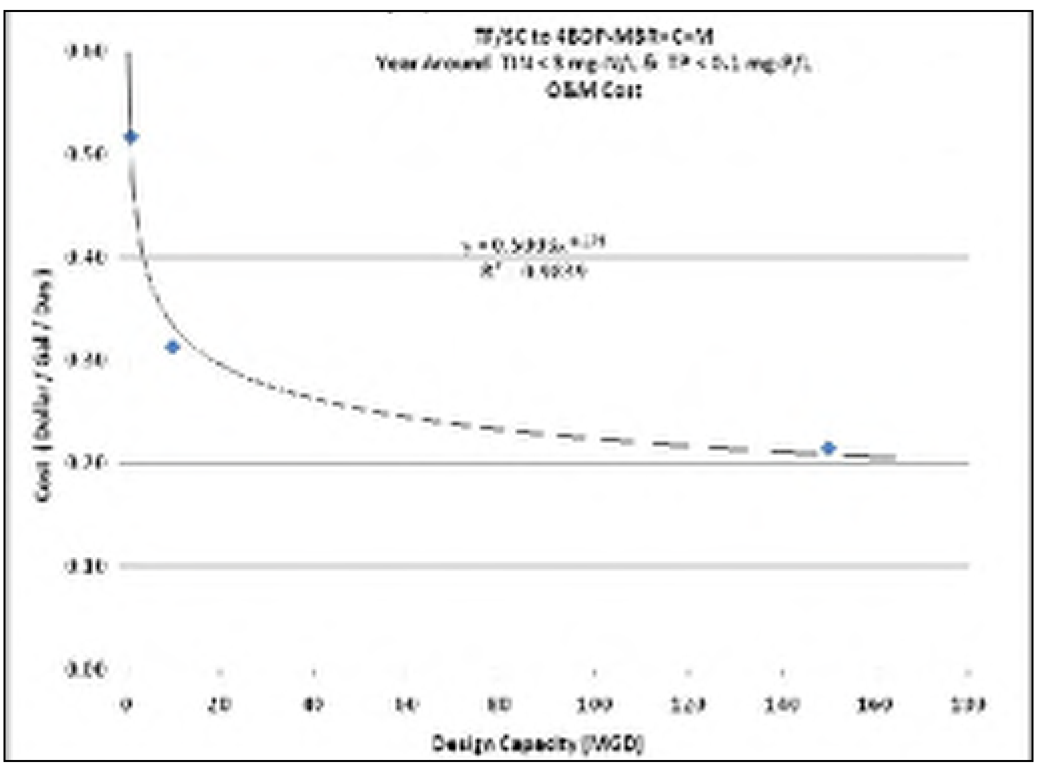


Figure 16-12. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective F Year-Round

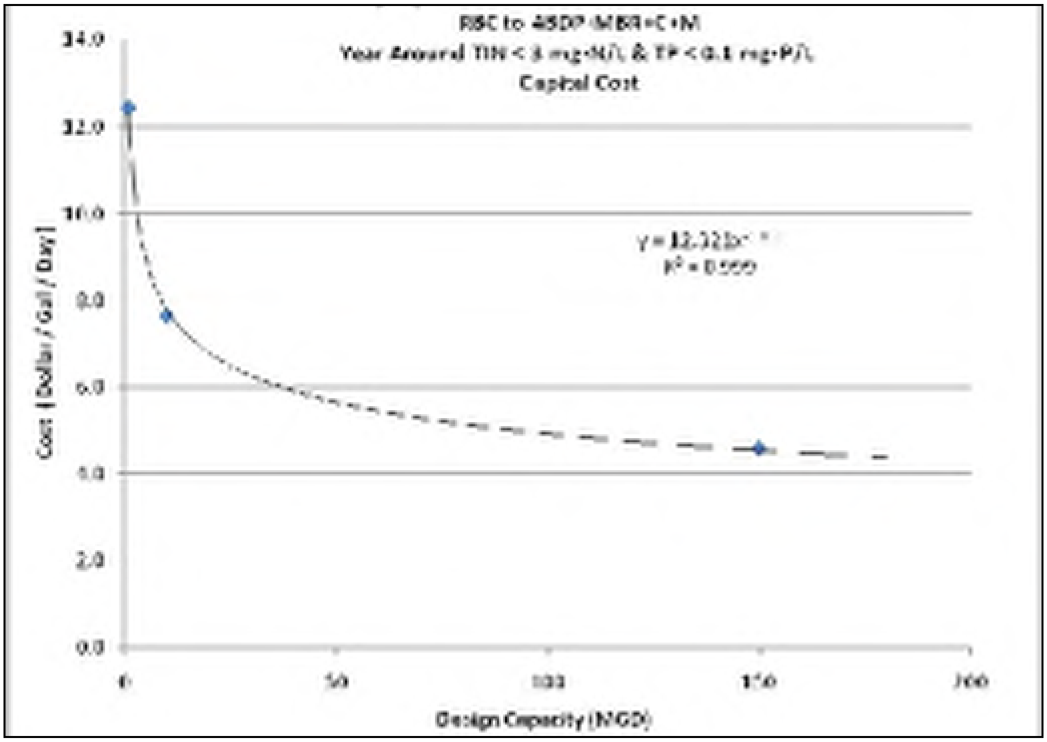


Figure 16-13. Capital Cost per Plant Capacity for RBC Upgraded for Objective F Year-Round

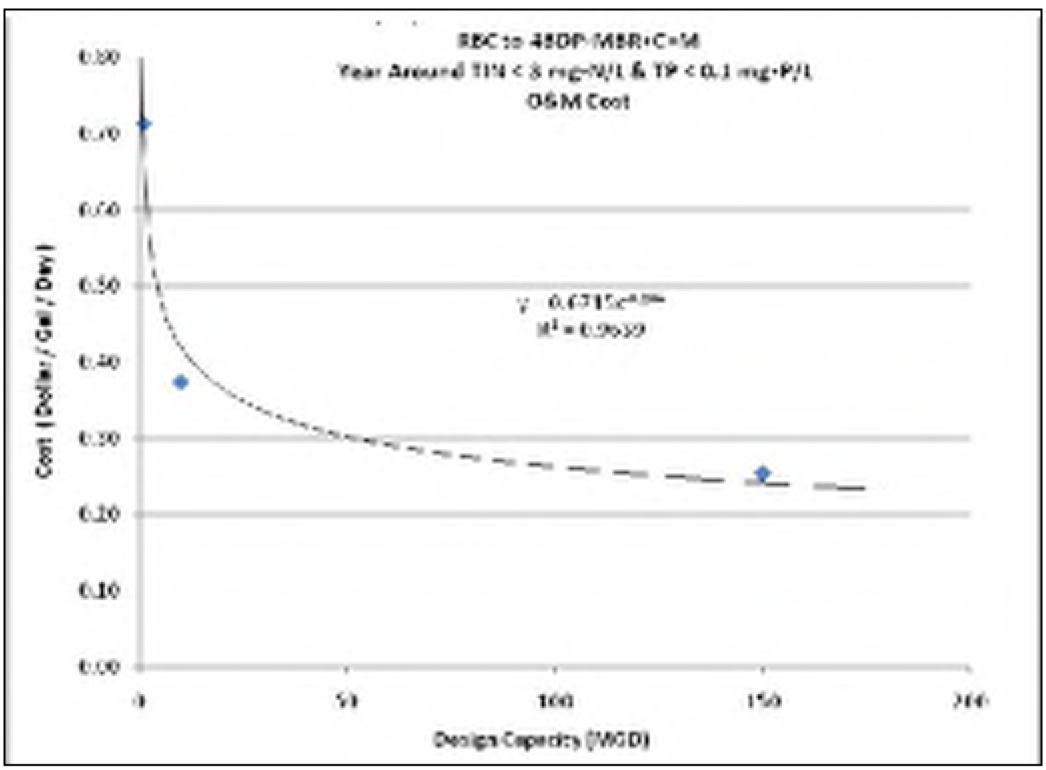


Figure 16-14. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective F Year-Round

TABLE 16-12.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$913,676	$5,594,150	$49,901,730
2014 Incremental O&M Cost	$732,176	$3,998,971	$41,046,652
Total Annual Cost	**$1,645,852**	**$9,593,121**	**$90,948,382**
Annual TIN Load Reduction (lb/yr)	45,479	454,790	6,821,850
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$23.82	$14.70	$8.34
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$42.81	$22.13	$17.27

TIN Cost Equation:[a] .... $y = 225.12x^{-0.209}$
TIN Cost R-Square Value:.......... 1

TP Cost Equation:[b] .... $y = 213.36x^{-0.179}$
TP Cost R-Square Value: 0.911

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-13.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$820,226	$5,185,883	$46,395,714
2014 Incremental O&M Cost	$583,097	$3,531,660	$36,286,875
Total Annual Cost	**$1,403,323**	**$8,717,542**	**$82,682,589**
Annual TIN Load Reduction (lb/yr)	45,479	454,790	6,821,850
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$18.42	$12.72	$7.15
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$43.06	$22.33	$17.22

TIN Cost Equation:[a] .... $y = 143.98x^{-0.19}$
TIN Cost R-Square Value:.......... 0.9939

TP Cost Equation:[b] .... $y = 218.9x^{-0.18}$
TP Cost R-Square Value: 0.9173

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-14.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$914,005	$5,614,551	$50,425,740
2014 Incremental O&M Cost	$803,877	$4,213,437	$42,961,705
Total Annual Cost	**$1,717,881**	**$9,827,988**	**$93,387,446**
Annual TIN Load Reduction (lb/yr)	45,479	454,790	6,821,850
Annual TP Load Reduction (lb/yr)	13,140	131,400	1,971,000
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$25.33	$15.19	$8.71
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$43.07	$22.24	$17.24

TIN Cost Equation:[a] .... $y = 246.43x^{-0.213}$
TIN Cost R-Square Value:........ 0.9995

TP Cost Equation:[b] .... $y = 218.09x^{-0.18}$
TP Cost R-Square Value: 0.9141

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.1.5 Membrane Biological Reactor Plants

Table 16-15 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F year-round for an MBR plant. Figures 16-15 and 16-16 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-16 presents the annualized unit costs for reducing nutrient loads.

TABLE 16-15.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.35	$0.35	$0.28
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.20	$0.12	$0.10

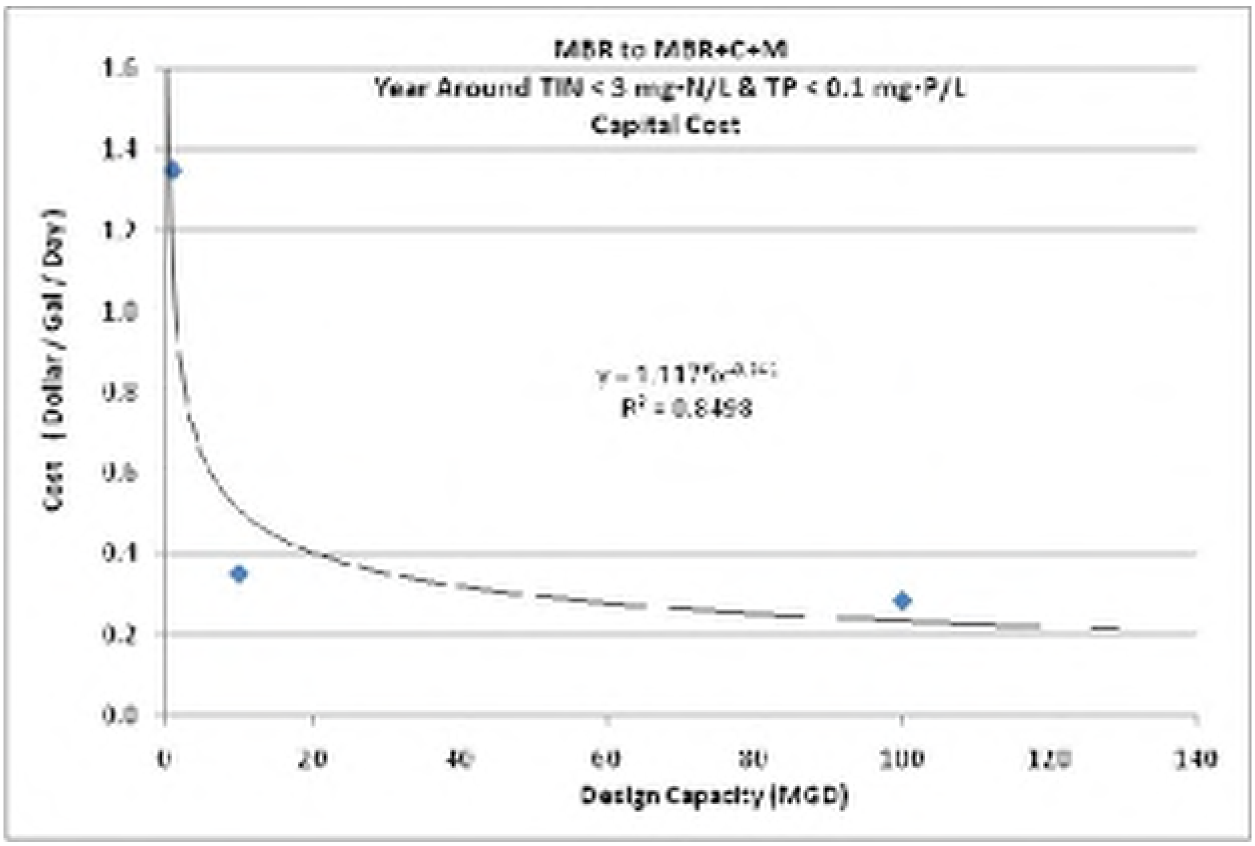


Figure 16-15. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective F Year-Round

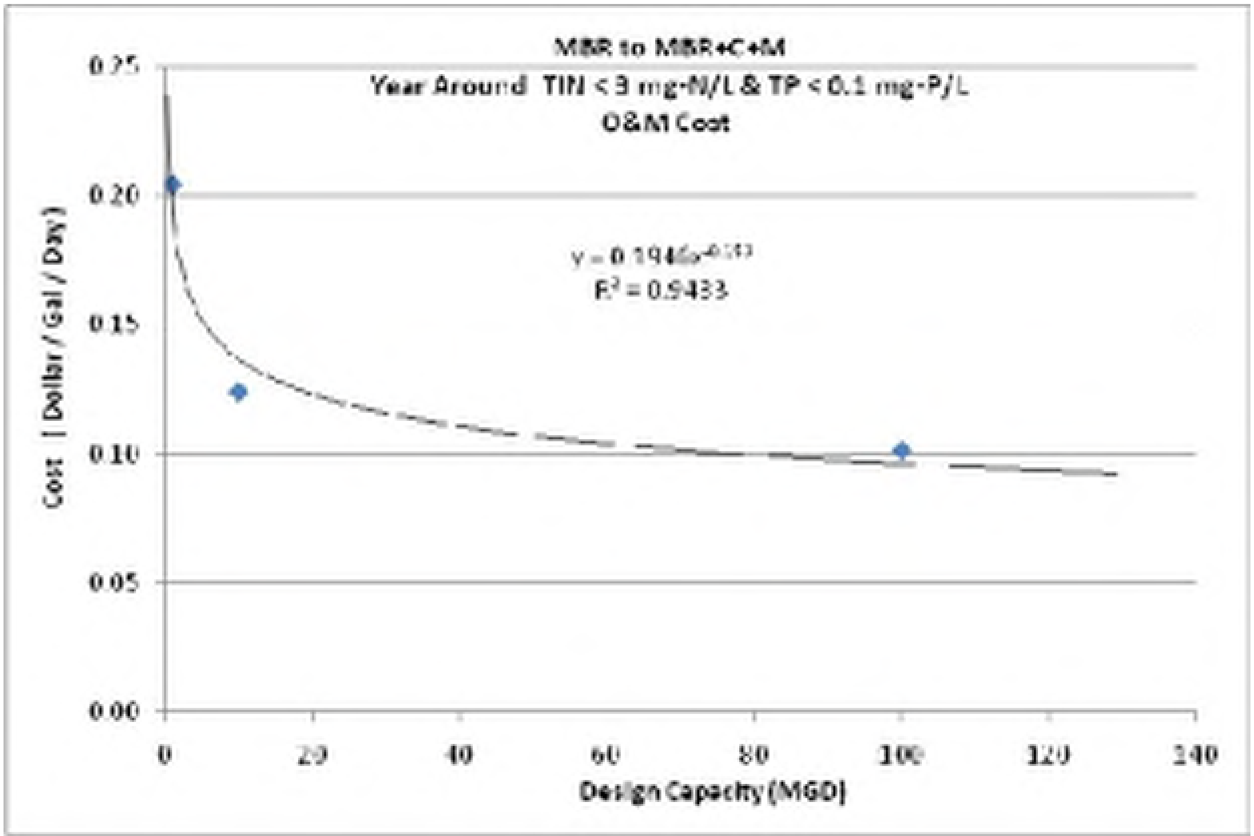


Figure 16-16. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective F Year-Round

TABLE 16-16.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$99,292	$256,052	$2,069,159
2014 Incremental O&M Cost	$230,266	$1,393,462	$11,375,377
Total Annual Cost	**$329,558**	**$1,649,514**	**$13,444,536**
Annual TIN Load Reduction (lb/yr)	9,600	95,995	959,950
Annual TP Load Reduction (lb/yr)	12,483	124,830	1,248,300
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$2.11	$1.90	$1.89
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$24.78	$11.75	$9.32

TIN Cost Equation:[a] .... $y = 2.584x^{-0.024}$
TIN Cost R-Square Value:.......... 0.7859

TP Cost Equation:[b] .... $y = 168.53x^{-0.212}$
TP Cost R-Square Value: 0.9155

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.1.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective F were developed for these plants.

16.1.7 Aerated or Facultative Lagoon Plants

Table 16-17 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F year-round for an aerated lagoon plant. Figures 16-17 and 16-18 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-18 and Figures 16-19 and 16-20 summarize these costs for a facultative lagoon plant. Tables 16-19 and 16-20 present the annualized unit costs for reducing nutrient loads for aerated lagoon and facultative lagoon plants, respectively.

TABLE 16-17.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$27.75	$21.63	$13.88	$9.59
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.49	$0.97	$0.52	$0.34

TABLE 16-18.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$27.61	$21.52	$13.79	$9.54
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.76	$1.20	$0.68	$0.37

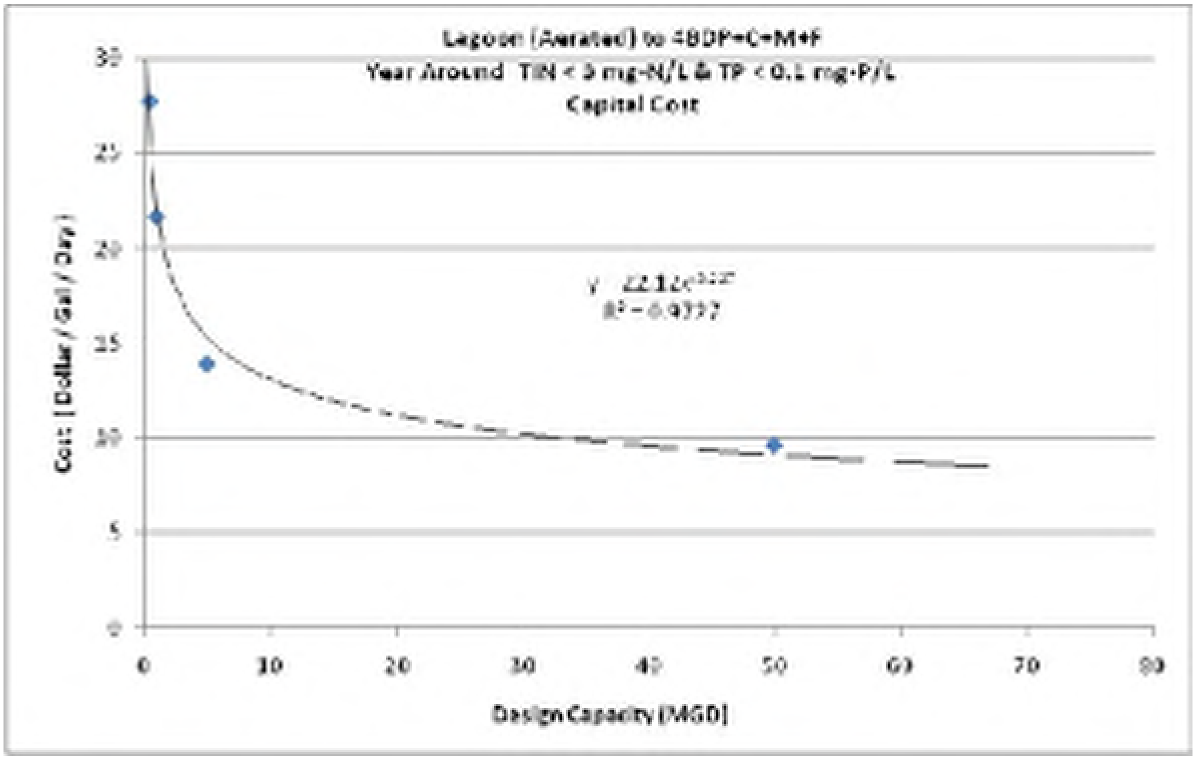


Figure 16-17. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective F Year-Round

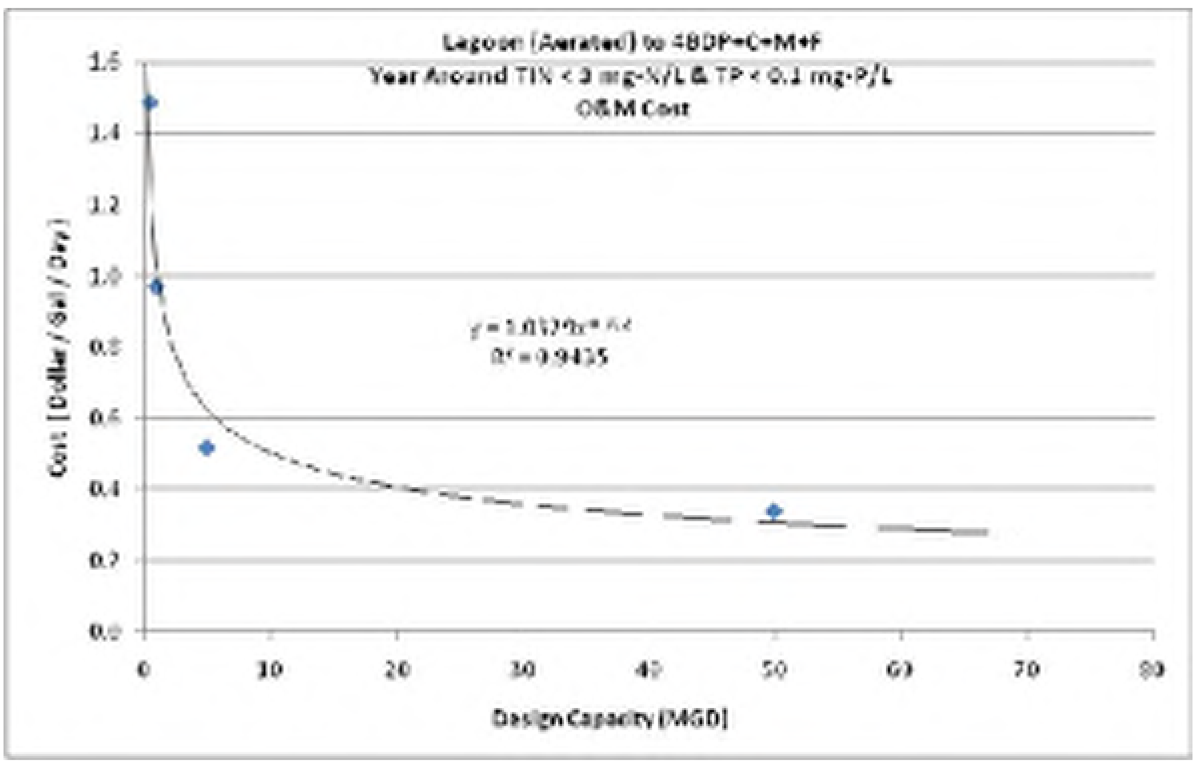


Figure 16-18. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective F Year-Round

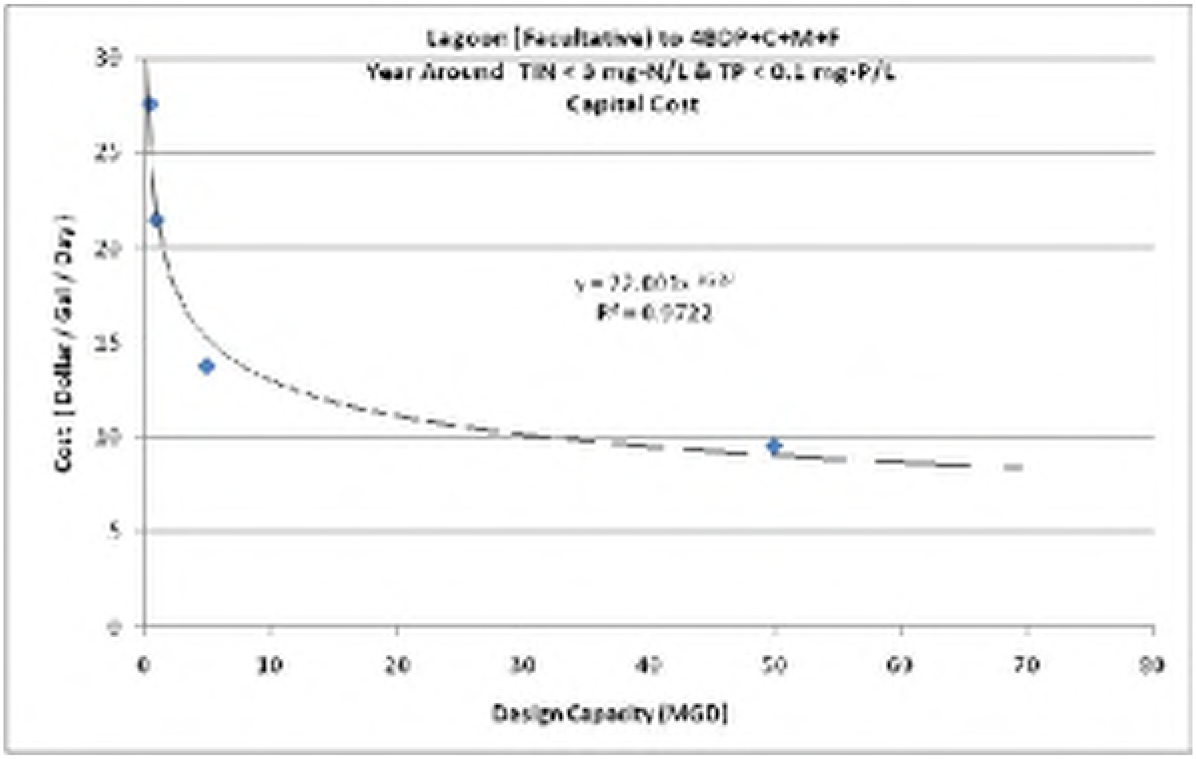


Figure 16-19. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective F Year-Round

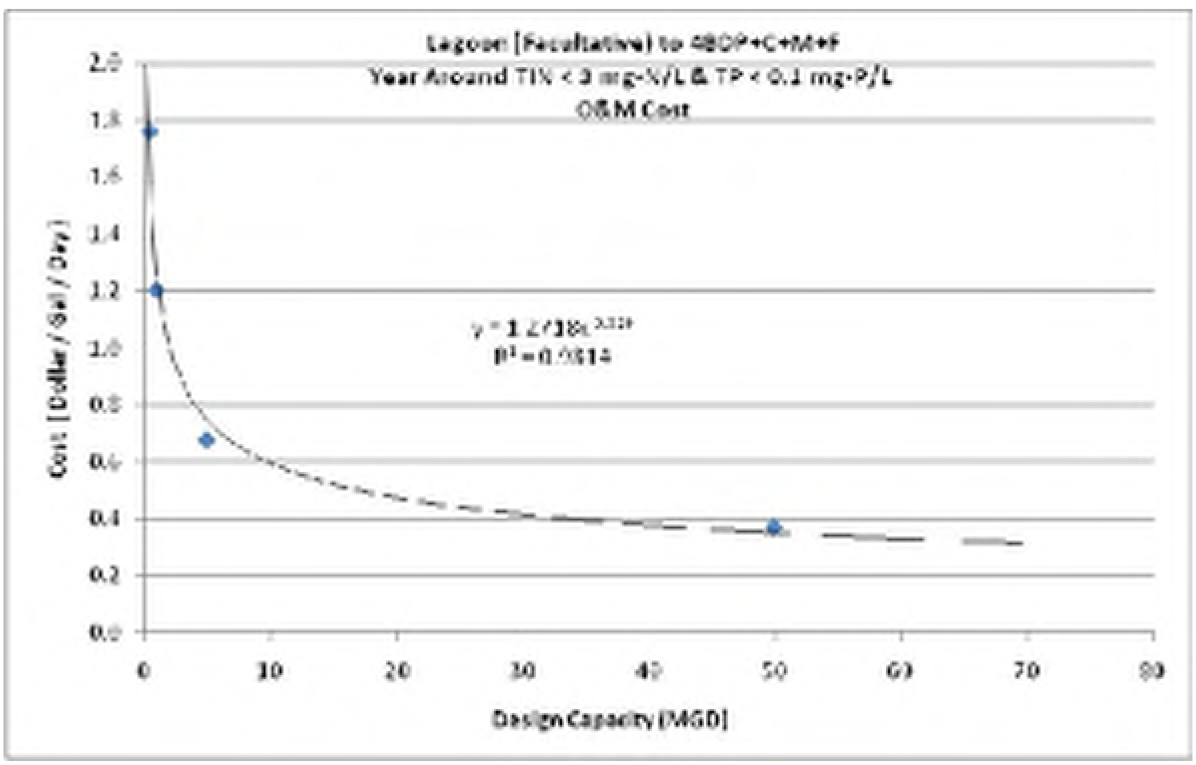


Figure 16-20. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective F Year-Round

TABLE 16-19.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$1,019,087	$1,588,845	$5,096,170	$35,210,268
2014 Incremental O&M Cost	$837,007	$1,090,989	$2,913,323	$19,071,325
Total Annual Cost	**$1,856,094**	**$2,679,834**	**$8,009,493**	**$54,281,593**
Annual TIN Load Reduction (lb/yr)	22,667	45,333	226,665	2,259,350
Annual TP Load Reduction (lb/yr)	6,570	13,140	65,700	657,000
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$61.17	$42.64	$26.34	$16.68
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$71.48	$56.84	$31.05	$25.24

TIN Cost Equation:[a] .... $y = 845.78x^{-0.273}$
TIN Cost R-Square Value:.......... 0.9676

TP Cost Equation:[b] .... $y = 489.23x^{-0.229}$
TP Cost R-Square Value: 0.9088

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-20.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE F YEAR-ROUND

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$1,014,069	$1,580,372	$5,063,018	$35,035,872
2014 Incremental O&M Cost	$990,177	$1,354,668	$3,816,150	$20,958,595
Total Annual Cost	**$2,004,245**	**$2,935,040**	**$8,879,169**	**$55,994,467**
Annual TIN Load Reduction (lb/yr)	22,667	45,333	226,665	2,259,350
Annual TP Load Reduction (lb/yr)	6,570	13,140	65,700	657,000
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$67.74	$48.28	$30.20	$17.42
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$71.35	$56.81	$30.96	$25.33

TIN Cost Equation:[a] .... $y = 1101.9x^{-0.286}$
TIN Cost R-Square Value:.......... 0.9844

TP Cost Equation:[b] .... $y = 483.82x^{-0.228}$
TP Cost R-Square Value: 0.906

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.2 SEASONAL NUTRIENT REMOVAL

16.2.1 Extended Aeration Plants

Table 16-21 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F seasonally for an extended aeration plant using mechanical aeration. Figures 16-21 and 16-22 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-22 and Figures 16-23 and 16-24 summarize these costs for an extended aeration plant using diffuser aeration. Tables 16-23 and 16-24 present the annualized unit costs for reducing nutrient loads for mechanical aeration and diffuser aeration plants, respectively.

TABLE 16-21.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$7.02	$3.56	$2.98
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.53	$0.19	$0.11

TABLE 16-22.
ESTIMATED COST PER CAPACITY FOR UPGRADING EXTENDED AERATION (DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$3.29	$2.07	$1.11
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.34	$0.13	$0.08

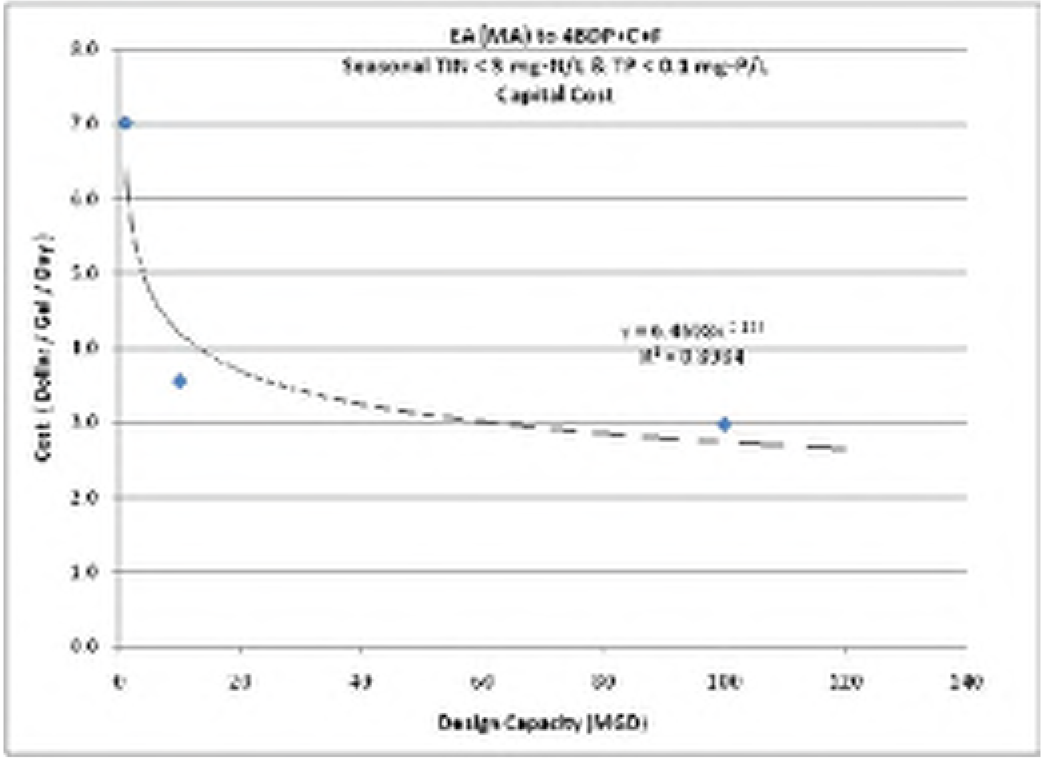


Figure 16-21. Capital Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective F Seasonally

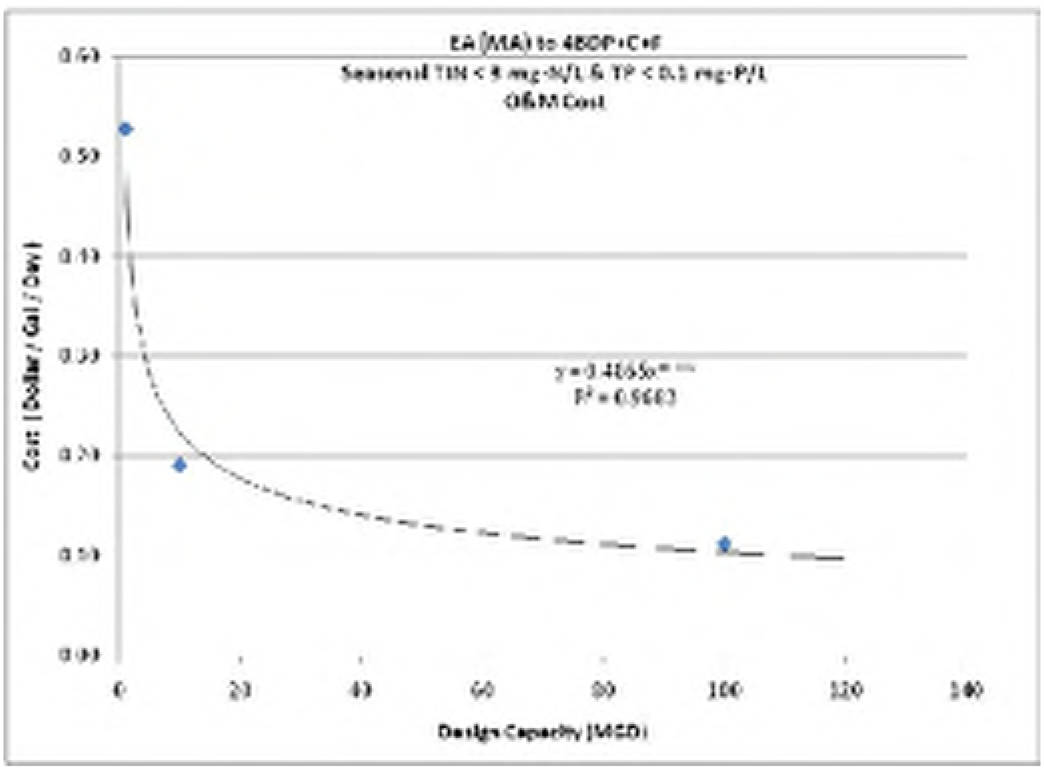


Figure 16-22. O&M Cost per Plant Capacity for Extended Aeration (Mechanical Aeration) Plant Upgraded for Objective F Seasonal

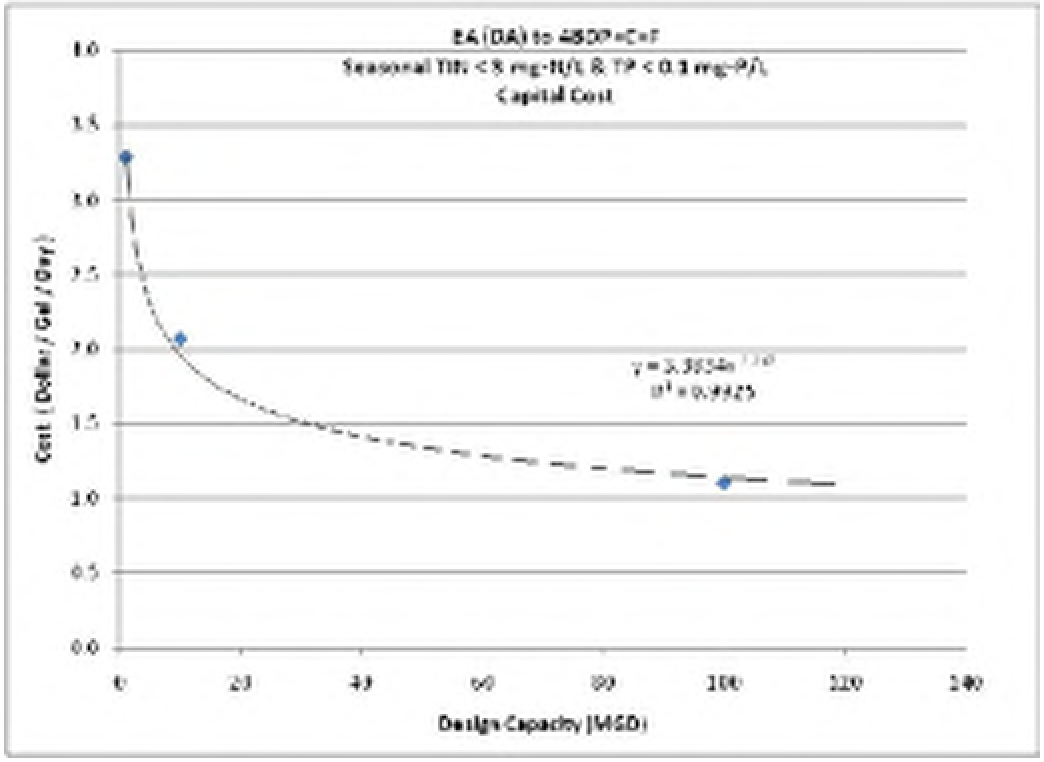


Figure 16-23. Capital Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective F Seasonally

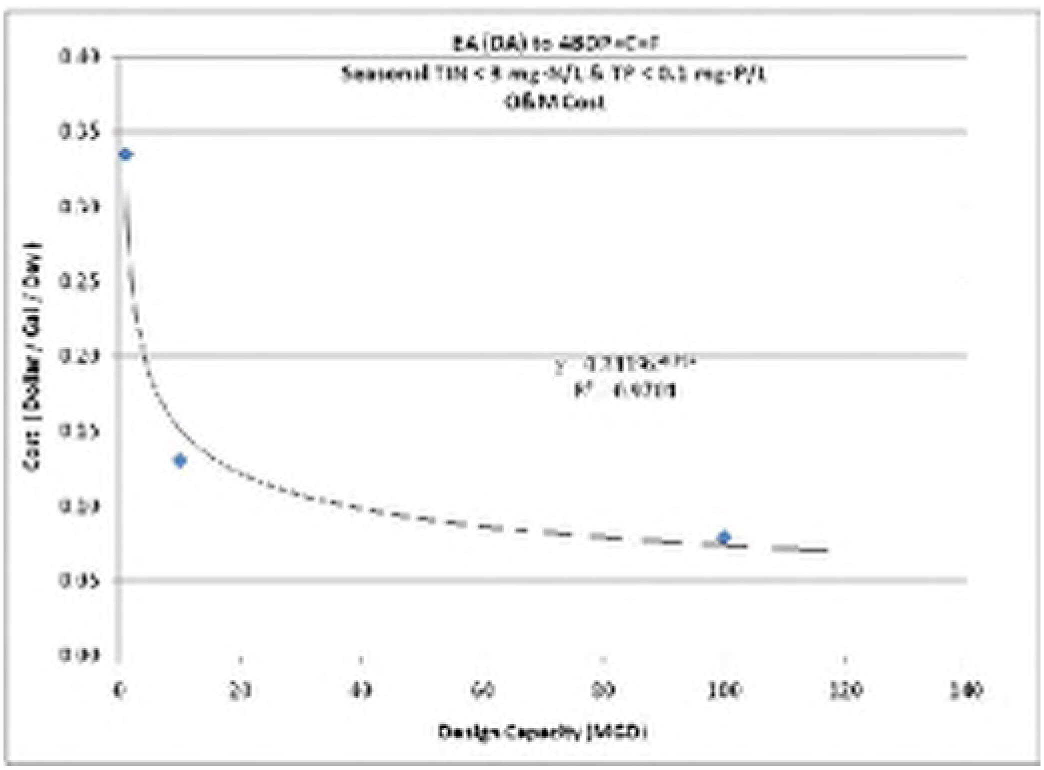


Figure 16-24. O&M Cost per Plant Capacity for Extended Aeration (Diffuser Aeration) Plant Upgraded for Objective F Seasonal

TABLE 16-23.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA (MECHANICAL AERATION) PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$515,745	$2,615,929	$21,868,804
2014 Incremental O&M Cost	$593,790	$2,145,974	$12,606,374
Total Annual Cost	**$1,109,535**	**$4,761,903**	**$34,475,178**
Annual TIN Load Reduction (lb/yr)	23,506	235,060	2,350,600
Annual TP Load Reduction (lb/yr)	6,388	63,875	638,750
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$32.92	$11.05	$7.43
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$52.57	$33.87	$26.63

TIN Cost Equation:[a] .... $y = 762.22x^{-0.324}$
TIN Cost R-Square Value:........ 0.9322

TP Cost Equation:[b] .... $y = 185.49x^{-0.148}$
TP Cost R-Square Value: 0.9722

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-24.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING EA ((DIFFUSER AERATION) PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$241,811	$1,521,842	$8,131,012
2014 Incremental O&M Cost	$377,749	$1,472,582	$8,907,389
Total Annual Cost	**$619,560**	**$2,994,424**	**$17,038,401**
Annual TIN Load Reduction (lb/yr)	23,488	234,878	2,348,775
Annual TP Load Reduction (lb/yr)	6,388	63,875	638,750
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$11.90	$3.35	$0.53
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$53.22	$34.58	$24.74

TIN Cost Equation:[a] .... $y = 11759x^{-0.676}$
TIN Cost R-Square Value:........ 0.9887

TP Cost Equation:[b] .... $y = 224.95x^{-0.166}$
TP Cost R-Square Value: 0.9948

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.2.2 Conventional Activated Sludge Plants

Table 16-25 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F seasonally for a conventional activated sludge plant. Figures 16-25 and 16-26 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-26 presents the annualized unit costs for reducing nutrient loads.

TABLE 16-25.
ESTIMATED COST PER CAPACITY FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.06	$2.63	$2.08
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.45	$0.19	$0.13

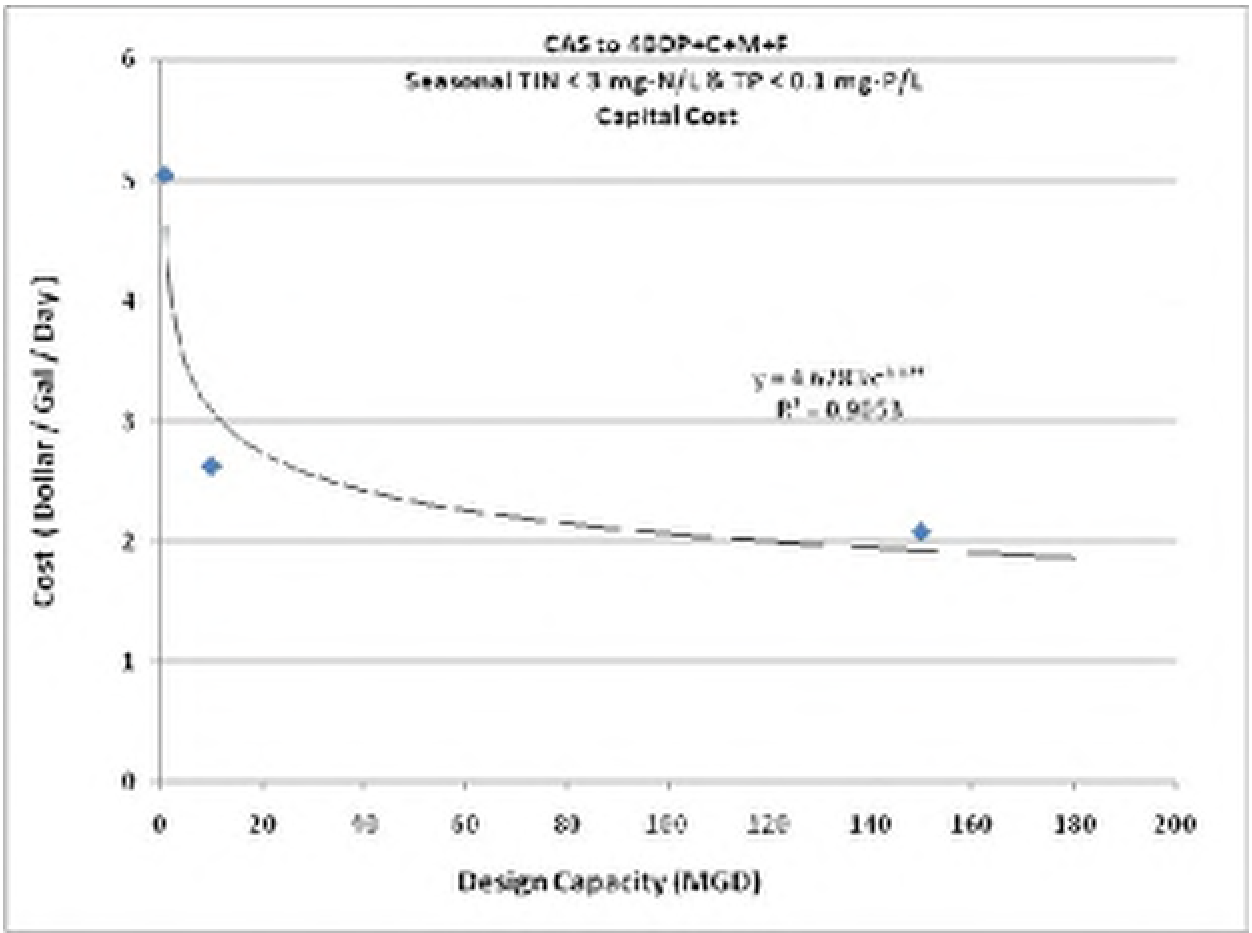


Figure 16-25. Capital Cost per Plant Capacity for CAS Plant Upgraded for Objective F Seasonally

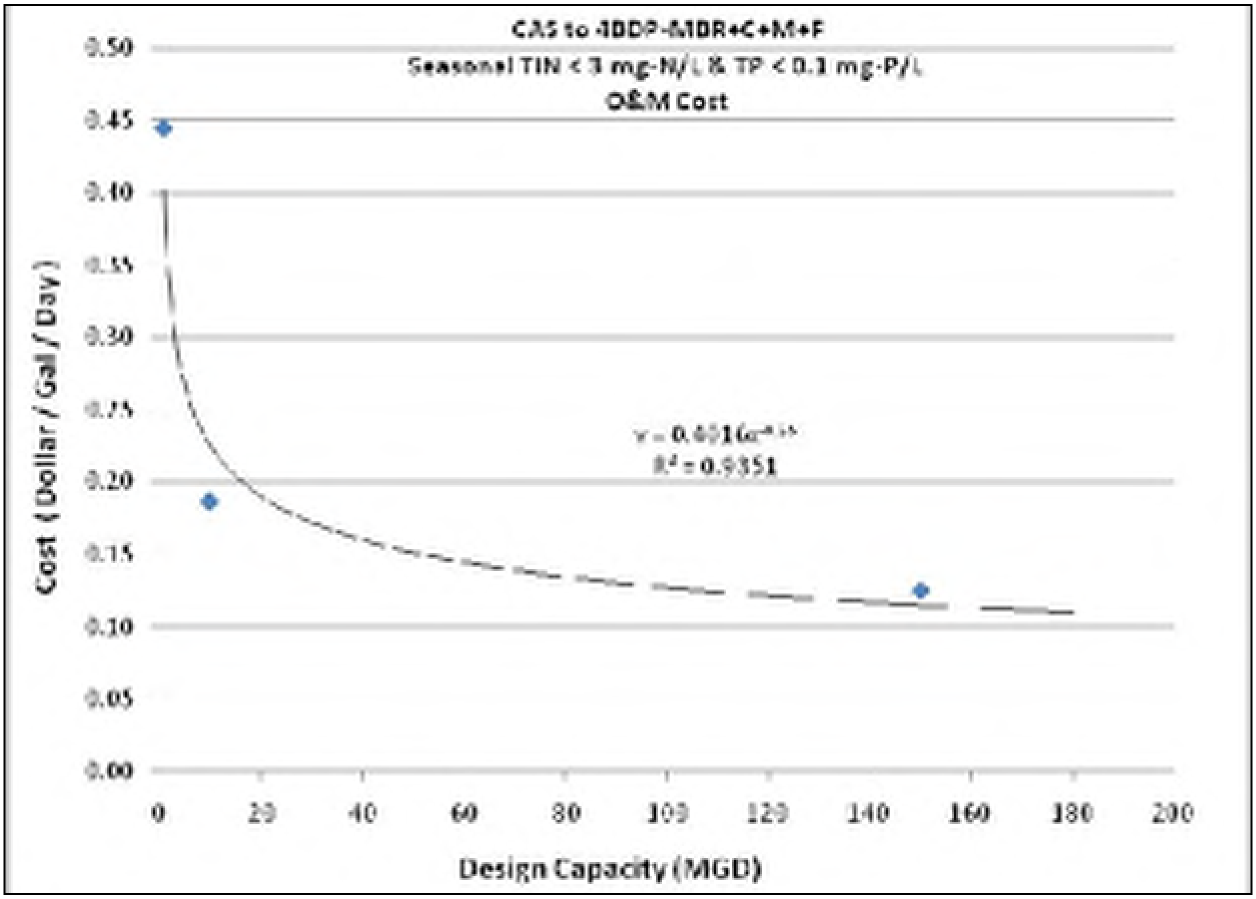


Figure 16-26. O&M Cost per Plant Capacity for CAS Plant Upgraded for Objective F Seasonal

TABLE 16-26.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING CAS PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$371,402	$1,928,646	$22,872,331
2014 Incremental O&M Cost	$501,029	$2,102,692	$21,173,550
Total Annual Cost	**$872,431**	**$4,031,339**	**$44,045,881**
Annual TIN Load Reduction (lb/yr)	23,068	230,680	3,460,200
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$19.33	$7.56	$5.45
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$64.74	$34.73	$25.50

TIN Cost Equation:[a] .... $y = 207.09x^{-0.249}$
TIN Cost R-Square Value:........ 0.9019

TP Cost Equation:[b] .... $y = 304x^{-0.184}$
TP Cost R-Square Value: 0.9441

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.2.3 Sequencing Batch Reactor Plants

Table 16-27 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F seasonally for an SBR plant. Figures 16-27 and 16-28 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-28 presents the annualized unit costs for reducing nutrient loads.

TABLE 16-27.
ESTIMATED COST PER CAPACITY FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Capital Cost per gpd of Plant Capacity	$4.44	$2.48	$1.41
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.72	$0.29	$0.12

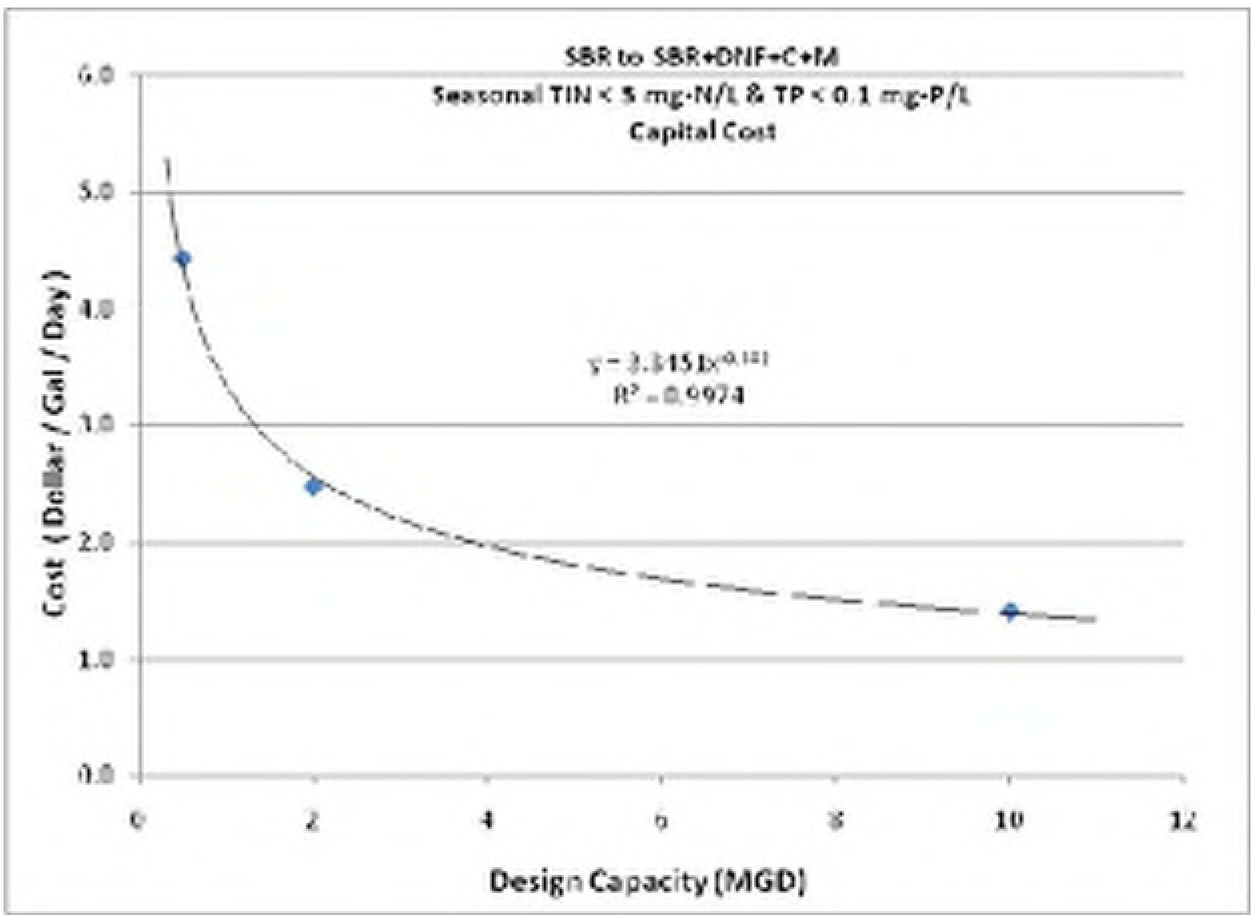


Figure 16-27. Capital Cost per Plant Capacity for SBR Plant Upgraded for Objective F Seasonally

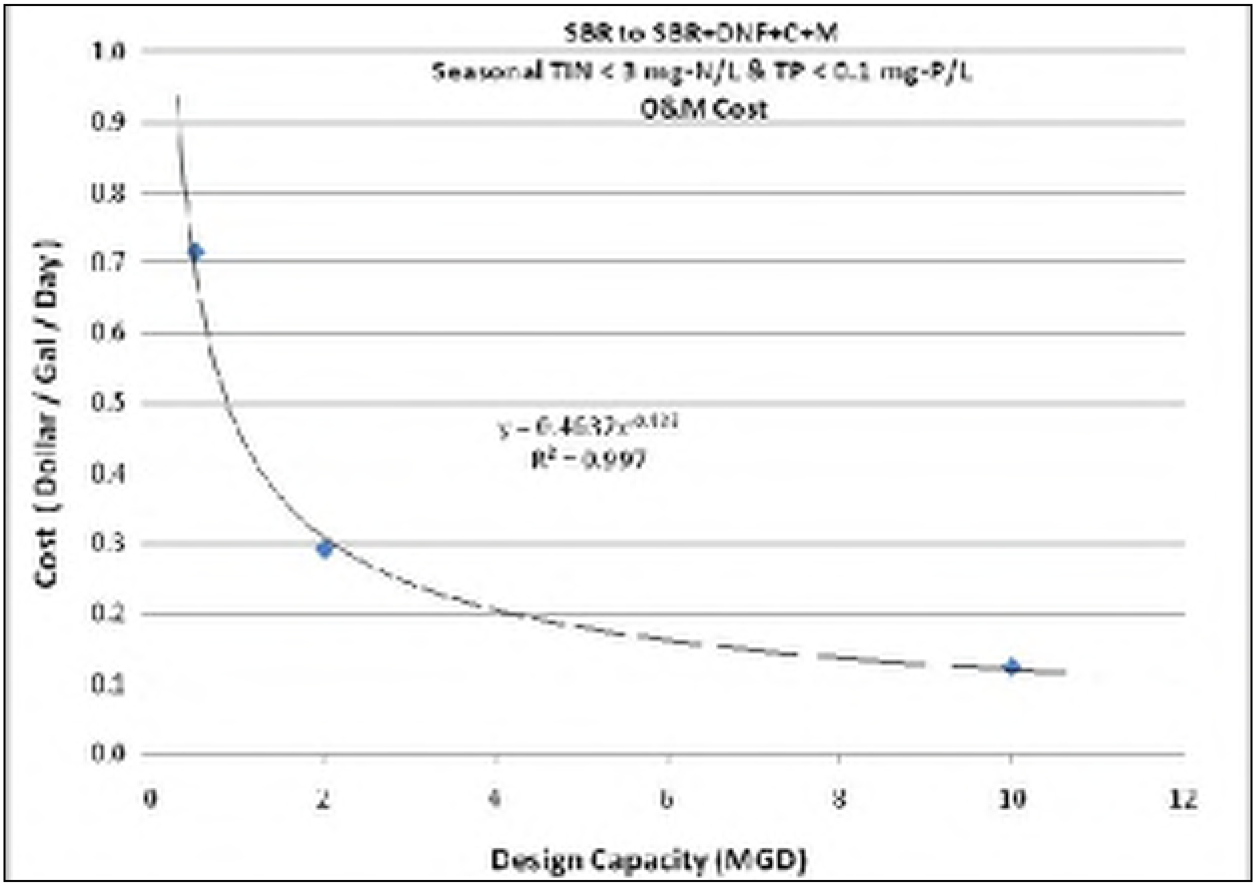


Figure 16-28. O&M Cost per Plant Capacity for SBR Plant Upgraded for Objective F Seasonal

TABLE 16-28.
UNIT NUTRIENT REMOVAL COSTS FOR UPGRADING SBR PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Annualized Capital Cost	$163,045	$364,500	$1,034,896
2014 Incremental O&M Cost	$402,993	$657,438	$1,390,054
Total Annual Cost	**$566,038**	**$1,021,937**	**$2,424,950**
Annual TIN Load Reduction (lb/yr)	475	1,898	9,490
Annual TP Load Reduction (lb/yr)	1,487	5,950	29,748
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$788.41	$309.62	$114.38
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$129.05	$72.99	$45.03

TIN Cost Equation:[a] .... $y = 41108x^{-0.644}$
TIN Cost R-Square Value:........ 0.9994

TP Cost Equation:[b] .... $y = 1616x^{-0.35}$
TP Cost R-Square Value: 0.9918

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.2.4 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Table 16-29 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F seasonally for a trickling filter plant. Figures 16-29 and 16-30 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-30 and Figures 16-31 and 16-32 summarize these costs for a trickling filter/solids contact plant. Table 16-31 and Figures 16-33 and 16-34 summarize these costs for an RBC plant. Tables 16-32, 16-33 and 16-34 present the annualized unit costs for reducing nutrient loads for TF, TF/SC and RBC plants, respectively.

TABLE 16-29.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$7.11	$4.16	$2.59
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.51	$0.21	$0.13

TABLE 16-30.
ESTIMATED COST PER CAPACITY FOR UPGRADING TRICKLING FILTER/SOLIDS CONTACT PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$5.37	$3.47	$2.18
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.38	$0.17	$0.10

TABLE 16-31.
ESTIMATED COST PER CAPACITY FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Capital Cost per gpd of Plant Capacity	$7.13	$4.18	$2.63
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.57	$0.23	$0.14

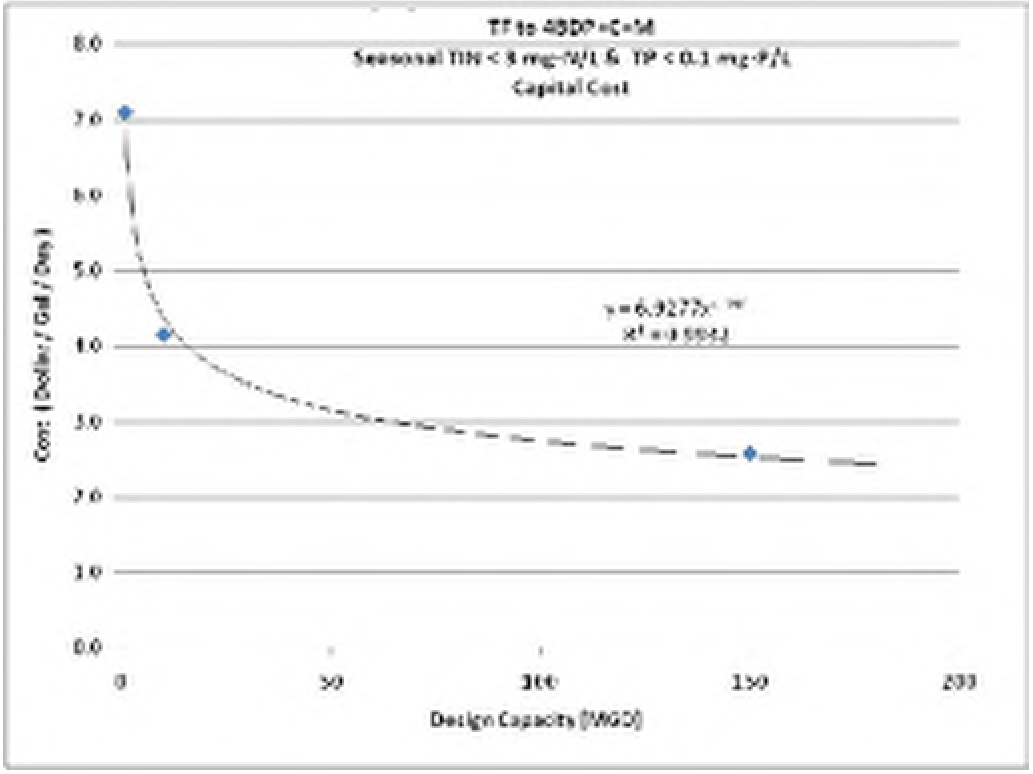


Figure 16-29. Capital Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective F Seasonally

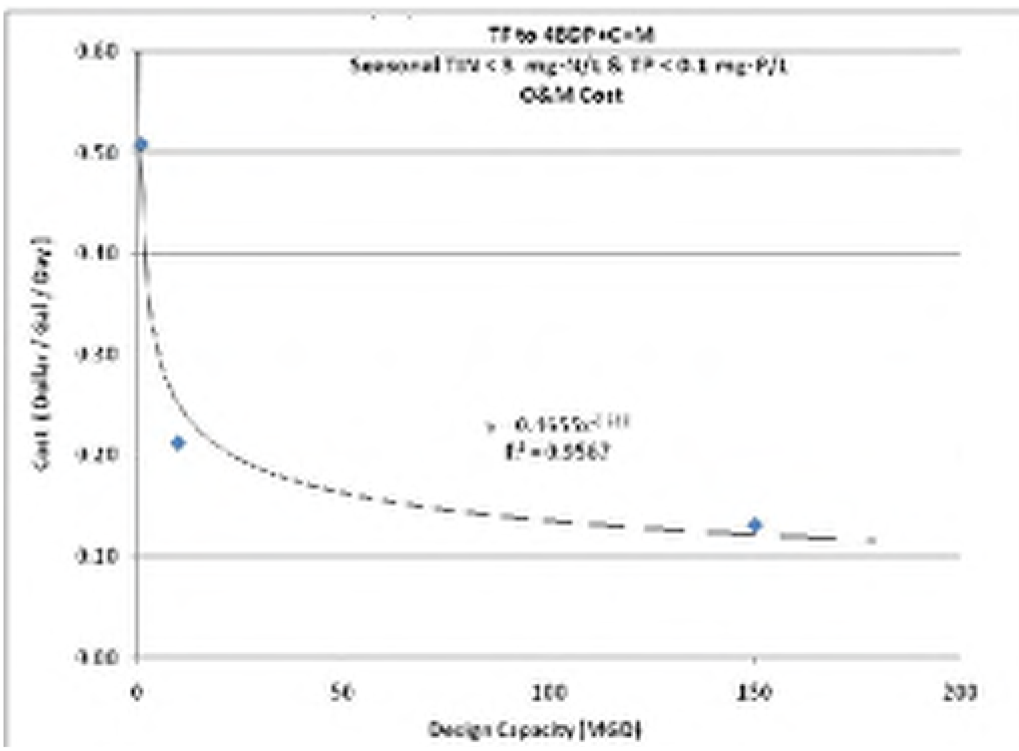


Figure 16-30. O&M Cost per Plant Capacity for Trickling Filter Plant Upgraded for Objective F Seasonal

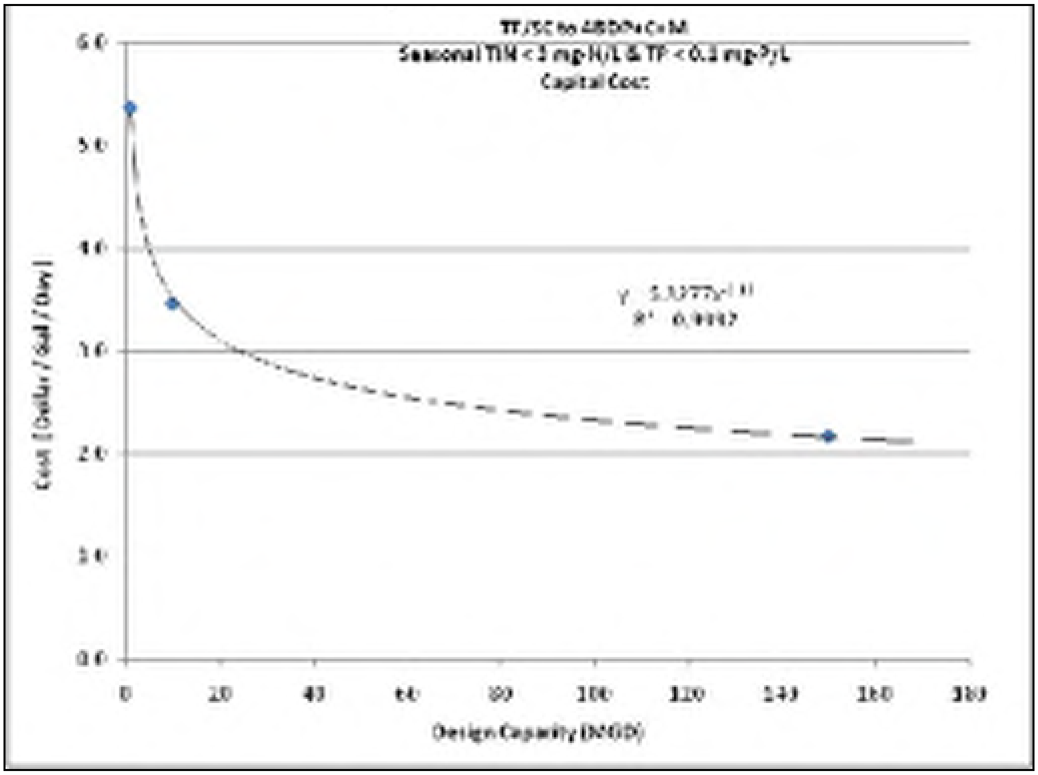


Figure 16-31. Capital Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective F Seasonally

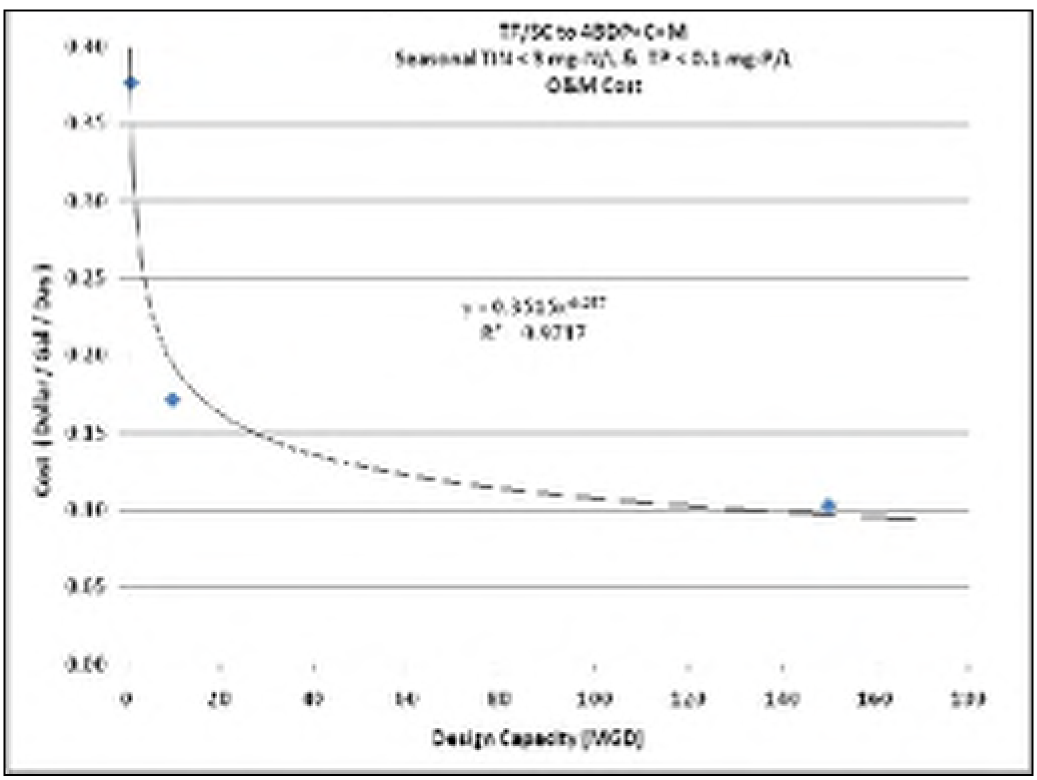


Figure 16-32. O&M Cost per Plant Capacity for Trickling Filter/Solids Contact Plant Upgraded for Objective F Seasonal

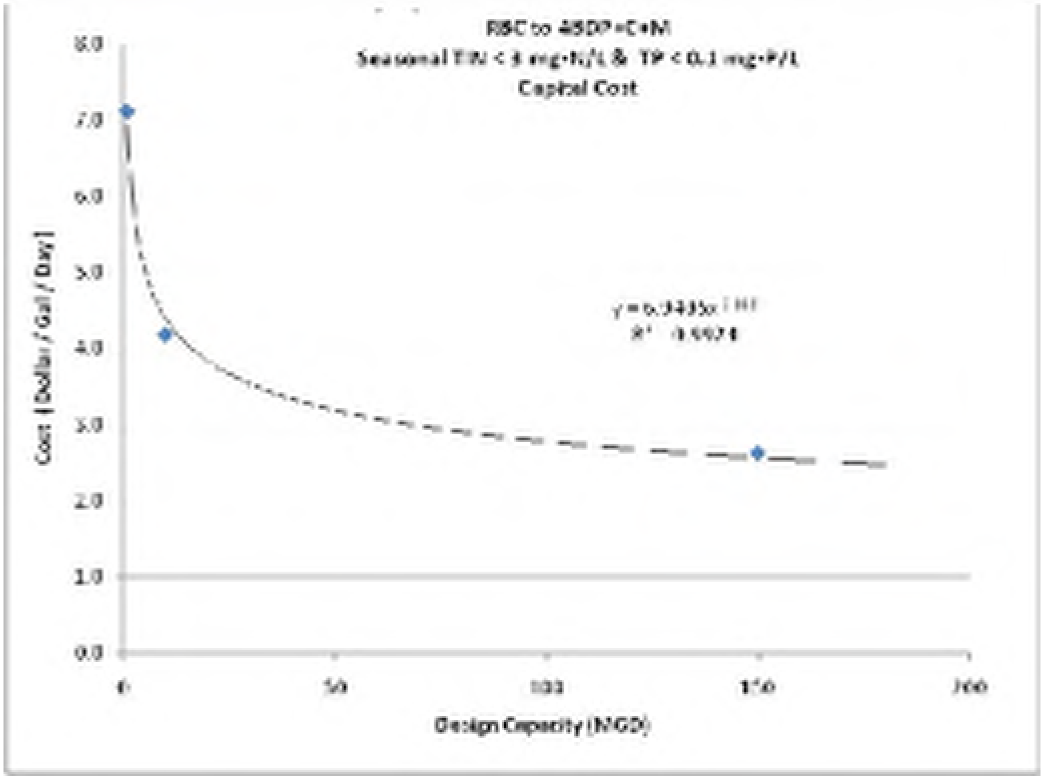


Figure 16-33. Capital Cost per Plant Capacity for RBC Plant Upgraded for Objective F Seasonally

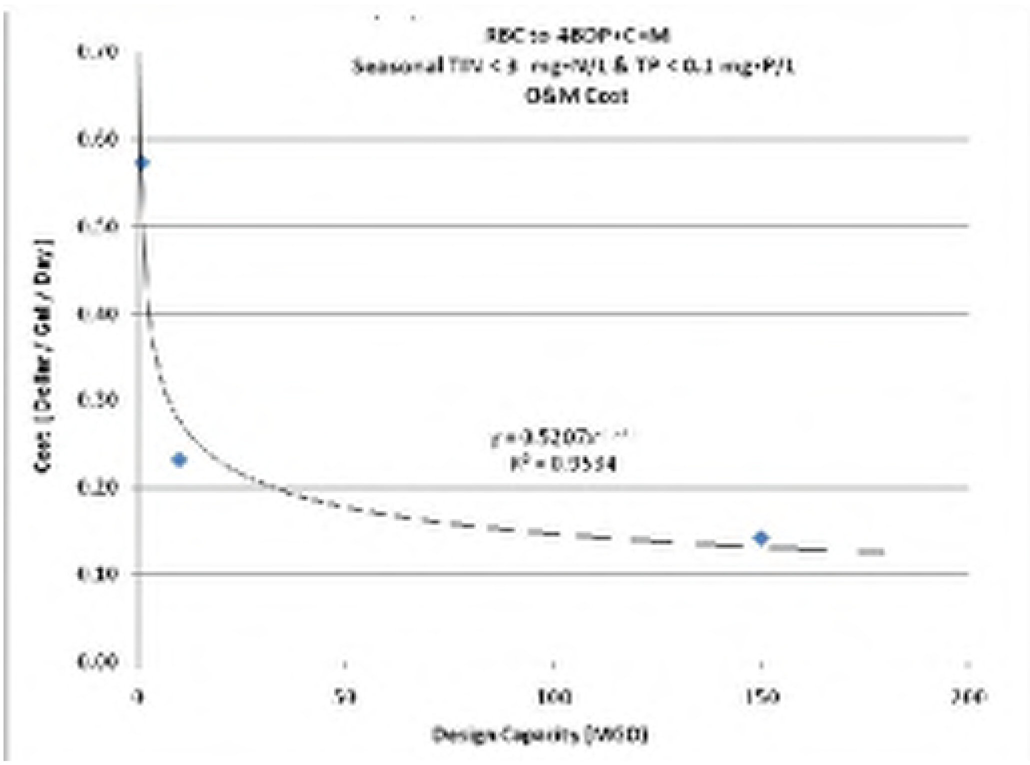


Figure 16-34. O&M Cost per Plant Capacity for RBC Plant Upgraded for Objective F Seasonal

TABLE 16-32.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$522,245	$3,054,433	$28,541,079
2014 Incremental O&M Cost	$572,876	$2,394,087	$22,094,779
Total Annual Cost	**$1,095,120**	**$5,448,520**	**$50,635,858**
Annual TIN Load Reduction (lb/yr)	23,068	230,680	3,460,200
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$29.59	$14.12	$7.66
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$62.60	$33.27	$24.40

TIN Cost Equation:[a] .... $y = 420.51x^{-0.268}$
TIN Cost R-Square Value:........ 0.9897

TP Cost Equation:[b] .... $y = 298.79x^{-0.186}$
TP Cost R-Square Value: 0.9428

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-33.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING TF/SC PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$394,434	$2,547,369	$23,973,880
2014 Incremental O&M Cost	$423,796	$1,926,775	$17,335,002
Total Annual Cost	**$818,230**	**$4,474,144**	**$41,308,882**
Annual TIN Load Reduction (lb/yr)	23,068	230,680	3,460,200
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$17.42	$9.77	$4.96
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$63.19	$33.69	$24.43

TIN Cost Equation:[a] .... $y = 216.12x^{-0.251}$
TIN Cost R-Square Value:........ 1

TP Cost Equation:[b] .... $y = 306.92x^{-0.188}$
TP Cost R-Square Value: 0.9474

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-34.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING RBC PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Annualized Capital Cost	$523,808	$3,071,873	$28,994,343
2014 Incremental O&M Cost	$644,576	$2,608,552	$24,009,832
Total Annual Cost	**$1,168,384**	**$5,680,425**	**$53,004,176**
Annual TIN Load Reduction (lb/yr)	23,068	230,680	3,460,200
Annual TP Load Reduction (lb/yr)	6,588	65,883	988,238
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$32.63	$15.09	$8.41
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$63.08	$33.40	$24.20

TIN Cost Equation:[a] .... $y = 461.44x^{-0.269}$
TIN Cost R-Square Value:.......... 0.9842

TP Cost Equation:[b] .... $y = 310.09x^{-0.189}$
TP Cost R-Square Value: 0.9465

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.2.5 Membrane Biological Reactor Plants

Table 16-35 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F seasonally for an MBR plant. Figures 16-35 and 16-36 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-36 presents the annualized unit costs for reducing nutrient loads.

TABLE 16-35.
ESTIMATED COST PER CAPACITY FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Capital Cost per gpd of Plant Capacity	$1.22	$0.27	$0.03
Incremental Annual O&M Cost per gpd of Plant Capacity	$0.16	$0.08	$0.06

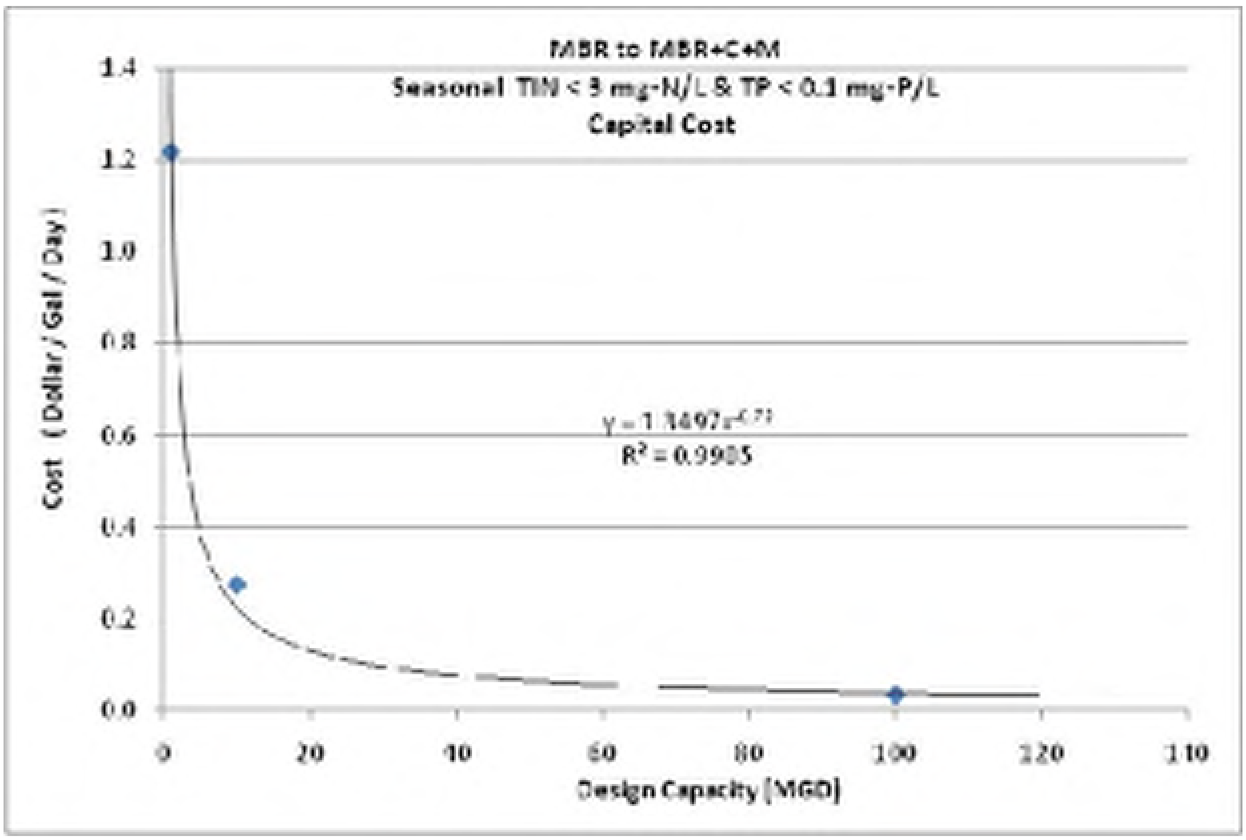


Figure 16-35. Capital Cost per Plant Capacity for MBR Plant Upgraded for Objective F Seasonally

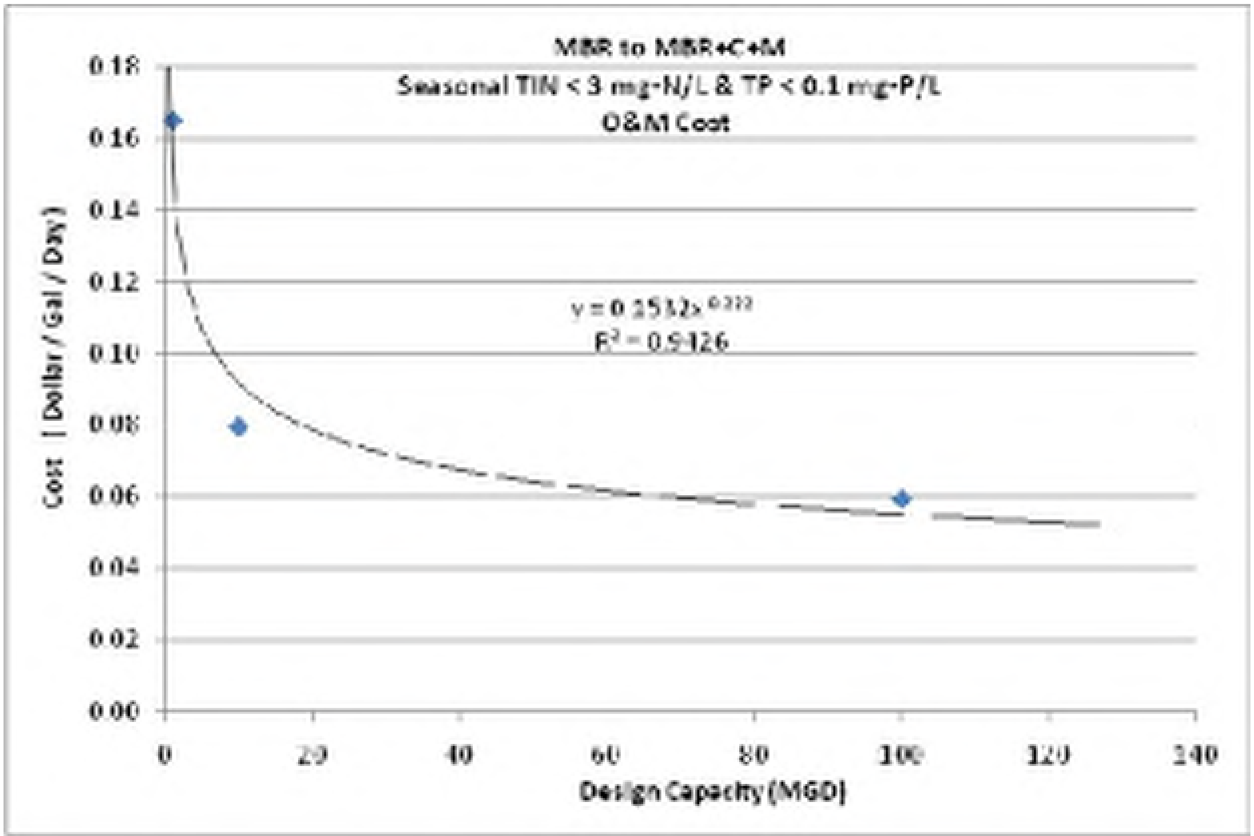


Figure 16-36. O&M Cost per Plant Capacity for MBR Plant Upgraded for Objective F Seasonal

TABLE 16-36.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING MBR PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Annualized Capital Cost	$89,545	$201,723	$246,882
2014 Incremental O&M Cost	$185,518	$893,767	$6,667,739
Total Annual Cost	**$275,063**	**$1,095,490**	**$6,914,621**
Annual TIN Load Reduction (lb/yr)	3,869	38,690	386,900
Annual TP Load Reduction (lb/yr)	6,169	61,685	616,850
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$4.27	$3.79	$3.76
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$41.91	$15.38	$8.85

TIN Cost Equation:[a] .... $y = 5.2658x^{-0.028}$
TIN Cost R-Square Value: 0.7967

TP Cost Equation:[b] .... $y = 740.77x^{-0.338}$
TP Cost R-Square Value: 0.9729

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

16.2.6 High-Purity Oxygen Activated Sludge Plants

High-purity oxygen activated sludge plants were not evaluated for any objectives that include phosphorus removal, so no costs associated with Objective F were developed for these plants.

16.2.7 Aerated or Facultative Lagoon Plants

Table 16-37 summarizes estimated capital costs and incremental O&M costs (compared to the existing plant) for achieving Objective F seasonally for an aerated lagoon plan. Figures 16-37 and 16-38 show graphs of the capital and O&M costs, respectively. The estimates are given in dollars per gallon per day of plant capacity. Table 16-38 and Figures 16-39 and 16-40 summarize these costs for a facultative lagoon plant. Tables 16-39 and 16-40 present the annualized unit costs for reducing nutrient loads for aerated lagoon an facultative lagoon plants, respectively.

**TABLE 16-37.
ESTIMATED COST PER CAPACITY FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE F SEASONALLY**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$26.26	$19.09	$12.68	$8.23
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.31	$0.82	$0.39	$0.20

**TABLE 16-38.
ESTIMATED COST PER CAPACITY FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE F SEASONALLY**

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Capital Cost per gpd of Plant Capacity	$26.12	$18.97	$12.59	$8.19
Incremental Annual O&M Cost per gpd of Plant Capacity	$1.58	$1.05	$0.55	$0.23

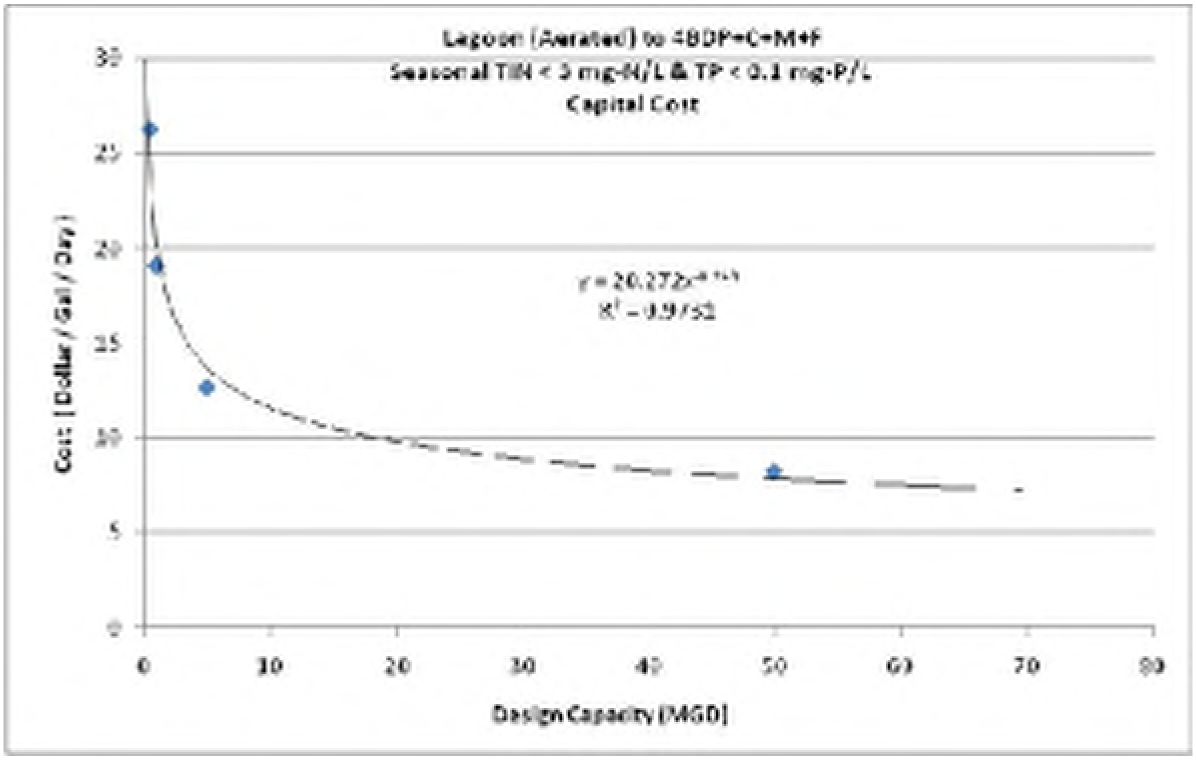


Figure 16-37. Capital Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective F Seasonally

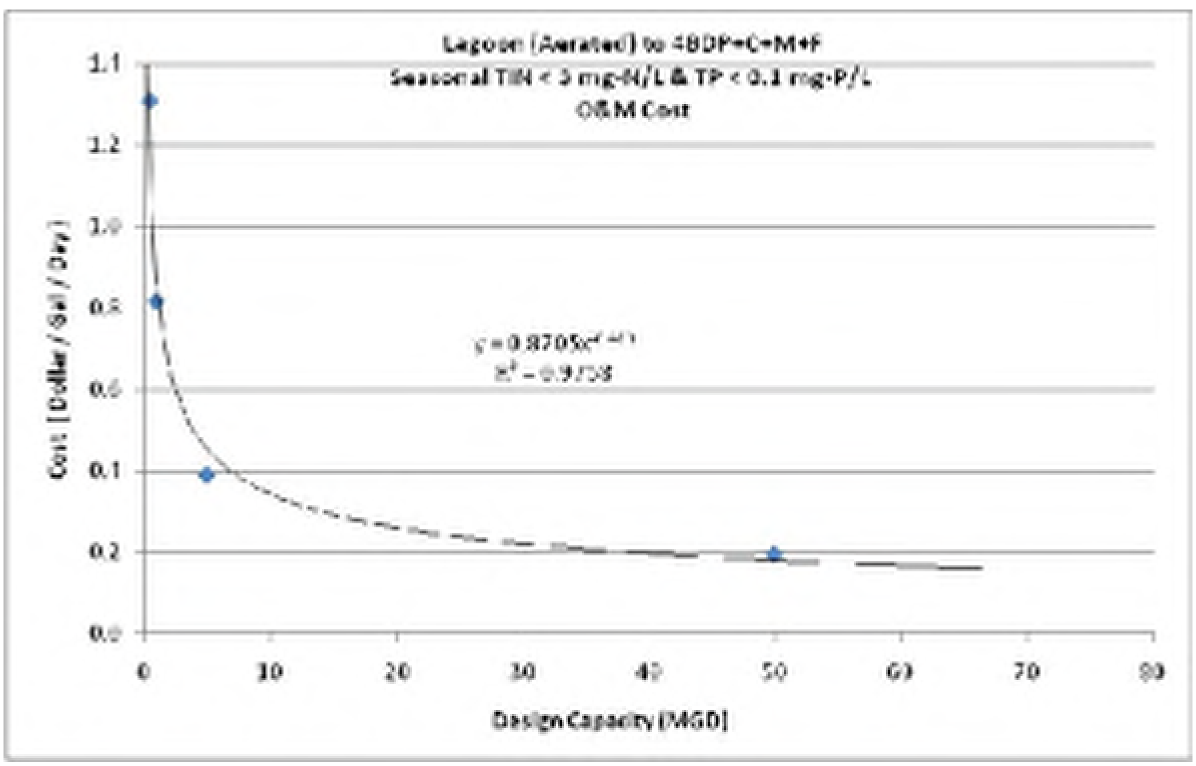


Figure 16-38. O&M Cost per Plant Capacity for Aerated Lagoon Plant Upgraded for Objective F Seasonal

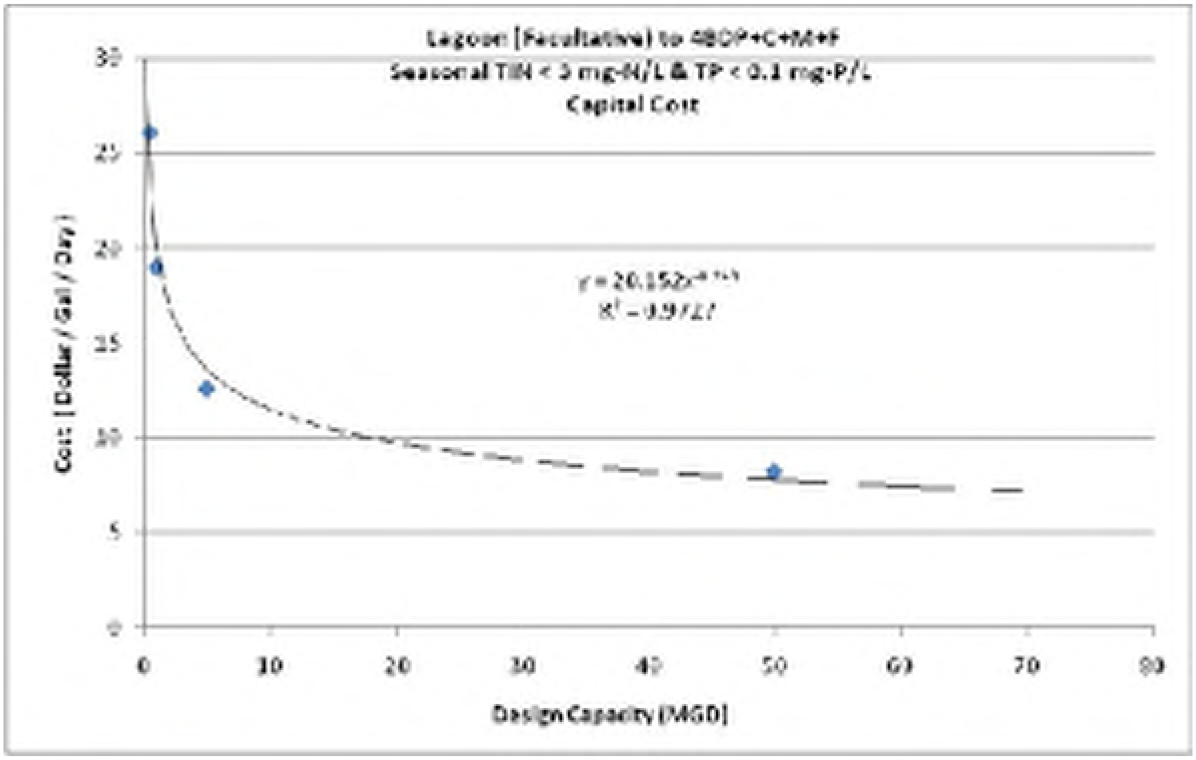


Figure 16-39. Capital Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective F Seasonally

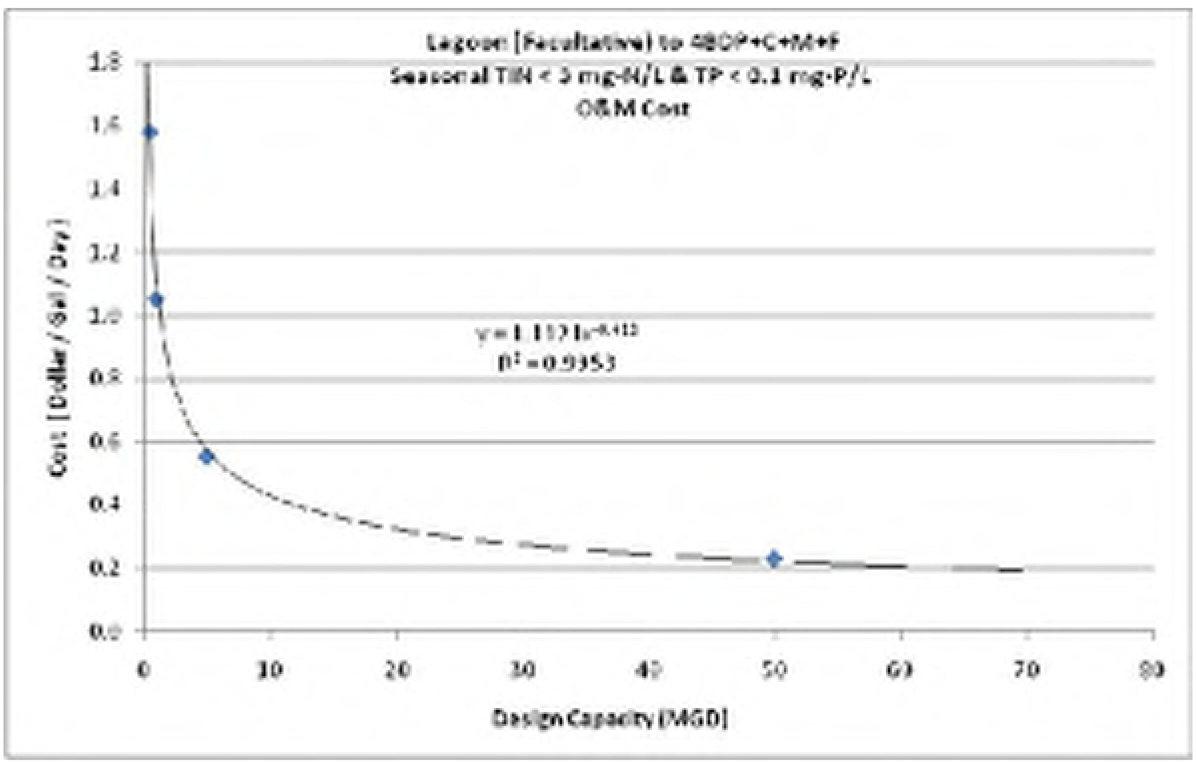


Figure 16-40. O&M Cost per Plant Capacity for Facultative Lagoon Plant Upgraded for Objective F Seasonal

TABLE 16-39.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING AERATED LAGOON PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$964,506	$1,401,842	$4,654,926	$30,238,589
2014 Incremental O&M Cost	$736,744	$920,616	$2,199,768	$11,006,857
Total Annual Cost	**$1,701,250**	**$2,322,458**	**$6,854,693**	**$41,245,446**
Annual TIN Load Reduction (lb/yr)	11,634	23,269	116,344	1,153,400
Annual TP Load Reduction (lb/yr)	3,294	6,588	32,941	329,413
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$106.84	$72.87	$43.23	$24.43
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$139.09	$95.14	$55.39	$39.67

TIN Cost Equation:[a] .... $y = 1775.1x^{-0.311}$
TIN Cost R-Square Value:........ 0.9795

TP Cost Equation:[b] .... $y = 1023.5x^{-0.263}$
TP Cost R-Square Value: 0.9326

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

TABLE 16-40.
ESTIMATED COST PER WEIGHT OF NUTRIENT REMOVAL FOR UPGRADING FACULTATIVE LAGOON PLANT TO ACHIEVE OBJECTIVE F SEASONALLY

	0.5-mgd Plant	1-mgd Plant	5-mgd Plant	50-mgd Plant
Annualized Capital Cost	$959,405	$1,393,369	$4,621,774	$30,064,193
2014 Incremental O&M Cost	$889,913	$1,184,294	$3,102,594	$12,894,127
Total Annual Cost	**$1,849,319**	**$2,577,664**	**$7,724,396**	**$42,958,320**
Annual TIN Load Reduction (lb/yr)	11,634	23,269	116,344	1,153,400
Annual TP Load Reduction (lb/yr)	3,294	6,588	32,941	329,413
Estimated Unit Cost for TIN Reduction ($/lb TIN removed)	$120.94	$85.15	$51.92	$26.48
Estimated Unit Cost for TP Reduction ($/lb TP removed)	$134.27	$90.52	$51.11	$37.70

TIN Cost Equation:[a] .... $y = 2288.9x^{-0.321}$
TIN Cost R-Square Value:........ 0.9921

TP Cost Equation:[b] .... $y = 1003.4x^{-0.267}$
TP Cost R-Square Value: 0.9193

a. x = Annual TIN Load Reduction (lb), y= Estimated Cost for TIN Reduction ($/lb TIN removed)
b. x = Annual TP Load Reduction (lb), y= Estimated Cost for TP Reduction ($/lb TP removed)

CHAPTER 17.
CUMULATIVE COST IMPACT SUMMARY

17.1 CUMULATIVE STATEWIDE COST

Cost models presented in previous chapters of this report represent expected costs for upgrading individual treatment plants to meet a range of potential objectives for limiting nitrogen and phosphorus in effluent discharged to surface waters. If the State of Washington were to adopt regulatory guidelines establishing such limits, then municipal treatment plants throughout the state would need to perform upgrades, with potentially significant statewide cost implications.

In order to assess the magnitude of such potential future cost impacts, the cost models developed for each of the respective nutrient removal objectives (i.e., Chapters 11-16) were applied to Ecology's list of all municipal treatment plants operating in Washington. As described in Chapter 2, there are currently 304 such plants operating in the state. Using a list of the treatment type and maximum-month capacity for each of these plants, the upgrade capital and O&M cost models identified in the previous chapters for several capacities for each type of plant were used to estimate upgrade costs for each specific plant operating in the state. These costs were then totaled by treatment type and on a statewide basis. Tables 17-1, 17-2 and 17-3 present the results for capital cost, annual O&M cost and 20-year annualized total cost (assuming a 3-percent discount rate), respectively. The expected accuracy range for these estimates is +100% to -50% percent. Actual costs for a specific facility would have to be determined through a site specific engineering study.

17.2 POTENTIAL SEWER RATE IMPACTS

Based on the cumulate statewide costs estimated as described above, an evaluation was performed to estimate the likely cost impact on sewer rates per household. The monthly increase was calculated from the annualized statewide costs, assuming a statewide population of about 5.5 million, an average household size of 2.5 persons, a per capita maximum-month wastewater flow of 160 gallons, and a future number of households at design capacity equal to 1.33 times the current number of households. The resulting rate impact estimates are shown in Table 17-4.

17.3 WATERSHED-WIDE COSTS FOR NUTRIENT REMOVAL

For planning purposes, the Washington Department of Ecology has divided the state into 62 Water Resource Inventory Areas (WRIAs), representing the watershed, or drainage area, of all major water bodies in the state (see Figure 17-1). Water quality assessments and measures to address water quality problems often are developed based on these watershed designations, because the WRIAs represent all the area potentially contributing nutrients and other contaminants to affected water bodies. Therefore, if a given water body is experiencing water quality problems related to high levels of nitrogen or phosphorus, then nutrient discharge limits might be established that apply to all dischargers within that water body's WRIA. For this reason, it is useful to estimate the potential cost of upgrading all municipal treatment plants in each WRIA to achieve the various nutrient removal objectives. These estimates were made using the same approach described above for the statewide cost estimates. Tables 17-5 and 17-6 present the results for capital cost and annual O&M cost. Additional detail on costs in each WRIA is provided in Appendix D. The expected accuracy range for these estimates is +100% to -50% percent. Actual costs for a specific facility would have to be determined through a site specific engineering study.

TABLE 17-1.
ESTIMATED CAPITAL COSTS FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Capital Cost ($ millions, 2010)					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	204	239	29	133	221	360
Extended Aeration (Diffused Aeration)	4	7	3	11	5	16
Extended Aeration (with Biological Nutrient Removal)	29	128	75	328	94	414
Conventional Activated Sludge	1625	1773	142	559	1725	2253
Sequencing Batch Reactor	7	28	18	54	18	76
Trickling Filter	177	195	15	58	186	246
Rotating Biological Contactor	140	155	13	47	148	197
Trickling Filter/Solids Contact	193	207	15	59	193	252
Membrane Bioreactor	0	0	11	10	11	11
Lagoons (Aerated)	773	797	163	234	836	931
Lagoons (Facultative)	170	182	40	62	184	218
High Purity Oxygen	942	1134	N/A	N/A	942(1)	1134(1)
Statewide Total	**$4,264**	**$4,844**	**$522**	**$1,555**	**$4,564**	**$6,107**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	192	217	28	84	227	308
Extended Aeration (Diffused Aeration)	2	5	3	7	6	11
Extended Aeration (with Biological Nutrient Removal)	38	76	76	252	66	272
Conventional Activated Sludge	564	629	185	429	660	1032
Sequencing Batch Reactor	6	25	18	46	18	66
Trickling Filter	96	105	18	42	102	138
Rotating Biological Contactor	76	84	15	33	82	111
Trickling Filter/Solids Contact	88	93	20	46	88	127
Membrane Bioreactor	0	0	10	10	10	10
Lagoons (Aerated)	773	797	163	234	836	931
Lagoons (Facultative)	164	168	35	50	177	197
High Purity Oxygen	363	477	N/A	N/A	363(1)	477(1)
Statewide Total	**$2,360**	**$2,674**	**$570**	**$1,233**	**$2,635**	**$3,680**

;

Note: (1) costs are for nitrogen removal only

TABLE 17-2.
ESTIMATED ANNUAL O&M COSTS FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Annual O&M Cost ($ millions, 2010)					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	0	13	9	14	16	26
Extended Aeration (Diffused Aeration)	0	0	0	1	1	1
Extended Aeration (with Biological Nutrient Removal)	0	0	16	33	11	38
Conventional Activated Sludge	45	57	55	69	90	122
Sequencing Batch Reactor	0	9	1	3	0	12
Trickling Filter	5	7	4	6	9	12
Rotating Biological Contactor	5	6	4	4	8	11
Trickling Filter/Solids Contact	4	6	6	7	9	12
Membrane Bioreactor	0	0	1	2	1	2
Lagoons (Aerated)	24	28	10	12	31	37
Lagoons (Facultative)	7	8	2	2	10	12
High Purity Oxygen	44	53	N/A	N/A	44(1)	53(1)
Statewide Total	**$135**	**$187**	**$108**	**$152**	**$230**	**$338**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	9	12	6	9	15	21
Extended Aeration (Diffused Aeration)	0	0	0	1	1	1
Extended Aeration (with Biological Nutrient Removal)	0	0	10	19	11	28
Conventional Activated Sludge	17	24	41	49	54	72
Sequencing Batch Reactor	0	8	1	2	1	9
Trickling Filter	3	4	4	4	7	8
Rotating Biological Contactor	3	4	3	3	6	8
Trickling Filter/Solids Contact	1	2	4	5	5	7
Membrane Bioreactor	0	0	1	1	1	1
Lagoons (Aerated)	24	28	10	12	31	37
Lagoons (Facultative)	7	8	2	2	9	10
High Purity Oxygen	27	32	N/A	N/A	27	32
Statewide Total	**$90**	**$121**	**$81**	**$107**	**$166**	**$236**

Note: (1) costs are for nitrogen removal only

TABLE 17-3.
ESTIMATED ANNUAL CAPITAL AND O&M COSTS FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Annual Cost ($ millions, 2010)[1]					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	14	29	11	23	31	50
Extended Aeration (Diffused Aeration)	0	0	1	1	1	2
Extended Aeration (with Biological Nutrient Removal)	2	9	21	55	17	66
Conventional Activated Sludge	154	176	64	106	206	273
Sequencing Batch Reactor	1	11	2	7	1	17
Trickling Filter	17	20	6	10	22	29
Rotating Biological Contactor	14	16	4	8	18	24
Trickling Filter/Solids Contact	17	19	7	11	22	29
Membrane Bioreactor	0	0	2	2	2	2
Lagoons (Aerated)	75	81	21	27	87	100
Lagoons (Facultative)	19	21	5	7	22	26
High Purity Oxygen	108	129	N/A	N/A	108[2]	129[2]
Statewide Total	**$421**	**$513**	**$143**	**$256**	**$537**	**$748**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	21	27	8	14	30	42
Extended Aeration (Diffused Aeration)	0	0	1	1	1	2
Extended Aeration (with Biological Nutrient Removal)	3	5	15	36	15	47
Conventional Activated Sludge	55	66	53	78	98	141
Sequencing Batch Reactor	0	10	2	5	2	14
Trickling Filter	9	11	5	7	13	18
Rotating Biological Contactor	8	9	4	6	12	15
Trickling Filter/Solids Contact	7	8	5	8	10	15
Membrane Bioreactor	0	0	2	2	2	2
Lagoons (Aerated)	75	81	21	27	87	100
Lagoons (Facultative)	18	19	4	6	21	23
High Purity Oxygen	51	64	N/A	N/A	51[2]	64[2]
Statewide Total	**$248**	**$300**	**$120**	**$190**	**$344**	**$483**

Notes: [1] Capital cost were annualized for 20 years at 3% discount rate
[2] Cost is for nitrogen removal only

**TABLE 17-4.
ESTIMATED MONTHLY HOUSEHOLD SEWER RATE INCREASE FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON**

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Monthly Household Sewer Rate Increase (1)					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	$11.29	$24.30	$9.26	$18.96	$25.20	$41.13
Extended Aeration (Diffused Aeration)	$4.09	$7.01	$9.91	$22.18	$15.29	$36.23
Extended Aeration (with Biological Nutrient Removal)	$0.37	$1.66	$4.07	$10.50	$3.31	$12.68
Conventional Activated Sludge	$17.48	$19.95	$7.25	$12.03	$23.33	$30.97
Sequencing Batch Reactor	$1.16	$22.37	$4.71	$13.09	$2.45	$33.21
Trickling Filter	$27.43	$31.48	$8.85	$15.26	$35.23	$46.42
Rotating Biological Contactor	$29.77	$34.14	$9.24	$15.92	$38.27	$49.99
Trickling Filter/Solids Contact	$17.79	$20.08	$6.86	$11.38	$22.33	$30.00
Membrane Bioreactor	$0.00	$0.81	$9.46	$10.67	$9.46	$11.46
Lagoons (Aerated)	$57.67	$62.05	$15.87	$20.91	$66.71	$76.37
Lagoons (Facultative)	$66.89	$74.14	$16.43	$23.38	$78.62	$94.66
High Purity Oxygen	$16.24	$19.47	N/A	N/A	16.24	19.47
Weighted Average	**$16.00**	**$19.48**	**$7.29**	**$13.02**	**$20.40**	**$28.43**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	$17.71	$22.12	$6.25	$11.73	$24.88	$34.67
Extended Aeration (Diffused Aeration)	$2.34	$4.73	$8.45	$14.66	$15.55	$28.56
Extended Aeration (with Biological Nutrient Removal)	$0.48	$0.98	$2.96	$6.98	$2.97	$8.99
Conventional Activated Sludge	$6.23	$7.46	$6.01	$8.78	$11.15	$16.02
Sequencing Batch Reactor	$0.83	$18.88	$4.54	$10.35	$4.68	$27.51
Trickling Filter	$14.74	$17.01	$7.69	$11.32	$21.47	$28.34
Rotating Biological Contactor	$16.93	$19.46	$8.06	$11.80	$24.21	$31.42
Trickling Filter/Solids Contact	$7.20	$8.19	$5.66	$8.37	$10.84	$15.53
Membrane Bioreactor	$0.00	$0.66	$8.60	$8.77	$8.60	$9.39
Lagoons (Aerated)	$57.67	$62.05	$15.87	$20.91	$66.71	$76.37
Lagoons (Facultative)	$64.37	$68.74	$14.66	$19.74	$73.51	$83.15
High Purity Oxygen	$7.68	$9.70	N/A	N/A	$7.69 (2)	$9.70 (2)
Weighted Average	**$9.43**	**$11.41**	**$6.08**	**$9.64**	**$13.05**	**$23.28**

Assumptions:

- Maximum-month wastewater flow per capita = 160 gallons
- Population served by treatment plants = 5,484,396
- 2.5 persons per household
- Existing households = 75% of households at design capacity

Notes (1) Capital cost were annualized for 20 years at 3% discount rate
(2) Cost is for nitrogen removal only

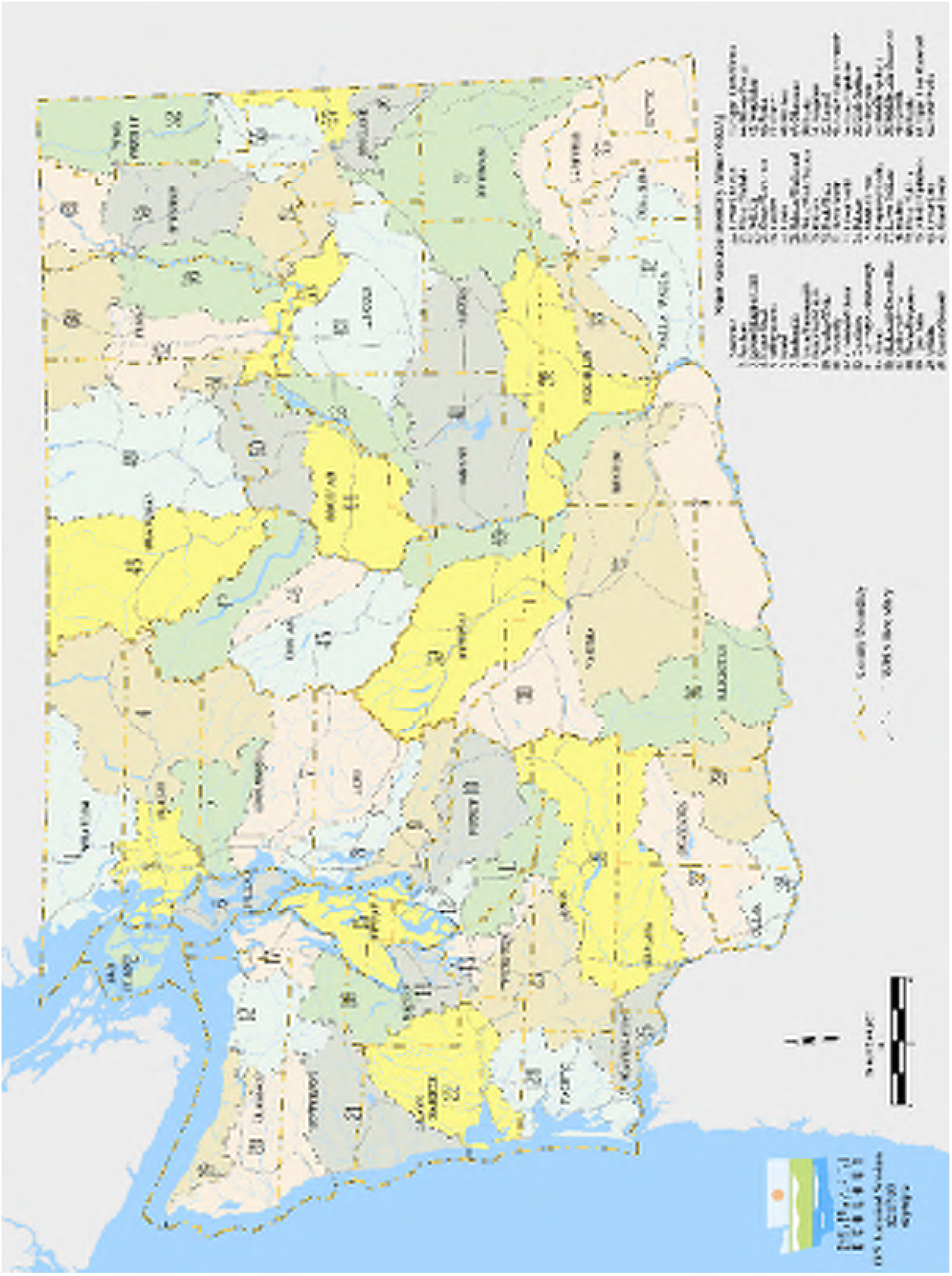


Figure 17-1. Water Resource Inventory Areas in Washington

TABLE 17-5.
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR YEAR-ROUND NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 1	236.4	7.1	260.5	9.8	28.1	3.4	61.1	4.6	248.8	10.9	306.5	14.4
WRIA 2	6.9	0.3	8.6	0.8	2.4	0.2	5.3	0.3	8.2	0.5	12.6	1.1
WRIA 3	63.2	1.7	76.8	2.9	14.1	3.7	53.0	5.5	72.0	5.2	123.2	8.7
WRIA 4	127.7	3.4	155.3	5.8	29.0	7.6	107.4	11.2	146.2	10.6	249.5	17.6
WRIA 5	10.5	0.2	13.5	1.3	2.9	0.4	9.5	0.7	12.2	0.8	21.7	2.0
WRIA 6	42.2	1.6	46.7	2.6	10.0	0.6	17.5	0.8	46.5	2.5	58.5	3.5
WRIA 7	365.7	7.3	388.2	11.0	54.0	8.6	129.0	11.2	383.8	15.7	482.9	21.7
WRIA 8	1235.6	45.4	1408.5	54.6	40.4	19.8	167.5	25.0	1253.4	61.1	1538.3	78.0
WRIA 9	227.8	6.7	249.7	8.4	19.2	6.2	74.0	7.7	238.4	12.6	313.5	16.5
WRIA 10	481.5	17.1	548.3	21.2	29.0	10.1	111.0	13.4	495.8	25.7	638.6	35.1
WRIA 11	7.3	0.3	9.9	1.2	2.7	0.3	7.1	0.4	9.1	0.5	16.0	1.5
WRIA 12	117.6	3.2	127.6	4.0	9.5	4.0	38.3	5.0	124.1	6.4	160.1	8.7
WRIA 13	0.3	0.0	22.6	0.6	14.2	3.1	43.2	5.1	20.9	2.3	58.2	6.1
WRIA 14	14.8	0.0	18.2	1.2	3.2	0.8	11.3	1.1	16.8	1.1	28.4	2.3
WRIA 15	98.7	2.9	112.2	4.2	14.3	3.9	47.7	5.0	110.8	6.6	155.9	9.2
WRIA 17	12.1	0.2	14.3	0.7	1.9	0.5	7.4	0.7	13.6	0.9	21.2	1.4
WRIA 18	39.8	0.9	44.6	1.6	4.2	1.2	15.8	1.6	42.1	2.1	58.3	3.0
WRIA 19	5.5	0.3	6.1	0.4	0.9	0.1	1.9	0.1	6.2	0.4	7.6	0.4
WRIA 20	15.0	0.6	15.7	0.7	2.9	0.2	4.1	0.3	16.3	0.8	18.0	0.9
WRIA 21	1.6	0.0	1.9	0.2	0.6	0.1	1.5	0.1	2.1	0.2	3.3	0.3
WRIA 22	78.1	1.6	89.6	3.8	9.7	2.9	38.9	4.0	85.6	5.0	125.3	7.7
WRIA 23	5.1	0.0	15.8	1.7	11.3	2.0	43.6	3.9	9.8	2.1	52.6	6.1
WRIA 24	42.8	1.9	47.0	2.8	10.0	0.7	18.4	0.9	47.3	2.6	59.9	3.8
WRIA 25	39.2	1.6	42.1	1.9	9.2	0.4	14.2	0.5	42.4	2.2	50.4	2.7
WRIA 26	14.6	0.5	16.1	1.4	4.3	0.7	9.4	0.9	18.0	1.4	24.5	1.9
WRIA 27	4.6	0.2	8.3	1.2	3.2	0.3	11.0	0.7	6.6	0.5	18.2	1.9
WRIA 28	9.4	0.0	45.2	0.5	29.3	6.8	105.7	11.6	34.8	5.8	131.9	13.9
WRIA 29	5.7	0.0	6.8	0.5	0.9	0.2	4.0	0.4	6.2	0.5	10.5	0.8
WRIA 30	45.4	1.4	47.2	1.7	9.6	0.6	14.0	0.7	49.5	1.9	55.5	2.3
WRIA 31	100.3	1.8	101.9	2.3	22.5	0.9	33.9	1.2	107.8	2.9	122.4	3.7
WRIA 32	10.3	0.0	17.9	0.9	8.7	1.8	31.5	3.0	14.3	2.0	44.5	4.6
WRIA 34	143.2	5.2	158.8	6.8	34.8	2.6	65.4	3.6	156.9	8.5	202.9	11.3
WRIA 35	15.9	0.6	18.2	0.9	2.1	0.5	7.2	0.6	17.8	1.0	24.9	1.4

TABLE 17-5 (continued).
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR YEAR-ROUND NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 36	48.5	2.0	52.5	2.3	7.5	1.2	16.3	1.4	53.2	2.8	65.0	3.5
WRIA 37	197.5	5.9	217.8	8.1	22.5	5.8	72.9	7.4	213.1	10.9	280.5	15.0
WRIA 38	13.2	0.4	15.3	0.8	1.9	0.5	6.6	0.6	14.9	0.9	21.5	1.3
WRIA 39	49.6	1.6	57.0	2.9	7.4	1.5	24.7	2.2	54.7	2.8	78.3	4.9
WRIA 40	53.8	1.6	59.6	2.0	5.1	1.8	19.9	2.3	58.0	3.1	77.5	4.2
WRIA 41	83.5	2.5	89.3	3.1	17.9	1.6	34.7	2.0	91.7	4.0	114.3	5.4
WRIA 42	11.8	0.6	12.6	0.7	2.4	0.2	3.7	0.3	13.0	0.7	14.8	0.9
WRIA 43	36.5	1.5	40.3	1.8	4.9	1.0	13.0	1.3	40.0	2.2	51.1	2.8
WRIA 44	21.9	0.7	24.8	1.1	2.5	0.7	9.2	0.9	24.1	1.4	33.3	1.8
WRIA 45	55.1	1.7	60.5	2.6	9.4	1.5	21.8	1.9	61.2	3.2	78.3	4.3
WRIA 47	13.3	0.5	14.9	0.6	1.3	0.3	4.9	0.4	14.4	0.8	19.5	1.1
WRIA 48	11.1	0.4	12.5	0.7	1.9	0.3	4.9	0.4	12.4	0.7	16.5	1.0
WRIA 49	19.4	0.4	22.7	1.2	2.8	0.7	11.1	1.0	21.5	1.5	33.0	2.1
WRIA 50	10.1	0.4	10.6	0.5	2.0	0.2	2.9	0.2	11.0	0.5	12.3	0.6
WRIA 52	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 53	2.6	0.2	2.8	0.2	0.5	0.1	0.6	0.1	2.9	0.2	3.1	0.2
WRIA 54	29.4	0.0	45.4	0.0	0.2	0.0	63.1	5.1	38.3	-2.8	114.7	4.5
WRIA 55	3.8	0.3	4.0	0.3	0.7	0.1	0.9	0.1	4.1	0.3	4.5	0.3
WRIA 56	53.7	1.9	57.0	2.7	10.0	1.2	18.5	1.5	58.3	3.0	69.6	3.8
WRIA 60	0.8	0.1	0.9	0.1	0.1	0.0	0.2	0.0	0.9	0.1	1.0	0.1
WRIA 61	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 62	17.4	0.8	20.0	1.0	5.1	0.6	11.0	0.8	19.9	1.3	27.9	1.9

TABLE 17-6.
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR DRY-SEASON NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 1	160.6	5.7	177.7	7.4	28.3	2.6	51.2	3.4	174.3	8.5	215.5	11.1
WRIA 2	6.6	0.3	8.1	0.7	2.4	0.2	4.3	0.3	8.3	0.5	11.6	1.0
WRIA 3	27.5	1.3	35.5	1.8	15.2	2.7	38.7	3.7	38.0	3.9	70.0	5.9
WRIA 4	55.3	2.6	71.5	3.6	31.2	5.4	78.4	7.4	77.1	7.9	141.7	12.0
WRIA 5	10.1	0.5	12.6	1.2	2.8	0.3	7.3	0.5	12.3	0.8	19.2	1.6
WRIA 6	38.1	1.7	40.4	2.3	9.0	0.5	13.6	0.7	42.4	2.2	49.5	2.9
WRIA 7	253.6	5.1	264.8	7.0	58.9	6.6	108.7	8.3	273.2	11.4	343.8	15.4
WRIA 8	477.6	22.8	564.0	28.2	59.6	13.7	139.6	16.6	497.7	35.1	694.0	44.5
WRIA 9	113.5	3.2	124.1	4.2	23.7	4.8	54.6	5.7	122.0	8.4	169.0	10.8
WRIA 10	182.2	8.3	220.7	10.9	37.2	7.3	86.8	9.2	200.1	15.5	299.1	21.1
WRIA 11	5.1	0.3	7.3	1.0	2.7	0.3	5.9	0.4	6.9	0.5	12.3	1.3
WRIA 12	41.1	1.0	45.3	1.4	13.1	2.9	30.3	3.5	47.6	3.7	73.8	5.0
WRIA 13	0.3	0.0	5.0	0.6	14.3	2.0	35.6	3.1	8.0	1.8	33.3	4.0
WRIA 14	13.5	0.4	16.1	1.1	3.1	0.5	8.0	0.7	16.6	1.0	24.1	1.9
WRIA 15	35.0	1.7	42.8	2.3	15.8	3.1	33.7	3.7	47.1	4.6	75.2	6.2
WRIA 17	8.6	0.4	10.1	0.6	1.9	0.4	4.8	0.5	10.6	0.8	15.1	1.2
WRIA 18	19.0	0.5	21.6	0.8	5.0	0.9	11.3	1.2	21.3	1.4	31.2	2.0
WRIA 19	4.5	0.3	5.0	0.4	0.9	0.1	1.5	0.1	5.1	0.4	6.1	0.4
WRIA 20	15.0	0.6	15.7	0.7	2.9	0.2	4.1	0.3	16.3	0.8	18.0	0.9
WRIA 21	1.4	0.2	1.7	0.2	0.6	0.1	1.0	0.1	2.1	0.2	2.8	0.2
WRIA 22	40.9	1.5	48.0	2.6	10.6	2.2	27.2	2.8	49.8	3.8	74.7	5.5
WRIA 23	4.6	0.3	12.4	1.3	11.3	1.4	32.7	2.4	12.3	1.7	40.7	4.3
WRIA 24	37.6	1.8	40.6	2.6	9.2	0.6	14.8	0.8	42.1	2.4	50.5	3.3
WRIA 25	37.8	1.5	38.9	1.7	8.1	0.4	11.6	0.5	40.9	1.9	45.6	2.2
WRIA 26	12.4	1.1	14.0	1.2	4.2	0.6	6.7	0.7	16.5	1.5	20.4	1.8
WRIA 27	1.8	0.1	4.9	1.0	3.1	0.3	8.3	0.5	4.2	0.4	12.5	1.5
WRIA 28	8.1	0.3	20.9	0.5	29.8	4.2	81.3	6.9	25.6	4.6	87.6	9.1
WRIA 29	5.2	0.4	6.0	0.5	0.9	0.2	2.4	0.2	6.4	0.5	8.8	0.7
WRIA 30	44.7	1.4	46.5	1.7	9.6	0.6	13.8	0.7	48.8	1.9	54.5	2.3
WRIA 31	98.3	1.8	99.8	2.3	22.5	0.9	33.3	1.2	105.8	2.9	119.6	3.7
WRIA 32	9.8	0.3	15.2	0.8	8.8	1.2	22.8	1.9	16.8	1.7	35.6	3.4
WRIA 34	132.7	5.3	139.9	6.2	31.0	2.2	50.7	2.8	147.4	7.4	174.4	9.3
WRIA 35	6.4	0.5	7.8	0.6	2.3	0.4	4.9	0.5	8.1	0.8	12.3	1.0

**TABLE 17-6 (continued).
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR DRY-SEASON NUTRIENT REMOVAL**

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 36	33.8	1.6	36.8	1.9	8.0	1.1	13.6	1.2	38.2	2.4	46.8	2.9
WRIA 37	92.2	3.3	103.6	4.6	26.3	4.6	56.0	5.5	106.8	7.5	152.6	10.1
WRIA 38	5.0	0.4	6.3	0.5	2.1	0.4	4.4	0.4	6.7	0.7	10.6	1.0
WRIA 39	23.5	0.9	28.4	1.9	8.3	1.3	19.5	1.6	28.3	2.0	45.4	3.4
WRIA 40	18.1	0.6	21.0	0.9	6.5	1.4	14.9	1.7	22.1	1.9	35.1	2.6
WRIA 41	70.3	2.3	75.0	2.8	18.0	1.4	29.2	1.8	79.2	3.7	95.3	4.8
WRIA 42	11.6	0.6	12.4	0.7	2.4	0.2	3.4	0.3	12.9	0.8	14.5	0.9
WRIA 43	20.4	1.1	22.8	1.3	5.4	0.9	10.2	1.0	23.7	1.7	31.2	2.2
WRIA 44	7.9	0.5	9.6	0.6	2.9	0.6	6.5	0.7	10.0	1.0	15.7	1.3
WRIA 45	35.8	1.4	39.4	1.9	10.0	1.3	17.6	1.5	42.1	2.6	53.8	3.4
WRIA 47	7.2	0.3	8.1	0.4	1.5	0.3	3.3	0.3	8.1	0.6	11.0	0.8
WRIA 48	8.8	0.5	9.8	0.6	1.9	0.3	3.6	0.3	10.2	0.7	12.8	0.9
WRIA 49	13.9	0.8	16.2	1.1	2.7	0.5	6.9	0.7	16.8	1.3	23.2	1.8
WRIA 50	10.1	0.5	10.6	0.5	2.0	0.2	2.9	0.2	11.0	0.5	12.2	0.6
WRIA 52	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 53	2.6	0.2	2.8	0.2	0.5	0.1	0.6	0.1	2.9	0.2	3.1	0.2
WRIA 54	38.0	0.0	41.8	0.0	0.2	0.0	51.3	2.7	19.1	0.1	72.7	6.4
WRIA 55	3.8	0.3	4.0	0.3	0.7	0.1	0.9	0.1	4.1	0.3	4.5	0.3
WRIA 56	52.8	2.2	56.0	2.6	9.9	1.0	16.2	1.2	58.3	3.0	67.0	3.6
WRIA 60	0.8	0.1	0.9	0.1	0.1	0.0	0.2	0.0	0.9	0.1	1.0	0.1
WRIA 61	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 62	16.9	0.9	19.1	1.0	5.1	0.5	8.7	0.7	20.3	1.3	25.6	1.7

17.4 CONCLUSIONS

17.4.1 Nitrogen Removal

For nitrogen removal, seasonal operation is slightly more cost-effective (per pound of nitrogen removed) than year-round operation. Year-round removal requires significantly more capital investment to upgrade treatment facilities. However, seasonal removal generally would provide only about 60 percent of the nitrogen removal provided by year-round removal, on an annual mass basis.

Implementing nitrogen removal generally would slightly reduce the amount of sludge produced at a treatment plant (up to 3 percent). Reducing nitrogen to 3 mg/L, however, generally requires the addition of a carbon substrate, which would produce additional sludge—up to 5 percent above existing rates.

Energy consumption for nitrogen removal would be significant. Reducing the TIN effluent concentration statewide to less than 8 mg/L would require approximately two to three times the amount of electrical energy currently used by municipal wastewater treatment facilities. Moreover, existing energy recovery processes at treatment facilities that rely on the production of methane gas from sludge would produce approximately 5 to 10 percent less energy as a consequence of the removal of nitrogen.

17.4.2 Phosphorus Removal

For phosphorus removal, seasonal removal is generally less cost-effective (per pound of phosphorus removed) than year-round removal. Both approaches require about the same capital investment to upgrade treatment facilities, but seasonal removal generally would provide only about 60 percent of the phosphorus removal provided by year-round removal, on an annual mass basis.

Phosphorus removal by chemical precipitation produces significantly more sludge than existing processes—approximately 25 to 35 percent more.

Energy consumption would increase for phosphorus removal, but significantly less than for nitrogen removal. Reducing the TP effluent concentration statewide to less than 1 mg/L would increase treatment plant electrical energy consumption by approximately 15 to 20 percent.

CHAPTER 17.
CUMULATIVE COST IMPACT SUMMARY

17.1 CUMULATIVE STATEWIDE COST

Cost models presented in previous chapters of this report represent expected costs for upgrading individual treatment plants to meet a range of potential objectives for limiting nitrogen and phosphorus in effluent discharged to surface waters. If the State of Washington were to adopt regulatory guidelines establishing such limits, then municipal treatment plants throughout the state would need to perform upgrades, with potentially significant statewide cost implications.

In order to assess the magnitude of such potential future cost impacts, the cost models developed for each of the respective nutrient removal objectives (i.e., Chapters 11-16) were applied to Ecology's list of all municipal treatment plants operating in Washington. As described in Chapter 2, there are currently 304 such plants operating in the state. Using a list of the treatment type and maximum-month capacity for each of these plants, the upgrade capital and O&M cost models identified in the previous chapters for several capacities for each type of plant were used to estimate upgrade costs for each specific plant operating in the state. These costs were then totaled by treatment type and on a statewide basis. Tables 17-1, 17-2 and 17-3 present the results for capital cost, annual O&M cost and 20-year annualized total cost (assuming a 3-percent discount rate), respectively. The expected accuracy range for these estimates is +100% to -50% percent. Actual costs for a specific facility would have to be determined through a site specific engineering study.

17.2 POTENTIAL SEWER RATE IMPACTS

Based on the cumulate statewide costs estimated as described above, an evaluation was performed to estimate the likely cost impact on sewer rates per household. The monthly increase was calculated from the annualized statewide costs, assuming a statewide population of about 5.5 million, an average household size of 2.5 persons, a per capita maximum-month wastewater flow of 160 gallons, and a future number of households at design capacity equal to 1.33 times the current number of households. The resulting rate impact estimates are shown in Table 17-4.

17.3 WATERSHED-WIDE COSTS FOR NUTRIENT REMOVAL

For planning purposes, the Washington Department of Ecology has divided the state into 62 Water Resource Inventory Areas (WRIAs), representing the watershed, or drainage area, of all major water bodies in the state (see Figure 17-1). Water quality assessments and measures to address water quality problems often are developed based on these watershed designations, because the WRIAs represent all the area potentially contributing nutrients and other contaminants to affected water bodies. Therefore, if a given water body is experiencing water quality problems related to high levels of nitrogen or phosphorus, then nutrient discharge limits might be established that apply to all dischargers within that water body's WRIA. For this reason, it is useful to estimate the potential cost of upgrading all municipal treatment plants in each WRIA to achieve the various nutrient removal objectives. These estimates were made using the same approach described above for the statewide cost estimates. Tables 17-5 and 17-6 present the results for capital cost and annual O&M cost. Additional detail on costs in each WRIA is provided in Appendix D. The expected accuracy range for these estimates is +100% to -50% percent. Actual costs for a specific facility would have to be determined through a site specific engineering study.

TABLE 17-1.
ESTIMATED CAPITAL COSTS FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Capital Cost ($ millions, 2010)					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	204	239	29	133	221	360
Extended Aeration (Diffused Aeration)	4	7	3	11	5	16
Extended Aeration (with Biological Nutrient Removal)	29	128	75	328	94	414
Conventional Activated Sludge	1625	1773	142	559	1725	2253
Sequencing Batch Reactor	7	28	18	54	18	76
Trickling Filter	177	195	15	58	186	246
Rotating Biological Contactor	140	155	13	47	148	197
Trickling Filter/Solids Contact	193	207	15	59	193	252
Membrane Bioreactor	0	0	11	10	11	11
Lagoons (Aerated)	773	797	163	234	836	931
Lagoons (Facultative)	170	182	40	62	184	218
High Purity Oxygen	942	1134	N/A	N/A	942(1)	1134(1)
Statewide Total	**$4,264**	**$4,844**	**$522**	**$1,555**	**$4,564**	**$6,107**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	192	217	28	84	227	308
Extended Aeration (Diffused Aeration)	2	5	3	7	6	11
Extended Aeration (with Biological Nutrient Removal)	38	76	76	252	66	272
Conventional Activated Sludge	564	629	185	429	660	1032
Sequencing Batch Reactor	6	25	18	46	18	66
Trickling Filter	96	105	18	42	102	138
Rotating Biological Contactor	76	84	15	33	82	111
Trickling Filter/Solids Contact	88	93	20	46	88	127
Membrane Bioreactor	0	0	10	10	10	10
Lagoons (Aerated)	773	797	163	234	836	931
Lagoons (Facultative)	164	168	35	50	177	197
High Purity Oxygen	363	477	N/A	N/A	363(1)	477(1)
Statewide Total	**$2,360**	**$2,674**	**$570**	**$1,233**	**$2,635**	**$3,680**

Note: (1) costs are for nitrogen removal only

TABLE 17-2.
ESTIMATED ANNUAL O&M COSTS FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Annual O&M Cost ($ millions, 2010)					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	0	13	9	14	16	26
Extended Aeration (Diffused Aeration)	0	0	0	1	1	1
Extended Aeration (with Biological Nutrient Removal)	0	0	16	33	11	38
Conventional Activated Sludge	45	57	55	69	90	122
Sequencing Batch Reactor	0	9	1	3	0	12
Trickling Filter	5	7	4	6	9	12
Rotating Biological Contactor	5	6	4	4	8	11
Trickling Filter/Solids Contact	4	6	6	7	9	12
Membrane Bioreactor	0	0	1	2	1	2
Lagoons (Aerated)	24	28	10	12	31	37
Lagoons (Facultative)	7	8	2	2	10	12
High Purity Oxygen	44	53	N/A	N/A	44(1)	53(1)
Statewide Total	**$135**	**$187**	**$108**	**$152**	**$230**	**$338**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	9	12	6	9	15	21
Extended Aeration (Diffused Aeration)	0	0	0	1	1	1
Extended Aeration (with Biological Nutrient Removal)	0	0	10	19	11	28
Conventional Activated Sludge	17	24	41	49	54	72
Sequencing Batch Reactor	0	8	1	2	1	9
Trickling Filter	3	4	4	4	7	8
Rotating Biological Contactor	3	4	3	3	6	8
Trickling Filter/Solids Contact	1	2	4	5	5	7
Membrane Bioreactor	0	0	1	1	1	1
Lagoons (Aerated)	24	28	10	12	31	37
Lagoons (Facultative)	7	8	2	2	9	10
High Purity Oxygen	27	32	N/A	N/A	27	32
Statewide Total	**$90**	**$121**	**$81**	**$107**	**$166**	**$236**

Note: (1) costs are for nitrogen removal only

TABLE 17-3.
ESTIMATED ANNUAL CAPITAL AND O&M COSTS FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Annual Cost ($ millions, 2010)(1)					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	14	29	11	23	31	50
Extended Aeration (Diffused Aeration)	0	0	1	1	1	2
Extended Aeration (with Biological Nutrient Removal)	2	9	21	55	17	66
Conventional Activated Sludge	154	176	64	106	206	273
Sequencing Batch Reactor	1	11	2	7	1	17
Trickling Filter	17	20	6	10	22	29
Rotating Biological Contactor	14	16	4	8	18	24
Trickling Filter/Solids Contact	17	19	7	11	22	29
Membrane Bioreactor	0	0	2	2	2	2
Lagoons (Aerated)	75	81	21	27	87	100
Lagoons (Facultative)	19	21	5	7	22	26
High Purity Oxygen	108	129	N/A	N/A	108(2)	129(2)
Statewide Total	**$421**	**$513**	**$143**	**$256**	**$537**	**$748**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	21	27	8	14	30	42
Extended Aeration (Diffused Aeration)	0	0	1	1	1	2
Extended Aeration (with Biological Nutrient Removal)	3	5	15	36	15	47
Conventional Activated Sludge	55	66	53	78	98	141
Sequencing Batch Reactor	0	10	2	5	2	14
Trickling Filter	9	11	5	7	13	18
Rotating Biological Contactor	8	9	4	6	12	15
Trickling Filter/Solids Contact	7	8	5	8	10	15
Membrane Bioreactor	0	0	2	2	2	2
Lagoons (Aerated)	75	81	21	27	87	100
Lagoons (Facultative)	18	19	4	6	21	23
High Purity Oxygen	51	64	N/A	N/A	51(2)	64(2)
Statewide Total	**$248**	**$300**	**$120**	**$190**	**$344**	**$483**

Notes: (1) Capital cost were annualized for 20 years at 3% discount rate
(2) Cost is for nitrogen removal only

TABLE 17-4.
ESTIMATED MONTHLY HOUSEHOLD SEWER RATE INCREASE FOR NUTRIENT REMOVAL UPGRADES OF ALL TREATMENT PLANTS IN WASHINGTON

	Obj. A	Obj. B	Obj. C	Obj. D	Obj. E	Obj. F
Effluent TIN Limit (mg/L):	<8	<3	—	—	<8	<3
Effluent TP Limit (mg/L):	—	—	<1	<0.1	<1	<0.1
Existing Plant Type	Estimated Monthly Household Sewer Rate Increase [1]					
Year-Round Nutrient Removal						
Extended Aeration (Mechanical Aeration)	$11.29	$24.30	$9.26	$18.96	$25.20	$41.13
Extended Aeration (Diffused Aeration)	$4.09	$7.01	$9.91	$22.18	$15.29	$36.23
Extended Aeration (with Biological Nutrient Removal)	$0.37	$1.66	$4.07	$10.50	$3.31	$12.68
Conventional Activated Sludge	$17.48	$19.95	$7.25	$12.03	$23.33	$30.97
Sequencing Batch Reactor	$1.16	$22.37	$4.71	$13.09	$2.45	$33.21
Trickling Filter	$27.43	$31.48	$8.85	$15.26	$35.23	$46.42
Rotating Biological Contactor	$29.77	$34.14	$9.24	$15.92	$38.27	$49.99
Trickling Filter/Solids Contact	$17.79	$20.08	$6.86	$11.38	$22.33	$30.00
Membrane Bioreactor	$0.00	$0.81	$9.46	$10.67	$9.46	$11.46
Lagoons (Aerated)	$57.67	$62.05	$15.87	$20.91	$66.71	$76.37
Lagoons (Facultative)	$66.89	$74.14	$16.43	$23.38	$78.62	$94.66
High Purity Oxygen	$16.24	$19.47	N/A	N/A	16.24	19.47
Weighted Average	**$16.00**	**$19.48**	**$7.29**	**$13.02**	**$20.40**	**$28.43**
Dry-Season-Only Nutrient Removal						
Extended Aeration (Mechanical Aeration)	$17.71	$22.12	$6.25	$11.73	$24.88	$34.67
Extended Aeration (Diffused Aeration)	$2.34	$4.73	$8.45	$14.66	$15.55	$28.56
Extended Aeration (with Biological Nutrient Removal)	$0.48	$0.98	$2.96	$6.98	$2.97	$8.99
Conventional Activated Sludge	$6.23	$7.46	$6.01	$8.78	$11.15	$16.02
Sequencing Batch Reactor	$0.83	$18.88	$4.54	$10.35	$4.68	$27.51
Trickling Filter	$14.74	$17.01	$7.69	$11.32	$21.47	$28.34
Rotating Biological Contactor	$16.93	$19.46	$8.06	$11.80	$24.21	$31.42
Trickling Filter/Solids Contact	$7.20	$8.19	$5.66	$8.37	$10.84	$15.53
Membrane Bioreactor	$0.00	$0.66	$8.60	$8.77	$8.60	$9.39
Lagoons (Aerated)	$57.67	$62.05	$15.87	$20.91	$66.71	$76.37
Lagoons (Facultative)	$64.37	$68.74	$14.66	$19.74	$73.51	$83.15
High Purity Oxygen	$7.68	$9.70	N/A	N/A	$7.69[2]	$9.70[2]
Weighted Average	**$9.43**	**$11.41**	**$6.08**	**$9.64**	**$13.05**	**$23.28**

Assumptions:
- Maximum-month wastewater flow per capita = 160 gallons
- Population served by treatment plants = 5,484,396
- 2.5 persons per household
- Existing households = 75% of households at design capacity

Notes [1] Capital cost were annualized for 20 years at 3% discount rate
[2] Cost is for nitrogen removal only

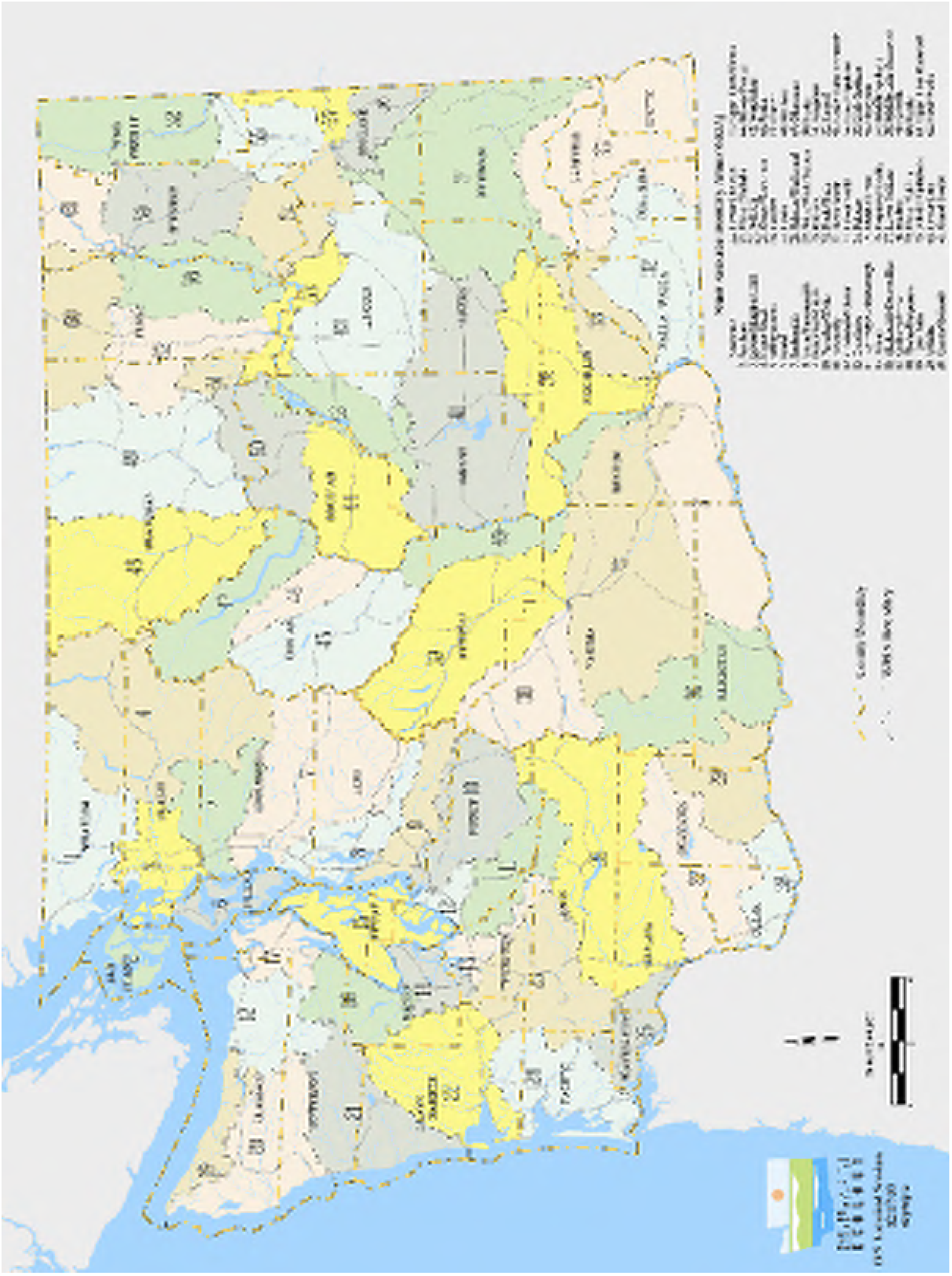


Figure 17-1. Water Resource Inventory Areas in Washington

TABLE 17-5.
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR YEAR-ROUND NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 1	236.4	7.1	260.5	9.8	28.1	3.4	61.1	4.6	248.8	10.9	306.5	14.4
WRIA 2	6.9	0.3	8.6	0.8	2.4	0.2	5.3	0.3	8.2	0.5	12.6	1.1
WRIA 3	63.2	1.7	76.8	2.9	14.1	3.7	53.0	5.5	72.0	5.2	123.2	8.7
WRIA 4	127.7	3.4	155.3	5.8	29.0	7.6	107.4	11.2	146.2	10.6	249.5	17.6
WRIA 5	10.5	0.2	13.5	1.3	2.9	0.4	9.5	0.7	12.2	0.8	21.7	2.0
WRIA 6	42.2	1.6	46.7	2.6	10.0	0.6	17.5	0.8	46.5	2.5	58.5	3.5
WRIA 7	365.7	7.3	388.2	11.0	54.0	8.6	129.0	11.2	383.8	15.7	482.9	21.7
WRIA 8	1235.6	45.4	1408.5	54.6	40.4	19.8	167.5	25.0	1253.4	61.1	1538.3	78.0
WRIA 9	227.8	6.7	249.7	8.4	19.2	6.2	74.0	7.7	238.4	12.6	313.5	16.5
WRIA 10	481.5	17.1	548.3	21.2	29.0	10.1	111.0	13.4	495.8	25.7	638.6	35.1
WRIA 11	7.3	0.3	9.9	1.2	2.7	0.3	7.1	0.4	9.1	0.5	16.0	1.5
WRIA 12	117.6	3.2	127.6	4.0	9.5	4.0	38.3	5.0	124.1	6.4	160.1	8.7
WRIA 13	0.3	0.0	22.6	0.6	14.2	3.1	43.2	5.1	20.9	2.3	58.2	6.1
WRIA 14	14.8	0.0	18.2	1.2	3.2	0.8	11.3	1.1	16.8	1.1	28.4	2.3
WRIA 15	98.7	2.9	112.2	4.2	14.3	3.9	47.7	5.0	110.8	6.6	155.9	9.2
WRIA 17	12.1	0.2	14.3	0.7	1.9	0.5	7.4	0.7	13.6	0.9	21.2	1.4
WRIA 18	39.8	0.9	44.6	1.6	4.2	1.2	15.8	1.6	42.1	2.1	58.3	3.0
WRIA 19	5.5	0.3	6.1	0.4	0.9	0.1	1.9	0.1	6.2	0.4	7.6	0.4
WRIA 20	15.0	0.6	15.7	0.7	2.9	0.2	4.1	0.3	16.3	0.8	18.0	0.9
WRIA 21	1.6	0.0	1.9	0.2	0.6	0.1	1.5	0.1	2.1	0.2	3.3	0.3
WRIA 22	78.1	1.6	89.6	3.8	9.7	2.9	38.9	4.0	85.6	5.0	125.3	7.7
WRIA 23	5.1	0.0	15.8	1.7	11.3	2.0	43.6	3.9	9.8	2.1	52.6	6.1
WRIA 24	42.8	1.9	47.0	2.8	10.0	0.7	18.4	0.9	47.3	2.6	59.9	3.8
WRIA 25	39.2	1.6	42.1	1.9	9.2	0.4	14.2	0.5	42.4	2.2	50.4	2.7
WRIA 26	14.6	0.5	16.1	1.4	4.3	0.7	9.4	0.9	18.0	1.4	24.5	1.9
WRIA 27	4.6	0.2	8.3	1.2	3.2	0.3	11.0	0.7	6.6	0.5	18.2	1.9
WRIA 28	9.4	0.0	45.2	0.5	29.3	6.8	105.7	11.6	34.8	5.8	131.9	13.9
WRIA 29	5.7	0.0	6.8	0.5	0.9	0.2	4.0	0.4	6.2	0.5	10.5	0.8
WRIA 30	45.4	1.4	47.2	1.7	9.6	0.6	14.0	0.7	49.5	1.9	55.5	2.3
WRIA 31	100.3	1.8	101.9	2.3	22.5	0.9	33.9	1.2	107.8	2.9	122.4	3.7
WRIA 32	10.3	0.0	17.9	0.9	8.7	1.8	31.5	3.0	14.3	2.0	44.5	4.6
WRIA 34	143.2	5.2	158.8	6.8	34.8	2.6	65.4	3.6	156.9	8.5	202.9	11.3
WRIA 35	15.9	0.6	18.2	0.9	2.1	0.5	7.2	0.6	17.8	1.0	24.9	1.4

TABLE 17-5 (continued).
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR YEAR-ROUND NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 36	48.5	2.0	52.5	2.3	7.5	1.2	16.3	1.4	53.2	2.8	65.0	3.5
WRIA 37	197.5	5.9	217.8	8.1	22.5	5.8	72.9	7.4	213.1	10.9	280.5	15.0
WRIA 38	13.2	0.4	15.3	0.8	1.9	0.5	6.6	0.6	14.9	0.9	21.5	1.3
WRIA 39	49.6	1.6	57.0	2.9	7.4	1.5	24.7	2.2	54.7	2.8	78.3	4.9
WRIA 40	53.8	1.6	59.6	2.0	5.1	1.8	19.9	2.3	58.0	3.1	77.5	4.2
WRIA 41	83.5	2.5	89.3	3.1	17.9	1.6	34.7	2.0	91.7	4.0	114.3	5.4
WRIA 42	11.8	0.6	12.6	0.7	2.4	0.2	3.7	0.3	13.0	0.7	14.8	0.9
WRIA 43	36.5	1.5	40.3	1.8	4.9	1.0	13.0	1.3	40.0	2.2	51.1	2.8
WRIA 44	21.9	0.7	24.8	1.1	2.5	0.7	9.2	0.9	24.1	1.4	33.3	1.8
WRIA 45	55.1	1.7	60.5	2.6	9.4	1.5	21.8	1.9	61.2	3.2	78.3	4.3
WRIA 47	13.3	0.5	14.9	0.6	1.3	0.3	4.9	0.4	14.4	0.8	19.5	1.1
WRIA 48	11.1	0.4	12.5	0.7	1.9	0.3	4.9	0.4	12.4	0.7	16.5	1.0
WRIA 49	19.4	0.4	22.7	1.2	2.8	0.7	11.1	1.0	21.5	1.5	33.0	2.1
WRIA 50	10.1	0.4	10.6	0.5	2.0	0.2	2.9	0.2	11.0	0.5	12.3	0.6
WRIA 52	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 53	2.6	0.2	2.8	0.2	0.5	0.1	0.6	0.1	2.9	0.2	3.1	0.2
WRIA 54	29.4	0.0	45.4	0.0	0.2	0.0	63.1	5.1	38.3	-2.8	114.7	4.5
WRIA 55	3.8	0.3	4.0	0.3	0.7	0.1	0.9	0.1	4.1	0.3	4.5	0.3
WRIA 56	53.7	1.9	57.0	2.7	10.0	1.2	18.5	1.5	58.3	3.0	69.6	3.8
WRIA 60	0.8	0.1	0.9	0.1	0.1	0.0	0.2	0.0	0.9	0.1	1.0	0.1
WRIA 61	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 62	17.4	0.8	20.0	1.0	5.1	0.6	11.0	0.8	19.9	1.3	27.9	1.9

TABLE 17-6.
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR DRY-SEASON NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 1	160.6	5.7	177.7	7.4	28.3	2.6	51.2	3.4	174.3	8.5	215.5	11.1
WRIA 2	6.6	0.3	8.1	0.7	2.4	0.2	4.3	0.3	8.3	0.5	11.6	1.0
WRIA 3	27.5	1.3	35.5	1.8	15.2	2.7	38.7	3.7	38.0	3.9	70.0	5.9
WRIA 4	55.3	2.6	71.5	3.6	31.2	5.4	78.4	7.4	77.1	7.9	141.7	12.0
WRIA 5	10.1	0.5	12.6	1.2	2.8	0.3	7.3	0.5	12.3	0.8	19.2	1.6
WRIA 6	38.1	1.7	40.4	2.3	9.0	0.5	13.6	0.7	42.4	2.2	49.5	2.9
WRIA 7	253.6	5.1	264.8	7.0	58.9	6.6	108.7	8.3	273.2	11.4	343.8	15.4
WRIA 8	477.6	22.8	564.0	28.2	59.6	13.7	139.6	16.6	497.7	35.1	694.0	44.5
WRIA 9	113.5	3.2	124.1	4.2	23.7	4.8	54.6	5.7	122.0	8.4	169.0	10.8
WRIA 10	182.2	8.3	220.7	10.9	37.2	7.3	86.8	9.2	200.1	15.5	299.1	21.1
WRIA 11	5.1	0.3	7.3	1.0	2.7	0.3	5.9	0.4	6.9	0.5	12.3	1.3
WRIA 12	41.1	1.0	45.3	1.4	13.1	2.9	30.3	3.5	47.6	3.7	73.8	5.0
WRIA 13	0.3	0.0	5.0	0.6	14.3	2.0	35.6	3.1	8.0	1.8	33.3	4.0
WRIA 14	13.5	0.4	16.1	1.1	3.1	0.5	8.0	0.7	16.6	1.0	24.1	1.9
WRIA 15	35.0	1.7	42.8	2.3	15.8	3.1	33.7	3.7	47.1	4.6	75.2	6.2
WRIA 17	8.6	0.4	10.1	0.6	1.9	0.4	4.8	0.5	10.6	0.8	15.1	1.2
WRIA 18	19.0	0.5	21.6	0.8	5.0	0.9	11.3	1.2	21.3	1.4	31.2	2.0
WRIA 19	4.5	0.3	5.0	0.4	0.9	0.1	1.5	0.1	5.1	0.4	6.1	0.4
WRIA 20	15.0	0.6	15.7	0.7	2.9	0.2	4.1	0.3	16.3	0.8	18.0	0.9
WRIA 21	1.4	0.2	1.7	0.2	0.6	0.1	1.0	0.1	2.1	0.2	2.8	0.2
WRIA 22	40.9	1.5	48.0	2.6	10.6	2.2	27.2	2.8	49.8	3.8	74.7	5.5
WRIA 23	4.6	0.3	12.4	1.3	11.3	1.4	32.7	2.4	12.3	1.7	40.7	4.3
WRIA 24	37.6	1.8	40.6	2.6	9.2	0.6	14.8	0.8	42.1	2.4	50.5	3.3
WRIA 25	37.8	1.5	38.9	1.7	8.1	0.4	11.6	0.5	40.9	1.9	45.6	2.2
WRIA 26	12.4	1.1	14.0	1.2	4.2	0.6	6.7	0.7	16.5	1.5	20.4	1.8
WRIA 27	1.8	0.1	4.9	1.0	3.1	0.3	8.3	0.5	4.2	0.4	12.5	1.5
WRIA 28	8.1	0.3	20.9	0.5	29.8	4.2	81.3	6.9	25.6	4.6	87.6	9.1
WRIA 29	5.2	0.4	6.0	0.5	0.9	0.2	2.4	0.2	6.4	0.5	8.8	0.7
WRIA 30	44.7	1.4	46.5	1.7	9.6	0.6	13.8	0.7	48.8	1.9	54.5	2.3
WRIA 31	98.3	1.8	99.8	2.3	22.5	0.9	33.3	1.2	105.8	2.9	119.6	3.7
WRIA 32	9.8	0.3	15.2	0.8	8.8	1.2	22.8	1.9	16.8	1.7	35.6	3.4
WRIA 34	132.7	5.3	139.9	6.2	31.0	2.2	50.7	2.8	147.4	7.4	174.4	9.3
WRIA 35	6.4	0.5	7.8	0.6	2.3	0.4	4.9	0.5	8.1	0.8	12.3	1.0

TABLE 17-6 (continued).
ESTIMATED CAPITAL AND O&M COSTS BY WRIA FOR DRY-SEASON NUTRIENT REMOVAL

	Cost ($ millions, 2010)											
	Objective A		Objective B		Objective C		Objective D		Objective E		Objective F	
	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M	Capital	O&M
WRIA 36	33.8	1.6	36.8	1.9	8.0	1.1	13.6	1.2	38.2	2.4	46.8	2.9
WRIA 37	92.2	3.3	103.6	4.6	26.3	4.6	56.0	5.5	106.8	7.5	152.6	10.1
WRIA 38	5.0	0.4	6.3	0.5	2.1	0.4	4.4	0.4	6.7	0.7	10.6	1.0
WRIA 39	23.5	0.9	28.4	1.9	8.3	1.3	19.5	1.6	28.3	2.0	45.4	3.4
WRIA 40	18.1	0.6	21.0	0.9	6.5	1.4	14.9	1.7	22.1	1.9	35.1	2.6
WRIA 41	70.3	2.3	75.0	2.8	18.0	1.4	29.2	1.8	79.2	3.7	95.3	4.8
WRIA 42	11.6	0.6	12.4	0.7	2.4	0.2	3.4	0.3	12.9	0.8	14.5	0.9
WRIA 43	20.4	1.1	22.8	1.3	5.4	0.9	10.2	1.0	23.7	1.7	31.2	2.2
WRIA 44	7.9	0.5	9.6	0.6	2.9	0.6	6.5	0.7	10.0	1.0	15.7	1.3
WRIA 45	35.8	1.4	39.4	1.9	10.0	1.3	17.6	1.5	42.1	2.6	53.8	3.4
WRIA 47	7.2	0.3	8.1	0.4	1.5	0.3	3.3	0.3	8.1	0.6	11.0	0.8
WRIA 48	8.8	0.5	9.8	0.6	1.9	0.3	3.6	0.3	10.2	0.7	12.8	0.9
WRIA 49	13.9	0.8	16.2	1.1	2.7	0.5	6.9	0.7	16.8	1.3	23.2	1.8
WRIA 50	10.1	0.5	10.6	0.5	2.0	0.2	2.9	0.2	11.0	0.5	12.2	0.6
WRIA 52	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 53	2.6	0.2	2.8	0.2	0.5	0.1	0.6	0.1	2.9	0.2	3.1	0.2
WRIA 54	38.0	0.0	41.8	0.0	0.2	0.0	51.3	2.7	19.1	0.1	72.7	6.4
WRIA 55	3.8	0.3	4.0	0.3	0.7	0.1	0.9	0.1	4.1	0.3	4.5	0.3
WRIA 56	52.8	2.2	56.0	2.6	9.9	1.0	16.2	1.2	58.3	3.0	67.0	3.6
WRIA 60	0.8	0.1	0.9	0.1	0.1	0.0	0.2	0.0	0.9	0.1	1.0	0.1
WRIA 61	2.0	0.1	2.2	0.1	0.4	0.0	0.5	0.0	2.2	0.1	2.4	0.2
WRIA 62	16.9	0.9	19.1	1.0	5.1	0.5	8.7	0.7	20.3	1.3	25.6	1.7

17.4 CONCLUSIONS

17.4.1 Nitrogen Removal

For nitrogen removal, seasonal operation is slightly more cost-effective (per pound of nitrogen removed) than year-round operation. Year-round removal requires significantly more capital investment to upgrade treatment facilities. However, seasonal removal generally would provide only about 60 percent of the nitrogen removal provided by year-round removal, on an annual mass basis.

Implementing nitrogen removal generally would slightly reduce the amount of sludge produced at a treatment plant (up to 3 percent). Reducing nitrogen to 3 mg/L, however, generally requires the addition of a carbon substrate, which would produce additional sludge—up to 5 percent above existing rates.

Energy consumption for nitrogen removal would be significant. Reducing the TIN effluent concentration statewide to less than 8 mg/L would require approximately two to three times the amount of electrical energy currently used by municipal wastewater treatment facilities. Moreover, existing energy recovery processes at treatment facilities that rely on the production of methane gas from sludge would produce approximately 5 to 10 percent less energy as a consequence of the removal of nitrogen.

17.4.2 Phosphorus Removal

For phosphorus removal, seasonal removal is generally less cost-effective (per pound of phosphorus removed) than year-round removal. Both approaches require about the same capital investment to upgrade treatment facilities, but seasonal removal generally would provide only about 60 percent of the phosphorus removal provided by year-round removal, on an annual mass basis.

Phosphorus removal by chemical precipitation produces significantly more sludge than existing processes—approximately 25 to 35 percent more.

Energy consumption would increase for phosphorus removal, but significantly less than for nitrogen removal. Reducing the TP effluent concentration statewide to less than 1 mg/L would increase treatment plant electrical energy consumption by approximately 15 to 20 percent.

CHAPTER 18.
TREATMENT REQUIREMENTS AND COSTS FOR RECLAIMED WASTEWATER

This chapter identifies process upgrades and associated costs required to upgrade existing treatment plants so that the effluent meets state requirements for reclaimed water used for groundwater recharge.

18.1 APPLICABLE STANDARDS

The State of Washington at Chapter 90 Article 90.46 of the Revised Code of Washington (90.46 RCW) defines reclaimed water as "effluent derived in any part from wastewater with a domestic wastewater component that has been adequately and reliably treated, so that it can be used for beneficial purposes. Reclaimed water is not considered a wastewater." The state's Reclaimed Water Reclamation and Reuse Standards of 1997 define four classes of reclaimed water:

- Class A—Reclaimed water that is oxidized, coagulated, filtered and disinfected, with the median number of total coliform organisms in the wastewater after disinfection over 7 days not exceeding 2.2 per 100 milliliters and the number of total coliform organisms in any sample not exceeding 23 per 100 milliliters.
- Class B—Reclaimed water that is oxidized and disinfected, with the median number of total coliform organisms in the wastewater after disinfection over 7 days not exceeding 2.2 per 100 milliliters and the number of total coliform organisms in any sample not exceeding 23 per 100 milliliters.
- Class C—Reclaimed water that is oxidized and disinfected, with the median number of total coliform organisms in the wastewater after disinfection over 7 days not exceeding 23 per 100 milliliters and the number of total coliform organisms in any sample not exceeding 240 per 100 milliliters.
- Class D—Reclaimed water that is oxidized and disinfected, with the median number of total coliform organisms in the wastewater after disinfection over 7 days not exceeding 240 per 100 milliliters.

The term "oxidized" is defined by the standard as "wastewater in which organic matter has been stabilized such that the biochemical oxygen demand (BOD) does not exceed 30 mg/L and the total suspended solids (TSS) do not exceed 30 mg/L, is non-putrescible and contains dissolved oxygen." The definition does not include any limits on nutrients. An oxidized wastewater does not mean that ammonia has been oxidized.

In practice, conventional secondary treatment achieves oxidized wastewater, so only Class A reclaimed water requires a level of treatment prior to disinfection that is greater than conventional secondary treatment. Class B, C and D reclaimed waters require only secondary treatment and differ only in concentration of total coliform bacteria remaining in the wastewater after disinfection.

The standards limit nutrient concentrations for some specific uses of reclaimed water, including groundwater recharge by surface percolation, and direct potable water aquifer recharge. The standard for reclaimed water to be used for groundwater recharge by surface percolation requires a nitrogen removal treatment process beyond that provided by conventional secondary treatment; however, no numeric values or performance criteria are stipulated.

A draft regulation for reclaimed water (included in revised 1997 standards issued for public comment in 2010 as WAC Chapter 173-219) would require that median nitrogen concentration in the reclaimed water after disinfection over 30 days not exceed 10 mg/L and that no single sample exceed 15 mg/L.

18.2 EVALUATION APPROACH

18.2.1 Technology Assumptions

The evaluation of water reclamation for this report is based on the existing 1997 standards for Class A reclaimed water to be used for groundwater recharge by surface percolation, as well as the draft new standard that would establish a 10-mg/L limit on monthly average concentration. Nutrient removal Objective A would reduce nitrogen to < 8 mg/L, so it was assumed that the Objective A improvements would be implemented for all plants. Additional improvements assumed to achieve Class A standards depend on whether the plant as upgraded to achieve Objective A includes MBR treatment:

- For plants with MBR treatment after upgrades to achieve Objective A, the following additional processes would be required:
  - Upgrade or replacement of the disinfection process to a UV process that reliably achieves Class A standards
  - A post-chlorination process using bulk-delivered sodium hypochlorite to maintain a minimum chlorine residual of 0.5 mg/L to the point of application of the water for recharge
- For plants without MBR treatment after upgrades to achieve Objective A, the following additional processes would be required:
  - Upgrade or replacement of the disinfection process to a UV process that reliably achieves Class A standards
  - A post-chlorination process using bulk-delivered sodium hypochlorite to maintain a minimum chlorine residual of 0.5 mg/L to the point of application of the water for recharge
  - A new filtration process with coagulation/flocculation (only for upgraded plants that would not include membrane bioreactors)

In this report, plants that would include MBR treatment when upgraded to achieve Objective A are referred to as “membrane plants” and those that would not include MBR treatment after upgrade are referred to as “non-membrane plants.” Existing plant types are grouped in these two categories as follows:

- Membrane plants—Plants that currently use conventional activated sludge, trickling filters, trickling filter-solids contact, rotating biological contactors, high purity oxygen or MBR
- Non-membrane plants—Plants that currently use extended aeration, sequencing batch reactors or lagoons.

Table 18-1 lists the design criteria for the assumed upgrades for each category. Cost estimates were developed for producing Class A reclaimed water year-round and seasonally for the two categories of upgraded plants. Four plant maximum-month capacities were evaluated: 0.5 mgd, 5 mgd, 50 mgd and 220 mgd. The evaluation assumed that existing methods for wastewater disposal would be retained as a backup should effluent fail to meet reclaimed water requirements, so no costs were developed for standby or redundant process equipment. Costs for storage and distribution of reclaimed water from the treatment plant to the point of application for groundwater recharge are beyond the scope of this project.

TABLE 18-1.
DESIGN CRITERIA FOR PROCESSES TO PROVIDE CLASS A RECLAIMED WATER

Process	Design Criterion: Non-Membrane Plants	Design Criterion: Membrane Plants
Disinfection		
• Turbidity	2 NTU mo. average; 5 NTU max	0.2 NTU mo. average; 0.5 NTU max
• UV transmittance	55%	65%
• Min UV Dose @ 254 nm	100 mJ/cm^2	80 mJ/cm^2
• Bacteriological Quality	7-day median total coliform equal or less than 2.2 MPN/100 mL and no sample above 23 MPN/100 mL	7-day median total coliform equal or less than 2.2 MPN/100 mL and no sample above 23 MPN/100 mL
Assumed Post-Chlorination System		
• Total chlorine residual after 20 minutes contact	2 mg/L chlorine as NaOCL	2 mg/L chlorine as NaOCL
Filtration w/Coagulation		
• Rapid Mix	1 second @ peak hour flow	Not applicable
• Coagulant dosing	10 mg/L alum	Not applicable
• Sand filtration rate	5 gpm/sq. ft. @ peak daily flow including recycle	Not applicable

18.2.2 Cost Approach

CapdetWorks was used to estimate capital and annual O&M costs for year-round and seasonal reclaimed water upgrades for each category of plant. O&M costs include labor, materials, chemicals and energy. Annualized capital costs over 20 years were calculated assuming a 3-percent discount rate. Cost curves and best-fit equations of unit cost (per plant capacity) vs. plant capacity were then used to estimate annualized costs for the three plant capacities used in the nutrient-removal evaluation for each type of existing plant. Reclaimed water upgrade costs were then calculated as a percentage of nutrient removal upgrade costs estimated earlier in this report.

18.3 YEAR-ROUND RECLAIMED WATER UPGRADE COST ESTIMATES

18.3.1 Non-Membrane Plants

Table 18-2 lists unit capital costs for the year-round reclaimed water upgrades for non-membrane plants. Figure 18-1 shows the cost curve for these estimates and a best-fit parametric equation based on the data. Table 18-3 lists unit O&M costs for these upgrades; the generalized O&M cost curve and best-fit equation are shown on Figure 18-2. Annualized cost results are presented in Table 18-4 and Figure 18-3.

18.3.2 Membrane Plants

Table 18-5 lists unit capital costs for the year-round reclaimed water upgrades for membrane plants. Figure 18-4 shows the cost curve for these estimates and a best-fit parametric equation based on the data. Table 18-6 lists unit O&M costs for these upgrades; the O&M cost curve and best-fit equation are shown on Figure 18-5. Annualized cost results are summarized in Table 18-7 and Figure 18-6.

TABLE 18-2.
ESTIMATED CAPITAL COSTS FOR YEAR-ROUND RECLAIMED WATER UPGRADES FOR NON-MEMBRANE PLANTS

	Estimated Capital Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Coagulation /Filtration	$4.10	$1.79	$1.02	$0.66
UV Disinfection	$5.29	$6.63	$4.56	$4.08
Post-Disinfection Chlorination	$1.67	$0.33	$0.16	$0.09
Total	**$11.06**	**$8.76**	**$5.71**	**$4.55**

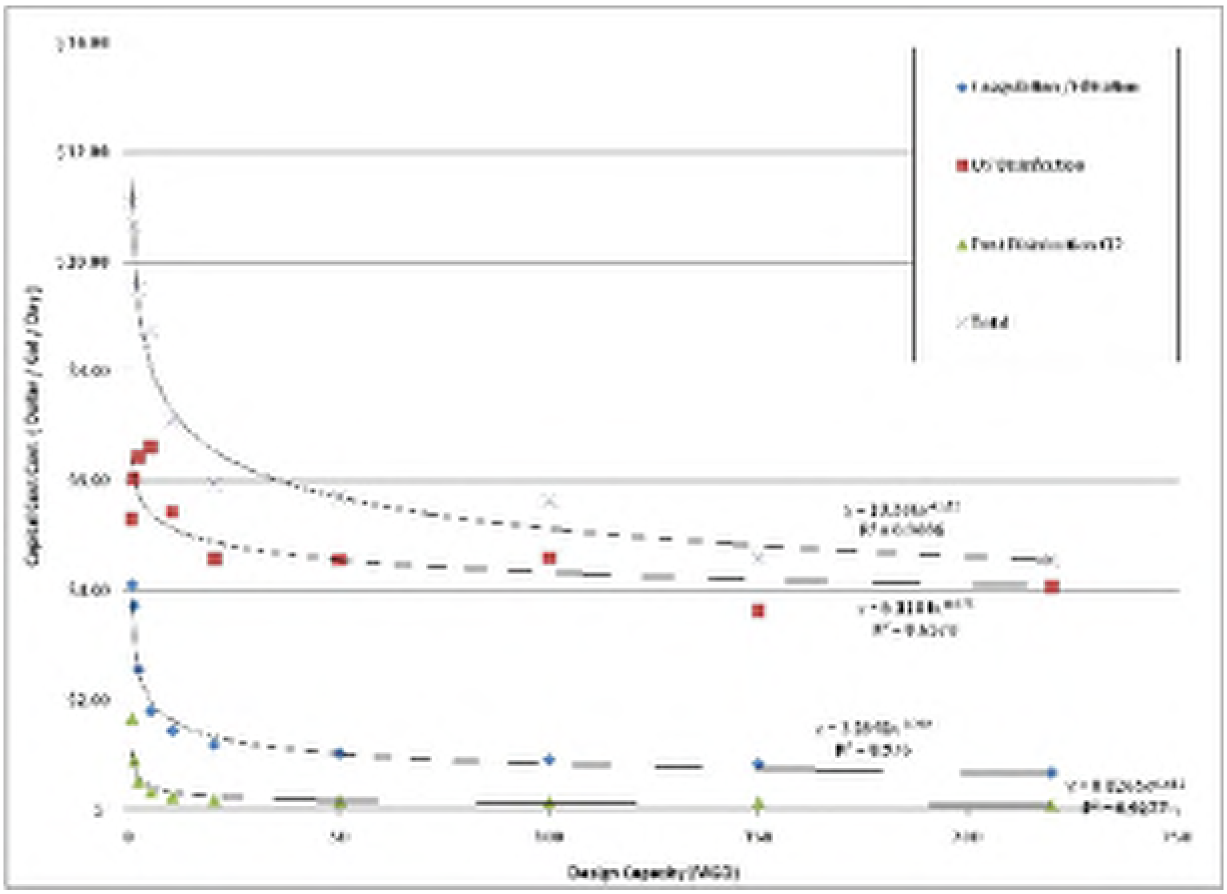


Figure 18-1. Capital Costs for Year-Round Reclaimed Water Upgrades for Non-Membrane Plants

TABLE 18-3.
ESTIMATED ANNUAL O&M COSTS FOR YEAR-ROUND RECLAIMED WATER UPGRADES FOR NON-MEMBRANE PLANTS

	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annual O&M Cost per gpd of Maximum-Month Capacity [a]	$0.99	$0.23	$0.15	$0.09

a. Includes labor, materials, chemicals and energy

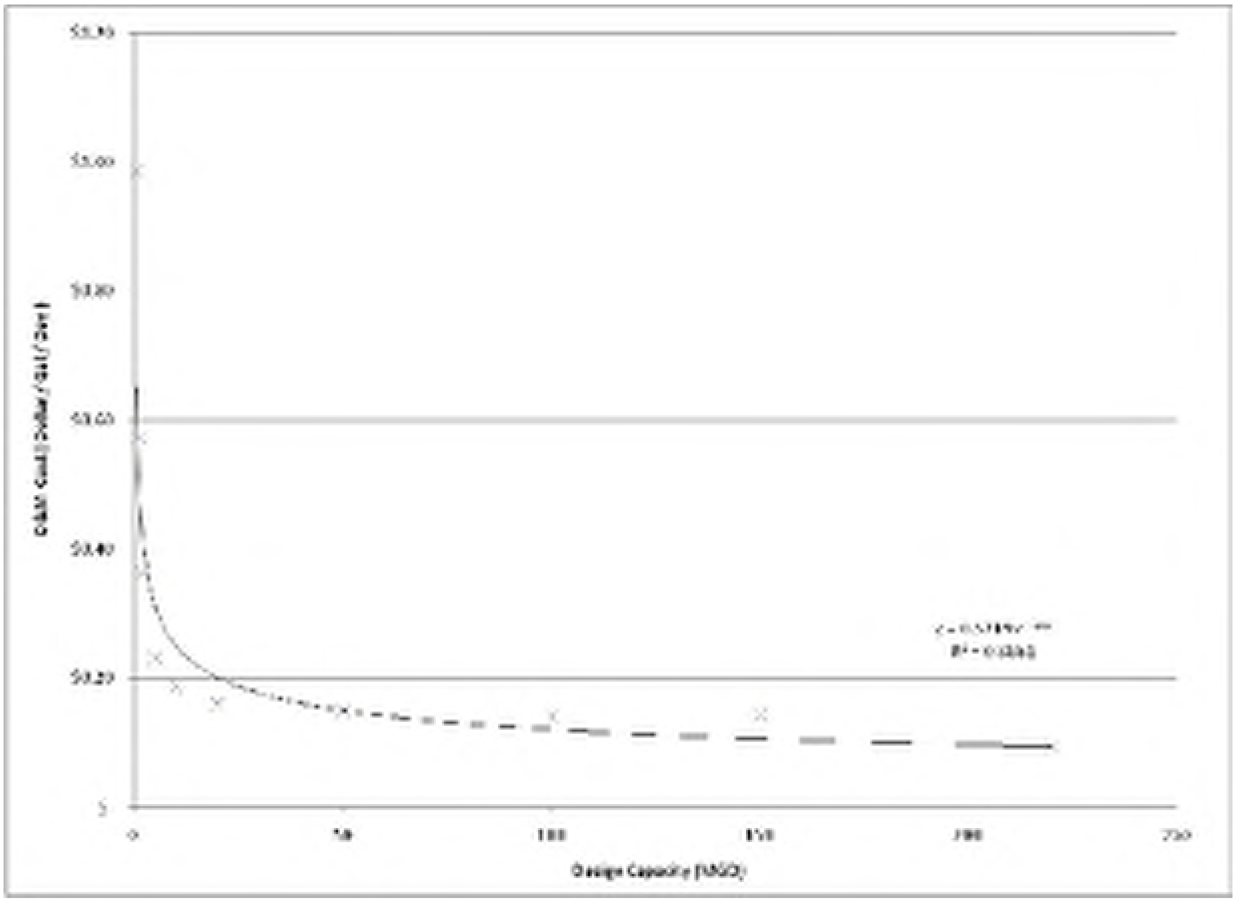


Figure 18-2. Annual O&M Costs for Year-Round Reclaimed Water Upgrades for Non-Membrane Plants

TABLE 18-4.
ESTIMATED ANNUALIZED CAPITAL AND O&M COSTS FOR YEAR-ROUND RECLAIMED WATER UPGRADES FOR NON-MEMBRANE PLANTS

	Estimated Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annualized Capital Cost	$0.74	$0.59	$0.38	$0.31
Annual O&M Cost	$0.99	$0.23	$0.15	$0.09
Total Annualized Cost	**$1.73**	**$0.82**	**$0.53**	**$0.38**

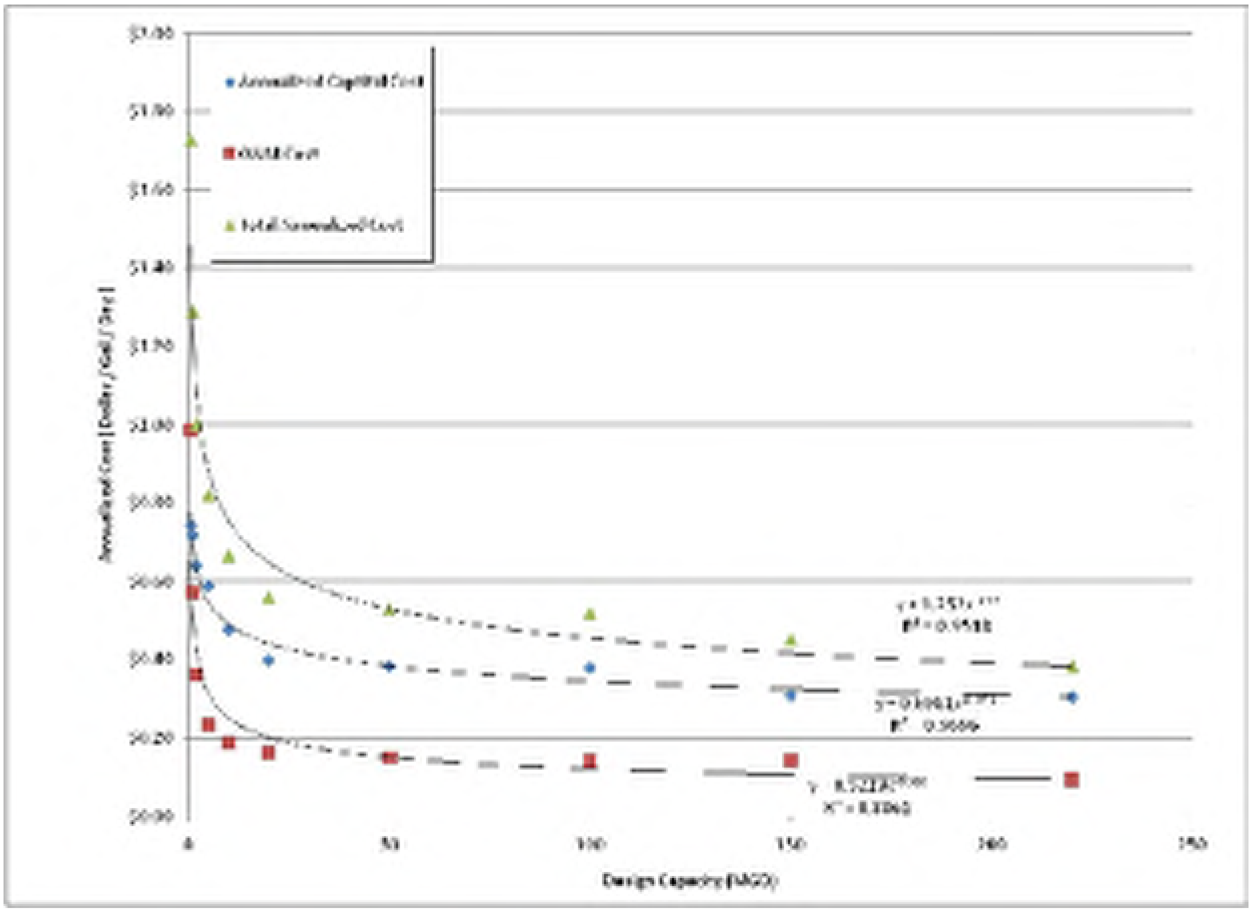


Figure 18-3. Annualized Capital and O&M Costs for Year-Round Reclaimed Water Upgrades for Non-Membrane Plants

TABLE 18-5.
ESTIMATED CAPITAL COSTS FOR YEAR-ROUND RECLAIMED WATER UPGRADES FOR MEMBRANE PLANTS

	Estimated Capital Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
UV Disinfection	\$5.29	\$6.63	\$4.56	\$4.08
Post-Disinfection Chlorination	\$1.67	\$0.33	\$0.16	\$0.09
Total	**\$6.96**	**\$6.96**	**\$4.70**	**\$4.02**

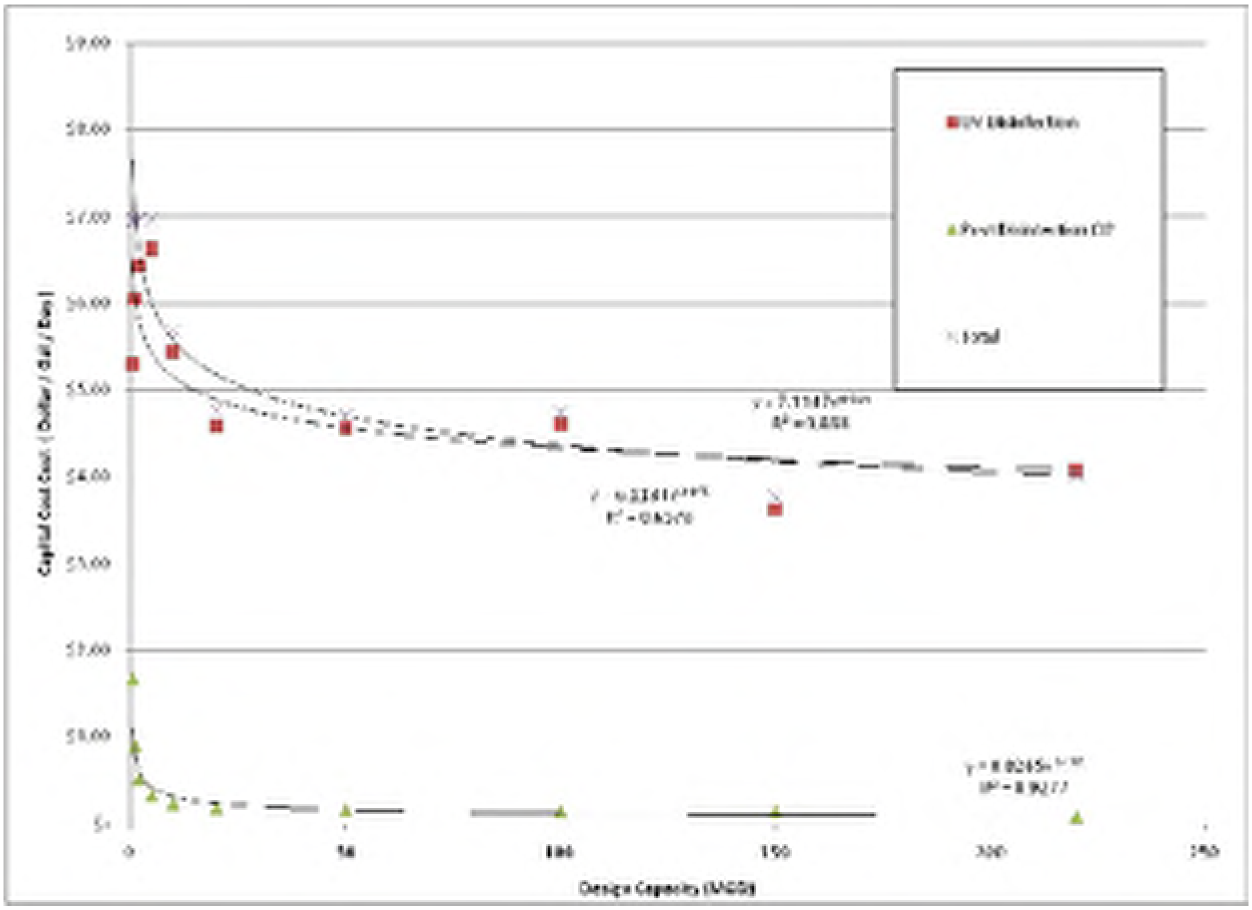


Figure 18-4. Capital Costs for Year-Round Reclaimed Water Upgrades for Membrane Plants

TABLE 18-6.
ESTIMATED ANNUAL O&M COSTS FOR YEAR-ROUND RECLAIMED WATER UPGRADES FOR MEMBRANE PLANTS

	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annual O&M Cost per gpd of Maximum-Month Capacity [a]	$0.20	$0.14	$0.12	$0.11

a. Includes labor, materials, chemicals and energy

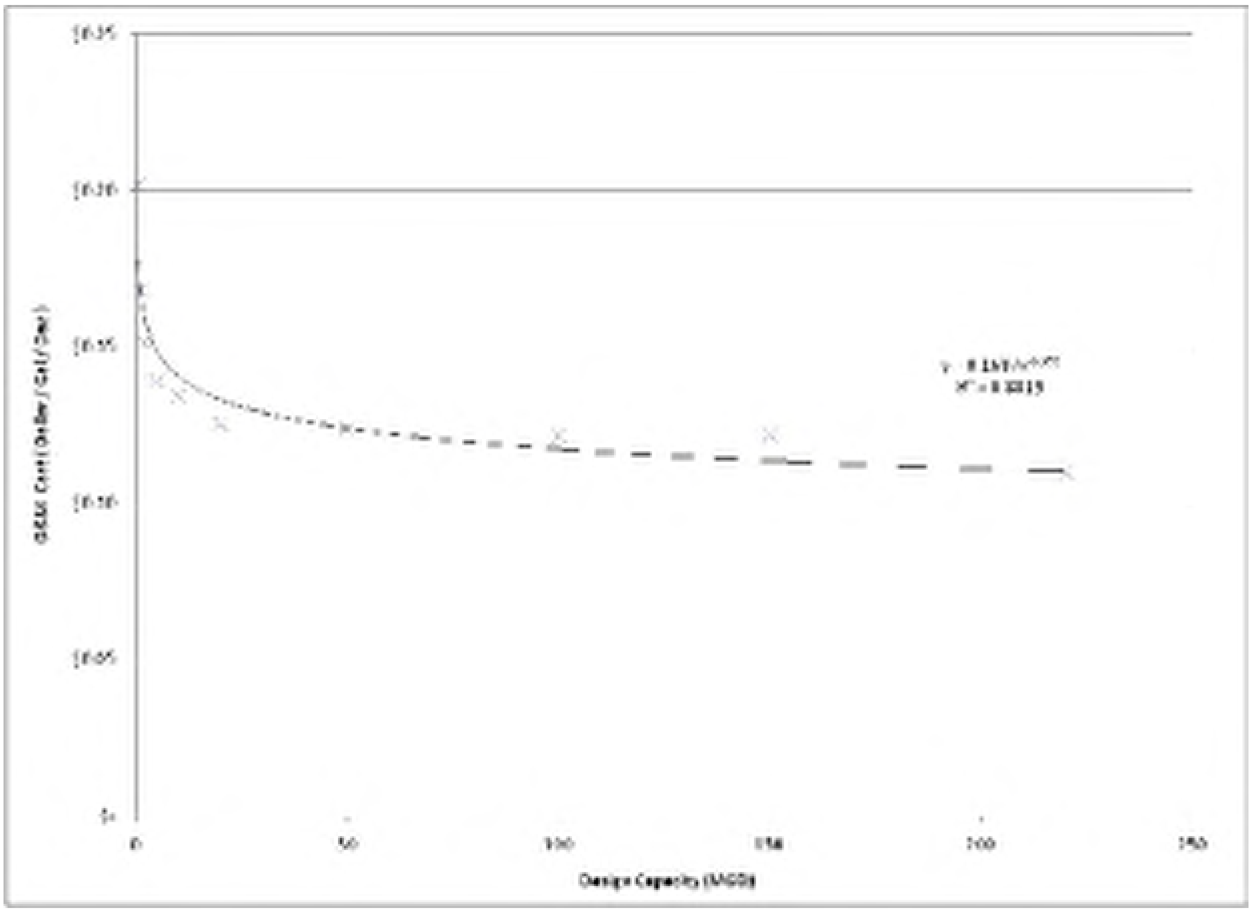


Figure 18-5. Annual O&M Costs for Year-Round Reclaimed Water Upgrades for Membrane Plants

TABLE 18-7.
ESTIMATED ANNUALIZED CAPITAL AND O&M COSTS FOR YEAR-ROUND RECLAIMED WATER UPGRADES FOR MEMBRANE PLANTS

	Estimated Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annualized Capital Cost	$0.47	$0.47	$0.32	$0.27
Annual O&M Cost	$0.20	$0.14	$0.12	$0.11
Total Annualized Cost	**$0.67**	**$0.61**	**$0.44**	**$0.38**

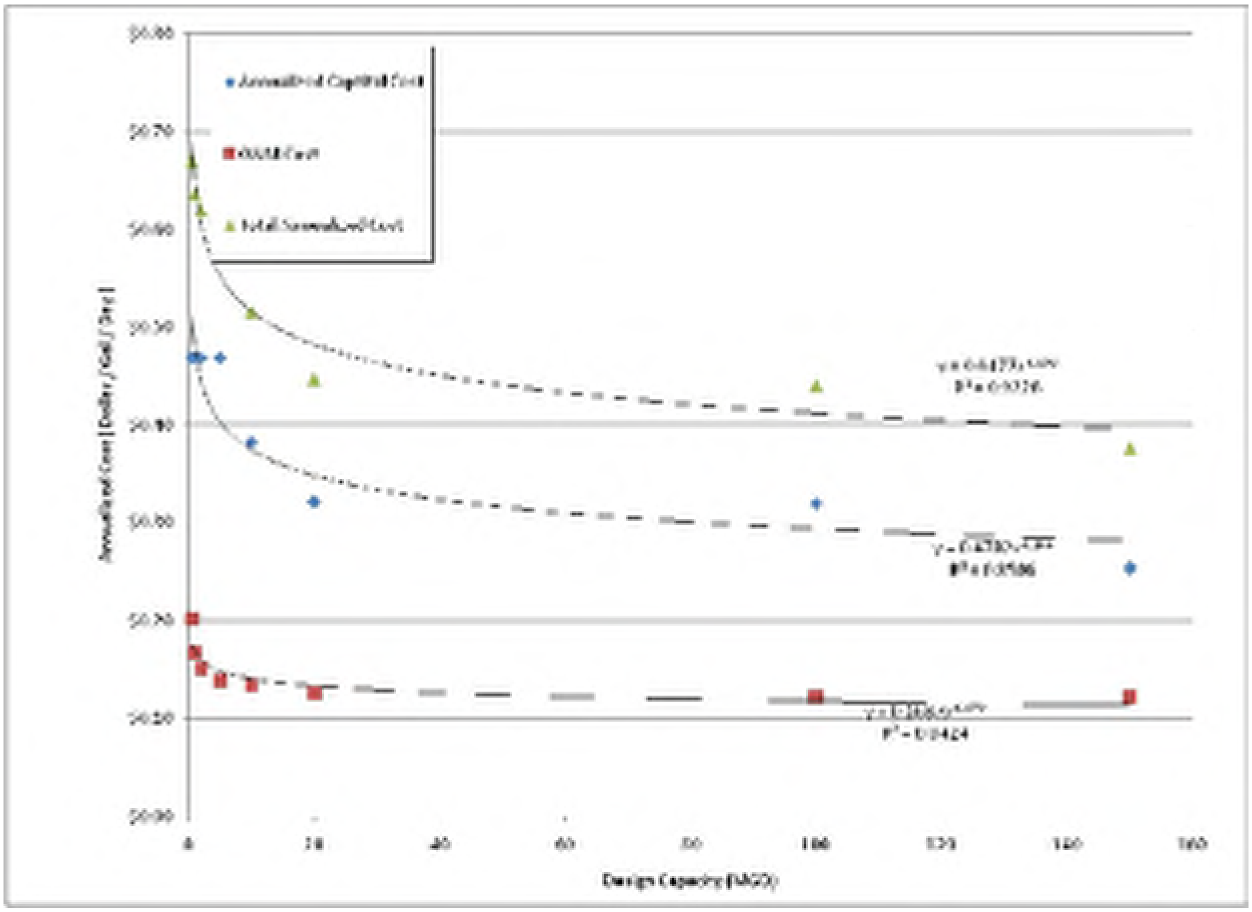


Figure 18-6. Annualized Capital and O&M Costs for Year-Round Reclaimed Water Upgrades for Membrane Plants

18.3.3 Extended Aeration Plants

Tables 18-8 through 18-11 show annualized capital and annual O&M cost estimates for upgrading both types of extended aeration plants (mechanical aeration and diffused aeration) to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-8.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (MECHANICAL AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$351,414	$1,656,556	$16,134,708
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$698,100	$4,908,148	$34,507,829
Total	**$1,049,514**	**$6,564,704**	**$50,642,537**
% Cost Increase for Reclaimed Water Upgrade	199%	296%	214%

TABLE 18-9.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (MECHANICAL AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$234,218	$142,715	($2,068,685)
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$521,900	$2,121,228	$8,621,589
Total	**$756,118**	**$2,263,943**	**$6,552,904**
% Cost Increase for Reclaimed Water Upgrade	223%	1486%	-417%

TABLE 18-10.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (DIFFUSED AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$78,303	$554,242	$2,298,201
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$698,100	$4,908,148	$34,507,829
Total	**$776,403**	**$5,462,390**	**$36,806,030**
% Cost Increase for Reclaimed Water Upgrade	892%	886%	1502%

TABLE 18-11.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (DIFFUSED AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$19,584	($526,175)	($574,741)
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$521,900	$2,121,228	$8,621,589
Total	**$541,484**	**$1,595,053**	**$8,046,848**
% Cost Increase for Reclaimed Water Upgrade	2665%	-403%	-1500%

18.3.4 Conventional Activated Sludge Plants

Tables 18-12 and 18-13 show annualized capital and annual O&M cost estimates for upgrading conventional activated sludge plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-12.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR CONVENTIONAL ACTIVATED SLUDGE PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$487,073	$3,341,694	$36,630,838
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$428,200	$3,354,646	$37,763,501
Total	**$915,273**	**$6,696,340**	**$74,394,339**
% Cost Increase for Reclaimed Water Upgrade	88%	100%	103%

TABLE 18-13.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR CONVENTIONAL ACTIVATED SLUDGE PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$262,642	$1,451,579	$13,597,000
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$168,700	$1,406,420	$17,033,156
Total	**$431,342**	**$2,857,999**	**$30,630,156**
% Cost Increase for Reclaimed Water Upgrade	64%	97%	125%

18.3.5 Sequencing Batch Reactors

Tables 18-14 and 18-15 show annualized capital and annual O&M cost estimates for upgrading sequencing batch reactor plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-14.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR SEQUENCING BATCH REACTOR PLANTS

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$0	$0	$0
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$388,101	$1,255,712	$4,908,148
Total	**$388,101**	**$1,255,712**	**$4,908,148**
% Cost Increase for Reclaimed Water Upgrade	Undefined	Undefined	Undefined

**TABLE 18-15.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR SEQUENCING BATCH REACTOR PLANTS**

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$4,615	$11,368	$43,332
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$342,184	$796,003	$2,121,228
Total	**$346,799**	**$807,371**	**$2,164,560**
% Cost Increase for Reclaimed Water Upgrade	7415%	7002%	4895%

18.3.6 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Tables 18-16 through 18-21 show annualized capital and annual O&M cost estimates for upgrading trickling filter, trickling filter/solids contact and rotating biological contactor plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

**TABLE 18-16.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER PLANTS**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$601,194	$4,278,563	$42,098,874
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$428,200	$3,354,646	$37,763,501
Total	**$1,029,394**	**$7,633,209**	**$79,862,375**
% Cost Increase for Reclaimed Water Upgrade	71%	78%	90%

**TABLE 18-17.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER PLANTS**

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$328,594	$1,672,797	$13,518,789
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$168,700	$1,406,420	$17,033,156
Total	**$497,294**	**$3,079,217**	**$30,551,945**
% Cost Increase for Reclaimed Water Upgrade	51%	84%	126%

TABLE 18-18.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR ROTATING BIOLOGICAL CONTACTOR PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$601,523	$4,298,964	$42,622,884
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$428,200	$3,354,646	$37,763,501
Total	**$1,029,723**	**$7,653,610**	**$80,386,385**
% Cost Increase for Reclaimed Water Upgrade	71%	78%	89%

TABLE 18-19.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR ROTATING BIOLOGICAL CONTACTOR PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$389,616	$1,824,178	$14,526,119
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$168,700	$1,406,420	$17,033,156
Total	**$558,316**	**$3,230,598**	**$31,559,275**
% Cost Increase for Reclaimed Water Upgrade	43%	77%	117%

TABLE 18-20.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER/SOLIDS CONTACT PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$507,744	$3,870,296	$38,592,858
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$428,200	$3,354,646	$37,763,501
Total	**$935,944**	**$7,224,942**	**$76,356,359**
% Cost Increase for Reclaimed Water Upgrade	84%	87%	98%

TABLE 18-21.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER/SOLIDS CONTACT PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$203,721	$1,409,147	$11,856,412
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$168,700	$1,406,420	$17,033,156
Total	**$372,421**	**$2,815,567**	**$28,889,568**
% Cost Increase for Reclaimed Water Upgrade	83%	100%	144%

18.3.7 Membrane Biological Reactor Plants

Tables 18-22 and 18-23 show annualized capital and annual O&M cost estimates for upgrading MBR plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-22.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR MEMBRANE BIOREACTOR PLANTS

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$0	$0	$0
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$428,200	$3,354,646	$26,281,289
Total	**$428,200**	**$3,354,646**	**$26,281,289**
% Cost Increase for Reclaimed Water Upgrade	undefined	undefined	undefined

TABLE 18-23.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR MEMBRANE BIOREACTOR PLANTS

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$ 0	$0	$0
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$168,700	$1,406,420	$11,725,060
Total	**$168,700**	**$1,406,420**	**$11,725,060**
% Cost Increase for Reclaimed Water Upgrade	undefined	undefined	undefined

18.3.8 High-Purity Oxygen Activated Sludge Plants

Tables 18-24 and 18-25 show annualized capital and annual O&M cost estimates for upgrading high-purity oxygen activated sludge plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-24.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE PLANTS

	20-mgd Plant	220-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$5,745,000	$48,960,000
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$6,234,000	$53,183,000
Total	**$11,979,000**	**$102,143,000**
% Cost Increase for Reclaimed Water Upgrade	109%	109%

TABLE 18-25.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE PLANTS

	20-mgd Plant	220-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$4,172,000	$35,520,000
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$2,663,000	$24,237,000
Total	**$6,835,000**	**$59,757,000**
% Cost Increase for Reclaimed Water Upgrade	64%	68%

18.3.9 Lagoon Plants

Tables 18-26 through 18-29 show annualized capital and annual O&M cost estimates for upgrading both types of lagoon plants (aerated and facultative) to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-26.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR FACULTATIVE LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$815,034	$4,073,790	$23,994,247
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$388,101	$2,728,634	$19,184,268
Total	**$1,203,135**	**$6,802,424**	**$43,178,515**
% Cost Increase for Reclaimed Water Upgrade	48%	67%	80%

TABLE 18-27.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR FACULTATIVE LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$665,608	$2,224,005	$7,997,263
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$342,184	$1,390,785	$5,652,753
Total	**$1,007,792**	**$3,614,790**	**$13,650,016**
% Cost Increase for Reclaimed Water Upgrade	51%	63%	71%

TABLE 18-28.
ANNUALIZED CAPITAL COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR AERATED LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$820,052	$4,106,942	$24,168,643
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$388,101	$2,728,634	$19,184,268
Total	**$1,208,153**	**$6,835,576**	**$43,352,911**
% Cost Increase for Reclaimed Water Upgrade	47%	66%	79%

TABLE 18-29.
ANNUAL O&M COSTS FOR YEAR-ROUND NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR AERATED LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$512,439	$1,321,179	$6,109,993
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$342,184	$1,390,785	$5,652,753
Total	**$854,623**	**$2,711,964**	**$11,762,746**
% Cost Increase for Reclaimed Water Upgrade	67%	105%	93%

18.4 SEASONAL RECLAIMED WATER UPGRADE COST ESTIMATES

18.4.1 Non-Membrane Plants

Table 18-30 lists unit capital costs for the seasonal reclaimed water upgrades for non-membrane plants. Figure 18-7 shows the cost curve for these estimates and a best-fit parametric equation based on the data. Table 18-31 lists unit O&M costs for these upgrades; the generalized O&M cost curve and best-fit equation are shown on Figure 18-8. Annualized cost results are presented in Table 18-32 and Figure 18-9.

18.4.2 Membrane Plants

Table 18-33 lists unit capital costs for the seasonal reclaimed water upgrades for membrane plants. Figure 18-10 shows the cost curve for these estimates and a best-fit parametric equation based on the data. Table 18-34 lists unit O&M costs for these upgrades; the O&M cost curve and best-fit equation are shown on Figure 18-11. Annualized cost results are summarized in Table 18-35 and Figure 18-12.

TABLE 18-30.
ESTIMATED CAPITAL COSTS FOR SEASONAL RECLAIMED WATER UPGRADES FOR NON-MEMBRANE PLANTS

	Estimated Capital Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Coagulation /Filtration	$3.67	$1.41	$0.76	$0.48
UV Disinfection	$3.17	$4.36	$3.24	$3.05
Post-Disinfection Chlorination	$1.62	$0.29	$0.12	$0.06
Total	**$8.46**	**$6.06**	**$4.08**	**$3.27**

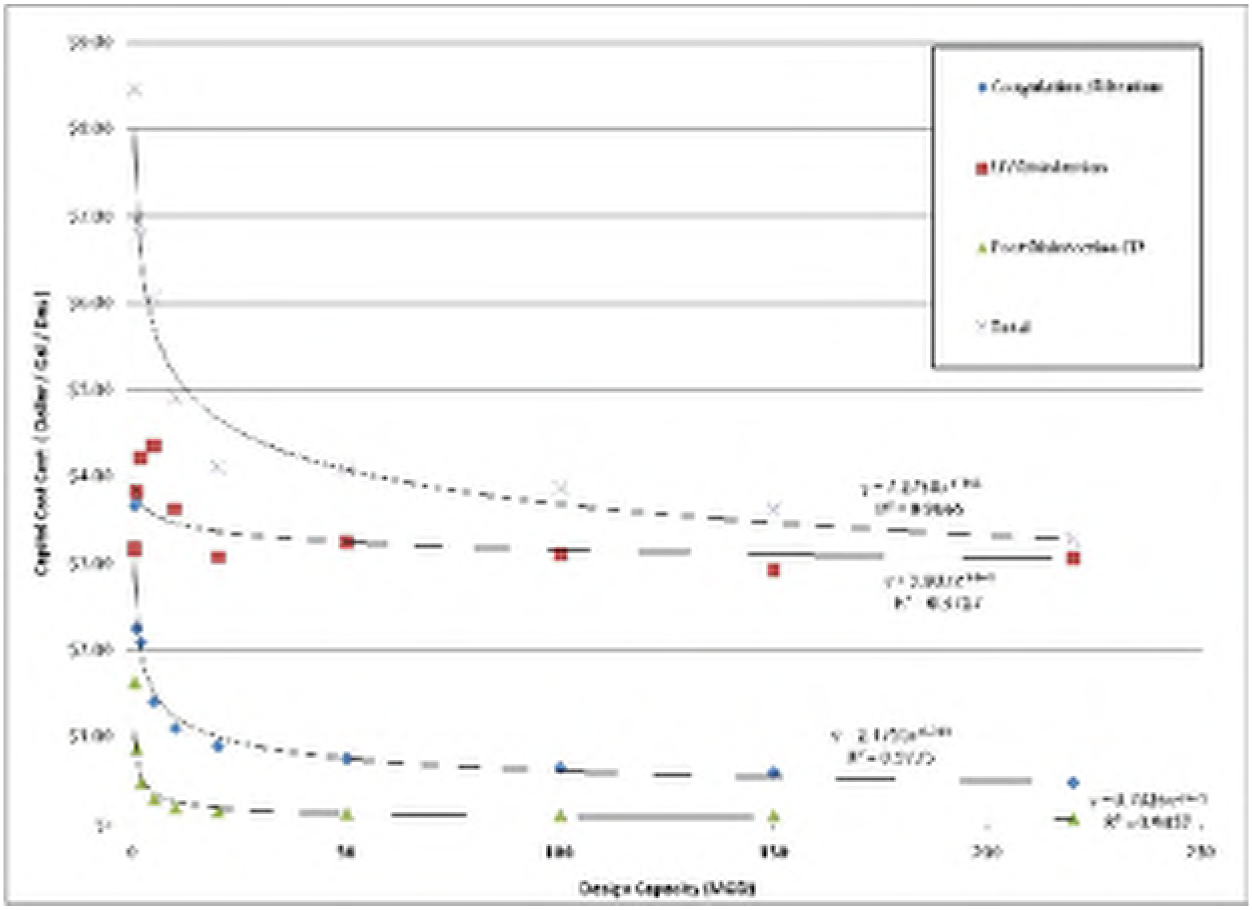


Figure 18-7. Capital Costs for Seasonal Reclaimed Water Upgrades for Non-Membrane Plants

**TABLE 18-31.
ESTIMATED ANNUAL O&M COSTS FOR SEASONAL RECLAIMED WATER UPGRADES FOR NON-MEMBRANE PLANTS**

	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annual O&M Cost per gpd of Maximum-Month Capacity [a]	$0.90	$0.16	$0.08	$0.04

a. Includes labor, materials, chemicals and energy

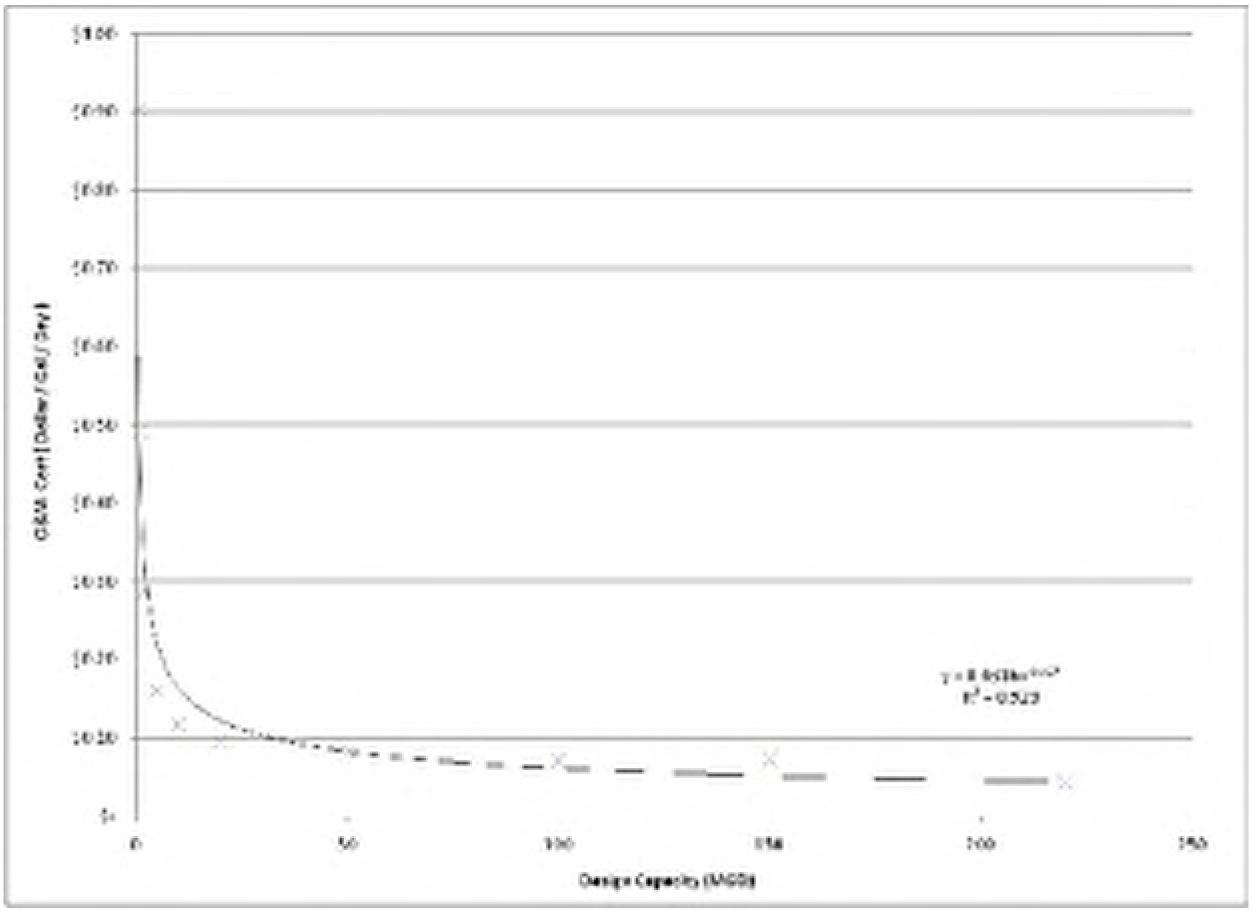


Figure 18-8. Annual O&M Costs for Seasonal Reclaimed Water Upgrades for Non-Membrane Plants

TABLE 18-32.
ESTIMATED ANNUALIZED CAPITAL AND O&M COSTS FOR SEASONAL RECLAIMED WATER UPGRADES FOR NON-MEMBRANE PLANTS

	Estimated Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annualized Capital Cost	$0.57	$0.41	$0.27	$0.22
Annual O&M Cost	$0.90	$0.16	$0.08	$0.04
Total Annualized Cost	**$1.47**	**$0.57**	**$0.35**	**$0.24**

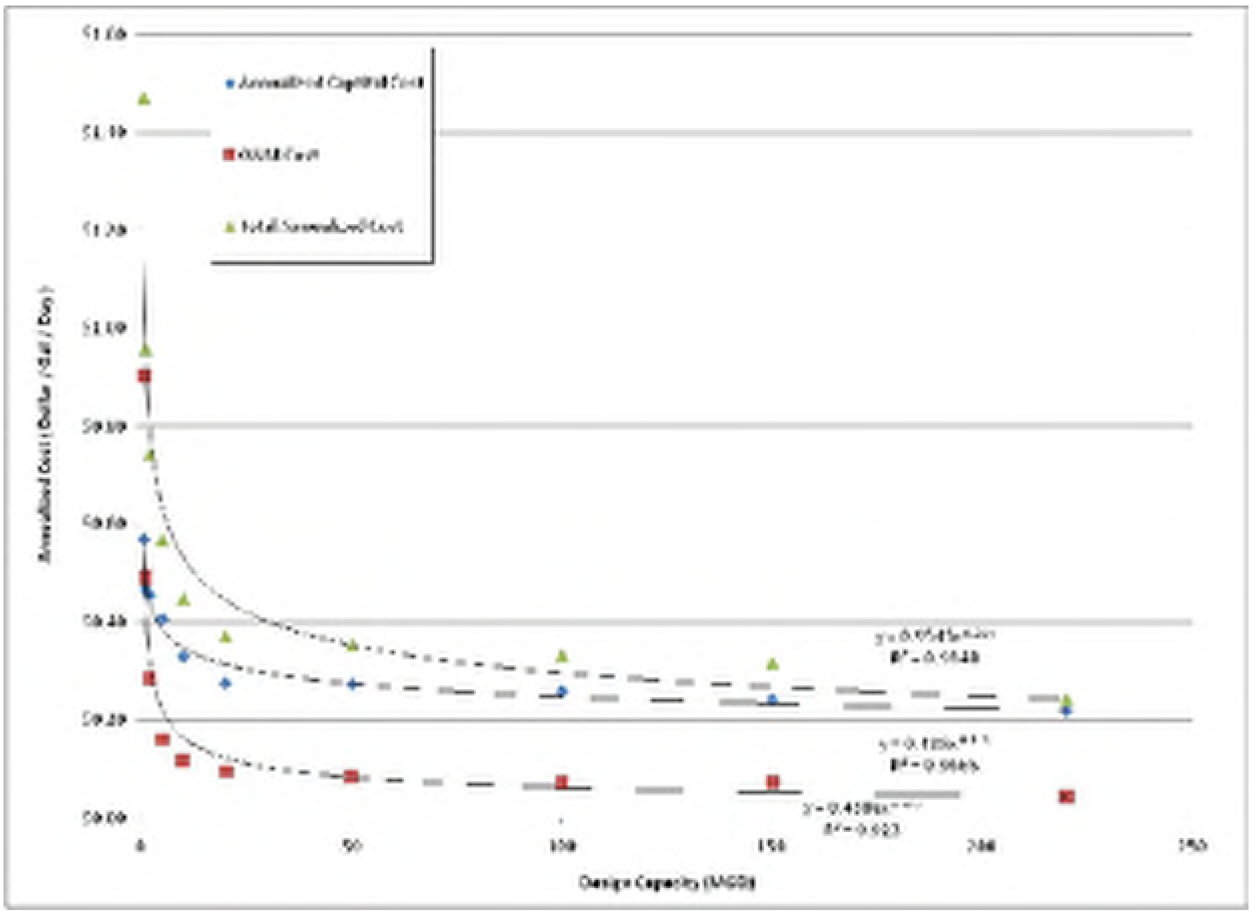


Figure 18-9. Annualized Capital and O&M Costs for Seasonal Reclaimed Water Upgrades for Non-Membrane Plants

TABLE 18-33.
ESTIMATED CAPITAL COSTS FOR SEASONAL RECLAIMED WATER UPGRADES FOR MEMBRANE PLANTS

	Estimated Capital Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
UV Disinfection	$3.17	$4.36	$3.24	$3.05
Post-Disinfection Chlorination	$1.62	$0.29	$0.12	$0.06
Total	**$4.79**	**$4.65**	**$3.33**	**$2.91**

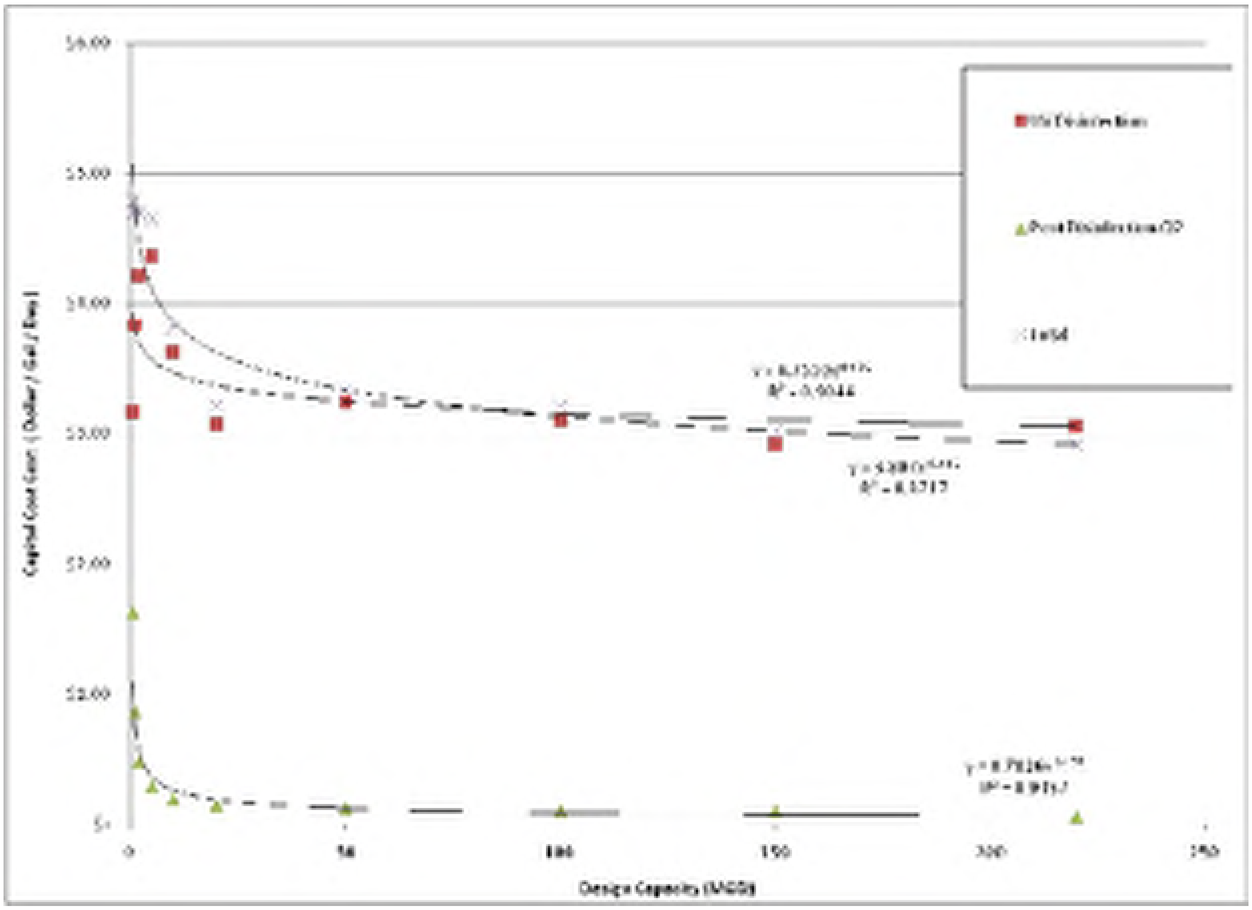


Figure 18-10. Capital Costs for Seasonal Reclaimed Water Upgrades for Membrane Plants

TABLE 18-34.
ESTIMATED ANNUAL O&M COSTS FOR SEASONAL RECLAIMED WATER UPGRADES FOR MEMBRANE PLANTS

	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annual O&M Cost per gpd of Maximum-Month Capacity [a]	$0.12	$0.07	$0.06	$0.05

a. Includes labor, materials, chemicals and energy

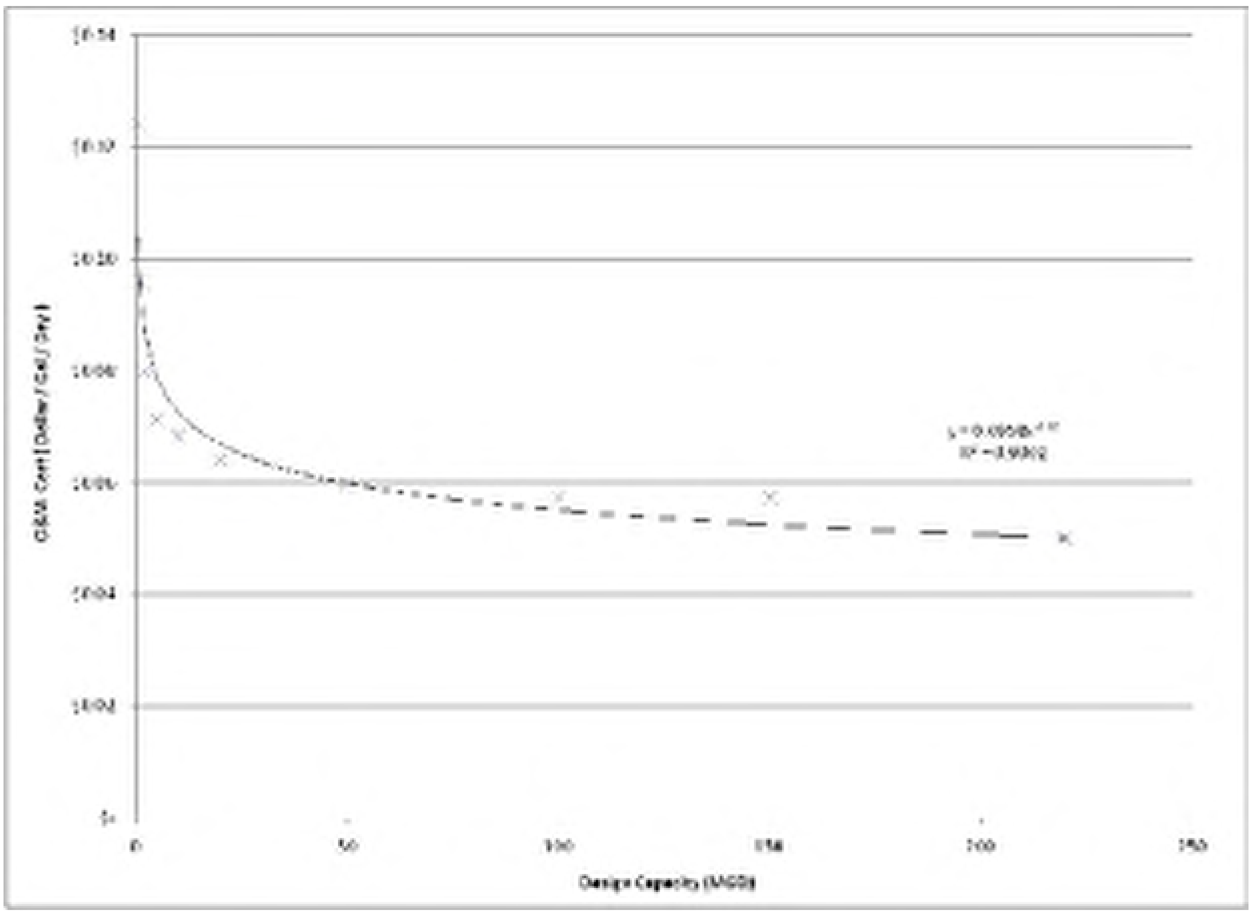


Figure 18-11. Annual O&M Costs for Seasonal Reclaimed Water Upgrades for Membrane Plants

TABLE 18-35.
ESTIMATED ANNUALIZED CAPITAL AND O&M COSTS FOR SEASONAL RECLAIMED WATER UPGRADES FOR MEMBRANE PLANTS

	Estimated Cost per gpd of Maximum-Month Capacity			
	0.5 mgd Plant	5 mgd Plant	50 mgd Plant	220 mgd Plant
Annualized Capital Cost	$0.32	$0.31	$0.22	$0.20
Annual O&M Cost	$0.12	$0.07	$0.06	$0.05
Total Annualized Cost	**$0.45**	**$0.38**	**$0.28**	**$0.25**

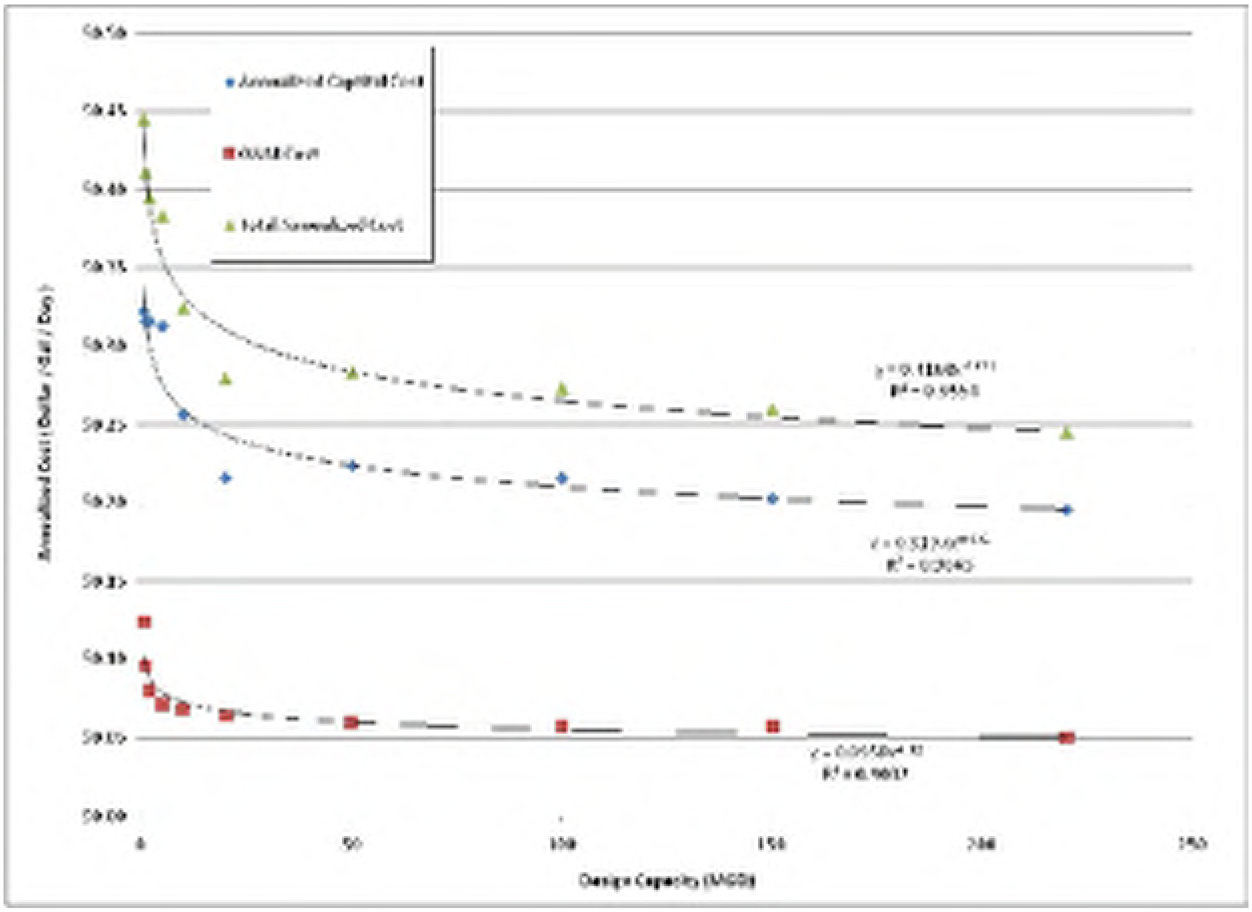


Figure 18-12. Annualized Capital and O&M Costs for Seasonal Reclaimed Water Upgrades for Membrane Plants

18.4.3 Extended Aeration Plants

Tables 18-36 through 18-39 show annualized capital and annual O&M cost estimates for upgrading both types of extended aeration plants (mechanical aeration and diffused aeration) to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-36.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (MECHANICAL AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$320,823	$1,674,036	$16,642,677
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$489,000	$3,477,834	$24,734,826
Total	**$809,823**	**$5,151,870**	**$41,377,503**
% Cost Increase for Reclaimed Water Upgrade	152%	208%	149%

TABLE 18-37.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (MECHANICAL AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$243,560	$433,659	$901,533
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$438,600	$1,640,849	$6,138,590
Total	**$682,160**	**$2,074,508**	**$7,040,123**
% Cost Increase for Reclaimed Water Upgrade	180%	378%	681%

TABLE 18-38.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (DIFFUSED AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$46,889	$579,949	$2,904,885
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$489,000	$3,477,834	$24,734,826
Total	**$535,889**	**$4,057,783**	**$27,639,711**
% Cost Increase for Reclaimed Water Upgrade	1043%	600%	851%

TABLE 18-39.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR EXTENDED AERATION PLANTS (DIFFUSED AERATION)

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$28,926	-$235,231	-$2,777,193
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$438,600	$1,640,849	$6,138,590
Total	**$467,526**	**$1,405,618**	**$3,361,397**
% Cost Increase for Reclaimed Water Upgrade	1516%	-698%	-221%

18.4.4 Conventional Activated Sludge Plants

Tables 18-40 and 18-41 show annualized capital and annual O&M cost estimates for upgrading conventional activated sludge plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-40.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR CONVENTIONAL ACTIVATED SLUDGE PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$172,242	$864,178	$15,467,709
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$319,700	$2,592,643	$30,395,521
Total	**$491,942**	**$3,456,821**	**$45,863,230**
% Cost Increase for Reclaimed Water Upgrade	186%	300%	197%

TABLE 18-41.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR CONVENTIONAL ACTIVATED SLUDGE PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$177,887	$486,220	$3,598,252
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$95,800	$726,717	$7,876,365
Total	**$273,687**	**$1,212,937**	**$11,474,617**
% Cost Increase for Reclaimed Water Upgrade	54%	149%	219%

18.4.5 Sequencing Batch Reactors

Tables 18-42 and 18-43 show annualized capital and annual O&M cost estimates for upgrading sequencing batch reactor plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-42.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR SEQUENCING BATCH REACTOR PLANTS

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$0	$0	$0
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$270,914	$882,646	$3,477,834
Total	**$270,914**	**$882,646**	**$3,481,773**
% Cost Increase for Reclaimed Water Upgrade	undefined	undefined	undefined

TABLE 18-43.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR SEQUENCING BATCH REACTOR PLANTS

	0.5-mgd Plant	2-mgd Plant	10-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$1,576	($563)	$3,939
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$294,835	$652,467	$1,640,849
Total	**$296,411**	**$651,904**	**$1,644,788**
% Cost Increase for Reclaimed Water Upgrade	18708%	-115891%	41656%

18.4.6 Trickling Filter, Trickling Filter/Solids Contact and Rotating Biological Contactor Plants

Tables 18-44 through 18-49 show annualized capital and annual O&M cost estimates for upgrading trickling filter, trickling filter/solids contact and rotating biological contactor plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-44.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$344,062	$2,059,887	$24,020,776
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$319,700	$2,592,643	$30,395,521
Total	**$663,762**	**$4,652,530**	**$54,416,297**
% Cost Increase for Reclaimed Water Upgrade	93%	126%	127%

TABLE 18-45.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$243,841	$707,439	$3,538,037
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$95,800	$726,717	$7,876,365
Total	**$339,641**	**$1,434,156**	**$11,414,402**
% Cost Increase for Reclaimed Water Upgrade	39%	103%	223%

TABLE 18-46.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR ROTATING BIOLOGICAL CONTACTOR PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$345,625	$2,077,327	$24,474,041
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$319,700	$2,592,643	$30,395,521
Total	**$665,325**	**$4,669,970**	**$54,869,562**
% Cost Increase for Reclaimed Water Upgrade	92%	125%	124%

TABLE 18-47.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR ROTATING BIOLOGICAL CONTACTOR PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$304,861	$858,819	$4,545,367
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$95,800	$726,717	$7,876,365
Total	**$400,661**	**$1,585,536**	**$12,421,732**
% Cost Increase for Reclaimed Water Upgrade	31%	85%	173%

TABLE 18-48.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER/SOLIDS CONTACT PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$216,251	$1,552,823	$19,453,578
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$319,700	$2,592,643	$30,395,521
Total	**$535,951**	**$4,145,466**	**$49,849,099**
% Cost Increase for Reclaimed Water Upgrade	148%	167%	156%

TABLE 18-49.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR TRICKLING FILTER/SOLIDS CONTACT PLANTS

	1-mgd Plant	10-mgd Plant	150-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$118,966	$443,788	$1,875,660
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$95,800	$726,717	$7,876,365
Total	**$214,766**	**$1,170,505**	**$9,752,025**
% Cost Increase for Reclaimed Water Upgrade	81%	164%	420%

18.4.7 Membrane Biological Reactor Plants

Tables 18-50 and 18-51 show annualized capital and annual O&M cost estimates for upgrading MBR plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-50.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR MEMBRANE BIOREACTOR PLANTS

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$0	$0	$0
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$319,700	$2,592,643	$21,025,321
Total	**$319,700**	**$2,592,643**	**$21,025,321**
% Cost Increase for Reclaimed Water Upgrade	undefined	undefined	undefined

TABLE 18-51.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR MEMBRANE BIOREACTOR PLANTS

	1-mgd Plant	10-mgd Plant	100-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$0	$0	$0
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$95,800	$726,717	$5,512,715
Total	**$95,800**	**$726,717**	**$5,512,715**
% Cost Increase for Reclaimed Water Upgrade	undefined	undefined	undefined

18.4.8 High-Purity Oxygen Activated Sludge Plants

Tables 18-52 and 18-53 show annualized capital and annual O&M cost estimates for upgrading high-purity oxygen activated sludge plants to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-52.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE PLANTS

	20-mgd Plant	220-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$1,646,890	$13,568,126
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$4,868,318	$43,053,142
Total	**$6,515,208**	**$56,621,268**
% Cost Increase for Reclaimed Water Upgrade	296%	317%

TABLE 18-53.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR HIGH-PURITY OXYGEN ACTIVATED SLUDGE PLANTS

	20-mgd Plant	220-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$948,084	$6,905,503
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$1,337,433	$11,033,098
Total	**$2,285,517**	**$17,938,601**
% Cost Increase for Reclaimed Water Upgrade	141%	160%

18.4.9 Lagoon Plants

Tables 18-54 through 18-57 show annualized capital and annual O&M cost estimates for upgrading both types of lagoon plants (aerated and facultative) to achieve Objective A nutrient removal and to provide Class A reclaimed water. The cost of the reclaimed water upgrade is also shown as a percent of the nitrogen removal upgrade cost.

TABLE 18-54.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR FACULTATIVE LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$783,969	$3,837,246	$24,741,394
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$270,914	$1,926,776	$13,703,494
Total	**$1,054,883**	**$5,764,022**	**$38,444,888**
% Cost Increase for Reclaimed Water Upgrade	35%	50%	55%

TABLE 18-55.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR FACULTATIVE LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$644,111	$2,119,896	$6,436,745
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$294,835	$1,103,007	$4,126,468
Total	**$938,946**	**$3,222,903**	**$10,563,213**
% Cost Increase for Reclaimed Water Upgrade	46%	52%	64%

TABLE 18-56.
ANNUALIZED CAPITAL COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR AERATED LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annualized Capital Costs for Nitrogen Removal Upgrade	$789,070	$3,870,397	$24,915,789
Estimated Annualized Capital Costs for Reclaimed Water Upgrade	$270,914	$1,926,776	$13,703,494
Total	**$1,059,984**	**$5,797,173**	**$38,619,283**
% Cost Increase for Reclaimed Water Upgrade	34%	50%	55%

TABLE 18-57.
ANNUAL O&M COSTS FOR SEASONAL NITROGEN REMOVAL AND RECLAIMED WATER UPGRADES FOR AERATED LAGOON PLANTS

	0.5-mgd Plant	5-mgd Plant	50-mgd Plant
Estimated Annual O&M Costs for Nitrogen Removal Upgrade	$490,941	$1,212,069	$4,519,475
Estimated Annual O&M Costs for Reclaimed Water Upgrade	$294,835	$1,103,007	$4,126,468
Total	**$785,776**	**$2,315,076**	**$8,645,943**
% Cost Increase for Reclaimed Water Upgrade	60%	91%	91%

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United States Environmental Protection Agency

Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants

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EXECUTIVE SUMMARY

Human-caused nutrient enrichment of waterbodies from excessive nitrogen (N) and phosphorus (P) is one of the most pervasive environmental issues facing the United States (U.S. EPA, 2015a). In many watersheds, municipal and industrial wastewater treatment plants (WWTPs) can be major point sources of nutrients. Recent efforts to derive numeric nutrient criteria to protect the designated uses of waterbodies have resulted in limits that may be challenging to meet for most WWTPs in the United States with the treatment configurations currently in place. However, many stakeholders have expressed concern that there may be significant undesirable environmental and economic impacts associated with upgrading treatment configurations, as these configurations may require greater use of chemicals and energy, release more greenhouse gases, and generate greater volumes of treatment residuals for disposal.

The impacts can be assessed using holistic, systematic approaches using life cycle impact assessment (LCIA) and life cycle cost analysis (LCCA). These approaches provide a "cradle-to-grave" analysis of the environmental impacts and benefits as well as the economic costs and benefits associated with individual products, processes, or services throughout their life cycle. This study used LCIA and LCCA approaches to assess cost, human health, and ecosystem metrics associated with nine distinct wastewater treatment configurations designed to reduce the nutrient content of effluent from municipal WWTPs.

Table ES-1 depicts the five different total nitrogen and phosphorus treatment levels used to configure nine different wastewater treatment systems commonly used in the U.S. to achieve the specified nutrient concentrations. Level 1 represents a standard secondary treatment configuration with no additional processes for nutrient removal. For Levels 2-5, two configurations that could meet the performance target were selected per level, representing contrasts in factors such as biological processes, costs, and energy requirements. Each configuration was modeled with an average flow rate of 10 million gallons per day (MGD) and a maximum flow rate of 20 MGD.

Table ES-1. Target Effluent Nutrient Concentrations by Level

Level	Total Nitrogen, mg/L	Total Phosphorus, mg/L
1	no target specified	no target specified
2	8	1
3	4-8	0.1-0.3
4	3	0.1
5	<2	<0.02

For the life cycle impact assessment, this study considered 12 impact categories: eutrophication potential, cumulative energy demand, global warming potential, acidification potential, fossil depletion, smog formation potential, human health-particulate matter formation potential, ozone depletion potential, water depletion, human health-cancer potential, human health-noncancer potential, and ecotoxicity potential. The majority of impact categories address air and water environmental impacts, while three categories are human health impact indicators.

Eutrophication potential (i.e., potential for enrichment of waterbodies with nutrients) is the combined effect of direct nutrient discharges in the effluent, landfilled sludge leachate, and the water discharges and air emissions from upstream inputs such as electricity and chemical production. Eutrophication potential decreased dramatically between Level 1 and Level 2 and to a smaller degree between Level 2 to Levels 3 and 4, which were similar to each other. Level 5 had higher eutrophication potential than Level 4 due to the energy requirement of reverse osmosis and brine injection, which off-set the impact reduction associated with the lower effluent nutrient concentration. However, based on the uncertainty thresholds for impact results, the difference between Level 3, Level 4 and Level 5 is not considered significant.

Cumulative energy demand, acidification potential, fossil depletion, smog formation potential, particulate matter formation, and global warming potential all showed a roughly similar trend. The values for these categories all increased from Level 1 to Level 5 due to increasing electricity use and natural gas heating consumption required to achieve the lower nutrient values for the treatment systems selected.

Water depletion results were dominated by the high-water use of Level 5 treatment configurations, approximately 100 times the other configurations, primarily for deepwell injection of brine. The potential for reuse of wastewater following Level 5 treatment was not considered in this study.

Although not specifically designed for it, the treatment configurations may also remove trace pollutants (metals, toxic organics, and disinfection by-products [DBPs]) from effluent, providing a toxicity reduction co-benefit. For configuration Levels 1-3, metals in liquid effluent dominated toxicity impacts, whereas for Level 5, contributions from material and energy inputs dominated, with Level 4 configurations having significant contributions from both sources. For human health-cancer potential, Levels 1, 3, and 4 had lower impacts than Levels 2 and 5, whereas for human health-noncancer potential, toxicity impacts decreased as treatment became more advanced For ecotoxicity, Levels 3, 4, and 5 had lower toxicity than Levels 1 and 2. Overall, one of the Level 4 configurations and, to a lesser degree, one of the Level 3 configurations stood out in most effectively balancing effluent toxicity reductions against the increase in materials and energy required. Uncertainty for the toxicity impact assessment was greater than for other impacts due to trace pollutant data limitations and to uncertainty inherent in the impact estimation method (USEtox™).

The life cycle cost analysis provided results for capital costs, annual operation and maintenance costs, and net present value, which combines the capital and operation and maintenance costs into a single cumulative value (all in 2014$). In general, the net present value increased with increasing nutrient control levels. The Level 2 configurations were an exception to the trend due to the high annual costs associated with the three separate biological units.

Sensitivity analyses considered different interest rates, electricity grid composition, improved energy capture at the facility, and a retrofit scenario instead of building a new facility. Since electricity was a primary driver for many of the impact categories assessed, many of the trade-offs associated with greater nutrient reductions could be significantly reduced if the WWTP were to use an electrical grid with r with lower emissions and/or to use recovered resources (e.g., biogas) to generate on-site energy, reducing the need for purchased electricity.

Overall, two key findings emerged from this analysis. First, clear trade-offs in cost and potential environmental impact were demonstrated between treatment level configurations. This suggests that careful consideration should be given to the benefits from lower nutrient levels compared to the potential environmental and economic costs associated with treatment processes used to achieve those levels. Combining outcomes into metrics such as nutrients removed per dollar or per unit energy may help to identify configurations that strike an efficient balance between these objectives. For example, this analysis found that electricity per unit of total N and P equivalents removed remained consistent from Level 2 through Level 4 but was 2-3 times higher for Level 5 configurations. Second, this analysis demonstrated the value of a life cycle approach to assessing costs and benefits. For example, considering trace pollutants from a life cycle perspective illuminated that the benefits of increased trace pollutant removal from effluent could be outweighed by trace pollutant emissions from materials and energy usage for the Level 5 configuration, an insight that would not have been gained by analyzing on-site WWTP processes alone. In summary, considering multiple economic, social, and environmental costs and benefits from a life cycle perspective can provide critical insights for informed decision-making about wastewater treatment technologies.

Foreword

The objective of this study is to assess a series of wastewater treatment system configurations designed to reduce the nutrient content of effluent from municipal wastewater treatment facilities. The combination of life cycle assessment (LCA) and life cycle cost analyses (LCCA) provides a full picture of costs, both quantitative and qualitative, for the various wastewater treatment configurations evaluated. This technical report presents the results of the study. It does not discuss the policy implications of the analysis, nor does it discuss the EPA's policy on nutrient pollution, the development of nutrient criteria, approaches for addressing the problem, nor the full suite of benefits from the different treatment configurations that can be realized.

This report complements and supplements the EPA's May 2015 publication, *A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution* (https://www.epa.gov/nutrient-policy-data/compilation-cost-data-associated-impacts-and-control-nutrient-pollution), which provides the public with information to assist stakeholders and decision-makers in addressing cultural eutrophication.

ACRONYMS AND ABBREVIATIONS

A2O	Anaerobic/Anoxic/Oxic
AS	Activated sludge
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
CAPDETWorks™	Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems
CBOD	Carbonaceous biochemical oxygen demand
CEC	Contaminants of emerging concern
CED	Cumulative Energy Demand
CHP	Combined heat and power
COD	Chemical oxygen demand
DBP	Disinfection byproduct
DBPFP	Disinfection byproduct formation potential
DQI	Data quality indicator
EDC	Endocrine disrupting chemicals
EF	Emission factor
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency (U.S.)
ERG	Eastern Research Group, Inc.
FP	Formation potential
GHG	Greenhouse gas
GT	Gravity thickener
GWP	Global warming potential
HAA	Haloacetic acid
HAB	Harmful algal blooms
HAN	Haloacetonitrile
HHV	High heating value
ICE	Internal combustion engine
ISO	International Standardization Organization
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MBR	Membrane bioreactor
MCF	Methane conversion factor
N	Nitrogen
NNC	Numeric nutrient criteria
NOM	Natural organic matter
NPCC	NorthEast Power Coordinating Council
ORD	Office of Research and Development (U.S. EPA)
P	Phosphorus
PM	Particulate matter
PPCP	Pharmaceuticals and personal care products
PPI	Producer's price indices
RO	Reverse osmosis
THM	Trihalomethanes
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen

TP	Total phosphorus
TRACI	Tool for the Reduction and Assessment of Chemical and Environmental Impacts
UF	Ultrafiltration
UIC	Underground injection control
UNFCCC	United Nations Framework Convention on Climate Change
US LCI	United States Life Cycle Inventory Database
VFA	Volatile fatty acids
WWT	Wastewater treatment

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1. GOAL AND SCOPE DEFINITION

1.1 Introduction and Objective

Cultural eutrophication of waterbodies across the United States is one of the most pervasive environmental issues facing the country today. Whether in lakes or reservoirs, rivers or streams, estuaries or marine coastal waters, the human health, environmental, and economic impacts from excessive amounts of nitrogen (N) and phosphorus (P) continue to rise year after year. Communities struggle with harmful algal blooms (HABs) that produce toxins which can sicken people and pets, contaminate food and drinking water sources, destroy aquatic life, and disrupt the balance of natural ecosystems. HABs can raise the cost of drinking water treatment, depress property values, close beaches and fishing areas, and negatively affect the health and livelihood of many Americans (U.S. EPA, 2015a). Global climate change is only expected to exacerbate eutrophication even as Federal, state, and local governments struggle to address the sources of nutrient pollution (USGCRP, 2015).

In partnership with states, tribes, and other Federal agencies, the U.S. Environmental Protection Agency (EPA) has led the effort to address nutrient pollution by assisting states in prioritizing waters, providing scientific and technical assistance in the development of water quality standards for total nitrogen (TN) and total phosphorus (TP), and helping to guide implementation of nutrient criteria in waterbody assessments, including the development of total maximum daily loads for impaired waters and the inclusion of water-quality based effluent limits for point source dischargers.

In many watersheds, municipal and industrial wastewater treatment plants (WWTPs) can be major point sources of nutrients. Removal of TN and TP can vary significantly depending on the raw wastewater characteristics and the treatment technologies used at each WWTP. Recent efforts by states and the EPA to derive numeric nutrient criteria (NNC) that will protect the designated uses under the Clean Water Act reveal limits that clearly push the boundaries of treatment technologies currently in place for most facilities in the United States. Operators and other stakeholders have expressed concern that there may be potentially significant environmental and health implications and economic impacts associated with pushing those boundaries, given it can lead to greater use of chemicals, treatment residuals disposal, increased energy demands, and greater release of greenhouse gases. Studies in other countries also suggest a point of diminishing returns where the economic and environmental consequences may begin to outweigh the benefits of certain advanced treatment technologies (e.g., Foley et al., 2010). Such issues, which encompass economic, environmental, and social costs, are at the center of sustainability evaluations, and can be assessed using holistic, systematic approaches such as life cycle assessment (LCA) and life cycle cost analysis (LCCA).

LCA is a widely accepted technique to assess the environmental aspects and potential impacts associated with individual products, processes, or services. It provides a "cradle-to-grave" analysis of environmental impacts and benefits that can better assist in selecting the most environmentally preferable choice among the various options. The steps for conducting an LCA include (1) identifying goal and scope, (2) compiling a life cycle inventory (LCI) of relevant energy and material inputs and environmental releases, (3) evaluating the potential environmental impacts associated with identified inputs and releases, and (4) interpreting the results to help individuals make a more informed decision.

LCCA is a complementary process to LCA for evaluating the total economic costs of an asset by analyzing initial costs and discounted future expenditures over the life cycle of an asset (Varnier, 2004). It is used to evaluate differences in cost and timing of those costs between alternative projects. The LCCA conducted in this study is not "cradle-to-grave", but rather considers only costs incurred by the facility for establishing a new WWTP (i.e., greenfield project[1]). A retrofit case study was performed and described later in this report.

The objective of this study is to assess a series of wastewater treatment system configurations (hereafter referred to as "wastewater treatment configurations") designed to reduce the nutrient content of effluent from municipal WWTPs. The assessment considers treatment costs as well as human health and ecosystem impacts from a life cycle perspective. The combination of LCA and LCCA provides a full picture of costs, both quantitative and qualitative, for the various wastewater treatment configurations evaluated. This report uses the term wastewater treatment plant, or WWTP, while recognizing that an effort is underway to transition to a new term: "water resource recovery facility". The use of WWTP was selected only as a reflection of historical usage and is not intended to convey preference.

This study compares cost, human health, and ecosystem metrics associated with nine distinct wastewater treatment configurations to provide context for understanding the outcomes from an environmental, economic, and social/societal perspective. The nine wastewater treatment configurations fall into one of five different levels of nutrient reductions, as defined in Table 1-1. Level 1 is a baseline system consisting of a standard secondary treatment configuration with no specific nutrient removal target. The other four levels considered here specify nutrient removal targets with increasing stringency. The wastewater treatment configurations selected for assessment include two alternative configurations for each of the nutrient reduction levels 2 through 5. These configurations were selected because they generally represent configurations commonly used to achieve the specified nutrient performance levels. These configurations were also selected to provide contrast in factors such as the biological processes used, capital costs, operating costs, energy requirements, and sludge generation.

While effluent nutrient concentrations are the main driver of the treatment configuration upgrades analyzed by this study, there is also growing concern over the impacts associated with trace pollutants (Choubert et al., 2011a; Martin Ruel et al., 2012; Montes-Grajales et al., 2017). Trace pollutants are a broad class of compounds that are generally toxic to humans or the aquatic environment even at very low concentrations (U.S. EPA, 2015). Although the list of individual

[1] Greenfield areas are normally undeveloped areas highly recommended for new construction. The benefits of greenfield construction relate to pristine pieces of land with little to no contamination that contain no structures in the premises. The most beneficial advantage is that there is no cost related to environmental remediation and is ready to start building right away. The most important drawback is that greenfield are usually located outside city centers that might require additional infrastructure upgrades but those are offset by more accessible land costs. Another advantage is that they offer larger pieces of real estate ideally for future expansion and their zoning classification is easier to be changed or adjusted as required. Keep in mind that greenfield usually require deforestation and could affect environmental sensitive areas including the habitat of endangered species.

compounds is continually evolving, the class generally includes pharmaceuticals and personal care products (PPCPs), toxic organics, disinfection byproducts (DBPs) and heavy metals. Importantly, as the prevalence of trace pollutants in modern waste streams is increasing (Ellis, 2008; U.S. EPA, 2015; Ebele et al., 2017), with varying levels of persistence in the environment, they are becoming an important component of modern waste stream management. Many of these pollutants already factor into standard LCA inventories, where emissions of upstream processes are accounted for and contribute to human and environmental health impact categories. However, very little work has been done to incorporate the effects of their direct management at WWTPs, especially in the context of LCA. Such an assessment would provide valuable information as to the full benefits afforded by advanced treatment technologies, as many of the same processes that are effective for nutrient removal are also effective at trace pollutant removal. Preliminary studies have been conducted on certain pollutant groups such as PPCPs and other toxic organics (Montes-Grajales et al., 2017; Rahman et al., 2018) though they have omitted important pollutant groups such as heavy metals and DBPs. This study, therefore, looked in greater detail at a more encompassing list of trace pollutants, including heavy metals, toxic organics and DBPs, to provide a more comprehensive description of the full costs and benefits afforded by advanced nutrient removal technologies.

The metrics used in this assessment are cost and a suite of LCA-related impacts. The LCA-related impacts include eutrophication, global warming, particulate matter formation, smog formation, acidification, and ozone depletion based on the Tool for Reduction and Assessment of Chemicals and other Environmental Impacts (TRACI) 2.1 life cycle impact assessment (LCIA) method; water use and fossil energy use based on the ReCiPe[2] method; human and ecosystem toxicity impacts based on the USEtox™ methodology version 2.02; and cumulative energy demand (Bare, 2012; Goedkoop et al., 2009; Huijbregts et al., 2010). These metrics are discussed in detail in Section 1.2.5 and Section 4.6. The trace pollutant removal analysis is integrated with the toxicity impact category results.

1.2 Scope

This study design follows the guidelines for LCA provided by ISO 14040/14044 (ISO, 2006a, b). The following subsections describe the scope of the study based on the wastewater treatment configurations selected and the functional unit used for comparison, as well as the system boundaries, LCIA methods, and datasets used in this study.

1.2.1 Wastewater Treatment Configurations

This study compares nine alternative wastewater treatment configurations that achieve varying levels of nutrient removal, including a baseline wastewater treatment configuration that is not specifically designed to remove nutrients and eight wastewater treatment configurations that are designed to achieve varying advanced levels of nitrogen and phosphorus removal. The target effluent concentrations for TN and TP for each of the performance levels are presented in Table 1-1, and are based on performance levels analyzed in a study by Falk and colleagues (2011). The wastewater treatment configurations selected for this study are presented in Table

[2] The name of this method "ReCiPe" is derived from two factors. First, the method provides a recipe to calculate life cycle impact categories. Second, the acronym represents the initials of institutes that were the main contributors: RIVM and Radboud University, CML, and PRè (Goedkoop et al., 2008).

1-2 and described further in Section 1.2.4 and Appendix A. Table 1-2 also lists the abbreviated name used for each wastewater treatment configuration throughout this study. Selected configurations generally represent those most commonly used to achieve the desired performance levels for nutrient requirements and provide contrast in biological processes, capital and/or annual costs, or other factors such as energy requirements and sludge generation. The most common reasons wastewater treatment configurations were not selected include: 1) they are unique retrofits and otherwise not commonly used, 2) they are very similar to another selected technology, or 3) they exhibit a wide range of performance, which raises uncertainty as to the reliability with which the process can achieve a specific performance level. Ultimately, two wastewater treatment configurations were selected for each of Levels 2 through 5 to illustrate the range of costs and environmental impacts associated with varying levels of treatment performance. More detail on the system configuration selection process is included in Appendix A.

Table 1-1. Target Effluent Nutrient Concentrations by Level

Level	Total Nitrogen, mg/L	Total Phosphorus, mg/L
1	[a]	[a]
2	8	1
3	4-8	0.1-0.3
4	3	0.1
5	<2	<0.02

a – No target effluent concentration specified.

Table 1-2. Wastewater Treatment Configurations Selected for this Study

Full Name [a]	Performance Level	Abbreviated Name	Phosphorus Precipitation	Fermenter	Sand Filter	Denitrification Filter	Ultra-filtration	Reverse Osmosis
Conventional Plug Flow Activated Sludge	1	Level 1, AS						
Anaerobic/ Anoxic/Oxic	2	Level 2-1, A2O						
Activated Sludge, 3-Sludge System	2	Level 2-2, AS3	✓					
5-Stage Bardenpho	3	Level 3-1, B5	✓	✓	✓			
Modified University of Cape Town Process	3	Level 3-2, MUCT	✓	✓	✓			
5-Stage Bardenpho with Denitrification Filter	4	Level 4-1, B5/Denit	✓	✓	✓	✓		
4-Stage Bardenpho Membrane Bioreactor	4	Level 4-2, MBR	✓					
5-Stage Bardenpho with Sidestream Reverse Osmosis	5	Level 5-1, B5/RO	✓	✓	✓	10% [b]	90% [b]	90% [b]
5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis	5	Level 5-2, MBR/RO	✓	✓				85% [b]

✓ Indicates technology is used in wastewater treatment configuration.

a – Refer to Section 1.2.4 for the system descriptions.

b – Percentages describe the relative flow of wastewater entering these processes at the WWTP.

1.2.2 Functional Unit

A functional unit provides the basis for comparing results in an LCA. The key consideration in selecting a functional unit is to ensure the wastewater treatment configurations are compared on the basis of equivalent performance. In other words, an appropriate functional unit allows for an apples-to-apples comparison. The functional unit for this study is the treatment of a cubic meter of municipal wastewater with the composition described in Table 1-3. The pH of the reference wastewater is 7.6 and the temperature averages are 23°C summer and 10°C winter.

The study evaluated theoretical wastewater treatment configurations with an average flow rate of 10 million gallons per day (MGD) and a maximum flow rate of 20 MGD[3]. The study results do not represent a specific, existing WWTP. As discussed in Section 3 the operational calculations are based on a year of treatment and standardized to a cubic meter basis using the total volume of water treated in the year. Infrastructure requirements are amortized over individual lifetimes associated with the equipment or buildings. Section 3 provides the lifetimes modeled for all infrastructure components captured in the study. While the WWTP infrastructure requirements are modeled, plant decommissioning is outside of the scope of the study.

It is important to note that the composition of effluent resulting from the wastewater treatment configurations is not part of the definition of the functional unit. Rather the level of treatment performance is a key differentiator of the configurations. Differences in effluent composition are captured in the estimation of impacts associated with the effluent discharges for each system. Effluent quality values for standard water quality parameters for the nine wastewater treatment configurations are depicted in Table 1-4. The effluent quality in Table 1-4 is based on the CAPDETWorks™ output and may vary from actual WWTP effluent for the same wastewater treatment configuration. However, these wastewater treatment configurations were chosen based on actual effluent nutrient concentrations from literature as discussed in Appendix A. Effluent quality values for trace pollutants, which include toxic organics, DBPs and heavy metals, are discussed in further detail in Section 2.

Table 1-3. Composition of Influent Wastewater Considered in this Study

Characteristic	Value	Unit	Reference(s)
Suspended Solids	220	mg/L	1, 2, 3, 4
Volatile Solids	75	%	1, 2, 3, 4
Biological Oxygen Demand (BOD)	220	mg/L	1, 2, 3, 4
Soluble BOD	80	mg/L	2, 3, 4
Chemical Oxygen Demand (COD)	500	mg/L	1, 2, 3, 4
Soluble COD	300	mg/L	2, 3, 4
Total Nitrogen (TN) [a]	40	mg/L N	calculated

[3] ERG used a 2.0 peaking factor for the study, assuming the WWTP served approximately 100,000 people (Health Research, Inc., 2014).

Table 1-3. Composition of Influent Wastewater Considered in this Study

Characteristic	Value	Unit	Reference(s)
Total Kjeldahl Nitrogen (TKN) [b]	40	mg/L N	1, 2, 3, 4
Soluble TKN	25	mg/L N	2, 3
Ammonia	22	mg/L N	1, 4
Nitrate	0	mg/L N	1, 2, 3, 4
Nitrite	0	mg/L N	1, 2, 3, 4
Total Phosphorus (TP)	5	mg/L P	2, 3
Cations	160	mg/L	3, 4
Anions	160	mg/L	3, 4
Settleable Solids	10	mg/L	1, 3, 4
Oil and Grease	100	mg/L	1, 3, 4
Nondegradable Fraction of Volatile Suspended Solids (VSS)	40	%	3, 4

[1] Tchobanoglous and Burton, 1991; [2] U.S. EPA OWM, 2008b; [3] ERG, 2009; [4] Hydromantis, 2014

a – TN is the sum of TKN, nitrate, and nitrite.

b – TKN is the sum of ammonia, organic nitrogen, and reduced nitrogen.

Table 1-4. Effluent Composition for the Nine Wastewater Treatment Configurations (mg/L)

Constituent	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Suspended Solids	20	20	20	8.0	8.0	8.0	9.0	1.3	1.9
BOD	7.7	4.7	3.1	2.3	2.3	7.0	3.1	1.2	0.62
Soluble BOD	3.9	2.3	1.5	2.3	2.3	7.0	2.1	1.2	0.45
COD	28	25	8.9	3.5	3.5	11	13	1.8	2.6
Soluble COD	5.8	3.5	2.3	3.5	3.5	11	3.21	1.8	0.70
Total Phosphorus	4.9	0.28	1.0	0.20	0.20	0.10	0.10	0.02	0.02
Total Nitrogen	30	8.0	7.8	6.0	6.0	3.0	3.0	0.73	2.0
TKN	30	1.9	2.1	0.52	0.52	0.52	1.0	0.15	0.20
Soluble TKN	29	0.52	1.6	0.52	0.52	0.52	0.42	0.09	0.08
Ammonia	15	0.52	0	0.52	0.52	0.52	0.42	0.09	0.08
Nitrate	0	6.1	5.7	5.5	5.5	2.4	2.0	0.63	1.8
Organic Nitrogen	15	1.4	2.1	0	0	0	0.58	0.06	0.12

1.2.3 System Definition and Boundaries

This section describes general aspects of each wastewater treatment configuration that are included in the LCA system boundary. The boundary for processes included in the assessment of each of the wastewater treatment configurations selected for evaluation includes all onsite wastewater and sludge treatment processes from the municipal WWTP headworks through final discharge of the treated effluent and disposal of sludge and other wastes. Off-site costs and environmental impacts associated with release of the effluent to the receiving stream, sludge transport and disposal, and for facilities with reverse osmosis (RO) units, brine disposal into onsite underground injection control (UIC) wells are also considered. The system boundary includes all relevant details of the wastewater treatment processes, environmental releases from each process, and the supply chains associated with the inputs to each process. Chemicals associated with periodic cleaning of equipment (e.g., membranes) are within the system boundary. Production of concrete, excavation activities, building materials, and a limited quantity of steel are included as infrastructure materials in the LCA. Pumps, in-unit mechanical systems, and electronics are excluded from the LCA study boundary due to lack of detailed information, although these types of equipment are included in the LCCA. The LCCA also includes costs for engineering and professional services that are not part of the LCA. A simplified system diagram is presented in Figure 1-1, which depicts the main materials and emission sources included in the model.

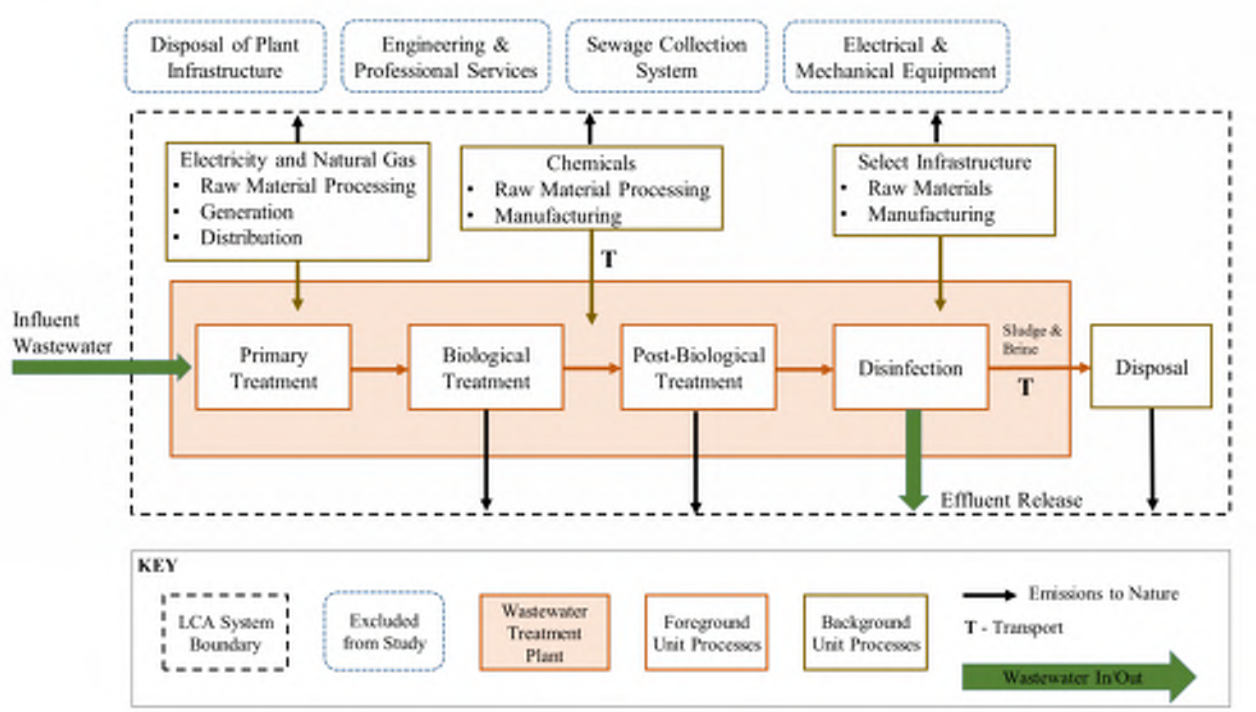

Figure 1-1. Generalized Study System Boundary

The four orange boxes in Figure 1-1 comprise the foreground unit processes that make up the wastewater treatment configuration at each WWTP. Electricity generation, chemical production, material extraction and manufacturing, and disposal processes are considered background unit processes. Disposal processes include landfilling of treated sludge and underground injection of brine solution. Background processes are still within the system boundary and are quantified within the analysis, although they exist beyond the physical boundaries of the wastewater treatment plant. The exterior dotted line in Figure 1-1 represents the system boundary considered in this LCA. The emissions to various compartments within nature (soil, air, water) are used in the estimation of environmental impacts. Details related to the calculation procedure and the environmental impacts included in this study are discussed in Section 4.

Excluded from the system boundaries are production of the components that make up the wastewater (e.g., drinking water treatment, residential organic waste, industrial wastewater pretreatment) and the collection system, including any raw sewage pump stations. It is assumed that these elements would be equivalent for all examined wastewater treatment configurations, and, therefore can be excluded from the scope of the analysis.

It is important to note that some potential benefits that may be realized from level 4 and level 5 wastewater treatment configuration are not captured in the system boundaries of this study. For instance, it may be possible to recycle the effluent from wastewater treatment for non-potable uses like toilet flushing or irrigation as the effluent quality may achieve non-potable requirements. Utilization of this recycled water would avoid production of potable water elsewhere. In an expanded system boundary, avoided production of potable water would result in an overall credit for these higher nutrient removal wastewater treatment configurations that is not included in this LCA study. Another potential benefit not included is the pathogen or other microbial contaminant removal.

1.2.4 System Descriptions of Wastewater Treatment Configurations

Flow diagrams of each wastewater treatment configuration are provided in Figure 1-2 through Figure 1-10. Each of these figures provides a visual representation of the detailed unit processes included in the relevant wastewater treatment configuration. The figures also show the source of process greenhouse gas (GHG) emissions and the type of chemical inputs.

In each wastewater treatment configuration, wastewater is first treated by screening, grit removal, and primary clarification. Screening removes large debris from the wastewater flow and grit removal extracts stone, grit, and other separable debris. Debris from this stage is transported to a landfill. In the next stage, primary clarification, solids are allowed to settle from the wastewater and grease to float to the top. Solids are pumped out from the bottom of the tank and scum and grease are skimmed off the top. These materials are either sent directly to a gravity thickener (configuration levels 1, 2-1, 2-2, 4-2) or first sent to a fermenter and then to the gravity thickener (configuration levels 3-1, 3-2, 4-1, 5-1, and 5-2) then to anaerobic digestion, and ultimately hauled away by truck for disposal in a landfill. The assumed distance from the wastewater treatment plant to the landfill is 25 miles one-way. In all cases, it is assumed the biogas from anaerobic digestion is flared. A detailed emission inventory associated with biogas flaring process is included in Appendix F. The sludge is assumed to be disposed in an average

U.S. municipal solid waste landfill in which methane is recovered for energy. The same biogas flaring and sludge landfilling assumptions were made for all wastewater treatment configurations as the study focuses on differentiating factors for nutrient removal technologies rather than options for sludge handling. Alternative treatment options for biogas is addressed later in the sensitivity analysis later in this report (Section 9.5).

After pretreatment and primary treatment, the processes involved in each wastewater treatment configuration varies. A description of each wastewater treatment configuration is provided in the subsequent sections, while a summary of their relevant attributes is given in Table 1-5.

1.2.4.1 Level 1: Conventional Plug Flow Activated Sludge (Level 1, AS)

The Level 1 configuration represents typical secondary treatment used by municipal WWTPs in the United States. This system focuses on reducing BOD and TSS concentrations to 30 mg/L and has no specific nutrient removal targets. In the conventional plug flow activated sludge wastewater treatment configuration, following pretreatment and primary treatment, wastewater is sent to a plug flow activated sludge reactor for carbonaceous biochemical oxygen demand (CBOD) removal. After plug flow activated sludge treatment, wastewater is sent to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is disinfected using chlorine gas[4] followed by dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Secondary clarifier sludge is pumped out from the bottom of the clarifier. Of this sludge, a portion is sent back to the plug flow activated sludge treatment process (return activated sludge) and the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.2 Level 2-1: Anaerobic/Anoxic/Oxic (Level 2-1, A2O)

In the Level 2-1 anaerobic/anoxic/oxic (A2O) wastewater treatment configuration, following pretreatment and primary treatment, wastewater is sent to the A2O process, which consists of an anaerobic zone, an anoxic zone, and an oxic zone for biological phosphorus removal, CBOD removal, nitrification (conversion of ammonia to nitrate), and denitrification (conversion of nitrate to nitrogen gas, which is released to the atmosphere). There is an internal recycle that returns nitrified mixed liquor from the oxic zone to the anoxic zone. A secondary clarifier follows the A2O process where solids are allowed to settle from the wastewater. Clarified effluent is disinfected using chlorine gas followed by dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Secondary clarifier sludge is pumped out from the bottom

[4] Chlorination using hypochlorite is more common than gaseous chlorine due to safety concerns and regulations on the handling and storage of pressurized liquid chlorine (Tchobanoglous et al., 2014). However, CAPDETWorks™ only includes disinfection using chlorine gas (Hydromantis, 2014). As a result, ERG used chlorine gas for this study.

of the tank with a portion returned to the influent of the A2O process (return activated sludge) and the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.3 Level 2-2: Activated Sludge, 3-Sludge System (Level 2-2, AS3)

In the Level 2-2 activated sludge, 3-sludge wastewater treatment configuration, wastewater undergoes pretreatment and primary treatment before entering a plug flow activated sludge reactor for CBOD removal. Wastewater is then sent to the secondary clarifier where solids are allowed to settle from the wastewater. Sludge is pumped out from the bottom of the clarifier. Of this sludge, a portion is sent back to the plug flow activated sludge treatment process (return activated sludge) and the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Wastewater from the secondary clarifier is sent to a suspended growth nitrification reactor to convert ammonia nitrogen to nitrate, followed by a tertiary clarifier where solids are allowed to settle from the wastewater. A portion of the tertiary clarifier sludge is sent back to the nitrification reactor (return activated sludge) and the remainder (waste activated sludge) is sent to gravity thickening. Wastewater from the tertiary clarifier is sent to a suspended growth denitrification reactor to convert nitrate to nitrogen gas. Methanol is added immediately preceding the denitrification reactor as a supplemental carbon source. Prior to a final clarification step, the wastewater undergoes chemical phosphorus precipitation using aluminum salts, where solids are allowed to settle from the wastewater. A portion of the final clarifier sludge is sent back to the denitrification reactor (return activated sludge) and the remainder (waste activated sludge) is sent to gravity thickening. Clarified effluent is disinfected using chlorine gas followed by dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.4 Level 3-1: 5-Stage Bardenpho (Level 3-1, B5)

In the Level 3-1 5-Stage Bardenpho wastewater treatment configuration, wastewater undergoes pretreatment and primary treatment. Sludge from the primary clarifier enters a fermentation vessel to convert complex proteins and carbohydrates to volatile fatty acids (VFAs) that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enter a 5-stage Bardenpho nutrient removal reactor wherein the wastewater enters an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive stages for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, part of the remaining phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is passed through a sand filter for tertiary solids removal prior to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Sludge is removed from the bottom of the secondary clarifier. Of this sludge, a portion is sent back to the influent of the Bardenpho reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.5 Level 3-2: Modified University of Cape Town Process (Level 3-2, MUCT)

In the Level 3-2 modified University of Cape Town process wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enter a 4-stage biological nutrient removal (BNR) reactor, referred to as the modified University of Cape Town process. Within the reactor, wastewater enters an anaerobic phase and passes through two successive anoxic stages before a final aerobic stage for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the end of the first anoxic stage to the head of the anaerobic stage, and an additional internal recycle that returns wastewater from the aerobic stage to the second anoxic stage. Following biological nutrient removal, phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is passed through a sand filter for tertiary solids removal prior to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Sludge is removed from the bottom of the secondary clarifier. Of this sludge, a portion is returned to the first anoxic stage in the BNR reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are also returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.6 Level 4-1: 5-Stage Bardenpho with Denitrification Filter (Level 4-1, B5/Denit)

In the Level 4-1 5-Stage Bardenpho with denitrification filter wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enter a 5-stage Bardenpho nutrient removal reactor wherein the wastewater enters an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive steps for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent then enters an upflow, attached growth denitrification filter for additional nitrogen removal. Methanol is added immediately preceding the denitrification filter as a supplemental carbon source. Wastewater is finally passed through a sand filter for tertiary solids removal prior to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. Sludge is removed from the bottom of the secondary clarifier. Of this sludge, a portion is returned to the influent of the Bardenpho reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.7 Level 4-2: 4-Stage Bardenpho Membrane Bioreactor (Level 4-2, MBR)

In the Level 4-2 4-Stage Bardenpho membrane bioreactor wastewater treatment configuration, wastewater undergoes primary treatment before entering a 4-stage Bardenpho nutrient removal reactor. Within the reactor wastewater alternates twice between anoxic and aerobic stages for CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Methanol is added as a supplemental carbon source in the Bardenpho reactor in the second anoxic zone. Following the Bardenpho reactor, phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves on for membrane filtration to remove solids from the wastewater, generating a permeate (effluent) and reject stream (sludge). Effluent is sent to disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge. Effluent from the wastewater treatment process is discharged to surface water. A portion of the sludge from the membrane filter is returned to the influent to the 4-stage Bardenpho (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.8 Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Treatment (Level 5-1, B5/RO)

In the Level 5-1 5-Stage Bardenpho with sidestream reverse osmosis (RO) wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enters a 5-stage Bardenpho nutrient removal reactor wherein the wastewater goes through an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive steps for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, additional phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to secondary clarification where solids are allowed to settle from the wastewater. Clarified effluent is split into two streams for further treatment. In order to meet the designed effluent quality, ten percent of the flow enters an upflow, attached growth denitrification filter for additional nitrogen removal, followed by a sand filter for tertiary solids removal. Methanol is added immediately preceding the denitrification reactor as a supplemental carbon source. The remaining 90 percent of the flow first undergoes a series of RO pre-treatment steps, including ultrafiltration for solids removal; chlorine gas addition for biofouling control (followed by dechlorination with sodium bisulfite due to low chlorine tolerance of the RO membranes); and antiscalant addition for scale control. Following pretreatment, the effluent underdoes RO treatment, generating a permeate (effluent) and reject stream (brine). Effluent from the 10 percent and 90 percent side stream steps are then recombined for final disinfection using chlorine gas and dechlorination using sodium bisulfite to remove residual chlorine prior to discharge to surface water. Brine from the RO unit is disposed of by injection into an onsite disposal well. A portion of the clarified sludge is returned to the influent of the Bardenpho reactor (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

1.2.4.9 Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis Treatment (Level 5-2, MBR/RO)

In the Level 5-2 5-Stage Bardenpho membrane bioreactor with sidestream RO wastewater treatment configuration, wastewater first undergoes pretreatment and primary treatment. Sludge from primary clarification enters a fermentation vessel to convert complex proteins and carbohydrates to VFAs that provide an internal carbon source for biological nutrient removal. Sludge from the fermenter is sent to gravity thickening. Primary clarifier effluent and fermenter supernatant enters a 5-stage Bardenpho nutrient removal reactor wherein the wastewater enters an anaerobic stage before alternating between anoxic and aerobic conditions in a total of five successive steps for biological phosphorus removal, CBOD removal, and enhanced nitrification and denitrification. There is an internal mixed liquor recycle that returns wastewater from the first aerobic zone to the first anoxic zone. Following the Bardenpho reactor, additional phosphorus in the wastewater is chemically precipitated, using aluminum salts, after which the effluent moves along to membrane filtration to remove solids from the wastewater, generating permeate (effluent) and a reject stream (sludge). In order to meet the designed effluent quality, effluent then splits into two streams with 15 percent of the flow receiving no sidestream treatment. The remaining 85 percent of flow undergoes a series of RO pre-treatment steps, including chlorine gas addition for biofouling control (followed by dechlorination with sodium bisulfite due to low chlorine tolerance of the RO membranes); and antiscalant addition for scale control. Following pretreatment, the effluent undergoes RO treatment, generating a permeate (effluent) and reject stream (brine). Effluent from the RO unit is recombined with the 15 percent stream for final disinfection using chlorine gas and dechlorinated using sodium bisulfite to remove residual chlorine prior to discharge to surface water. Brine from the RO unit is disposed of by injection into an onsite disposal well. A portion of sludge from the membrane filter is returned to the influent of the Bardenpho (return activated sludge) while the remainder (waste activated sludge) is combined with primary sludge before being sent to gravity thickening. Following the gravity thickener, the sludge is sent for anaerobic digestion followed by further dewatering by centrifuge. Filtrate from the gravity thickener, centrate from the centrifuge, and supernatant from the anaerobic digester are returned to the influent stream at the headworks to the wastewater treatment system. Dewatered sludge is transported to a landfill by truck.

Table 1-5. Study Treatment Configuration Characteristics

Treatment Level ID		**L1**	**L2-1**	**L2-2**	**L3-1**	**L3-2**	**L4-1**	**L4-2**	**L5-1**	**L5-2**
Characteristic	***Description***	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3[a]**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR[c]**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO[c]**
SRT (days)	Primary Biological Process	10	15	10	15	15	15	19	15	21
	Secondary Biological Process	-	-	50	-	-	attached[b]	-	attached[b]	-
	Tertiary Biological Process	-	-	10	-	-	-	-	-	-
Quantify nitrification	Primary Biological Process	Minimal	Partial	Minimal	High	High	High	High	High	High
	Secondary Biological Process	-	-	High	-	-	N/A	Minimal	N/A	Minimal
	Tertiary Biological Process	-	-	N/A	-	-	-	-	-	-
HRT (hours)[d]	Aerobic	5.7	8.8	6.0	10	10	10	5.3	10	6.2
	Anoxic	-	6.0	6.2	7.4	8.2	10	2.6	9.2	3.7
	Anaerobic	-	2.5	4.3	2.5	1.6	0.77	0.94	1.7	0.69
	Total	*5.7*	*17*	*16*	*20*	*20*	*21*	*8.8*	*21*	*11*
Redox condition summary[d]		Aero	An-Anox-Aero	Aero-Aero-An	An-Anox-Aero-Anox-Aero	An-Anox-Anox-Aero	An-Anox-Aero-Anox-Aero-Anox	Anox-Aero-Anox-Aero	An-Anox-Aero-Anox-Aero-Anox	An-Anox-Aero-Anox-Aero
MLSS Concentration (mg/L)	Primary Biological Process	2500	3000	2500	3000	3000	3000	9000	3000	9000
	Secondary Biological Process	-	-	2500	-	-	N/A	9000	N/A	9000
	Tertiary Biological Process	-	-	2500	-	-	-	-	-	-

a - Secondary biological process is a nitrification reactor. Tertiary biological process is denitrification reactor.

b - Secondary biological process is an attached growth denitrification reactor with an HRT of 1 hour.

c - Secondary biological process is membrane filter with an HRT of 1.78 hours.

d - Aggregates information for primary, secondary and tertiary biological processes.

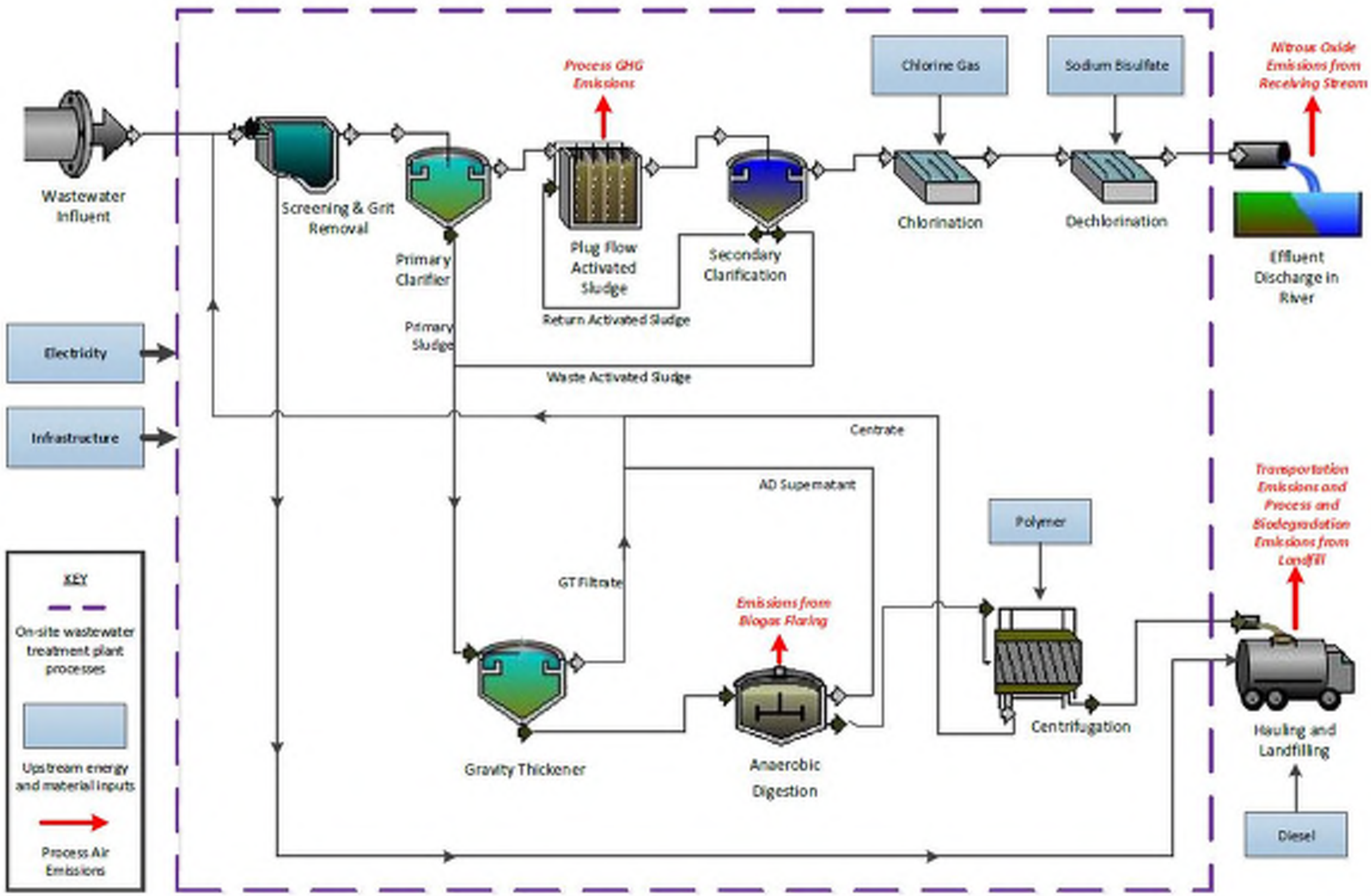

Figure 1-2. Level 1: Conventional Plug Flow Activated Sludge Wastewater Treatment Configuration

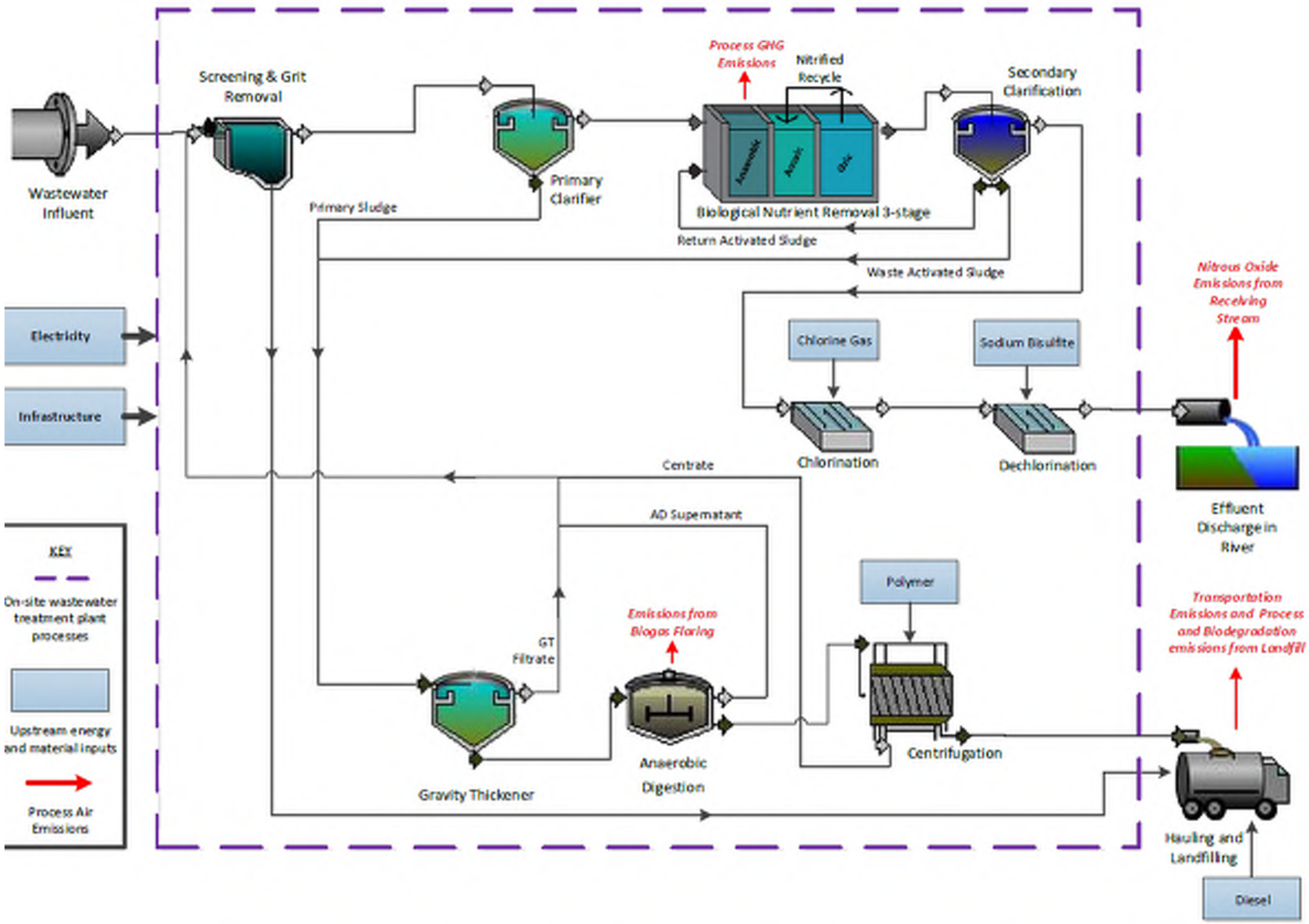

Figure 1-3. Level 2-1: Anaerobic/Anoxic/Oxic Wastewater Treatment Configuration

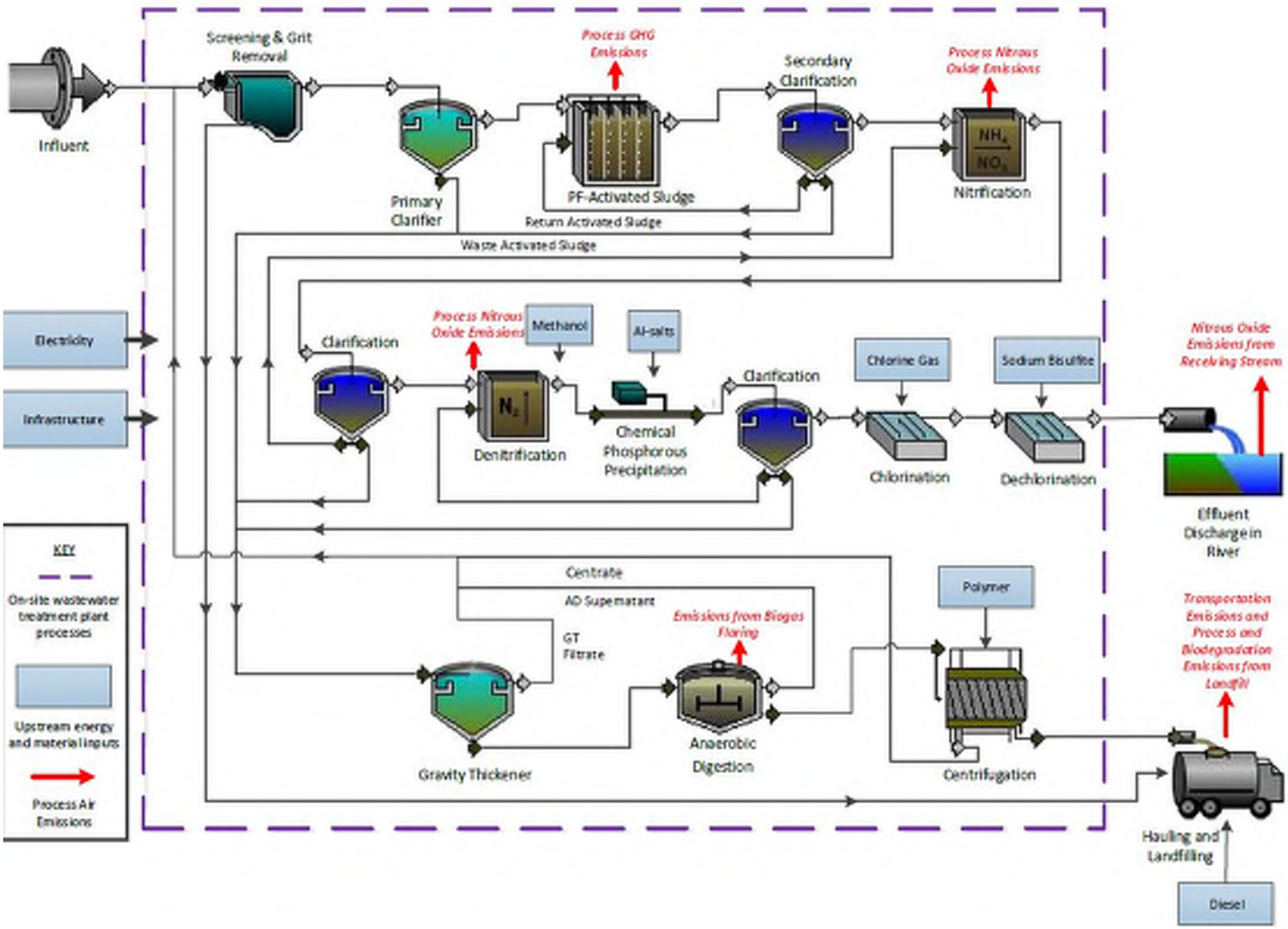

Figure 1-4. Level 2-2: Activated Sludge, 3-Sludge System Wastewater Treatment Configuration

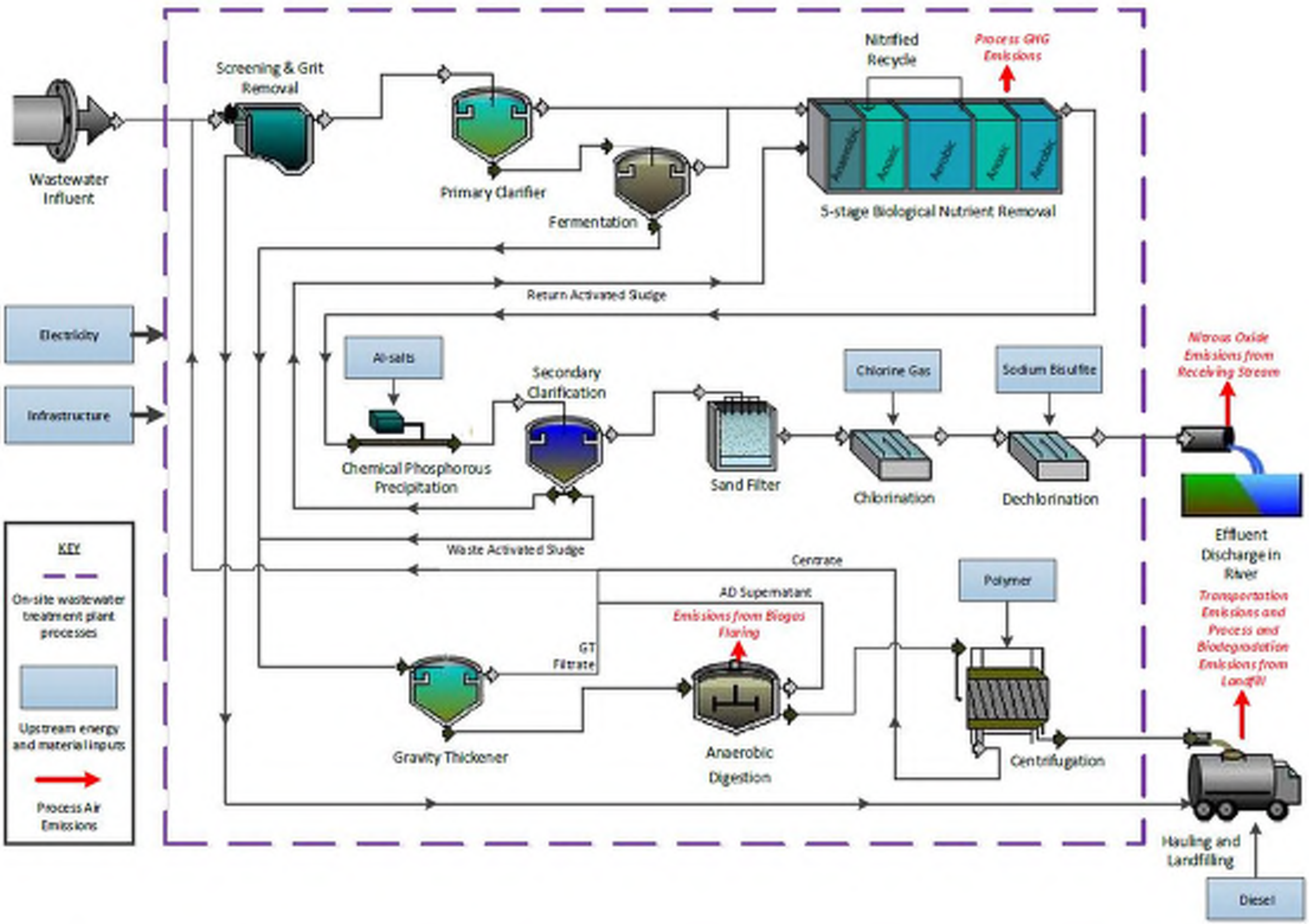

Figure 1-5. Level 3-1: 5-Stage Bardenpho System Wastewater Treatment Configuration

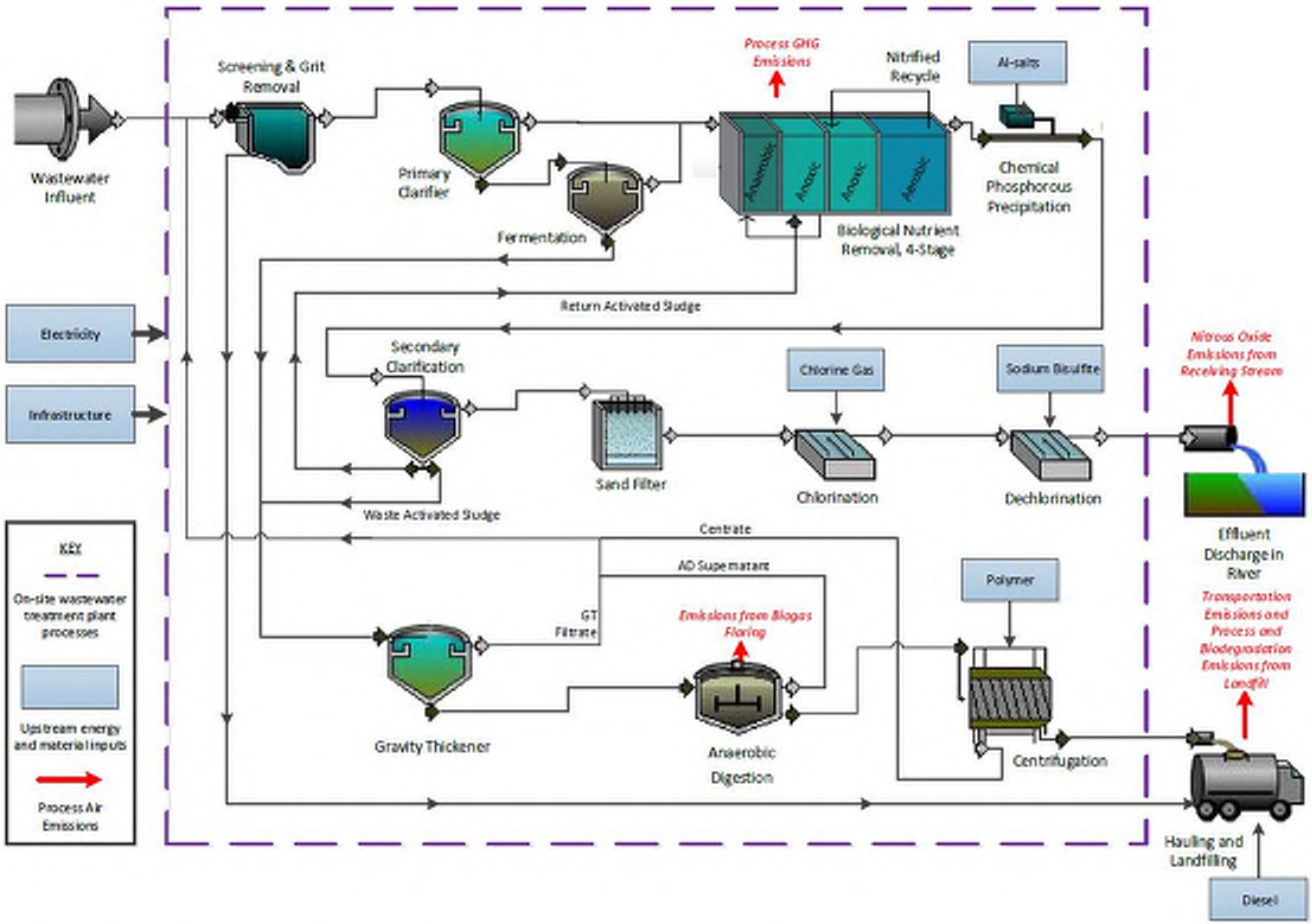

Figure 1-6. Level 3-2: Modified University of Cape Town Process Wastewater Treatment Configuration

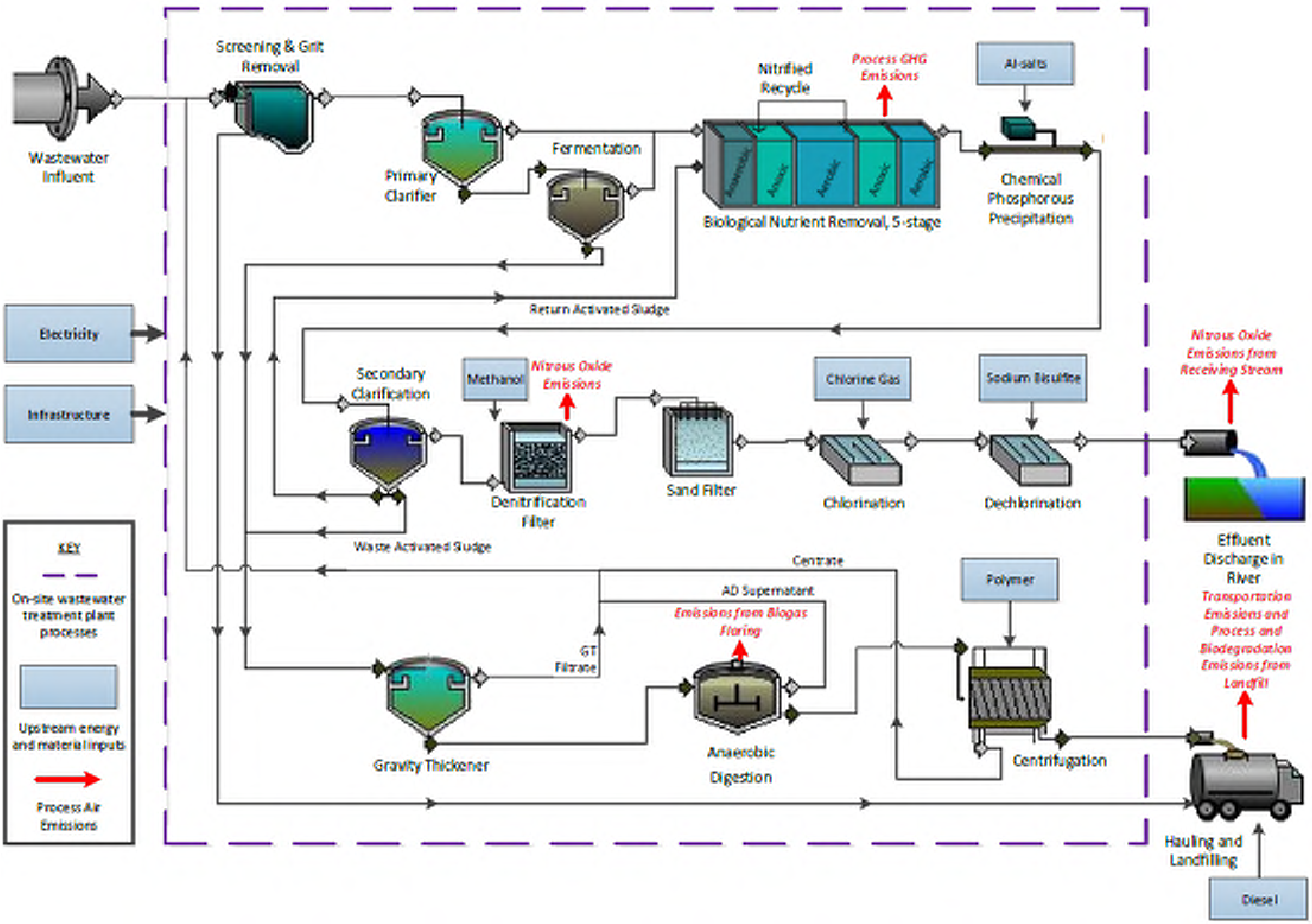

Figure 1-7. Level 4-1: 5-Stage Bardenpho System with Denitrification Filter Wastewater Treatment Configuration

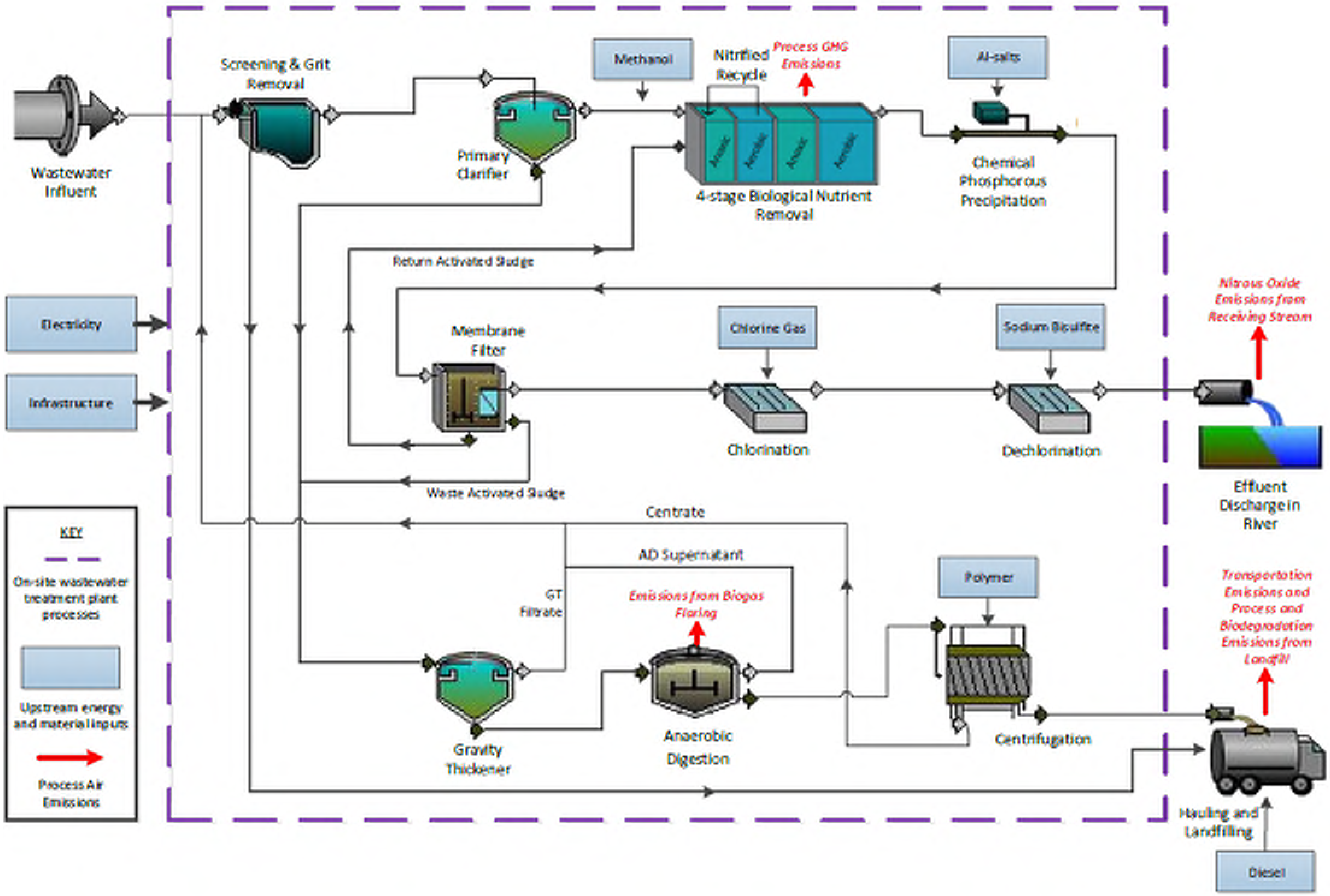

Figure 1-8. Level 4-2: 4-Stage Bardenpho Membrane Bioreactor System Wastewater Treatment Configuration

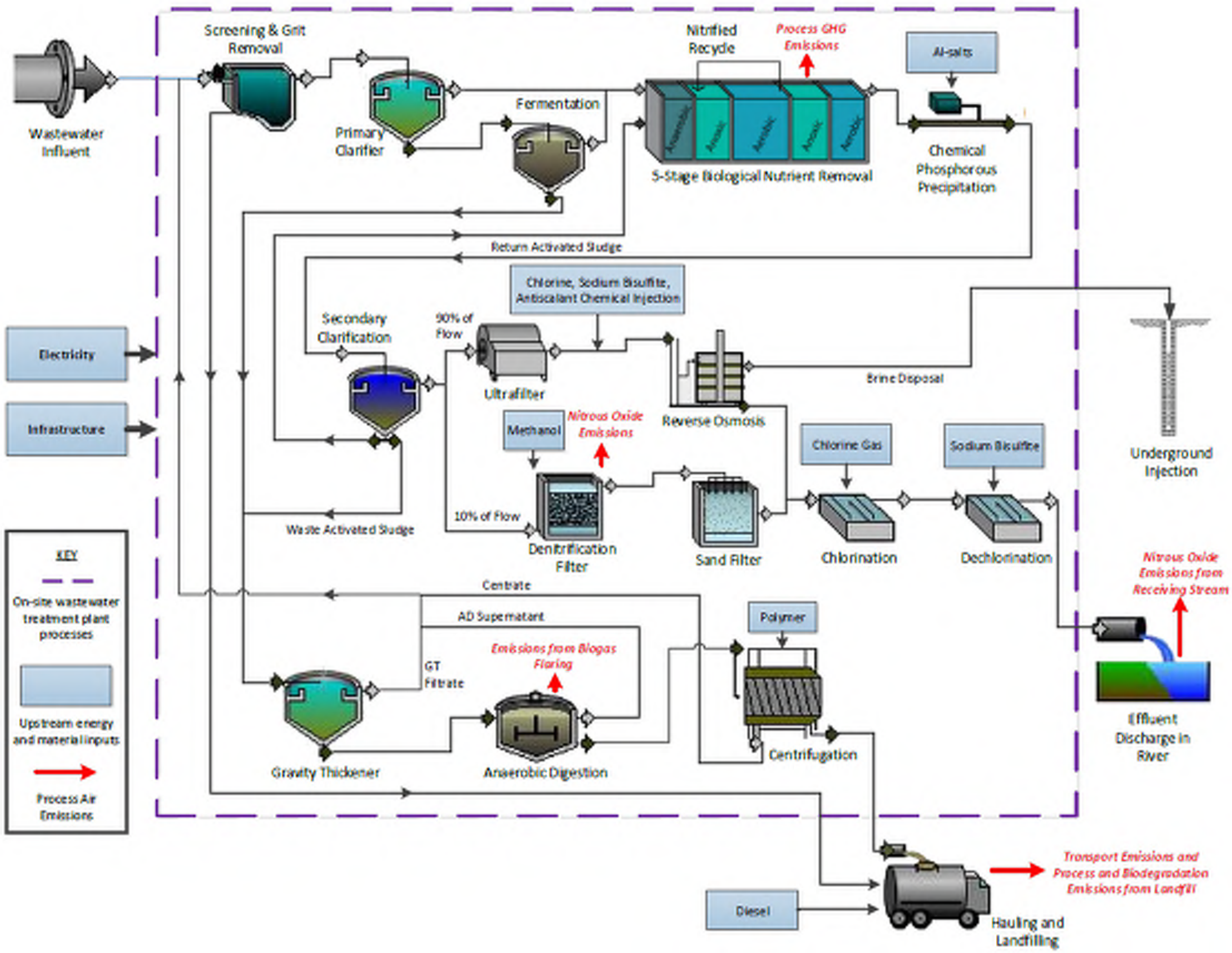

Figure 1-9. Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Wastewater Treatment Configuration

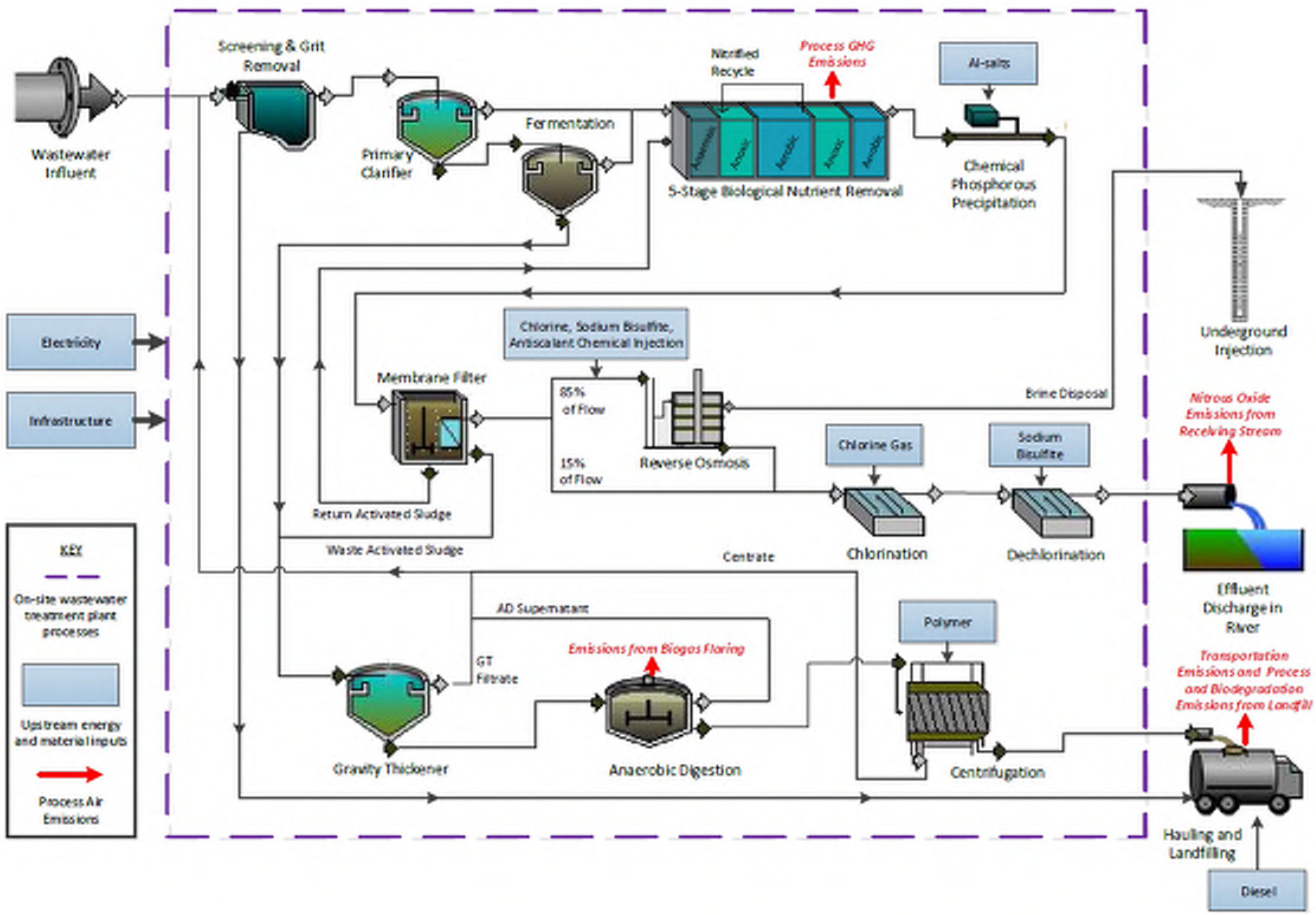

Figure 1-10. Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis Wastewater Treatment Configuration

1.2.5 Metrics and Life Cycle Impact Assessment

Table 1-6 summarizes the metrics estimated in connection with each of the system configurations, together with the method and units used to characterize each.

The cost of each system configuration is estimated using standard approaches for life cycle costing, with more detail on the costing methodology provided in Section 2. Most of the LCIA metrics are estimated using the Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI), version 2.1 (Bare et al., 2003; Bare, 2011). TRACI is an LCIA method developed by the U.S. EPA. It includes a compilation of methods representing current best practice for estimating human health and ecosystem impacts based on U.S. conditions in conjunction with the information provided by life cycle inventory models. Toxicity impacts (e.g., human health toxicity – cancer, human health toxicity – non-cancer, and ecotoxicity) are based on the USEtox™ method (Rosenbaum et al., 2011) version 2.02. Global warming potential (GWP) is estimated in the baseline results using the 100-year characterization factors provided by the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, which are the GWPs currently used for international reporting (Myhre et al., 2013). GWPs are also estimated in a sensitivity analysis using the more recent 100-year characterization factors provided by the IPCC 5th Assessment Report. In addition to TRACI, the ReCiPe LCIA method is used to characterize water consumption and fossil energy use (Goedkoop et al., 2008), impacts which are not included in the current version of TRACI. To provide another perspective on energy, cumulative energy demand including the energy content of all non-renewable and renewable energy resources extracted throughout the supply chains associated with each configuration is estimated using a method adapted from one provided by the Ecoinvent Centre (Ecoinvent Centre, 2010a). Detailed descriptions of each of the LCIA impact categories are also provided in Section 4.6.

The metrics included in this study range in geographic scale from global metrics such as GWP and fossil fuel depletion potential, to impact categories such as ecosystem toxicity potential, smog formation potential, and eutrophication potential that tend to be more local or regional in nature. In other words, some emissions/pollutants result in environmental impacts on a global level (e.g., emissions with long atmospheric lifetimes like greenhouse gases), while other pollutants primarily impact the regions or locations close to the point of release.

Table 1-6. Metrics Included in the LCA and LCCA Results

Metric	Method	Unit
Cost	LCCA	USD2014
Eutrophication Potential	TRACI 2.1	kg N eq.
Cumulative Energy Demand	ecoinvent	MJ-eq.
Global Warming Potential	TRACI 2.1	kg CO_2 eq.
Acidification Potential	TRACI 2.1	kg SO_2 eq.
Fossil Depletion	ReCiPe	kg oil eq.
Smog Formation Potential	TRACI 2.1	kg O_3 eq.
Human Health - Particulate Matter Formation	TRACI 2.1	$PM_{2.5}$ eq.

Table 1-6. Metrics Included in the LCA and LCCA Results

Metric	Method	Unit
Ozone Depletion Potential	TRACI 2.1	kg CFC-11 eq.
Water Depletion	ReCiPe	m^3
Human Health Toxicity – Cancer Potential	USEtox™ 2.02	CTUh
Human Health Toxicity – Noncancer Potential	USEtox™ 2.02	CTUh
Ecotoxicity Potential	USEtox™ 2.02	CTUe

2. TRACE POLLUTANT REMOVAL PERFORMANCE CHARACTERIZATION

Although the nine wastewater configurations evaluated in this study are designed to achieve various levels of nutrient removal targets, these treatment trains also remove other trace pollutants in the influents. It is important to capture these treatment performances in the holistic analysis in order to have a complete understanding of treatment strategies. This section summarizes the steps taken to characterize three major groups of trace pollutants with respect to their expected influent concentrations, fate within the study's nine wastewater treatment configurations, and final discharge into the environment. The groups include heavy metals, toxic organics and disinfection byproducts (DBPs). Depending on the pollutant, the final receiving environment (and thus the potential for impact) may include surface water discharge from the WWTP, partitioning to sludge with subsequent landfill disposal, or deep well injection in the case of RO brine. It was assumed that no toxicity-related impacts were associated with deep well injection. Volatilization was not found to be a major loss pathway for any of the included pollutants.

In the case of landfill disposal, environmental impact only occurs if the landfill liner fails and leachate is released. However, little data exists on actual failure rates. For this study, a failure rate of 5% was assumed based on a probabilistic modeling study that found, given typical landfill construction, failures generally occur within 10-30 years after landfill closure (Pivato, 2011).

For further reference, a full description of background, methods and results is provided in Appendix B, Appendix C and Appendix D, for heavy metals, toxic organics and DBPs, respectively.

2.1 Heavy Metals

The discharge of metals to the environment represents an ever-present concern, given their potential toxicity at even trace levels. WWTPs receive variable but sometimes high loads of metals depending on the mix of sources in their watershed, which can include industrial activities, domestic sources and stormwater (Yost et al., 1981; Ruel et al., 2011; Choubert et al., 2011b).

The direct management of metals has generally not been the focus of municipal WWTP design given the prioritization of organics and nutrient treatment. Heavy metals from industrial source are subject to other more targeted regulatory programs like the National Pretreatment Program (U.S. EPA, 2019a) which applies to industrial facilities. Nevertheless, trace heavy metals may still be present in municipal influents. Many common treatment processes allow for effective partitioning of metals to the sludge fraction, thus greatly reducing the quantity discharged in effluent.

Seven metals were included in this study that are commonly regulated and prevalent in the case study literature. Both criteria were assumed to be indirect indicators of the metal's demonstrated potential to cause environmental or human health impacts. The metals include Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), and Zinc (Zn). Table 2-1 summarizes ranges of influent concentrations established in several literature reviews, relevant effluent limits, and ranges of influent concentrations observed in the case studies used herein.

Table 2-1. Summary of Literature and Case Study Metal Influent Concentrations and Regulatory Effluent Concentrations.

Value		Concentrations in μg/L							Notes	Source
		Pb	Cu	Zn	Ni	Cr	Cd	Hg		
Influent Concentrations - Literature Reviews		5.7	63	181	11	10	0.21	0.36	19 Plants, France	1
		25	78	155	14	12.0	0.8	0.5	30 Plants, UK	2
		140-600	--	--	--	--	--	--	Combined WW	3
		232	489	968	455	378	19	--	12+ Cities, US	4
Case Study Ranges	High	68	118	493	77	290	10	7.0	This Study	5
	Medium	21	65	350	24	59	4.9	3.8	This Study	5
	Low	10.8	25	204	11	19	0.94	0.37	This Study	5
US CCC[a]		2.5	9	120	52	74/11[b]	0.25	0.77	Effluent Limits	6
US CMC[a]		65	13	120	470	570/16[b]	2	1.4	Effluent Limits	6

a - Criterion Continuous Concentration/Criteria Maximum Concentration, hardness dependent except for Cr (VI) and Hg. Values shown assume a hardness of 100 mg/L.

b - Chromium (III/VI)

1 - Choubert et al., 2011b; Ruel et al., 2012

2 - Rule et al., 2006

3 - Metcalf and Eddy, 2014

4 – Yost et al., 1981

5 - Linstedt et al., 1971; Brown et al., 1973; Chen et al., 1974; Oliver and Cosgrove, 1974; Aulenbach and Chan, 1988; Huang et al., 2000; Innocenti et al., 2002; Chipasa, 2003; Karvelas et al., 2003; Qdais and Moussa, 2004; Buzier et al., 2006; da Dilva Oliveira et al., 2007; Mohsen et al., 2007; Obarska-Pempkowiak and Gajewska, 2007; Carletti et al, 2008; Johnson et al., 2008; Dialynas and Diamadopoulos, 2009; Renman et al., 2009; Malamis et al., 2012; Arevalo et al., 2013; Garcia et al., 2013; Salihoglu, 2013; Inna et al., 2014; Reddy et al., 2014

6 - U.S. EPA, 2019b

Metal removal efficiencies for study system configurations were estimated based on a detailed literature review of performance results from similar systems. For system levels where no representative equivalent was identified but the important components were characterized, a composite removal efficiency was calculated based upon case study performance data of its major unit processes. For example, Level 3-1 includes a 5-stage Bardenpho process with subsequent sand filtration. However, results of the literature review only identified 5-stage Bardenpho WWTPs without sand filtration, and sand filtration as a standalone process. Therefore, a composite removal efficiency was calculated assuming a realistic stepwise removal, combining removal efficiencies for a 5-stage Bardenpho process with removal efficiencies for sand filtration. Table 2-2 summarizes the resulting minimum, average and maximum removal efficiencies for each treatment configuration. Supporting details for calculations and calculation assumptions are provided in Appendix B.

Table 2-2. Summary of Estimated Metal Removal Efficiencies[a]

Metal		Level 1 AS	Level 2-1 A2O	Level 2-2 AS3	Level 3-1 B5	Level 3-2 MUCT	Level 4-1 B5/Denit	Level 4-2 MBR	Level 5-1 B5/RO	Level 5-2 MBR/RO
Cu	Min	35%	35%	35%	75%	52%	75%	68%	93%	96%
	Mean	62%	62%	62%	80%	77%	80%	90%	97%	99%
	Max	84%	84%	84%	83%	96%	83%	99%	98%	100%
Pb	Min	40%	40%	40%	55%	39%	55%	68%	95%	97%
	Mean	65%	65%	65%	66%	70%	66%	88%	96%	99%
	Max	97%	97%	97%	75%	94%	75%	100%	97%	100%
Ni	Min	16%	16%	16%	42%	66%	42%	64%	82%	91%
	Mean	39%	39%	39%	45%	67%	45%	82%	90%	97%
	Max	91%	91%	91%	47%	68%	47%	100%	94%	100%
Zn	Min	12%	12%	12%	57%	83%	57%	75%	94%	97%
	Mean	42%	42%	42%	72%	89%	72%	85%	96%	99%
	Max	77%	77%	77%	83%	94%	83%	91%	98%	99%
Cd	Min	11%	11%	11%	40%	23%	40%	96%	93%	99%
	Mean	59%	59%	59%	47%	41%	47%	97%	94%	100%
	Max	83%	83%	83%	57%	59%	57%	98%	95%	100%
Cr	Min	16%	16%	16%	78%	88%	78%	83%	97%	99%
	Mean	64%	64%	64%	81%	88%	81%	91%	98%	100%
	Max	79%	79%	79%	84%	89%	84%	95%	98%	100%
Hg[b]	Min	17%	17%	17%	17%	17%	17%	93%	84%	98%
	Mean	53%	53%	53%	53%	53%	53%	97%	93%	100%
	Max	85%	85%	85%	85%	85%	85%	99%	98%	100%

a – "Removal Efficiency" used loosely; data more explicitly represents partitioning to sludge. Min and max represent minimum and maximum removal efficiencies reported in the literature. Where removal efficiencies are composites of multiple processes, minimum represents the composite of both contributing minimums, likewise for maximum.

b – No data for Hg removal found for 4-stage Bardenpho, 5-stage Bardenpho or MUCT. Therefore, conservatively assumed same removal for these biological treatment processes as documented for CAS (Level 1). Data for Levels 4-2, 5-1 and 5-2 represent the effect of tertiary polishing step alone, i.e. MBR and RO.

2.2 Toxic Organic Pollutants

Toxic organics are a diverse and growing category of chemical substances that includes commonly referred to pollutant groups such as contaminants of emerging concern (CECs), pharmaceuticals and personal care products (PPCPs), and endocrine disrupting chemicals (EDCs). The pollutant category includes medications, fragrances, insect repellents and other household items that can be harmful to environmental and human health at even trace levels (U.S. EPA, 2015; Montes-Grajales et al., 2017). Per- and polyfluoroalkyl substances (PFAS) are not included in this study.

Toxic organics are present in surface waters, groundwater, wastewater and WWTP effluent, both in the U.S. and globally (Ellis, 2008; Ebele et al., 2017; Montes-Grajales et al., 2017). No comprehensive list exists, though based on a diverse literature the number of contaminants is at least in the hundreds (if not thousands) and is continually being expanded upon as analytical techniques for measuring both presence and toxicity are continually refined. In order to provide a targeted analysis of their behavior in WWTPs, a restricted group of 43 pollutants (Table 2-3) has been included in this study. The list has been adapted and updated from two previous studies (Montes-Grajales et al., 2017; Rahman et al., 2018) where pollutants were selected based on frequency of detection in WWTPs and the availability of information regarding concentration, degradation, transformation and removal.

The concentration of trace pollutants can vary considerably on a daily and seasonal basis and between WWTPs (Martin Ruel et al., 2012). Based on a detailed review of the literature, influent concentration ranges were established for each pollutant (Table 2-3). For subsequent calculations, the medians of pollutant influent concentrations were used as means had a tendency to be biased by a small number of very high concentrations.

Table 2-3. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (µg/L)				Sample Size
		Average	Median	Minimum	Maximum	
acetaminophen[a]	pain reliever, anti-inflammatory	97	19	0.02	400	12
androstenedione[a]	steroid hormone	0.29	0.10	0.02	1.3	7
atenolol	beta blocker	4.3	1.1	0.03	26	10
atorvastatin	lipid regulator	0.49	0.22	0.07	1.6	6
atrazine[b]	pesticide	0.02	0.02	1.0E-3	0.06	5
benzophenone	PCP, sunscreen	0.24	0.27	7.0E-3	0.42	4
bisphenol A	EDC, plasticizer	4.6	0.84	0.01	44	16
butylated hydroxyanisole[c]	beta blocker	1.3	0.16	0.13	3.5	3
butylated hydroxytoluene	beta blocker, cosmetic	0.93	0.41	0.05	3.5	5
butylbenzyl phthalate[d]	plasticizer	0.11	0.11	0.08	0.14	2
carbamazepine[a]	anti-convulsant	0.92	0.69	0.04	3.8	28
N,N-diethyl-meta-toluamide (DEET)	insect repellent	1.4	0.40	0.02	6.9	6
diclofenac	analgesics, anti-inflammatory	2.1	0.96	1.0E-3	17	20
dilantin	anti-seizure medication	0.16	0.17	0.05	0.24	4
dioctyl phthalate[b]	plasticizer, industry	23	1.4	1.1	67	3
estradiol[a,c]	EDC, steroid hormone	0.59	0.03	8.0E-3	5.0	11
estrone[a,c]	EDC, steroid hormone	0.17	0.05	0.01	1.0	9
galaxolide	beta blocker, PCP, fragrance	4.3	2.3	1.4E-3	25	16
gemfibrozil[a]	lipid regulator	3.1	1.6	0.02	22	15
hydrocodone	analgesic, opioid	0.08	0.11	0.02	0.12	5
ibuprofen[a]	analgesics, anti-inflammatory	7.8	2.4	1.0E-3	39	27
iopromide	contrast agent	7.4	0.05	0.01	38	6
meprobamate	tranquilizer, medication	0.40	0.35	0.01	0.97	5
naproxen[a]	analgesics, anti-inflammatory	8.5	2.5	2.0E-3	53	20
nonylphenol[b,c]	EDC, disinfectant, surfactant, solvent	3.4	2.3	0.02	9.7	14

Table 2-3. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (µg/L)				Sample Size
		Average	Median	Minimum	Maximum	
octylphenol[b]	EDC, surfactant, solvent	1.9	0.41	0.12	8.7	12
o-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
oxybenzone	PCP	1.2	0.39	0.03	3.8	4
p-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
progesterone[a]	EDC	0.02	0.01	3.1E-3	0.06	4
sulfamethoxazole[a]	antibiotic	1.1	0.43	0.04	4.5	14
tris(2-chloroethyl) phosphate (TCEP)	flame retardant, plasticizer	0.35	0.24	0.17	0.65	3
tris(2-chloroisopropyl) phosphate (TCPP)	flame retardant	1.2	1.2	1.1	1.3	2
testosterone[a]	EDC	0.06	0.05	0.01	0.14	5
triclosan[a]	pesticide, disinfectant	2.7	0.80	2.3E-3	24	17
trimethoprim[a]	antibiotic	0.52	0.53	0.10	1.4	8
triclocarban[a]	disinfectant	0.42	0.42	0.29	0.54	2
tonalide	beta blocker, PCP, fragrance	1.5	0.80	5.0E-5	7.6	13
celestolide	PCP, fragrance	5.1	0.07	0.04	15	3
phantolide	fragrance	0.10	0.10	0.04	0.15	2
clofibric acid	lipid regulator	0.46	0.29	0.03	1.1	3
musk ketone	fragrance	0.12	0.12	0.10	0.15	3
diuron[b, c]	fragrance	0.14	0.11	0.05	0.25	3

a – Identifies substances with EPA developed analytical methods for detection of contaminants of emerging concern per (EPA, 2017).

b –Identifies substances with a European Quality Standard per (European Parliament, 2008).

c – Identifies substances identified in EPA's Candidate Contaminant List (CCL), version 4 (U.S. EPA, 2016c). The CCL identifies chemicals that are currently unregulated but may pose a risk to drinking water.

d - Identifies substances identified as human health criteria in Section 304(a) of the Clean Water Act (U.S. EPA, 2019c).

Table Acronyms: EDC – endocrine disrupting chemical, PCP – personal care product.

The behavior of toxic organics within study treatment configurations was estimated based on a review of the relevant literature for major unit processes, including:

- Biological Treatment
- Chemical Phosphorus Removal
- Membrane Filtration
- Anaerobic Digestion

Given the large list of pollutants and varying levels of available information, a combination of quantitative and qualitative information was used to arrive at final treatment performance ranges. The ranges take into account possible loss pathways that include transformation or degradation within biological unit processes, partitioning to solids and transformation or degradation during anaerobic digestion. Table 2-4 provides the resulting estimated range of cumulative removal efficiency for each of the nine WWTP configurations. Degradation and removal efficiency estimates were calculated as a weighted average of values for the 43 included pollutants. Relative influent concentration was used as the weighting factor. Additional background discussion and supporting calculations are provided in Appendix C.

Table 2-4. Summary of Cumulative Toxic Organics Degradation and Removal Efficiency in Study Treatment Configurations[a]

Treatment Level	Fraction Degraded			Fraction Removed (includes solids)		
	Minimum	Median	Maximum	Minimum	Median	Maximum
L1	52%	70%	85%	67%	81%	89%
L2-1	52%	73%	90%	67%	86%	95%
L2-2	52%	73%	90%	67%	86%	95%
L3-1	52%	75%	92%	67%	88%	97%
L3-2	52%	75%	92%	67%	88%	97%
L4-1	52%	75%	92%	67%	88%	97%
L4-2	52%	75%	91%	67%	88%	97%
L5-1	52%	75%	91%	94%	99%	100%
L5-2	52%	75%	91%	93%	98%	99%

a – Table values represent the cumulative effect of all the described treatment processes, calculated as a weighted average of the 43 toxic organics using influent concentration as the weighting factor.

2.3 Disinfection Byproducts

Disinfection of WWTP effluent is a necessary practice to minimize the acute risk associated with exposure to microbial pathogens, however it must be balanced with the chronic risk posed by the creation of disinfection byproducts (DBPs). DBPs are a class of chemical compounds that can be harmful to both aquatic and human health (Boorman, 1999; Nieuwenhuijsen et al., 2000; Mizgireuv et al., 2004; Villanueva et al., 2004; Muellner et al., 2007; Richardson et al., 2007; Watson et al., 2012).

DBPs are formed when DBP precursors, generally organic carbonaceous or nitrogenous compounds, are oxidized during chlorination or chloramination (Christman et al., 1983). By regulation, certain DBPs are managed at drinking water treatment plants, as their presence in water supplies poses a direct threat to human health (Sedlak and Gunten, 2011; US EPA, 2015c). Furthermore, as water recycling and reclamation programs expand (and as indirect potable reuse continues), management of DBPs and DBP precursors has become increasingly important at the WWTP as well (Krasner et al., 2008; Tang et al., 2012).

The importance of DBP and DBP precursor control at WWTPs has been growing in recent years for several reasons. First, the type of precursors formed through biological wastewater treatment are complex and, although overlapping with, are in many ways dissimilar from the natural organic matter (NOM)-derived precursors of drinking water-based DBPs. Therefore, lessons learned in drinking water DBP formation prediction and control are not directly translatable to WWTPs (Drewes and Croue, 2002; Tang et al., 2012). Additionally, there has been increasing concern over emerging and more toxic nitrogenous DBPs such as nitrosamines, halonitroalkanes, haloacetonitriles (HANs) and haloacetamides (Westerhoff and Mash, 2002; Joo and Mitch, 2007; Lee et al., 2007), which can be produced to varying degrees from dissolved organic nitrogen (DON) found in wastewater and WWTP effluent. Haloacetamides and HANs in particular are approximately two orders of magnitude more cytotoxic and genotoxic than the regulated trihalomethanes (THMs) and haloacetic acids (HAAs) (Muellner et al., 2007; Plewa and Wagner, 2009). The concentration of ammonia further complicates DBP formation kinetics, favoring the formation of certain groups at high concentrations and others at low (Krasner et al., 2008; Krasner et al., 2009b; Sedlak and Gunten, 2011). Similarly, chlorination practices, which can vary considerably between WWTPs, can have large effects on the overall formation of DBPs and, in combination with ammonia concentrations, can favor certain DBP groups over others. It is therefore important that comparisons of treatment configurations with differing nitrification and denitrification capabilities take into account multiple groups of DBPs that can capture these relative benefits and drawbacks.

For this study, models for DBP formation potential (FP) were used to compare the differences in DBP formation between study treatment configurations. FP is determined using a standardized procedure, eliminating variability from case study data that may arise owing to different disinfection practices. Ultimately, this allows for a clearer distinction between the effects of different treatment approaches on precursor control. To model disinfection byproduct formation potential (DBPFP), a comprehensive dataset linking effluent water quality of 23 different WWTPs to DBPFP was used (Krasner et al., 2008). The DBP and DBP groups included in the study include the regulated carbonaceous DBPs (THMs and HAAs) along with emerging and more toxic carbonaceous and nitrogenous DBPs (Table 2-5).

Table 2-5. Summary of Study Disinfection Byproducts

DBP (group/compound)	Characteristics	Precursors	Limit	Regulatory Authority
Trihalomethanes (THM)[a,b]				
Chloroform	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	80 µg/L (TTHM)	U.S. EPA, Stage 1/2 DBP Rule
Bromodichloromethane (BDCM)				
Chlorodibromomethane (DBCM)				
Bromoform				

Table 2-5. Summary of Study Disinfection Byproducts

DBP (group/compound)	Characteristics	Precursors	Limit	Regulatory Authority
Haloacetic Acids (HAA)[b,c]				
Monochloroacetic acid	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	60 µg/L (HAA5)	U.S. EPA, Stage 1/2 DBP Rule
Dichloroacetic acid (DXAA)				
Trichloroacetic acid (TXAA)				
Bromoacetic acid				
Dibromoacetic acid				
Nitrosamines[d]				
N-nitrosodimethylamine (NDMA)	nitrogenous, unhalogenated	DON, dimethylamine	10 ng/L	CA (action level)
Aldehydes				
Formaldehyde	carbonaceous, halogenated	DON, amino acids	N/A	N/A
Acetaldehyde				
Chloroacetaldehyde				
Dichloroacetaldehyde				
Trichloroacetaldehyde (chloral hydrate)				
Haloacetonitriles (HANs)				
Chloroacetonitrile	nitrogenous, halogenated	DON, amino acids	N/A	N/A
Bromoacetonitrile				
Iodoacetonitrile				
Trichloroacetonitrile				
Bromodichloroacetonitrile				
Dibromochloroacetonitrile				
Tribromoacetonitrile				

a - The four compounds together comprise the four primary trihalomethanes, sometimes referred to as TTHM or THM4

b - https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100C8XW.txt (U.S. EPA, 2015b)

c - These five compounds together comprise the five primary haloacetic acids, sometimes referred to as HAA5

d - California Department of Health Services, action level (CDHS, 2018)

Multiple linear regression models were constructed linking relevant water quality parameters with DBPFP. This was done by first performing a linear correlation analysis, which indicated COD and TKN to be the most influential predictors. Next, models were built for each DBP group (Table 2-5) using the adjusted coefficient of determination (R^2). Final models were significant at a >95% confidence level with the exception of NDMA, which was significant at a 93% confidence level. Table 2-6 gives model results for the nine study treatment configurations. Further discussion of methods, model construction and model results can be found in Appendix D.

Table 2-6. DBPFP Model Results for Study Treatment Configurations

Study Configuration	THMs	HANs	DXAAs	TXAAs	dihaloacet-aldehydes	trihaloacet-aldehydes	NDMA
	µg/L						ng/L
Level 1, AS	204	32	145	127	8.8	95	692
Level 2-1, A2O	274	14	129	113	4.9	54	680
Level 2-2, AS3	95	4.9	43	40	1.5	18	230
Level 3-1, B5	41	0.78	14	15	0.16	3.3	83
Level 3-2, MUCT	41	0.78	14	15	0.16	3.3	83
Level 4-1, B5/Denit	124	5.2	54	49	1.7	21	292
Level 4-2, MBR	144	6.6	65	59	2.2	26	347
Level 5-1, B5/RO	23	0.010	5.4	7.4	0.010	0.010	36
Level 5-2, MBR/RO	32	0.066	10	11	0.010	0.87	58

3. LIFE CYCLE COST ANALYSIS METHODOLOGY

This section presents ERG's methodology for developing life cycle costs for the nine greenfield wastewater treatment configurations included in this study. As such, the costs presented in the report are not applicable to operations that retrofit existing treatment systems to achieve further nutrient removal, and the difference from one treatment level to another may not represent the incremental retrofit costs due to existing infrastructure and site-specific conditions. In addition, the costs (as well as life cycle impacts discussed later in the report) are for the entire wastewater treatment configuration, not just those steps used to achieve nutrient removal.

The life cycle costs in the study are based primarily on the use of CAPDETWorks™, a model that performs planning-level design and cost estimation of WWTP construction projects. These planning-level costs do not include site-specific factors that may impact the costs (e.g., high groundwater table, shallow bedrock, deep excavation) as they are intended to represent the national average. These costs are supplemented with costs for additional unit processes that are not included in CAPDETWorks™ to provide costs for the entire wastewater treatment configuration. Section 3.1 describes CAPDETWorks™ and the data sources used for the additional unit processes. Section 3.2 describes the engineering cost estimation methodology. To the extent possible, purchased equipment and annual cost results are developed by unit process to allow for consistent presentation alongside results of the LCA model. Section 3.3 describes the life cycle cost analysis (LCCA) calculations that provide for a plant-level comparison of costs that occur throughout the life of the wastewater treatment configurations. The total plant costs are presented as: 1) total capital costs and total annual costs and 2) net present value that combines the one-time capital costs and annual costs into one value. The capital costs include the purchased equipment, direct costs (e.g., site preparation, site electrical, yard piping), and indirect costs (e.g., land, engineering design fee, interest during the 3-year construction period). The annual costs include the operating and maintenance labor, materials including replacement equipment, chemicals, and energy. In general, the purchased equipment costs were based on equipment sizing for the 20 MGD peak flow rate, while the annual costs were based on the 10 MGD annual average flow rate. For the net present value, the construction costs (in present value) are combined with the discounted annual costs during the WWTP planning period. Section 3.4 describes the quality of the data sources used in the LCCA.

3.1 Data Sources

ERG obtained cost data from the following sources or categories of sources:

- CAPDETWorks™ Version 3.0 (Hydromantis, 2014)
- EPA reports and fact sheets
- Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability (Falk et al, 2011)
- Wastewater treatment design textbooks
- Personal communication with technology vendors
- RSMeans Building Construction Cost Data (RSMeans, 2010)
- RSMeans Construction Cost Index (RSMeans, 2017)

The majority of the life cycle costs are based on CAPDETWorks™ Version 3.0 (Hydromantis, 2014) modeling output, supplemented with costs for unit processes that are not in CAPDETWorks™ (see Section 3.2.2 for details). EPA and the U.S. Army Corps of Engineers originally developed CAPDETWorks™ as a planning tool for WWTPs; Hydromantis Corporation now maintains and updates CAPDETWorks™. As described in Section 4.2.1 of *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b), CAPDETWorks™ is used as follows:

> The user generates a process layout involving a number of unit operations. The user can also define input variables, including wastewater flow rate, wastewater influent quality, and desired effluent quality or other performance coefficients. Alternatively, the user can choose to use default values developed by Hydromantis. The software then calculates the required sizes of the unit operations and uses cost-curve models from the software's database to estimate the capital, labor, chemical, and energy costs that would be incurred. …The model uses several standard indices to update costs to current dollars: the Engineering News-Record (ENR) Construction Cost Index, the Marshall & Swift Index, and the Pipe Index. Values were obtained from a U.S. Department of Agriculture Web site (USDA, 2007) that transcribes historical values of these indices.

The cost functions included in CAPDETWorks™ Version 3.0 (the version used for this study) were updated in 2014. CAPDETWorks™ also allows users to input design values for each unit process (e.g., solids retention time, surface overflow rate) or use the default values developed by Hydromantis. CAPDETWorks™ also allows users to input unit costs (e.g., concrete, construction labor rate, polymer).

ERG relied primarily on the following two EPA reports to evaluate and modify, as necessary, the default input design values in CAPDETWorks™ and support development of costs for the unit processes that are not in CAPDETWorks™:

- *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b)
- *Nutrient Control Design Manual* (U.S. EPA, 2010)

The *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b) is intended to provide information to assist local decision makers and regional and state regulators in planning cost-effective nutrient removal projects for WWTPs. This EPA report provides capital and operation and maintenance costs for case study WWTPs, as well as costs estimated using CAPDETWorks™. The purpose of the *Nutrient Control Design Manual* (U.S. EPA, 2010) is to provide guidance and design considerations for nitrogen and phosphorus control using biological nutrient removal and chemical phosphorus removal for WWTPs.

ERG also relied on *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011), a report published by Water Environment Research Foundation (WERF). This report is an LCA/LCCA evaluation of WWTPs with nitrogen and phosphorus treatment technologies to achieve five levels of effluent nutrient targets that match the five levels included in this study. While the WERF study used a different cost estimation tool, ERG used the WERF design input values to evaluate and modify, as necessary, the default input design values in CAPDETWorks™. ERG also used *Wastewater Engineering –*

Treatment and Resource Recovery (Tchobanoglous et al., 2014), a wastewater treatment design textbook, and the following documents to verify the default input design values and unit costs in CAPDETWorks™:

- *Wastewater Technology Fact Sheet – Screening and Grit Removal* (U.S. EPA, 2003b)
- Biosolids Technology Fact Sheet – Gravity Thickening (U.S. EPA, 2003a)
- *May 2016 National Industry-Specific Occupational Employment and Wage Estimates for NAICS 221300 – Water, Sewage and Other Systems* (U.S. DOL, 2017)

EPA's wastewater and biosolids technology fact sheets provide general design and cost information. ERG used these technology fact sheets to evaluate and modify, as necessary, the default input design values in CAPDETWorks™. ERG also compared the purchased equipment process costs from CAPDETWorks™ to the technology fact sheets and updated the purchased equipment costs where appropriate. The May 2016 National Industry-Specific Occupational Employment and Wage Estimates for NAICS 221300 – Water, Sewage and Other Systems (U.S. DOL, 2017) calculates average wages from data collected in a national survey of employers of every size, state, and industry for metropolitan and nonmetropolitan areas. ERG used this report to verify and update as necessary the labor rates in CAPDETWorks™ where appropriate.

The primary source of costs for the unit processes that are not in CAPDETWorks™ are from personal communication with technology vendors. ERG contacted companies that manufacture, distribute, or install dechlorination, ultrafiltration, reverse osmosis, and deep well injection systems. The vendors provided the following types of information for EPA's analysis:

- Operations and maintenance requirements (e.g., equipment replacement frequency)
- Ancillary equipment required for the system (e.g., antiscalant chemicals)
- Capital cost information
- Operations and maintenance cost information, including energy requirements

ERG used vendor contacts from previous studies for the dechlorination system costs (ERG, 2011a; ERG, 2011b; ERG, 2011c) and contacted vendors for information on ultrafiltration, reverse osmosis, and deep well injection as part of this study (ERG, 2015a; ERG, 2015b). The majority of the vendors provided supporting documentation, which were also used to develop the cost estimates for the unit processes not included in CAPDETWorks™.

ERG supplemented the information provided by vendors with unit costs for building components from the RSMeans Building Construction Cost Data (RSMeans, 2010) to calculate costs for general components of the unit processes not in CAPDETWorks™ (e.g., reinforced concrete basins). ERG used RSMeans Construction Cost Index (RSMeans, 2017) to convert costs obtained outside of CAPDETWorks™ to 2014 $ for consistency.

3.2 Engineering Cost Estimation

ERG developed engineering cost estimates that included the following components:

- Capital costs (one-time costs).

- Operation and maintenance costs that reoccur annually or on a set frequency (e.g., 5-year recurring costs for equipment replacement).

Capital costs include the purchased equipment, direct, and indirect costs to design and build the wastewater treatment configuration. Operating and maintenance costs include the operation and maintenance labor, materials, chemicals, and energy required to ensure long-term operation of the WWTP. In general, the capital costs are based on the 20 MGD maximum flow rate, while the operating and maintenance costs are based on the 10 MGD average flow rate.

Section 3.2.1 presents the calculations to convert all of the costs to a consistent dollar basis. Section 3.2.2 presents ERG's methodology for calculating the capital and operating and maintenance costs for the individual unit processes included in the wastewater treatment configurations. These unit process costs are presented alongside results from the LCA model and used in the LCCA. Discussion of the methodology for estimating the wastewater treatment configuration-wide direct and indirect costs is presented in Section 3.3.

3.2.1 Dollar Basis

The majority of the life cycle costs are based on CAPDETWorks™ modeling output, supplemented with costs for unit processes that are not in CAPDETWorks™. output is provided in 2014 dollars. As a result, ERG standardized and presented all costs in 2014 dollars using Equation 1 and the RS Means Historical Cost Index, presented in Figure 3-1.

$$\text{Cost (2014 \$)} = \text{Cost (20XX \$)} \times \frac{\text{2014 Cost Index}}{\text{20XX Cost Index}}$$

Equation 1

where:

Cost (2014 $) = Cost in 2014 dollars

Cost (20XX $) = Cost in pre- or post-2014 dollars, where XX represents the specific year

2014 Cost Index = 204.9

20XX Cost Index = See Figure 3-1, using the Historical Cost Index where January 1, 1993=100

Historical Cost Indexes

The table below lists both the RSMeans® historical cost index based on Jan. 1, 1993 = 100 as well as the computed value of an index based on Jan. 1, 2017 costs. Since the Jan. 1, 2017 figure is estimated, space is left to write in the actual index figures as they become available through the quarterly *RSMeans Construction Cost Indexes*.

To compute the actual index based on Jan. 1, 2017 = 100, divide the historical cost index for a particular year by the actual Jan. 1, 2017 construction cost index. Space has been left to advance the index figures as the year progresses.

Year	Historical Cost Index Jan. 1, 1993 = 100		Current Index Based on Jan. 1, 2017 = 100		Year	Historical Cost Index Jan. 1, 1993 = 100	Current Index Based on Jan. 1, 2017 = 100		Year	Historical Cost Index Jan. 1, 1993 = 100	Current Index Based on Jan. 1, 2017 = 100	
	Est.	Actual	Est.	Actual		Actual	Est.	Actual		Actual	Est.	Actual
Oct 2017*					July 2002	128.7	61.7		July 1984	82.0	39.3	
July 2017*					2001	125.1	60.0		1983	80.2	38.4	
April 2017*					2000	120.9	58.0		1982	76.1	36.5	
Jan 2017*	208.5		100.0	100.0	1999	117.6	56.4		1981	70.0	33.6	
July 2016		207.3	99.4		1998	115.1	55.2		1980	62.9	30.2	
2015		206.2	98.9		1997	112.8	54.1		1979	57.8	27.7	
2014		204.9	98.3		1996	110.2	52.9		1978	53.5	25.7	
2013		201.2	96.5		1995	107.6	51.6		1977	49.5	23.7	
2012		194.6	93.3		1994	104.4	50.1		1976	46.9	22.5	
2011		191.2	91.7		1993	101.7	48.8		1975	44.8	21.5	
2010		183.5	88.0		1992	99.4	47.7		1974	41.4	19.9	
2009		180.1	86.4		1991	96.8	46.4		1973	37.7	18.1	
2008		180.4	86.5		1990	94.3	45.2		1972	34.8	16.7	
2007		169.4	81.2		1989	92.1	44.2		1971	32.1	15.4	
2006		162.0	77.7		1988	89.9	43.1		1970	28.7	13.8	
2005		151.6	72.7		1987	87.7	42.1		1969	26.9	12.9	
2004		143.7	68.9		1986	84.2	40.4		1968	24.9	11.9	
2003		132.0	63.3		1985	82.6	39.6		1967	23.5	11.3	

Source: (RSMeans, 2017).

Figure 3-1. RSMeans Historical Cost Indexes

3.2.2 Unit Construction and Labor Costs

As mentioned in Section 2, ERG developed the purchased equipment and annual cost results by unit process to allow for consistent presentation alongside results of the LCA model and use in the LCCA. ERG used CAPDETWorks™ Version 3.0 (Hydromantis, 2014), a software package designed for estimating the cost of wastewater treatment configurations, to calculate the unit process costs for each wastewater treatment configuration. Each of the wastewater treatment configurations used the same influent wastewater composition and flow rate discussed in Section 1.2.2 and presented in Table 1-3.

CAPDETWorks™ includes default unit construction and labor costs that are used to calculate the purchased equipment and annual costs. ERG reviewed the CAPDETWorks™ default unit construction and labor costs against those used in *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011). The most notable differences were for wall and slab concrete, and construction labor rate. For wall and slab concrete, ERG used the average of the costs from CAPDETWorks™ and *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011), as presented in Table 3-1.

Table 3-1. Unit Construction and Labor Costs

Unit Construction Cost	CAPDETWorks™ Default Cost ($/cuyd)	Falk et al, 2011 Cost ($/cuyd)	Average Cost ($/cuyd)
Wall Concrete	350	750	550
Slab Concrete	650	1,250	950

For the construction labor rate, ERG used the average of seven labor rates for construction activities relevant to construction of a WWTP from the May 2016 National Industry-Specific Occupational Employment and Wage Estimates for NAICS 221300 – Water, Sewage and Other Systems (U.S. DOL, 2017). The seven labor categories that ERG used and their labor rates in 2016 $ were:

- First-Line Supervisor of Construction Trades: $34.38/hr
- Construction Laborers: $17.88/hr
- Construction Equipment Operators: $23.12/hr
- Electricians: $31.60/hr
- Pipelayers, Plumbers, Pipefitters, and Steamfitters: $22.16/hr
- Construction Trades Helpers: $15.91/hr
- Other Construction and Related Workers: $21.91/hr

The resulting average labor rate is $23.85/hr in 2016 $, which is $23.58/hr in 2014 $ using Equation 1 in Section 3.2.1. The U.S. DOL wages do not include overhead to account for employee benefits. ERG assumed that contractors would be used for the construction and applied a 2.1 private industry (i.e., contractors) multiplier (consultant multipliers typically range from 2-2.2), resulting in an average construction labor rate of $49.51/hr. ERG rounded the construction labor rate to $50/hr for use in this study.

3.2.3 Unit Process Costs

As mentioned in Section 2, ERG developed the purchased equipment and annual cost results by unit process to allow for consistent presentation alongside results of the LCA model and use in the LCCA. ERG used CAPDETWorks™ Version 3.0 (Hydromantis, 2014), a software package designed for estimating the cost of wastewater treatment configurations, to calculate the unit process costs for each wastewater treatment configuration. Each of the wastewater treatment configurations used the same influent wastewater composition and flow rate discussed in Section 1.2.2 and presented in Table 1-3.

CAPDETWorks™ includes all of the unit processes included in the nine wastewater treatment configurations for this study with the exception of:

- Dechlorination. Included in all nine wastewater treatment configurations.
- Fermentation. Included in:
  - — Level 3-1 B5
  - — Level 3-2 MUCT

- — Level 4-1 B5/Denit
- — Level 5-1 B5/RO
- — Level 5-2 MBR/RO

- 4-Stage Biological Nutrient Removal. Included in:
    - — Level 3-2 MUCT
    - — Level 4-2 MBR
- Methanol addition as a biological nutrient removal supplemental carbon source. Included in Level 4-2 MBR.[5]
- Ultrafiltration. Included in Level 5-1 B5/RO.
- Reverse Osmosis and Antiscalant Chemical Injection Pretreatment. Included in:
    - — Level 5-1 B5/RO
    - — Level 5-2 MBR/RO
- Deep Well Injection. Included in:
    - — Level 5-B5/RO
    - — Level 5-2 MBR/RO

Details on the approach developed for these unit processes are presented in the following subsections. The unit process costs for these unit processes were incorporated into the CAPDETWorks™ output for comparison to the LCA model results and development of the total plant costs.

Each of the nine wastewater treatment configurations was developed in CAPDETWorks™. As part of this study, ERG reviewed the *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA, 2008b), *Nutrient Control Design Manual* (U.S. EPA, 2010), *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al., 2011), *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014), and additional EPA wastewater treatment process fact sheets to confirm that the CAPDETWorks™ default design values were appropriate for use for this study. Based on our review, ERG used the CAPDETWorks™ default design values for the unit processes below that are included in one or more of the wastewater treatment configurations. Appendix E.1 includes the key parameters and default design values for the unit processes that were modeled using the CAPDETWorks™ default design values. For the remaining unit processes below, ERG revised the CAPDETWorks™ default design values. See Appendix E.1 for the details on the revised default design values. Note that ERG used these design values in the initial CAPDETWorks™ model for each wastewater treatment configuration. ERG then revised some of the design values to eliminate errors in CAPDETWorks™ (e.g., subsequent unit process designs were outside recommended design values) and achieve the effluent wastewater objectives for each of the treatment levels. The final design values used for each wastewater

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[5] Methanol addition is also required for Level 2-2 AS3 for the denitrification – suspended growth unit process and Level 4-1 B5/Denit and Level 5-1 B5/RO for the denitrification filters. However, CAPDETWorks™ includes the methanol addition for these unit processes.

treatment configuration are included in the final CAPDETWorks™ cost output discussed in Section 5.

- Default Design Values Used:
  - Membrane Bioreactor
  - Sand Filter
  - Centrifugation – Sludge
- Design Values Revised:
  - Preliminary Treatment – Screening
  - Preliminary Treatment – Grit Removal
  - Primary Clarifier
  - Plug Flow Activated Sludge
  - Biological Nutrient Removal 3/5 Stage
  - Denitrification – Suspended Growth
  - Denitrification – Attached Growth
  - Nitrification – Suspended Growth
  - Chemical Phosphorus Removal
  - Secondary Clarifier
  - Chlorination
  - Gravity Thickener
  - Anaerobic Digestion – Sludge
  - Haul and Landfill – Sludge

ERG updated the CAPDETWorks™ default anaerobic digestion energy costs for all nine wastewater treatment configurations to rely on natural gas rather than using the produced gas for the reasons discussed in Section 3.2.3.8. ERG also determined that the CAPDETWorks™ default electricity cost of $0.10/kWh was appropriate for use for this study based on the national average electricity price as of May 2014 (U.S. EIA, 2015). The 2014 electricity costs match the 2014-dollar basis discussed in Section 3.2.1.

3.2.3.1 Dechlorination

Dechlorination is not a unit process available in CAPDETWorks™. Therefore, ERG developed a costing methodology for dechlorination based on the CAPDETWorks™ chlorination unit process and vendor costs, which was then incorporated into the CAPDETWorks™ outputs to calculate the total costs of all nine wastewater treatment configurations.

Capital cost elements for dechlorination include the dechlorination contact tank, dechlorination building, chemical storage building, sodium bisulfite liquid feed system, and miscellaneous items (e.g., grass seeding, site cleanup, piping). The dechlorination contact tank, dechlorination building, chemical storage building, and miscellaneous items are similar to the components included in the CAPDETWorks™ chlorination unit process. As a result, ERG estimated costs for these capital cost elements using the CAPDETWorks™ chlorination unit process with design values for contact time and chemical dose to simulate dechlorination. ERG estimated purchase costs for the sodium bisulfite liquid feed system based on cost information provided by a vendor.

Operating and maintenance cost elements for dechlorination include operating labor, maintenance labor, materials and supplies costs, sodium bisulfite chemicals, and energy. ERG estimated operating and maintenance labor, materials, and supplies costs using the CAPDETWorks™ chlorination unit process with design values for contact time and chemical dose to simulate dechlorination. Estimated energy costs for the sodium bisulfide feed system pump is based on energy usage provided by the vendor and the energy rate used for the CAPDETWorks™ costing ($0.10/kWh). Sodium bisulfite chemical costs are estimated using the following sodium bisulfite dosages with the chlorination effluent flow rate provided from the CAPDETWorks™ chlorination unit process:

- 1.5 mg/L for Levels 1, 2-1, 2-2, 3-1, 3-2, 4-1, and 4-2 wastewater treatment configurations.
- 3.0 mg/L for Levels 5-1 and 5-2 that includes 1.5 mg/L for the dechlorination requirement and 1.5 mg/L for the reverse osmosis pretreatment requirement.

ERG used a 40% sodium bisulfite solution cost of $344/ton in 2010 $ as provided by a vendor, converted to 2014 $ using the methodology presented in Section 3.2.1.

Detailed descriptions of the dechlorination costing approach are provided in Appendix E.2, including all cost bases, assumptions, and calculations.

3.2.3.2 Fermentation

Fermentation is not a unit process available in CAPDETWorks™. However, as detailed in *Municipal Nutrient Removal Technologies Reference Document* (EPA, 2008), a fermenter is an oversized gravity thickener with additional piping and mixers. In the *Municipal Nutrient Removal Technologies Reference Document*, the fermenter was modeled using the CAPDETWorks™ gravity thickener module and escalating the results by 50 percent (EPA, 2008). ERG used best professional judgement to confirm this approach and modeled the gravity thickener unit process in CAPDETWorks™ and multiplied the capital, operating, and maintenance costs by 1.5 to account for the larger size, additional equipment, and associated increased energy.

3.2.3.3 4-Stage Biological Nutrient Removal (Modified UCT and 4-Stage Bardenpho)

CAPDETWorks™ does not include a 4-stage biological nutrient removal (BNR) unit process, like those included in Level 3-2 as a 4-stage Modified University of Cape Town (UCT) and Level 4-2 as a 4-stage Bardenpho with membrane bioreactor. However, CAPDETWorks™ includes 3-stage and 5-stage BNR unit processes. For each of the wastewater treatment configurations with 4-stage BNR unit processes, ERG developed two separate CAPDETWorks™ models that included all of the same unit processes, except model 1 included the 3-stage BNR unit process and model 2 included the 5-stage BNR unit process. ERG combined the CAPDETWorks™ output from models 1 and 2 to estimate the capital, operating, and maintenance costs for the 4-stage BNR units, as described below.

Capital cost elements for BNRs include the BNR tank, blower system, internal recycle pumps, and sludge recycle pumps. Operating and maintenance cost elements for BNRs include operating labor, maintenance labor, materials costs, and energy.

For the 4-stage Modified UCT in Level 3-2, ERG modeled the 3-stage version using a 3-stage BNR with two internal recycle pumps to reflect the multiple recycles in the Modified UCT. ERG used the Level 3-1 wastewater treatment configuration for the 5-stage version. The capital costs for the BNR tanks, blower system, and BNR sludge recycle pumps were averaged for the 3- and 5-stage models, while the capital costs from the 3-stage model were used for the BNR internal recycle pumps. The capital costs for all other unit processes in these models had the same capital costs. The operating and maintenance costs for the BNR tank, BNR sludge recycle pumps, and blower system were averaged for the 3- and 5-stage models; the 3-stage model costs were used for the BNR internal recycle pumps; and the 5-stage model costs were used for the chemical phosphorus removal and alum feed system because the Modified UCT will achieve biological phosphorus removal closer to the 5-stage BNR model and, therefore, would require less alum to achieve the target effluent phosphorus concentration. The operating and maintenance costs for all other unit processes in these models had negligible differences between the 3- and 5-stage models.

For the 4-stage Bardenpho with membrane bioreactor, ERG modeled the 3-stage model using the 3-stage BNR with membrane bioreactor and 5-stage model using the 5-stage BNR with membrane bioreactor. The capital, operating, and maintenance costs for the BNR tank, BNR internal recycle pumps, and BNR sludge recycle pumps were averaged for the 3- and 5-stage models. The capital costs for all other unit processes in these models had negligible differences in the capital costs. The operating and maintenance costs for the chemical phosphorus removal and alum feed system from the 5-stage model were used because the 4-stage Bardenpho with membrane bioreactor will achieve biological phosphorus removal closer to the 5-stage BNR model and, therefore, would require less alum to achieve the target effluent phosphorus concentration. The operating and maintenance costs for all other unit processes in these models had negligible differences between the 3- and 5-stage models.

Details on how the 3- and 5-stage models were combined for the Level 3-2 and Level 4-2 wastewater treatment configurations are included in Section 5.

3.2.3.4 Methanol Addition for Biological Nutrient Removal Supplemental Carbon for Level 4-2 MBR

Biological nitrogen removal requires an adequate supply of carbon for denitrification. CAPDETWorks™ includes an external carbon source (i.e., methanol addition) to:

- Level 2-2 AS3's denitrification – suspended growth
- Level 4-1 B5/Denit's denitrification filter
- Level 5-1 B5/RO's denitrification filter

ERG included fermenters to provide an internal carbon source for biological nitrogen removal occurring in the Bardenpho and Modified University of Cape Town reactors in:

- Level 3-1 B5
- Level 3-2 MUCT
- Level 4-1 B5/Denit
- Level 5-1 B5/RO
- Level 5-2 MBR/RO

However, there is no internal carbon source for denitrification in Level 4-2 MBR. As a result, the Level 4-2 wastewater treatment configuration required methanol addition from an external carbon source. CAPDETWorks™ Version 3.0 does not include a stand-alone methanol addition unit process. Therefore, ERG developed a costing methodology for supplemental methanol addition based on the effluent nitrate target in CAPDETWorks™ denitrification filter unit process, which was then incorporated into the CAPDETWorks™ outputs to calculate the total costs for the Level 4-2 wastewater treatment configuration. CAPDETWorks™ calculates the methanol addition in the denitrification filter unit process based on 3 mg methanol per mg nitrate removed (Hydromantis, 2014). ERG determined the CAPDETWorks™ effluent nitrate target for the denitrification filter unit process as 1.95 mg/L nitrate based on the required denitrification to achieve the 3 mg/L total nitrogen for Level 4 (total Kjeldahl nitrogen effluent is 1.05 mg/L).

Capital cost elements for methanol addition include a methanol liquid feed system, chemical storage area, and miscellaneous items (e.g., grass seeding, site cleanup, piping). The methanol liquid feed system is the same as the methanol liquid feed system included in CAPDETWorks™ denitrification filter unit process with design values for the effluent nitrate target to simulate the denitrification requirement. CAPDETWorks™ does not include separate methanol storage area costs or miscellaneous items in the denitrification filter unit process. As such, ERG assumed that these costs are minimal and would be accounted for in the 4-stage Bardenpho costs.

Operating and maintenance cost elements for methanol addition include operating labor, maintenance labor, materials and supplies costs, methanol chemicals, and energy. ERG estimated methanol chemicals using the CAPDETWorks™ denitrification filter unit process with design values for the effluent nitrate target to simulate the denitrification requirement. CAPDETWorks™ does not include separate operating labor, maintenance labor, materials and supplies costs, and energy costs for the methanol system in the denitrification filter unit process. As a result, ERG assumed that these costs are minimal and would be accounted for in the 4-stage Bardenpho operating and maintenance costs. Methanol chemical costs are based on the CAPDETWorks™ default cost of $0.60/lb methanol in 2014 $ (Hydromantis, 2014).

Detailed descriptions of the methanol addition for biological nutrient removal supplemental carbon are provided in Appendix E.4, including all cost bases, assumptions, and calculations.

3.2.3.5 Ultrafiltration

Ultrafiltration is not a unit process available in CAPDETWorks™ Version 3.0. Therefore, ERG developed a costing methodology for ultrafiltration outside of CAPDETWorks™ and then incorporated the cost elements into the CAPDETWorks™ outputs to calculate the total cost of each wastewater treatment configuration that includes ultrafiltration (Level 5-1 B5/RO).

Capital cost elements for ultrafiltration include the membrane filtration system (membrane equipment and all appurtenances such as feed pumps, backwash system, and clean-in-place system) and a building to house the membrane filtration system. ERG estimated purchased equipment costs for the membrane filtration system based on cost information provided by a vendor. ERG estimated capital costs for the building using a CAPDETWorks™ building unit total capital cost of $110/square foot and an estimated building footprint provided by the vendor.

Operating and maintenance cost elements for ultrafiltration include operating labor, maintenance labor, materials costs (assumed a 7-year membrane life), chemicals (membrane cleaning), and energy. Operating and maintenance labor costs were estimated using a combination of information provided by the vendor, best professional judgement, and labor rates from CAPDETWorks™. Membrane replacement and chemicals costs are based on cost information provided by the vendor. Estimated energy usage for the membrane filtration system is based on a combination of information provided by the vendor and literature sources. ERG then calculated estimated energy costs by multiplying the estimated energy usage by the energy rate used for the CAPDETWorks™ costing ($0.10/kWh).

Detailed descriptions of our ultrafiltration costing approach are provided in Appendix E.5, including all cost bases, assumptions, and calculations.

3.2.3.6 Reverse Osmosis (RO)

RO is not a unit process available in CAPDETWorks™ Version 3.0. Therefore, ERG developed a costing methodology for RO outside of CAPDETWorks™ and then incorporated the cost elements into the CAPDETWorks™ outputs to calculate the total cost of for each wastewater treatment configuration that includes RO (Level 5-1 B5/RO and Level 5-2 MBR/RO).

Capital cost elements for RO include the RO system (membrane equipment and all appurtenances such as feed pumps, backwash system, and clean-in-place system), a chlorine gas feed system, a dechlorination feed system, an antiscalant feed system, a brine surge sump, and a building to house the RO system. ERG estimated purchased equipment costs for the RO system based on cost information provided by a RO vendor. ERG estimated capital costs for the building using a CAPDETWorks™ building unit total capital cost of $110/square foot and an estimated building footprint provided by the RO vendor. Costs for the chlorination feed system are included within the CAPDETWorks™ chlorination module discussed previously in this section. Costs for the dechlorination and antiscalant feed systems were estimated based on cost information provided by a feed system vendor. For the brine surge sump, ERG first estimated the required sump volume, assuming a 60-minute hydraulic residence time, based on best professional judgement. ERG then estimated the brine sump total capital costs using online RS Means Building Construction Cost Data.

Operating and maintenance cost elements for RO include operating labor, maintenance labor, materials costs (assumed a 4-year membrane life), chemicals (membrane cleaning, antiscalant, chlorine gas, and sodium bisulfite dechlorination), and energy. Operating and maintenance labor costs were estimated using a combination of information provided by the RO vendor, best professional judgement, and labor rates from CAPDETWorks™. Membrane replacement and membrane cleaning chemical costs are based on cost information provided by the vendor. Antiscalant chemical costs were estimated using the dosage rate provided by the RO vendor and a chemical cost provided by a chemical vendor. Chlorine gas and sodium bisulfite chemical costs are included within the CAPDETWorks™ chlorination module and the supplemental dechlorination module developed by ERG discussed previously in this section. Estimated energy usage for the RO system is based on a combination of information provided by the RO vendor and literature sources; estimated energy usage for the dechlorination and antiscalant feed systems is based on information provided by the chemical feed system vendor. ERG then calculated estimated RO and feed system energy costs by multiplying the estimated energy usage by the energy rate used for the CAPDETWorks™ costing ($0.10/kWh).

Detailed descriptions of our RO system costing approach are provided in Appendix E.6, including all cost bases, assumptions, and calculations.

3.2.3.7 Deep Injection Well

Deep well injection is not a unit process available in CAPDETWorks™ Version 3.0. Therefore, ERG developed a costing methodology for deep well injection outside of CAPDETWorks™ and then incorporated the cost elements into the CAPDETWorks™ outputs to calculate the total cost of each wastewater treatment configuration that includes brine disposal (Level 5-1 B5/RO and Level 5-2 MBR/RO).

Capital cost elements for deep well injection include injection well pumps, a building to house the injection pumps and electrical control panel and drilling the underground injection well. Purchase costs for the injection well pumps were based on information provided by a pump vendor; pump freight costs were estimated based on information from an equipment supply vendor. ERG estimated capital costs for the building using a CAPDETWorks™ building unit total capital cost of $110/square foot and an estimated building footprint developed based on best professional judgement. ERG estimated costs for drilling a new underground injection well based on cost information provided by a waste disposal vendor.

Operating and maintenance cost elements for deep well injection include operating labor, maintenance labor, materials costs, and energy. Operating and maintenance labor costs were estimated using a combination of best professional judgement and labor rates from CAPDETWorks™. Materials costs were estimated as 2 percent of injection well pump purchase cost, based on CAPDETWorks™ methodology. ERG estimated energy usage for the injection well pumps using the pump HP rating and assuming continuous operation. ERG then calculated estimated injection well pump energy costs by multiplying the estimated energy usage by the energy rate used for the CAPDETWorks™ costing ($0.10/kWh).

Detailed descriptions of our deep well injection costing approach are provided in Appendix E.7, including all cost bases, assumptions, and calculations.

3.2.3.8 Anaerobic Digester Natural Gas Usage

CAPDETWorks™ assumes that the gas produced by the anaerobic digester is used to supply heat to the anaerobic digester. If the digester gas produced is insufficient, CAPDETWorks™ uses natural gas for the difference. Because most WWTPs flare the digester gas, ERG revised the energy calculations for the anaerobic digester to assume that all the heat required was provided by natural gas using Equation 2 and Equation 3, and that all digester gas produced was flared.

$$\text{Energy Costs} = \text{Electricity Cost} + \text{Total Natural Gas Required} \times \text{Natural Gas Cost}$$

Equation 2

where:

Energy Costs (2014 $/yr) = Energy cost to run the anaerobic digester for a year

Electricity Cost (2014 $/yr) = Electricity cost from CAPDETWorks™ to run the anaerobic digester for a year

Total Natural Gas Required (1,000 cuft/yr) = Natural gas required to heat the anaerobic digester (see Equation 3)

Natural Gas Cost (2014 $/1,000 cuft) = $15,500/1,000 cuft

$$\text{Total Natural Gas Required} = \frac{\text{Heat Required}}{\text{Boiler Efficiency} \times \text{Heat Exchanger Efficiency}} \times \frac{\text{Hours per Year Conversion}}{\text{Natural Gas Heating Value}} \times \text{Unit Conversion}$$

Equation 3

where:

Total Natural Gas Required (1,000 cuft/yr) = Natural gas required to heat the anaerobic digester

Heat Required (BTU/hr) = Heat required to heat the anaerobic digester

Boiler Efficiency (%) = 80%

Heat Exchanger Efficiency (%) = 90%

Hours per Year Conversion (hr/yr) = 8,760 hr/yr

Natural Gas Heating Value (BTU/cuft) = 1,000 BTU/cuft

Unit Conversion (1,000 cuft/cuft) = 1,000 cuft (with 1,000 cuft as the unit)/ 1,000 cuft (with cuft as the unit)

3.3 LCCA

LCCA enables a total cost comparison of the nine wastewater treatment configurations including all of the relevant costs that occur throughout the life of the treatment alternatives. The total plant costs are presented in two ways: 1) total capital costs along with total annual costs (see Section 3.3.1) and 2) net present value (see Section 3.3.2). The net present value is a method to combine one-time capital costs and periodic (annual) operating and maintenance costs into one value for direct comparison of costs for alternative wastewater treatment configurations.

3.3.1 Total Capital and Total Annual

The total capital costs include the purchased equipment, direct costs, and indirect costs. The purchased equipment includes the cost to purchase the equipment and freight to get the equipment to the WWTP site. The direct costs are costs incurred as a direct result of installing the WWTP. For this study, the direct costs include mobilization, site preparation, site electrical, yard piping, instrumentation and control, and lab and administration building. The indirect costs are non-direct costs incurred as a result of installing the WWTP. For this study, the indirect costs include land, miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, technical, interest during construction, and profit. The total capital costs are calculated using Equation 4 for each wastewater treatment configuration.

$$\text{Total Capital Costs} = \text{Purchased Equipment Costs} + \text{Direct Costs} + \text{Indirect Costs}$$

Equation 4

where:

Total Capital Cost (2014 \$) = Total capital costs

Purchased Equipment Costs (2014 \$) = Costs to purchase the equipment for the WWTP, including ancillary equipment and freight costs (see the following subsection for details)

Direct Costs (2014 \$) = Costs incurred as a direct result of installing the WWTP (see the following subsection for details)

Indirect Costs (2014 \$) = Costs for all non-direct costs incurred as a result of installing the WWTP (see the following subsection for details)

The total annual costs (often referred to as O&M) include the operation and maintenance labor, materials, chemicals, and energy. CAPDETWorks™ includes the periodic replacement of equipment parts (e.g., membranes, filter media, pumps) in the materials' annual costs. ERG used the same methodology for the membrane replacement costs for ultrafiltration and RO, which are detailed in Sections 3.2.3.4 and 3.2.3.6. ERG calculated total annual costs using Equation 5.

$$\text{Total Annual Costs} = \text{Operation Costs} + \text{Maintenance Costs} + \text{Materials Costs} + \text{Chemical Costs} + \text{Energy Costs}$$

Equation 5

where:

Total Annual Costs (2014 \$/year) = Total annual operation and maintenance costs

Operation Costs (2014 \$/year) = Labor costs for manual labor required to operate the WWTP for a year, including operation, administrative, and laboratory labor

Maintenance Costs (2014 \$/year) = Labor costs for manual labor required to maintain the WWTP for a year

Materials Costs (2014 \$/year) = Materials costs for operation and maintenance of the WWTP for a year, including replacement equipment

Chemical Costs (2014 \$/year) = Chemical costs for chemicals required for WWTP operation (e.g., alum, polymer) for a year

Energy Costs (2014 \$/year) = Electricity costs to run the WWTP for a year

CAPDETWorks™ calculates the operation and maintenance costs based on labor required and average salary for each job description: administrative, operation, maintenance, and laboratory. The administrative and laboratory labor hours are based on the WWTP flow rate, while the operation and maintenance hours are calculated for each process based on factors like the flow rate, number of units in each process, wastewater characteristics (e.g., total dissolved solids), and process design factors (e.g., required air rate). CAPDETWorks™ calculates the materials costs for operation and maintenance for each unit process based on factors like flow rate, unit capacity, and total construction cost. CAPDETWorks™ calculates the chemical costs based on the specific unit processes and the dosage rate. CAPDETWorks™ calculates the energy costs using the energy consumption requirements for the unit processes and \$0.10/kWh. As of May 2014, the average price of electricity for all sectors was \$0.1023/kWh as published by the U.S. Energy Information Administration (US EIA, 2015). As a result, ERG used the CAPDETWorks™ default electricity price, which is reflective of 2014 to match the 2014-dollar basis discussed in Section 3.2.1.

ERG used the CAPDETWorks™ total annual costs for unit processes in CAPDETWorks™. For unit processes not in CAPDETWorks™, ERG calculated total annual costs including the same components as CAPDETWorks™, as applicable for the specific unit process.

Purchased Equipment Costs

ERG costed the purchased equipment primarily using CAPDETWorks™, as described in Section 3.2.2 above. However, certain unit processes comprising the system configurations are not available in CAPDETWorks™. For these unit processes, ERG developed costs outside of CAPDETWorks™ and then incorporated these cost elements into the CAPDETWorks™ outputs to calculate the total purchased equipment costs for each wastewater treatment configuration, as presented in Equation 6.

$$\text{Purchased Equipment Costs} = \sum \text{Unit Process Equipment Costs} \qquad \text{Equation 6}$$

where:

Purchased Equipment Costs (2014 $) = Costs to purchase the equipment for the WWTP, including ancillary equipment and freight costs

Unit Process Equipment Costs (2014 $) = Costs to purchase the equipment for each unit process at the WWTP, including costs from CAPDETWorks™ and developed outside of CAPDETWorks™ (see Section 3.2.2 for details)

Direct Costs

CAPDETWorks™ includes direct costs for mobilization, site preparation, site electrical, yard piping, instrumentation and control, and lab and administration building. These direct costs account for the portions of the wastewater treatment configuration that are not directly associated with a unit process. CAPDETWorks™ calculates direct costs proportional to the WWTP flow based on cost curves generated from EPA's *Construction Costs for Municipal Wastewater Treatment Plants: 1973-1978* (U.S. EPA, 1980). Using this approach would not account for differences in the direct costs due to the increasing complexity of the nine wastewater treatment configurations. The CAPDETWorks™ approach is also inconsistent with standard engineering costing that calculates direct costs as a percentage of purchased equipment costs (Peters and Timmerhaus, 1991; Falk et al., 2011). As a result, ERG used the CAPDETWorks™ results from the Level 1 wastewater treatment configuration with the CAPDETWorks™ default unit process inputs to calculate direct cost factors for each direct cost element as a percentage of total purchased equipment cost as presented in Equation 7. Because CAPDETWorks™ calculates the same direct costs for all nine wastewater treatment configurations, calculating the direct cost factors using the lowest purchased equipment costs of the nine wastewater treatment configurations (i.e., Level 1), will result in the highest direct costs factors. ERG confirmed the calculated direct cost factors were reasonable based on other engineering sources (Falk et al., 2010).

$$\text{Direct Cost Factor} = \frac{\text{Level 1 Direct Cost}}{\text{Level 1 Purchased Equipment Cost}}$$

Equation 7

where:

Direct Cost Factor (%) = Direct cost factor for each direct cost element, see Table 1 below

Level 1 Purchased Equipment Cost (2014 $) = $19,600,000 (see Appendix E.8)

Level 1 Direct Cost (2014 $) = see Table 3-2 below

Table 3-2. Direct Cost Factors

Direct Cost Elements	Level 1 Direct Costs (2014 $)	Direct Cost Factor (%)
Mobilization	$818,000	4%
Site Preparation	$1,090,000	6%
Site Electrical	$2,360,000	12%

Table 3-2. Direct Cost Factors

Direct Cost Elements	Level 1 Direct Costs (2014 $)	Direct Cost Factor (%)
Yard Piping	$1,550,000	8%
Instrumentation and Control	$1,240,000	6%
Lab and Administration Building	$1,930,000	10%

Source: Appendix E.8.

ERG applied the direct cost factors from Table 3-2 to the total purchased equipment cost for each of the nine wastewater treatment configurations using Equation 8 to calculate the direct costs for each direct cost element.

$$\text{Direct Cost} = \text{Direct Cost Factor} \times \text{Purchased Equipment Cost}$$

Equation 8

where:

Direct Cost (2014 $) = Direct cost for each direct cost element

Direct Cost Factor (%) = Direct cost factor for each direct cost element, see Table 3-2

Purchased Equipment Cost (2014 $) = Total purchased equipment cost for each wastewater treatment configuration (see Equation 6)

Indirect Costs

CAPDETWorks™ includes indirect costs for land, miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, technical, interest during construction, and profit. ERG used Equation 9 to calculate the total indirect costs.

$$\text{Indirect Costs} = \text{Land Cost} + \text{Remaining Indirect Costs} + \text{Interest During Construction}$$

Equation 9

where:

Indirect Costs (2014 $) = Costs for all non-direct costs incurred as a result of installing the WWTP

Land Cost (2014 $) = Total cost for the land required for the WWTP, see Equation 10 below

Remaining Indirect Costs (2014 $) = Indirect costs associated with miscellaneous costs, legal costs, engineering design fee, inspection costs, contingency, technical, and profit, see Equation 11 below

Interest During Construction (2014 $) = Interest paid during construction, see Equation 12 below

ERG used CAPDETWorks™ land costs, which are calculated using Equation 10.

$$\text{Land Cost} = \text{Treatment Area} \times \text{Land Unit Cost}$$

Equation 10

where:

Land Cost (2014 \$) = Total cost for the land required for the WWTP

Treatment Area (acres) = Required treatment area for the WWTP based on the unit processes costed from CAPDETWorks™[6]

Land Unit Cost (2014 \$/acre) = \$20,000/acre, the CAPDETWorks™ default land unit cost, (Hydromantis, 2014)

For the remaining indirect costs ERG used contingency cost percentage based on cost estimate recommended practices (ACCEI, 2016) and CAPDETWorks™' indirect cost percentages (Table 3-3) to calculate indirect costs as a percentage of purchased equipment cost and direct construction costs for each wastewater treatment configuration as presented in Equation 11.

$$\text{Remaining Indirect Costs} = \text{Indirect Cost Factor} \times (\text{Purchased Equipment Cost} + \text{Direct Cost})$$

Equation 11

where:

Remaining Indirect Cost (2014 \$) = Indirect costs associated with miscellaneous costs, legal costs, engineering design fee, inspection costs, contingency, technical, and profit

Indirect Cost Factor (%) = Indirect cost factor for each indirect cost element, see Table 3-3

Purchased Equipment Cost = Total purchased equipment cost (see Equation 6)

Direct Cost (2014 \$) = Total direct costs (see Equation 8)

Table 3-3. Indirect Cost Factors

Indirect Cost Elements	Indirect Cost Factor (%)
Miscellaneous Costs	5%
Legal Costs	2%
Engineering Design Fee	15%

[6] All unit processes in the wastewater treatment configurations for Levels 1 through 4 are included in CAPDETWorks™ land area calculations. For the Level 5 wastewater treatment configurations, ERG determined that the land requirements for the non-CAPDETWorks™ unit processes (i.e., Level 5-1: ultrafiltration, reverse osmosis, and deep injection well; Level 5-2: reverse osmosis and deep injection well) was minimal and would fit within the CAPDETWorks™ land area.

Table 3-3. Indirect Cost Factors

Indirect Cost Elements	Indirect Cost Factor (%)
Inspection Costs	2%
Contingency	20%
Technical	2%
Profit	15%

Source: Hydromantis, 2014; AACEI, 2016.

For the interest during construction, ERG used Equation 12.

$$\text{Interest During Construction} = (\text{Purchased Equipment Cost} + \text{Direct Costs} + \text{Select Indirect Costs}) \times \text{Construction Period} \times \frac{\text{Interest Rate During Construction}}{2}$$

Equation 12

where:

Interest During Construction (2014 $) = Interest paid during construction

Purchased Equipment Cost (2014 $) = Total purchased equipment cost for each wastewater treatment configuration (see Equation 6)

Direct Costs (2014 $) = Total direct costs (see Equation 8)

Select Indirect Costs (2014 $) = Indirect costs, including miscellaneous items, legal costs, engineering design fee, inspection costs, contingency, and technical

Construction Period (years) = 3 years based on CAPDETWorks™ default construction period (Hydromantis, 2014)

Interest Rate During Construction (%) = Interest rate during construction

ERG used 3% and 5% interest rates during construction, which are the same values ERG used for the discount rates discussed in Section 3.3.2. The 3% interest rate represents a conservative interest rate for a State Revolving Fund (SRF) loan as the SRF average loan rate was 1.7% in April 2016 (U.S. EPA, 2016a). The 5% interest rate represents a worse-case scenario reflective of rates that WWTPs in poor financial shape, but still able to borrow, would be able to obtain.

3.3.2 Net Present Value

ERG calculated the net present value using Equation 13. This equation assumes that the only value remaining in the WWTP at the end of the planning period is in the land, which increases in value by 3% over the planning period using CAPDETWorks™' approach.

$$\text{NPV} = \frac{(1+i)^{PP}-1)}{i \times (1+i)^{PP}} \times (\text{Amortized Construction Cost} + \text{Total O\&M Cost})$$

$$+ \text{Land} \times \left(1 - (1.03^{PP}) \times \frac{1}{(1+i)^{PP}}\right)$$

Equation 13

where:

NPV (2014 $) = Net present value of all costs necessary to construct and operate the WWTP

Amortized Construction Cost (2014 $/yr) = Total construction costs amortized over the WWTP planning period, see Equation 14 below

Total O&M Costs (2014 $/yr) = Total annual operation and maintenance costs, see the previous subsection

Land (2014 $) = Land costs from CAPDETWorks™ models for each wastewater treatment configuration

i (%) = Real discount rate

PP (years) = WWTP planning period

1.03 = Factor to account for a 3% increase in land value over the WWTP planning period

ERG used 3% and 5% real discount rates, which are the same values ERG used to calculate the interest during construction. See the indirect costs subsection within Section 3.3.1 for a discussion on the basis for the selected interest rates. The real discount rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years and has been adjusted to eliminate the effect of expected inflation. As a result, ERG did not adjust the construction or O&M costs for inflation. ERG used 20 years as the WWTP planning period.

ERG calculated amortized construction costs using Equation 14.

$$\text{Amortized Construction Cost} = -12 \times \text{PMT}\left(\frac{i}{12}, \text{PP}, \text{Total Capital Cost}, 0, 0\right)$$

Equation 14

where:

Amortized Construction Cost (2014 $) = Total construction costs amortized over the WWTP planning period

PMT = Excel® function that calculates the stream of equal periodic payments that has the same present value as the actual stream of unequal payments over the project life at a constant interest rate (for example, a mortgage converts the one-time cost of a house to a stream of constant monthly payments)

i (%) = 3% and 5% discount rates

PP (years) = WWTP planning period (20 years)

Total Capital Cost (2014 $) = Total capital costs, see Equation 4

3.4 Data Quality

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* approved by EPA on March 25, 2015 (ERG, 2015c), ERG collected existing data[7] to develop cost estimates for the nine wastewater treatment configurations in this study. As discussed in Section 3.1, the cost estimate data sources include CAPDETWorks™ Version 3.0 (Hydromantis, 2014), EPA reports, peer-reviewed literature, publicly available equipment costs from and communication with technology vendors, and industry-accepted construction cost data and indices. ERG evaluated the collected information for completeness, accuracy, and reasonableness. In addition, ERG considered publication date, accuracy/reliability, and costs completeness when reviewing data quality. Finally, ERG performed conceptual, developmental, and final product internal technical reviews of the costing methodology and calculations for this study.

Table 3-4 presents the data quality criteria ERG used when evaluating collected cost data. ERG documented the data quality for each data source for each criterion in a spreadsheet for EPA's use in determining whether the cost data are acceptable for use. All of the references used to develop the costs met all of the data quality criteria with the exceptions of EPA's Wastewater Technology Fact Sheet – Dechlorination (U.S. EPA. 2000), EPA's Biosolids Technology Fact Sheet – Gravity Thickening (U.S. EPA, 2003a), and EPA's Wastewater Technology Fact Sheet – Screening and Grit Removal (U.S. EPA, 2003b). These references did not meet the criteria for currency (up to date). ERG used the Wastewater Technology Fact Sheet – Dechlorination to develop the contact time required to dechlorinate the residual chlorine. Although this EPA report is not current, the contact time for dechlorination has not changed since the fact sheet was published. ERG used the Biosolids Technology Fact Sheet – Gravity Thickening to revise the gravity thickener default CAPDETWorks™ values for depth and standard cost for a 90 ft diameter thickener. ERG used the Wastewater Technology Fact Sheet – Screening and Grit Removal to revise the CAPDETWorks™ purchased equipment cost for the preliminary treatment unit process (i.e., screening and grit removal). Although these EPA reports are not current, ERG revised the default values based on feedback from Falk et al. (2017) that the CAPDETWorks™ default values, designed in the 1970s, were no longer appropriate.

Table 3-4. Cost Data Quality Criteria

Quality Criterion: Cost Data	Description/Definition
Current (up to date)	Report the time period of the data. Year of publication (or presentation, if a paper presented at a conference) is 2005 or after.
Complete	Identify if all units are reported. Identify the cost per year basis reported. [a]
Representative	Report if the costs are for unit processes used in the selected nutrient wastewater treatment configurations.

[7] *Existing data* means information and measurements that were originally produced for one purpose that are recompiled or reassessed for a different purpose. Existing data are also called secondary data. Sources of existing data may include published reports, journal articles, LCI and government databases, and industry publications.

Table 3-4. Cost Data Quality Criteria

Quality Criterion: Cost Data	Description/Definition
Accurate/Reliable	Document the source of the data. Were the data (1) obtained from well-known technical references for engineering design and cost information, as well as for general cost factors (e.g., engineering, permitting, scheduling), or (2) from selected vendors that are the leaders within their areas of expertise determined based on the use of their technologies at municipal facilities that have well designed and operated wastewater treatment systems?

a – See Section 3.2.1 for the calculation ERG used to convert all costs to a standard year basis using RSMeans Construction Cost Index (RSMeans, 2017).

ERG developed the CAPDETWorks™ input files containing all the necessary information and data required for the tool to execute the wastewater treatment designs and engineering costing. All CAPDETWorks™ input files were reviewed by a team member knowledgeable of the project, but who did not develop the input files. The reviewer ensured the accuracy of the data transcribed into the input files, the technical soundness of methods and approaches used (i.e., included all of the cost components and LCA inputs) and the accuracy of the calculations (i.e., used the methodology in Section 3.3 to calculate the costs).

ERG developed the supplemental cost estimates for ultrafiltration, reverse osmosis, and deep well injection in an Excel® Workbook. A team member knowledgeable of the project, but who did not develop the Excel® workbook, reviewed the workbook to ensure the accuracy of the data transcribed into the workbook, the technical soundness of methods and approaches used, and the accuracy of calculations.

4. LCA METHODOLOGY

This chapter covers the data collection process, data sources, assumptions, methodology and parameters used to construct the LCI model for this study. Following the LCI discussion, details on the impact assessment are provided.

4.1 Life Cycle Inventory Structure

LCI data are the foundation of any LCA study. Every element included in the analysis is modeled as its own LCI unit process entry (see Appendix G for an example). It is the connection of LCI unit process data that constitutes the LCA model. A simplified depiction of a subset of this structure for this study is shown in Figure 4-1. The overall system boundaries were previously presented in Figure 1-1, and include all unit processes associated with plant operations and disposal of sludge, not just those processes associated with nutrient removal. It is not possible to display this type of figure for the entire LCA model, as each LCA model includes thousands of connected unit process inputs and outputs. Each box in the figure represents an LCI unit process. The full system is a set of nested LCIs where the primary process outputs, in red, of one process serve as inputs, in blue, to another process. Within each nested level, there can be flows both to and from the environment. Flows from the environment are written in black in Figure 4-1 and are represented by the thin black arrows crossing the system boundary from nature. Emissions to the environment are listed in green, and it is these flows that are tabulated in the calculation of environmental impacts. Intermediate inputs are shown in blue text. Intermediate inputs are those that originate from an extraction or manufacturing process within the supply-chain.

The distinction between the foreground and background systems is not a critical one. The foreground system tends to be defined as those LCIs that are the focus of the study. In this case, that is the WWTP itself. Foreground information was drawn directly from the CAPDETWorks™ Version 3.0 modeling software or calculated separately for input and output flows not captured by the software. Background LCI information is comprised of extractive and manufacturing processes that create material and energy inputs required by the wastewater treatment systems. Background data are drawn from a version of the U.S. LCI as well as ecoinvent databases that have been harmonized and modified by EPA's Office of Research and Development (ORD) (LCA Research Center, 2015). Details on the data sources for the background databases used is provided in Section 4.2 and detailed data sources and input and output flow values for the foreground unit processes are provided in Section 4.3.

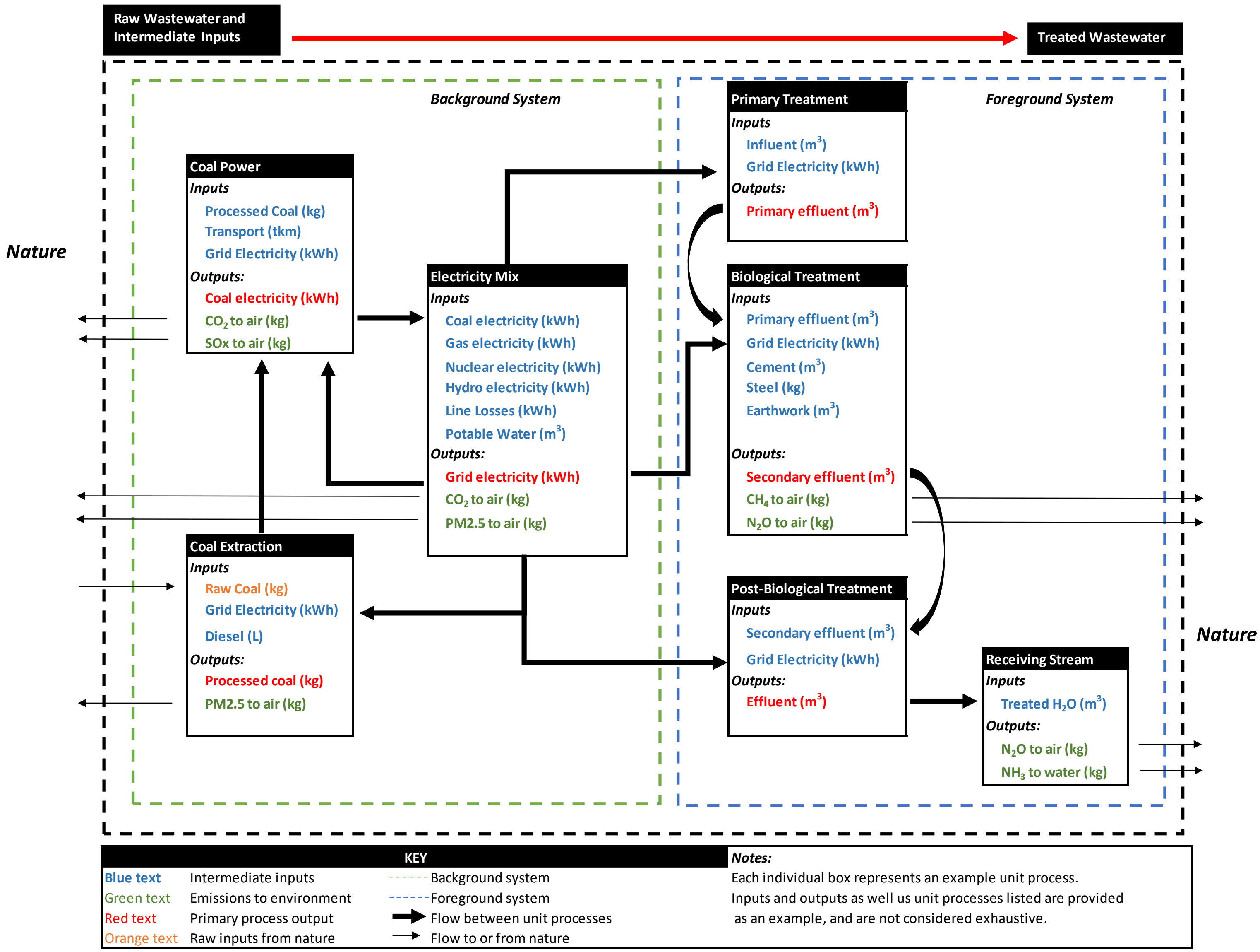


Figure 4-1. Subset of LCA Model Structure with Example Unit Process Inputs and Outputs

4.2 LCI Background Data Sources

The supply chains of inputs to the wastewater treatment processes are represented where possible using the EPA ORD LCA database (U.S. EPA, 2015f), which is a modified combination of the National Renewable Energy Laboratory's U.S. Life Cycle Inventory database (U.S. LCI) and ecoinvent Version 2.2 (NREL, 2015; Ecoinvent Centre, 2010b). The U.S. LCI is a publicly available life cycle inventory database widely used by LCA practitioners. Ecoinvent is also a widely used global LCI database available by paid subscription. Both allow the user access to inputs to and outputs from each unit process. Ecoinvent Version 3.2 is used to fill any gaps where data do not exist in the EPA ORD LCA database, U.S. LCI or ecoinvent Version 2.2 (Ecoinvent Centre, 2015). The list of background unit processes and their associated database source used in the LCA model is presented in Table 4-1.

Table 4-1. Background Unit Process Data Sources

Background Input	Original Unit Process Name	LCI Database
Electricity	Electricity, at industrial user	EPA ORD LCA Database
Natural Gas	Natural gas, combusted in industrial equipment	U.S. LCI
Chlorine Gas	chlorine, gaseous, diaphragm cell, at plant	ecoinvent v2.2
Polymer	polyacrylamide	ecoinvent v3.2
Sodium Bisulfite (40%)	Sodium hydrogen Sulfite, 40% in solution	ecoinvent v3.2
Sodium Bisulfite (12.5%)	Sodium hydrogen Sulfite, 12.5% in solution	ecoinvent v3.2
Truck Transport	Truck transport, class 8, heavy heavy-duty (HHD), diesel, short-haul, load factor 0.5	ecoinvent v2.2
Al Sulfate	Aluminium sulphate, powder, at plant	ecoinvent v2.2
Calcium Carbonate	Lime, from carbonation, at regional storehouse	ecoinvent v2.2
Methanol	Methanol, at plant	ecoinvent v2.2
Antiscalant	Polycarboxylates, 40% active substance | polycarboxylates production, 40% active substance	ecoinvent v3.2
Citric Acid	Citric acid | citric acid production	ecoinvent v3.2
Sodium Hypochlorite	Sodium hypochlorite, 15% in H2O, at plant	ecoinvent v2.2
Sulfuric Acid	Sulphuric acid, liquid, at plant_50% in solution	ecoinvent v2.2
Sodium Hydroxide	Sodium hydroxide, 50% in H2O, production mix, at plant	ecoinvent v2.2
Earthwork	Excavation, hydraulic digger	ecoinvent v2.2
Concrete	Ready mixed concrete, 20 MPa, at plant	EPA ORD LCA Database

Table 4-1. Background Unit Process Data Sources

Background Input	Original Unit Process Name	LCI Database
Building	Building, hall, steel construction	ecoinvent v2.2
Steel	Steel, low-alloyed, at plant	ecoinvent v2.2
Gravel	Gravel, crushed, at mine	ecoinvent v2.2
Anthracite	Anthracite, sand filter media	ecoinvent v2.2
Sand	Silica sand, at plant	ecoinvent v2.2

Electricity is a key background unit process for all the wastewater treatment configurations investigated. Table 4-2 displays the U.S. average electrical grid mix applied in the LCA model. This grid mix represents the weighted average of all U.S. grid regions, and as such is not representative of the grid mix in any specific location. For electricity at an industrial user, there is assumed to be a 21% increase in required electrical production attributable to losses during distribution and the energy industries own use. These data are based on the Emissions & Generation Resource Integrated Database (eGRID) information from 2009, which is currently applied in the EPA ORD LCA Database (LCA Research Center, 2015).

Table 4-2. U.S. Average Electrical Grid Mix

Fuel	%
Coal	44.8%
Natural Gas	24.0%
Nuclear	19.6%
Hydro	6.18%
Wind	2.29%
Woody Biomass	1.36%
Oil	1.02%
Geothermal	0.37%
Other Fossil	0.35%
Solar	0.03%

4.3 LCI Foreground Data Sources

As discussed earlier, for this study, the foreground system is defined as the WWTP itself. For each of the nine wastewater treatment configurations evaluated, foreground information was drawn directly from the CAPDETWorks™ Version 3.0 modeling software or calculated separately for input and output flows not captured by the software. This section describes the unit process LCI calculations, the methods used to estimate wastewater treatment process air emissions, and a summary of the LCI foreground data used. The foreground LCI unit process data developed for this study for all levels are summarized in Appendix H in Table H-1 through Table H-10. Table H-11 displays the sludge quantity produced and sent to landfill for each of the nine wastewater treatment configurations.

4.3.1 Foreground Unit Processes Calculations

Table 4-3 provides an overview of the foreground unit processes that make up each of the wastewater treatment configurations evaluated in this study. The quantity and quality of water inputs to and outputs from each unit process are tracked throughout the wastewater treatment configurations. Energy, chemical, and material inputs (e.g., background unit processes) to each of the unit processes are tracked in terms of energy, mass, or volume units. Also, rough estimates of the construction and maintenance requirements of the infrastructure for each unit process are tracked based on greenfield installations of the wastewater treatment configurations. In the case of infrastructure and capital equipment requirements, past analyses have shown the contribution of infrastructure to the overall results to be relatively insignificant (Emmerson et al., 1995). In general, these types of capital equipment are used to treat large volumes of wastewater over a useful life of many years. Thus, energy and emissions associated with the production of these facilities and equipment generally become negligible. Only major infrastructure elements such as concrete, earthwork, and buildings were, therefore, included in the study. Buildings were modeled using a general material inventory per square meter of floor area (Ecoinvent, 2010b).

Releases to air and water as well as waste outputs are also tracked for each unit process. Releases to air and water are tracked together with information about the environmental compartment to which they are released to allow for appropriate characterization of their impacts. Waste streams are connected to supply chains associated with providing waste management services such as landfilling.

Table 4-3. Foreground Unit Processes Included in Each Wastewater Treatment Configuration

Unit Process	Wastewater Treatment Configuration								
	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Preliminary Treatment – Screening	✓	✓	✓	✓	✓	✓	✓	✓	✓
Preliminary Treatment – Grit Removal	✓	✓	✓	✓	✓	✓	✓	✓	✓
Primary Clarification	✓	✓	✓	✓	✓	✓	✓	✓	✓
Plug Flow Activated Sludge	✓		✓						
Biological Nutrient Removal – 3-Stage		✓							
Fermenter				✓	✓	✓		✓	✓
Biological Nutrient Removal – 4-Stage					✓		✓		
Biological Nutrient Removal – 5-Stage				✓		✓		✓	✓
Chemical Phosphorus Removal			✓	✓	✓	✓	✓	✓	✓

Table 4-3. Foreground Unit Processes Included in Each Wastewater Treatment Configuration

Unit Process	Wastewater Treatment Configuration								
	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Nitrification – Suspended Growth			✓						
Denitrification – Suspended Growth			✓						
Secondary Clarifier	✓	✓	✓	✓	✓	✓		✓	
Membrane Filter [a, b]							✓		✓
Tertiary Clarification			✓ [c]						
Denitrification – Attached Growth						✓		✓	
Filtration – Sand Filter				✓	✓	✓		✓	
Chlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dechlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ultrafiltration [a]								✓	
Reverse Osmosis [a, d]								✓	✓
WWTP Effluent Discharge	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Gravity Thickening	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Anaerobic Digestion	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Centrifugation	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sludge – Haul and Landfill	✓	✓	✓	✓	✓	✓	✓	✓	✓
Brine – Underground Inject								✓	✓

✓ Indicates unit process is relevant for select wastewater treatment configuration.

a – Periodic chemical cleaning is included for all membranes.

b – Membrane bioreactor wastewater treatment configurations use a membrane filter for the solid-liquid separation process instead of a traditional secondary clarifier.

c – This configuration includes two instances of tertiary clarification.

d – Includes chlorination and dechlorination pretreatment.

Foreground information was drawn directly from the CAPDETWorks™ Version 3.0 modeling software or calculated separately for input and output flows not captured by the software. Although CAPDETWorks™ is designed for cost estimation, the underlying models include a number of parameters which can be accessed and used to describe the physical processes involved at each stage in the wastewater treatment configurations, such as sludge generation or treatment chemical usage. An example of converting CAPDETWorks™ output to

LCI is provided in Appendix G. Where CAPDETWorks™ parameters are not available for populating relevant items in the unit processes underlying the LCA model, values are estimated based on the best available information identified through literature review. Values for GHG emissions from the wastewater treatment processes are not provided by CAPDETWorks™ and, therefore, are estimated independently (See Section 4.3.2 and Appendix F). Calculation of inputs and outputs for unit processes not covered in CAPDETWorks™ are also described separately in Appendix E: Sections E.2 through E.7)

4.3.2 Process Air Emissions Estimation Methodologies

For this study it is necessary to separately estimate process-based greenhouse gas (GHG) emissions for the nine wastewater treatment configurations. Emissions are already captured in the background existing unit processes for fuel production and combustion as well as material and chemical production (e.g., unit processes listed in Table 4-1). Estimates of process-based air emissions are made for methane (CH_4) production from biological treatment, anaerobic digestion, landfill disposal of biosolids, and biogas flaring at the anaerobic digester. Estimates of nitrous oxide (N_2O) emissions from biological treatment and receiving waters are also included in the analysis (IPCC, 2006). Separate methodologies have been developed based on the available literature for each of these sources of GHGs. Carbon dioxide (CO_2) emissions from wastewater treatment processes are not included in the calculation of GHG emissions from wastewater treatment processes because they are of biogenic origin and are not included in national total emissions in accordance with IPCC Guidelines for national inventories (IPCC, 2006). The methodology for calculating GHG emissions associated with wastewater treatment is generally based on guidance provided in the IPCC Guidelines for national inventories; however, more specific emission factors for both CH_4 and N_2O are used based on site-specific emissions data from representative systems. A detailed discussion of the process GHG emission values incorporated in the model is provided in Appendix F. Appendix F also provides the GHG emissions methodology developed for biogas flaring at the anaerobic digester (Table F-3) as well as the GHG emissions methodology associated with avoided electricity from landfill CH_4 recovery (Table F-7).

4.4 LCI Limitations

Some of the main limitations that readers should understand when interpreting the LCI data and findings are as follows:

- **Support Personnel Requirements:** Support personnel requirements are included in the cost analysis but excluded from the LCA model. The energy and wastes associated with research and development, sales, and administrative personnel or related activities are not included, as energy requirements and related emissions are assumed to be quite small for support personnel activities.
- **Representativeness of Background Data:** Background processes are representative of either U.S. average data (in the case of data from U.S. EPA ORD or U.S. LCI) or European or Global average (in the case of ecoinvent) data. In some cases, European ecoinvent processes were used to represent U.S. inputs to the model (e.g., for chemical inputs) due to lack of available representative U.S. processes for these

inputs. The background data, however, met the criteria listed in the project QAPP for completeness, representativeness, accuracy, and reliability.

- **Process GHG Estimates:** There is uncertainty in estimating CH_4 and N_2O process emissions from biological treatment and in differentiating the various treatment levels due to the limited measurement data associated with the different wastewater treatment configurations evaluated. Based on current international guidance, many governments ignore CH_4 GHG emissions in their national inventories from centralized aerated treatment plants because they are considered negligible when compared to other sources. The source of emission can be highly variable from facility to facility and is not associated with the type of treatment configuration. Facility-level process GHGs are also highly dependent on the specific operational characteristics of a system used at one plant versus another, including pH, temperature, and level of aeration. Minimum thresholds for determining differences in GHG results between the waste treatment configurations are discussed in Section 4.6.15.
- **Full LCI Model Data Accuracy and Uncertainty:** In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a difficult subject, and one that does not lend itself to standard error analysis techniques. The reader should keep in mind the uncertainty associated with LCI models (and the underlying CAPDETWorks™ model) when interpreting the results. Comparative conclusions should not be drawn based on small differences in impact results. For this study, minimum threshold guidelines to determine differences in impact results are provided by category in Section 4.6.15.
- **Temporal Considerations:** The LCI model does not distinguish based on temporal correlations and treat short-term and long-term impacts similarly. ~~between emissions or discharges that occur immediately and those that are long-term~~. For instance, long-term emissions of COD in landfill leachate from sludge disposal is incorporated in the model. For the first 100 years, it is assumed the leachate is sent to a WWTP. However, after 100 years it is assumed the landfill ceases to operate and there are still some residual leachate emissions.
- **Transferability of Results:** The LCI data presented here relate to a theoretical average U.S. WWTP with a greenfield installation and the conditions specified in Section 1.2. LCI results may vary substantially for case-specific operating conditions and facilities, and for retrofits of existing systems.

4.5 LCA Modeling Procedure

Development of an LCA requires significant input data, an LCA modeling platform, and impact assessment methods. This section provides a brief summary of the LCA modeling procedure. Each unit process in the life cycle inventory was constructed independently of all other unit processes. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. Also, because these data are reviewed individually, EPA reviewed assumptions based on their relevance to the process rather than their effect on the overall outcome of the study. In most cases, individual unit processes were parameterized to dynamically represent multiple treatment levels and configurations.

The model was constructed in OpenLCA Version 1.4.2, an open-source LCA software package provided by GreenDelta (GreenDelta, 2015). This open-source format allowed seamless sharing of the LCA model between project team members. For all novel foreground unit processes developed under this work, individual unit process templates were completed into the United States Department of Agriculture (USDA) and U.S. EPA's US Federal LCA Commons Life Cycle Inventory Unit Process Template (USDA and U.S. EPA, 2015). The OpenLCA model was reviewed to ensure that all inputs and outputs, quantities, units, and metadata correctly matched the unit process templates. Associated metadata for each unit process was recorded in the unit process templates along with the model values. This metadata includes detailed data quality indicators (DQI) for each flow within each unit process.

Once all necessary data were input into the OpenLCA software and reviewed, system models were created for each treatment level configuration. The models were reviewed to ensure that each elementary flow (e.g., environmental emissions, consumption of natural resources, and energy demand) was characterized under each impact category for which a characterization factor was available. The draft final system models were also reviewed prior to calculating results to make certain all connections to upstream processes and weight factors were valid. LCIA results were then calculated by generating a contribution analysis for the selected treatment configuration product system based on the defined functional unit of treatment of one cubic meter of wastewater. The subsequent section discusses the detailed LCIA methods used to translate the LCI model in OpenLCA into the impact categories assessed in this study.

4.6 Life Cycle Impact Assessment (LCIA)

LCIA is defined in ISO 14044 section 3.4 as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO, 2006b)." Within LCIA, the multitude of environmental LCI flows throughout the entire study boundaries (e.g., raw material extraction through chemical and energy production and through wastewater treatment and effluent release) are classified according to whether they contribute to each of the selected impact categories. Following classification, all of the relevant pollutants are normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance. One well known example is the reporting of all GHG emissions in CO_2-eq. The LCI and LCIA steps together compromise the main components of a full LCA.

ISO 14040 recommends that an LCA be as comprehensive as possible so that "potential trade-offs can be identified and assessed (ISO, 2006a)." Given this recommendation, this study applies a wide selection of impact categories that encompass both environmental and human health indicators. The selected LCIA categories address impacts at global, regional, and local scales.

This study considers 12 impact categories in assessing the environmental burdens of the nine wastewater treatment configurations. The majority of impact categories address air and water environmental impacts, while three of the selected impact categories are human health impact indicators. There are two main methods used to develop LCIA characterization factors: midpoint and endpoint. The impact categories selected for this study are all midpoint indicators.

Midpoint indicators are directly associated with a specific environmental or human health pathway. Specifically, midpoint indicators lie at the point along the impact pathway where the various environmental flows that contribute to these issues can be expressed in a common unit (e.g., CO_2-eq). Units such as CO_2 equivalents express a relevant environmental unit, in this case radiative forcing (W-yr/m^2/kg), in the context of a reference substance. This is mentioned to reinforce the fact that there are physical mechanisms underlying all of the impact assessment methods put forward. Endpoint indicators build off of these midpoint units and translate them into impacts more closely related to the final damage caused by the substance, which include: (1) human health, (2) man-made environment, (3) natural environment, and (4) natural resources (Udo de Haes et al., 1999). It is commonly believed that endpoint indicators are easier for many audiences to understand, but suffer due to the fact that they significantly increase the level of uncertainty associated with the results because the translation to final damage are typically less understood and lack data. To reduce uncertainty of the results, this work generally focuses on indicators at the midpoint level.

The LCIA method provided by the Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI), version 2.1, developed by the U.S. EPA specifically to model environmental and human health impacts in the U.S., is the primary LCIA method applied in this study (Bare, 2012). Additionally, the ReCiPe LCIA method is recommended to characterize fossil fuel depletion and water use (Goedkoop et al., 2009). Energy is tracked based on point of extraction using the cumulative energy demand method developed by ecoinvent (Ecoinvent Centre, 2010a).

Summaries of each of the 12 impact categories evaluated as part of this study are provided in the subsequent sections. Each summary includes a table of the main substances considered in the impact category, associated substance characterization factor, and the compartment (e.g., air, water, soil) the substance is released to or extracted from (in the case of raw materials). These tables highlight key substances but should not be considered comprehensive.

4.6.1 Eutrophication Potential

Eutrophication occurs when excess nutrients (e.g., nitrogen or phosphorus) are introduced to surface and coastal water causing the rapid growth of aquatic plants. This growth (generally referred to as an “algal bloom”) reduces the amount of dissolved oxygen in the water, thus decreasing oxygen available for other aquatic species. Eutrophication midpoint indicators, applied in this study, can lead to a number of negative endpoint effects on human and ecosystem health. Oxygen depletion or changing nutrient availability can affect species composition and ecosystem function. Additionally, the proliferation of certain algal species can result in toxic releases that directly impact human health (Henderson, 2015).

Table 4-4 provides a list of common substances that contribute to eutrophication along with their associated characterization factors. As indicated in the table, air emissions can also contribute to eutrophication through the atmospheric deposition of nitrogen compounds. The TRACI 2.1 eutrophication method considers emissions to both fresh and coastal waters. TRACI 2.1 characterization factors for eutrophication are the product of a nutrient factor and a transport factor (Bare et al., 2003). The nutrient factor is based on the amount of algae growth caused by each pollutant. The relative eutrophying effect of a nitrogen or phosphorus species is determined by its stoichiometric relationship to the Redfield ratio (Norris, 2003). The Redfield ratio is the average C:N:P ratio of phytoplankton, and describes the necessary building blocks to facilitate algal growth and reproduction (Redfield, 1934). The transport factor accounts for the likelihood that the pollutant will reach a body of water based on the average hydrology considerations for the U.S. The transport factor is used to account for the fact that a nutrient reaching a body of water where it is not limiting will not contribute to eutrophication. Both air and water emissions have the potential to contribute to eutrophication; however, the fraction of air emissions which make their way into bodies of water is often lower, which is reflected in a smaller transport factor, and the correspondingly lower characterization factors of nitrogen oxide air emissions in Table 4-4.

Both BOD and COD are also shown in Table 4-4 as contributing to eutrophication impacts. Although the mechanism of oxygen consumption differs from that associated with nutrient emissions of nitrogen and phosphorus, the result remains the same. Only COD (and not BOD) values are characterized in this study to avoid double-counting (Norris, 2003).

In this study, U.S. average characterization factors are used, which are created as a composite of all water basins in the U.S. For a discussion of the procedure used to produce composite U.S. characterization factors, see Norris (2003). Using these factors, the results account for regional variation in nutrient and transport factors, although that regional variability is not presented in a disaggregated form. This is appropriate for the scope of this study as our aim is to estimate average U.S. impacts of wastewater treatment. However, it must be recognized that context specific features of an individual WWTP could serve to ameliorate or increase site-specific impacts. In addition, waterbody-specific nutrient limitations and local transport characteristics tend to be the most decisive factors in determining regional differences in eutrophication impacts (Henderson, 2015).

Table 4-4. Main Pollutants Contributing to Eutrophication Potential Impacts (kg N eq/ kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
BOD_5, Biological Oxygen Demand	N/A	Water	0.05
COD, Chemical Oxygen Demand	N/A	Water	0.05
Ammonia	NH_3	Water	0.78
Nitrate	NO_3-	Water	0.24
Nitrogen dioxide	NO_2	Air	0.04
Nitrogen monoxide	NO	Air	0.04
Nitrogen oxides	NO_x	Air	0.04
Nitrogen, organic bound	N/A	Water	0.99
Phosphate	PO_4^{3-}	Water	2.4
Phosphorus [a]	P	Water	7.3
Selected Method—			TRACI 2.1

a – Represents phosphorus content of unspecified phosphorus pollutants (e.g., “total phosphorus” in effluent composition).

4.6.2 *Cumulative Energy Demand*

The cumulative energy requirements for a system can be categorized by the fuels from which energy is derived. This method is not an impact assessment, but rather is a cumulative inventory of all energy extracted and utilized. Energy sources consist of non-renewable fuels (natural gas, petroleum, nuclear and coal) and renewable fuels. Renewable fuels include hydroelectric energy, wind energy, energy from biomass, and other non-fossil sources. Cumulative energy demand (CED) includes both renewable and non-renewable sources as well as the embodied energy in biomass and petroleum feedstocks. CED is measured in MJ/kg. Energy is tracked based on the higher heating value (HHV) of the fuel at the point of extraction. Table 4-5 includes a few examples of fuels that contribute to CED in this project and their associated characterization factors.

Table 4-5. Main Energy Resources Contributing to Cumulative Energy Demand

Energy Resource	Compartment	Units	Characterization Factor
Energy, gross calorific value, in biomass	Resource (biotic)	MJ/kg	1.0
Coal, hard, unspecified, in ground	Resource (in ground)	MJ/kg	19
Gas, natural, in ground	Resource (in ground)	MJ/kg	47
Oil, crude, in ground	Resource (in ground)	MJ/kg	46
Selected Method—		Ecoinvent	

4.6.3 *Global Warming Potential*

Global warming refers to an increase in the earth's temperature in relation to long-running averages. In accordance with IPCC recommendations, TRACI's GWP calculations are based on a 100-year time frame and represent the heat-trapping capacity of the gases relative to an equal weight of carbon dioxide. Relative heat-trapping capacity is a function of a molecule's radiative forcing value as well as its atmospheric lifetime. Table 4-6 provides a list of the most common GHGs along with their corresponding GWPs, or CO_2 equivalency factors, used in TRACI 2.1. Contributing elementary flows can be characterized using GWPs reported by the IPCC in either 2007 (Fourth Assessment Report) or in 2013 (Fifth Assessment Report) (IPCC, 2007; IPCC, 2013). While the 2013 GWPs are the most up-to-date, the 2007 GWPs have been officially adopted by the United Nations Framework Convention on Climate Change (UNFCCC) for international greenhouse gas reporting standards and are used by EPA in their annual greenhouse gas emissions report. The baseline results in this study apply the 2007 GWPs, but results with the 2013 GWPs are provided in a sensitivity analysis in Chapter 9.

Table 4-6. Main GHG Emissions Contributing to Global Warming Potential Impacts ($kg\ CO_2\ eq/kg\ GHG$)

GHG	Chemical Formula	Compartment	GWP (IPCC 2007)	GWP (IPCC 2013)
Carbon dioxide	CO_2	Air	1.0	1.0
Nitrous oxide	N_2O	Air	3.0E+2	2.7E+2

Table 4-6. Main GHG Emissions Contributing to Global Warming Potential Impacts ($kg\ CO_2$ eq/kg GHG)

GHG	Chemical Formula	Compartment	GWP (IPCC 2007)	GWP (IPCC 2013)
Methane	CH_4	Air	25	28
Sulfur hexafluoride	SF_6	Air	2.3E+4	2.4E+4
Selected Method—			IPCC 2007 or 2013 100a	

4.6.4 Acidification Potential

The deposition of acidifying substances such as those listed in Table 4-7 have an effect on the pH of the terrestrial ecosystem. Each species within these ecosystems has a range of pH tolerance, and the acidification of the environment can lead to shifting species composition over time. Acidification can also cause damage to buildings and other human infrastructure (Bare, 2012). The variable buffering capacity of terrestrial environments yields a correspondingly varied response per equivalent unit of acidification. Due to a lack of data, the variable sensitivity of receiving regions is not captured in TRACI characterization factors (Norris, 2003). The acidification method in TRACI utilizes the results of an atmospheric chemistry and transport model, developed by the US National Acid Precipitation Assessment Program (NAPAP), to estimate total North American terrestrial deposition of expected SO_2 equivalents due to atmospheric emissions of NO_x and SO_2 and other acidic substances such as HCl and HF, as a function of the emissions location (Bare et al., 2003). Emissions location is modeled in this study as average U.S. using TRACI's composite annual North American emissions average of U.S. states.

Table 4-7. Main Pollutants Contributing to Acidification Potential Impacts ($kg\ SO_2$ eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Sulfur dioxide	SO_2	Air	1.0
Ammonia	NH_3	Air	1.9
Nitrogen dioxide	NO_2	Air	0.70
Nitrogen oxides	NO_x	Air	0.70
Hydrogen chloride	HCl	Air	0.88
Hydrogen fluoride	HF	Air	1.6
Hydrogen sulfide	H_2S	Air	1.9
Selected Method—		TRACI 2.1	

4.6.5 *Fossil Depletion*

Fossil depletion is a measure of the study systems demand for non-renewable energy resources. As non-renewable resources, the availability of fossil energy will not change (i.e., new fossil energy will not be produced) on relevant human timescales. When these resources are depleted and resource quality declines, the cost and environmental impact of accessing a given quantity of energy increases. Fossil depletion is measured in kg oil equivalent based on each fuel's heating value. Renewable energy systems and uranium are not included in the fossil depletion metric but are assessed within the CED methodology previously discussed. Table 4-8 presents common fossil fuel flows and their associated characterization factors for this impact category.

Table 4-8. Main Fossil Fuel Resource Contributing to Fossil Depletion (kg oil eq/kg Fossil Fuel Resource)

Fossil Fuel Resource	Compartment	Characterization Factor
Oil, crude, 42 MJ per kg	Resource (in ground)	1.0
Coal, 18 MJ per kg	Resource (in ground)	0.43
Coal, 29.3 MJ per kg	Resource (in ground)	0.70
Gas, natural, 30.3 MJ per kg	Resource (in ground)	0.72
Gas, natural, 35 MJ per m3	Resource (in ground)	0.83
Methane	Resource (in ground)	0.86
Selected Method—		ReCiPe

4.6.6 *Smog Formation Potential*

The smog formation impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone (O_3) and particulate matter. Potential endpoints of such smog creation include increased human mortality, asthma, and deleterious effects on plant growth. Smog formation potential impacts are measured in kg of O_3 equivalents. Table 4-9 includes a list of smog forming chemicals expected to be associated with this project along with their characterization factors.

Table 4-9. Main Pollutants Contributing to Smog Formation Impacts (kg O_3 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Sulfur monoxide	SO	Air	1.0
Carbon monoxide	CO	Air	0.06
Methane	CH_4	Air	0.01
Nitrogen dioxide	NO_2	Air	17
Nitrogen oxides	NO_x	Air	25
VOC, volatile organic compounds	N/A	Air	3.6

Table 4-9. Main Pollutants Contributing to Smog Formation Impacts (kg O_3 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Selected Method—			TRACI 2.1

4.6.7 Human Health—Particulate Matter Formation Potential

Particulate matter (PM) emissions have the potential to negatively impact human health. Respiratory complications are particularly common among children, the elderly, and individuals with asthma (U.S. EPA, 2008a). Respiratory impacts can result from a number of types of emissions including PM10, PM2.5, and precursors to secondary particulates such as sulfur dioxide and nitrogen oxides. Respiratory impacts are a function of the fate of responsible pollutants as well as the exposure of human populations. Table 4-10 provides a list of common pollutants contributing to impacts in this category along with their associated characterization factors. Impacts are measured in relation to PM2.5 emissions.

Table 4-10. Main Pollutants Contributing to Human Health-Particulate Matter Formation Potential (kg PM2.5 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Particulates, < 2.5 µm	N/A	Air	1.0
Particulates, > 2.5 µm, and < 10 µm	N/A	Air	0.23
Ammonia	NH_3	Air	0.07
Nitrogen oxides	NO_x	Air	7.2E-3
Sulfur oxides	SO_x	Air	0.06
Selected Method—			TRACI 2.1

4.6.8 Ozone Depletion Potential

Stratospheric ozone depletion is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substance (e.g., CFCs and halons). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical's reactivity and atmospheric lifetime. Potential impacts related to ozone depletion includes skin cancer, cataracts, immune system suppression, crop damage, other plant and animal effects. Ozone depletion potential is measured in kg CFC-11 equivalents. Table 4-11 lists common ozone depleting chemicals and their associated characterization factors in TRACI 2.1. Nitrous oxide is incorporated in the results based on the ReCiPe hierarchies midpoint method (Goedkoop et al., 2009).

Table 4-11. Main Pollutants Contributing to Ozone Depletion Potential Impacts (kg CFC11 eq/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	$C_2Cl_3F_3$	Air	1.0
Methane, bromochlorodifluoro-, Halon 1211	$CBrClF_2$	Air	7.1
Methane, bromotrifluoro-, Halon 1301	$CBrF_3$	Air	16
Methane, chlorodifluoro-, HCFC-22	$CHClF_2$	Air	0.05
Methane, trichlorofluoro-, CFC-11	CCl_3F	Air	1.0
Nitrous oxide	N_2O	Air	0.01
Selected Method—			TRACI 2.1, ReCiPe

4.6.9 Water Depletion

Water use results are displayed on a consumptive basis (i.e., depletion). When water is withdrawn from one water source and returned to another watershed this is considered consumption, as there is a net removal of water from the original water source. For instance, it is assumed that deepwell injection of the brine fluid from RO is consumptive water use, since water is being diverted from a watershed making it unavailable for subsequent environmental or human uses. Consumption also includes water that is withdrawn and evaporated or incorporated into the product. Cooling water that is closed-loop circulated, and does not evaporate, is not considered consumptive use. Water consumption is only included as an inventory category in this study, which is a simple summation of water inputs. The analysis does not attempt to assess water-related damage factors. For instance, there is no differentiation between water consumption that occurs in water-scarce or water-abundant regions of the world. Water consumption in this study includes values for upstream fuel and electricity processes. In addition to water consumption associated with thermal generation of electricity from fossil and nuclear fuels, the water consumption for power generation includes evaporative losses due to establishment of dams for hydropower. Table 4-12 shows some of the common flows associated with water use along with their characterization factors. Section 4.6.15 also discusses some of the uncertainty associated with calculating water depletion in LCA.

Table 4-12. Main Water Flows Contributing to Water Depletion

Water Flow	Compartment	Units	Characterization Factor
Water, lake	Resource (in water)	$m^3\ H_2O/m^3$	1.0
Water, river	Resource (in water)	$m^3\ H_2O/m^3$	1.0
Water, unspecified natural origin	Resource (in water)	$m^3\ H_2O/m^3$	1.0
Water, well, in ground	Resource (in water)	$m^3\ H_2O/m^3$	1.0
Water, unspecified natural origin/kg	Resource (in water)	$m^3\ H_2O/kg$	1.0E-3
Selected Method—		ReCiPe	

4.6.10 Human Health—Cancer Potential

Carcinogenic human health results in this study are expressed on the basis of Comparative Toxic Units (CTU_h) based on the USEtox™ method (Huijbregts et al. 2010). Characterization factors within the USEtox™ model are based on fate, exposure, and effect factors. Each chemical included in the method travels multiple pathways through the environment based on its physical and chemical characteristics. The potential for human exposure (e.g., ingestion or inhalation) varies according to these pathways. The effect factor characterizes the probable increase in cancer-related morbidity for the total human population per unit mass of a chemical emitted (i.e., cases per kg) (Rosenbaum et al., 2008). The full USEtox™ model contains over 3,000 chemicals of global relevance and is the product of an international project to harmonize the approach to evaluation of toxicity effects. The USEtox™ model develops characterization factors at the continental and global scale. The exclusion of more localized parameters is justified in that it was found during the harmonization process that site-specific parameters have a far lower impact on results than do the substances themselves.

Global midpoint characterization factors are employed from the most recent version of USEtox™ available in OpenLCA, version 2.02. An updated version of USEtox™, version 2.11, was released in April 2019. Characterization factors for the heavy metals, toxic organics and DBPs were updated in the OpenLCA USEtox™ LCIA method to match version 2.11. All other characterization factors remain at the default value for OpenLCA's USEtox version 2 (recommended+interim) database. Not all heavy metals, toxic organics and DBPs have established characterization factors in the USEtox™ method. Several additional sources were used to identify appropriate characterization factors. When no appropriate characterization factor was identified, the pollutant was assigned a characterization factor equal to the median characterization factor for its trace pollutant group. Table B-5, Table C-8, and Table D-4 list values and sources of characterization factors for all heavy metals, toxic organics, and DBPs. For illustration purposes, Table 4-13 lists five of the primary chemicals contributing to cancer human health impacts in the US and Canada (Ryberg, 2014) along with their associated characterization factors.

The developers of the USEtox™ method are clear to point out that some of the characterization factors associated with human health effects should be considered interim, owing to uncertainty in their precise values ranging across one to three orders of magnitude. Sources of uncertainty are often attributable to the use of one exposure route as a proxy for another (route-to-route extrapolation). For a more detailed discussion of uncertainty present in these models, see the USEtox™ User's Manual (Huijbregts et al., 2010). Appropriate interpretation of results must consider the uncertainty associated with the use of interim characterization factors.

Table 4-13. Main Pollutants Contributing to Human Health - Cancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Arsenic	As	Soil	1.8E-4[a]
Formaldehyde	CH_2O	Air	2.5E-5

Table 4-13. Main Pollutants Contributing to Human Health - Cancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Chromium VI	Cr	Soil	5.0E-3[a]
Chromium VI	Cr	Air, urban	3.8E-3[a]
Chromium VI	Cr	Water	0.01[a]
Selected Method—			USEtox™ 2.11

a – Designates an interim characterization factor.

4.6.11 Human Health—Noncancer Potential

Non-carcinogenic human health results in this study are expressed on the basis of Comparative Toxic Units (CTU_h) based on the USEtox™ method, which is incorporated in TRACI 2.1. The impact method characterizes the probable increase in noncancer related morbidity for the total human population per unit mass of a chemical emitted (i.e., cases per kg) (Rosenbaum et al., 2008). These impacts are calculated using the same approach as that taken for human health - cancer (Section 4.6.10).

Global midpoint characterization factors are employed from the most recent version of USEtox™ available in OpenLCA, version 2.02. An updated version of USEtox™, version 2.11, was released in April 2019. Characterization factors for the heavy metals, toxic organics and DBPs were updated in the OpenLCA USEtox™ LCIA method to match version 2.11. All other characterization factors remain at the default value for OpenLCA's USEtox version 2 (recommended+interim) database. Not all heavy metals, toxic organics and DBPs have established characterization factors in the USEtox™ method. Several additional sources were used to identify appropriate characterization factors. When no appropriate characterization factor was identified, the pollutant was assigned a characterization factor equal to the median characterization factor for its trace pollutant group. Table B-5, Table C-8, and Table D-4 list values and sources of characterization factors for all heavy metals, toxic organics, and DBPs. For illustration purposes, Table 4-14 lists the main chemicals contributing to noncancer, human health impacts (Ryberg, 2014) along with their associated characterization factors.

As is discussed in Section 4.6.10, uncertainty in USEtox factors can range across one to three orders of magnitude for interim characterization factors, which are identified in Table 4-14. At the current time, all characterization factors for metal compounds are considered interim. Appropriate interpretation of results must consider the uncertainty associated with the use of interim characterization factors.

Table 4-14. Main Pollutants Contributing to Human Health—Noncancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Acrolein	C_3H_4O	Soil	3.4E-5
Zinc, ion	Zn^{2+}	Soil	1.4E-4[a]

Table 4-14. Main Pollutants Contributing to Human Health—Noncancer Potential Impacts (CTU_h/kg Pollutant)

Pollutant	Chemical Formula	Compartment	Characterization Factor
Arsenic, ion	As^{3+}	Soil	0.01[a]
Zinc, ion	Zn^{2+}	Air, urban	5.7E-3[a]
Mercury (+II)	Hg(II)	Air, urban	1.24[a]
Selected Method—			USEtox™ 2.11

a – Designates an interim characterization factor.

4.6.12 Ecotoxicity Potential

Ecotoxicity is a measure of the effect of toxic substances on ecosystems. The effects on freshwater ecosystems are used as a proxy for general ecological impact. Characterization factors within the ecotoxicity model are based on fate, exposure, and effect factors. Each chemical included in the method travels multiple pathways through the environment. As a result of these pathways, various compartments (e.g., freshwater, terrestrial) and the species they contain will have differing opportunities to interact with the chemical in question (exposure). The effect factor refers to the potential negative consequences on ecosystem health when exposure does occur (Huijbregts, 2010). The exclusion of more localized parameters is justified in that it was found during the harmonization process that these parameters have a far lower impact on results than do the substances themselves. Ecotoxicity impacts are measured in terms of the Potentially Affected Fraction of species due to a change in concentration of toxic chemicals (PAF m^3 ·day/kg). These units are also known as comparative toxicity units (CTUe).

Global midpoint characterization factors are employed from the most recent version of USEtox™ available in OpenLCA, version 2.02. An updated version of USEtox™, version 2.11, was released in April 2019. Characterization factors for the heavy metals, toxic organics and DBPs were updated in the OpenLCA USEtox™ LCIA method to match version 2.11. All other characterization factors remain at the default value for OpenLCA's USEtox version 2 (recommended+interim) database. Not all heavy metals, toxic organics and DBPs have established characterization factors in the USEtox™ method. Several additional sources were used to identify appropriate characterization factors. When no appropriate characterization factor was identified, the pollutant was assigned a characterization factor equal to the median characterization factor for its trace pollutant group. Table B-5, Table C-8, and Table list values and sources of characterization factors for all heavy metals, toxic organics, and DBPs. For illustration purposes, Table 4-15 lists some of the main chemicals found to contribute to ecotoxicity impacts (Ryberg, 2013) and their USEtox™ global characterization factors.

As is discussed in Section 4.6.10, uncertainty in USEtox factors can range across one to three orders of magnitude for interim characterization factors, which are identified in Table 4-15. At the current time, all characterization factors for metal compounds are considered interim. Appropriate interpretation of results must consider the uncertainty associated with the use of interim characterization factors.

Table 4-15. Main Pollutants Contributing to Ecotoxicity Potential Impacts ($CTUe$ [PAF m^3.day/kg Pollutant])

Pollutant	Chemical Formula	Compartment	Characterization Factor
Zinc, ion	Zn^{2+}	Ground water	1.3E+5[a]
Chromium VI	Cr(VI)	Ground water	1.0E+5[a]
Nickel, ion	Ni^{2+}	Ground water	3.0E+5[a]
Chromium VI	Cr(VI)	River	1.0E+5[a]
Arsenic, ion	As^{3+}	Ground water	1.5E+4[a]
Selected Method—			USEtox™ within TRACI 2.11

a – Designates an interim characterization factor.

4.6.13 Normalization

Normalization is an optional step in LCIA that aids in understanding the significance of the impact assessment results. Normalization is conducted by dividing the impact category results by a normalized value. The normalized value is typically the environmental burdens of the region of interest either on an absolute or per capita basis. The results presented in this study are normalized to reflect person equivalents in the U.S. using TRACI v2.1 normalization factors (Ryberg et al., 2013). Only impacts with TRACI normalization factors are shown. Some categories like water use and CED are excluded due to lack of available normalization factors.

4.6.14 LCIA Limitations

While limitations of the LCI model are specifically discussed in Section 4.4, some of the main limitations that readers should understand when interpreting the life cycle impact assessment findings are as follows:

- **Coverage of Emissions Leading to Toxicity:** ~~The scope for the results for the three USEtox™ categories (human health - cancer, human health - noncancer, and ecotoxicity) excludes toxicity from wastewater effluent and should be considered with low confidence. These category results are largely dependent on toxic pollutants from sludge in a landfill. However, these toxic pollutants may also be present in the effluent release at the WWTP.~~ The toxicity impacts associated with the sludge and the effluent are limited to pollutants selected in Chapter 2. Such toxic pollutants in the effluent were not assessed in the baseline LCA model; therefore, the toxicity impact categories are showing incomplete results.
- **Transferability of Results:** While this study is intended to inform decision-making for a wide range of stakeholders, the impacts presented here relate to a theoretical average U.S. WWTP. For instance, this study does not address geographic differences that could impact WWTP design, cost options, or local variation in environmental impacts. Further work is recommended to understand the variability of key parameters across specific regional and facility-level situations. Also, the study

looked at greenfield installations only so impacts or benefits would vary for retrofitted operations.

- **LCIA Method Uncertainty:** In addition to the uncertainty of the LCI data, there is uncertainty associated with the application of LCIA methodologies and normalization factors to aggregated LCI. For example, two systems may release the same total amount of the same substance, but one quantity may represent a single high-concentration release to a stressed environment while the other quantity may represent the aggregate of many small dilute releases to environments that are well below threshold limits for the released substance. The actual impacts would likely be very different for these two scenarios, but the LCI does not track the temporal and spatial resolution or concentrations of releases in sufficient detail for the LCIA methodology to model the aggregated emission quantities differently. Therefore, it is not possible to state with complete certainty that differences in potential impacts for two systems are significant differences. Although there is uncertainty associated with LCIA methodologies, all LCIA methodologies are applied to different wastewater treatment configurations uniformly. Therefore, comparative results can be determined with a greater confidence than absolute results for one system. Minimum threshold values for determining meaningful impact differences between wastewater treatment configurations by category are provided in the next section.

4.6.15 Interpreting LCIA Results Differences

Interpretation of LCIA results requires interpretation of the uncertainty associated with inventory data (lists of compounds and resources emitted or extracted by the system under study) and the impact models used to characterize inventory data, translating emissions into impacts. Note that there is also uncertainty associated with the definition of system boundaries, and determination of cutoff values for exclusion of data.

The current state of practice in life cycle assessment includes a quantitative analysis of the uncertainty in inventory data. In this study, much of the background process data, which is part of the ecoinvent database, includes such uncertainty analyses. Possible underestimations of uncertainty associated with ecoinvent are known (Weidema et al., 2011); however, ecoinvent and agricultural inventory uncertainties are expected to be lower overall than impact uncertainty.

At the impact level, uncertainty is not yet typically included in LCA studies; indeed, not all LCA software has this ability. A spatially explicit model of aquatic acidification (Roy et al., 2014) analyzed both parameter uncertainty (via a Monte Carlo approach) and spatial uncertainty. At the characterization factor level, parameter uncertainty contributed a factor of 100 uncertainty, whereas spatial variability ranged from 5 to 8 orders of magnitude for different acidifying compounds.

At the analysis level, it is important to consider that uncertainty in inventory or characterization is not purely multiplicative when considering differences between systems (Hong et al., 2010). For many LCA analyses, many background and some foreground processes will be shared between systems. For example, background electricity generation is often shared, while chemical additives or concrete could be shared foreground processes for wastewater treatment. Therefore, analyses of *differences* between systems must account for these shared processes. Within confidence bounds, systems may be different even if the difference between their impact scores is less than the absolute uncertainty on the corresponding characterization factor (e.g., factor 100 for acidification, from above).

In a case study, Humbert et al. (2009) provide guidelines for determining whether differences in LCA impact results are meaningful. In the energy and global warming category, this minimum significant difference is a 10 percent threshold (i.e., in comparing contributions to this category, a difference lower than 10 percent is not considered to be significant). For particulate matter formation, smog formation, acidification, ozone depletion, and eutrophication, the minimum significant difference is 30 percent. For the toxicity categories, an order of magnitude (factor 10) difference is typically required for a difference to be significant, especially if the dominant emissions are different between scenarios or are dominated by long-term emissions from landfills that can be highly uncertain. In the absence of a detailed uncertainty analysis, these threshold guidelines may serve to help interpretation. This study uses the percent difference thresholds defined by the Humbert et al. 2009 case study with the exception of GWP impact results. As discussed in Section 4.4, there are case-specific uncertainties for estimating GHG emissions from biological treatment. Therefore, this study uses a higher threshold of 30 percent to determine whether a notable GWP difference exists between wastewater treatment configurations. There are also specific considerations for uncertainty thresholds for water depletion results as discussed below.

There is currently a lack of water use data on a unit process level for LCIs. In addition, water use data that are available from different sources do not use a consistent method of distinguishing between consumptive use and non-consumptive use of water or clearly identifying the water sources used (freshwater versus saltwater, groundwater versus surface water). A recent article in the International Journal of Life Cycle Assessment summarized the status and deficiencies of water use data for LCA, including the statement, “To date, data availability on freshwater use proves to be a limiting factor for establishing meaningful water footprints of products” (Koehler, 2008). The article goes on to define the need for a standardized reporting format for water use, taking into account water type and quality as well as spatial and temporal level of detail.

Water consumption is modeled using values reported in literature. In some cases, consumptive use data may not be available. The ecoinvent database includes water in the life cycle inventory as an input and does not record water released to the environment (i.e., as an emission) or water consumed. However, ecoinvent is currently one of the most comprehensive LCI sources on water for upstream processes; many other available databases do not report water input/use as an inventory item. Therefore, when case-specific data were not available, ecoinvent data were utilized for the water calculations. When utilizing ecoinvent, the data are adapted to represent consumptive use to the extent possible: fresh water removed from the environment that is not internally recirculated.

Because water consumption values are uncertain, a minimum 30 percent difference is required to consider water consumption results significantly different. Comparative results can be determined with a greater confidence than absolute results for one system.

5. LIFE CYCLE COST BASELINE RESULTS

This section presents the LCCA results for the nine wastewater treatment configurations included in this study. Table 5-1 presents the total capital, total annual, and net present value for each of the wastewater treatment configurations. As discussed in Section 3.3.2, the net present value combines the one-time capital costs and periodic (annual) operating and maintenance costs into one value for direct comparison of costs. The following sections provide additional discussion differences with the results of the total capital and annual costs (Section 5.1) and net present value (Section 5.2). The results are discussed by unit process and aggregated treatment group, as shown in Table 5-2. For treatment groups, the unit processes are generally grouped sequentially; however, preliminary treatment stages are grouped with disinfection, even though these are not sequential unit processes because, in this study, these unit processes do not vary between wastewater treatment configurations. Complete cost results are presented in Appendix H.

Table 5-1. Total Costs by Wastewater Treatment Configuration

Wastewater Treatment Configuration	Total Capital Cost (2014 $)	Total Annual Cost [a] (2014 $/yr)	Net Present Value (2014 $)
Level 1, AS	$55,300,000	$5,140,000	$204,000,000
Level 2-1, A2O	$71,400,000	$5,470,000	$236,000,000
Level 2-2, AS3	$93,100,000	$10,150,000	$378,000,000
Level 3-1, B5	$86,400,000	$5,800,000	$267,000,000
Level 3-2, MUCT	$88,900,000	$5,960,000	$275,000,000
Level 4-1, B5/Denit	$92,800,000	$6,840,000	$301,000,000
Level 4-2, MBR	$90,100,000	$6,340,000	$285,000,000
Level 5-1, B5/RO	$160,000,000	$8,320,000	$439,000,000
Level 5-2, MBR/RO	$144,000,000	$8,070,000	$409,000,000

a – Total annual cost includes operational labor, maintenance labor, materials, chemicals, and energy (see Section 3.3 for details).

Table 5-2. Unit Processes by Treatment Group

Treatment Group	Unit Processes Included in the Stage	
Preliminary/Primary/Disinfection	Screening and Grit Removal	Chlorination
	Primary Clarifier	Dechlorination
Biological Treatment	Activated Sludge	Tertiary Clarification, Nitrification
	Secondary Clarifier	Denitrification, Suspended Growth
	Anaerobic/Anoxic/Oxic (A2O)	Nitrification, Suspended Growth
	4-Stage Bardenpho	Membrane Filter
	5-Stage Bardenpho	Fermentation
	Tertiary Clarification, Denitrification	Modified University of Cape Town
Post-Biological Treatment	Sand Filtration	Ultrafiltration
	Reverse Osmosis	Chemical Phosphorus Removal
	Denitrification, Attached Growth	

Table 5-2. Unit Processes by Treatment Group

Treatment Group	Unit Processes Included in the Stage	
Sludge Processing and Disposal	Centrifuge	Sludge Hauling and Landfill
	Anaerobic Digester	Gravity Thickener
Effluent Release	Effluent Release	
Brine Injection	Brine Injection	

5.1 Total Capital and Total Annual Cost Results

As described in Section 3.3, the total plant costs are presented as the total capital costs along with the total annual costs. This section presents the total capital and total annual costs and describes the differences in cost by process contribution and treatment group.

5.1.1 Total Capital Costs

Total capital costs generally increase from Level 1 to Level 5, as presented in Figure 5-1. For Level 2, the Level 2-1 A2O total capital costs are almost $22 million lower than the Level 2-2 AS3 total capital costs. The total capital costs for Level 2-2 AS3 are also over $4 million higher than both Level 3 wastewater treatment configurations. This is because the Level 2-2 AS3 wastewater treatment configuration includes three separate biological units (plug-flow activated sludge, nitrification, and denitrification) with dedicated clarifiers, while the Level 2-1 A2O, Level 3-1 B5, and Level 3-2 MUCT wastewater treatment configurations only include one biological unit that have three to five chambers with a secondary clarifier. The multiple clarifiers in Level 2-2 AS3 also results in more sludge generation and, as a result, has larger sludge processing and disposal units, which also contribute to the higher total capital cost for Level 2-2 AS3 compared to Level 2-1 A2O and both Level 3 wastewater treatment configurations. The total capital cost for Level 2-2 AS3 is more comparable to both Level 4 wastewater treatment configurations. Increasing effluent quality from Level 4 to Level 5 increases the total capital costs by over $50 million because of the added post-biological treatment units (i.e., ultrafiltration, reverse osmosis, and deep injection well for Level 5-1 B5/RO and reverse osmosis and deep injection well for Level 5-2 MBR/RO). Total capital costs for the preliminary/primary/disinfection treatment group are included but are comparable for all of the wastewater treatment configurations, as there are no significant design differences between these portions of the wastewater treatment configurations.

For this study, the total capital costs for the biological treatment group generally increases with increasing effluent quality because the biological treatment units are designed to achieve increased nitrogen and phosphorus removals; increased nitrogen and phosphorus removals require a larger sized and/or more complex biological treatment unit. Note that there are biological treatment units outside of the study that may not follow this trend. However, the Level 5-1 B5/RO biological treatment group total capital costs are similar to both Level 3 and Level 4-1 B5/Denit biological treatment group costs because they have the same biological unit processes (BNR plus secondary clarifier) and are designed to achieve the same nitrogen and phosphorus removals. The Level 4-2 MBR and Level 5-2 B5/RO have higher biological treatment group costs by more than $5 million. Although they are designed to achieve the same nitrogen and phosphorus removals as Level 3, Level 4-1 B5/Denit, and Level 5-1 B5/RO, the Level 4-2 MBR and Level 5-2 B5/RO have membrane bioreactors instead of secondary clarifiers, which increases cost. For all these wastewater treatment configurations, the nitrogen and phosphorus removed beyond the Level 3 targets is achieved through post-biological treatment units (e.g., denitrification filter, ultrafiltration, reverse osmosis).

The post-biological treatment group is a component of all levels except Level 1 AS and Level 2-1 A2O since these levels do not require chemical phosphorus removal or additional nutrient control unit processes. The lowest post-biological treatment capital costs are for Level 2-2 AS3 and Level 4-2 MBR, which only require chemical phosphorus removal. There is a large jump in post-biological treatment capital costs for the Level 5 wastewater treatment system configurations due to the addition of ultrafiltration and the reverse osmosis unit. The Level 5-1 B5/RO post-biological treatment capital cost is more than double the Level 5-2 MBR/RO because Level 5-1 B5/RO also includes the sand filter, ultrafiltration, and has a larger reverse osmosis unit.

The sludge processing and disposal treatment group capital costs are comparable for all the wastewater treatment configuration except for Level 2-2 AS3, which has a larger anaerobic digester, larger centrifuge, increased number of vehicles (hauling and land filling), and larger onsite sludge storage shed (hauling and land filling) capital costs. As discussed previously, the Level 2-2 AS3 system has three separate clarifiers and a very high alum dose that increases the quantity of sludge generated even beyond that of higher performing wastewater treatment configurations, which are able to achieve their level of phosphorus removal performance through a combination of chemical precipitation and other unit processes.

The Level 5 wastewater treatment configurations both have RO which requires brine disposal capital costs, while the other wastewater treatment configurations do not. The other capital costs include the direct and indirect costs that are calculated as a percentage of the purchased equipment cost component of the total capital cost (see Section 3.3.1 for details). As a result, the other capital costs increase as the other components of the total capital costs increase.

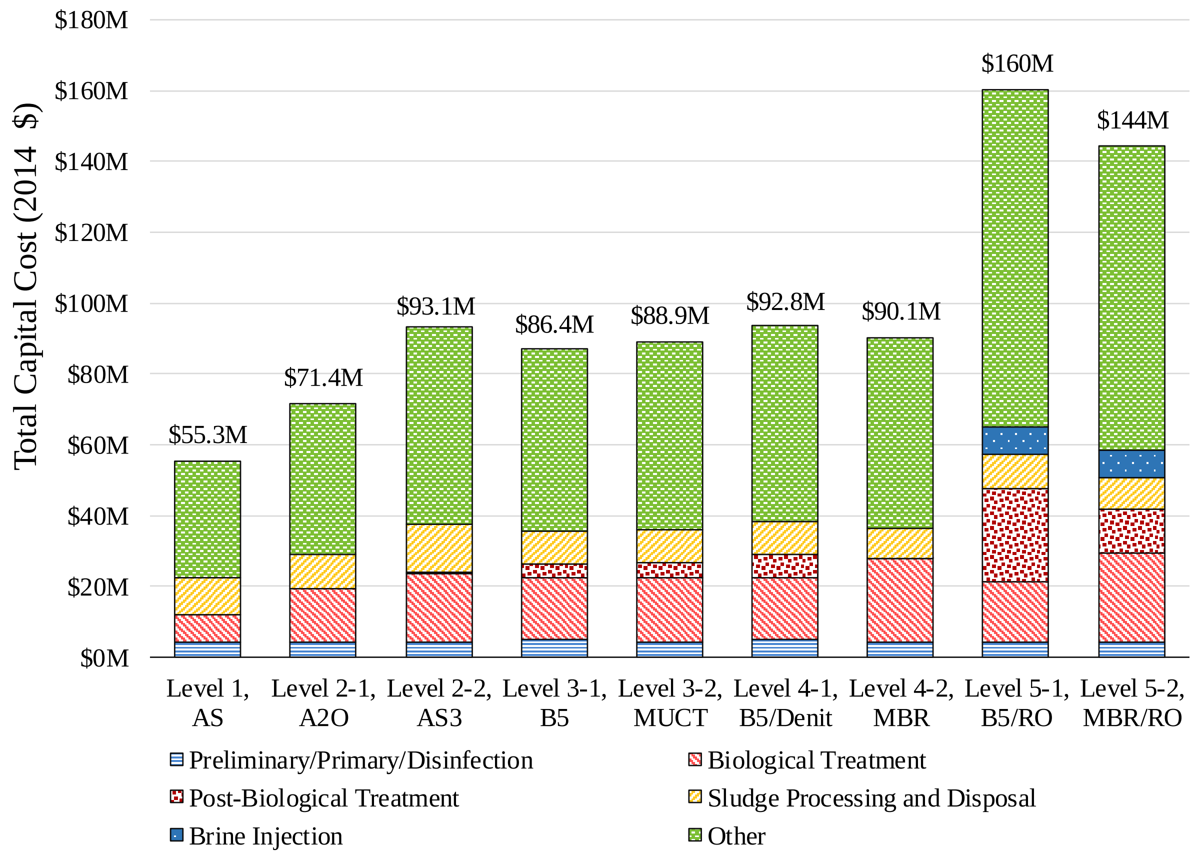


Figure 5-1. Total Capital Costs by Aggregated Treatment Group

5.1.2 Total Annual Costs

Figure 5-2 presents the total annual costs for all the wastewater treatment configurations broken into the annual cost components. The total annual costs are highest for Level 2-2 AS3, followed by Level 5-1 B5/RO and Level 5-2 MBR/RO. The annual costs for operation labor is highest for Level 2-2 AS3 because of the increased sludge processing and disposal from the 3-sludge system. The maintenance labor for Level 1, Level 2-1 A2O, and both Level 3 wastewater treatment configurations is generally comparable, while the maintenance labor for Level 2-2 AS3, both Level 4, and both Level 5 wastewater treatment configurations is generally comparable. The maintenance labor for Level 2-2 AS3, both Level 4, and both Level 5 wastewater treatment configurations is higher because these wastewater treatment configurations have more unit processes. The materials annual costs are highest for Level 2-2 AS3, again due to the increased sludge processing and disposal from the 3-sludge system. Level 2-2 AS3 annual chemical costs are between 3.3 times (Level 5-1 B5/RO) and almost 8.5 times (Level 2-1 A2O) higher than the other wastewater treatment configurations due to the large alum dose for chemical phosphorus removal in Level 2-2 AS3. This large dose is needed compared to other wastewater treatment configurations because Level 2-2 AS3 achieves phosphorus removal solely through chemical phosphorus precipitation while the other wastewater treatment configurations have some level of biological phosphorus removal. The annual costs for Levels 5-1 B5/RO and

5-2 MBR/RO are driven by the annual energy costs, which are between 2 times (Level 4-1 B5/MBR) and almost 4 times (Level 1 AS) higher than the annual energy costs for the other wastewater treatment configurations because both Level 5 configurations include an energy-intensive reverse osmosis unit.

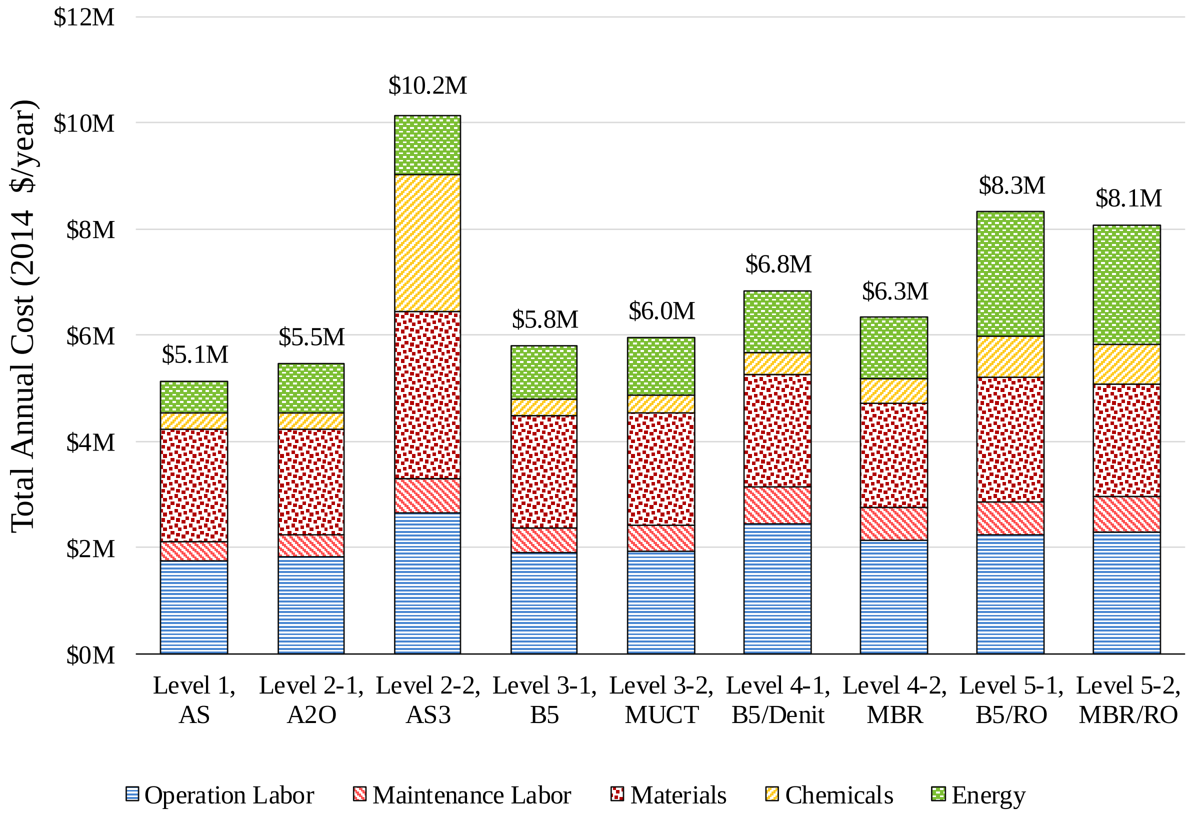


Figure 5-2. Annual Costs by Wastewater Treatment Configuration

Figure 5-3 presents the total annual costs for all the wastewater treatment configurations broken out according to treatment group. The total annual costs for the preliminary/primary/disinfection treatment group are comparable for all of the wastewater treatment configurations, as there are no significant operating differences between the various wastewater treatment configurations.

The biological treatment total annual costs are the highest for Level 2-2 AS3 due to the operational labor, maintenance labor, and chemical costs associated with the three separate biological units. The only chemical addition in the biological treatment portion of Level 2-2 AS3 is for methanol addition in the suspended growth denitrification process unit. The 4-stage and 5-stage Bardenpho and Modified University of Cape Town unit processes in Level 3-1 through Level 5-2 have comparable total annual costs, however the total annual costs for the membrane bioreactors are much higher than the total annual costs for the secondary clarifiers. As a result, the biological treatment total annual costs for the Level 4-2 MBR and Level 5-2 MBR/RO wastewater treatment configurations are high. These wastewater treatment configurations have higher annual operational labor due to the membrane bioreactor and membrane cleaning chemical costs. The Level 4-2 MBR also has supplemental methanol addition immediately preceding the 4-stage Bardenpho reactor, which accounts for the higher chemical costs than Levels 2-1 A2O and both Level 3 wastewater treatment configurations. The Level 4-1 B5/Denit wastewater treatment configuration also has supplemental methanol addition to the denitrification filter, but the methanol dose is lower than the Level 4-2 MBR.

The total annual costs for post-biological treatment are highest for Level 5-1 B5/RO, followed by Levels 2-2 AS3, Level 4-1 B5/Denit, and Level 5-2 MBR/RO, which are all comparable. The Level 5-1 B5/RO annual costs are the highest because of the high energy demand for the ultrafiltration, reverse osmosis unit, and brine injection well, along with having high material replacement costs for the ultrafiltration and reverse osmosis membranes. The Level 2-2 AS3 post-biological treatment annual costs are driven by the alum chemical costs for chemical phosphorus removal. Level 4-1 B5/Denit post-biological treatment annual costs are driven by operational and maintenance labor. The Level 5-1 MBR/RO post-biological treatment annual costs are driven by energy demand for the reverse osmosis and brine injection well, along with the materials replacement cost for the reverse osmosis membranes.

The sludge processing and disposal costs are comparable for all of the wastewater treatment configurations, except for Level 2-2 AS3, which is about $1 million/year more than the other configurations due to the additional sludge generated from the three clarifiers and high alum dose for chemical phosphorus removal.

The Level 5 wastewater treatment configurations both have brine disposal, while the other wastewater treatment configurations do not. The annual costs for the brine disposal are the same for both Level 5 configurations.

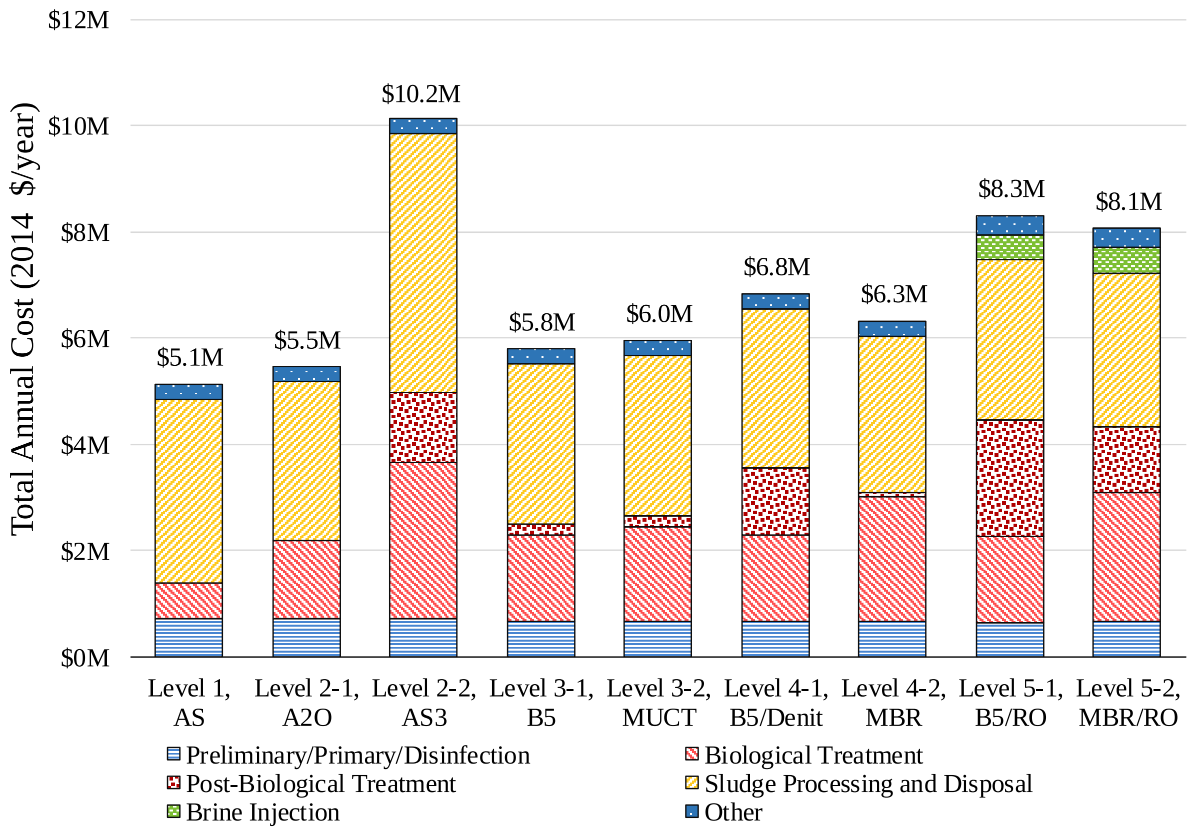


Figure 5-3. Annual Costs by Aggregated Treatment Group

5.2 <u>Net Present Value Cost Results</u>

The net present value, presented in Figure 5-4, trends similarly to the total annual costs discussed in Section 5.2. The net present value for Level 1 AS is the lowest, while the Level 5-1 B5/RO the highest. In general, the net present value increases with increasing nutrient control levels, except for Level 2-2 AS3, which has a net present value almost as high as the Level 5-2 MBR/RO wastewater treatment configuration due to the high annual costs associated with the three separate biological units as discussed in Section 5.1.2. The net present value for both Level 3 wastewater treatment configurations are similar, with only a $8 million difference. The net present value for both Level 4 wastewater treatment configurations are also similar, with only a $2 million difference.

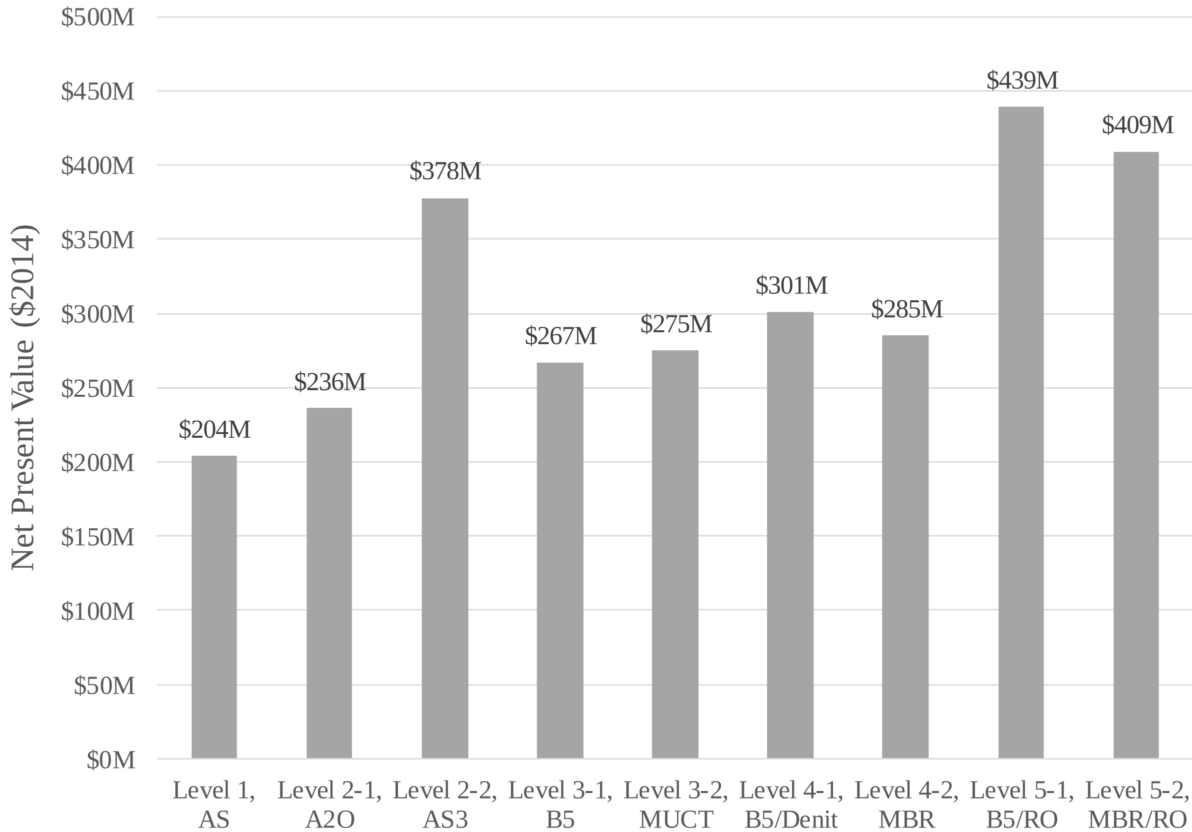


Figure 5-4. Net Present Value by Wastewater Treatment Configuration

5.3 Cost Results Quality Discussion

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* approved by EPA on March 25, 2015 (ERG, 2015c), ERG subjected the LCCA results to a multi-stage review, verification, and validation process.

The LCCA methodology and results received three levels of technical review, including conceptual review, developmental review, and final product review. ERG developed the planned LCCA approaches and methods; subjected them to internal review by ERG technical reviewers with knowledge relevant to engineering costing, but not directly involved in the approach development; and discussed them with GLEC and EPA during regular project meetings. During development of the LCCA methodologies and results, all CAPDETWorks™ output files and supplemental cost estimation spreadsheets underwent internal technical review to verify the estimates and calculations comported with the planned methods and approaches and confirm the accuracy of the calculations. Finally, ERG conducted an overall assessment of the reasonableness of the final LCCA results. For example, ERG confirmed that differences among the unit-process and configuration-level costs, and other factors such as chemical demand, energy use, and sludge generation, were reasonable based on engineering judgement of the relative size and complexity of the units and systems.

ERG validated the LCCA results by comparing them against available data that were not used in the project to develop the LCCA. For the CAPDETWorks™ costing, ERG compared the total capital and total annual costs and net present value costs for Level 1 AS, Level 2-1 A2O, Level 3-1 B5, Level 4-1 B5/Denit, and Level 5-1 B5/RO to similar treatment systems in Falk et al., 2011, which are presented in Table 5-3. ERG was unable to identify additional literature that included planning-level costs for greenfield wastewater treatment plants with similar wastewater treatment configurations. The other wastewater treatment configurations were not included in Falk et al., and are therefore not included in Table 5-3. In general, Falk et al. included limited detail for a direct comparison with the wastewater treatment configurations included in this study. As an example, Falk et al. did not provide the software used to develop the costs, only included select design parameters for select unit processes, and did not present the unit process-specific costs. The total capital costs in this study are 50-66% of the capital costs presented in Falk et al. Falk (2017) noted that Falk et al. included a raw sewage pump station, more conservative construction assumptions associated with site conditions (e.g., sheeting, shoring, dewatering), and higher concrete unit costs than for this study. The total annual costs for this study are between 1.5 and 5.0 times higher than the total annual costs in Falk et al. This difference is predominately due to the scope of the annual costs; this study included operational labor, maintenance labor, materials, chemicals, and energy, while Falk et al. only included chemicals and energy. For this study, the operational labor, maintenance labor, and materials accounted for 63 to 82% of the total annual costs. Although there are differences between the costs developed for this study and presented in Falk et al., literature sources indicate that CAPDETWorks™ construction estimates are within 20% of actual construction costs (U.S. EPA OWM, 2008b). The net present value for this study are $66 million to $104 million higher than the net present value from Falk et al. This is primarily due to the differences in total annual costs discussed above, but also because Falk et al. used 5% discount rate and 3.5% escalation rate for capital, energy, and non-energy components. This study calculated net present value using 3% discount rate and did not escalate any costs.

Table 5-3. Total Costs Compared to Falk et al., 2011

Wastewater Treatment Configuration	Total Capital Cost (2014 $)	Falk et al. Total Capital Costs (2014 $) [a]	Total Annual Cost (2014 $/yr)	Falk et al. Total Annual Costs (2014 $) [a]	Net Present Value (2014 $)	Falk et al. Net Present Value (2014 $) [a]
Level 1, AS	$55,300,000	$103,000,000	$5,140,000	$1,020,000	$204,000,000	$123,000,000
Level 2-1, A2O	$71,400,000	$142,000,000	$5,470,000	$1,410,000	$236,000,000	$167,000,000
Level 3-1, B5	$93,100,000	$161,000,000	$10,150,000	$2,620,000	$378,000,000	$201,000,000
Level 4-1, B5/Denit	$86,400,000	$171,000,000	$5,800,000	$3,570,000	$267,000,000	$234,000,000
Level 5-1, B5/RO	$88,900,000	$243,000,000	$5,960,000	$5,570,000	$275,000,000	$335,000,000

a – ERG converted Falk et al.’s costs from 2010 dollars to 2014 dollars using the calculations presented in Section 3.2.1.

b – Total annual cost includes operational labor, maintenance labor, materials, chemicals, and energy (see Section 3.3 for details).

Validation of the cost results for ultrafiltration, reverse osmosis, and brine disposal was difficult as these technologies represent the state-of-the-art in the municipal wastewater treatment industry with few or no applications in the U.S. and little or no published data. For ultrafiltration, ERG compared the cost results to Noble et al., 2003. Noble et al. describes a study of the performance of a pilot-scale microfiltration treatment system, and provides detailed capital and O&M cost estimates for a full-scale 5 MGD system. The vendor, US Filter, is a major membrane technology provider. The study regards surface-water treatment, rather than domestic wastewater treatment, and is somewhat dated. ERG found the capital costs for the two data sources differed by approximately 11%, which is well within the range of uncertainty for planning-level costs. ERG did not compare the operating and maintenance costs, as the Noble et al., 2003 costs are specific to treatment of surface water and are not applicable to domestic wastewater treatment.

For reverse osmosis, ERG compared the cost results to costs published by the Orange County Water District, 2010. The Orange County report described the estimated capital costs for a planned 30 MGD expansion of their Groundwater Replenishment System, which includes treatment of domestic wastewater using reverse osmosis and other technologies. We found the reverse osmosis capital costs for the two data sources differed by approximately 9%, which is well within the range of uncertainty for planning-level costs.

Energy usage is a significant component of total operating and maintenance costs for membrane technologies such as ultrafiltration and reverse osmosis. ERG validated the estimated energy usage provided by vendors to a literature source WateReuse Research Foundation, 2014. For ultrafiltration, estimated energy usage by the vendor (ERG, 2015a) and WateReuse Research Foundation, 2014 were 0.5 kWh/kgal and 0.75 to 1.1 kWh/kgal, respectively. Due to concerns regarding the validity of estimated energy usage, for the final ultrafiltration costs estimates, ERG used the average estimated energy usage reported by these two sources (see Appendix E.5). For reverse osmosis, estimated energy usage by the vendor (ERG, 2015b) and WateReuse Research Foundation, 2014 were 1.2 to 2.4 kWh/kgal and 1.9 to 2.3 kWh/kgal, respectively. These two estimates are similar and overlap for much of their range. For consistency with the ultrafiltration cost methodology, for the final reverse osmosis cost estimates, ERG used the average estimated energy usage reported by these two sources (see Appendix E.6).

ERG was unable to validate estimated brine disposal costs as published costs for deep well disposal of domestic wastewater are not available.

6. LIFE CYCLE IMPACT ASSESSMENT BASELINE RESULTS BY TREATMENT GROUP

This section presents the LCA results for the nine wastewater treatment configurations by impact category. Throughout this section, results calculated at the unit process level have been aggregated by treatment group, as shown in Table 5-2. For the treatment groups, the unit processes are generally grouped sequentially; however, preliminary treatment stages are grouped with disinfection, even though these are not sequential unit processes because, in this study, these unit processes do not vary by wastewater treatment configuration. In general, add-on technologies that occur in the treatment train after the main biological treatment unit process are classified as post-biological treatment, regardless of their treatment mechanism. The figures presented in this section include the abbreviated wastewater treatment configuration names. The associated full names with information on the differentiating unit processes were previously provided in Table 1-2. Full LCIA results by unit process are provided separately in Appendix I. For three high priority impact categories, eutrophication potential, CED, and GWP, results are also presented according to the underlying processes that contribute to results regardless of their treatment group. For example, all of the electricity use from each of the wastewater treatment unit processes are combined to show the cumulative contribution of electricity use to each impact category. It is important to note that uncertainties in life cycle data and LCIA are present in all modeled treatment configurations. As discussed in Section 4.6.15, any difference lower than 10 percent is not considered significant for CED. Differences lower than 30 percent are not considered significant for particulate matter formation, acidification, eutrophication, water depletion, smog formation, fossil depletion, and ozone depletion. For the toxicity categories, an order of magnitude (factor 10) difference is typically required to be meaningful. Because of this uncertainty magnitude, the toxicity results are presented and discussed separately in Section 7. Although there is uncertainty associated with LCIA methodologies, all LCIA methodologies are applied to different treatment configurations uniformly. Therefore, comparative results can be determined with a greater confidence than absolute results for one treatment configuration.

6.1 Eutrophication Potential

Given the focus of this project on wastewater treatment nutrient removal capacity, eutrophication is a critical metric for measuring the environmental performance of the nine studied treatment configurations. As discussed in Section 4.6.1, eutrophication occurs when excess nutrients are introduced to surface and coastal water causing the rapid growth of aquatic plants. Table 6-1 presents the nutrient concentrations and annual loads for the influent and effluent from the nine wastewater treatment configurations. Although the modeled concentrations and resulting loads are not identical between the two alternatives for some of the levels, the treatment objectives are the same and would generally result in the same effluent quality, with the possible exception of Level 2. The results associated with the Level 2 treatment configuration is provided in the next paragraph.

For this study, ERG designed the wastewater treatment configuration models in CAPDETWorks™ to achieve specific effluent nutrient concentrations. As such, there is a step-wise decreasing trend in total nitrogen and total phosphorus effluent concentrations and loads with increasing treatment levels. The only exception to this is the total phosphorus effluent concentration for Level 2-1 A2O, which is lower than the Level 2 total phosphorus effluent target of 1 mg/L. This is due to the way CAPDETWorks™ calculates effluent total phosphorus from secondary clarifiers. To achieve total suspended solids of 20 mg/L for Level 2-1 A2O, the total phosphorus effluent concentration is about 0.3 mg/L; revising the clarifier design parameters to achieve total phosphorus effluent concentration of 1 mg/L results in total suspended solids around 70 mg/L, which is over the secondary treatment standards.

Table 6-1. Nutrient Discharges by Wastewater Treatment Configuration

Wastewater Treatment Configuration	Total Nitrogen		Total Phosphorus	
	Long-Term Average Concentration (mg/L)	Annual Load (lb/yr)	Long-Term Average Concentration (mg/L)	Annual Load (lb/yr)
Influent	40	1,220,000	5.0	152,000
Effluent Concentrations				
Level 1, AS	30	908,000	4.9	150,000
Level 2-1, A2O	8.0	244,000	0.29	8,570
Level 2-2, AS3	7.8	237,000	1.0	30,500
Level 3-1, B5	6.0	183,000	0.22	6,770
Level 3-2, MUCT	6.0	183,000	0.22	6,770
Level 4-1, B5/Denit	3.0	91,100	0.10	3,050
Level 4-2, MBR	3.0	91,500	0.10	3,020
Level 5-1, B5/RO	0.78	23,800	0.02	457
Level 5-2, MBR/RO	1.9	58,800	0.02	549

Figure 6-1 presents eutrophication potential results grouped according to treatment group. Eutrophication is the combined effect of direct nutrient discharges in the effluent, landfilled sludge leachate, and the water discharges and air emissions from upstream inputs to the treatment steps such as electricity and chemical production. The green bar represents the eutrophication potential related to effluent release and is directly related to the designed performance of each treatment level. As expected, the potential eutrophication impact from effluent release for the conventional activated sludge configuration (Level 1) are significantly greater compared to the other treatment configurations. The impact of effluent drops off markedly for Level 2 treatment configurations and remain consistently lower throughout the remaining treatment levels. Eutrophication impact potential is very similar for Levels 3 and 4; although the effluent nitrate values for Level 4 are lower than Level 3, they are offset by an increase in COD in the effluent (as shown in the effluent characteristics in Table 1-4).

The release of organic nitrogen, ammonia and phosphorus in the effluent drives the observed potential eutrophication impact for the majority of wastewater treatment configurations evaluated, whereas the contributions to eutrophication of the sludge and biological treatment groups are relatively consistent across Levels 2 through 5. The eutrophication potential impact from sludge disposal are primarily related to the long-term release of COD in landfill leachate described previously in Section 4.4. Sludge processing and disposal eutrophication impact generally does not vary substantially since the wastewater treatment configurations produce a similar quantity of sludge sent to landfill, with the exception of Level 2-2. Level 2-2 has higher eutrophication impact for the sludge processing and disposal treatment group because of the higher sludge generation in this level from the significant use of chemical phosphorus precipitation. The biological treatment step for conventional activated sludge has a noticeably lower impact than the other levels, which is due to the lower energy intensity of the more basic activated sludge treatment process. Overall, it is apparent that the potential cumulative eutrophication impact generally decreases between Level 1 and Level 2 and then again between Level 2 and Level 3 and Level 4. Level 5 results in an increase in eutrophication impact compared to Level 4 due to the high energy intensity of RO and brine injection, which off-set the reduction in impact associated with the effluent release. However, based on the uncertainty thresholds for impact results, the eutrophication potential difference between Level 3, Level 4 and Level 5 wastewater treatment configurations is not considered significant. As discussed in Section 4.6.1, both indirect and direct air and water emissions have the potential to contribute to eutrophication. Eutrophication from these energy intensive unit processes is largely due to the portion of the nitrogen oxide air emissions from upstream fuel combustion for electricity production that is modeled as deposited in water bodies. Nitrogen oxide emissions are largely associated with deposition from the combustion of coal in the average US electrical grid (coal is currently estimated to contribute approximately 45 percent to the average U.S. electrical grid as shown in Table 4-2, Section 4.2, which comes from 2009). For more detail, Table J-1 in Appendix J shows the contribution of each individual unit process to the overall eutrophication potential for each wastewater treatment configuration. To compare electricity consumption across the wastewater treatment configurations refer to Table H-1 through Table H-10 in Appendix H.

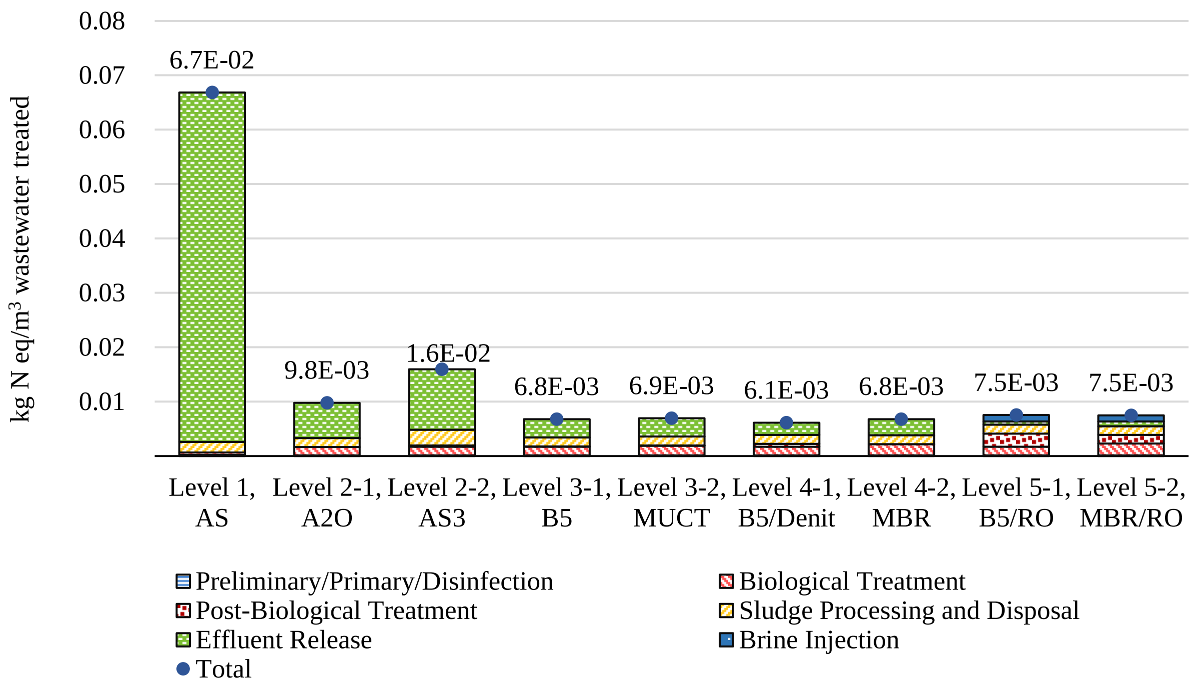


Figure 6-1. Eutrophication Potential Results by Treatment Group

The impact of increased energy use, particularly in Level 5, is visible in Figure 6-2. As previously discussed, disposal of sludge in a municipal solid waste landfill also contributes to eutrophication impact, primarily related to the long-term release of COD in landfill leachate.

Natural gas, infrastructure, chemicals, process emissions, and sludge transport cumulatively contribute between 0.3 and 4 percent of eutrophication impact depending on treatment level.

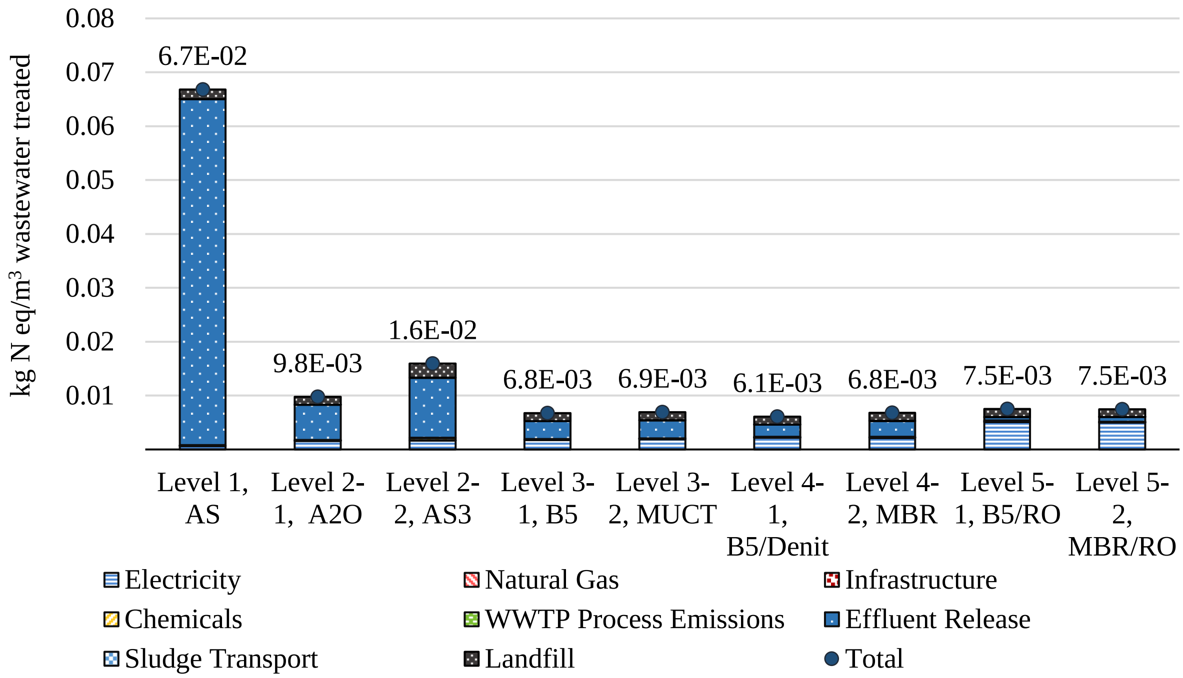


Figure 6-2. Eutrophication Potential Results by Process Contribution

6.2 Cumulative Energy Demand

Figure 6-3 and Figure 6-4 present CED results grouped according to treatment group and by process contribution. The CED results are driven by direct energy use in the form of electricity and natural gas at the WWTP as well as energy consumption associated with upstream chemical and infrastructure production. Fuel inputs for transportation and landfill management are also incorporated in the CED results.

The separation processes selected for use in this study to remove nutrients from wastewater require energy, and this energy requirement generally increases with the level of separation. Between 43 and 88 percent of CED is attributable to electricity use associated with each wastewater treatment configuration, including supply-chain electricity use. Natural gas consumption, primarily to provide heat for anaerobic digestion, is the second largest contributor to CED, accounting for between five and 30 percent of CED.

The biological treatment units and sludge processing and disposal from Level 2 through Level 5 all produce a relatively consistent energy demand. More significant differences in energy demand between treatment systems are associated with the post-biological treatment units, such as denitrification, membrane bioreactors, ultrafiltration, and RO. For Levels 5-1 and 5-2, RO filtration and brine injection cumulatively contribute 48 and 49 percent of CED impact, respectively. For more detail, Table J-2 shows the contribution of each individual unit process to the overall CED for each wastewater treatment configuration. The upstream energy demand of chemical production is visible in Figure 6-4, particularly for Level 2-2. Level 2-2 CED from chemical production is largely associated with the methanol requirement for denitrification and aluminum sulfate used for chemical phosphorus precipitation.

As discussed in Section 1.2.3, it may be possible, depending on the demand, to recycle the effluent from Levels 1 through 5 for a variety of reuse applications ranging from landscape irrigation to indirect potable reuse (U.S. EPA 2012b). While recycled water was not considered in the system boundaries of this study, recycling the water would likely offset some of the increased CED of the higher nutrient removal wastewater treatment configurations by displacing production of potable water elsewhere. The magnitude of the offset would depend upon the current source of water for that reuse application.

The effect of biogas energy recovery on CED is discussed in Section 9.5.

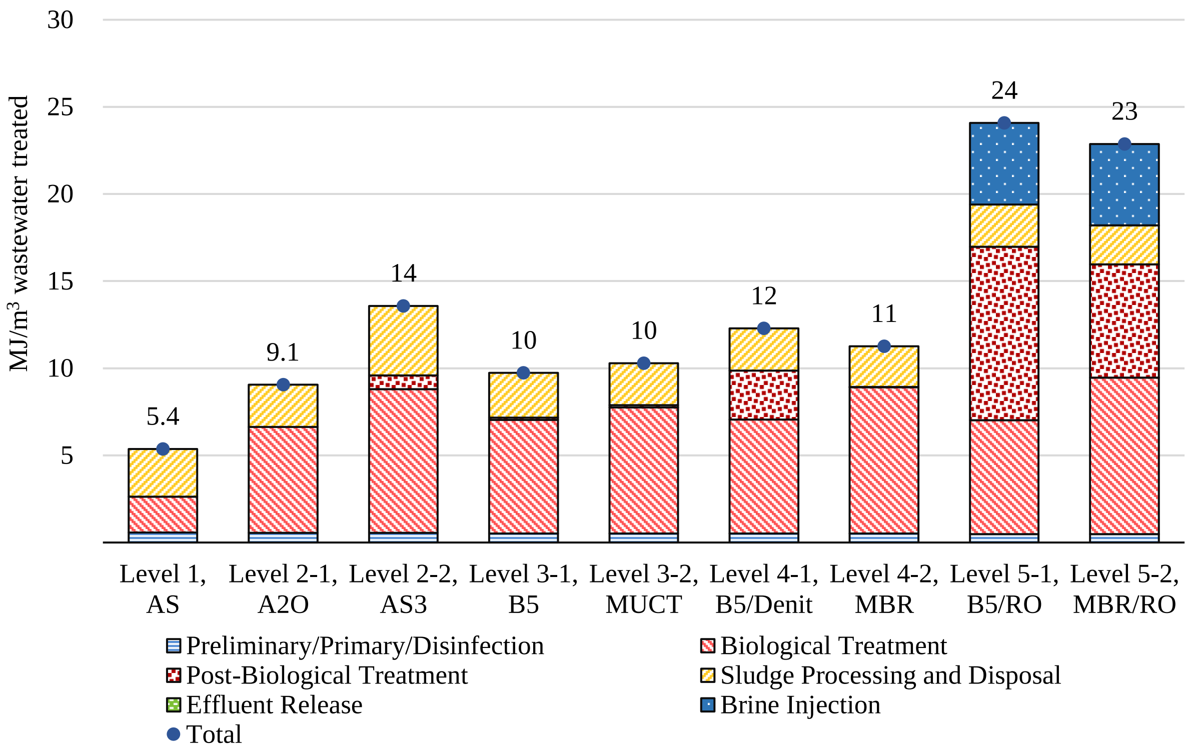


Figure 6-3. Cumulative Energy Demand Results by Treatment Group

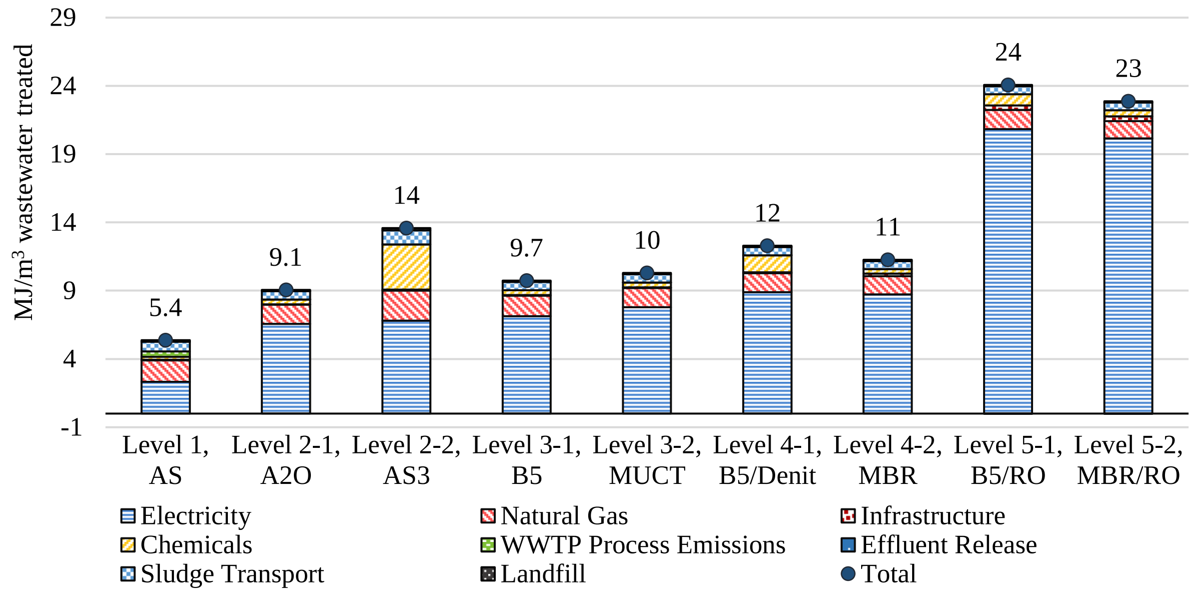


Figure 6-4. Cumulative Energy Demand Results by Process Contribution

6.3 Global Warming Potential

Figure 6-5 presents the GWP results grouped according to treatment group. Overall, the GWP of the treatment configurations increases with the stringency of effluent quality criteria, as additional unit processes are required. The total GWP of Level 5 is over three times greater than that for Level 1. The GWP of the biological treatment subcategory increases by approximately 415 percent as we progress from Level 1 to Level 3. GWP impact associated specifically with biological treatment then remains relatively constant between Levels 3 and 5. The increase between Level 1 and Level 3, is due both to the increasing energy demand of the biological treatment configurations as well as the increased production of process GHG emissions. The advanced biological treatment units contain a combination of aerobic, anoxic, and anaerobic stages, in which both CH_4 and N_2O emissions may be generated and ultimately emitted from the treatment system. Based on available data to characterize these types of treatment configurations, as described in Appendix F, CH_4 emissions from biological treatment are the most impactful process GHGs; however, there is uncertainty associated with estimating these process GHGs and in differentiating the various treatment levels due to the limited measurement data associated with the different treatment configurations evaluated.

RO and brine injection together increase the GWP of Levels 5-1 and 5-2 by approximately 35 percent. The attached growth denitrification filter contributes just over 10 percent of GWP impact to Level 4-1. Sludge processing and disposal, shown in yellow, contributes between 0.22 and 0.27 kg of CO_2 eq. per cubic meter of wastewater for each treatment system. Over half of the sludge processing and disposal impact is attributable to operation of anaerobic digesters. Although the absolute contribution demonstrates consistency between treatment levels, the relative contribution to total impact scores decreases from a high of 53 percent for Level 1 to only 12 percent for Level 5-1. Fugitive release of CH_4 from landfilled biosolids at end-of-life (EOL) is responsible for approximately one-quarter of total sludge processing and disposal GWP emissions. While indirect N_2O emissions from wastewater after discharge of effluent into receiving waters contribute less than three percent of GWP impact for Levels 2 through 5, this source of GHG emissions constitutes nearly 13 percent of Level 1 GWP. These emissions decrease across the treatment levels corresponding to increased removal of nitrogen from the final effluent. Nitrous oxide emissions from wastewater effluent are the result of denitrification processes that occur in the receiving water after wastewater is discharged from the treatment facility. Documentation of the N_2O GHG calculations for receiving waters is provided in Appendix F.

For more detail, please refer to Table J-3 and Table J-4, which shows the contribution of individual unit processes to the overall GWP.

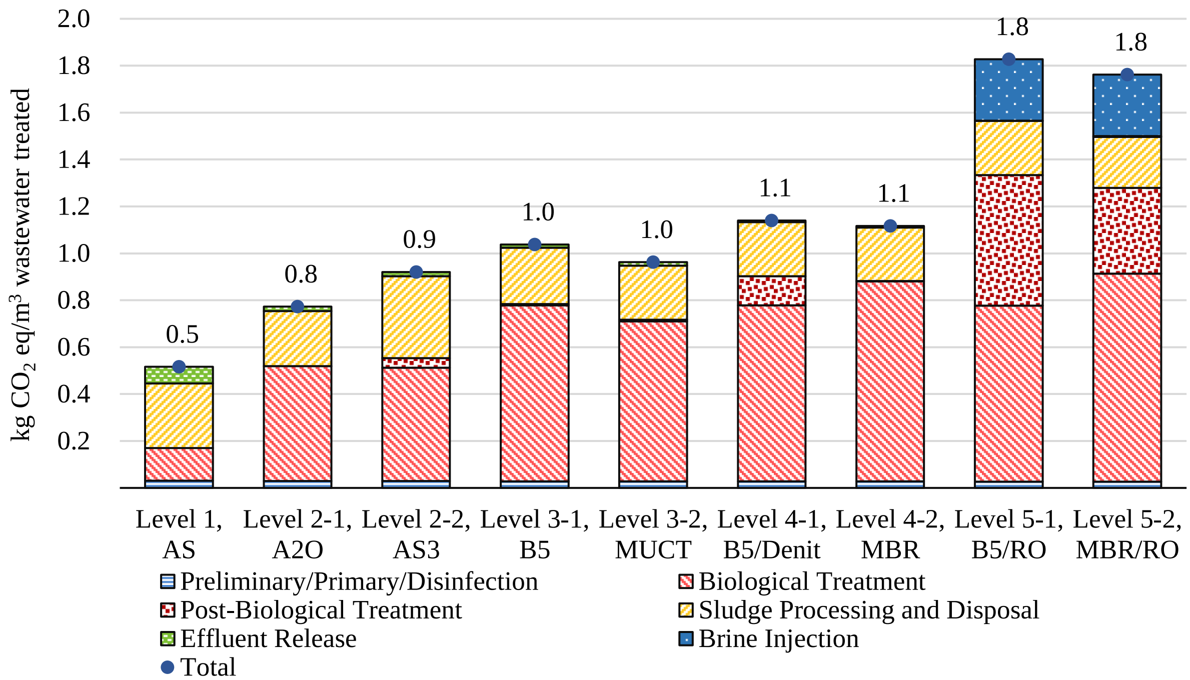


Figure 6-5. Global Warming Potential Results by Treatment Group

Figure 6-6 aggregates GWP impact according to process contribution, highlighting the dominant contribution of electricity use to GWP impact. The relative percentage of GWP impact provided by electricity use increases from a low of 28 percent for Level 1 to a high of 64 percent for Level 5-2. Process GHG emissions from biological treatment units and anaerobic digestion are the second largest source of GWP impact and are similar in magnitude to electricity contributions for several treatment levels. The relative contribution of GHG process emissions is greatest for Levels 3 and 4 due to the unit processes used to attain the high degree of nutrient removal combined with a relatively lower energy footprint as compared to Level 5 configurations. For Level 1, the release of N_2O emissions is shifted to receiving streams.

Natural gas use and landfill disposal of biosolids are both noticeable contributors to GWP impact, remaining consistent across treatment configurations. Natural gas contributes between four and 18 percent of GWP impact. Fugitive landfill methane emissions contribute a further three to 13 percent, depending upon the configuration. It is important to remember that fugitive landfill emissions occur over long periods of time as the anaerobic degradation of sludge proceeds in the landfill environment. Although the fugitive landfill methane releases occur gradually over many years, the approach used here models the impacts of the aggregated emissions using 100-year GWPs. This is consistent with the use of 100-year GWPs used for all other life cycle GHG emissions, as discussed in Section 4.6.3. Future refinements to landfill LCA modeling may include time-scale modeling of landfill methane emissions; however, this is not part of the current study. Such future refinements of time scale modeling of long-term GHGs may lead to exclusion of methane emissions released after 100 years. As discussed in Appendix F Section F.1.5, this study has assumed landfill gas capture and energy recovery is based on average municipal landfill statistics in the U.S. There are a few instances where relative impact associated with these unit process categories can rise above ten percent for a specific treatment level. Effluent release, landfill emissions, and natural gas use contribute 14, 13, and 18 percent of Level 1 impact, respectively. Chemical use in Level 2-2, which relies heavily on chemical phosphorus precipitation, contributes 11 percent of GWP impact.

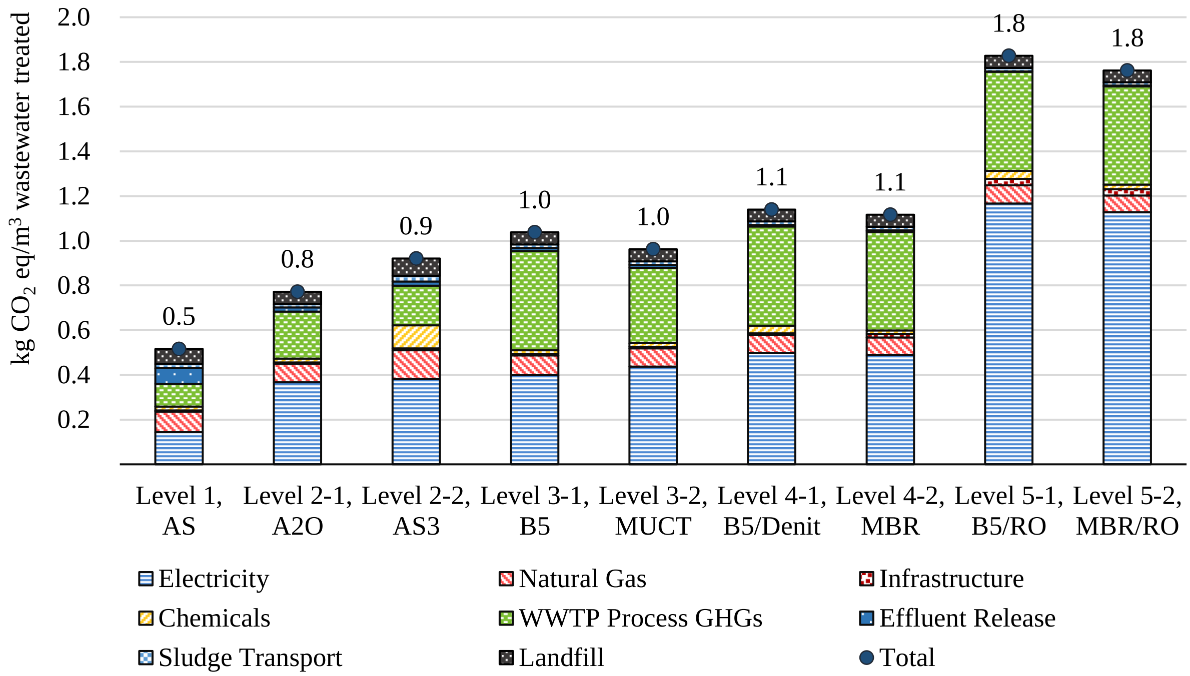


Figure 6-6. Global Warming Potential Results by Process Contribution

6.4 Acidification Potential

Figure 6-7 presents results for acidification potential grouped according to treatment group. Acidification impact associated with biological treatment, post-biological treatment, and brine disposal are the dominant treatment groups contributing to acidification impact. Electricity use attributable to these treatment processes is the primary source of acidifying emissions. Eighty-eight percent of Level 1 impact in this category is associated with electricity use, and the relative contribution rises to over 95 percent for Level 5. Approximately 70 to 80 percent of acidification impact is associated with sulfur dioxide and nitrogen oxide emissions from coal combustion. The contribution of biogas flaring to acidification impact, again from sulfur oxides and nitrogen oxide emissions, varies between 0.1 and 9 percent depending on the treatment level with lower levels having higher relative contributions from biogas flaring. The effect of biogas energy recovery on acidification potential impact is discussed in Section 9.5. For more detail, Table J-4. presents the contribution of individual unit processes to acidification potential impact.

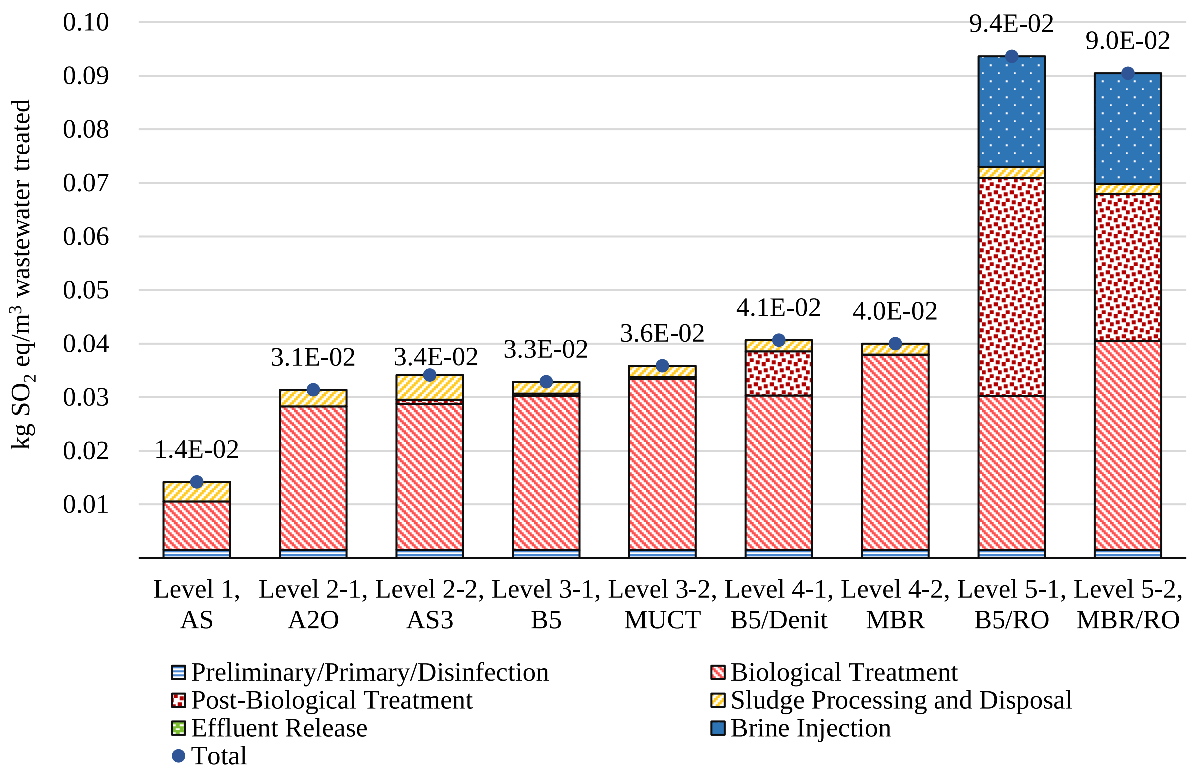


Figure 6-7. Acidification Potential Results by Treatment Group

6.5 Fossil Depletion

Figure 6-8 presents the fossil depletion results according to treatment group. Approximately 50 percent of fossil depletion impact for the Level 1 treatment system are attributable to electricity consumption. Electricity contributes over 90 percent of total fossil depletion impact for Level 5 configurations. Within electricity consumption, the contribution to fossil depletion is associated with coal, natural gas, and crude oil in a static ratio of approximately 2:1:1. An electricity credit, derived from the combustion of landfill gas, is reflected in the figure and serves to reduce relative fossil depletion impact by between one and six percent depending upon the treatment level, with greater relative decreases being associated with lower levels of nutrient removal.

Natural gas combustion used to provide process heat for anaerobic digestion contributes 31 percent of the relative impact for Level 1. The relative contribution of natural gas combustion decreases for higher treatment levels. Truck transport of processed biosolids to the landfill also figures prominently in the results, contributing approximately 13 percent of the impact associated with Level 1. The absolute contribution of sludge hauling to fossil depletion is greatest for Level 2-2 due to the increase in sludge volume associated with chemical precipitation. The contribution of chemical use to fossil depletion amounts to over five percent of impact for Level 1 and over nine percent for Level 4-1. The increase associated with Level 4-1 is due to the use of methanol for denitrification. For more detail, Table J-5 shows the contribution of individual unit processes to fossil depletion potential.

The high energy use in the biological treatment group is due to the biological treatment units (e.g., 3-stage Bardenpho, Modified University of Cape Town) and membrane filtration solids separation in Levels 4-2 and 5-2. For the biological treatment units, energy use is due to aeration, mixing, internal recycle and return activated sludge pumping. Membrane filtration use energy for aeration, permeate pumping, and internal recycle. Energy use for the post-biological treatment group is high for Levels 4-1, 5-1, and 5-2. For Level 4-1, over 95 percent of post-biological energy use is associated with the denitrification filter. For Level 5-1, post-biological energy use is approximately 70 percent for the RO and 25 percent for ultrafiltration. For Level 5-2, close to 100 percent post-biological energy use is for RO.

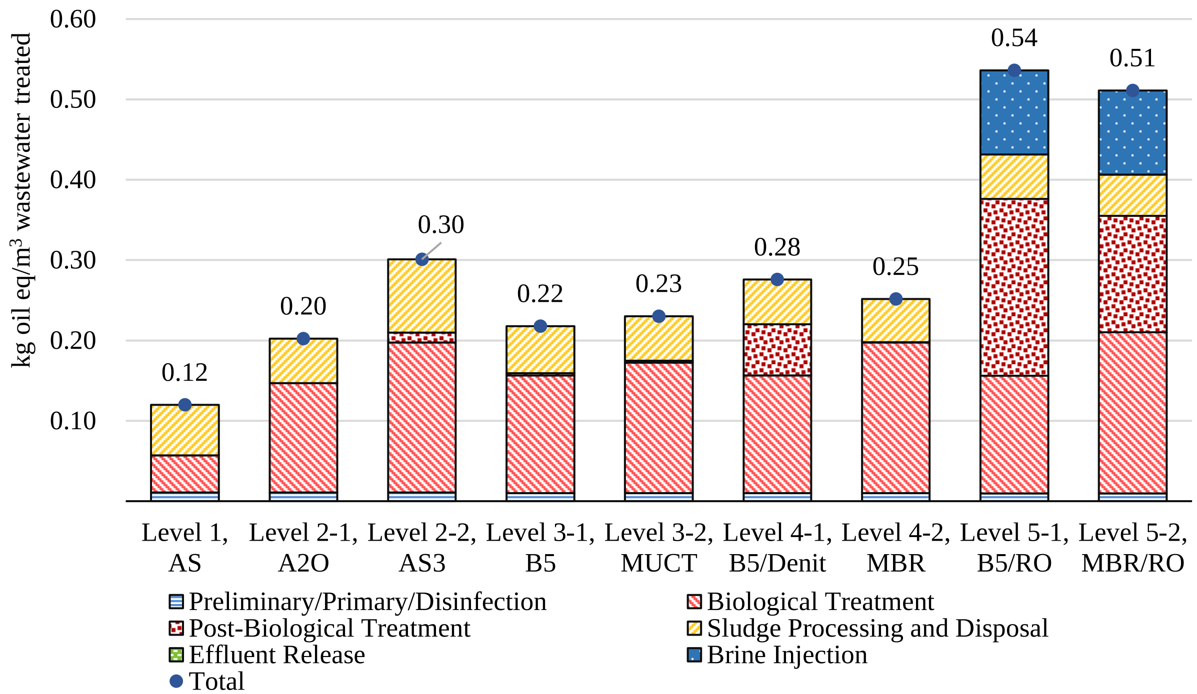


Figure 6-8. Fossil Depletion Results by Treatment Group

6.6 Smog Formation Potential

Figure 6-9 presents the smog formation potential results by treatment group. Greater than 95 percent of smog formation potential is linked to air emissions of nitrogen oxides from fuel combustion processes. Coal combustion, which is primarily associated with electricity generation, produces high nitrogen oxide emissions. For the Level 5 wastewater treatment configurations, coal combustion contributes most of the impact. However, only about half of the smog formation potential is due to coal combustion for the conventional activated sludge system configuration. For Level 1, the relative smog formation impact of biogas flaring is 27 percent, with the absolute impact of biogas flaring consistent across wastewater treatment configuration. Other typical combustion processes such as transport and industrial manufacturing contribute less than one percent of cumulative impact in this category. For more detail, Table J-6 shows the contribution of individual unit processes to smog formation potential.

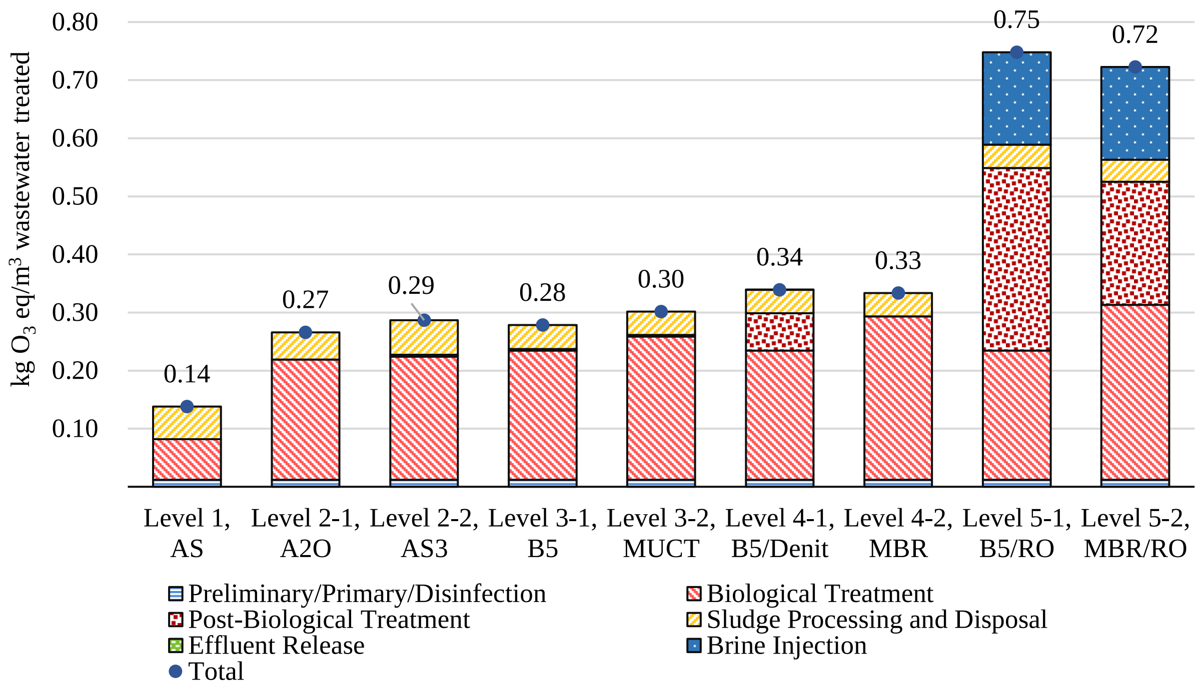


Figure 6-9. Smog Formation Potential Results by Treatment Group

6.7 Human Health-Particulate Matter Formation Potential

Figure 6-10 presents the PM formation potential results by treatment group. PM formation is considered a human health impact category due to its close association with respiratory conditions, leading to increased morbidity (Bare, 2012). Over 92 percent of the impact in this category is attributable to the combustion of fossil fuels for electricity production. Biogas flaring produces a relatively low level of PM-related emissions and does not contribute greater than three percent of total PM impact for any treatment level assessed. Approximately 45 to 50 percent of PM impact is attributable to PM2.5 for all treatment levels. Sulfur dioxide, a precursor to secondary particulates (Bare, 2012), contributes a further 30 to 40 percent of total impact in this category. Recovery of methane energy at the landfill, and the corresponding electricity off-set, provides a credit that reduces impact in this category by just under 12 percent for the Level 1 treatment system. The relative contribution of electricity off-sets to reductions in particulate matter formation potential impact decreases with increasing energy intensity as the level of nutrient removal increase. For more detail, Table J-7 shows the contribution of individual unit processes to particulate matter formation potential.

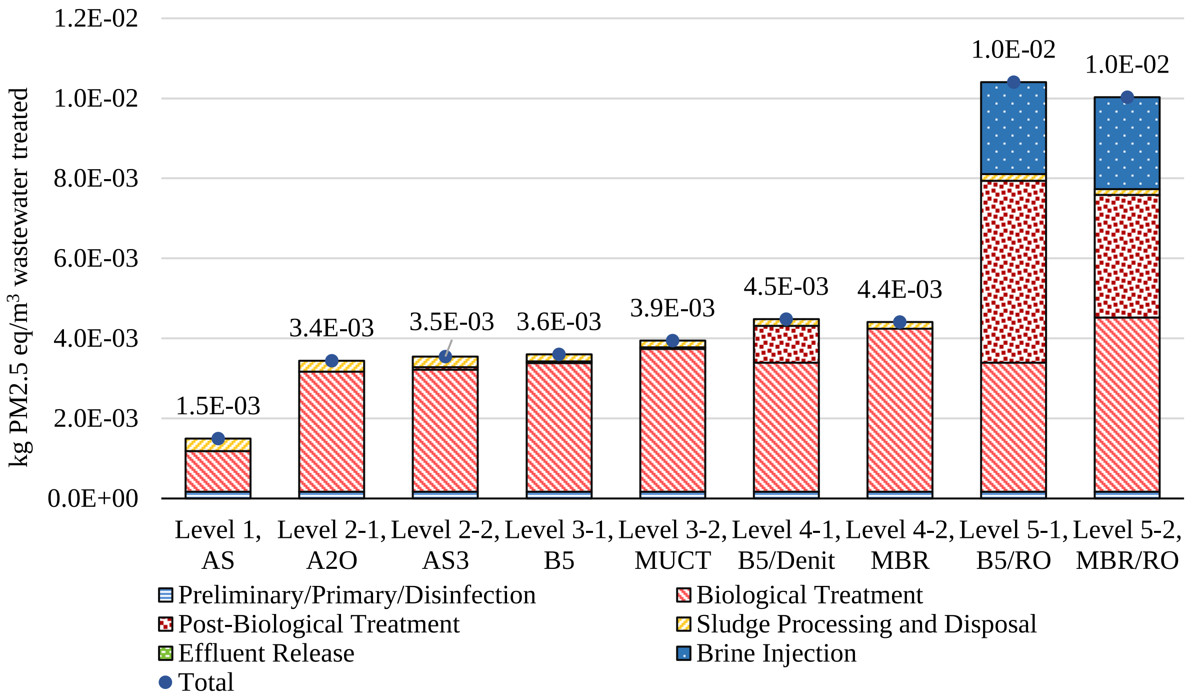


Figure 6-10. Human Health Particulate Matter Formation Potential Results by Treatment Group

6.8 Ozone Depletion Potential

Figure 6-11 presents ozone depletion potential results by treatment group. Results are driven by process and effluent related N_2O emissions. Combustion processes, such as biogas flaring, are also sources of N_2O. Electricity use accounts for most of the remaining ozone depletion potential. Electricity related impact is driven by the assumed use of three refrigerant substances[8] in power generation facilities. These substances were widely used refrigerants, but their incidence is currently decreasing following the implementation of the Montreal Protocol, which legislates the global phase out of the most powerful ozone depleting substances. Overall, the normalized impact from ozone depletion tends to be lower compared to other impacts assessed in this study due to the benefits realized from the Montreal Protocol, see Table 8-3. For more detail, Table J-8 shows the contribution of individual unit processes to ozone depletion potential.

[8] R-40 = monochloromethane, R-10 = tetrachloromethane, and HCFC-140 = 1,1,1 trichloroethane

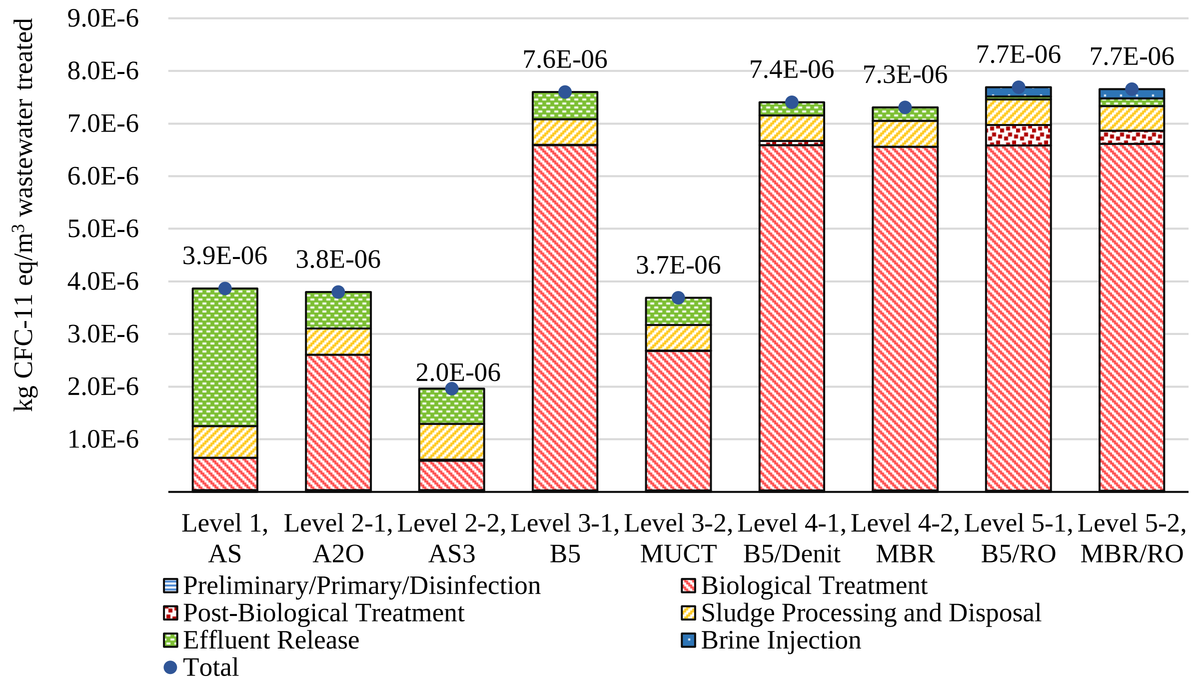


Figure 6-11. Ozone Depletion Potential Results by Treatment Group

6.9 Water Depletion

For Levels 1 through 4 between 55 and 75 percent of water depletion is due to consumptive water use in fuel and electricity production. Chemical manufacturing also contributes strongly to water use. Chlorine production is responsible for 16 percent of the impact for Level 1 treatment. Alum, methanol, and chlorine production contribute 15 percent of impact for Level 4-1, despite the rise in energy intensity. For Level 2-2, the use of alum for chemical phosphorus removal accounts for approximately 55 percent of water depletion impact associated with this wastewater treatment configuration. Level 2-2 relies on chemical precipitation for phosphorus removal, whereas other treatment systems also utilize biological nutrient removal, which lowers their alum requirement. Water use at the landfill facility is responsible for between 4 and 11 percent of impact Level 1 through Level 4 systems. For foreground unit processes, there was no direct water use (e.g., for washing) modeled; however, the loss of water from deepwell injection for Level 5 wastewater treatment configurations was considered in the analysis. As seen in Figure 6-12, the water depletion results are dominated by deepwell injection of brine resulting from Level 5 RO filtration. Approximately 17 percent of influent wastewater is diverted to deepwell injection in these wastewater treatment configurations. This water was originally drawn from surface or groundwater, and diversion to deepwell injection makes it unavailable for subsequent environmental or human uses. Reuse of treated wastewater was not considered in the system boundaries of this study, which is a possibility for all treatment levels, and would serve to reduce water depletion impact. Table J-9 shows the contribution of individual unit processes to water depletion.

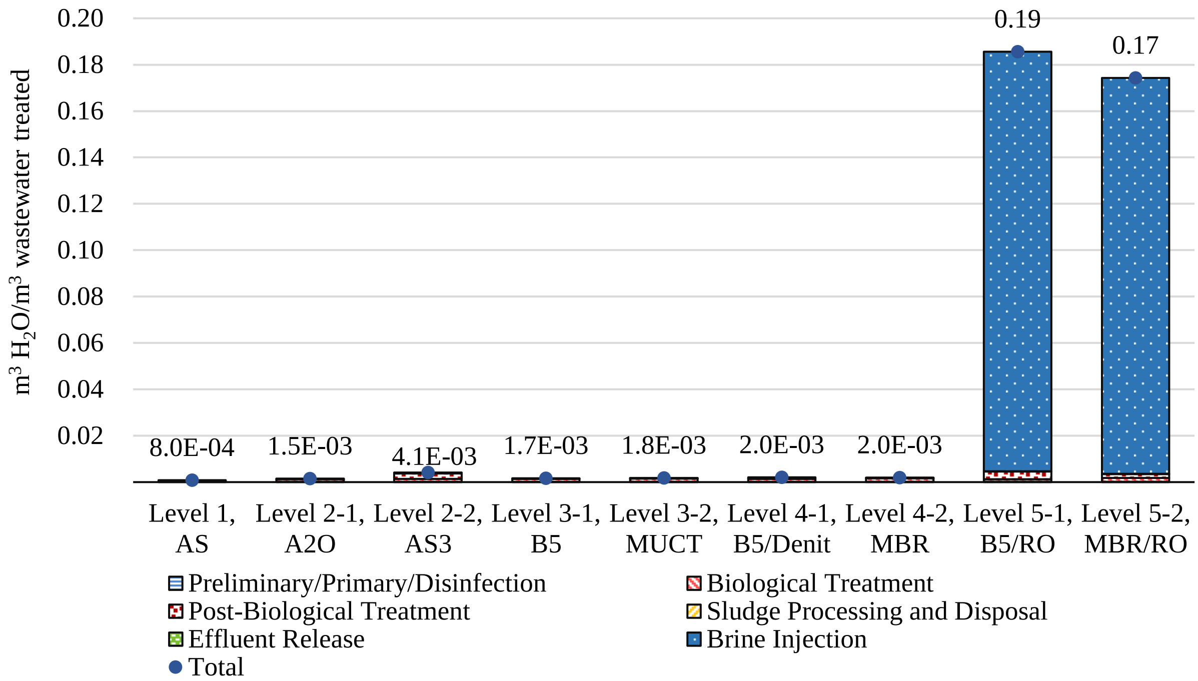


Figure 6-12. Water Depletion Results by Treatment Group

7. TOXICITY LCIA RESULTS

Toxicity results are presented for the three USEtox™ impact categories. Presented results include impacts associated with metals, toxic organics and DBPs in effluent and sludge for each wastewater treatment configuration as well as upstream impacts associated with energy, chemical and material production.

Figure 7-1 presents summary contribution results for all nine treatments systems in the three toxicity impact categories. The figure is intended to highlight the most important aspects of each treatment configuration that contributes to toxicity impacts. All results in Figure 7-1 are standardized such that the total impact of each treatment configuration equals 100%. Contributions to impact are aggregated in the following groups: material and energy inputs, effluent metals, effluent toxic organics, effluent DBPs, metals in sludge, and toxic organics in sludge. Metals in liquid effluent are the dominant contributor among the three trace pollutant categories. For treatment Levels 1 thorough 4-1, metals in liquid effluent are the single largest contributor to ecotoxicity and non-cancer human health impacts. For Levels 4-2 through 5-2, contributions from plant material and energy inputs dominate toxicity impacts. As treatment becomes more rigorous from Level 1 to Level 5, the contributions of trace pollutants to toxicity impact decrease. There is a slight increase in toxicity impacts associated with sludge landfilling along the same continuum, however total toxicity contributions from sludge disposal never exceed 10%. Contributions from toxic organic chemicals, either in sludge or liquid effluent, are only visible for the non-cancer human health impact category amounting to four percent or less of total impact for all treatment configurations. DBPs contribute greater than 10% of total impact for the cancer human health impact category in Levels 1, 2-1, and 4-2.

It is important to consider the uncertainty inherent in the calculation of toxicity related impacts using the USEtox™ method (Huijbregts et al., 2010). Many of the characterization factors used to quantify impacts in these categories are considered interim by USEtox™ developers. All toxicity related characterization factors associated with metals and metal ions, which dominate the results of this study, are considered interim at this time. Moreover, the characterization factors assume impacts result from a specific ionic form of each metal species that is not necessarily the same form in which the metal is emitted from treatment systems. This is a common limitation of the USEtox™ method, and it implies the assumption that once emitted, transformations to a more toxic form may occur within the receiving environment. Overall, the uncertainty associated with interim characterization factors is between one and three orders of magnitude (Huijbregts et al., 2010).

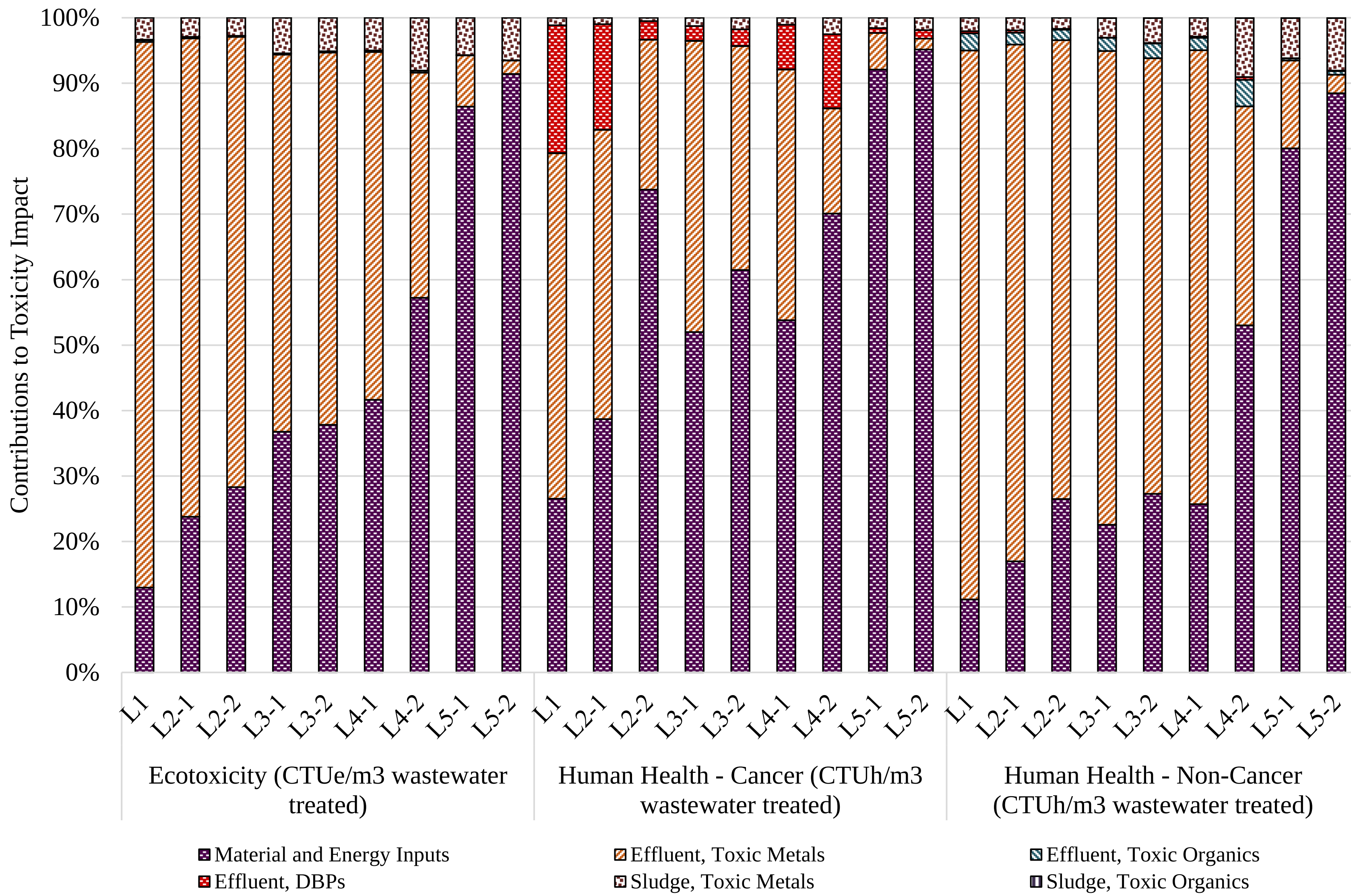


Figure 7-1. Contribution Analysis of Cumulative Toxicity Impacts

7.1 Human Health-Cancer Potential

Figure 7-2 presents the human health-cancer results by treatment group. Error bars in the figure represent the range of results generated by applying minimum and maximum removal efficiency scenario assumptions outlined in Sections 2.1 and 2.2 for metals and toxic organic pollutants, respectively. Contributions to toxicity impact from metals, toxic organics and DBPs summarized in Figure 7-1 are included in this figure within the effluent release and sludge processing and disposal treatment groups.

This figure reinforces the important contribution of metals in treatment plant effluent to cumulative human health-cancer impacts for the lower treatment Levels. The figure also demonstrates that for Level 5 treatment configurations, the increasing contribution of plant material and energy inputs outweighs the benefits of effluent improvements. Electricity consumption of the RO filter and brine injection system is primarily responsible for this increase. The Level 2-2 treatment system is associated with the highest cancer potential impacts attributable largely to aluminum sulphate production for chemical phosphorus precipitation.

When considering the average removal efficiency scenario, Levels 3-2 and 4-2 most effectively balance improvements in effluent quality against the increase in material and energy inputs required to achieve this goal. This is in large part due to the effectiveness of the MUCT unit process (Level 3-2) and the MBR unit process (Level 4-2) in removing metals from the liquid effluent. The MBR unit process, in particular, showed metal removal performance almost on par with RO, though without the detrimentally high energy requirements.

The range of impacts found for Level 1 and 2-1 are also worth noting, as although average metal removal efficiencies of these levels are lower than other configurations (around 40-60% depending on the metal), there is evidence to suggest that removals can be greater than 80% in some cases. Combined with lower process-based impacts, a high efficiency Level 1 or Level 2-1 system may perform best with respect to human health-cancer potential impacts.

Table J-10 documents the contribution of individual unit processes to the human health – cancer potential.

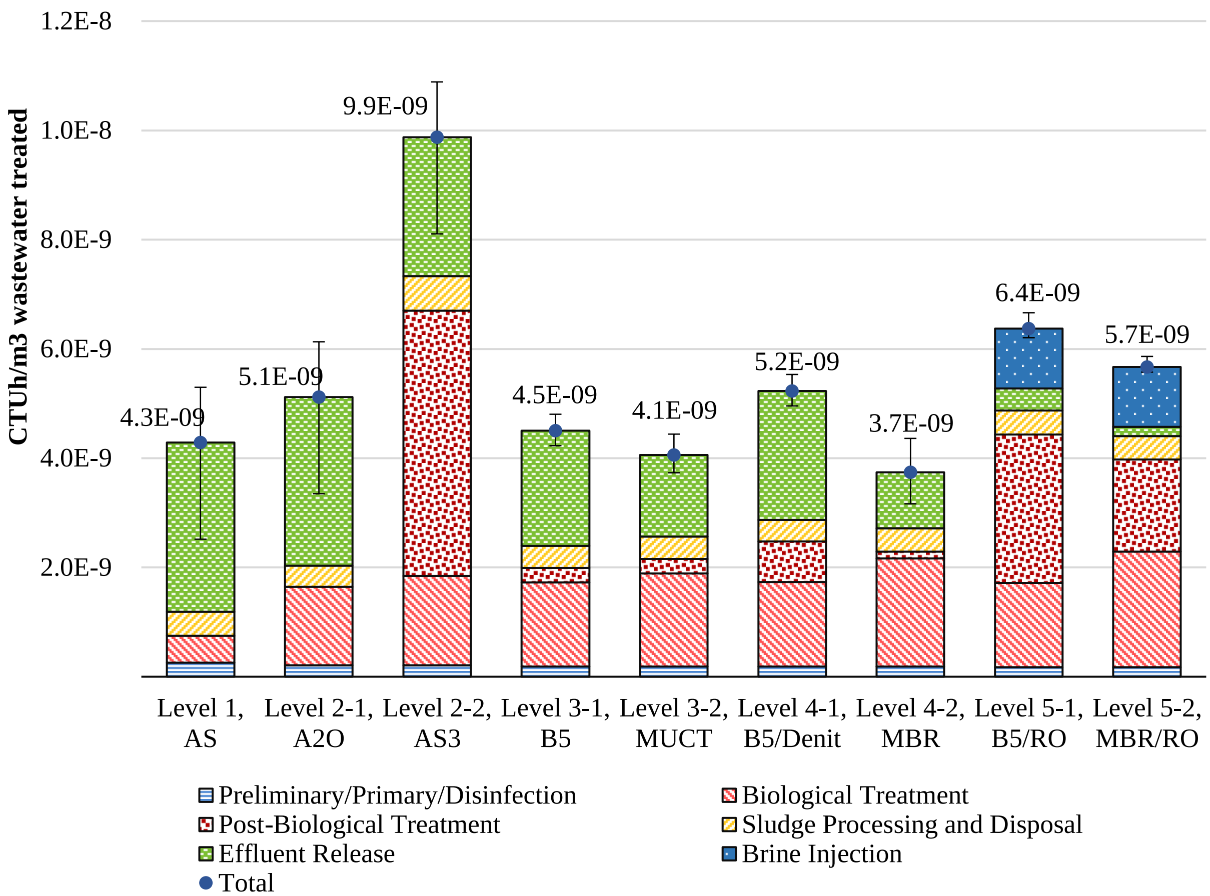


Figure 7-2. Human Health – Cancer Potential Results by Treatment Group (CTUh/m3 wastewater treated)

7.2 Human Health-Noncancer Potential

Figure 7-3 presents the human health-noncancer results by treatment group. Error bars in the figure represent the range of results generated by applying minimum and maximum removal efficiency scenario assumptions outlined in Sections 2.1 and 2.2 for metals and toxic organic pollutants, respectively. Contributions to toxicity impact from metals, toxic organics and DBPs summarized in Figure 7-1 are included in this figure within the effluent release and sludge processing and disposal treatment groups.

The toxicity impact of metals in treatment plant effluent is even more pronounced for the non-cancer human health impact category where it dominates contributions for Level 1 through Level 4-1 treatment configurations. Figure 7-1 shows that DBPs also contribute to non-cancer human health potential especially for Levels 1 and 2-1. When considering the average removal efficiency scenario, total toxicity impacts generally decrease as you move from lower treatment levels to the Level 4-2 treatment system before again increasing for Level 5. The low impacts associated with Level 4-2 are again associated with the high metals removal performance of the MBR unit process without the high energy inputs required of the RO membrane separation process. Also, the removal efficiency range is narrower for the membrane separation processes than for the lower treatment levels that rely more heavily on less precise biological processes for partitioning of metals to sludge. Even considering the high removal efficiency scenario for the lower three treatment levels, total non-cancer potential impacts are greater than or equal to the toxicity impact of Levels 4-2 and 5.

Table J-11 shows the contribution of individual unit processes to human health–noncancer potential.

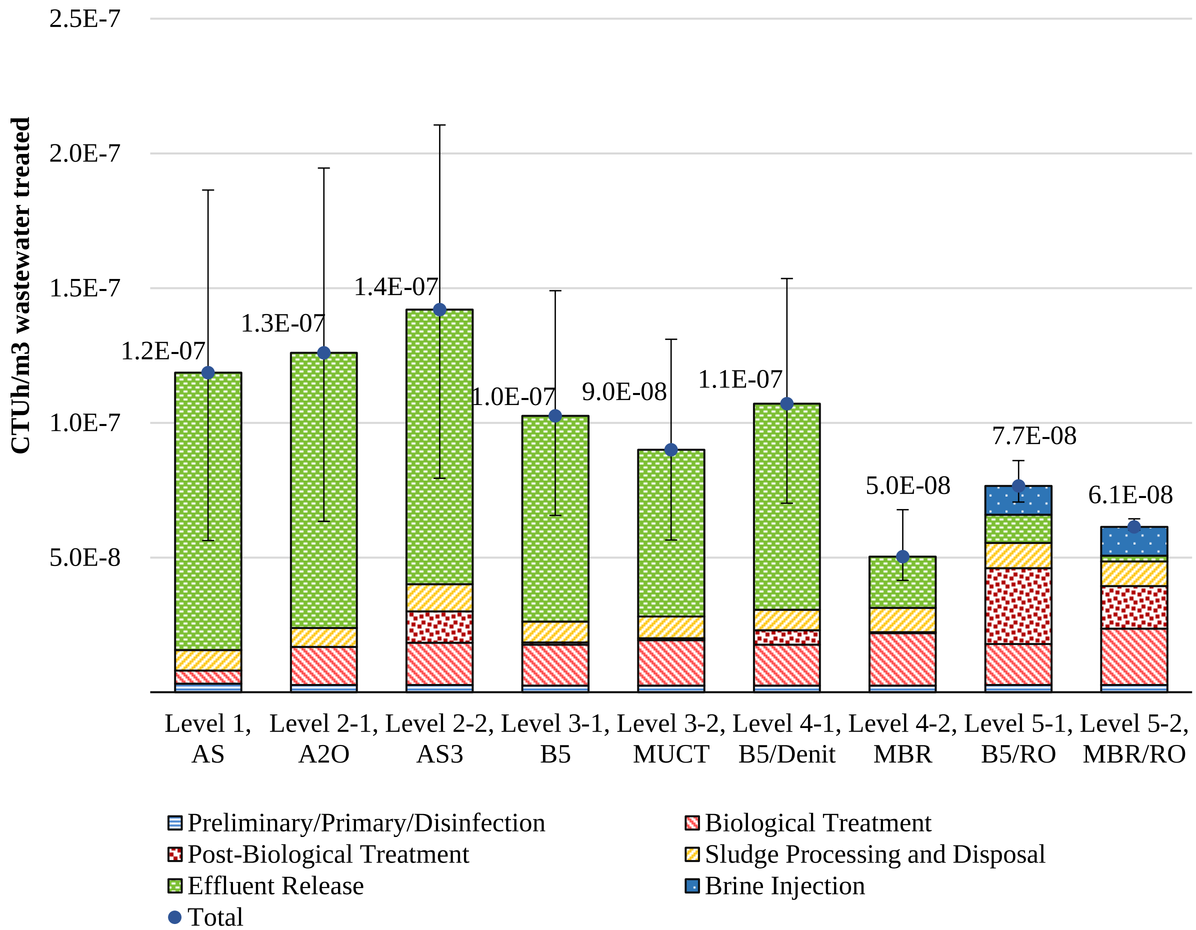


Figure 7-3. Human Health – Noncancer Potential Results by Treatment Group (CTUh/m^3 wastewater treated)

7.3 Ecotoxicity Potential

Figure 7-4 presents ecotoxicity results by treatment group. Error bars in the figure represent the range of results generated by applying minimum and maximum removal efficiency scenario assumptions outlined in Sections 2.1 and 2.2 for metals and toxic organic pollutants, respectively. Contributions to toxicity impact from metals, toxic organics and DBPs summarized in Figure 7-1 are included in this figure within the effluent release and sludge processing and disposal treatment groups.

Ecotoxicity impacts are also strongly linked to metals released with the liquid effluent, especially for Levels 1 and 2. Similar to the previous toxicity impact categories, the average removal efficiency results demonstrate a minimum toxicity impact associated with the Level 4-2 treatment system. However, taking into account the range of potential removal efficiencies, there is considerable overlap in results between Level 4-2 and other configurations. For example, the Level 5 treatment systems perform well compared to the lower treatment levels and provide greater assurances of reaching the average removal efficiency performance due to the greater reliability of their membrane processes. However, when compared against high removal efficiency scenarios for lower treatment levels, Level 5 systems may result in greater potential impact. Likewise, considerable overlap in the estimated removal efficiency performance of Levels 1 through 4-1 make it challenging to draw reliable conclusions regarding their relative performance.

Table J-12 shows the contribution of individual unit processes to ecotoxicity potential.

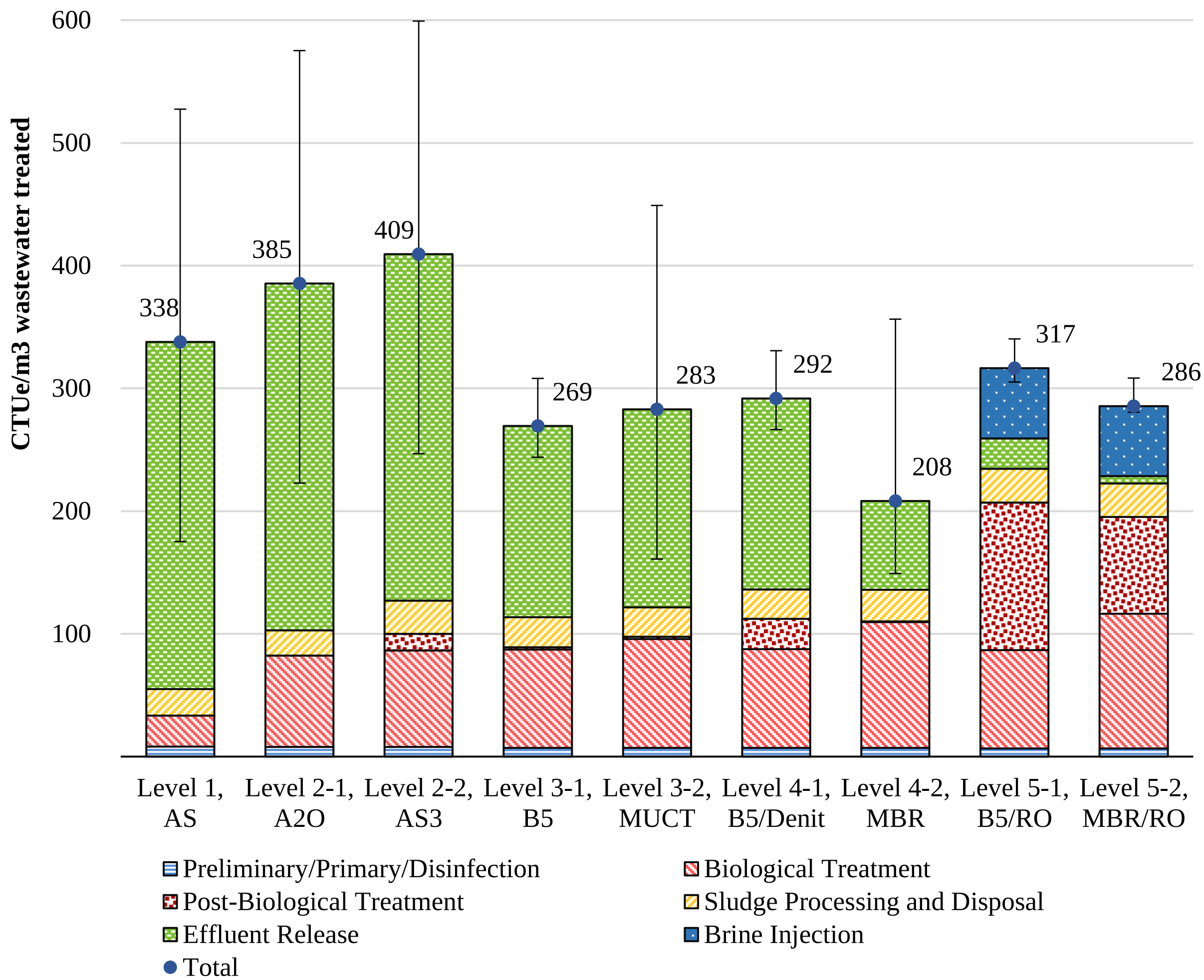


Figure 7-4. Ecotoxicity Potential Results by Treatment Group (CTUe/m^3 wastewater treated)

8. SUMMARY BASELINE RESULTS

This section presents the baseline summary LCIA and cost (as net present value) results to understand the trade-offs in impacts between operation of the different wastewater treatment configurations. Following a presentation of the baseline summary results, a normalization step is applied to the LCIA results to interpret the relative magnitude of the different impact categories assessed.

8.1 Baseline Results Summary

presents a summary of the relative results for the main impact categories. Results have been normalized to the maximum impact within each category. The side-by-side presentation of the results serves to highlight the trade-offs that exist between the various treatment configurations for traditional LCIA categories. Summary results are also displayed in a table format in Table 8-1. **Figure 8-2** presents the results in Table 8-1 for three representative treatment configurations in a graphical format to help visualize the relative impacts and trade-offs. In this graph, seven of the LCIA endpoints and costs are displayed on their own axis in spiral format, with the greatest impact furthest from the center. The shaded areas reflect a "footprint" of impact. Graphical displays of the results in this manner can aid in interpreting results and facilitating associated decision-making when comparing options. The specific information presented in Figure 8-2 is intended to be purely illustrative and is not intended to imply the relative importance of any endpoint or any winnowing of treatment configurations.

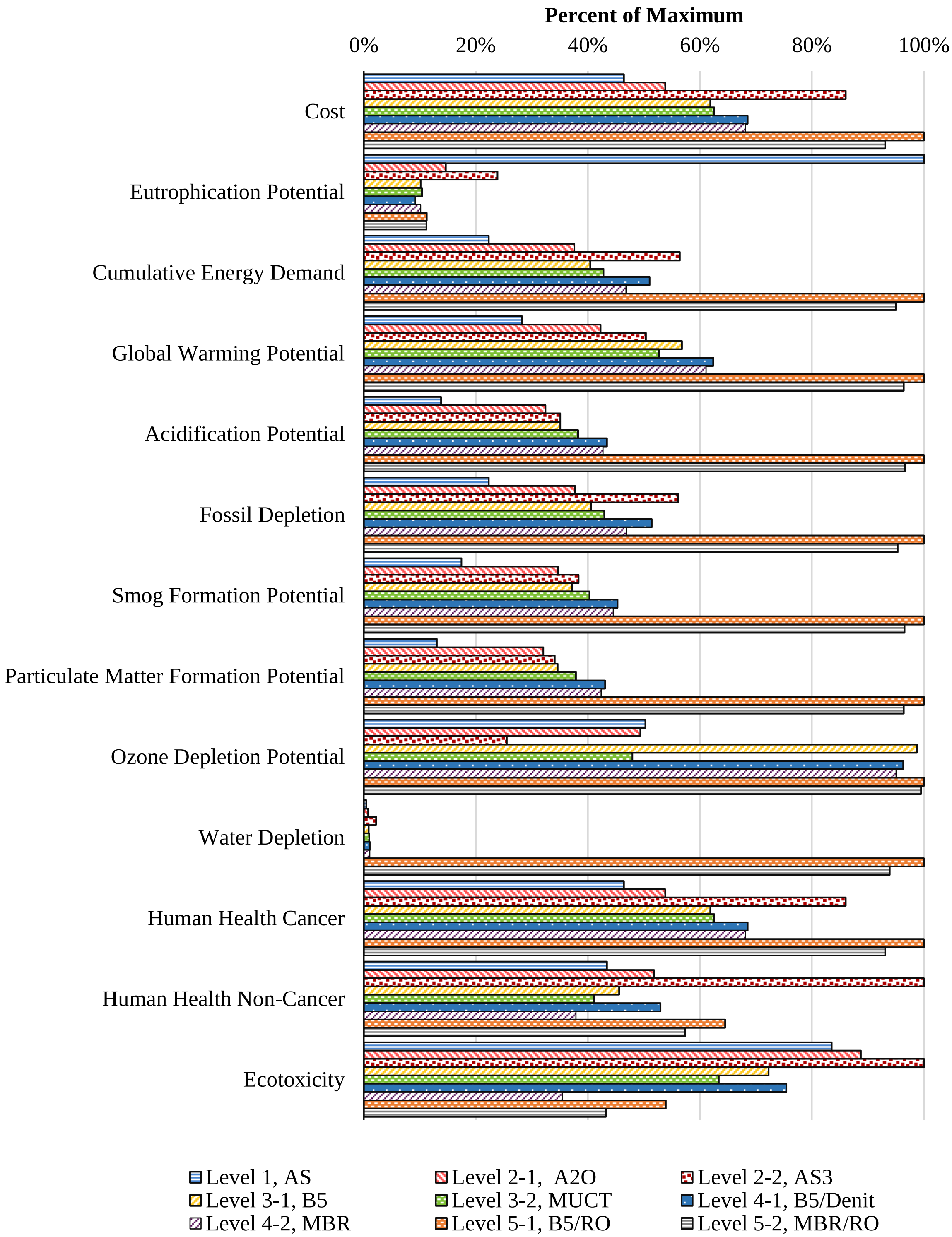


Figure 8-1. Relative LCIA and Cost Results for Nine Wastewater Treatment Configurations

Table 8-1. Summary LCIA and Cost Results for Nine Wastewater Treatment Configurations (per m^3 wastewater treated)

Impact Name	Unit	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Cost	*$ USD*	0.64	0.74	1.2	0.84	0.86	0.94	0.89	1.4	1.3
Eutrophication Potential	*kg N eq*	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	6.1E-3	6.8E-3	7.5E-3	7.5E-3
Cumulative Energy Demand	*MJ*	5.4	9.1	14	9.7	10	12	11	24	23
Global Warming Potential	*kg CO2 eq*	0.52	0.77	0.92	1.0	0.96	1.1	1.1	1.8	1.8
Acidification Potential	*kg SO2 eq*	0.01	0.03	0.03	0.03	0.04	0.04	0.04	0.09	0.09
Fossil Depletion	*kg oil eq*	0.12	0.20	0.30	0.22	0.23	0.28	0.25	0.54	0.51
Smog Formation Potential	*kg O3 eq*	0.13	0.26	0.29	0.28	0.30	0.34	0.33	0.75	0.72
Particulate Matter Formation	*PM2.5 eq*	1.4E-3	3.3E-3	3.5E-3	3.6E-3	3.9E-3	4.5E-3	4.4E-3	0.01	0.01
Ozone Depletion Potential	*kg CFC-11 eq*	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	7.4E-6	7.3E-6	7.7E-6	7.7E-6
Water Depletion	*m3 H2O*	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	2.0E-3	2.0E-3	0.19	0.17
Human Health Cancer Potential	*CTUh*	4.3E-9	5.1E-9	9.9E-9	4.5E-9	4.1E-9	5.2E-9	3.7E-9	6.4E-9	5.7E-9
Human Health Non-Cancer Potential	*CTUh*	1.2E-7	1.3E-7	1.4E-7	1.0E-7	9.0E-8	1.1E-7	5.0E-8	7.7E-8	6.1E-8
Ecotoxicity Potential	*CTUe*	338	385	409	269	283	292	208	317	286

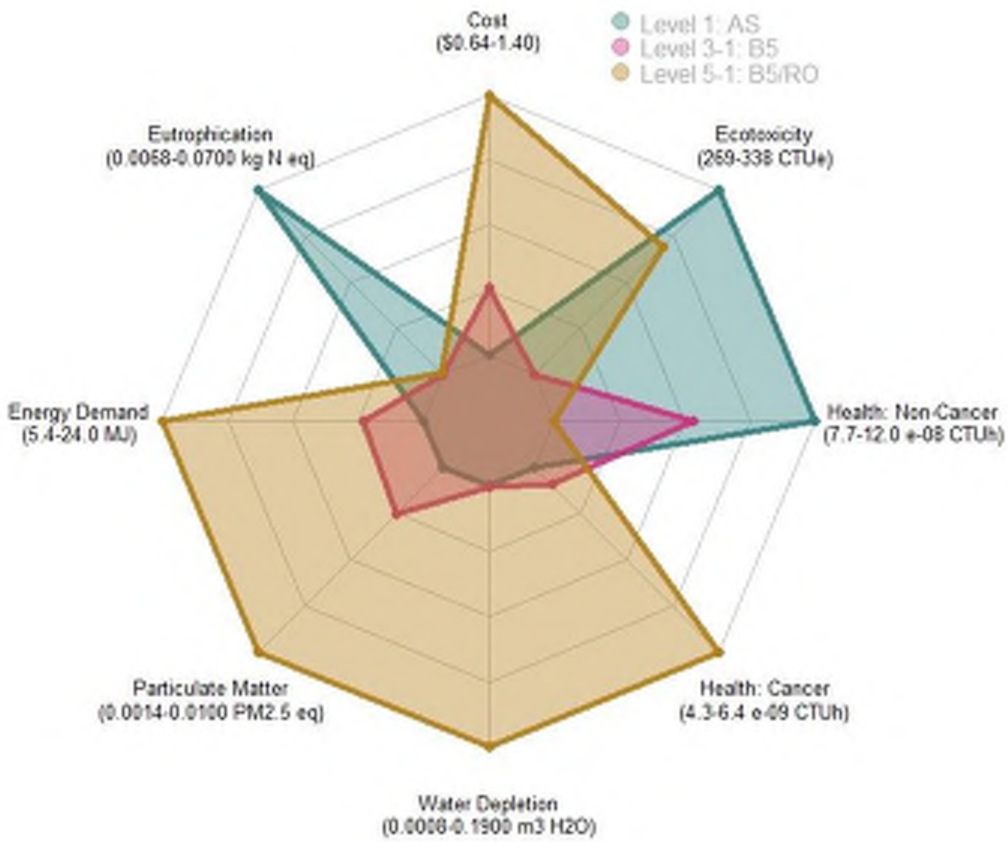


Figure 8-2. Illustrative Comparison of LCIA and Cost Results for Three Wastewater Treatment Configurations

8.2 Normalized Baseline Results

Normalization is a process of standardizing impact results in all categories such that the contribution of impact results associated with the functional unit can be judged relative to total national or global impact for a given category. Table 8-2 shows normalization factors and U.S. national per capita impacts in the year 2008. This is the most recent year normalization factors for LCA are available (Ryberg et al., 2014; Lippiatt et al., 2013). Normalization factors are not available for the impact categories fossil depletion and CED; therefore, these categories are excluded from the normalization step. Toxicity results are also excluded due to the higher magnitude of uncertainty associated with normalization factors for these categories. The normalization factor is the total U.S. impact for the specified category in 2008. Impact per person is estimated by dividing the normalization factor by the U.S. population. The U.S. population in 2008 is estimated as 304,100,000 people (World Bank, 2016). So, for example, the second row of Table 8-2 indicates that average per capita GHG emissions from all U.S. sources was just over 24 metric tons of CO_2 eq in 2008.

Table 8-2. 2008 U.S. Normalization Factors and Per Capita Annual Impacts

Impact Category [a]	Unit	Normalization Factor (US-2008)	Impact per Person [b]	Source
Eutrophication	kg N eq/yr	6.6E+9	22	Ryberg et al., 2014
Global Warming	kg CO2 eq/yr	7.4E+12	2.4E+4	Ryberg et al., 2014
Acidification	kg SO2 eq/yr	2.8E+10	92	Ryberg et al., 2014
Smog	kg O3 eq/yr	4.2E+11	1.4E+3	Ryberg et al., 2014
Particulate Matter Formation	kg PM2.5 eq/yr	7.4E+9	24	Ryberg et al., 2014
Ozone Depletion	kg CFC-11 eq/yr	4.9E+7	0.16	Ryberg et al., 2014
Water Depletion	liter H2O eq/yr	1.7E+14	5.6E+2	Lippiatt et al., 2013

a – Normalization factor not available for cumulative energy demand and fossil depletion, so these categories are excluded from normalization step.

b – Impact per person calculated using 2008 population of 304,100,000.

The process of normalization allows us to better assess the significance of impacts by providing absolute benchmarks at the national level. The functional unit for this study is a cubic meter of wastewater treated. In order to provide a gross, general context to these numbers, this presentation of normalized results calculates values based on the range of per capita municipal wastewater that is generated each year. The average generation of domestic municipal wastewater in the U.S. is estimated to be between 50 and 89 gallons per person per day (Tchobanoglous et al., 2014). This is a large range, reflecting the wide variation in use patterns as determined by factors such as climate, household size, and home and community conservation measures. This level of daily use translates to an annual domestic wastewater generation between 70 and 123 cubic meters per year per person. By multiplying impact results calculated in this study by the annual cubic meters of domestic wastewater treated each year at municipal wastewater facilities and dividing by per capita normalization factors, it is possible to calculate the approximate annual contribution of domestic wastewater treatment to total per capita impact in each of the included impact categories. This calculation excludes wastewater generated by commercial, public, and industrial sources, and therefore overestimates the impact from individuals and does not reflect the full national burden of wastewater treatment. The results of this calculation for the nine treatment systems and environmental impact in seven categories are presented in Table 8-3.

The overall trend in results is the same as that for unnormalized results, with impact in most categories increasing with the level of treatment. However, we can now more easily see the dramatic reduction in normalized contribution to eutrophication between conventional activated sludge treatment and all of the advanced treatment options. Overall per capita eutrophication impact may decrease 12 to 36 percent when shifting from the Level 1 wastewater treatment configuration to the higher nutrient removal wastewater configurations. The results highlight the fact that emissions resulting from wastewater treatment do not contribute equally to all impact categories. Wastewater treatment contributions to GWP and ozone depletion are less than one percent of the average national per capita emissions that contribute to these impact categories across all treatment levels. This implies that more emphasis should be put on eutrophication results compared to GWP or ozone depletion results for the wastewater treatment sector. Emissions associated with impact categories linked strongly with energy consumption such as acidification, smog formation, particulate matter formation, and human health-cancer start out at levels between zero and four percent per capita impacts, but rise to between three and 19 percent per capita impacts by the time Level 5 treatment is reached. These results also demonstrate the significance of impacts associated with a broad range of impact categories not typically thought of in relation to wastewater treatment, particularly at the more advanced levels of nutrient removal, and indicate a possibility for shifting burdens from eutrophication to other categories of environmental impact.

Table 8-3. Estimated Annual Contribution of Municipal Wastewater Treatment Per Capita Impact in Seven Impact Categories

Impact Category [a]	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Eutrophication Potential	21 - 38%	3 - 6%	5 - 9%	2 - 4%	2 - 4%	2 - 3%	2 - 4%	2 - 4%	2 - 4%
Global Warming Potential	0.1 - 0.3%	0.2 - 0.4%	0.3 - 0.5%	0.3 - 0.5%	0.3 - 0.5%	0.3 - 0.6%	0.3 - 0.6%	0.5 - 0.9%	0.5 - 0.9%
Acidification Potential	1 - 2%	2 - 4%	2 - 4%	2 - 4%	3 - 5%	3 - 5%	3 - 5%	7 - 13%	7 - 12%
Smog Formation Potential	1%	1 - 2%	1 - 3%	1 - 2%	2 - 3%	2 - 3%	2 - 3%	4 - 7%	4 - 6%
Particulate Matter Formation Potential	0 - 1%	1 - 2%	1 - 2%	1 - 2%	1 - 2%	1 - 2%	1 - 2%	3 - 5%	3 - 5%
Ozone Depletion Potential	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
Water Depletion	<1%	<1%	<1%	<1%	<1%	<1%	<1%	2 - 4%	2 - 4%

a – Normalization factor not available for cumulative energy demand and fossil depletion, so these categories are excluded from normalization step.

b – Toxicity results are interim.

9. SENSITIVITY ANALYSIS

9.1 Overview

Sensitivity analysis is an important component in the production of robust LCA and LCCA study results. As with any modeling process, the construction and analysis of an LCA and LCCA model and results requires making and documenting many assumptions. Many individual assumptions are known to have only an insignificant effect on the final impact results calculated for a given functional unit, but the effect of other assumptions is uncertain or is known to be significant. In the latter two cases, sensitivity analysis is employed to quantify the effect of modeling choices on LCA results. In this study, a sensitivity analysis was performed on the interest rate used in the LCCA analysis, the choice of GWP factors, the modeled electrical grid fuel mix, and the treatment of anaerobic digestion biogas. A case study is also presented illustrating cost results for a WWTP incorporating nutrient control technology as a retrofit rather than as a greenfield plant. The details of what elements were changed in each of the models and the subsequent effect on results categories are documented in the following subsections.

9.2 Interest and Discount Rates

As discussed in Section 3.3, ERG used the same value for the interest and discount rates. While there are slight differences in the interest and discount rates, it is appropriate to use the same value for the interest and discount rates when developing planning level costs. In this sensitivity analysis, ERG changed the interest rate during construction (see Equation 12), which is part of the total capital costs, and the real discount rate used to calculate the net present value (see Equation 13) from 3% to 5%. The interest and discount rates are not used to calculate the annual costs; as a result, this section focuses on changes to the total construction costs and net present value. The 3% interest rate represents a conservative interest rate for a State Revolving Fund (SRF) loan as the SRF average loan rate was 1.7% in April 2016 (U.S. EPA, 2016a). The 5% interest rate represents a worse-case scenario reflective of rates that WWTPs in poor financial shape, but still able to borrow, would be able to obtain.

Figure 9-1 presents the total construction costs using the 3% and 5% interest and discount rates. On average, the total construction costs increased by approximately 2.6% using the 5% interest rate, due to an increase in the interest paid during construction. **Figure** 9-2 presents the net present value using the 3% and 5% interest and discount rates. The net present value decreased using the 5% interest and discount rates by an average of 18%. The difference in the net present value is primarily because the majority of the costs for the wastewater treatment configurations are annual costs that occur in the future, which become smaller when using the 5% discount rate versus the 3% discount rate.

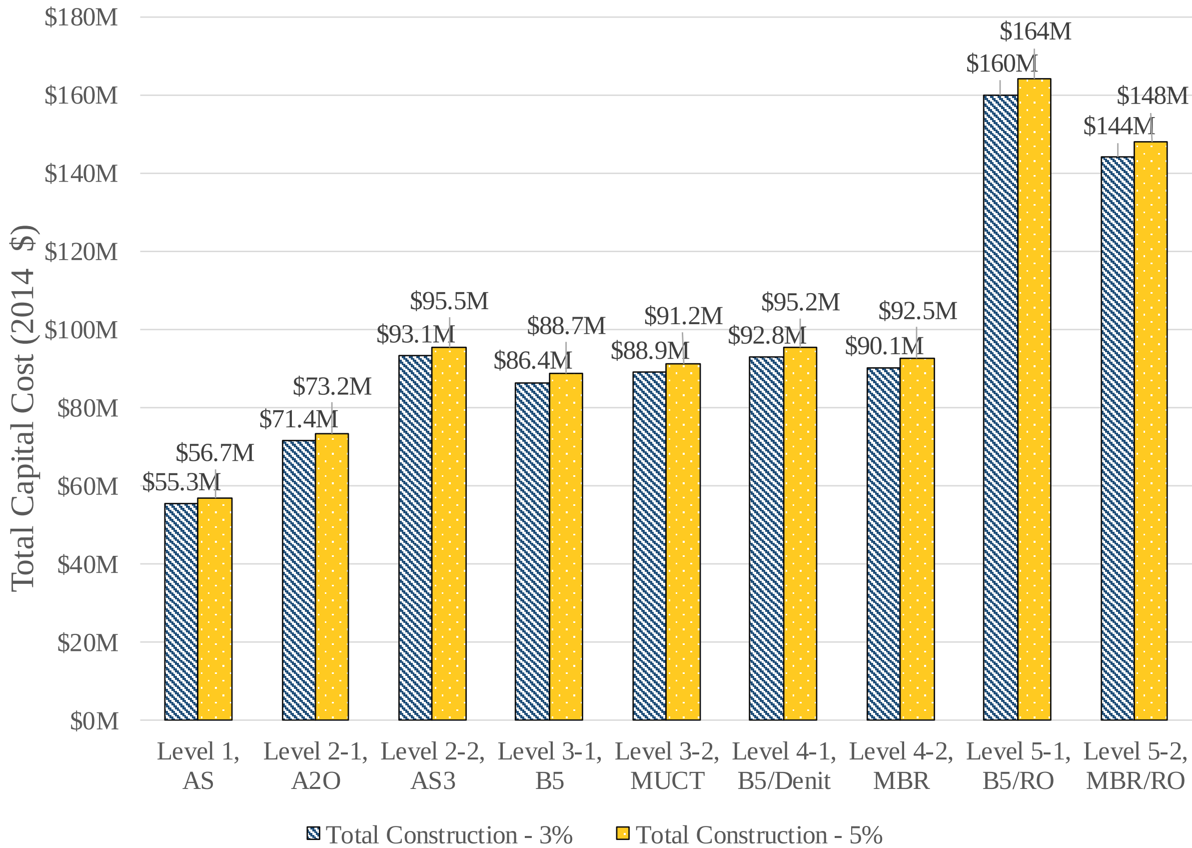


Figure 9-1. 3% versus 5% Interest Rate Total Construction Sensitivity Analysis Results

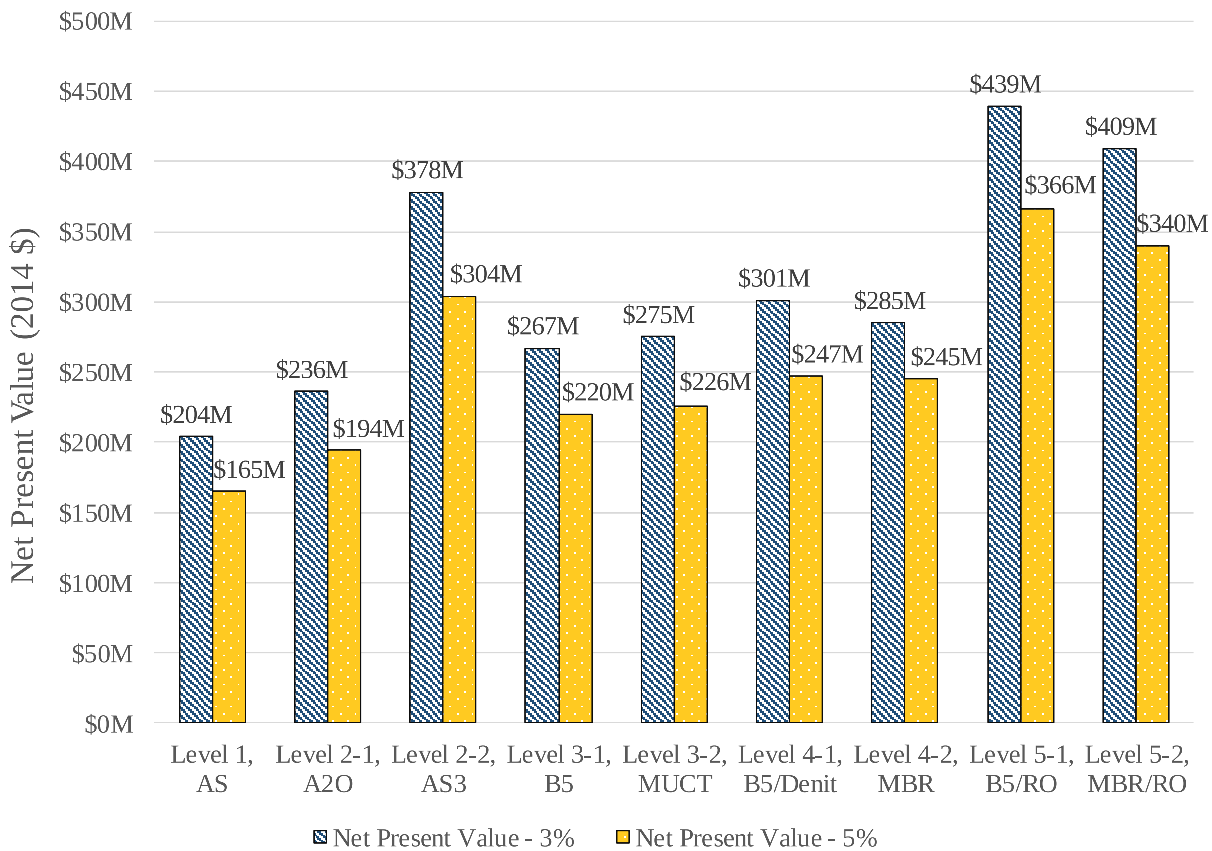


Figure 9-2. 3% versus 5% Interest and Discount Rate Net Present Value Sensitivity Analysis Results

9.3 Global Warming Potential

In this sensitivity analysis, the effect of using IPCC's most recent 2013 GWPs from the Fifth Assessment Report was assessed (IPCC, 2013). The baseline study used 2007 GWP factors from the IPCC Fourth Assessment Report, which have been officially adopted by the UNFCCC for international GHG reporting standards and are used by EPA in their annual greenhouse gas emissions report (IPCC, 2007). GWPs are the values used to transform the emission of all molecules that have heat trapping potential into a standardized unit. The standardization process takes CO_2 as its reference value setting its value to one, with all other factors being set relative to that standard (i.e., kilograms CO_2 eq.). There are many parameters that feed into determination of CO_2 eq. values, and the scientific basis for these values continues to evolve, with the IPCC reviewing and updating factors as the evidence improves. Table 9-1 shows both the 2007 and the updated 2013 IPCC GWP factors for the primary GHGs resulting from the life cycle of wastewater treatment. The last column in the table show the percent change associated with the 2013 update relative to the 2007 values.

Table 9-1. 2007 versus 2013 IPCC GWPs

GHG	GWP		Percent Change
	IPCC 2007	IPCC 2013	
Carbon dioxide	1.0	1.0	0%
Nitrous oxide	3.0E+2	2.7E+2	-12%
Methane	25	28	+11%

The effect of the GWP update on cumulative results depends upon the relative contribution of each GHG to the total GWP impact for each of the wastewater treatment configurations. Across all nine wastewater treatment configurations, the effect of selecting the 2007 versus 2013 GWP factors was shown to alter the GWP impact scores by between 1.8 and 3.8 percent. Figure 9-3 shows the magnitude of these effects per cubic meter of treated wastewater for each of the nine wastewater treatment configurations. The stacked bars correspond to the three main GHGs, which are responsible for the majority of GWP impact. The fact that methane and nitrous oxide are both prevalent GHGs for these systems, and the similarly equal and opposite change in GWP results for these two gases served to mitigate the impact of the update on cumulative results for this study. Table 9-2 lists the percent change in GWP impact that results from the choice between 2007 and 2013 GWP factors. At an aggregate level, the results of this study were not notably affected by GWP factor selection.

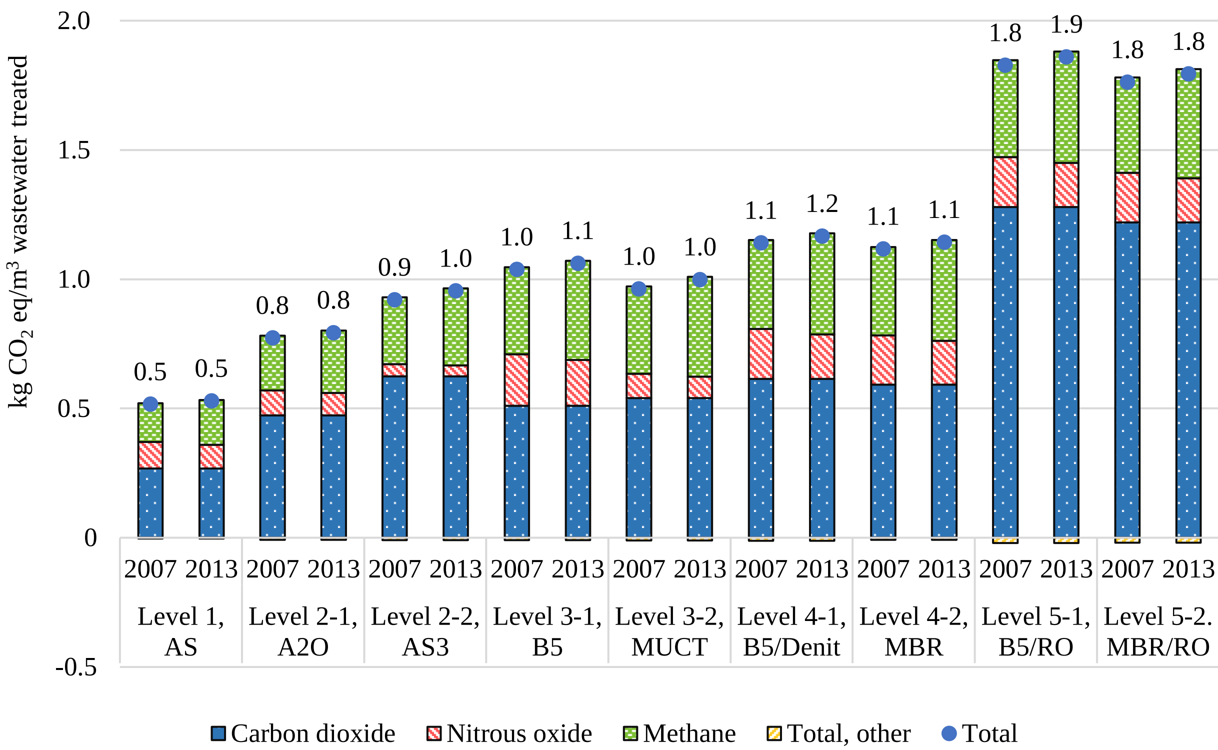


Figure 9-3. 2007 versus 2013 IPCC GWP Sensitivity Analysis Results

Table 9-2. Percent Change in GWP Impact due to GWP Factor Selection

	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2. MBR/RO
Percent Change[a]	2.5%	2.7%	3.7%	2.3%	3.8%	2.3%	2.4%	1.8%	1.8%

a – Percent Change = $(GWP_{2013}\text{-}GWP_{2007})/GWP_{2007}$

9.4 Electrical Grid Mix

In this sensitivity analysis, an alternative electrical mix with a "cleaner" grid (e.g., shift away from coal) was applied. Table 9-3 displays the electrical grid mix for the NorthEast Power Coordinating Council (NPCC), in addition to the baseline average mix of fuels used as the basis for this study. This information is based on eGRID data from 2012. NPCC covers states such as New York, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and Maine. This electrical grid is included in a sensitivity analysis, as it contains a higher portion of electricity from natural gas, nuclear, and hydro and a lower portion of electricity from coal as compared to the U.S. average electrical grid. The last column of Table 9-3 presents the percent change within individual fuel types when shifting from the baseline U.S. average electrical grid mix to the NPCC electrical grid mix.

Table 9-3. NPCC eGRID Regional versus U.S. Average Electrical Grid Mix

Fuel	Baseline U.S. Average Percent of Mix	NPCC Sensitivity Analysis Percent of Mix	Percent Change
Coal	45%	3.1%	-93%
Natural Gas	24%	49%	+100%
Nuclear	20%	30%	+51%
Hydro	6.2%	12%	+94%
Wind	2.3%	1.6%	-28%
Biomass	1.4%	3.6%	+170%
Oil	1.0%	0.38%	-63%
Geothermal	0.37%	0%	-100%
Other Fossil	0.35%	1.1%	+220%
Solar	0.03%	0.03%	0%

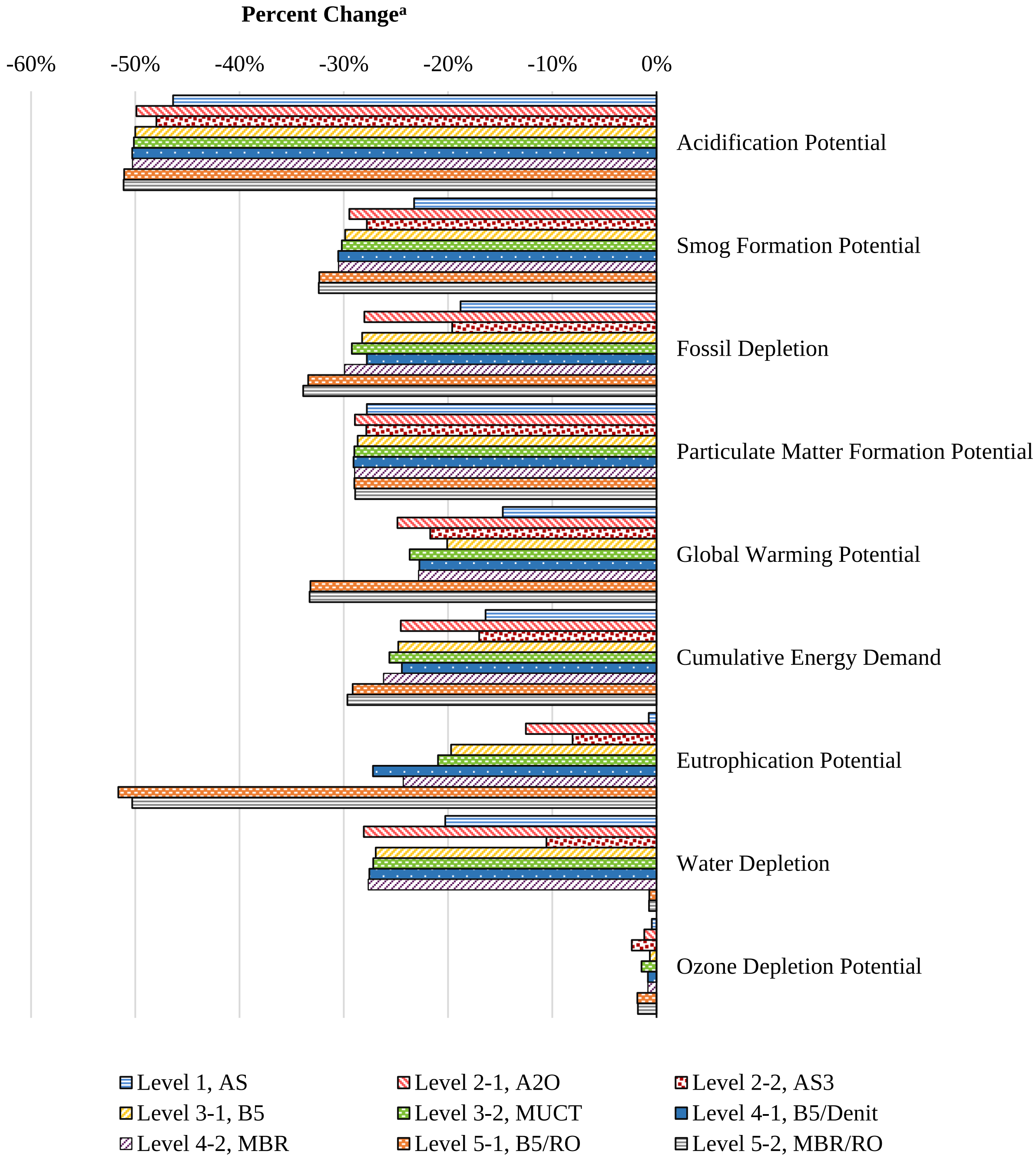
When conducting the sensitivity analysis, the electrical grid mix that serves the wastewater treatment plant is varied for each of the nine wastewater treatment configurations, while the electrical grid mixes associated with background processes remain constant. This is reasonable since it is likely background chemicals and fuels are not produced in the same region of the U.S. that they are utilized. Results for all of the impact categories were rerun and compared to the baseline values. As displayed in Figure 9-4, the relative impact of this substitution depends both upon the wastewater treatment configuration and on the impact category. The impacts in this figure are sorted, with the greatest average reduction across all treatment levels shown at the top and the smallest average reduction across all treatment levels shown at the bottom. The effect of this substitution of electrical grid mix on cumulative impact scores is significant across the majority of impact categories and treatment levels with a few notable exceptions. Ozone depletion potential impact is not shown to be sensitive to the choice of electrical grid with the percent change for all wastewater treatment configurations being less than one percent. The impact on eutrophication potential for Levels 1 and 2 are overshadowed by the predominance of eutrophying emissions associated with effluent release. Similarly, the effect on water depletion impact for Level 5 is reduced due to the predominant impact of brine injection to results in this category.

In general, those wastewater treatment configurations with a higher energy demand per cubic meter of wastewater treated show a greater sensitivity to the source of electricity. A number of interesting patterns are visible in Figure 9-4. The relative effect of this sensitivity analysis between wastewater treatment configurations is most pronounced for eutrophication potential. The percent change associated with eutrophication impacts in Level 1 and Level 5– are approximately -1 and -50 percent, respectively. The large variation in these values can be explained by large differences in the aspects of the LCA model that contribute to impact in each category. As mentioned above, eutrophication impact for Level 1 is predominated by effluent release, so the change in grid energy has little influence on impact. Alternatively, by the time water is cleaned to Level 5 standards, there is so little nutrient content in the effluent itself that electricity impact predominates. Similarly, for other impact categories that show an increasing sensitivity to electricity choice as we move from Level 1 to Level 5, we can attribute this to the increased contribution of electricity to impact results as effluent standards increase.

The consistently high effect on acidification and particulate matter impacts across the treatment systems is demonstrative of the dependence of these impact categories on emissions resulting from electricity production. Toxicity results are excluded from Figure 9-3.

The deviation in general trends associated with Level 2-2 are due to the exceptional reliance of this wastewater treatment configuration on chemical flocculent for phosphorus removal, and the impact associated with these chemical additions. In this way, this wastewater treatment configuration is less sensitive to overall changes in the electrical grid fuel mix.

The findings of this sensitivity analysis indicate that electricity is a primary driver for many of the impact categories assessed in this study. Utilization of “cleaner” fuels for electricity or recovery of resources at the WWTP to produce energy on-site could serve to offset some of the burdens realized when including additional energy intensive unit processes to achieve increased nutrient removal.



[a] Percent Change = [(NPCC$_{impact}$-AvgGrid$_{impact}$)/AvgGrid$_{impact}$]

Figure 9-4. Electrical Grid Mix Sensitivity Analysis Results

Table 9-4. Electrical Grid Sensitivity Analysis, U.S. Average versus NPCC Electrical Grid (per m^3 wastewater treated)

		Level 1, AS		Level 2-1, A2O		Level 2-2, AS3		Level 3-1, B5		Level 3-2, MUCT		Level 4-1, B5/Denit		Level 4-2, MBR		Level 5-1, B5/RO		Level 5-2, MBR/RO	
Impact Name	**Unit**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**	**U.S. Avg.**	**NPCC**
Global Warming Potential	**kg CO2 eq**	0.52	0.44	0.77	0.58	0.92	0.72	1.0	0.83	0.96	0.73	1.1	0.88	1.1	0.86	1.8	1.2	1.8	1.2
Eutrophication Potential	**kg N eq**	0.07	0.07	9.8E-3	8.6E-3	0.02	0.01	6.8E-3	5.4E-3	6.9E-3	5.5E-3	6.1E-3	4.5E-3	6.8E-3	5.1E-3	7.5E-3	3.6E-3	7.5E-3	3.7E-3
Acidification Potential	**kg SO2 eq**	0.01	6.9E-3	0.03	0.02	0.03	0.02	0.03	0.02	0.04	0.02	0.04	0.02	0.04	0.02	0.09	0.05	0.09	0.04
Fossil Depletion	**kg oil eq**	0.12	0.10	0.20	0.15	0.30	0.24	0.22	0.16	0.23	0.16	0.28	0.20	0.25	0.18	0.54	0.36	0.51	0.34
Smog Formation Potential	**kg O3 eq**	0.13	0.10	0.26	0.18	0.29	0.21	0.28	0.20	0.30	0.21	0.34	0.24	0.33	0.23	0.75	0.51	0.72	0.49
Particulate Matter Formation	**PM2.5 eq**	1.4E-3	9.8E-4	3.3E-3	2.4E-3	3.5E-3	2.6E-3	3.6E-3	2.6E-3	3.9E-3	2.8E-3	4.5E-3	3.2E-3	4.4E-3	3.1E-3	0.01	7.4E-3	0.01	7.1E-3
Ozone Depletion Potential	**kg CFC-11 eq**	3.9E-6	3.9E-6	3.8E-6	3.8E-6	2.0E-6	1.9E-6	7.6E-6	7.5E-6	3.7E-6	3.6E-6	7.4E-6	7.3E-6	7.3E-6	7.2E-6	7.7E-6	7.6E-6	7.7E-6	7.5E-6
Cumulative Energy Demand	**MJ**	5.4	4.5	9.1	6.8	14	11	9.7	7.3	10	7.7	12	9.3	11	8.3	24	17	23	16
Water Depletion	**m3 H2O**	8.0E-4	6.4E-4	1.5E-3	1.1E-3	4.1E-3	3.7E-3	1.7E-3	1.2E-3	1.8E-3	1.3E-3	2.0E-3	1.5E-3	2.0E-3	1.4E-3	0.19	0.18	0.17	0.17

9.5 <u>Biogas Energy Recovery</u>

The baseline model assumes flaring of biogas produced during anaerobic digestion. This sensitivity analysis investigates the effect on plant level environmental impact and life cycle cost from shifting to energy recovery using a combined heat and power (CHP) engine.

9.5.1 System Description

Biogas system components include the prime mover, which drives the electrical generator, a heat exchanger, gas processing/cleaning equipment, electrical controls and enclosure. An Internal Combustion Engine (ICE) is modeled as the CHP prime mover. ICEs are a common and industry tested technology (Wiser et al. 2010). Biogas exiting the anaerobic digesters is at ambient pressure and is saturated with moisture. Compression, drying and removal of impurities is required before gas can be combusted in a CHP engine. The biogas processing and CHP system boundary is depicted in Figure 9-5. Biogas and CHP system specifications are listed in Table 9-5.

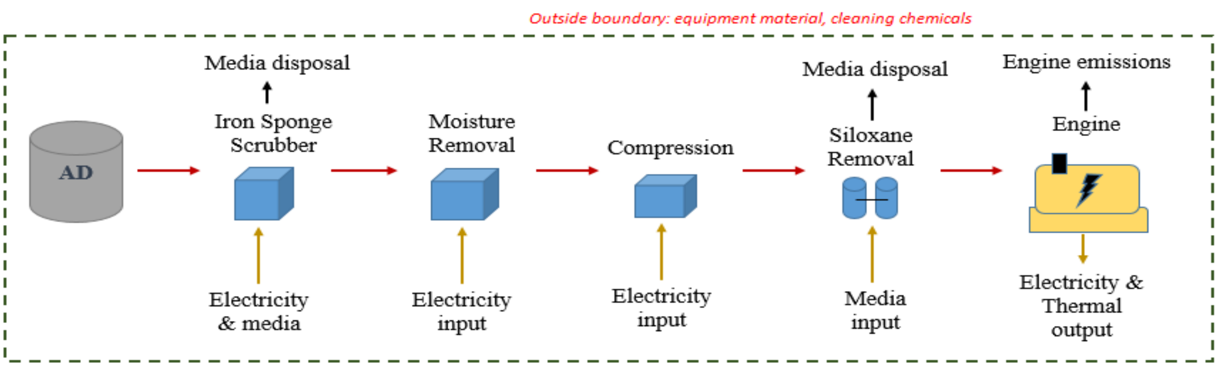


Figure 9-5. System Diagram of Biogas Processing and CHP System

Iron sponge scrubbers are assumed for hydrogen sulfide (H_2S) removal, being a widely used and commercially proven technology. H_2S is corrosive of metallic system components in the presence of water, and can lead to elevated sulfur oxide (SO_x) emissions from the prime mover. H_2S is a common constituent of biogas generated at municipal WWTPs often comprising 200-3500 ppmv of biogas (Wiser et al. 2010). A representative H_2S concentration of 500 ppmv is used to estimate iron sponge requirements (Wiser et al. 2010). The desired temperature range for adsorption via iron sponge is between 25 and 60 °C, which corresponds to the temperature of biogas as it exits the anaerobic digesters. Hydrated iron oxide is usually sold embedded onto wood chips. Iron sponge adsorption requires the presence of moisture in the biogas, so process placement before moisture removal is common. Approximately 20 kg of H_2S can be adsorbed per 100 kg of sorbent material (Ong et al. 2017). The oxide impregnated wood chips can be regenerated by flushing the bed with atmospheric oxygen, which releases H_2S as elemental sulfur. The regeneration process can be repeated approximately 1-2 times before the adsorbent media requires replacement (Abatzoglou and Boivin 2009). This analysis assumes 1 regeneration cycle, achieving 85 percent of original sorbent capacity. The necessary equipment has a modest footprint and is usually located outdoors to mitigate safety concerns.

Table 9-5. Biogas Processing and CHP System Specifications for Nine Treatment System Configurations

System Parameter	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Annual Biogas Production (m^3)	1.6E+6	1.3E+6	1.8E+6	1.3E+6	1.3E+6	1.3E+6	1.3E+6	1.3E+6	1.2E+6
Biogas Production (scfm)	1.1E+2	88	1.2E+2	85	85	85	87	85	82
Available Biogas Energy (MJ)[a]	2.7E+7	2.4E+7	3.2E+7	2.3E+7	2.3E+7	2.3E+7	2.3E+7	2.3E+7	2.2E+7
ICE Availability	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
ICE Power (kw)	3.2E+2	2.8E+2	3.8E+2	2.7E+2	2.7E+2	2.7E+2	2.8E+2	2.7E+2	2.6E+2
Electricity Production (kWh/yr)	2.5E+6	2.2E+6	3.0E+6	2.2E+6	2.2E+6	2.2E+6	2.2E+6	2.2E+6	2.1E+6
Thermal Energy (MJ/yr)	1.2E+7	1.1E+7	1.4E+7	1.0E+7	1.0E+7	1.0E+7	1.0E+7	1.0E+7	9.9E+6
AD Heat Requirement (MJ/yr)[b,c]	1.7E+7	1.6E+7	2.4E+7	1.5E+7	1.5E+7	1.5E+7	1.5E+7	1.5E+7	1.4E+7
WWTP Electricity Requirement (kWh/yr)	2.8E+6	6.7E+6	6.8E+6	8.1E+6	8.6E+6	9.8E+6	8.2E+6	2.2E+7	2.0E+7
Percent of AD Heat Demand Satisfied (%)	70%	68%	59%	67%	67%	67%	70%	67%	71%
Percent of Facility Electricity Demand Satisfied (%)	90%	33%	43%	30%	27%	24%	25%	10%	10%
H_2S removed (kg/day)	1.9	1.6	2.2	1.6	1.6	1.6	1.6	1.6	1.5
Iron Oxide requirement (kg/yr)	1.8E+3	1.6E+3	2.2E+3	1.6E+3	1.6E+3	1.6E+3	1.6E+3	1.6E+3	1.5E+3
Siloxane removed (kg/day)	0.44	0.36	0.48	0.35	0.35	0.35	0.36	0.35	0.33
Activated Carbon requirement (kg/yr)	1.6E+3	1.3E+3	1.8E+3	1.3E+3	1.3E+3	1.3E+3	1.3E+3	1.3E+3	1.2E+3

[a] Accounts for 5 percent fugitive biogas loss and 20 percent flaring rate.

[b] Expressed as CHP thermal energy, accounts for 90 percent efficiency of heat exchanger.

[c] AD – anaerobic digester/digestion

Moisture removal is the next step in biogas processing as it enhances performance of the subsequent siloxane removal step (Wiser et al. 2010). Moisture removal via chilling and condensation is proposed to ensure sufficiently dry biogas. Refrigeration energy demands typically account for less than two percent of the energy content of the processed biogas. A conservative value of two percent is used to estimate electricity demands of the refrigeration process (Ong et al. 2017).

Compression of biogas is necessary prior to combustion in the prime mover. Fuel pressurization to between 3 and 5 psi is sufficient for use in ICEs. Use of a blower is recommended for moderate compression requirements up to 15 psig (Wiser et al. 2010). Compression follows H_2S and moisture removal to ensure longevity of compressor components. Blowers have the benefit of being low cost, require no oil, lack VOC emissions and have minimal maintenance requirements (Wiser et al. 2010). Energy requirements for compression are estimated based on the use of heavy duty rotary blowers that operate at brake horsepowers of between 2.4 and 3.3 depending upon the biogas flowrate in standard cubic feet per minute (scfm), which ranges between 82 and 118 scfm depending upon the system configuration (see Table 9-5).

The final biogas cleaning and processing step involves removal of siloxanes, which are another common contaminant of biogas generated via anaerobic digestion of wastewater sludge. Siloxanes can be removed using refrigeration or sorbents such as activated carbon, alumina, synthetic resins, or liquid sorbents. Siloxane removal via activated carbon adsorption is modeled given its prevalent use, low cost and maintenance requirements. Coal is modeled as the activated carbon feedstock, based on LCI information presented in Bayer et al. (2005).

The ICE is sized based upon the available energy content of biogas produced by each system assuming a 90 percent availability factor (i.e. 10 percent system downtime). The quantity of biogas available for energy consumption equals total biogas production less fugitive emissions (5 percent) and flared biogas (UNFCCC 2012). The analysis assumes that 20 percent of biogas is flared due to system downtime, upsets and lack of available storage capacity required to handle inconsistency in biogas production. ICE power requirements range from approximately 260 to 380 kW depending upon the system configuration, placing it in line with other WWTP CHP installations based on installed kW/MGD (U.S. DOE 2016). Electrical and thermal efficiency values of 34 percent and 45 percent are selected, respectively, representing the average of the reported ICE efficiency range in Wiser et al. (2010). ICE emissions are representative of an ICE engine utilizing selective catalytic reduction for NO_x control, and an oxidation catalyst system for carbon monoxide and VOC emission control.

9.5.2 Biogas Sensitivity LCIA Results

LCIA results by treatment group are presented for GWP in Figure 9-6. The addition of energy recovery yields a decrease in GWP impact for all system configurations due to the avoided environmental burdens of natural gas and grid electricity consumption associated with the electrical and thermal products of the CHP system. The absolute decrease in GWP impact varies between 0.21 and 0.31 kg CO_2-eq. per m^3 wastewater treated according to the quantity of biogas available for energy recovery. The relative effect on system level GWP impact is greatest for treatment Level 1, and decreases as total GWP impact increases for the higher levels of nutrient removal. The addition of energy recovery reduces Level 1 GWP impact by approximately 50 percent, while the reduction in GWP impact for Level 5 treatment configurations is less than 15 percent of base GWP impact. Base and CHP sensitivity LCIA results and corresponding percent reduction values are presented for all impact categories in Table 9-6. Figure 9-6 shows that the benefits of energy recovery are sufficient to offset the GWP impact of the sludge processing and disposal treatment group.

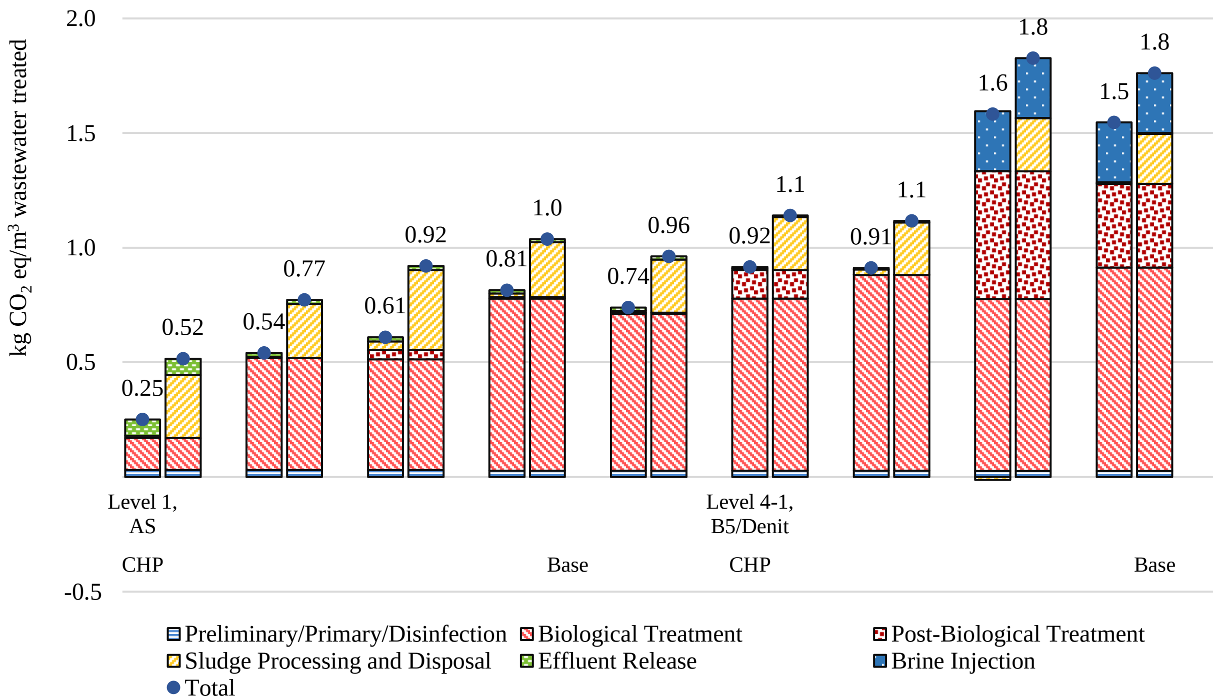


Figure 9-6. Global Warming Potential by Treatment Group for Base Results and the CHP Energy Recovery Sensitivity

Figure 9-7 presents results by treatment group for the CED inventory indicator, and demonstrates reductions in system level energy demand for all treatment configurations. Absolute reduction in CED range from 3.5 to 5.4 MJ/m^3 wastewater treated, according to biogas production associated with each configuration. The relative reduction in CED is greater than that observed for GWP, and varies between 16 and 86 percent for Levels 5-2 and 1, respectively. Figure 9-7 shows that the sludge processing and disposal treatment group now contributes an energy credit to the system, reducing the net CED of each treatment configuration.

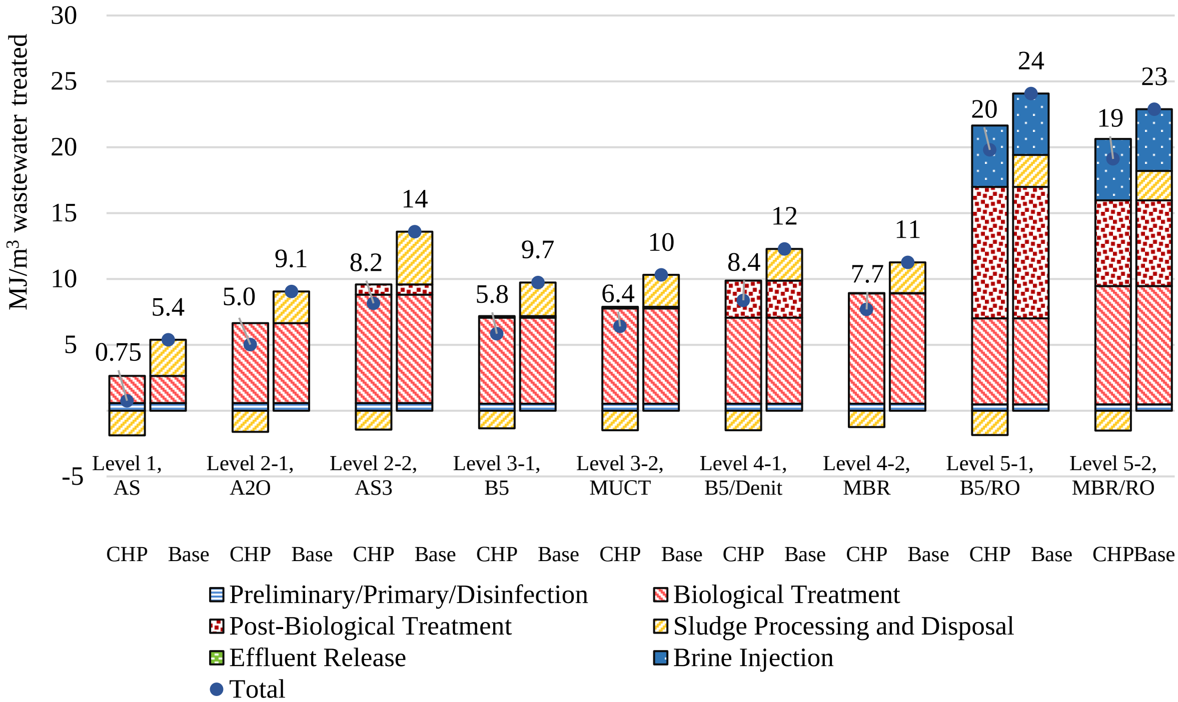


Figure 9-7. Cumulative Energy Demand by Treatment Group for Base Results and the CHP Energy Recovery Sensitivity

Table 9-6 shows that acidification, PM formation, smog formation, and fossil depletion potential all show significant reductions in system level impact in response to biogas energy recovery. Relative reductions in impact for these four impact categories are all greater for the lower treatment levels where absolute impact results are lower owing to lower relative energy and material consumption. Biogas production is also greatest for Level 1 and Level 2-2, leading to greater quantities of recovered energy. Energy recovery has a less dramatic effect on ozone depletion and eutrophication potential impact, with relative reductions in impact potential of between 1 and 26 percent. Eutrophication potential demonstrates a pattern unlike the other impact categories, where percent reductions in eutrophication impact are greatest for the higher treatment levels, which are associated with the lowest absolute eutrophication impact.

Table 9-6. Summary of Comparative Impact Assessment Results for the Base Case and CHP Energy Recovery Sensitivity

Impact Category	Description	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Global Warming Potential	Base Results	0.52	0.77	0.92	1.0	0.96	1.1	1.1	1.8	1.8
	CHP Sensitivity	0.25	0.54	0.61	0.81	0.74	0.92	0.91	1.6	1.5
	Percent Reduction[a]	*51%*	*30%*	*34%*	*21%*	*23%*	*20%*	*18%*	*13%*	*12%*
Cumulative Energy Demand	Base Results	5.4	9.1	14	9.7	10	12	11	24	23
	CHP Sensitivity	0.75	5.0	8.2	5.8	6.4	8.4	7.7	20	19
	Percent Reduction[a]	*86%*	*45%*	*40%*	*40%*	*38%*	*32%*	*32%*	*18%*	*16%*
Eutrophication Potential	Base Results	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	6.1E-3	6.8E-3	7.5E-3	7.5E-3
	CHP Sensitivity	0.07	9.2E-3	0.02	6.2E-3	6.4E-3	5.6E-3	6.3E-3	6.9E-3	7.0E-3
	Percent Reduction[a]	*1%*	*6%*	*5%*	*8%*	*8%*	*9%*	*7%*	*8%*	*7%*
Water Depletion	Base Results	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	2.0E-3	2.0E-3	0.19	0.17
	CHP Sensitivity	3.9E-4	1.1E-3	3.6E-3	1.3E-3	1.4E-3	1.7E-3	1.7E-3	0.19	0.17
	Percent Reduction[a]	*51%*	*25%*	*12%*	*21%*	*20%*	*18%*	*14%*	*0%*	*0%*
Acidification Potential	Base Results	0.01	0.03	0.03	0.03	0.04	0.04	0.04	0.09	0.09
	CHP Sensitivity	1.1E-3	0.02	0.02	0.02	0.03	0.03	0.03	0.08	0.08
	Percent Reduction[a]	*92%*	*36%*	*44%*	*30%*	*28%*	*25%*	*21%*	*12%*	*11%*
Particulate Matter Formation	Base Results	1.5E-3	3.4E-3	3.5E-3	3.6E-3	3.9E-3	4.5E-3	4.4E-3	0.01	1.0E-2
	CHP Sensitivity	1.1E-4	2.2E-3	2.1E-3	2.6E-3	2.9E-3	3.4E-3	3.5E-3	9.2E-3	9.0E-3
	Percent Reduction[a]	*93%*	*35%*	*41%*	*29%*	*27%*	*24%*	*20%*	*12%*	*10%*
Smog Formation Potential	Base Results	0.14	0.27	0.29	0.28	0.30	0.34	0.33	0.75	0.72
	CHP Sensitivity	0.02	0.16	0.15	0.18	0.21	0.24	0.25	0.64	0.63
	Percent Reduction[a]	*88%*	*39%*	*46%*	*34%*	*31%*	*28%*	*25%*	*14%*	*13%*
Ozone Depletion Potential	Base Results	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	7.4E-6	7.3E-6	7.7E-6	7.7E-6
	CHP Sensitivity	3.4E-6	3.4E-6	1.5E-6	7.2E-6	3.3E-6	7.0E-6	7.0E-6	7.3E-6	7.3E-6
	Percent Reduction[a]	*12%*	*10%*	*26%*	*5%*	*10%*	*5%*	*5%*	*5%*	*5%*
Fossil Depletion	Base Results	0.12	0.20	0.30	0.22	0.23	0.28	0.25	0.54	0.51
	CHP Sensitivity	0.01	0.11	0.18	0.13	0.14	0.19	0.17	0.44	0.42
	Percent Reduction[a]	*89%*	*46%*	*42%*	*41%*	*39%*	*33%*	*33%*	*18%*	*17%*

a – Percent Reduction = $(Base_{GWPimpact} - CHP_{GWPimpact})/Base_{GWPimpact}$

9.5.3 Biogas Sensitivity LCCA

The base case LCCA results were updated to reflect the increased capital and O&M costs associated with the installation and ongoing maintenance of a CHP system. The cost sensitivity includes the avoided cost of reduced natural gas consumption, as well as revenue from the sale of electricity. Equipment costs for ICE CHP generally fall in the range of $465 to $1600 per kW of installed generation capacity (Wiser et al. 2010). The average of this range, $1033/kW, is used in this analysis. Gas processing costs typically add $600/kW of generation capacity (Darrow et al. 2017). The same direct and indirect cost factors are applied to the CHP system as are described in Section 2. Inclusive operation and maintenance costs are estimated per kWh of electricity production. Gas cleaning and processing O&M costs typically range from 0.015 to 0.025 $/kWh, while prime mover maintenance costs typically fall in the range of 0.01 to 0.025 $/kWh (Wiser et al. 2010). The average of these reported ranges is used in this analysis, 0.02 and 0.0175 $/kWh, respectively.

Electricity revenue is estimated using the same cost factor, $0.10/kWh, that is used to estimate system energy cost in the main LCCA analysis. Avoided natural gas costs are based on a natural gas purchase price of $15.50 per 1000 ft^3.

Figure 9-8 summarizes the effect of including CHP and energy recovery on total system cost. The effect on system net present value over a 30-year time horizon is relatively modest, yielding a reduction in system net present value of between six and nine million dollars depending upon the configuration. The relative reduction in system net present value is greatest for level 1, yielding a 3.5 percent reduction in system net present value relative to the base scenario that assumes flaring of biogas. Table 9-7 summarizes base case and biogas case study life cycle costs.

Table 9-7. Summary of Biogas LCCA Costs (million 2014 $s)

Treatment System Configuration	Net Present Value		Annual Labor, Material and Chemical Cost		Annual Energy Cost		Annual Amortization Cost	
	with CHP	Base	with CHP	Base	with CHP	Base	with CHP	Base
Level 1, AS	$197	$204	$4.6	$4.5	$0.11	$0.59	$3.8	$3.7
Level 2-1, A2O	$230	$236	$4.6	$4.5	$0.5	$0.9	$4.8	$4.8
Level 2-2, AS3	$369	$378	$9.1	$9.0	$0.6	$1.1	$6.3	$6.2
Level 3-1, B5	$261	$267	$4.9	$4.8	$0.6	$1.0	$5.8	$5.8
Level 3-2, MUCT	$269	$275	$4.9	$4.9	$0.7	$1.1	$6.0	$5.9
Level 4-1, B5/Denit	$295	$301	$5.8	$5.7	$0.8	$1.2	$6.3	$6.2
Level 4-2, MBR	$294	$285	$5.9	$5.2	$0.7	$1.1	$6.1	$6.0
Level 5-1, B5/RO	$433	$439	$6.1	$6.0	$1.9	$2.3	$11	$11
Level 5-2, MBR/RO	$403	$409	$5.9	$5.8	$1.9	$2.2	$10	$10

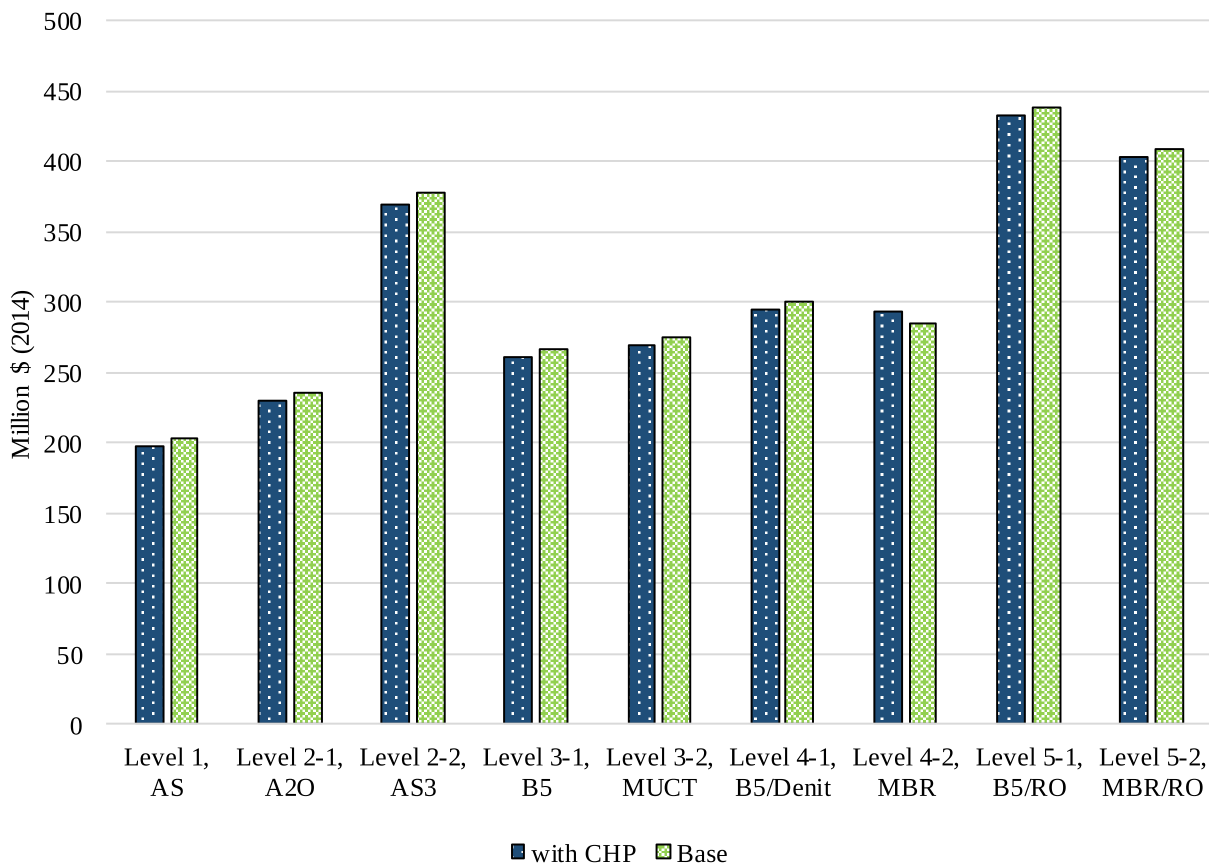


Figure 9-8. Biogas Case Study Net Present Value Comparison

9.6 Retrofit Case Study

While this report displays cost results for greenfield installations, existing plants may incorporate nutrient control technology in a retrofit. In this section, ERG conducted a case study to investigate the potential cost implications of such a retrofit. This case study considers a retrofit of the Level 2-1 A2O wastewater treatment configuration as the baseline (see Figure 9-9) with the addition of chemical phosphorus removal and a denitrification filter to achieve the Level 4 target effluent nutrient concentrations of 3 mg/L total nitrogen and 0.1 mg/L total phosphorus (see Figure 9-10).

Table 9-8 presents the total capital, total annual, and net present value for the nine greenfield wastewater treatment configurations and the Level 2-1 greenfield wastewater treatment configuration plus the cost for the retrofit chemical phosphorus removal and denitrification filter (Level 2-1 to 4 Retrofit) (presented in bold). While the Level 2-1 to 4 Retrofit wastewater treatment configuration achieves the Level 4 effluent nutrient targets, the total capital cost, total annual cost, and net present value are between the greenfield Level 2-1 A2O and both greenfield Level 3 wastewater treatment configurations. As shown in Figure 9-11, the capital cost for the Level 2-1 to 4 Retrofit wastewater treatment configuration is $12M to $15M lower than the greenfield Level 4 wastewater treatment configurations, but is designed to achieve the same effluent nutrient concentrations, due to lower biological treatment and post-biological treatment capital costs. The chemical phosphorus removal and denitrification filter portion of the Level 2-1 to 4 Retrofit capital costs are $6.9M. As shown in Figure 9-12, the total annual costs for Level 2-1 to 4 Retrofit are about $0.6M/yr to $0.8M/yr higher than the greenfield Level 3 wastewater treatment configurations, but $0.3M/yr to $0.4M/yr lower than the greenfield Level 4 wastewater treatment configurations. The annual costs for just the chemical phosphorus removal and denitrification filter portion of the Level 2-1 to 4 Retrofit is $1.11M/yr.

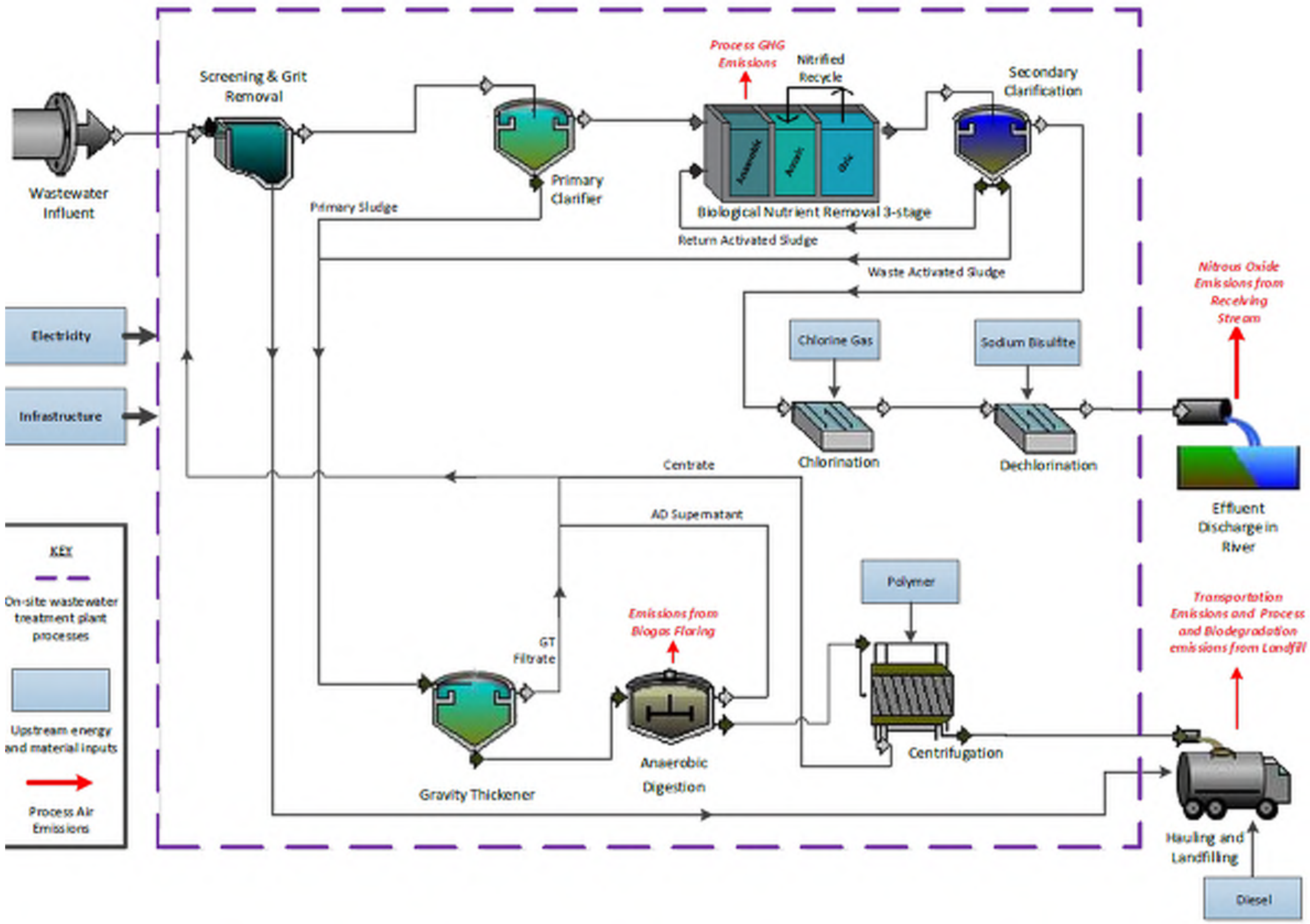


Figure 9-9. Level 2-1: Anaerobic/Anoxic/Oxic Wastewater Treatment Configuration (Baseline for Retrofit)

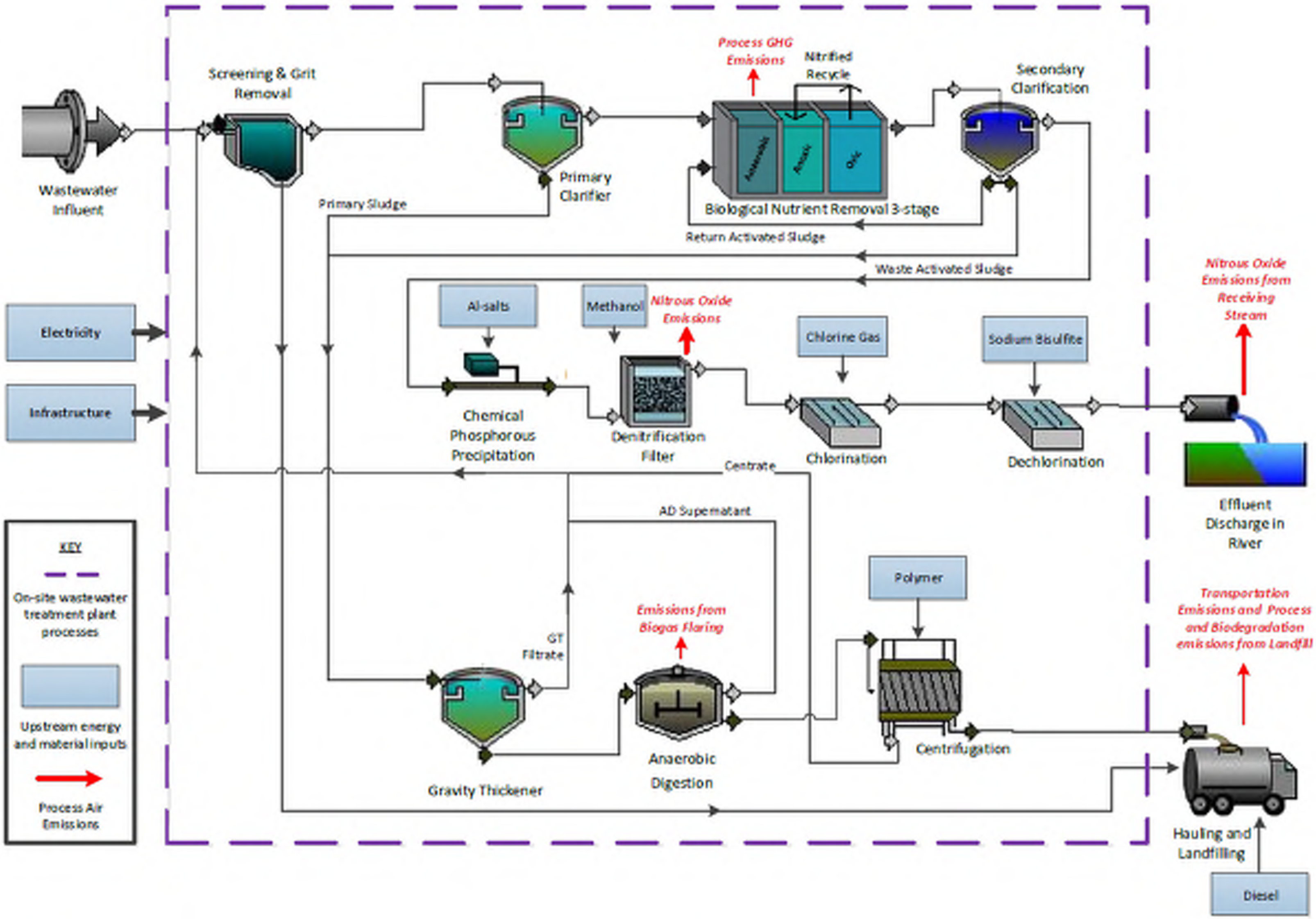


Figure 9-10. Level 2-1 to 4 Retrofit: Anaerobic/Anoxic/Oxic with Chemical Phosphorus Removal and Denitrification Filter Wastewater Treatment Retrofit Configuration

Table 9-8. Greenfield and Level 2-1 to 4 Retrofit Total Costs

Wastewater Treatment Configuration	Total Capital Cost (2014 $)	Total Annual Cost [a] (2014 $/yr)	Net Present Value (2014 $)
Level 1, AS	$55,300,000	$5,140,000	$204,000,000
Level 2-1, A2O	$71,400,000	$5,470,000	$236,000,000
Level 2-2, AS3	$93,100,000	$10,150,000	$378,000,000
Level 3-1, B5	$86,400,000	$5,800,000	$267,000,000
Level 3-2, MUCT	$88,900,000	$5,960,000	$275,000,000
Level 4-1, B5/Denit	$92,800,000	$6,840,000	$301,000,000
Level 4-2, MBR	$90,100,000	$6,330,000	$285,000,000
Level 2-1 to 4, Retrofit [b]	**$78,300,000**	**$6,580,000**	**$273,000,000**
Level 5-1, B5/RO	$160,000,000	$8,320,000	$439,000,000
Level 5-2, MBR/RO	$144,000,000	$8,080,000	$409,000,000

a – Total annual cost includes operational labor, maintenance labor, materials, chemicals, and energy (see Section 3.3 for details).

b – Costs are presented for the greenfield Level 2-1 plus the retrofit chemical phosphorus removal and denitrification filter. The capital cost, annual cost, and net present value for the chemical phosphorus removal and denitrification filter retrofit are $6.9M, $1.11M, and $37M, respectively.

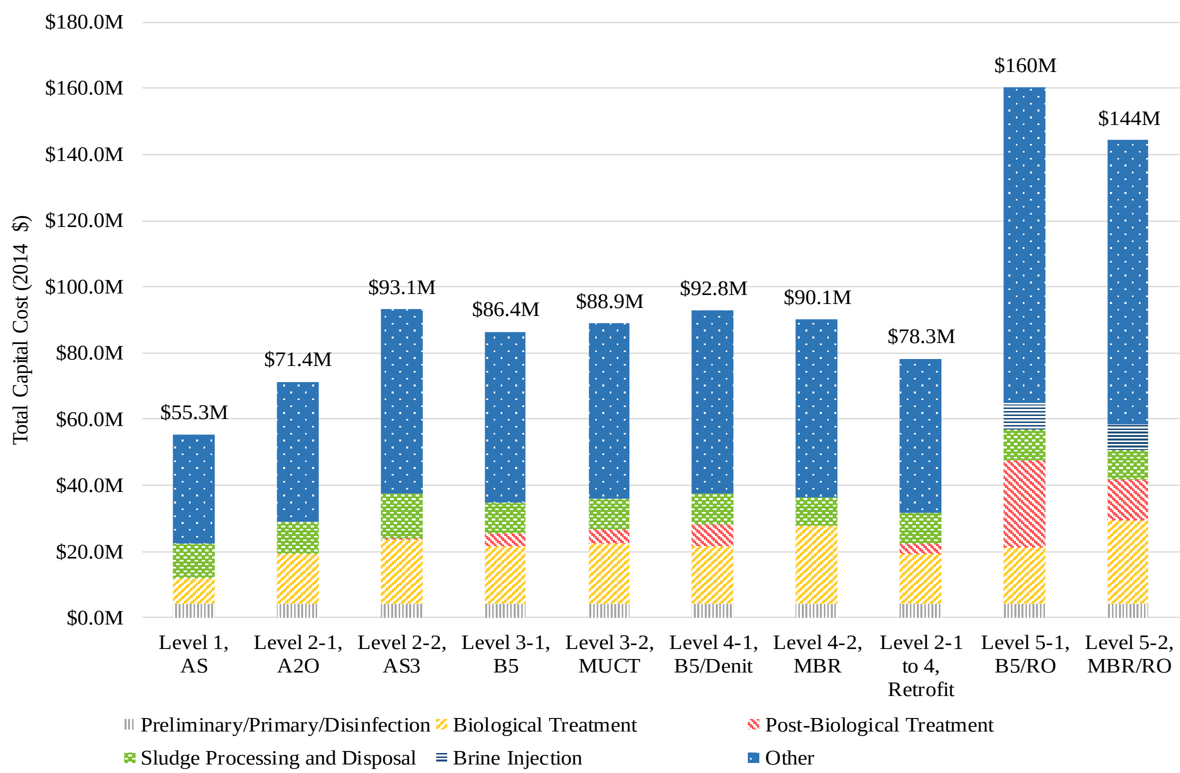


Figure 9-11. Level 2-1 A2O Baseline and Retrofit Total Capital Costs by Aggregated Treatment Group

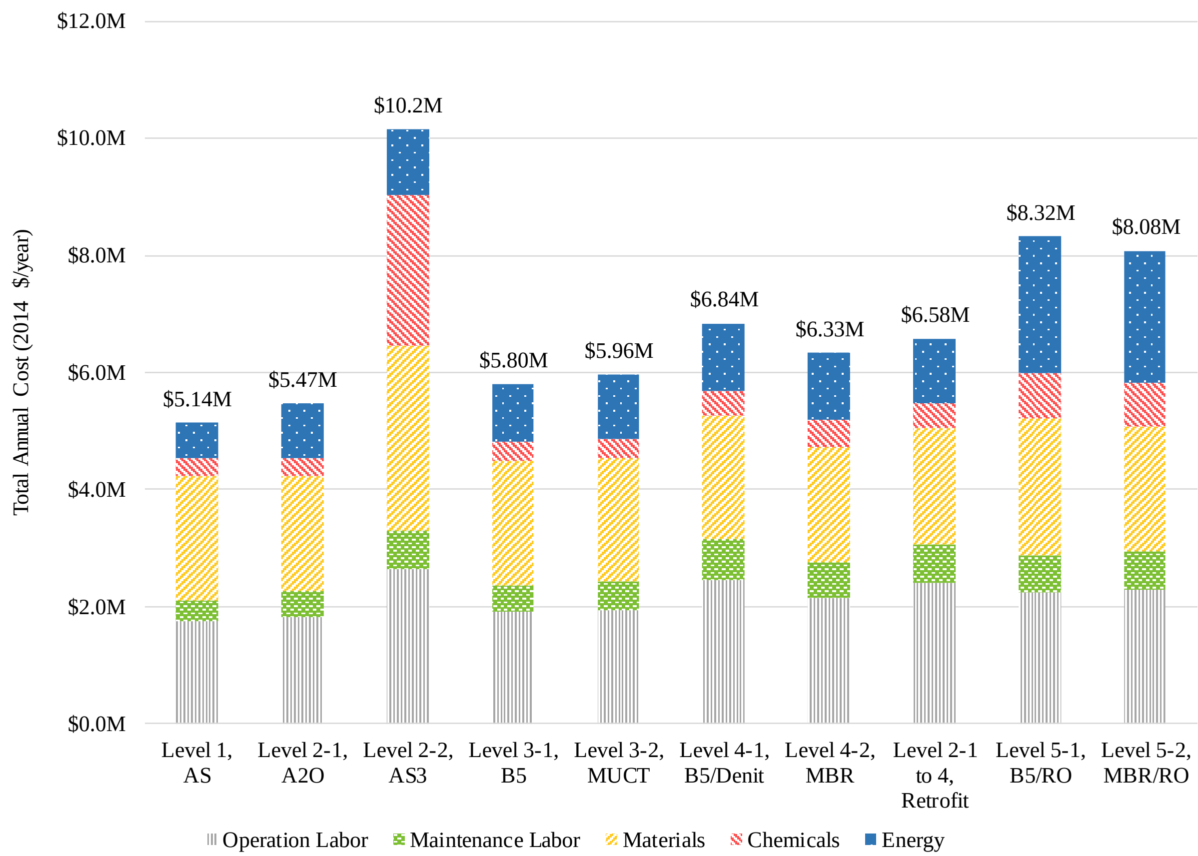


Figure 9-12. Level 2-1 A2O Baseline and Retrofit Total Annual Costs by Annual Cost Category

Figure 9-13 presents relative impact results for all greenfield treatment configurations plus the Level 2 retrofit case study. Retrofit LCIA results are generally in line with those associated with other Level 4 treatment configurations. GWP and ozone depletion potential lower for the retrofit case study, relative to other Level 4 treatment configurations, due to lower estimated N2O emissions. Eutrophication impacts are slightly elevated, compared to Level 4-1 and 4-2. Table 9-9 lists summary LCIA results for all treatment levels plus the Level 2 retrofit case study system. Retrofit results are in bold in Table 9-9.

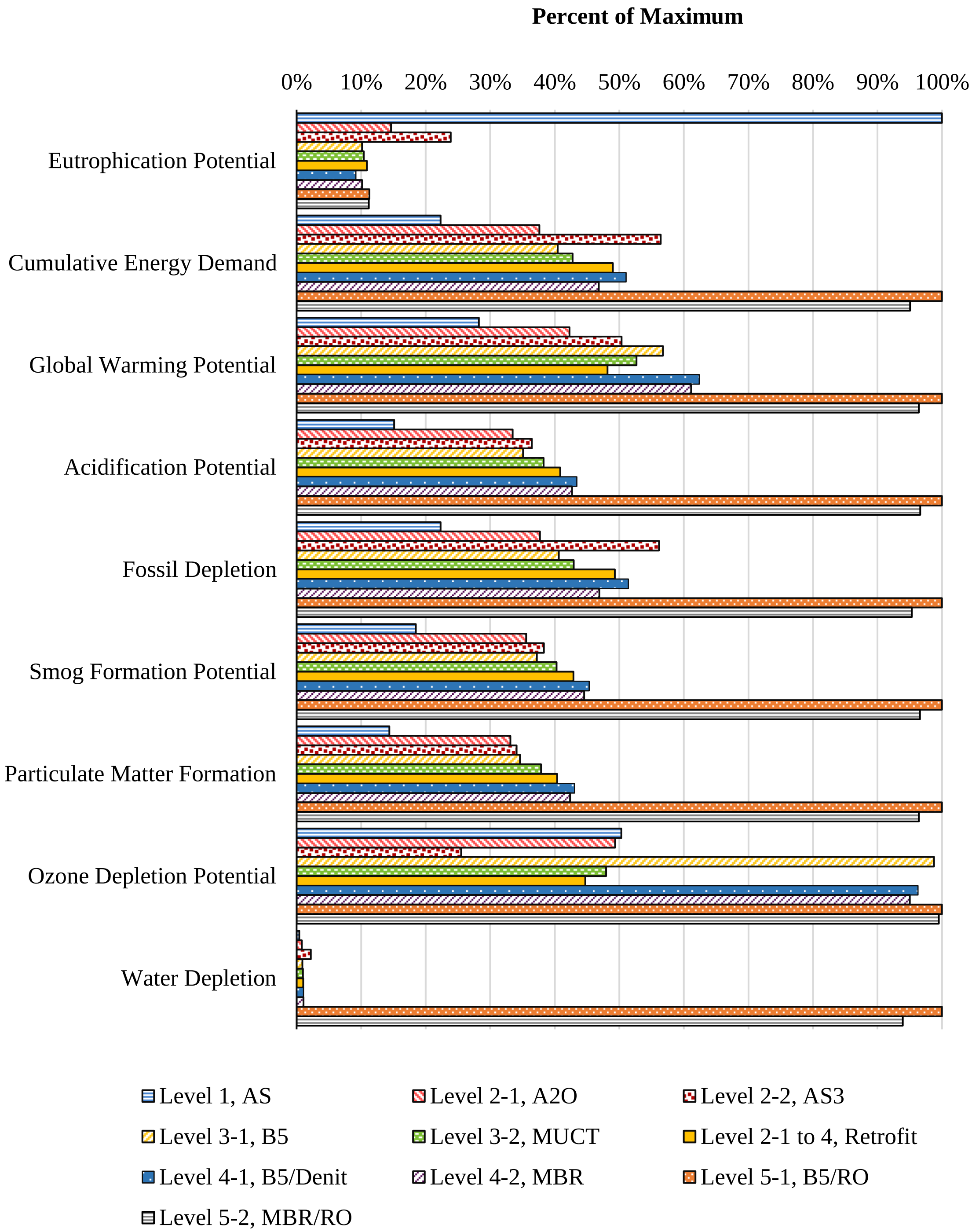


Figure 9-13. Relative LCIA Results for Nine Greenfield Wastewater Treatment Configurations and the Level 2 Retrofit Case Study

Table 9-9. Summary LCIA and Cost Results for Nine Greenfield Wastewater Treatment Configurations and the Level 2 Retrofit Case Study (per m^3 wastewater treated)

Impact Category	**Unit**	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 2-1 to 4, Retrofit**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Cost	$ USD	$0.64	$0.74	$1.18	$0.84	$0.86	**$0.85**	$0.94	$0.89	$1.37	$1.28
Global Warming Potential	kg CO2 eq	0.52	0.77	0.92	1.0	0.96	**0.88**	1.1	1.1	1.8	1.8
Cumulative Energy Demand	MJ	5.4	9.1	14	9.7	10	**12**	12	11	24	23
Eutrophication Potential	kg N eq	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	**7.3E-3**	6.1E-3	6.8E-3	7.5E-3	7.5E-3
Water Depletion	m3 H2O	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	**1.9E-3**	2.0E-3	2.0E-3	0.19	0.17
Acidification Potential	kg SO2 eq	0.01	0.03	0.03	0.03	0.04	**0.04**	0.04	0.04	0.09	0.09
Particulate Matter Formation	PM2.5 eq	1.5E-3	3.4E-3	3.5E-3	3.6E-3	3.9E-3	**4.2E-3**	4.5E-3	4.4E-3	0.01	0.01
Smog Formation Potential	kg O3 eq	0.14	0.27	0.29	0.28	0.30	**0.32**	0.34	0.33	0.75	0.72
Ozone Depletion Potential	kg CFC-11 eq	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	**3.4E-6**	7.4E-6	7.3E-6	7.7E-6	7.7E-6
Fossil Depletion	kg oil eq	0.12	0.20	0.30	0.22	0.23	**0.26**	0.28	0.25	0.54	0.51

10. CONCLUSIONS

This study met its goal to assess a series of wastewater treatment configurations that reduce the nutrient content of effluent from municipal WWTPs considering treatment costs as well as human health and ecosystem impacts from a life cycle perspective.

The LCA results highlight the trade-offs that exist between the various treatment configurations for cost and traditional LCIA impact categories. The largest normalized impact observed across all combinations of treatment configurations and impact categories was the eutrophication impact for the Level 1 treatment configuration. It is clear that use of a traditional Level 1 treatment configuration results in the lowest costs, but also significantly higher normalized eutrophication impacts compared to all other study treatment system configurations. When considering the impaired state of many of this nation's water bodies related to nutrients, the use of nutrient removal technologies explored in this study are tools that could be used to improve water quality. This study aims to help communities and businesses consider the environmental and economic costs and benefits of advanced nutrient removal options.

Given the predominant contribution of electricity and energy consumption to impact results in many of the impact categories, it is necessary to think critically about the energy efficiency of treatment processes, particularly in relation to their level of nutrient removal. A series of ratios are presented in Table 10-1 to help in this process. The aggregate level of nutrient removal increases rapidly as nutrient removal standards progress from Level 1 to Level 5. The total electricity demand that coincides with increasing levels of nutrient removal, increases substantially across the treatment configurations, from 0.20 to 1.5 kWh/m^3 wastewater treated. However, when considering the electricity consumption compared to each unit of nutrient removed reveals that the electricity demand does not increase across the majority of the treatment configurations on the basis of nutrient equivalents removed. Electricity per unit of total nitrogen and phosphorus equivalents removed remains consistent from Level 2 through Level 4. However, due to the large electrical demand of the reverse osmosis process, total electricity per nutrient removal is generally two to three times higher for the Level 5 treatment configurations compared to Levels 2 through 4.

Table 10-1. Nutrient Removal Electricity Performance Metrics

Treatment Level	**1**	**2-1**	**2-2**	**3-1**	**3-2**	**4-1**	**4-2**	**5-1**	**5-2**
Total P removed (g/m^3)	0.06	4.7	4.0	4.8	4.8	4.9	4.9	5.0	5.0
Total N removed (g/m^3)	9.7	32	32	34	34	37	37	39	38
Total Electricity Demand (kWh/m^3)	0.20	0.48	0.51	0.52	0.57	0.65	0.64	1.5	1.4
Total Electrical Demand/Total P removed (kWh/g)	N/A[a]	0.10	0.13	0.11	0.12	0.13	0.13	0.30	0.29
Total Electrical Demand/Total N removed (kWh/g)	N/A[a]	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04

a – Values not shown for Level 1 since this treatment configuration not designed for nutrient removal.

While this work was primarily focused on nutrients, the effect of study treatment configurations on the removal of trace pollutants was also reviewed to determine if additional benefits, not part of the original treatment design, may be realized from the implementation of more advanced treatment processes. This part of the project focused on potential toxicity impacts associated with heavy metals, toxic organics and disinfection byproducts. Results showed that metals were by far the most influential pollutant group in terms of life cycle toxicity impacts. Similar to nutrients, tradeoffs were identified between high effluent-based impacts at low levels of treatment and high process-based impacts at high levels of treatment. Generally, Levels 3 and 4 (and specifically Levels 3-2 and 4-2) resulted in the lowest overall toxicity impacts, owing to their high metal removal efficiencies and moderate material and energy requirements. Relative to Level 4-2 in particular, the higher and more consistent degree of metal removal provided by Level 5 was outweighed by greater process-based impacts, resulting in greater total impacts in all toxicity categories. Results of the analysis reveal that heavy metals contribute more strongly to human health and ecotoxicity impacts than do the toxic organics and DBPs with sufficient data to be evaluated.

The electrical grid sensitivity analysis showed that the importance of electricity and energy use and the trade-offs associated with achieving the key eutrophication reductions could largely be offset if the WWTP were to utilize an electrical grid with reliance on energy sources such as natural gas, hydro, and nuclear or use of recovered resources to generate on-site energy in order to reduce the need for purchased electricity. While an effort to achieve reductions in the environmental burdens associated with electricity production is certainly warranted given the information presented in the results section, Table 10-1 provides an indication of which treatment options may serve communities and businesses attempting to reduce environmental impacts while simultaneously controlling energy costs. The realization of benefits associated with these insights is not dependent on improvements in the electrical grid, which lie outside of the control of many WWTPs. Other strategies within the facilities boundaries, such as energy recovery from biogas, may help to offset environmental impacts from increased nutrient removal.

Generally, the results show the benefits to eutrophication impact associated with more stringent levels of nutrient removal. This benefit is generally increasingly offset by increases in other environmental impacts as the standard of removal progresses from Level 2 to Level 5, with Level 5 showing the most dramatic increase in cost and other impacts due to the exacting standard of treatment required. However, given local and regional environmental and economic considerations, the selection of the most appropriate treatment configuration will vary by location. This work cannot answer the question of how much nutrient removal can be considered sufficient for any specific WWTP or body of water. The question is inherently local or regional in nature, and an individual or institution must consider a number of factors when trying to determine what is appropriate for their situation. This study does indicate that careful consideration should be given to the benefits that are expected to be gained by pursuing the more advanced levels of nutrient removal, and that these benefits should be weighed against the environmental and economic costs discussed in Sections 5, 6 and 7. As discussed earlier, this study focused on the implementation of greenfield treatment configurations, and the economic impacts may vary significantly for retrofitted operations.

Overall, this study built a comprehensive framework to assess the environmental, human health, and cost implications of shifting to higher nutrient removal wastewater treatment configurations. The LCCA and LCA models constructed here can be continually built upon to improve the baseline analysis or investigate additional wastewater treatment configurations or variability with regional conditions. The system boundaries could also be expanded to understand the influence and potential benefit of recycling water from the effluent of the higher nutrient removal wastewater configurations to displace production of potable water elsewhere.

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Ziolko, D., O. V. Martin, M. D. Scrimshaw, and J. N. Lester. 2011. An Evaluation of Metal Removal During Wastewater Treatment: The Potential to Achieve More Stringent Final Effluent Standards. *Critical Reviews in Environmental Science and Technology* 41: 733–769. doi:10.1080/10643380903140299.

APPENDIX A
SELECTION OF WASTEWATER TREATMENT CONFIGURATIONS

Appendix A: Selection of Wastewater Treatment Configurations

ERG searched the literature to compile performance information on wastewater treatment configurations which remove both TN and TP from municipal wastewater. ERG recorded the type of biological treatment used and the use or absence of chemical addition for phosphorus precipitation, fermenter, sand filter, and other technology components. ERG assumed preliminary treatment with screens, a grit chamber, and primary clarification. Sludge management was assumed to include gravity thickening, anaerobic digestion, dewatering (centrifugation), and transport of wastewater solids to a landfill. ERG gathered performance data from nine key sources:

- Bickler, S. Wigen Water Technologies. 2015. Technical Feedback Requested Regarding Reverse Osmosis. Email from S. Bickler, to A. Allen, ERG. (June).

- Bott, C. and Parker, D. 2011. Nutrient Management Volume II: Removal Technology Performance & Reliability. Water Environment Research Federation Report NUTR1R06k. IWA Publishing, London, U.K.

- Dukes, S. and von Gottberg, A. Koch Membrane Systems. 2006. Membrane Bioreactors for RO Pretreatment. Water Environment Foundation. WEFTEC® 2006.

- Eastern Research Group, Inc. 2009. Draft Technical Support Document: Analysis of Secondary Treatment and Nutrient Control at POTWs. (December).

- Eastern Research Group, Inc. 2015b. Personal communication between Amber Allen, Debra Falatko, and Mark Briggs of ERG and Stacey Bickler of Wigen Water Technologies.

- Falk, M.W., Neethling, J.B., and Reardon, D.J. 2011. Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability. Water Environment Research Federation Report NUTR1R06n. IWA Publishing, London, U.K.

- Hartman, P. and Cleland, J. ICF International. 2007. Wastewater Treatment Performance and Cost Data to Support an Affordability Analysis for Water Quality Standards. Montana Department of Environmental Quality. (May). Available online at http://www.kysq.org/docs/Wastewater_2007.pdf.

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ERG recorded performance data for all wastewater treatment configurations and assigned each a performance level as defined in Falk et al. (2011), Table ES-1:

- Level 1 – No target effluent concentration specified;
- Level 2 – 8 mg N/L, 1 mg P/L;
- Level 3 – 4-8 mg N/L, 0.1-0.3 mg P/L;
- Level 4 – 3 mg N/L, 0.1 mg P/L; and
- Level 5 – 2 mg N/L, <0.02 mg P/L.

In many cases, performance levels for wastewater treatment configurations differ for TN and TP (i.e., a configuration achieves a certain level for TN and a different level for TP).

ERG examined the set of identified wastewater treatment configurations for which TN and TP performance levels match to identify nine which are commonly used and provide contrast. Contrast was defined by differences in terms of performance level, type of biological nutrient reduction, combinations of additional treatment steps, costs (capital and operating), and other contrasting parameters such as energy requirements, chemical usage, and sludge generation. For level 1, ERG recommended one wastewater treatment configuration, and for each of levels 2 to 5 ERG recommended two wastewater treatment configurations. ERG's rationale for these recommendations is described below.

A.1 Results and Recommendations

ERG identified 37 wastewater treatment configurations that achieve the same performance level for both TN and TP (see Table A-1). The technologies used in these wastewater treatment configurations include a variety of biological nutrient removal and enhanced nutrient removal technologies.

The sections below describe the wastewater treatment configurations identified for each performance level and discuss ERG's rationale for selection of specific wastewater treatment configurations to be evaluated in the LCA. Selected configurations generally represent those most commonly used to achieve the desired performance levels, and that also provide contrast in biological processes, capital and/or annual costs, or other factors such as energy requirements and sludge generation. The most common reasons wastewater treatment configurations were not selected include: 1) they are unique retrofits and otherwise not commonly used, 2) they are very similar to another selected technology, or 3) they exhibit a wide range of performance, spanning multiple performance levels, which raises uncertainty as to the reliability with which the process can achieve a specific performance level.

Table A-1. Identified Wastewater Treatment Configurations

Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
1	3-stage Westbank					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
2	3-stage Westbank	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
3	4-stage Bardenpho	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
4	5-stage Bardenpho (Level 3)	x	x	x		4 to 8	2,3	0.1 to 0.3	3	b, Table 3-1 and 2-b, pages 56, 57, 59.
5	5-stage Bardenpho (Level 4)	x	x	x	Denitrification filter	3	4	0.1	4	b, Table 3-1 and 2-b, pages 56, 57, 60-61; also a, Table 5-d, page 237
6	5-stage Bardenpho	x		x		3	4	0.1	4	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
7	5-stage Bardenpho (Level 5)	x	Not listed in reference (Falk et al), but may be appropriate	x	Denitrification filter (10% flow) + ultrafiltration and reverse osmosis (90% flow)	<2	5	<0.02	5	b, Table 3-1 and 2-b, pages 56, 57, 61; also a, Table 5-d, page 237
8	Activated sludge + Modified Ludzack-Ettinger				Biological activated filter	4	3	<=0.3	3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
9	Activated sludge + Modified Ludzack-Ettinger	x				3	4	0.1	4	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
10	Activated sludge (Level a, assuming conventional activated sludge treatment)					3 to 9	a,2,3	0.3 to 2	a,2	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)

Table A-1. Identified Wastewater Treatment Configurations

Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
11	Activated sludge, 3-sludge system (Level 2)	x				6 to 8	2	0.43	2	a, pages 2-5 and 3-5/6 (pg 59 and 151/152)
12	Aerobic lagoons					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
13	Anaerobic/Anoxic/Oxic (Level 2)					8; 3 to 8	2; 2,3	1; 0.5 to 1	2; 2	b, Table 3-1 and 2-b, pages 56, 57, 58.; a, Table 5-d, page 237
14	Anaerobic/Oxic, Phoredox					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
15	Cyclic activated sludge	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
16	Integrated fixed-film activated sludge	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
17	Extended aeration					3 to 8	2,3	0.1 to 1 (2)	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
18	Facultative lagoon					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
19	Membrane bioreactor (Level 4)	x				<3	4	<=0.1	4	a, Table 5-d, page 237
20	Membrane bioreactor (Level 5)	x	Not listed in reference (Falk et al), but may be appropriate		Reverse osmosis (85% flow)	<2; <0.1	5	<0.02; -	5	b, Table 3-1 and 2-b, pages 56, 57, 61; a, Table 5-d, page 237; 8, page 6127; 9, page 1

Table A-1. Identified Wastewater Treatment Configurations

Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
21	Membrane bioreactor		x		Land application/ infiltration bed	<3	4	<=0.1	4	a, Table 5-d, page 237, also land application note on pages 13d, 27, and 39
22	Modified Ludzack-Ettinger	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
23	Modified Ludzack-Ettinger	x	x	x	Denitrification filter	<3	4	<=0.1	4	a, Table 5-d, page 237, page 63
24	Moving-bed biofilm reactor (Level 2)	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
25	Phased isolation ditch					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
26	PhoStrip II					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
27	Post-aeration anoxic with methanol (Blue Plains process, a retrofit system)	x				3 to 8; 4 to 8	2,3	0.5 to 1; 0.18	2; 3	a, Table 5-d, page 237; 7, page 3-43 (pg 83)
28	Rotating biological contactor (assume Level 3 performance)					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
29	Sequencing batch reactor					3 to 8	2,3	0.1 to 1	2,3	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
30	Sequencing batch reactor			x		3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
31	Sequencing batch reactor	x				3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
32	Step-feed activated sludge					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237

Table A-1. Identified Wastewater Treatment Configurations

Recommended wastewater treatment configuration

All configurations assumed to also include preliminary/primary treatment and sludge management.

No.	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Additional Treatment	Long Term Average Effluent TN Concentration (mg/L as N)	TN Level	Long Term Average Effluent TP Concentration (mg/L)	TP Level	Performance Source [1]
33	Step-feed activated sludge (Level 4)	x	x	x	Chemically assisted clarification	<3	4	<=0.1	4	a, Table 5-d, page 237
34	Trickling filter				Submerged biological filter	3	4	0.1	4	c, Figure IV-9, page IV-11 (pg 58), Figure IV-16, page IV-17 (pg 64), page E-1 (pg 97)
35	Suspended growth activated sludge	x	x		Inclined plate settling tanks, deep bed sand filter	3 to 6	3	0.18	3	d, page 3-39 (pg 79-80)
36	University of Cape Town process, modified					3 to 8	2,3	0.5 to 1	2	a, Table 5-d, page 237
37	University of Cape Town process, modified (Level 3)	x	x	x		<3	3	0.1 to 0.5	3	a, Table 5-d, pages 5-5 (pg 237), ES-22 (pg 40), UCTm equivalent to technologies in Table 5-2 on page 5-4 (pg 236)

1 – Sources: a – U.S. EPA OWM, 2008b; b – Falk et al., 2011; c – U.S. EPA OST, 2015a; d – Bott and Parker, 2011.

2 – This phosphorus removal capability is unexpected, but is included as reported in the cited wastewater treatment configuration source document.

A.1.1 Level 1

Level 1 technologies are not designed to specifically remove nutrients, although some removal of nutrients occurs with the wastewater treatment configuration. ERG recommended the conventional plug flow activated sludge system to represent level 1 performance.

A.1.2 Level 2

Twenty-two wastewater treatment configurations performed at level 2 for both TN and TP. These wastewater treatment configurations included the biological and enhanced nutrient reduction technologies listed in Table A-1. ERG selected the anaerobic/anoxic/oxic (A2O) system as a typical level 2 wastewater treatment configuration and then reviewed the remaining level 2 wastewater treatment configurations for contrast, performance, and likelihood of use.

ERG considered and rejected the moving-bed biofilm reactor because it is most frequently used as a retrofit but otherwise is not commonly used. The integrated fixed-film activated sludge and anaerobic/oxic Phoredox systems were rejected as too similar to the selected A2O system. The Modified University of Cape Town process and 4-stage Bardenpho were rejected at level 2 to allow for their selection as contrasting wastewater treatment configurations for other performance levels.

The sequencing batch reactor, 3-stage Westbank, cyclic activated sludge, step-feed activated sludge, phased isolation ditch, modified Ludzack-Ettinger (MLE), and PhoStrip II were rejected due to concerns that their performance ranges were too wide, raising uncertainty regarding their ability to reliably achieve level 2 performance. The extended aeration system was rejected because of concerns about the performance data presented in the reference. The Blue Plains Process was rejected because it is a unique retrofit system. The aerobic and facultative lagoons were rejected because lagoons are not applicable for all publicly owned treatment works (POTWs). A rotating biological contactor (RBC) system was initially considered because it offers the advantages of low energy usage, low solids generation, and good settling. However, the RBC technology was ultimately rejected because its use is predominately restricted to small plants; the technology also exhibited a number of problems in the 1970s and 1980s, some of which remain unresolved today.

After eliminating the other level 2 options for the reasons discussed above, ERG recommended a common alternative level 2 configuration of plug flow activated sludge followed by separate stage nitrification and separate stage denitrification with chemical phosphorus removal. This technology contrasts with the recommended A2O system in its relative ease of operation and control (due to segregated treatment components for BOD, ammonia, and nitrate removal) and relatively higher cost due to multiple biological reactors and associated clarifiers/sludge recycling.

In summary, ERG recommended the following two technologies to represent level 2 performance in the LCA:

- 2-1) A2O with chemical phosphorus precipitation; and
- 2-2) 3-Sludge activated sludge system with chemical phosphorus precipitation.

A.1.3 Level 3

Ten wastewater treatment configurations performed within the level 3 range. Of these, six were rejected from further consideration because their TN/TP performance spans levels two and three (included in the level 2 description above). The remaining four wastewater treatment configurations perform at level 3 for both TN and TP. The first system, which uses activated sludge, MLE, and a biological activated filter, was not recommended because it is a unique retrofit system. The second system, which uses suspended growth in high purity oxygen activated sludge, inclined plate setting tanks, and a deep bed sand filter, was rejected because suspended growth systems are not applicable for all POTWs. The remaining two systems are commonly used systems that ERG recommended to represent level 3 performance in the LCA:

- 3-1) 5-Stage Bardenpho with chemical phosphorus precipitation, fermenter, and sand filter; and
- 3-2) Modified University of Cape Town process with chemical phosphorus precipitation, fermenter, and sand filter.

A.1.4 Level 4

Eight wastewater treatment configurations perform at level 4 for both TN and TP. These processes included a 5-stage Bardenpho activated sludge coupled with a MLE unit, 4- and 5-stage Bardenpho systems coupled with membrane filtration, denitrification filters coupled with a MLE unit or with a 5-stage Bardenpho, a trickling filter coupled with a submerged biological filter, and a step-feed activated sludge process with chemically assisted clarification. Most of these wastewater treatment configurations also include chemical phosphorus precipitation, and half also include either a fermenter or a sand filter.

ERG selected the 5-stage Bardenpho with denitrification filter as a typical level 4 wastewater treatment configuration. For the contrasting level 4 wastewater treatment configuration, ERG considered and rejected the membrane bioreactor with land infiltration and the trickling filter because neither is applicable for all POTWs. The activated sludge coupled with a MLE unit was rejected as a unique retrofit system. The 5-stage Bardenpho without denitrification filter was rejected as too similar to the typical level 4 configuration. Of the remaining three options (step-feed activated sludge, MLE with denitrification filter, and 4-stage Bardenpho with membrane filter), ERG selected the membrane bioreactor (MBR) system as a contrasting alternative because of its increasing popularity.

In summary, ERG recommended the following technologies to represent level 4 performance in the LCA:

- 4-1) 5-Stage Bardenpho with chemical phosphorus precipitation, fermenter, sand filter, and denitrification filter; and
- 4-2) 4-Stage Bardenpho MBR and chemical phosphorus precipitation.

A.1.5 Level 5

Two wastewater treatment configurations performed at level 5 for both TN and TP. The first configuration includes 5-stage Bardenpho, chemical precipitation, and fermentation. The wastestream is then split with a portion of the flow undergoing side stream treatment by reverse osmosis (RO) and the remainder of the flow undergoing side stream treatment by a denitrification filter and sand filter. The second wastewater treatment configuration is a 5-stage Bardenpho MBR with chemical phosphorus precipitation and fermenter followed by a portion of the flow to RO and the remainder of the flow not requiring additional side stream treatment. This second process is a modification of the first, substituting a 5-stage Bardenpho MBR for the 5-stage Bardenpho and clarifier. The MBR allows the wastewater treatment configuration to achieve similar TN and TP performance without a denitrification filter and sand filter.

ERG conducted additional literature reviews and communications with RO vendors to determine RO pretreatment requirements. For the first configuration, RO pretreatment includes solids removal (ultrafiltration, UF), biofouling control (chlorination followed by dechlorination), and scale control (antiscalant addition). RO pretreatment for the second configuration is similar to the first, except that use of the 5-stage Bardenpho MBR precludes the need for solids removal via UF.

ERG performed calculations to determine the percentage of flow requiring side stream treatment for each configuration to achieve the target TN and TP effluent concentrations. For TN, ERG assumed the following effluent quality achieved by nutrient control technologies:

- A 5-stage Bardenpho TN effluent concentration of 4 - 8 mg/L (based on the performance of the level 3 5-stage Bardenpho configuration).
- A denitrification and sand filter TN effluent concentration of 3 mg/L (based on the performance of the level 4 5-stage Bardenpho configuration).
- A 5-stage Bardenpho MBR TN effluent concentration of 3 mg/L (based on the performance of the level 4 5-stage Bardenpho MBR configuration).
- A RO removal of 95 percent (based on information from RO vendors).

Using these assumptions, and a target overall TN effluent concentration of 2 mg/L, approximately 35 to 40 percent of flow would need to undergo side stream treatment by RO.

For TP, ERG assumed the following effluent quality achieved by nutrient control technologies:

- A 5-stage Bardenpho TP effluent concentration of 0.1 to 0.3 mg/L (based on the performance of the level 3 5-stage Bardenpho configuration).
- A denitrification and sand filter TP effluent concentration of 0.1 mg/L (based on the performance of the level 4 5-stage Bardenpho configuration).
- A 5-stage Bardenpho MBR TP effluent concentration of 0.1 mg/L (based on the performance of the level 4 5-stage Bardenpho MBR configuration).
- A RO removal of 95 percent (based on information from RO vendors).

Using these assumptions, and a target overall TP effluent concentration of 0.02 mg/L, approximately 85 to 90 percent of flow (for the second and first configurations, respectively) would need to undergo side stream treatment by RO.[9]

These calculations demonstrate that TP removal, rather than TN removal, drives the percentage of wastewater requiring RO treatment to achieve level 5 performance.

In summary, ERG recommended the following technologies to represent level 5 performance in the LCA:

- 5-1) 5-stage Bardenpho with chemical phosphorus precipitation, fermenter, and sand filter followed by 10 percent of the flow to a denitrification filter and sand and 90 percent of the flow to UF and RO; and
- 5-2) 5-stage Bardenpho MBR with chemical phosphorus precipitation and fermenter followed by 85 percent of the flow to RO.

A summary of these recommendations is found in Table A-2 below.

Table A-2. Recommended Technologies

Performance Level	Type of Biological Treatment	Phosphorus Precipitation	Fermenter	Sand Filter	Other Technical Components	Reference
1	Plug Flow Activated Sludge					OST, 2015
2	Anaerobic/Anoxic/Oxic					Falk, 2011
2	Activated Sludge, 3-Sludge System	X				OWM, 2008
3	5-Stage Bardenpho	X	X	X		Falk, 2011
3	University of Cape Town Process, Modified	X	X	X		OWM, 2008
4	5-stage Bardenpho	X	X	X	Denitrification Filter	Falk, 2011
4	4-stage Bardenpho MBR	X				OWM, 2008
5	5-Stage Bardenpho	X	X	X	10%: Denitrification Filter 90%: UF and RO	Falk, 2011 and OWM, 2008
5	5-stage Bardenpho MBR	X	X		85% RO	Falk, 2011 and OWM, 2008

[9] Note that RO effluent quality expressed as a percentage of TP removal may not be the most appropriate measure of RO performance, but rather an effluent concentration of non-detect (detection limit 0.02 mg/L). Under this scenario, assuming an average effluent concentration equal to the detection limit, ½ the detection limit, and zero, approximately 80 to 100 percent of flow would need to undergo side stream treatment by reverse osmosis.

A.2 Technology Selection Data Quality

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* (ERG, 2015c) approved by EPA on March 25, 2015, ERG collected existing data[10] via a literature search to determine the performance of identified wastewater treatment configurations. The literature search focused on peer-reviewed literature, EPA projects, and publicly available equipment specifications from and communications with technology vendors. ERG evaluated the collected information for completeness, accuracy, and reasonableness. In addition, ERG considered publication date, accuracy/reliability, and nutrient concentrations (reported as TN and TP) when reviewing data quality. Finally, ERG performed conceptual, developmental, and final product internal technical reviews of the data compilation and this Appendix.

Completeness. The descriptions of wastewater treatment configurations in the literature vary in level of detail. Descriptions used in this analysis were limited to those sufficiently detailed to be classified into one of the performance level categories and to identify the major technology components (e.g., type of biological treatment, chemical treatments, sand filter). ERG reviewed the treatment system descriptions, and did not include data for incomplete treatment systems.

Accuracy. ERG evaluated sources to ensure that the descriptions of each treatment system represent current operations at municipal treatment systems, and that nutrient reductions reflect the performance of the identified control technologies rather than other design or operational factors.

Reasonableness. ERG evaluated sources to ensure that the type of treatment correlates with expected nutrient reduction performance; for example, treatment systems with nutrient control should have lower nutrient concentrations than systems with secondary treatment only.

The criteria ERG used in evaluating the quality of information collected during the literature review are summarized in Table A-3.

Table A-3. Literature Review Data Quality Criteria

Quality Criterion	Description/Definition
Current (up to date)	Report the time period of the data. Year of publication (or presentation, if a paper presented at a conference) is 2005 or after.
Accurate/Reliable	U.S. government publications assumed accurate. For academic researcher: • Publication in peer reviewed journal. • Presentation at professional technical conference. For vendor researcher: • Publication in peer reviewed journal.

[10] *Existing data* means information and measurements that were originally produced for one purpose that are recompiled or reassessed for a different purpose. Existing data are also called secondary data. Sources of existing data may include published reports, journal articles, LCI and government databases, and industry publications.

Table A-3. Literature Review Data Quality Criteria

Quality Criterion	Description/Definition
Analyte Scope	Nutrient concentrations, reported as TN and TP.

In accordance with the QAPP, ERG performed conceptual, developmental, and final product technical reviews of the spreadsheet included as Table A-1. These reviews included the following general steps:

- The spreadsheet developer verified the accuracy of any data that were transcribed into the spreadsheet;
- The team member reviewer also verified the accuracy of any data that were transcribed into the spreadsheet;
- The team member reviewer evaluated the technical soundness of methods and approaches used;
- The ERG spreadsheet developer maintained version control of interim spreadsheets; and
- The ERG spreadsheet developer maintained documentation in the project files.

APPENDIX B
DETAILED CHARACTERIZATION OF HEAVY METALS BEHAVIOR IN STUDY TREATMENT CONFIGURATIONS

Appendix B: Detailed Characterization of Heavy Metals Behavior in Study Treatment Configurations

B.1 Introduction

The discharge of metals to the environment represents an ever-present concern, given their potential toxicity at even trace levels. Wastewater treatment plants (WWTP) receive variable but sometimes high loads of metals depending on the mix of sources in their watershed, which can include industrial activities, domestic sources and stormwater (Yost et al. 1981; Rule et al. 2006; J.-M. Choubert et al. 2011b). Given a WWTP's position as a final barrier between source and environmental discharge, they are an opportunity for smart management of potentially toxic substances like metals.

The direct management of metals in conventional, municipal WWTPs has traditionally not been a focus of WWTP design and operation as measures like the National Pretreatment Program[11] are in place to limit the concentration and load of metals coming from industrial facilities. Rather, most discussion surrounding the treatment of metals by municipal WWTPs has dealt with the ancillary benefits afforded by existing processes that impact metals as well as the organics and nutrients these processes were designed to address (Choubert et al. 2011a; Choubert et al. 2011b; Ziolko et al. 2011; Cantinho et al. 2016). Additionally, little to no attention has been paid to the life cycle impacts of metal emissions associated with upstream processes, especially in conjunction with and relative to direct effluent emissions. To date, the most comprehensive study performed to address the 'co-benefits' of various treatment processes from a life cycle perspective only qualitatively discussed the effects of metals from both upstream and direct discharge impact calculations (Rahman et al. 2018). This study is therefore intended to address these gaps, which will help to both characterize the ability of a variety of commonly used wastewater treatment practices to partition metals from the liquid phase, as well as to help inform the full potential benefits of these treatment trains from a comprehensive life cycle perspective.

The metals reviewed for this study were selected based on two main criteria: the metal's recurrent presence in lists of regulated substances and its prevalence in the literature regarding treatability in the study treatment configurations. Indirectly, these two criteria were assumed to be indicators of demonstrated potential of the metal to cause environmental or human health impacts. The resulting list of metals includes Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), and Zinc (Zn). Each of these metals have been regulated in different countries. Four of them (Cd, Hg, Ni and Pb) were classified by the European Water Framework Directive (EUWFD) as priority substances and two (Hg and Cd) were additionally classified as hazardous substances (EU 2013; Cantinho et al. 2016). In the United States (US), guidance is provided for concentration limits of each of these metals in WWTP effluent through National Recommended Water Quality Criteria (EPA 2009). Table B-1 summarizes relevant regulatory criteria for the metals included in this study. Metal concentrations in land-applied sludge are also regulated in the US through the Part 503 Rule (NRC 2002).

[11] https://www.epa.gov/npdes/national-pretreatment-program

Elevated levels of metals in the environment can result from both natural and anthropogenic sources. In the urban environment, metals are present in mixed municipal wastewater owing to the contribution of commercial and industrial sources, residential sources, contact with piping, and stormwater runoff (Yost et al. 1981; Thornton et al. 2001; Jones et al. 2017). Often, domestic inputs tend to be the largest sources of Cu, Zn and Pb, whereas commercial and industrial sources contribute greater proportions of Hg and Cr (Makepeace et al. 1995; Cantinho et al. 2016). Table B-1 summarizes ranges of influent concentrations established in several literature reviews, along with the ranges that were compiled from the case study data reviewed as part of this effort. These concentrations, as well as concentrations throughout this document, represent total concentrations (as opposed to specific fractions) unless otherwise noted.

Table B-1. Summary of Literature and Case Study Metal Influent Concentrations and Regulatory Effluent Concentrations

Value		Concentrations in µg/L							Notes	Source
		Pb	Cu	Zn	Ni	Cr	Cd	Hg		
Influent Concentrations - Literature Reviews		5.7	63	181	11	10	0.21	0.36	19 Plants, France	1
		25	78	155	14	12.0	0.8	0.5	30 Plants, UK	2
		140-600	--	--	--	--	--	--	Combined WW	3
		232	489	968	455	378	19	--	12+ Cities, US	4
Case Study Ranges	High	68	118	493	77	290	10	7.0	This Study	5
	Medium	21	65	350	24	59	4.9	3.8	This Study	5
	Low	10.8	25	204	11	19	0.94	0.37	This Study	5
US CCC[a]		2.5	9	120	52	74/11[b]	0.25	0.77	Effluent Limits	6
US CMC[a]		65	13	120	470	570/16[b]	2	1.4	Effluent Limits	6

a - Criterion Continuous Concentration/Criteria Maximum Concentration, hardness dependent except for Cr (VI) and Hg. Values shown assume a hardness of 100 mg/L.

b - Chromium (III/VI)

1 - Choubert et al., 2011b; Ruel et al., 2012

2 - Rule et al., 2006

3 - Metcalf and Eddy, 2014

4 – Yost et al., 1981

5 - Linstedt et al., 1971; Brown et al., 1973; Chen et al., 1974; Oliver and Cosgrove, 1974; Aulenbach and Chan, 1988; Huang et al., 2000; Innocenti et al., 2002; Chipasa, 2003; Karvelas et al., 2003; Qdais and Moussa, 2004; Buzier et al., 2006; da Dilva Oliveira et al., 2007; Mohsen et al., 2007; Obarska-Pempkowiak and Gajewska, 2007; Carletti et al, 2008; Johnson et al., 2008; Dialynas and Diamadopoulos, 2009; Renman et al., 2009; Malamis et al., 2012; Arevalo et al., 2013; Garcia et al., 2013; Salihoglu, 2013; Inna et al., 2014; Reddy et al., 2014

6 - U.S. EPA, 2019b

B.2 Metal Chemistry

With the exception of Cr, the metals selected in this study are commonly found in the 2+ oxidation state (Huang et al. 2000). Chromium mainly occurs in the Cr(III) and Cr(VI) oxidation states. While the Cr(VI) form is more labile and toxic to a number of organisms, it is generally associated with industrial effluent and is therefore less prevalent in both raw municipal wastewater and WWTP effluent (Jan and Young 1978; Stasinakis et al. 2003; Stasinakis and Thomaidis 2010). Moreover, Cr(VI) can be reduced to Cr(III) in the presence of suitable electron donors (e.g., organic substrates), whereas experimental results have shown that Cr(III) is not oxidized to Cr(VI) under the aerobic conditions found in AS plants (Stasinakis et al. 2003). A possible explanation is that oxidation of Cr(III) may be so slow that biosorption occurs before any oxidation can occur (Schroeder and Lee 1975).

With respect to treatability, the fraction in which the metal exists (solid or dissolved) is more important than its oxidation state which, under average municipal wastewater conditions, tends not to vary. Throughout the wastewater treatment process, metals generally exist in precipitated (strong complex), organically complexed (weak complex) or soluble forms (Nelson et al. 1981; Huang et al. 2000; Buzier et al. 2006). The type and fraction of precipitates present, which are considered insoluble and often the strongest of the complexes, depend on pH, solubility of the metal species, and the availability of complexing reagents including hydroxides, carbonates, and phosphates (Stoveland and Lester 1980; Huang et al. 2000; Wang et al. 2006). However, the solubility coefficients and products of metals reported in the literature vary markedly (Cheng et al. 1975) and direct application to study systems may not be appropriate as site-specific calculated solubilities can be up to two orders of magnitude different than experimental determinations (Nelson et al. 1981; Parker et al. 1994).

The unprecipitated fraction of metals tend to form weak organic complexes, which can be both settleable or dissolved (distinguished by the fraction passing through a 0.45 µm filter). The process of metal ion sorption to organic material is typically referred to as biosorption, and its effectiveness varies with the type of metal, ambient water quality, and the source of the organic material (Cheng et al. 1975; Huang et al. 2000; Arican et al. 2002; Chang et al. 2007). With the exception of Ni and Cd, which show an intermediate and variable affinity to solids partitioning (Cheng et al. 1975; Wang et al. 2006), the study metals tend to readily adsorb to particulate matter in raw, mixed municipal wastewater (mean dissolved fractions below 30%) (Goldstone et al. 1990a; Goldstone et al. 1990b; Goldstone et al. 1990c; Buzier et al. 2006; Choubert et al. 2011b). Accordingly, processes that remove solids or metal-organic complexes are often effective at removing metals as well.

Extracellular polymers (ECPs) have been found to play a key role in biosorption (Brown and Lester 1979; Hunter et al. 1983; Lawson et al. 1984; Norberg and Persson 1984; Rudd et al. 1984) as they contain negatively charged functional groups such as phosphoryl, carboxyl, sulphydryl, and hydroxyl groups which can serve as adsorption sites (Kelly et al. 1979; Nelson et al. 1981). Additionally, the metal affinity of ECPs has been shown to depend on the microorganism (MO) or MO consortium that produced them. In general, slower growing MOs produce more ECPs (Nelson et al. 1981; Hunter et al. 1983; Ghosh and Bupp 1992). Operationally, solids retention time (SRT) is typically used (along with ambient redox and nutrient conditions) to hold the bacterial growth rate constant, which in turn maintains consistent sorption characteristics of the biosolids. Conversely, increasing the SRT tends to select for slower-growing MOs, which in turn can increase the metal sorption capacity of the biosolids (Stensel and Shell 1974; Chao and Keinath 1979; Nelson et al. 1981). For example, the floc produced by slow-growing phosphate accumulating organisms (PAOs) and denitrifying organisms (DNOs) that are selected for in biological nutrient removal (BNR) processes with high SRTs have been found to have greater affinity towards Cd and Ni than conventional activated sludge floc (Chang et al. 2007). Notably, biosorption is a passive process taking place on the order of minutes to hours and does not depend on the viability of biological floc (Cheng et al. 1975; Neufeld and Hermann 1975; Nelson et al. 1981); the influence of active metabolic processes can therefore be considered unimportant (Huang et al. 2000). Moreover, for this study, hydraulic retention time (HRT) is maintained on the order of hours rather than minutes and will likely have little effect on the removal of metals by the different treatment levels.

Dissolved organic matter (DOM), for which COD can be considered a surrogate, also has a significant effect on metal sorption by biosolids (Sterritt and Lester 1983; Rudd et al. 1984; Tien and Huang 1991). High DOM can prevent both metal precipitation and metal uptake by sludge particulates by lowering ambient pH and competing for sorption sites, respectively (Cheng et al. 1975; Lo et al. 1989). In a detailed study of the factors influencing metals removal in four full-scale conventional activated sludge (AS) wastewater treatment (WWT) systems, Huang et al. (2000) found COD and SS concentrations to be the most important as indicators of effective biosorption of the dissolved fraction to biosolids, and biosolids removal, respectively.

B.3 Fate of Metals During Wastewater Treatment

The fate of metals during wastewater treatment depends on a number of chemical, physical, and operational parameters of the treatment process. Many processes commonly found in municipal wastewater treatment plants result in the effective removal of certain metals from the liquid fraction, thus limiting emissions to receiving waters. Depending on the type of unit processes present, the metals removed from the liquid fraction are partitioned to either the solids (sludge) fraction or in the case of this study where reverse osmosis is used, the brine solution. Although volatilization was proposed as a loss pathway for Hg in the early wastewater treatment literature (Yamada et al. 1969), results from full-scale systems indicate that this is likely an artifact of startup conditions. In continuously operating full scale WWTPs, adsorption to biomass is the dominant partitioning mechanism and volatilization is negligible (Goldstone et al. 1990c; Pomiès et al. 2013).

In general, metal concentrations tend to decrease during primary treatment. Metals present as precipitated species or adsorbed to settleable solids (i.e. the non-dissolved fraction) are the main fractions that are removed. As such, many authors have found a correlation between primary treatment solids removal and metal removal, with reported metal removals ranging from 40-70% when solids removal is high (Rossin et al. 1982; Lester 1983; Kempton et al. 1987). However, where primary solids removal is lower or concentrated supernatant is recirculated to the headworks (in effect increasing internal, dissolved metal loadings), reported total metal removals can be on the order of 1-10% (Oliver and Cosgrove 1974) and can even be negative depending on the strength of recirculated supernatant (Huang et al. 2000; Inna et al. 2014). Due to the variability of this documented performance, the similarity of primary treatment unit processes and the incorporation of internal circulation within most study configurations, it was conservatively assumed that no metals removal was directly attributed to primary treatment. Primary treatment performance was instead aggregated with secondary biological processes, both because proper functioning of secondary processes implicitly assumes proper primary treatment or pretreatment, and because most performance data obtained for secondary processes implicitly accounted for the presence of standard primary treatment.

In secondary biological unit processes, SRT, COD, and TSS tend to be important indicators of metals partitioning (Lo et al. 1989; Huang et al. 2000). Systems that provide better COD removal tend to allow for greater sorption potential between metals and biological flocs, which can then be removed through efficient suspended solids removal. The sorption process varies by metal type as well, depending on the affinity of metal species to sludge and the stability of the sludge metal complexes. Results from batch equilibrium adsorption experiments using solids from conventional activated sludge (CAS) systems indicate that the stability constants of the sludge-metal complexes follow the order of Hg(II)≈Pb(II)≈Cu(II)≈Cr(II)>Zn(II)> Cd(II)>Ni(II) (Wang 1997). This is supported by results from full scale case studies as well, with removals of Hg, Pb, Cu, Cr, Cd, and Zn often in the range of 40-60% and the removal of Ni often less than 40% for sorption-based processes like CAS (Lester 1983; Cantinho et al. 2016). For more advanced biological treatment processes like Bardenpho or Modified University Cape Town (MUCT) systems, much less work has been done to characterize the biosorption and metals partitioning dynamics, however the limited case studies available suggest that due to the greater SRT, COD removal and diversity of microbial consortiums (and by extension variety of metal-binding ECPs), overall metal removal performances are marginally better than CAS, ranging from approximately 60-80% for all metals except Cd and Ni, which are around 30-40% (Chipasa 2003; Obarska-Pempkowiak and Gajewska 2007; Salihoglu 2013; Emara et al. 2014). Aside from potential detection limit influences on full removal potentials, no mechanistic explanations of the lower Cd and Ni removal efficiencies were given (Chipasa 2003; Salihoglu 2013)

Following biological treatment, advanced filtration in the form of sand filters, MBR, and RO can be effective in physically removing the remaining soluble or colloidal fractions, as well as what remains of the insoluble fraction. Of the three, sand filters tend to be the least effective, owing to the larger pore spaces through which water can travel. Still, as a tertiary treatment process, removals of remaining organics can be on the order of 10-50%, and metals 0-35% (Linstedt et al. 1971; Aulenbach and Chan 1988; Renman et al. 2009). Next, MBRs have proven very effective as a tertiary polishing step, with removals of most metals on the order of 50% to greater than 95% (Innocenti et al. 2002; Carletti et al. 2008; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013). Last, with the smallest effective pore size, RO is the most effective unit process for metals removal with the case study literature indicating consistent removal efficiencies of 90% or greater (Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013; Garcia et al. 2013).

For this study there are also several unit processes that through either limited, contradictory or inconclusive evidence, were not assigned any removal credit. Chemical phosphorus precipitation is a unit process that can be effective at removing metals, however it is dependent upon the chemicals used for precipitation and the conditions of the plant. In a study of three WWTPs using only alum or sodium aluminate for enhanced phosphorus removal, Aulenbach et al. (1984) found statistically insignificant effects for Pb and Cr removal and only a minor benefit to Cu removal (less than a 10% difference), noting that Cd, Hg, and Zn were removed to undetectable levels prior to alum dosing. Accordingly, chemical phosphorus precipitation using alum salts alone (U9, Table B-2) was not considered to provide an additional metals removal benefit.

The metals removal performance of tertiary biological nutrient removal processes, including nitrification reactors, denitrification reactors and tertiary clarification, has also not been extensively researched. Conceptually, the additional contact time between remaining soluble metal species and a new, distinct biological consortium (compared to upstream secondary unit processes) could reasonably be thought to provide for additional metals removal. However, in a study using copper as an indicator of the comparative metal removing performance of tertiary vs. secondary WWTPs, Inna et al. (2014) found that while tertiary processes like biological aerated flooded filters and nitrifying trickling filters provided some degree of additional copper removal, the tertiary return flows tended to have adverse and somewhat unpredictable effects on the performance of upstream unit processes. While they found total removal efficiencies of 57% for the three secondary plants and 78% for the two tertiary plants with nitrifying filters, the removal attributed directly to the nitrifying trickling filters was just 11% (-15% to 37%). Given the lack of information obtained for other metals, the marginal performance documented by Inna et al. (2014) and the potential for adverse effects from concentrated return flows, tertiary biological nutrient removal processes (U11-U14) were assumed to have no net effect on metals.

Table B-2. Unit Process Composition of Study Treatment Configurations

Unit Process		Wastewater Treatment Configuration								
		Level 1, AS	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
U1	Preliminary Treatment – Screening and grit removal	✓	✓	✓	✓	✓	✓	✓	✓	✓
U2	Primary Clarification	✓	✓	✓	✓	✓	✓	✓	✓	✓
U3	Fermenter				✓	✓	✓		✓	✓
U4	Plug Flow Activated Sludge	✓		✓						
U5	Biological Nutrient Removal – 3-Stage		✓							
U6	Biological Nutrient Removal – 5-Stage				✓		✓		✓	✓
U7	Biological Nutrient Removal – 4-Stage (Bardenpho)							✓		
U8	Biological Nutrient Removal – 4-Stage (MUCT)					✓				
U9	Chemical Phosphorus Removal			✓	✓	✓	✓	✓	✓	✓
U10	Secondary Clarifier	✓	✓	✓	✓	✓	✓		✓	
U11	Nitrification – Suspended Growth			✓						
U12	Tertiary Clarification			✓ [c]						
U13	Denitrification – Suspended Growth			✓						
U14	Denitrification – Attached Growth						✓		✓	
U15	Membrane Filtration [a, b]							✓		✓
U16	Final Clarification									
U17	Filtration – Sand Filter				✓	✓	✓		✓	
U18	Reverse Osmosis [a, d]								✓	✓
U19	Ultrafiltration [a]								✓	
U20	Chlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
U21	Dechlorination	✓	✓	✓	✓	✓	✓	✓	✓	✓
U22	WWTP Effluent Discharge	✓	✓	✓	✓	✓	✓	✓	✓	✓
U23	Sludge – Gravity Thickening	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table B-2. Unit Process Composition of Study Treatment Configurations

Unit Process		Wastewater Treatment Configuration								
		Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
U24	Sludge – Anaerobic Digestion	✓	✓	✓	✓	✓	✓	✓	✓	✓
U25	Sludge – Centrifugation	✓	✓	✓	✓	✓	✓	✓	✓	✓
U26	Sludge – Haul and Landfill	✓	✓	✓	✓	✓	✓	✓	✓	✓
U27	Brine – Underground Inject								✓	✓

✓ Indicates unit process is relevant for select wastewater treatment configuration.

a – Periodic chemical cleaning is included for all membranes.

b – Membrane bioreactor wastewater treatment configurations use a membrane filter for the solid-liquid separation process instead of a traditional secondary clarifier.

c – This configuration includes two instances of tertiary clarification.

d – Includes chlorination and dechlorination pretreatment.

B.4 Metals Removal Performance Estimation Methods

Metal removal efficiencies for study system configurations were estimated based on a detailed literature review of performance results from similar systems. Sources reviewed include peer-reviewed literature, government reports and book chapters, covering a range of bench-scale experiments to performance characterization of full-scale treatment systems. Given the complexity of conditions and partitioning processes that can occur within WWTPs, empirical results were prioritized where the demonstrated metals removal performance of comparable treatment configurations or unit processes could be used to estimate performance of the study configurations. Where possible, mechanistic discussion was provided, though it is qualitative in nature as the factors affecting metal partitioning and removal are highly site specific (Cheng et al. 1975; Nelson et al. 1981; Huang et al. 2000) and mechanistic modelling is beyond the capability of the existing CAPDETWorks models used to develop the LCA and cost analysis.

For system levels where no representative equivalent was identified but the important components were characterized, a composite removal efficiency was calculated based upon case study performance data of its major unit processes. For example, Level 3-1 includes a 5-stage Bardenpho process with subsequent sand filtration. However, results of the literature review only identified 5-stage Bardenpho WWTPs without sand filtration. Therefore, Equation B-1 below represents a two-step linear process and was used to combine these results with removal efficiencies identified for sand filtration as a standalone process.

$$R_{total} = f_1 R_1 + f_2 (1 - R_1) R_2$$

Equation B-1

where

R_{total} = composite metal removal efficiency

f_1 = fraction of flow diverted to process 1

R_1 = removal efficiency of process 1

f_2 = fraction of flow diverted to process 2

R_2 = removal efficiency of process 2

In this example, R_1 would be representative of the combined effects of U1, U2, U6, and U10 (pretreatment + 5-stage Bardenpho + secondary clarification), while R_2 would be representative of U17 (sand filter). The functional form has also been adapted to account for more than two stepwise processes (e.g. Level 5-2) or parallel streams (e.g. Level 5-1), as demonstrated below. Note that the unit code descriptions are provided in Table B-2.

B.5 Metals Removal Performance Estimation Results

Following the approach outlined in Section B.4, Table B-3 shows how removal efficiencies for each study configuration were calculated based on major unit process combinations and supporting literature. Final composite removal efficiencies for each metal, by treatment configuration, are provided in Table B-4 and illustrated in Figure B-1. A more detailed discussion of each treatment configuration follows.

Table B-3. Summary of Composite Removal Calculations used in Equation 1

Level	Level Unit Processes[a]	Case Study Unit Process(es)[b]	R[c]	f[d]	Description
Level 1, AS	**U1**+**U2**+**U4**+**U10**	**U1**+**U2**+**U4**+**U10**	N/A	100%	Conventional Activated Sludge[e]
Level 2-1, A2O	**U1**+**U2**+**U5**+**U10**	**U5**	q	100%	Anaerobic/Anoxic/ Oxic[f]
Level 2-2, AS3	**U1**+**U2**+**U4**+*U9*+**U10**+*U11*+*U12*+*U13*	**U1**+**U2**+**U4**+**U10**	q	100%	3-Sludge System[g]
Level 3-1, B5	**U1**+**U2**+*U3*+**U6**+*U9*+**U10**+**U17**	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U17	R2	100%	Sand filter[i]
Level 3-2, MUCT	**U1**+**U2**+*U3*+**U8**+*U9*+**U10**+**U17**	**U1**+**U2**+**U8**+**U10**	R1	100%	Modified University Cape Town process[j]
		U17	R2	100%	Sand filter[i]
Level 4-1, B5/Denit	**U1**+**U2**+*U3*+**U6**+*U9*+**U10**+*U14*+**U17**	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U17	R2	100%	Sand filter[i]
Level 4-2, MBR	**U1**+**U2**+**U7**+*U9*+**U15**	**U7**	q	100%	4-stage Bardenpho[k]
		U15	R2	100%	Membrane bioreactor[l]
Level 5-1, B5/RO	**U1**+**U2**+*U3*+**U6**+*U9*+**U10**+*U14*+**U17**+**U18** +*U19*	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U17	R2a	10%	Sand filter[i]
		U18	R2b	90%	Reverse osmosis[m]
Level 5-2, MBR/RO	**U1**+**U2**+*U3*+**U6**+*U9*+**U15**+**U18**	**U1**+**U2**+**U6**+**U10**	R1	100%	5-stage Bardenpho[h]
		U15	R2	100%	Membrane bioreactor[l]
		U18	R3	85%	Reverse osmosis[m]

a - Bold unit processes affect metals removal, italicized unit processes were determined to have no significant effect.

b - Unit process or unit process configurations represented in the case study literature.

c - Removal efficiency determined from the literature and used in stepwise removal calculations (see Equation B-1. ‘NA’ indicates that Equation B-1 was not used, as documented removal efficiencies could be used directly to represent the entire treatment system. 'q' indicates that only qualitative conclusions can be drawn from the applicable literature.

d - Proportion of flow directed to unit process(es), see Equation B-1.

e - Brown et al., 1973; Oliver and Cosgrove, 1974; da Silva Oliveira et al., 2007; Carletti et al., 2008; Karvelas et al., 2003

f - Chang et al., 2007

g - Metal-affecting unit processes same as Level 1, use Level 1 for conservative estimation

h - Salihoglu et al., 2013

i - Linstedt et al., 1971; Aulenbach and Chan, 1988; Renman et al., 2009; Reddy et al., 2014

j - Chipasa, 2003; Obarska-Pempkowiak and Gajewska, 2007. Data describe the metals removal performance of membrane bioreactors. Data were assumed to be representative of membrane filtration as well, as the physical filtration is the dominant partitioning mechanism of metals sorbed to dissolved organic complexes.

k - Emara et al., 2014

l - Innocenti et al., 2002; Carletti et al., 2008; Dialynas and Diamadopoulos, 2009; Malamis et al., 2012; Arevalo et al., 2013

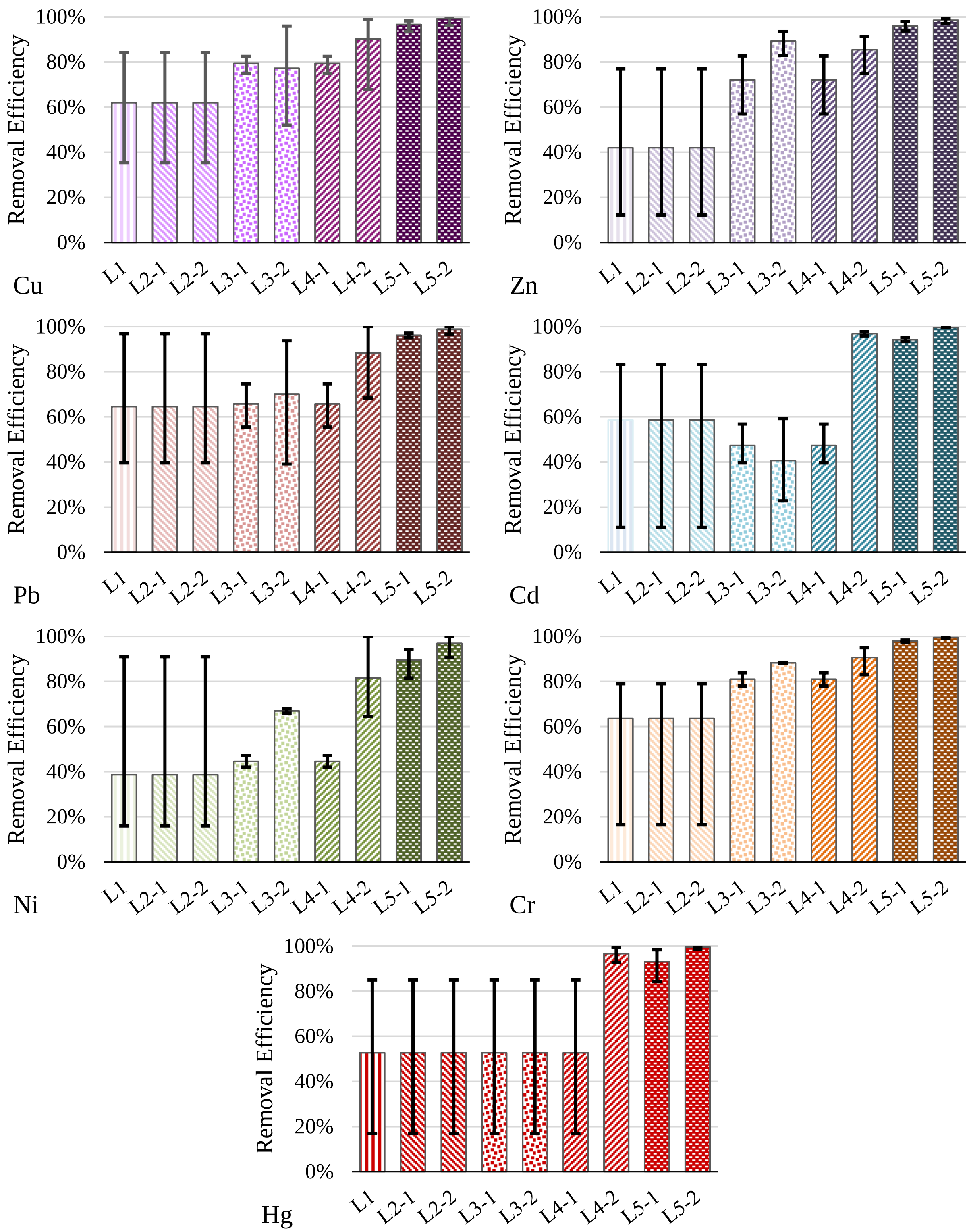
m - Dialynas and Diamadopoulos, 2009; Malamis et al., 2012; Garcia et al., 2013; Arévalo et al. 2013

Table B-4. Summary of Estimated Metal Removal Efficiencies[a]

Metal		Level 1 AS	Level 2-1 A2O	Level 2-2 AS3	Level 3-1 B5	Level 3-2 MUCT	Level 4-1 B5/Denit	Level 4-2 MBR	Level 5-1 B5/RO	Level 5-2 MBR/RO
Cu	Min	35%	35%	35%	75%	52%	75%	68%	93%	96%
	Mean	62%	62%	62%	80%	77%	80%	90%	97%	99%
	Max	84%	84%	84%	83%	96%	83%	99%	98%	100%
Pb	Min	40%	40%	40%	55%	39%	55%	68%	95%	97%
	Mean	65%	65%	65%	66%	70%	66%	88%	96%	99%
	Max	97%	97%	97%	75%	94%	75%	100%	97%	100%
Ni	Min	16%	16%	16%	42%	66%	42%	64%	82%	91%
	Mean	39%	39%	39%	45%	67%	45%	82%	90%	97%
	Max	91%	91%	91%	47%	68%	47%	100%	94%	100%
Zn	Min	12%	12%	12%	57%	83%	57%	75%	94%	97%
	Mean	42%	42%	42%	72%	89%	72%	85%	96%	99%
	Max	77%	77%	77%	83%	94%	83%	91%	98%	99%
Cd	Min	11%	11%	11%	40%	23%	40%	96%	93%	99%
	Mean	59%	59%	59%	47%	41%	47%	97%	94%	100%
	Max	83%	83%	83%	57%	59%	57%	98%	95%	100%
Cr	Min	16%	16%	16%	78%	88%	78%	83%	97%	99%
	Mean	64%	64%	64%	81%	88%	81%	91%	98%	100%
	Max	79%	79%	79%	84%	89%	84%	95%	98%	100%
Hg[1]	Min	17%	17%	17%	17%	17%	17%	93%	84%	98%
	Mean	53%	53%	53%	53%	53%	53%	97%	93%	100%
	Max	85%	85%	85%	85%	85%	85%	99%	98%	100%

a – "Removal Efficiency" used loosely; data more explicitly represents partitioning to sludge. Min and max represent minimum and maximum removal efficiencies reported in the literature. Where removal efficiencies are composites of multiple processes, minimum represents the composite of both contributing minimums, likewise for maximum.

b – No data for Hg removal found for 4-stage Bardenpho, 5-stage Bardenpho or MUCT. Therefore, conservatively assumed same removal for these biological treatment processes as documented for CAS (Level1). Data for Levels 4-2, 5-1 and 5-2 represent the effect of tertiary polishing step alone, i.e. MBR and RO.



a – Distinct bar patterns are used to distinguish treatment systems in each of the five nutrient removal levels.
b - Error bars represent the minimum and maximum removal efficiencies reported in the literature.

Figure B-1. Summary of Estimated Metal Treatment Performance[a, b]

B.5.1 Level 1: Conventional Plug Flow Activated Sludge (AS)

Level 1 is the most commonly represented treatment configuration within the case study literature. Overall, seven conventional activated sludge (CAS) systems were reviewed providing a range of performance results. Metals with the highest mean removals were Pb, Cr and Cu, each with a mean removal >60%. Intermediate mean removals of 40-60% were determined for Cd, Hg and Zn, while Ni returned the lowest mean removal of 39%. This pattern is to be expected, with previous reviews showing good (>50%) removals of Cd, Cr, Cu and Pb, and lower removals (<30%) for Ni (Stephenson and Lester 1987). For all metals, variability in results was high, with ranges from less than half to more than double the mean for most metals.

B.5.2 Level 2-1: Anaerobic/Anoxic/Oxic (A2O)

Level 2-1 is differentiated from Level 1 by its three-stage biological nutrient removal system which consists of sequential anaerobic, anoxic, and oxic basins. No performance data for A2O systems were found in the literature review, however a study conducted to determine the metal affinity of A2O sludge was reviewed (Chang et al. 2007). While data were not provided that could provide an input/output removal performance, results indicated that A2O sludge exhibited higher biosorption affinities than CAS sludge for Cd and Ni, and similar affinity for Zn (only three metals were evaluated). Based on these relative conclusions and in combination with the slightly longer SRT (Table 1-5) and better removal performance of COD (Table 1-4), it was conservatively assumed that the metal removal performance of Level 2-1 was equivalent to Level 1.

B.5.3 Level 2-2: Activated Sludge, 3-Sludge System (A3S)

Level 2-2 is similar to Level 1, with the addition of post-secondary suspended growth nitrification and denitrification reactors, as well as chemical phosphorus precipitation. No performance data for A3S systems were found in the literature review. Despite the greater SRT (Table 1-5) and better removal performance of COD (Table 1-4), in the absence of literature specifically documenting effects of this process on metal concentrations, it was conservatively assumed that the metal performance of Level 2-2 was equivalent to Level 1.

B.5.4 Level 3-1: 5-Stage Bardenpho System (B5)

Level 3-1 is characterized by a combination of case studies that are representative of its major metal-affecting unit processes, including the 5-stage Bardenpho process and sand filtration. Salihoglu (2013) reviewed the metals removal performance of two WWTPs that utilized the 5-stage Bardenpho process in the Turkish city of Bursa. The treatment plants, which serve populations of 170,000 and 85,000 in mixed urban areas, consist of pretreatment (screening and grit removal) followed by an equalization tank, 5-stage Bardenpho process and a clarifier. In terms of applicability to Level 3-1, the plants describe the beginning of the treatment train including pretreatment (U1), 5-stage Bardenpho process (U6) and secondary clarification (U10). Although primary sedimentation (U2) is not included, it is assumed that the level of treatment conferred by the particular combination of unit processes (U1+U6+U10) allows for sufficient settleable solids removal such that the absence of U2 can be considered negligible.

Data for sand filtration came from a range of studies, including pilot- or bench-scale tests of sand filtration as a tertiary treatment unit process (Linstedt et al. 1971; Aulenbach and Chan

1988), as a polishing step for septic effluent (Renman et al. 2009) and for the treatment of stormwater (Reddy et al. 2014). Although stormwater is compositionally different than wastewater, it is arguably closer to secondary effluent than raw wastewater and the inclusion of these results helped fill data gaps left by the wastewater-specific studies.

Reported removal efficiencies for the 5-stage Bardenpho system for all metals except Cd and Pb (data were not given for Hg) tended to be similar to those reported for CAS, while the removal efficiency for Cd was lower than CAS and Pb was higher (Salihoglu 2013). No mechanistic explanations were provided for these deviations by Salihoglu (2013), though possible reasons may have to do with the relatively high affinity of Pb and relatively low affinity of Cd to organic matter, respectively (e.g., Wang, 1997) Mean removal efficiencies for sand filtration case studies ranged from 2% to 29%, bounded by Cr (2%) and Ni (3%) at the low end and Pb (22%) and Zn (29%) at the high end. Composite removal efficiencies for L3-1 were greater than Level 1 for all metals except Cd (and Hg, as no data were reported for U6 or U17 unit processes), owing to low removals of Cd in both 5-stage Bardenpho (41%) and sand filtration (11%).

B.5.5 Level 3-2: Modified University of Cape Town (MUCT)

Level 3-2 is characterized by a combination of case studies that are representative of its major metal-affecting unit processes, including the Modified University of Cape Town process and sand filtration. Metals performance data for MUCT systems come from a pair of case studies conducted in Poland (Chipasa 2003; Obarska-Pempkowiak and Gajewska 2007). The first system, reviewed by Chipasa (2003), includes screening and grit removal (U1), primary sedimentation (U2), MUCT reactors (U8), and secondary clarification (U10). The second system, reviewed in Obarska-Pempkowiak and Gajewska (2007), refers to a 23 MGD plant receiving mixed municipal wastewater with roughly 10% coming from industrial sources. Primary treatment consists of screening, an aerated sand trap and primary sedimentation, which was assumed equivalent to screening and grit removal (U1) and primary sedimentation (U2). Biological treatment consists of six sequential reactors that make up the MUCT process (U8) followed by secondary sedimentation (U10).

Data for sand filtration come from a range of studies, including pilot- or bench-scale tests of sand filtration as a tertiary treatment unit process (Linstedt et al. 1971; Aulenbach and Chan 1988), as a polishing step for septic effluent (Renman et al. 2009) and for the treatment of stormwater (Reddy et al. 2014). Although stormwater is compositionally different than wastewater, it is arguably closer to secondary effluent than raw wastewater and the inclusion of these results helped fill data gaps left by the wastewater-specific studies.

Mean removal efficiencies for the MUCT systems ranged from 66% to 88% with the exception of Cd, which had a mean removal of 34%. Mean removal efficiencies for sand filtration case studies ranged from 2% to 29%, bounded by Cr (2%) and Ni (3%) at the low end and Pb (22%) and Zn (29%) at the high end. Composite removal efficiencies for Level 3-2 were slightly better than Level 3-1 for Pb, Zn, Ni and Cr and slightly worse for Cu and Cd. No data were reported for Hg.

B.5.6 Level 4-1: 5-Stage Bardenpho System with Denitrification Filter (B5/Denit)

The unit process configuration of Level 4-1 is identical to Level 3-1, with the exception of an attached growth denitrification reactor. Although no data were identified to directly characterize the metals removal performance of this unit process, it is likely that it provides some degree of metals removal as it allows for additional contact time between secondary effluent and a new, biologically distinct consortium. However, in the absence of literature specifically documenting effects of an attached growth denitrification reactor on metal concentrations, it was conservatively assumed that the performance of Level 4-1 was equivalent to that of Level 3-1.

B.5.7 Level 4-2: 4-Stage Bardenpho Membrane Bioreactor System (MBR)

Level 4-2 is characterized by a 4-stage Bardenpho system followed by a membrane bioreactor. The 4-stage Bardenpho system of Level 4-2 differs from the 5-stage Bardenpho system of Level 4-1, lacking the first anaerobic stage and having a total SRT of 19 days as opposed to 15 days for the 5-stage system. No data were found characterizing the metals performance of a 4-stage Bardenpho system, rather performance was estimated based on the comparative design and operation of the study configurations as well as results from a bench-scale study performed to directly compare the performance of 4-stage and 5-stage Bardenpho systems using Ni and Fe as indicators of metal removal (Emara et al. 2014). The study showed that after incorporation of the upstream anaerobic tank, thus modifying the 4-stage to a 5-stage system, Ni removal increased from 68% to 86% and Fe removal increased from 82% to 92%. This is to be expected, as the incorporation of the anaerobic stage is done to improve phosphorus removal through the promotion of phosphorus accumulating organisms, which produce floc that provides for an additional degree of biosorption. As such, it was conservatively assumed that the metal removal efficiency of the 4-stage system was 50% of the 5-stage system described by Salihoglu (2013). The greater SRT of the Level 4-2, 4-stage system compared to the Level 4-1, 5-stage system, adds a further degree of conservatism as it would suggest better performance than what is being assumed.

The metals removal performance of MBRs has been well characterized, with five applicable studies identified representing six different systems (Innocenti et al. 2002; Carletti et al. 2008; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013). The systems all treated mixed municipal primary effluent, ranged in size from a 100 gpd pilot plant to a 5.3 MGD full-scale plant, and had membrane pore sizes of either 0.020 µm or 0.040 µm. Average removal efficiencies across all studies were high, ranging from 76% (Ni) to 96% (Cd and Hg). That the removals are high relative to other unit processes discussed thus far is reasonable when considering the pore size of MBRs (0.020 to 0.040 µm) relative to the filter pore size generally used to delineate between dissolved and non-dissolved fractions (0.45 µm). This comparison suggests an ability to remove smaller dissolved organic complexes in the 0.04-0.45 µm range that may be missed by processes that rely on settling or clarification.

Although a conservative assumption was made regarding the treatment performance of the 4-stage Bardenpho system, composite removal efficiencies for the Level 4-2 configuration are greater than those of Level 4-1 for all metals reviewed, owing to the high removal efficiency of the MBR unit process. Moreover, although Hg was not included in any Bardenpho study, the two MBR studies that did evaluate Hg found an average removal of 96%, which could reasonably be interpreted as a total Hg removal efficiency for Level 4-2.

B.5.8 Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis (B5/RO)

Level 5-1 is characterized by a 5-stage Bardenpho system followed by two parallel processes. The first, treating 90% of the 5-stage Bardenpho effluent, consists of an ultrafilter followed by a reverse osmosis (RO) system. The remaining 10% is treated by a sand filter, similar to Level 3-1.

For the 5-stage Bardenpho system, Salihoglu (2013) reviewed the metals removal performance of two WWTPs that utilize this process in the Turkish city of Bursa. The treatment plants, which serve populations of 170,000 and 85,000 in mixed urban areas, consist of pretreatment (screening and grit removal) followed by a selector tank, 5-stage Bardenpho process and a clarifier. In terms of applicability to Level 5-1, the plants describe the beginning of the treatment train including pretreatment (U1), 5-stage Bardenpho process (U6) and secondary clarification (U10). Although primary sedimentation (U2) is not included, it is assumed that the level of treatment conferred by the particular combination of unit processes (U1+U6+U10) allows for sufficient settleable solids removal that the absence of U2 can be considered negligible.

For the first parallel process, consisting of an ultrafilter followed by an RO system, four studies were found evaluating the performance of five distinct RO systems (Qdais and Moussa 2004; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Garcia et al. 2013). The systems reviewed were mostly pilot scale treating mixed municipal primary effluent, with the exception of a 0.3 MGD full scale system (Garcia et al. 2013) and a pilot scale study evaluating synthetic industrial wastewater (Qdais and Moussa 2004). Ultrafiltration was not explicitly included as, in the case of most case study systems and study configurations, this step serves as a pretreatment step allowing for proper RO functioning and its performance was generally not characterized. Mean removal of each metal across all systems for which data were available were greater than 90%. The lowest removal efficiencies reported for any single system, and the only rates less than 90%, were those for the pilot plant treating pretreated, mixed municipal wastewater evaluated by Malamis et al. (2012) at 82% for Cu and 76% for Ni.

Data for sand filtration come from a range of studies, including pilot- or bench-scale tests of sand filtration as a tertiary treatment unit process (Linstedt et al. 1971; Aulenbach and Chan 1988), as a polishing step for septic effluent (Renman et al. 2009) and for the treatment of stormwater (Reddy et al. 2014). Although stormwater is compositionally different than wastewater, it is arguably closer to secondary effluent than raw wastewater and the inclusion of these results helped fill data gaps left by the wastewater-specific studies.

Composite removal efficiencies for Level 5-1 are 90-98% for all metals reviewed. Also, although sufficient data were not obtained for the full characterization of Hg removal in 5-stage Bardenpho or RO systems, Ruel et al. (2011) measured effluent concentrations in two full-scale municipal WWTPs that incorporated RO for advanced nutrient removal and found Hg to be below the level of detection in both cases.

B.5.9 Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis (MBR/RO)

Level 5-2, the most advanced study configuration, consists of a 5-stage Bardenpho system followed by an MBR, then treatment of 85% of MBR effluent by an RO system with the remaining 15% discharged with no further treatment.

For the 5-stage Bardenpho system, Salihoglu (2013) reviewed the metals removal performance of two WWTPs that utilized this process in the Turkish city of Bursa. The treatment plants, which serve populations of 170,000 and 85,000 in mixed urban areas, consist of pretreatment (screening and grit removal) followed by a selector tank, 5-stage Bardenpho process and a clarifier. In terms of applicability to Level 5-2, the plants describe the beginning of the treatment train including pretreatment (U1), 5-stage Bardenpho process (U6) and secondary clarification (U10). Although primary sedimentation (U2) is not included, it is assumed that the level of treatment conferred by the particular combination of unit processes (U1+U6+U10) allows for sufficient settleable solids removal that the absence of U2 can be considered negligible.

The metals removal performance of MBRs has been well characterized, with 5 applicable studies identified representing 6 different systems (Innocenti et al. 2002; Carletti et al. 2008; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Arévalo et al. 2013). The systems all treated mixed municipal primary effluent, ranged from a 100 gpd pilot plant to a 5.3 MGD full-scale plant and had membrane pore sizes of either 0.020 µm or 0.040 µm. Average removal efficiencies across all studies were high, ranging from 76% (Ni) to 96% (Cd and Hg). That the removals are high relative to other unit processes discussed thus far is reasonable when considering the pore size of MBRs (0.020 to 0.040 µm) relative to the filter pore size generally used to delineate between dissolved and non-dissolved fractions (0.45 µm). This comparison suggests an ability to remove much smaller, dissolved organic complexes missed by processes that rely on settling or clarification.

For the characterization of RO systems, four studies were found evaluating the performance of 5 distinct RO systems (Qdais and Moussa 2004; Dialynas and Diamadopoulos 2009; Malamis et al. 2012; Garcia et al. 2013). The systems reviewed were mostly pilot scale treating pretreated mixed municipal wastewater, with the exception of a 0.3 MGD full scale system (Garcia et al. 2013) and a pilot scale evaluating synthetic industrial wastewater (Qdais and Moussa 2004). Ultrafiltration was not explicitly included as, in the case of most case study systems and study configurations, this step serves as a pretreatment step allowing for proper RO functioning and its performance was generally not characterized. Mean removal of each metal across all systems for which data were available were greater than 90%. The lowest removal efficiencies reported for any single system, and the only rates less than 90%, were those for the pilot plant treating pretreated, mixed municipal wastewater evaluated by Malamis et al. (2012) at 82% for Cu and 76% for Ni.

Composite removal efficiencies for Level 5-2 are 97% to >99% for all metals reviewed. Also, although sufficient data were not obtained for the full characterization of Hg removal in 5-stage Bardenpho or RO systems, Ruel et al. (2011) measured effluent concentrations in two full-scale municipal WWTPs that incorporated RO for advanced nutrient removal and found Hg to be below the level of detection in both cases.

B.6 Heavy Metals Toxicity Characterization Factors

Table B-5 presents the characterization factors used to estimate toxicity impacts associated with heavy metals in treatment plant effluent and sludge. Not all heavy metals included in this study have associated characterization factors listed in the most recent versions of USEtox™, versions 2.02 and 2.11. Characterization factors that were not otherwise available were estimated using the median value of all other heavy metals for which data was available. Sources for individual characterization factors are listed in Table C-8.

Table B-5. Heavy Metals Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	USETox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m3.day/kg emitted)		Human Health cancer, freshwater (CTUh, cases/kg emitted)		Human Health noncancer, freshwater (CTUh, cases/kg emitted)	
		Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil
Lead	Pb(II)	6.9E+2	4.1E+2	1.4E-7	8.5E-8	5.0E-5	3.0E-5
Copper	Cu(II)	9.9E+6	5.2E+6	8.8E-6[a]	4.5E-6[a]	1.4E-7	7.2E-8
Zinc	Zn(II)	1.3E+5	7.3E+4	-	-	2.6E-4	1.4E-4
Nickel	Ni(II)	3.0E+5	1.5E+5	1.2E-4	6.1E-5	6.7E-6	3.4E-6
Chromium	Cr(III)	8.1E+3	4.1E+3	-	-	2.1E-11	1.0E-11
Cadmium	Cd(II)	2.3E+6	1.2E+6	1.7E-5	8.9E-6	4.7E-3	2.4E-3
Mercury	Hg(II)	2.2E+4	1.6E+4	1.5E-4	1.1E-4	0.02	0.01

a - Estimated using the median of heavy metals with available characterization factors.

APPENDIX C
DETAILED CHARACTERIZATION OF TOXIC ORGANICS BEHAVIOR IN STUDY TREATMENT CONFIGURATIONS

Appendix C: Detailed Characterization of Toxic Organics Behavior in Study Treatment Configurations

C.1 Toxic Organics: Introduction

This section presents background information and methods used to estimate the environmental impact associated with select trace organic chemical releases in the Level 1 through 5 treatment systems.

Toxic organics are a diverse and growing category of chemical substances that includes other commonly referred to pollutant groups such as contaminants of emerging concern (CECs), pharmaceuticals and personal care products (PPCPs), and endocrine disrupting chemicals (EDCs). The pollutant category includes medications, fragrances, insect repellents and other household items that can be harmful to environmental and human health at even trace levels (U.S. EPA 2015c; Montes-Grajales et al. 2017).

Many toxic organics have a documented presence in surface waters, groundwater, wastewater and WWTP effluent, both in the U.S. and globally (Ellis 2008; Ebele et al. 2017; Montes-Grajales et al. 2017). No comprehensive list exists, though based on the diverse literature the number of contaminants is at least in the hundreds (if not thousands) and is continually being expanded upon as analytical techniques for measuring both presence and toxicity are continually refined. In order to provide a targeted analysis of their behavior in WWTPs, a restricted group of 43 pollutants (Table C-1) has been selected for specific treatment in this analysis. The selected pollutant group uses the chemical list from Rahman et al. (2018) as a starting point. Rahman et al. (2018) performed a comparative LCA that examines the effect of toxic organics removal on life cycle human health and ecotoxicity impacts for treatment systems that correspond to three levels of nutrient removal, focusing on the use of advanced tertiary processes for toxic organics removal. Their selection of toxic organics was based on frequency of presence in WWTPs and availability of information regarding concentration, chemical degradation, transformation and removal. Several additional common chemicals, including triclocarban, tonalide, celestolide, phantolide and musk ketone, were added based on the assessment of Montes-Grajales et al. (2017), which looked at the presence of PPCPs in global water resources and found these compounds to be the most widely reported. Per- and Polyfluoroalkyl Substances (PFAS) are not included in this toxic organics' assessment.

The concentration of trace pollutants can vary considerably on a daily and seasonal basis and between WWTPs (Martin Ruel et al. 2012). Urban WWTPs have also been shown to receive higher influent concentrations of some toxic organics that are less common in rural water systems. As such, the median influent concentrations from Table C-1 were used as input to subsequent calculations as the averages had a tendency to be strongly influenced by a small number of very high influent concentration records. Figure C-1 and Figure C-2 present boxplots of the influent concentration of toxic organics. The figures divide the pollutants into two subgroups to allow better visualization across pollutants with considerably different influent concentrations. Acetaminophen is excluded from these figures due to its notably greater median influent concentration, 97 µg/L, as compared to the other included pollutants. The figures show the tendency for some pollutant distributions to skew towards large outlier values, causing a disparity between the median and average values.

Table C-1. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (μg/L)				Sample Size
		Average	Median	Minimum	Maximum	
acetaminophen[a]	pain reliever, anti-inflammatory	97	19	0.02	400	12
androstendione[a]	steroid hormone	0.29	0.10	0.02	1.3	7
atenolol	beta blocker	4.3	1.1	0.03	26	10
atorvastatin	lipid regulator	0.49	0.22	0.07	1.6	6
atrazine[b]	pesticide	0.02	0.02	1.0E-3	0.06	5
benzophenone	PCP, sunscreen	0.24	0.27	7.0E-3	0.42	4
bisphenol A	EDC, plasticizer	4.6	0.84	0.01	44	16
butylated hydroxyanisole[c]	beta blocker	1.3	0.16	0.13	3.5	3
butylated hydroxytoluene	beta blocker, cosmetic	0.93	0.41	0.05	3.5	5
butylbenzyl phthalate[d]	plasticizer	0.11	0.11	0.08	0.14	2
carbamazepine[a]	Anti-convulsant	0.92	0.69	0.04	3.8	28
N,N-diethyl-meta-toluamide (DEET)	insect repellent	1.4	0.40	0.02	6.9	6
diclofenac	Analgesics, anti-inflammatory	2.1	0.96	1.0E-3	17	20
dilantin	anti-seizure medication	0.16	0.17	0.05	0.24	4
dioctyl phthalate[b]	plasticizer, industry	23	1.4	1.1	67	3
estradiol[a,c]	EDC, steroid hormone	0.59	0.03	8.0E-3	5.0	11
estrone[a,c]	EDC, steroid hormone	0.17	0.05	0.01	1.0	9
galaxolide	beta blocker, PCP, fragrance	4.3	2.3	1.4E-3	25	16
gemfibrozil[a]	lipid regulator	3.1	1.6	0.02	22	15
hydrocodone	analgesic, opioid	0.08	0.11	0.02	0.12	5
ibuprofen[a]	Analgesics, anti-inflammatory	7.8	2.4	1.0E-3	39	27
iopromide	contrast agent	7.4	0.05	0.01	38	6
meprobamate	tranquilizer, medication	0.40	0.35	0.01	0.97	5
naproxen[a]	Analgesics, anti-inflammatory	8.5	2.5	2.0E-3	53	20
nonylphenol[b,c]	EDC, disinfectant, surfactant, solvent	3.4	2.3	0.02	9.7	14

Table C-1. Occurrence of the Selected Toxic Organic Compounds in WWTP Influent

Chemical Name	Chemical Type/Use	Influent Concentration (µg/L)				Sample Size
		Average	Median	Minimum	Maximum	
octylphenol[b]	EDC, surfactant, solvent	1.9	0.41	0.12	8.7	12
o-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
oxybenzone	PCP	1.2	0.39	0.03	3.8	4
p-hydroxy atorvastatin	lipid regulator	0.12	0.12	0.10	0.14	2
progesterone[a]	EDC	0.02	0.01	3.1E-3	0.06	4
sulfamethoxazole[a]	antibiotic	1.1	0.43	0.04	4.5	14
tris(2-chloroethyl) phosphate (TCEP)	flame retardant, plasticizer	0.35	0.24	0.17	0.65	3
tris(2-chloroisopropyl) phosphate (TCPP)	flame retardant	1.2	1.2	1.1	1.3	2
testosterone[a]	EDC	0.06	0.05	0.01	0.14	5
triclosan[a]	pesticide, disinfectant	2.7	0.80	2.3E-3	24	17
trimethoprim[a]	antibiotic	0.52	0.53	0.10	1.4	8
triclocarban[a]	disinfectant	0.42	0.42	0.29	0.54	2
tonalide	beta blocker, PCP, fragrance	1.5	0.80	5.0E-5	7.6	13
celestolide	PCP, fragrance	5.1	0.07	0.04	15	3
phantolide	fragrance	0.10	0.10	0.04	0.15	2
clofibric acid	lipid regulator	0.46	0.29	0.03	1.1	3
musk ketone	fragrance	0.12	0.12	0.10	0.15	3
diuron[b,c]	fragrance	0.14	0.11	0.05	0.25	3

a - Identifies substances with EPA developed analytical methods for detection of contaminants of emerging concern per (U.S. EPA, 2017).

b - Identifies substances with a European Quality Standard per (EP 2008).

c - Identifies substances identified in EPA's Candidate Contaminant List (CCL), version 4 (U.S. EPA, 2016). The CCL identifies chemicals that are currently unregulated but may pose a risk to drinking water.

d - Identifies substances identified as human health criteria in Section 304(a) of the Clean Water Act (U.S. EPA, 2019c).

Table Acronyms: EDC – endocrine disrupting chemical, PCP – personal care product.

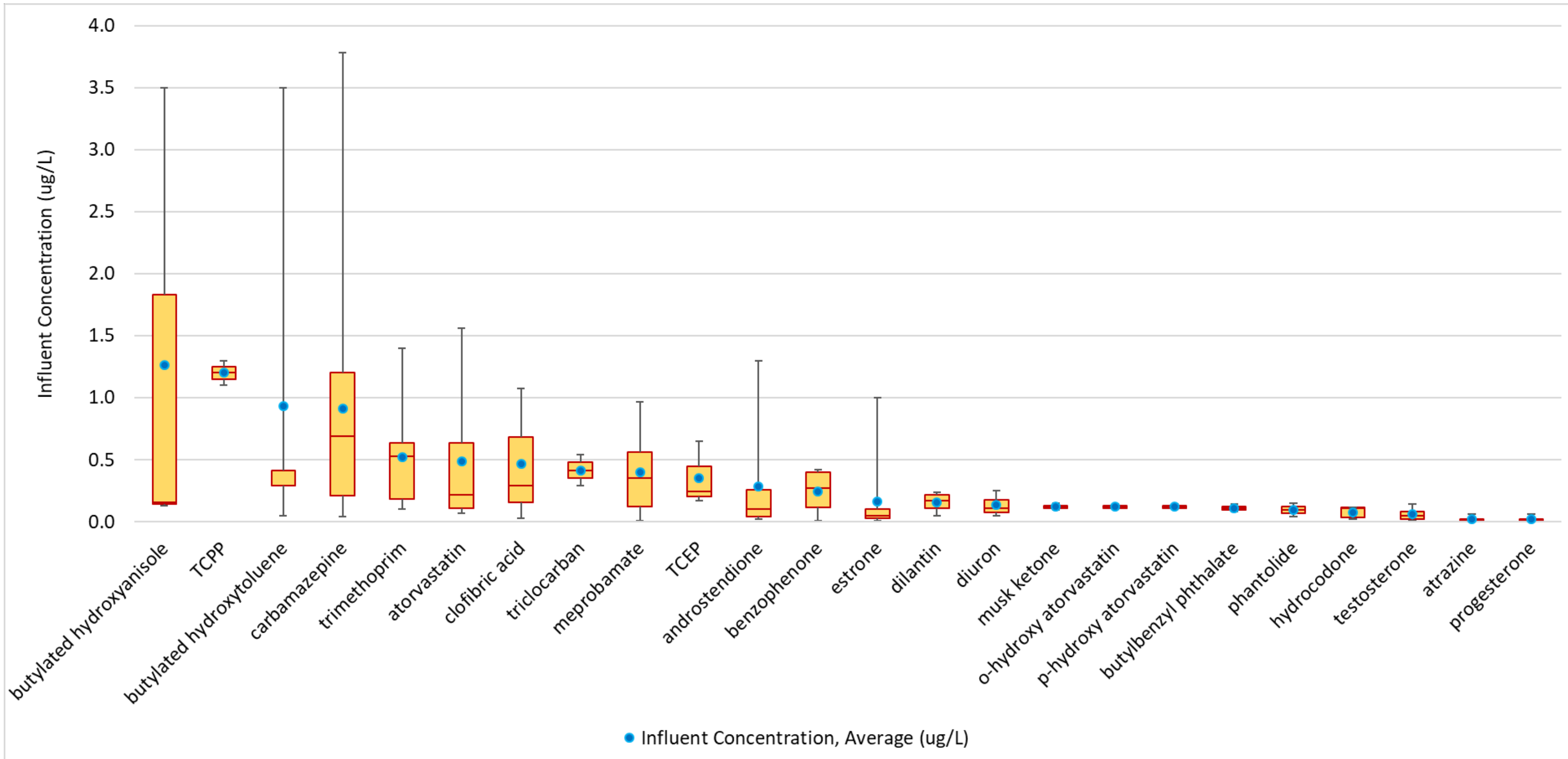


Figure C-1. Boxplot of the Influent Concentration of Toxic Organics with Maximum Concentration Less than 4 µg/L.

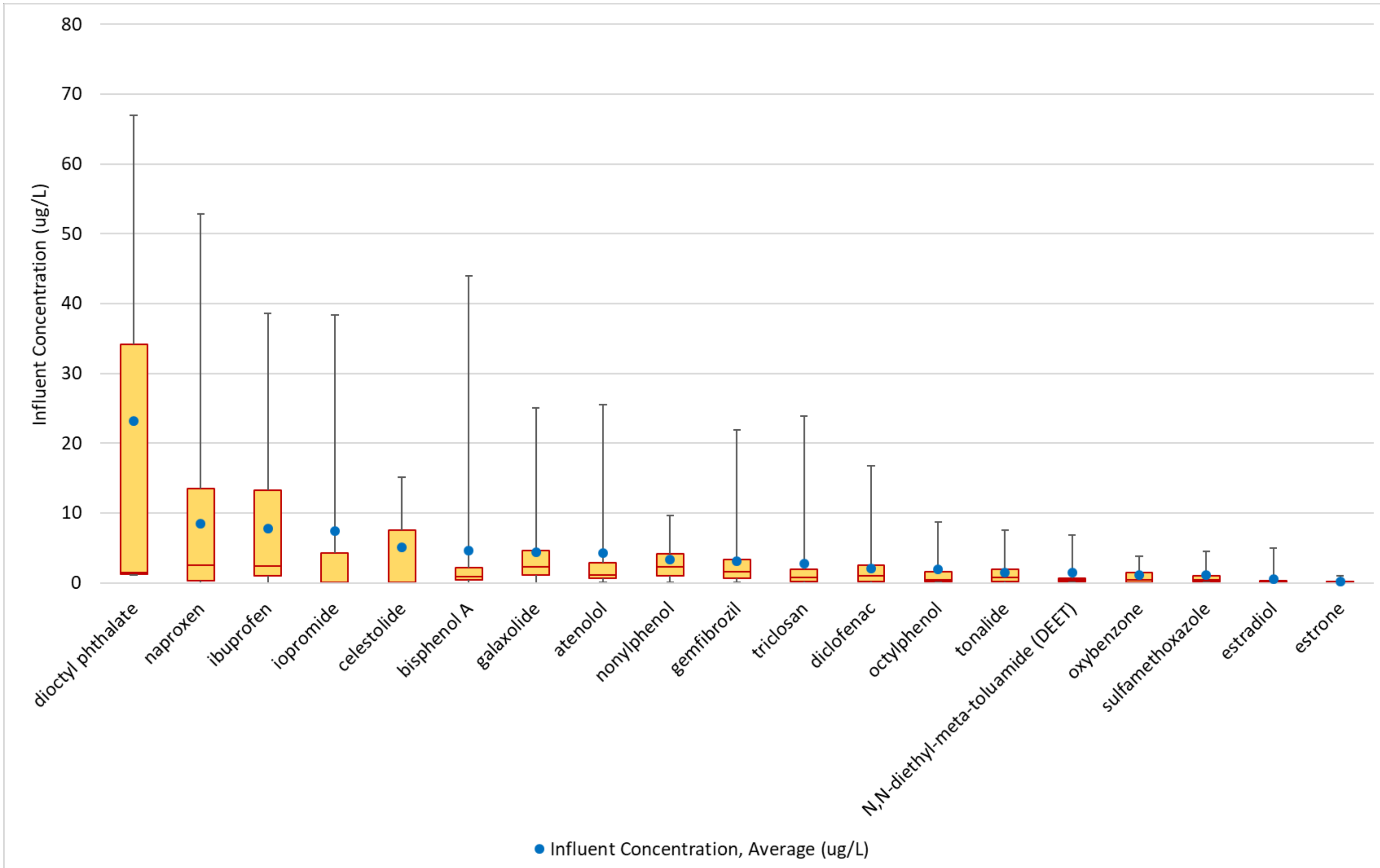


Figure C-2. Boxplot of the Influent Concentration of Toxic Organics with Maximum Concentration Greater than 4 µg/L.

C.2 Fate of Toxic Organics during Wastewater Treatment

A great deal of work has been done regarding the degradation and partitioning of toxic organics within municipal WWTPs. The extent of degradation as well as the mechanisms of removal can vary widely, reflecting the underlying diversity in the pollutants themselves and conditions and operational procedures practiced at WWTPs. For example, some chemicals such as acetaminophen and bisphenol A are highly degradable and exhibit excellent removal, often greater than 90 percent, in conventional (Level 1) treatment works (Liwarska-Bizukojc et al. 2018). Conversely, chemicals such as diclofenac and trimethoprim are more recalcitrant, exhibiting removal efficiencies of less than 80 percent in conventional treatment systems (Ahmed et al. 2017, Ogunlaja et al. 2013). The term removal efficiency is used to refer to the combined effect of biodegradation and partitioning to solids, unless otherwise specified.

As a general rule-of-thumb, Level 1 treatment systems remove approximately 80 percent of the toxic organic load from the liquid stream (Martin Ruel et al. 2012). Removal that is attributable to solids partitioning versus biodegradation varies according to pollutant. The reason for this variation is not well agreed upon within the literature. Martin Ruel et al. (2012) states that roughly two-thirds of pollutant removal can be accounted for by partitioning to sludge, while Jelic et al. (2011) found that this pathway was considerably less important. Biodegradation is a second important removal pathway, especially for chemicals that remain dissolved in the liquid fraction of wastewater. Volatilization of organic pollutants is expected to contribute negligibly to removal of most pollutants. Of the reviewed pollutants only celestolide is known to count volatilization as a significant loss pathway, accounting for up to 16% of total pollutant removal (Luo et al. 2014). Generally, volatilization is only expected to be relevant for treatment systems that have a large surface area (Liwarska-Bizukojc et al. 2018), which is not the case for any of the studied treatment configurations.

Several chemical properties of trace organics including the octanol-water coefficient (K_{ow}) and acid dissociation constant (pKa) affect the partitioning of individual organic pollutants between the solid and liquid phase in a WWTP (Alvarino et al. 2018). Pollutants with a high log K_{ow} should preferentially adsorb to the solid fraction of wastewater (Alvarino et al. 2018). Luo et al. (2014) identified a log K_{ow} threshold of 4, above which pollutants have a high sorption potential. Trace pollutants with a log K_{ow} of less than 2.5 (hydrophilic) have a low sorption potential and will tend to remain in the dissolved phase. For example, many pesticides have a log K_{ow} of less than three, are hydrophilic and predominantly exist in the dissolved phase (Martin Ruel et al. 2012). The solid-water distribution coefficient (K_d) is defined as the ratio between the concentration in the liquid and solid phases of a solution under equilibrium conditions and has been used to determine the fraction of trace pollutants that partition to sludge (Alvarino et al. 2018). For pollutants with a log K_d value of less than 2.5, sorption onto sludge can be considered negligible (Luo et al. 2014). Other authors indicate that K_{ow} alone does not provide a consistent indicator of removal performance (Oppenheimer et al. 2007), indicating that generalized approaches should be used with caution and interpreted appropriately. For example, Alvarino et al. (2018) state that hormones with high K_{ow} will tend to partition to sludge, however Martin Ruel et al. (2012) found that the majority of hormones are generally found in the dissolved phase, highlighting the complexity of these interactions.

Within the literature, there are three unit-process parameters most commonly found to affect pollutant degradation rates: (1) solids retention time (SRT), (2) hydraulic retention time (HRT), and (3) redox condition. Biomass conformation (i.e., size and type), use of adsorbents, pH, and temperature are additional unit process parameters that may vary between treatment configurations and affect pollutant degradation or removal (Alvarino et al. 2018). The pH of wastewater can affect removal of some micropollutants, particularly acidic pharmaceuticals for which the affinity to biosolids was pH affected (Luo et al. 2014). These additional factors were excluded from the current study as they are not expected to vary considerably between the nine treatment configurations, or are unknown, as in the case of biomass conformation.

Solids retention time is a measure of sludge age in secondary biological treatment processes. Longer SRT, in general, allows the growth and proliferation of slower growing microbial partners, and is thought to increase the diversity of organisms present in mixed liquor suspended solids (Luo et al. 2014). Biodegradation of organic pollutants has been shown to exhibit a variable dependence on SRT according to specific chemical characteristics. Oppenheimer et al. (2007) calculated the minimum SRT value required for 80 percent CEC removal (SRT80) for several common CECs. Easily degradable compounds such as ibuprofen and oxybenzone had an SRT80 of less than 5 days, while poorly degradable substances such as galaxolide had SRT80 values of greater than 15 days. Results showed a pronounced plateau in removal performance for SRTs greater than the SRT80 value for each respective chemical.

Hydraulic retention time measures the average period that water is retained in a given treatment unit. Longer HRT allows more time for biodegradation and partitioning to solids. HRT often correlates with SRT and it can therefore be difficult to determine the predominant factor contributing to variations in pollutant removal. The literature shows variable pollutant removal responses to HRT, which in some cases can be marginal (Oppenheimer et al. 2007).

Redox conditions are defined as the tendency of a given redox reaction to occur. In wastewater treatment, redox conditions are categorized into the three broad conditions of aerobic, anoxic, and anaerobic. Aerobic is the presence of free oxygen and indicates positive redox values. Anoxic indicates the presence of bound oxygen (e.g., nitrate) and redox values around zero. Negative redox conditions indicate the absence of free and/or bound oxygen. Redox values are indicators of what types of microbial communities may be active and which chemical reactions may occur in a given wastewater. Research has shown that the removal rate of specific organic pollutants varies according to the redox environment. Overall, aerobic conditions have been shown to more effectively degrade the broadest range of substances. Anaerobic environments had greater removal performance for a small number of compounds, some of which were not degraded in aerobic environments (Alvarino et al. 2018). Anoxic conditions were in many cases found to be a less effective environment for removal of toxic organics, however some chemicals such as diclofenac, clofibric acid, and contrast agents exhibited improved removal under anoxic conditions (Luo et al. 2014). It is suspected that anoxic conditions often found in advanced biological treatment systems, intended for nitrogen removal, are not particularly effective in the degradation of organic micropollutants (Alvarino et al. 2018). The effect of variable redox conditions, such as those present in the level 2 through 5 treatment systems assessed in this study, on toxic organics removal are still understudied (Alvarino et al. 2018).

The preceding unit process and chemical characteristics are some of the primary determinants of the fate of toxic organics within wastewater treatment systems. Those chemicals that partition readily to solids will tend to settle out with the sludge, be subject to anaerobic digestion and exit the plant heading to landfills or land application. Un-degraded dissolved chemicals will exit with the WWTP effluent and enter receiving surface waters.

C.3 Toxic Organics Removal Performance Estimation Methodology

This section describes the data and methods used to quantify a range of estimated removal efficiencies for individual unit processes that compose the 9 WWTP configurations of this study and to combine unit level removal efficiency data to estimate cumulative removal efficiency for each of the 9 WWTP configurations. Low, medium and high estimates of removal efficiency were developed for each unit process and are used to define corresponding estimates of cumulative removal efficiency for each configuration. Limited data were found to define chemical specific removal efficiencies for the advanced biological treatment units of Levels 2 through 5. Therefore, sensitivity approaches were used to assess the importance of biodegradation and solids partitioning in advanced biological treatment units to the overall environmental impact of each respective system described below.

C.3.1 Biological Treatment

Biological treatment processes contribute to both the degradation of toxic organic compounds and additional partitioning to solids by creating biological flocculants that provide adsorption sites and allow time for metabolic degradation and adsorption to take place. Owing to these processes, Miege et al. (2009) note that removal of toxic organics from the liquid portion of biological wastewater treatment is typically in the range of 50-90%, and that nitrogen removal improves the removal efficiency of many pharmaceutical compounds. Additionally, the work of Alvarino et al. (2018) concludes that hybrid biological reactors offer a "good alternative to enhance the removal of organic micropollutants." This is expected to be especially true for pollutants that are not readily degraded in aerobic conditions such as sulfamethoxazole and trimethoprim.

Table C-2 presents a summary of the Level 1, activated sludge removal efficiency of the toxic organics considered in this study. To facilitate discussion of diverse and sometimes divergent treatment performances, this study adopts a classification system for biological treatment systems developed by Oppenheimer et al. (2007) that characterizes overall treatment performance as "good", "moderate" or "low". Good removal efficiency is defined as 80% or greater. Moderate removal efficiency is classified as being in the range of 50-80% removal, while less than 50% removal efficiency is considered poor.

Based on Table C-2, Level 1 treatment systems promote "Good" removal efficiency of at least 30% of the toxic organics examined. The table also includes low, medium and high estimates of removal efficiency for the Level 1 treatment system, which includes the combined effect of primary and secondary treatment processes. Removal efficiency includes both biodegradation and the fraction of toxic organics that partition to solids and are removed in primary and waste activated sludge. Low, medium and high estimates in the table were defined as the 25th percentile, median and 75th percentile of the documented removal efficiencies. In instances where removal efficiencies are negative (i.e. formation), a value of zero has been substituted for use in this study (e.g. carbamazepine).

No removal efficiency data were found for eight of the 43 chemicals including: butylated hydroxyanisole, butylated hydroxytoluene, dilantin, hydrocodone, o-hydroxy atorvastatin, p-hydroxy atorvastatin, TCPP and triclocarban (marked with italics in Table C-2). Proxy values that bracket the extreme values for removal efficiency were used to determine if the removal of these chemicals is significant in the LCA results. Proxy removal efficiency values of 0%, 50%, and 100% were applied in the low, medium and high removal efficiency scenarios, respectively. The selection of 0% and 100% in the low and high removal efficiency scenarios was based on the minimum and maximum removal across the 35 pollutants with reported level 1 removal efficiency data. The removal efficiency estimate in the medium removal efficiency scenario is halfway between the minimum and maximum values.

Preliminary screening and grit removal were assumed to have no effect on partitioning and degradation of toxic organics. Reported removal performance of biological treatment units was assumed to include operation of the secondary clarifier, which is not assessed separately. It is important to note that within the literature it is often not clear whether pollutant removal is the result of solids partitioning or biodegradation.

Studies have shown that expected changes in toxic organic influent concentrations do not produce a noticeable effect on removal efficiency (Oppenheimer et al. 2007). One study looking at estradiol, diclofenac, and nonylphenol showed indistinguishable removal rates at influent concentrations of 1 and 10 µg/L (Liwarska-Bizukojc et al. 2018). Based on this observation, we utilized all available removal data for a given unit process, regardless of reported influent concentration.

Table C-2. Degradation and Removal of Toxic Organics within the Level 1 Biological Treatment System

Chemical Name	Removal – Class[a]	Removal Efficiency - Level 1		
		Low	Medium	High
acetaminophen	Good	92%	100%	100%
androstendione	Good	96%	98%	99%
atenolol	Medium	30%	70%	81%
atorvastatin	Good	88%	90%	92%
atrazine	Poor	26%	28%	29%
benzophenone	Good	79%	80%	80%
bisphenol A	Good	77%	85%	98%
*butylated hydroxyanisole**	N/A	*0%*	*50%*	*100%*
*butylated hydroxytoluene**	N/A	*0%*	*50%*	*100%*
butylbenzyl phthalate	Good	80%	80%	80%
carbamazepine	Poor	0%	0%	22%
N,N-diethyl-meta-toluamide (DEET)	Medium	50%	50%	50%
diclofenac	Poor	22%	49%	68%

Table C-2. Degradation and Removal of Toxic Organics within the Level 1 Biological Treatment System

Chemical Name	Removal – Class[a]	Removal Efficiency - Level 1		
		Low	Medium	High
*dilantin**	N/A	*0%*	*50%*	*100%*
dioctyl phthalate	Medium	70%	70%	70%
estradiol	Good	73%	96%	98%
estrone	Good	14%	81%	95%
galaxolide	Medium	47%	77%	87%
gemfibrozil	Medium	67%	70%	75%
*hydrocodone**	N/A	*0%*	*50%*	*100%*
ibuprofen	Good	80%	96%	99%
iopromide	Poor	0%	0%	8%
meprobamate	Poor	0%	0%	0%
naproxen	Medium	56%	73%	94%
nonylphenol	Medium	62%	78%	89%
octylphenol	Good	63%	80%	95%
*o-hydroxy atorvastatin**	N/A	*0%*	*50%*	*100%*
oxybenzone	Good	72%	80%	89%
*p-hydroxy atorvastatin**	N/A	*0%*	*50%*	*100%*
progesterone	Good	92%	93%	95%
sulfamethoxazole	Poor	31%	50%	66%
tris(2-chloroethyl)phosphate (TCEP)	Medium	50%	50%	50%
*tris(2-chloroisopropyl) phosphate (TCPP)**	N/A	*0%*	*50%*	*100%*
testosterone	Good	86%	90%	95%
triclosan	Medium	58%	71%	76%
trimethoprim	Poor	18%	20%	29%
*triclocarban**	N/A	*0%*	*50%*	*100%*
tonalide	Good	61%	84%	86%
celestolide	Medium	0%	60%	68%
phantolide	Poor	0%	9%	34%
clofibric acid	Medium	50%	52%	53%
musk ketone	Poor	0%	25%	38%
diuron	Poor	30%	30%	30%

a - Removal class refers to the qualitative removal efficiency classification thresholds defined by (Oppenheimer et al. 2007). Poor = <50% removal, Medium = 50-80% removal, Good = >80% removal. Classifications were assigned based on the median removal efficiency.

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

C.3.2 Advanced Biological Treatment

The majority of literature related to degradation and removal of toxic organics considers the removal efficiency of entire WWTPs or advanced tertiary processes (e.g. RO, ozonation). Because of this limitation it was not possible to determine individualized removal efficiencies that correspond to each of the advanced biological treatment units. Therefore, a more generalized approach was used to define low, medium and high estimates of removal efficiency for advanced biological treatment works.

As a conservative estimate, the low removal efficiency of the advanced treatment systems was set equal to the low removal efficiency of the Level 1 treatment system, which was based on the 25th percentile of documented values. The medium removal efficiency scenario value for Levels 2 through 5 was established assuming an increase in removal performance that is 25% ($EF_{inc.y}$) beyond the Level 1 median removal efficiency. The high removal efficiency scenario value assumes a removal performance that is 50% ($EF_{inc.y}$) above the Level 1 median removal efficiency as calculated in Equation C-1. For example, assuming a median removal efficiency for Level 1 treatment of 50%, the removal efficiency of advanced biological treatment units would be 62.5% and 75% (EF_x) in the medium and high removal efficiency scenarios. The proposed increases in removal efficiency attributed to Levels 2 through 5 are indicative of increased HRT, SRT and variable redox conditions that are known to increase removal efficiency of many toxic organics as discussed in Section C.2 and document in the removal notes of Table C-3.

$$EF_x = EF_{med} + [(1 - EF_{med}) \times EF_{\mathrm{inc.y}}]$$

Equation C-1

Where:

EF_x = Adjusted removal efficiency of scenario x

EF_{med} = Level 1 median removal efficiency

$EF_{inc.y}$ = Removal efficiency increase factor y (varies by scenario)

Table C-3 summarizes the calculated advanced biological process removal efficiency values for individual organic pollutants used in the sensitivity analysis. The notes in Table C-3 describe additional information that sheds light on how the studied compounds may respond to alternate redox conditions and longer HRTs and SRTs that characterize the advanced biological treatment units of Levels 2 through 5. As noted above, several authors state that current evidence indicates that comparable or improved removal efficiencies can be expected in advanced biological treatment works. Examination of removal notes in Table C-3 often confirms this perspective, however, there are also numerous instances where the findings of authors contradict one another. For example, Lakshminarasimman et al. (2018) identified improved removal of bisphenol A at high SRTs, whereas (Luo et al. 2014) identified no significant effect of SRT on removal efficiency. What is clear from Table C-2 and Table C-3 is the conclusion that individual toxic organics respond differently to the range of conditions that characterize both activated sludge and advance nutrient removal WWTPs. The sensitivity approach described in this section will allow the analysis to judge the importance of removal efficiency estimates on final LCA results.

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	Level 1	Removal Efficiency - Advanced Biological Processes (Levels 2-5)			Removal Notes
	Median	Low	Medium	High	
acetaminophen	100%	92%	100%	100%	
androstendione	98%	96%	98%	99%	
atenolol	70%	30%	78%	90%	Biodegrades in all three redox conditions. Degradation was greatest under aerobic conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Less than 20% removal under aerobic conditions (Miege et al. 2009) Poor to moderate removal in activated sludge, 45-80% (Martin Ruel et al. 2012)
atorvastatin	90%	88%	93%	96%	
atrazine	28%	26%	46%	64%	
benzophenone	80%	79%	85%	90%	
bisphenol A	85%	77%	89%	99%	Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Not affected by SRT (Luo et al. 2014) Better removal at high SRT (Lakshminarasimman et al. 2018)
*butylated hydroxyanisole**	*50%*	*0%*	*63%*	*100%*	
*butylated hydroxytoluene**	*50%*	*0%*	*63%*	*100%*	
butylbenzyl phthalate	80%	80%	85%	90%	
carbamazepine	0%	0%	25%	61%	Poor removal (Miege et al. 2009; Martin Ruel et al. 2012) Removal less than 20% under all redox conditions (Alvarino et al. 2018; Lakshminarasimman et al. 2018) Removal less than 25% under aerobic conditions (Jelic, (Miege et al. 2009; Jelic et al. 2011)
N,N-diethyl-meta-toluamide (DEET)	50%	50%	63%	75%	Degradation is primarily aerobic (Lakshminarasimman et al. 2018) Poor removal in anaerobic conditions

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	Level 1	Removal Efficiency - Advanced Biological Processes (Levels 2-5)			Removal Notes
	Median	Low	Medium	High	
					(Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018)
diclofenac	49%	22%	62%	84%	Removal <20% under all redox conditions (Alvarino et al. 2018) Anoxic conditions have a positive influence on removal (Luo et al. 2014) Exhibited inconsistent overall removal. (Jelic et al. 2011) Poor to moderate removal in activated sludge, less than 60% (Miege et al. 2009) Poor removal in activated sludge, <50% (Martin Ruel et al. 2012)
*dilantin**	*50%*	*0%*	*63%*	*100%*	
dioctyl phthalate	70%	70%	78%	85%	Poor to moderate removal in all three redox conditions (Luo et al. 2014) High HRT increases removal to sludge (Luo et al. 2014)
estradiol	96%	73%	97%	99%	Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Moderate to good removal in activated sludge, 65-100% (Miege et al. 2009) Good degradation in aerobic conditions (Alvarino et al. 2018) Moderate degradation in anaerobic conditions (Alvarino et al. 2018)

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	Level 1	Removal Efficiency - Advanced Biological Processes (Levels 2-5)			Removal Notes
	Median	Low	Medium	High	
estrone	81%	14%	85%	98%	Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Moderate to good removal in activated sludge, 45-100% (Miege et al. 2009) Good degradation in aerobic conditions (Alvarino et al. 2018) Moderate degradation in anaerobic conditions (Alvarino et al. 2018)
galaxolide	77%	47%	83%	93%	Poor degradation (Oppenheimer et al. 2007) Good aerobic degradation (Alvarino et al. 2018) Moderate anoxic degradation (Alvarino et al. 2018) Poor anaerobic degradation (Alvarino et al. 2018) Poor to moderate removal in activated sludge, 25-75% (Miege et al. 2009)
gemfibrozil	70%	67%	78%	87%	Moderate removal in activated sludge (Miege et al. 2009)
*hydrocodone**	*50%*	*0%*	*63%*	*100%*	
ibuprofen	96%	80%	97%	100%	Good degradation (Oppenheimer et al. 2007) Good aerobic degradation (Alvarino et al. 2018) Poor anaerobic and anoxic degradation (Alvarino et al. 2018) Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Moderate to good removal in activated sludge, 50-100% (Miege et al. 2009)

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	Level 1	Removal Efficiency - Advanced Biological Processes (Levels 2-5)			Removal Notes
	Median	Low	Medium	High	
iopromide	0%	0%	25%	54%	Anoxic conditions have a positive influence on removal (Luo et al. 2014) Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Demonstrated no removal in activated sludge (Miege et al. 2009)
meprobamate	0%	0%	25%	50%	
naproxen	73%	56%	79%	97%	Good degradation in aerobic and anaerobic conditions (Alvarino et al. 2018) Poor degradation in anoxic conditions (Alvarino et al. 2018) Biotransformation is catalyzed by nitrifying conditions (Lakshminarasimman et al. 2018) Better removal at high SRT (Lakshminarasimman et al. 2018) Good degradation. Does not accumulate in sludge (Jelic et al. 2011) Moderate to good removal in activated sludge, 65-95% (Miege et al. 2009)
nonylphenol	78%	62%	83%	94%	SRT greater than 20 hours improves removal (Luo et al. 2014)
octylphenol	80%	63%	85%	98%	
*o-hydroxy atorvastatin**	*50%*	*0%*	*63%*	*100%*	
oxybenzone	80%	72%	85%	95%	Good degradation (Oppenheimer et al. 2007)
*p-hydroxy atorvastatin**	*50%*	*0%*	*63%*	*100%*	
progesterone	93%	92%	95%	97%	

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	Level 1	Removal Efficiency - Advanced Biological Processes (Levels 2-5)			Removal Notes
	Median	Low	Medium	High	
sulfamethoxazole	50%	31%	62%	83%	Good degradation in anaerobic conditions (Alvarino et al. 2018) Poor degradation in anoxic and aerobic conditions (Alvarino et al. 2018) Comparable degradation under varying redox conditions (Lakshminarasimman et al. 2018) Mixed results on the effect of SRT (Lakshminarasimman et al. 2018) Poor to good removal in activated sludge, 35-80% (Miege et al. 2009)
tris(2-chloroethyl)phosphate (TCEP)	50%	50%	63%	75%	
*tris(2-chlorisopropyl) phosphate (TCPP)**	*50%*	*0%*	*63%*	*100%*	
testosterone	90%	86%	93%	97%	
triclosan	71%	58%	78%	88%	Better degradation under aerobic conditions (Lakshminarasimman et al. 2018) SRT greater than 20 hours improves removal (Luo et al. 2014) Removal rates do not vary with increasing SRT (Lakshminarasimman et al. 2018)
trimethoprim	20%	18%	40%	65%	Good degradation anaerobic conditions (Alvarino et al. 2018) Poor degradation under aerobic and anoxic conditions (Alvarino et al. 2018) Poor degradation under aerobic conditions, <40% (Miege et al. 2009) Demonstrated degradation under anaerobic and anoxic conditions (Lakshminarasimman et al. 2018) Mixed results on the effect of SRT (Lakshminarasimman et al. 2018)

Table C-3. Toxic Organic Removal Efficiency of Advanced Biological Treatment Process

Chemical Name	Level 1	Removal Efficiency - Advanced Biological Processes (Levels 2-5)			Removal Notes
	Median	Low	Medium	High	
					No significant removal under aerobic conditions (Jelic et al. 2011)
*triclocarban**	*50%*	*0%*	*63%*	*100%*	
tonalide	84%	61%	88%	93%	Good degradation under aerobic conditions (Alvarino et al. 2018) Moderate degradation under anaerobic and anoxic conditions (Alvarino et al. 2018) Poor to good degradation in activated sludge, 35-85% (Miege et al. 2009)
celestolide	60%	0%	70%	84%	Good degradation under aerobic conditions (Alvarino et al. 2018) Moderate degradation under anaerobic and anoxic conditions (Alvarino et al. 2018) Poor to moderate removal in activated sludge, less than 60% (Miege et al. 2009) Volatilization is a significant loss pathway, approximately 16% (Luo et al. 2014)
phantolide	9%	0%	32%	67%	
clofibric acid	52%	50%	64%	76%	Anoxic conditions have a positive influence on removal (Luo et al. 2014) Poor removal in activated sludge, less than 50% (Miege et al. 2009)
musk ketone	25%	0%	44%	69%	Poor degradation under aerobic conditions (Miege et al. 2009)
diuron	30%	30%	48%	65%	Poor degradation in activated sludge (Martin Ruel et al. 2012)

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

It was also necessary to estimate the fraction of pollutant removal that is attributable to solids partitioning as opposed to biological degradation. Miege et al. (2009) performed an in-depth review of studies looking at the fate of PPCPs in WWTPs and noted that the vast majority (87%) of studies focus on the aqueous phase. None of the reviewed studies looked at both aqueous and solid phases of PPCPs simultaneously. As noted earlier, (Martin Ruel et al. 2012) proposed that up to two-thirds of pollutant removal can be attributed to solids partitioning. Other authors disagree with this conclusion, proposing that the majority of removal efficiency is due to biodegradation (Liu et al. 2009). It is beyond the scope of this analysis to attempt to resolve this discrepancy.

In the low efficiency scenario, it was assumed that two-thirds of removal efficiency is due to solids partitioning (one-third biodegradation). The analysis does not specify if this removal occurs during primary or secondary clarification. The medium removal efficiency estimates assume a 50-50 split between solids partitioning and biodegradation, while the high removal efficiency estimates assume that one-third of removal is attributable to solids partitioning (two-thirds biodegradation). All assumptions related to solids partitioning were applied to the corresponding removal efficiency as documented in Table C-2.

C.3.3 Anaerobic Digestion

All 9 treatment systems include anaerobic digestion as a sludge processing step, and a low, medium and high estimate of removal efficiency was established for each of the 43 pollutants using the 25th percentile, median and 75th percentile degradation values. The reviewed research on anaerobic digestion deals more consistently with pollutants in both the liquid and solid phase. Removal efficiency measurements for anaerobic digestion tend to refer to biodegradation explicitly. Pollutant specific data were identified for 20 of the 43 pollutants and are summarized in Table C-4. Removal efficiency was set as zero for pollutants reporting negative values. Proxy values that bracket the extreme values for removal efficiency were used to determine if the removal of the 23 remaining chemicals is significant in the LCA results. Proxy removal efficiency values of 0%, 50%, and 100% were applied in the low, medium and high removal efficiency scenarios, respectively. The selection of 0% and 100% in the low and high removal efficiency scenarios was based on the minimum and maximum removal across the 20 pollutants with reported AD removal efficiency data. The removal efficiency estimate in the medium removal efficiency scenario is halfway between the minimum and maximum values.

A study by Malmborg and Magnér (2015) looked at several sludge treatment steps including pasteurization, thermal hydrolysis, advanced oxidation and ammonia treatment, concluding that anaerobic digestion was the most effective at removing organic substances. Toxic organics pollutants not degraded in anaerobic digestion remain with the solids for disposal in landfills.

Table C-4. Toxic Organic Removal Efficiency of Anaerobic Digestion

Chemical Name	Removal Efficiency (%)			
	Low	Medium	High	Range (min-max)
acetaminophen	89%	89%	96%	85-100
*androstendione**	*0%*	*50%*	*100%*	*N/A*
atenolol	61%	77%	89%	39-96

Table C-4. Toxic Organic Removal Efficiency of Anaerobic Digestion

Chemical Name	Removal Efficiency (%)			
	Low	Medium	High	Range (min-max)
*atorvastatin**	*0%*	*50%*	*100%*	*N/A*
*atrazine**	*0%*	*50%*	*100%*	*N/A*
*benzophenone**	*0%*	*50%*	*100%*	*N/A*
bisphenol A	12%	30%	84%	0-100
*butylated hydroxyanisole**	*0%*	*50%*	*100%*	*N/A*
*butylated hydroxytoluene**	*0%*	*50%*	*100%*	*N/A*
butylbenzyl phthalate	93%	93%	93%	93-93
carbamazepine	0%	0%	7%	0-15
N,N-diethyl-meta-toluamide (DEET)	0%	0%	0%	0-0
diclofenac	21%	34%	55%	0-78
*dilantin**	*0%*	*50%*	*100%*	*N/A*
*dioctyl phthalate**	*0%*	*50%*	*100%*	*N/A*
estradiol	85%	93%	96%	75-100
estrone	75%	79%	85%	70-95
galaxolide	58%	65%	73%	50-80
gemfibrozil	0%	0%	0%	0-0
*hydrocodone**	*0%*	*50%*	*100%*	*N/A*
ibuprofen	21%	27%	44%	0-70
iopromide	16%	23%	31%	8-38
*meprobamate**	*0%*	*50%*	*100%*	*N/A*
naproxen	86%	89%	93%	76-96
nonylphenol	43%	86%	100%	0-100
*octylphenol**	*0%*	*50%*	*100%*	*N/A*
*o-hydroxy atorvastatin**	*0%*	*50%*	*100%*	*N/A*
*oxybenzone**	*0%*	*50%*	*100%*	*N/A*
*p-hydroxy atorvastatin**	*0%*	*50%*	*100%*	*N/A*
*progesterone**	*0%*	*50%*	*100%*	*N/A*
sulfamethoxazole	79%	99%	100%	23-100
*tris(2-chloroethyl)phosphate (TCEP)**	*0%*	*50%*	*100%*	*N/A*
*tris(2-chloroisopropyl) phosphate (TCPP)**	*0%*	*50%*	*100%*	*N/A*
*testosterone**	*0%*	*50%*	*100%*	*N/A*
triclosan	45%	53%	55%	30-55
trimethoprim	90%	96%	99%	80-100
triclocarban	20%	40%	53%	0-65
tonalide	59%	65%	67%	52-68
*celestolide**	*0%*	*50%*	*100%*	*N/A*
*phantolide**	*0%*	*50%*	*100%*	*N/A*
*clofibric acid**	*0%*	*50%*	*100%*	*N/A*
*musk ketone**	*0%*	*50%*	*100%*	*N/A*
*diuron**	*0%*	*50%*	*100%*	*N/A*

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

C.3.4 Chemical Phosphorus Removal

The effect of chemical phosphorus removal was considered to the extent that it is expected to enhance partitioning and settling of toxic organics. Alexander et al. (2012) reviewed the available literature on the effect of chemical coagulation on trace organic pollutant removal. They found that chemical phosphorus removal (i.e. chemical coagulation) has been demonstrated to be an inefficient means of removing trace organics from the liquid phase of wastewater. Across different categories of organic chemicals, average removal efficiency of chemical coagulation varies between six and 77%.

Table C-5 lists low, medium and high removal efficiency scenario values used in this study. Pollutant specific data was identified for 9 of the 43 toxic organic compounds. Twenty-eight of the 43 chemicals were assigned removal efficiency data based on their assigned chemical class, as listed in Table C-5. No data was identified for 15 of the toxic organic chemicals, and they were assigned the median removal efficiency across all chemical classes of 34% (Alexander et al. 2012).

Six of the nine treatment systems included in this study utilize chemically enhanced secondary clarification. The low removal efficiency scenario assumes no increase in removal efficiency relative to secondary clarification without a preceding alum addition. The medium and high removal efficiency scenarios assume that 50% and 100% of the identified chemical coagulation removal efficiencies are in addition to the removal realized by the combined biological process and secondary clarification (without alum addition). The range of these assumptions is wide to accommodate the fact that Alexander et al. (2012) presents chemical coagulation as a stand-alone unit process. The precise relationship between the removal efficiency of stand-alone chemical coagulation and chemically enhanced secondary clarification is not known.

Table C-5. Toxic Organic Removal Efficiency of Chemical Coagulation

Chemical Name	Chemical Class[a]	Removal Efficiency - Chemical Coagulation[b]		
		Low	Medium	High
acetaminophen[3]	N/A	-	24%	48%
androstendione	hormone	-	9.5%	19%
atenolol[3]	beta-blocker	-	9.5%	19%
atorvastatin	hypolipidemic agent	-	13%	26%
atrazine	pesticide	-	15%	30%
*benzophenone**	*N/A*	-	*17%*	*34%*
*bisphenol A**	*N/A*	-	*17%*	*34%*
butylated hydroxyanisole	beta-blocker	-	17%	34%
butylated hydroxytoluene	beta-blocker	-	17%	34%
butylbenzyl phthalate	phthalate	-	25%	49%
carbamazepine[c]	N/A	-	15%	30%
N,N-diethyl-meta-toluamide (DEET)	pesticide	-	15%	30%
diclofenac[c]	anti-inflammatory	-	25%	50.0%
*dilantin**	*N/A*	-	*17%*	*34%*
dioctyl phthalate	phthalate	-	25%	49%
estradiol[c]	hormone	-	1.0%	2.0%

Table C-5. Toxic Organic Removal Efficiency of Chemical Coagulation

Chemical Name	Chemical Class[a]	Removal Efficiency - Chemical Coagulation[b]		
		Low	Medium	High
estrone[c]	hormone	-	6.0%	12%
galaxolide	beta-blocker	-	39%	77%
gemfibrozil	musk fragrance	-	13%	26%
hydrocodone[c]	N/A	-	12%	24%
ibuprofen	anti-inflammatory	-	18%	35%
*iopromide**	*N/A*	-	*17%*	*34%*
*meprobamate**	*N/A*	-	*17%*	*34%*
naproxen[c]	anti-inflammatory	-	11%	23%
*nonylphenol**	*N/A*	-	*17%*	*34%*
*octylphenol**	*N/A*	-	*17%*	*34%*
o-hydroxy atorvastatin	hypolipidemic agent	-	13%	26%
*oxybenzone**	*N/A*	-	*17%*	*34%*
p-hydroxy atorvastatin	hypolipidemic agent	-	13%	26%
progesterone[c]	hormone	-	6.3%	13%
sulfamethoxazole	antibiotic	-	20%	39%
*tris(2-chloroethyl)phosphate (TCEP)**	*N/A*	-	*17%*	*34%*
*tris(2-chloroisopropyl) phosphate (TCPP)**	*N/A*	-	*17%*	*34%*
testosterone	hormone	-	9.5%	19%
triclosan	pesticide	-	15%	30%
trimethoprim	antibiotic	-	20%	39%
*triclocarban**	*N/A*	-	*17%*	*34%*
tonalide	musk fragrance	-	28%	56%
celestolide	musk fragrance	-	39%	77%
phantolide	musk fragrance	-	39%	77%
clofibric acid	hypolipidemic agent	-	13%	26%
musk ketone	musk fragrance	-	39%	77%
*diuron**	*N/A*	-	*17%*	*34%*

a - Chemical classes are based on trace organic compound classes defined in Table 4 of (Alexander et al. 2012).

b - Removal efficiency of chemical coagulation is in addition to the removal efficiencies for combined biological treatment and secondary clarification listed in Table 1-3 and Table 1-4.

c - Chemical specific removal efficiency data was drawn from (Alexander et al. 2012).

* Marked values use median removal efficiency of all chemical classes defined in Alexander et al. (2012) as the proxy removal efficiency value.

C.3.5 Membrane Filtration

For the fraction of toxic organics that remain in the dissolved phase there are subsequent unit processes to consider following biological treatment. Media filters and ultrafiltration membranes do not physically screen toxic organic compounds as the molecules are often two orders of magnitude smaller than the membrane pores (Oppenheimer et al. 2007; Alvarino et al. 2018), or more in the case of sand filters. Ultrafiltration membranes replace traditional secondary clarifiers in Levels 4-2 and 5-2. In this capacity they increase total suspended solids removal by approximately 0.5%, which was considered negligible from the perspective of increasing the fraction of toxic organics exiting the WWTP with the sludge fraction. There is however evidence that certain toxic organics can be sorbed onto hydrophobic filtration membranes via electrostatic interactions and within the cake layer (Alvarino et al. 2018). Retention of toxic organics on filtration membranes was not able to be assessed in this study.

Reverse osmosis has been shown to be effective at removing residual toxic organics in secondary effluent to less-than-detectable levels (Oppenheimer et al. 2007). Reverse osmosis removal efficiency measurement data was found for 37 of the 43 toxic organic chemicals considered. Table C-6 lists the low, medium and high removal efficiency estimates calculated using the 25th percentile, median and 75th percentile of documented values. Data on the removal efficiency of reverse osmosis was not found for six chemicals. Proxy values that bracket the extreme values for removal efficiency were used to determine if the removal of these chemicals is significant in the LCA results. Proxy removal efficiency values of 0%, 49.9%, and 99.9% were applied in the low, medium and high removal efficiency scenarios, respectively. The selection of 0% and 99.9% in the low and high removal efficiency scenarios was based on the minimum and maximum removal across the 37 pollutants with reported RO removal efficiency data. The removal efficiency estimate in the medium removal efficiency scenario is halfway between the minimum and maximum values.

Table C-6. Toxic Organic Removal Efficiency of Reverse Osmosis

Chemical Name	Removal Efficiency - Reverse Osmosis		
	Low	**Medium**	**High**
acetaminophen	89%	90%	91%
androstendione	31%	62%	71%
atenolol	98%	98%	99%
atorvastatin	98%	98%	99%
atrazine	49%	97%	98%
benzophenone	40%	69%	98%
bisphenol A	98%	99%	99%
butylated hydroxyanisole	98%	98%	99%
butylated hydroxytoluene	98%	98%	99%
butylbenzyl phthalate	98%	98%	99%
carbamazepine	99%	99%	99%
N,N-diethyl-meta-toluamide (DEET)	94%	95%	99%
diclofenac	95%	97%	97%
dilantin	99%	99%	100%
dioctyl phthalate	98%	98%	99%
estradiol	-	80%	92%
estrone	90%	91%	95%
galaxolide	54%	88%	99%
gemfibrozil	98%	99%	100%
hydrocodone	98%	98%	99%
ibuprofen	97%	99%	99%
iopromide	98%	99%	99%
meprobamate	99%	100%	100%
naproxen	94%	96%	99%
nonylphenol	98%	98%	99%

Table C-6. Toxic Organic Removal Efficiency of Reverse Osmosis

Chemical Name	Removal Efficiency - Reverse Osmosis		
	Low	Medium	High
octylphenol	98%	98%	99%
o-hydroxy atorvastatin	98%	98%	99%
oxybenzone	85%	93%	95%
p-hydroxy atorvastatin	98%	98%	99%
progesterone	-	80%	97%
sulfamethoxazole	98%	99%	100%
TCEP	93%	95%	96%
TCPP	98%	98%	99%
testosterone	49%	97%	98%
triclosan	89%	92%	95%
trimethoprim	99%	99%	100%
*triclocarban**	*98%*	*98%*	*100%*
*tonalide**	*98%*	*98%*	*100%*
*celestolide**	*98%*	*98%*	*100%*
*phantolide**	*98%*	*98%*	*100%*
*clofibric acid**	*98%*	*98%*	*100%*
musk ketone	56%	68%	79%
*diuron**	*98%*	*98%*	*100%*

* Marked and italicized chemicals lack data on removal efficiency and use 0%, 50%, and 100% as proxy removal efficiency values to determine significance in LCA results.

C.3.6 Other Processes

Media filtration has not been shown to provide considerable removal beyond that provided by preceding secondary treatment processes, less than 15 percent (Oppenheimer et al. 2007). Removal efficiency data of standalone sand filters were identified for eight of the 43 pollutants. The low and medium removal efficiency scenarios both assume zero percent removal based on the 25th percentile and median of the eight identified values. The high removal efficiency scenarios assume 11% removal, based on the 75th percentile. The described values were applied to all 43 pollutants and were assumed to constitute additional biodegradation.

Chlorination, dechlorination and the sludge thickening processes were assumed not to affect the fate of toxic organics within the WWTP.

C.3.7 Total System Level Performance

Removal efficiency estimates for individual unit processes listed in Table C-2 through Table C-6 were used as inputs to Equation C-2 to calculate cumulative removal from the liquid effluent. The fraction of influent toxic organics that accumulate in sludge was estimated by adding the fraction of removal efficiency attributable to solids partitioning from the combined primary and secondary biological unit processes ($r_b \times r_s$) to the additional sludge removal that results from chemically enhanced secondary clarification (r_c) less the fraction of each compound that is degraded during anaerobic digestion ($1-r_{AD}$) as summarized in Equation C-2.

$$\boldsymbol{R_{s-total} = [(r_b \times r_s) + r_c] \times (1 - r_{AD})]}$$

Equation C-2

where

$R_{s\text{-}total}$ = total fraction of pollutant (in influent) that accumulates in sludge

r_b = fraction of pollutant removed in primary and secondary treatment, includes degradation and partitioning to solids.

r_s = fraction of primary and secondary removal efficiency attributable to solids partitioning and sludge removal (percentage of r_b).

r_c = additional fraction of pollutant removed by chemically enhanced secondary clarification.

r_{AD} = fraction of pollutant degraded during anaerobic digestion.

Table C-7 summarizes the cumulative fate of toxic organics across the nine system configurations. The presented values represent weighted average degradation and removal efficiencies across the 43 included chemicals and include the estimated effect of the listed unit processes. The median influent concentration of the 43 toxic organic chemicals was used as the weighting factor.

- Primary clarification, biological treatment and secondary/tertiary clarification - combined removal efficiency. Median values for the Level 1 low, medium and high removal efficiency scenarios range from 47 to 87% removal. Median values for the Level 2 through 5 low, medium and high removal efficiency scenarios range from 47 to 93%. Removal efficiency includes partitioning to solids and biodegradation.
- Chemical phosphorus removal – contributes additional partitioning to solids. Median values for the low, medium and high removal efficiency scenarios range from zero to 34% additional partitioning to solids.
- Sand filtration – assumed to increase biodegradation (minor). Low, medium and high removal efficiency scenario values range from 0 to 11% removal.
- Anaerobic digestion – biodegrades a fraction of toxic organics that partition to sludge. Median values for the low, medium and high removal efficiency scenarios range from 0 to 100% biodegradation.
- Reverse Osmosis – physically separates toxic organics from the liquid stream of wastewater, concentrating these substances in the brine solution for underground injection. Median values for the low, medium and high removal efficiency scenarios range from 98 to 99% removal from the liquid fraction of wastewater.

Table C-7. Summary of Total Toxic Organics Fate in the Nine Treatment Systems[a]

Treatment Level	Fraction Degraded			Fraction Removed (includes solids)		
	Low	Mid	High	Low	Mid	High
L1	51.7%	69.9%	84.8%	67.1%	81.1%	89.1%

Table C-7. Summary of Total Toxic Organics Fate in the Nine Treatment Systems[a]

Treatment Level	Fraction Degraded			Fraction Removed (includes solids)		
	Low	**Mid**	**High**	**Low**	**Mid**	**High**
L2-1	51.7%	73.5%	89.7%	67.1%	85.8%	94.6%
L2-2	51.7%	73.5%	89.7%	67.1%	85.8%	94.6%
L3-1	51.7%	74.9%	91.6%	67.1%	88.5%	97.0%
L3-2	51.7%	74.9%	91.6%	67.1%	88.5%	97.0%
L4-1	51.7%	74.9%	91.6%	67.1%	88.5%	97.0%
L4-2	51.7%	74.9%	91.2%	67.1%	88.5%	96.7%
L5-1	51.7%	74.9%	91.2%	94.2%	98.5%	99.7%
L5-2	51.7%	74.9%	91.2%	92.7%	98.0%	99.5%

a - Table values represent the cumulative effect of all the described treatment processes, calculated as a weighted average of the 43 toxic organics using influent concentration as the weighting factor.

C.3.8 Toxicity Characterization Factors

Table C-8 presents the characterization factors used to estimate toxicity impacts associated with toxic organics in treatment plant effluent and sludge. Not all toxic organics included in this study have associated characterization factors listed in the most recent versions of USEtox™, versions 2.02 and 2.11. Characterization factors for several of the pollutants were previously calculated by other authors (Rahman et al. 2018, Alfonsín et al. 2014). Characterization factors that were not otherwise available were estimated using the median value of all other toxic organic pollutants for which data was available. Sources for individual characterization factors are listed in Table C-8.

Table C-8. Toxic Organics Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	USETox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)		Human health cancer, freshwater (CTUh, cases/kg emitted)		Human Health noncancer, freshwater (CTUh, cases/kg emitted)	
		Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil
acetaminophen	acetamide	2.6	0.88	2.5E-7	8.5E-8	3.5E-6[d]	1.4E-7[d]
androstendione	androstenedione	5.1E+3	5.7E+2	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
atenolol	N/A[c]	1.2E+2[a]	57	-[d]	-[d]	8.0E-3[a]	4.0E-3[a]
atorvastatin	N/A[c]	8.4E+3[a]	4.2E+3[a]	-[d]	-[d]	9.6E-8[a]	4.8E-8[a]
atrazine	atrazine	8.7E+4	3.4E+3	3.7E-6	1.5E-7	4.3E-6	1.7E-7
benzophenone	benzophenone	5.2E+3	94	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
bisphenol A	bisphenol A	8.dE+3	2.0E+2	-	-	1.1E-6[d]	2.6E-8[d]
butylated hydroxyanisole	butylated hydroxyanisole	8.8E+3	1.6E+2	3.4E-7	1.0E-8	3.5E-6[d]	1.4E-7[d]
butylated hydroxytoluene	2,6-DI-T-BUTYL-4-METHYLPHENOL (BHT)	1.8E+3	3.6	3.4E-7	3.6E-9	3.5E-6[d]	1.4E-7[d]
butylbenzyl phthalate	phthalate, butyl-benzyl-	5.7E+3	9.1	5.0E-8	1.0E-9	7.3E-8	1.5E-9
carbamazepine	carbamazepine	7.8E+2	93	-	-	2.3E-6	2.8E-7
N,N-diethyl-meta-toluamide (DEET)	DEET [N,N,-DIET-3-ME BENZAMIDE]	2.2E+2	11	-	-	3.5E-6[d]	1.4E-7[d]
diclofenac	diclofenac	1.9E+3	1.5E+2	-	-	1.6E-4	1.2E-5
dilantin	phenytoin	1.0E+5[a]	5.0E+4[a]	2.9E-6	1.8E-7	5.3E-4[a]	2.7E-4[a]
dioctyl phthalate	phthalate, dioctyl-	30	0.01	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
estradiol	estradiol	2.2E+8	2.3E+6	-	-	1.0E-3[b]	1.4E-6[b]
estrone	estrone	2.4E+4	5.7E+2	-[d]	-[d]	3.2E-4[b]	5.4E-7[b]
galaxolide	N/A[3]	3.3E+5[b]	17[b]	-[d]	-[d]	5.0E-7[b]	4.7E-9[b]
gemfibrozil	gemfibrozil	7.0E+3[d]	1.6E+2[d]	3.1E-6	1.3E-7	3.5E-6[d]	1.4E-7[d]
hydrocodone	N/A	1.4E+4[a]	7.0E+3[a]	-[d]	-[d]	2.1E-5[a]	1.1E-4[a]
ibuprofen	ibuprofen	2.3E+2	7.3	-	-	3.7E-7[2]	1.7E-8[2]

Table C-8. Toxic Organics Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	USETox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)		Human health cancer, freshwater (CTUh, cases/kg emitted)		Human Health noncancer, freshwater (CTUh, cases/kg emitted)	
		Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil
iopromide	iopromide	24	10	-	-	2.4E-7	1.0E-7
meprobamate	N/A[c]	9.2E+2[a]	4.6E+2[a]	-[d]	-[d]	1.0E-c[a]	5.2E-4[a]
naproxen	N/A[c]	9.6E+2[b]	4.9 [b]	-[d]	-[d]	3.0E-7 [b]	6.6E-9 [b]
nonylphenol	nonylphenol	1.6E+4	8.8	-[d]	-[d]	5.6E-6 [b]	7.1E-10 [b]
octylphenol	N/A[c]	3.3E+5 [b]	1.4E+2 [b]	-[d]	-[d]	4.3E-6 [b]	3.3E-9 [b]
o-hydroxy atorvastatin	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
oxybenzone	N/A[c]	4.4E+4[a]	2.2E+4[a]	-[d]	-[d]	2.4E-6[a]	1.3E-6[a]
p-hydroxy atorvastatin	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
progesterone	N/A[c]	1.6E+4[a]	7.7E+3[a]	-[d]	-[d]	1.3E-5[a]	6.1E-6[a]
sulfamethoxazole	sulfamethoxazole	4.7E+3	1.2E+3	-	-	4.7E-7	1.2E-7
tris(2-chloroethyl)phosphate (TCEP)	tris(2-carboxyethyl)phosphine	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
tris(2-chloroisopropyl) phosphate (TCPP)	TRI-2-CHLOROETHYL PHOSPHATE	4.4E+2	1.1E+2	1.1E-6	2.8E-7	3.5E-6[d]	1.4E-7[d]
testosterone	testosterone	1.3E+4	4.0E+2	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
triclosan	5-CHLORO-2-(2,4-DICHLOROPHENOXY)PHENOL	1.3E+5	8.9E+2	-[d]	-[d]	2.2E-7 [b]	5.0E-10 [b]
trimethoprim	trimethoprim	1.0E+3	13	-	-	2.8E-6	3.7E-8
triclocarban	triclocarban	1.4E+6	7.7E+3	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
tonalide	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
celestolide	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
phantolide	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]

Table C-8. Toxic Organics Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name	USETox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)		Human health cancer, freshwater (CTUh, cases/kg emitted)		Human Health noncancer, freshwater (CTUh, cases/kg emitted)	
		Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil	Emissions to Freshwater	Emissions to Natural Soil
clofibric acid	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
musk ketone	N/A[c]	7.0E+3[d]	1.6E+2[d]	-[d]	-[d]	3.5E-6[d]	1.4E-7[d]
diuron	diuron	6.0E+4	4.6E+3	-	-	6.6E-6	5.1E-7

a – Characterizations factors sourced from Rahman et al. 2018.

b – Characterization factors sourced from Alfonsín et al. 2014.

c – Chemical is not present in the current USEtox™ LCIA method.

d - Estimated using the median of toxic organics with available characterization factors.

APPENDIX D
DETAILED CHARACTERIZATION OF DISINFECTION BYPRODUCT FORMATION POTENTIAL IN STUDY TREATMENT CONFIGURATIONS

Appendix D: Detailed Characterization of Disinfection Byproduct Formation Potential in Study Treatment Configurations

D.1 Disinfection Byproducts

Disinfection of wastewater treatment plant (WWTP) effluent is a necessary practice to minimize the acute risk associated with exposure to microbial pathogens, however it must be balanced with the chronic risk posed by the creation of disinfection byproducts (DBPs). DBPs are a class of chemical compounds that can be harmful to both aquatic and human health (Boorman G A 1999; Nieuwenhuijsen et al. 2000; Mizgireuv et al. 2004; Villanueva et al. 2004; Muellner et al. 2007; Richardson et al. 2007; Watson et al. 2012). Similar to other emerging contaminants, the understanding of the occurrence and variety of this class of chemicals is continually expanding as new analytical techniques enable finer characterization of individual compounds, though even by 2007 over 600 DBPs had been reported in the literature (Richardson et al. 2007).

DBPs are formed when DBP precursors, generally organic carbonaceous or nitrogenous compounds, are oxidized during chlorination or chloramination (Christman et al. 1983). By regulation, DBPs are managed at drinking water treatment plants, as their presence in water supplies poses a direct threat to human health (Sedlak and Gunten 2011; U.S. EPA 2015d). However, as water recycling and reclamation programs expand (and as indirect potable reuse continues), management of DBPs and DBP precursors has become increasingly important at the WWTP as well (Krasner et al. 2008; L. Tang et al. 2012).

In the U.S., DBPs are mainly regulated by the U.S. EPA through the Stage 1 and 2 Disinfectants/DBP Rules (U.S. EPA 2015e), which include maximum contaminant levels for the sum of four trihalomethanes (THM4) and the sum of five haloacetic acids (HAA5) (Table D-1).

Regulation focuses on these two groups, in part, as they generally have the highest occurrence in drinking water. More importantly however, they serve as indicators for the presence of other less common, though potentially more toxic, DBPs (Muellner et al. 2007; Richardson et al. 2007; Krasner et al. 2008). More recently, the US EPA has begun to focus on these emerging, high priority DBPs (Richardson et al. 2002). Additionally, the California Department of Health Services established notification levels for several highly toxic nitrosamines, including *N*-Nitrosodimethylamine (NDMA) (Table D-1).

The importance of DBP and DBP precursor control at WWTPs has been growing in recent years for several reasons. First, the type of precursors formed through biological wastewater treatment are complex and, although overlapping with, are in many ways dissimilar from the natural organic matter (NOM)-derived precursors of drinking water-based DBPs. For example, effluent organic matter (EfOM) is generally composed of NOM, synthetic organic compounds and soluble microbial products (SMP) (Doederer et al. 2014), the latter of which can be further decomposed into organic compounds generated during biological treatment processes including (but not limited to) humic and fulvic acids, polysaccharides, proteins, nucleic acids, organic acids, amino acids, structural components of cells and products of energy metabolism (Barker and Stuckey 1999). Given this potential chemical diversity, lessons learned in drinking water DBP formation prediction and control are not directly translatable (Drewes and Croue 2002; L. Tang et al. 2012).

In addition to precursor complexity, there has been increasing concern over emerging and more toxic nitrogenous DBPs such as nitrosamines, halonitroalkanes, haloacetonitriles (HANs) and haloacetamides (Westerhoff and Mash 2002; Joo and Mitch 2007; Lee et al. 2007). Haloacetamides and HANs in particular are approximately two orders of magnitude more cytotoxic and genotoxic than the regulated THMs and HAAs (Muellner et al. 2007; Plewa and Wagner 2009). The precursors for these nitrogenous DBPs are mostly dissolved organic nitrogen (DON) compounds, which are removed to varying degrees depending on the type of treatment process utilized. Secondary effluents are particularly rich in DON (Huang et al. 2016), which can be removed to varying degrees through the addition of nitrification and denitrification biological nutrient removal (BNR) processes (Huo et al. 2013). However, in a study of an A2O (anaerobic, anoxic, oxic), AO (anaerobic, oxic) and MBR treatment, it was found that approximately half of wastewater-derived DON was of low molecular weight (capable of passing through a 1 kDa ultrafilter) which is not effectively removed by BNR processes (Huo et al. 2013). Moreover, the low molecular weight fraction that remains after biological treatment also tends to be hydrophilic, which is challenging for even chemical and physical methods to remove (Pehlivanoglu-Mantas and Sedlak 2008; Huo et al. 2013).

A further complication is the effect of nitrogen, ammonia in particular, on the reaction kinetics of chlorination and chloramination. For example, formation of halogenated DBPs like THMs and HAAs can be greatly reduced if free chlorine is minimized in the disinfection process (Krasner et al. 2009b). This is done by either using chloramines directly or maintaining the Cl_2/N (mass/mass) ratio below 10 so that any free chlorine is quenched by ammonia. Ironically however, this effective control of halogenated DBPs favors the formation of more toxic nitrogenous DBPs like NDMA, especially when applied to poorly nitrified (high DON) effluent (Krasner et al. 2008; Sedlak and Gunten 2011). Thus, the presence of precursors does not necessarily entail DBP formation, which further depends on site-specific operational characteristics like disinfection practices.

Last, DBP precursors formed in biological treatment processes can potentially be recalcitrant, as they are generally composed of cellular debris leftover from substrate metabolism and biomass decay (Barker and Stuckey 1999). Owing to this potential recalcitrance, there is evidence of persistence at least on the order of days, which is of relevance for a typical river indirect potable reuse scenario. In a multi-season survey of a river determined to be effluent dominated (determined through use of primidone, a conservative wastewater tracer), Krasner et al. (2008) documented the presence of EfOM-derived nitrogenous DBP precursors at downstream locations, including the intake of a water treatment plant, with concentrations that suggested dilution, not degradation, to be the primary attenuation mechanism. Results for carbonaceous precursors, which tend to be humic compounds, were masked by the naturally high humic content of the river water.

Given that the formation potential of DBPs is dependent upon numerous variables which can change daily, for purposes of this study, it was decided to use the formation potential (FP) of DBPs (DBPFP) as a more conservative indicator of the concentration of DBPs that could be formed by the various treatment configurations used in this study. Moreover, FP is determined using a standardized procedure, eliminating variability that may arise owing to different disinfection practices, allowing for a clearer distinction between the effects of different treatment approaches on precursor control. Accordingly, to characterize the effects of the nine Study configurations on DBP formation, a comprehensive dataset linking effluent water quality to DBPFP was used for this analysis (Krasner et al. 2008). The DBP and DBP groups included in the study included the regulated carbonaceous DBPs (THMs and HAAs) along with emerging and more toxic carbonaceous and nitrogenous DBPs and are outlined in Table D-1. The general approach is discussed further below.

Table D-1. Summary of Regulated Disinfection Byproducts

DBP (group/compound)	Characteristics	Precursors	Limit	Regulatory Authority
Trihalomethanes (THM)[1,2]				
Chloroform	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	80 µg/L (TTHM)	U.S. EPA, Stage 1/2 DBP Rule
Bromodichloromethane (BDCM)				
Chlorodibromomethane (DBCM)				
Bromoform				
Haloacetic Acids (HAA)[2,3]				
Monochloroacetic acid	carbonaceous, halogenated	influent refractory NOM, EfOM, nitrified effluent, humic compounds	60 µg/L (HAA5)	U.S. EPA, Stage 1/2 DBP Rule
Dichloroacetic acid (DXAA)				
Trichloroacetic acid (TXAA)				
Bromoacetic acid				
Dibromoacetic acid				
Nitrosamines[4]				
N-nitrosodimethylamine (NDMA)	nitrogenous, unhalogenated	DON, dimethylamine	10 ng/L	CA (action level)
Aldehydes				
Formaldehyde	carbonaceous, halogenated	DON, amino acids	NA	NA
Acetaldehyde				
Chloroacetaldehyde				
Dichloroacetaldehyde				
Trichloroacetaldehyde (chloral hydrate)				
Haloacetonitriles (HANs)				
Chloroacetonitrile	nitrogenous, halogenated	DON, amino acids	NA	NA
Bromoacetonitrile				
Iodoacetonitrile				
Trichloroacetonitrile				
Bromodichloroacetonitrile				
Dibromochloroacetonitrile				
Tribromoacetonitrile				

1 The four compounds together comprise the four primary trihalomethanes, sometimes referred to as TTHM or THM4

2 (U.S. EPA 2015d)

3 These five compounds together comprise the five primary haloacetic acids, sometimes referred to as HAA5

4 California Department of Health Services, action level

D.2 Methods

The results of a comprehensive survey of the effluent DBPFP of 23 U.S. WWTPs (Survey) were used to construct multiple linear regression models (Models) for the prediction of DBPFP based on effluent water quality (Krasner et al. 2008; Krasner et al. 2009a). The Survey was conducted at WWTPs that utilize a range of common treatment technologies with differing abilities to control DBP precursors, including humic substances, amino acids and other organic nitrogen compounds. The treatment processes included oxidation ditch, aerated lagoon, trickling filter, activated sludge, nitrification/denitrification, soil aquifer treatment (SAT), powdered activated carbon (PAC) and granular activated carbon (GAC), MBR, RO and various combinations. A primary objective of the Survey was to establish a database of water quality and operational parameters that could be used to evaluate global and site-specific correlations between water quality and DBPFP.

In order to draw meaningful conclusions from the Survey, the authors divided the 23 WWTPs into nine general categories according to the dominant biological or physical treatment process. Figure D-1 shows the resulting water quality ranges of Survey categories (25th, 50th and 75th percentiles), along with effluent quality of the nine Study configurations plotted against their most similar Survey category. Although additional water quality parameters were measured in the Survey, only those relevant parameters (i.e. carbonaceous or nitrogenous) that were also defined for Study configurations (Table 1-4) were used in this analysis.

As can be seen from Figure D-1, although many Study configurations fit within the ~~second~~ first and third quartiles (between the 25th and 75th percentile of results) of at least one Survey category, some parameters fall outside of any range. This is especially true for COD, which is particularly important as a surrogate for carbonaceous DBP precursors. Accordingly, a direct translation of Survey categories to Study configurations is not fully appropriate. Therefore, a multiple linear regression modelling approach was used to estimate which water quality parameters were most appropriate for predicting DBPFP, and their approximate effect.

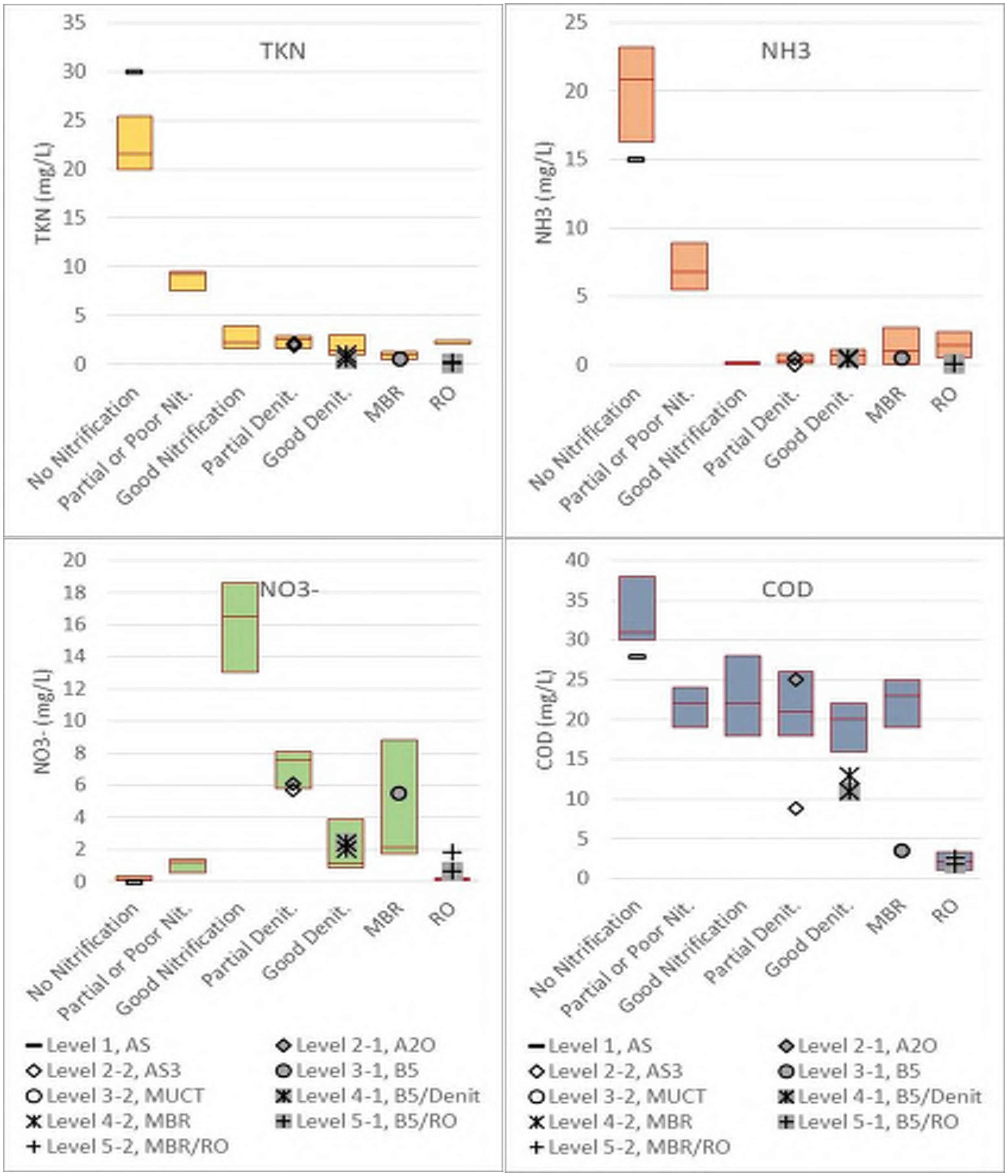


Figure D-1. Statistical summary of Survey category water quality, along with Study configuration water quality plotted within the most applicable Survey category. Ranges represent second and third quartiles, or 25th/50th/75th percentiles (Krasner et al. 2008; Krasner et al. 2009).

First, a linear correlation analysis was performed between relevant water quality parameters and DBPFP, using median values from each Survey category as input. Table D-2 shows the resulting correlations, in terms of the coefficient of determination (R^2). As shown, COD is the largest predictor of DBPFP for each DBP group, followed in most cases by TKN.

Table D-2. Linear Correlation Analysis between Median Water Quality Parameters and Median DBPFP for Survey Categories

DBPFP	Coefficient of Determination (R^2)			
	COD	**TKN**	**NH_3**	**$NO3^-$**
THMs	0.86	0.09	0.07	0.05
HANs	0.79	0.72	0.68	0.01
DXAAs	0.99	0.29	0.26	0.03
TXAAs	0.86	0.24	0.20	0.05
dihaloacetaldehydes	0.88	0.59	0.57	0.00
trihaloacetaldehydes	0.85	0.55	0.50	0.01
NDMA	0.73	0.18	0.20	0.00

Given the predictive ability of both COD and TKN especially, multiple linear regression models were constructed for each DBP group. Models were constructed in a stepwise fashion. Starting with COD as a single predictor, additional predictors were incorporated following the order of their coefficient of determination (Table D-2). Final Models reflect the combination of predictors that resulted in the greatest adjusted R^2. Although NH_3 was in many cases nearly as predictive as TKN, its contribution to overall model fit was generally less than TKN (i.e. the adjusted R^2 of models with COD and TKN were generally greater than that of models with COD and NH_3). Resulting Model coefficients, adjusted R^2 and overall significance (F) are provided in Table D-3. For DXAAs and TXAAs, COD alone provided the greatest predictive power (adjusted R^2). To illustrate the Models' predictive capabilities, Figure D-2 shows Model results using median water quality values for each Survey category as input, plotted against their actual DBPFP ranges (~~second~~ first and third quartiles). As shown, the Models are capable of predicting DBPFP within the 25^{th} to 75^{th} percentile ranges for most DBP categories, with the main exception of the Partial or Poor Nitrification and Good Nitrification categories for NDMA. Importantly however, the Models capture the low DBPFP provided by RO, which ultimately will provide for greater predictive capability in the water quality ranges not represented by Survey categories but occupied by many of the Study configurations (recall Figure D-1).

Table D-3. Multiple Linear Regression Model Parameters, Fit and Significance

DBP	Coefficient			Adjusted R^2	F (Signif.)
	COD	**TKN**	**Intercept**		
THMs	11.09	-3.68	3.66	0.89	0.005
HANs	0.59	0.58	-1.58	0.96	0.001
DXAAs	5.31		-4.15	0.99	0.000
TXAAs	4.57		-0.87	0.83	0.003
dihaloacetaldehydes	0.21	0.12	-0.63	0.95	0.001

Table D-3. Multiple Linear Regression Model Parameters, Fit and Significance

DBP	Coefficient			Adjusted R^2	F (Signif.)
	COD	TKN	Intercept		
trihaloacetaldehydes	2.30	1.19	-5.34	0.89	0.006
NDMA	27.92	-2.52	-13.65	0.60	0.072

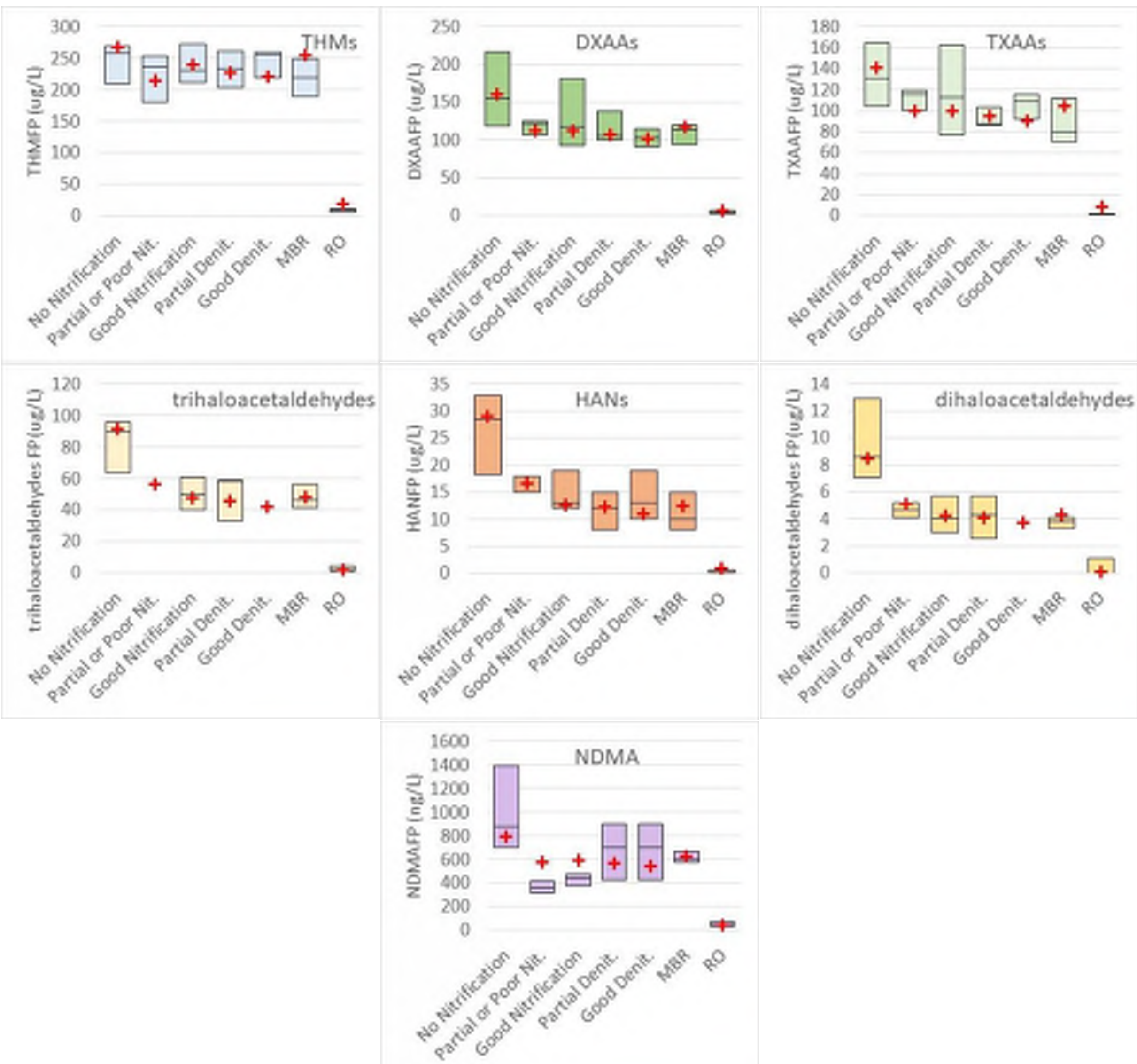


Figure D-2. Multiple linear regression model verification. Red crosses represent model results using median water quality values for each Survey category. DBPFP ranges represent second and third quartiles, or $25^{th}/50^{th}/75^{th}$ percentiles (Krasner et al. 2008; Krasner et al. 2009a).

Table D-4 presents the characterization factors used to estimate toxicity impacts associated with DBPs in treatment plant effluent. Not all DBPs included in this study have associated characterization factors listed in the most recent versions of USEtox™, versions 2.02 and 2.11. Characterization factors that were not otherwise available were estimated using the median value of all other DBPs for which data was available. Sources for individual characterization factors are listed in Table D-4.

Table D-4. DBP Toxicity Characterization Factors, USEtox™ version 2.11

Chemical Name/Class	USEtox Chemical Name	Freshwater Ecotoxicity, (CTUe, PAF m^3.day/kg emitted)	Human Health cancer, freshwater (CTUh, cases/kg emitted)	Human Health noncancer, freshwater (CTUh, cases/kg emitted)
		Emissions to Freshwater		
trihalomethanes[a]	N/A[c]	90	5.2E-7	8.0E-7
haloacetonitriles	chloroacetonitrile	7.6E+3	3.6E-7[b]	4.5E-7[b]
dichloroacetic Acid	dichloroacetic acid	52	6.7E-7	1.1E-6
trichloroacetic acid	trichloroacetic acid	34	2.9E-7	4.5E-7[b]
dihaloacet-aldehydes	N/A[c]	1.9E+2[b]	3.6E-7[b]	4.5E-7[b]
trihaloacet-aldehydes	chloral hydrate	2.5E+2	3.6E-7[b]	4.5E-7[b]
nitrosamines	N-nitrosodimethylamine	25	7.9E-4	N/A

a – Average of trichloromethane/chloroform, bromodichloromethane, dibromochloromethane, and tribromomethane.

b – Estimated using the median of DBPs with available characterization factors.

c – Chemical is not present in the current USEtox™ LCIA method.

D.3 Results and Discussion

Table D-5 and Figure D-3 give Model results for the nine Study treatment configurations. Effluent COD and TKN values (Table 1-4) were used as input, along with coefficients and intercepts given in Table D-3.

Table D-5. DBPFP Model Results for Study Treatment Configurations

Study Configuration	THMs	HANs	DXAAs	TXAAs	dihaloacet-aldehydes	trihaloacet-aldehydes	NDMA
	µg/L						ng/L
Level 1, AS	204	32	145	127	8.8	95	692
Level 2-1, A2O	274	14	129	113	4.9	54	680
Level 2-2, AS3	95	4.9	43	40	1.5	18	230
Level 3-1, B5	41	0.78	14	15	0.16	3.3	83
Level 3-2, MUCT	41	0.78	14	15	0.16	3.3	83
Level 4-1, B5/Denit	124	5.2	54	49	1.7	21	292
Level 4-2, MBR	144	6.6	65	59	2.2	26	347
Level 5-1, B5/RO	23	0.01	5.4	7.4	0.01	0.01	36
Level 5-2, MBR/RO	32	0.07	10	11	0.01	0.87	58

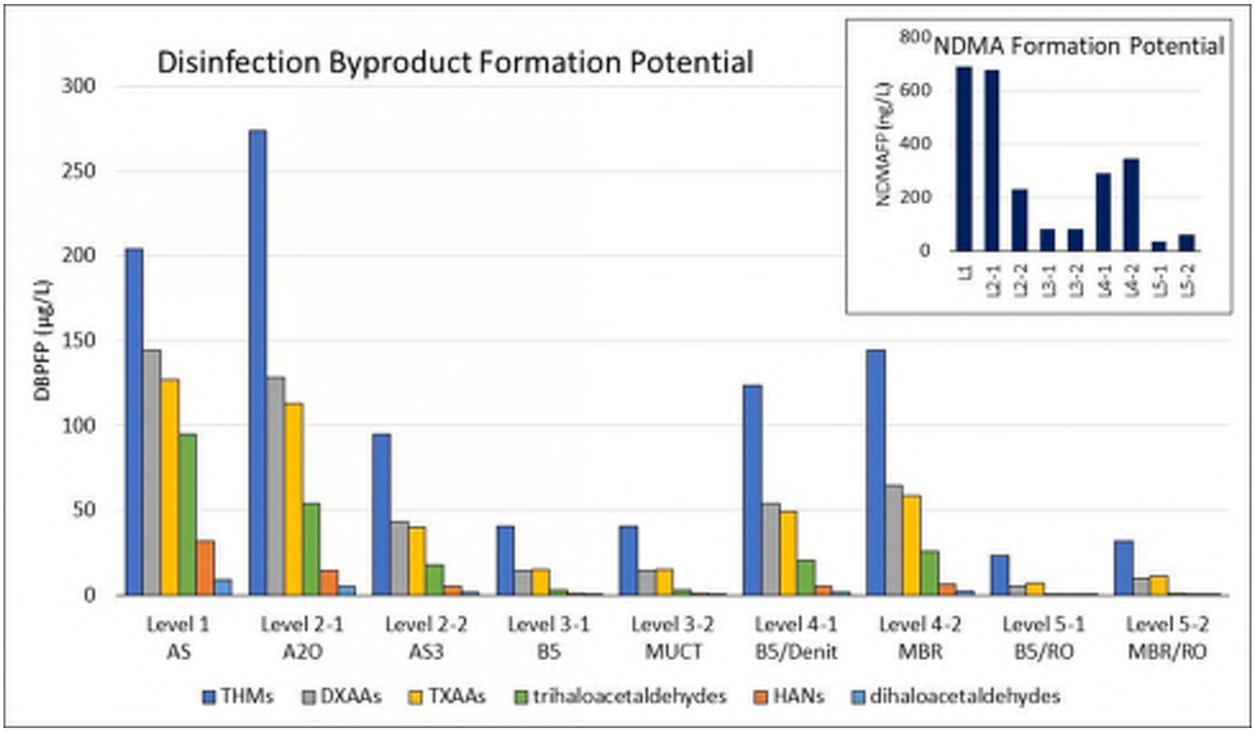


Figure D-3. DBPFP Model results for Study treatment configurations.

The formation potentials presented above are an upper bound to what could be formed at the WWTP. Using THMs as an example, ranges of THMs that actually formed at the surveyed WWTPs were also a function of chlorine dose and the Cl_2/N ratio. When the Cl_2/N ratio was above 10, allowing for the creation of free chlorine and enhanced THM formation, the 10^{th} and 90^{th} percentile concentrations of THMs were 20 µg/L and 80 µg/L, respectively (Krasner et al. 2009b). Compared to the formation potentials determined for each of the Survey groups (illustrated in Figure D-2) with medians largely in the range of 200-250 µg/L, this implies that upon discharge, there remains considerable additional formation potential in the form of unreacted precursors. Similarly, when the Cl_2/N ratio was less than 10, favoring chloramine creation and NDMA formation, the 10^{th} and 90^{th} percentile of observed concentrations of NDMA were 4 and 122 ng/L, compared to formation potentials that were sometimes an order of magnitude greater (also illustrated in Figure D-2). Thus, depending on factors like chlorination, temperature and pH (Doederer et al. 2014), which are assumed constant in Study configurations, formation of DBPs prior to discharge may be on the order of 10-50% of the formation potentials indicated above in Table D-5 and Figure D-3.

APPENDIX E
DETAILED COST METHODOLOGY

Appendix E: Detailed Cost Methodology

Appendix E includes supporting details for the methodology used to estimate costs associated with the nine wastewater treatment configurations. Appendix E.1 presents the unit design values for the unit processes included in CAPDETWorks^{TM}. Appendices E.2, E.4, B.4, E.6, and E.7 present the detailed cost methodologies for the dechlorination, ultrafiltration, reverse osmosis, and deep well injection, respectively. Appendix E.8 presents the CAPDETWorks™ file used to develop the direct cost factors discussed in Section 3.3.1.

E.1 <u>CAPDETWorks™ Process Unit Design Values</u>

This appendix includes the initial CAPDETWorks™ design values for the unit processes included in the nine wastewater treatment configurations. As discussed in Section 3.2.2, ERG revised some of the design values during development of the CAPDETWorks™ models to achieve the effluent wastewater objectives for each treatment level and/or address warnings in the CAPDETWorks^{TM}. For example, CAPDETWorks™ calculates the number of mixers for the Biological Nutrient Removal 3/5 Stage and provides a warning if the horsepower (HP) per mixer exceeds the CAPDETWorks™ recommended 5 HP/mixer. In this instance, ERG increased the number of mixers to eliminate the warning so the design reflected all of the equipment necessary. The final design values used for each wastewater treatment configuration are included in the final CAPDETWorks™ cost output discussed in Section 5. The following unit processes are not in CAPDETWorks^{TM}: modified University of Cape Town, 4-stage Bardenpho, fermentation, ultrafiltration, reverse osmosis (including pretreatment), deep well injection for brine disposal, and dechlorination. Costs for these unit processes were developed outside of CAPDETWorks™ and are documented in Sections 3.2.3.1 through 3.2.3.7 of this report.

ERG reviewed *EPA's Municipal Nutrient Removal Technologies Reference Document (U.S. EPA OWM, 2008b), WERF's Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk, 2011), EPA/ORD's Nutrient Control Design Manual (U.S. EPA ORD, 2010), and additional EPA wastewater treatment process fact sheets to confirm that the CAPDETWorks™ default design values (Hydromantis, 2014) are appropriate for use for this study. Based on our review, ERG used the CAPDETWorks™ default design values for the unit processes below that are included in one or more of the wastewater treatment configurations. Appendix E.1.14 includes key parameters and the default design values for these unit processes (Hydromantis, 2014).

- Membrane Bioreactor
- Sand Filter
- Centrifugation – Sludge

The remainder of Section E.1 provides the initial design values used for each of the remaining CAPDETWorks™ unit processes included in the nine wastewater treatment configurations.

E.1.1 Preliminary Treatment – Screening and Grit Removal

The default Preliminary Treatment design values were used. Key parameters and default design values for Preliminary Treatment – Screening include:

- Cleaning Method: Mechanically Cleaned

Key parameters and default design values for Preliminary Treatment – Grit Removal include:

- Type of Grit Removal: Horizontal
- Number of Units: 2
- Volume of Grit: 4.0 ft^3/MGal
- Detention Time: 2.5 min

However, the resulting purchased equipment costs were about half the construction costs presented in *Wastewater Technology Fact Sheet – Screening and Grit Removal* (U.S. EPA, 2003b). As a result, ERG doubled the CAPDETWorks™ Preliminary Treatment purchased equipment costs for all nine wastewater treatment configurations.

E.1.2 Primary Clarifier

The default Primary Clarifier design values were modified as follows, as recommended in *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014):

- Sidewater depth: 12.0 ft (instead of 9.0 ft)
- Underflow concentration: 3.5% (instead of 4.0%)

Note that this sidewater depth and underflow concentration are within CAPDETWorks™'s recommended ranges (7-12 ft and 3-6%, respectively) (Hydromantis, 2014).

Additional key parameters and default design values for Primary Clarifier include:

- Type of Clarifier: Circular
- Surface Overflow Rate: 1,000 gal/ft2-d
- Weir Overflow Rate: 15,000 gal/ft-d
- Suspended Solids Removal: 58%
- BOD Removal: 32%
- COD Removal: 40%
- TKN Removal: 5%
- Phosphorous Removal: 5%

E.1.3 Plug Flow Activated Sludge

Because the Level 1 wastewater treatment configuration represents a system that is not designed for nitrogen removal, and Level 2-2 requires higher effluent ammonia levels for the subsequent nitrification/denitrification processes, the default Plug Flow Activated Sludge design values was modified as follows:

- Process Design: Carbon Removal Only (instead of default Carbon Plus Nitrification)

Additional key parameters and default design values for Plug Flow Activated Sludge include:

- Aeration Type: Diffused Aeration
- Bubble Size: Fine Bubble
- Solids Retention Time (SRT): 10 days
- Mixed Liquor Suspended Solids (MLSS): 2,500 mg/L

E.1.4 Biological Nutrient Removal 3/5 Stage

When used for the Anaerobic/Anoxic/Oxic (A2O) unit process in Level 2-1, the default Biological Nutrient Removal 3/5 Stage design values were modified as follows:

- Number of Stages: 3-Stage (instead of 5-Stage)
- Internal Recycle from Anoxic to Anaerobic Zone: No (the A2O process does not include this recycle)
- Internal Recycle from the Oxic to Anoxic Zone: Yes
- Assume sufficient carbon in the wastewater to denitrify without an additional carbon source
- Effluent Total Kjeldahl Nitrogen (TKN): modified to achieve the 8 mg/L target effluent total nitrogen (TN) concentration
- Effluent Total Phosphorous (TP): modified to achieve the 1 mg/L target effluent TP concentration

When used for the 5-Stage Bardenpho unit process in Levels 3-1, 4-1, 5-1, and 5-2, the default Biological Nutrient Removal 3/5 Stage design values were modified as follows:

- Number of Stages: 5-Stage (instead of 3-Stage)
- Internal Recycle from Anoxic to Anaerobic Zone: No
- Internal Recycle from the Oxic to Anoxic Zone: Yes
- Effluent TKN: modified to achieve the target effluent total nitrogen concentrations of:
    - Level 3-1: 4–8 mg/L TN
    - Level 4-1: 3 mg/L TN

— Levels 5-1 and 5-2: 2 mg/L TN

- Effluent TP: modified to achieve the target effluent total phosphorous concentrations of:
  - Level 3-1: 0.1–0.3 mg/L TP
  - Level 4-1: 0.1 mg/L TP
  - Levels 5-1 and 5-2: <0.2 mg/L TP

In addition to the specific modifications proposed above, for instances when CAPDETWorks™ provided a warning that the number of mixers was insufficient for each mixer to be less than 5 HP/mixer, the CAPDETWorks™ default number of mixers per tank was increased until the mixers were less than 5 HP/mixer.

Additional key parameters and default design values for Biological Nutrient Removal 3/5 Stage include:

- Aeration Type: Diffused Aeration
- Bubble Size: Fine Bubble
- Total Reactor SRT: 15 days

E.1.5 Denitrification – Suspended Growth

The default Denitrification – Suspended Growth design values were modified for effluent nitrate to achieve the effluent total nitrogen concentration target for Level 2-2 of 8 mg/L TN.

In addition to the specific modifications proposed above, for instances when CAPDETWorks™ provided a warning that the number of mixers was insufficient for each mixer to be less than 5 HP/mixer, the CAPDETWorks™ default number of mixers per tank was increased until the mixers were less than 5 HP/mixer.

Additional key parameters and default design values for Denitrification – Suspended Growth include:

- Design SRT: 10 d
- MLSS: 2,500 mg/L

E.1.6 Denitrification – Attached Growth

The default Denitrification – Attached Growth design values were modified as follows:

- Allowable Effluent Nitrate:
  - Level 4-1: 3 mg/L TN
  - Levels 5-1 and 5-2: <0.02 mg/L TN (taking into consideration the RO TN removal)
- Application Rate: 1.5 gal/ft^2-min (instead of 1.0 gal/ft^2-min)

The recommended application rate matches that used in the analysis in WERF's *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk, 2011) and is more aligned with actual plant application rates of 2.2 and 3.0 gal/ft^2-min, as presented for two plants in the *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA OWM, 2008b). Note that this application rate is outside of CAPDETWorks™' recommended range (0.5 to 1.0 gal/ft^2-min). ERG reviewed the underlying cost curves for CAPDETWorks™' construction and O&M costs and considers the outputs to be reasonable at the 1.5 gal/ft^2-min application rate.

Additional key parameters and default design values for Denitrification – Attached Growth include:

- Methanol Requirement: 3 lb/lb NO_3
- Backwash Rate: 12 gal/ft^2-min

E.1.7 Nitrification – Suspended Growth

Because SRT is a key factor for achieving nitrification, the default Nitrification – Suspended Growth design values were modified as follows for the reasons described below:

- Design Basis: Specify Design SRT (instead of default Temperature Specific Growth Rates or pH Ammonia Sensitive Rates)
- Design SRT: 50 d (instead of 10 d)

Note that using a design basis that specifies the default Temperature Specific Growth Rates returned a unit design with a SRT of 5.89 hrs and hydraulic residence time (HRT) of 1.27 hrs, well below recommended SRT and HRT values[12]. Using a SRT of 24 d and the default MLSS of 2,500 mg/L returns a unit design with a HRT of 3.11 hrs, which is still below CAPDETWorks™ recommended minimum. A SRT of 50 d and the default MLSS of 2,500 mg/L returns a unit design with a HRT of 6.31 hours. These values are similar to those of the Western Branch WWTP with a 3-sludge system designed to achieve 1.0 mg/L effluent TP and 3.0 mg/L effluent TN. The Western Branch WWTP has nitrifying activated sludge system SRT ranging from 21.4 days (June) to 84.6 days (September), with an average of 47.6 days (U.S. EPA OWM, 2008b). As a result, ERG's recommended 50 d design SRT is reasonable.

Additional key parameters and default design values for Nitrification – Suspended Growth include:

- Aeration Type: Diffused Aeration
- Bubble Type: Fine Bubble
- MLSS: 2,500 mg/L

[12] A SRT of 24 days is recommended for general nitrification systems from *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA OWM, 2008b) and a minimum HRT of 6 hrs from CAPDETWorks™ (Hydromantis, 2014).

E.1.8 Chemical Phosphorus Removal

The default effluent phosphorus concentration target for each level that includes chemical phosphorous removal was adjusted to achieve the following effluent total phosphorous concentration targets:

- Level 2-2: 1 mg/L TP
- Levels 3-1 and 3-2: 0.3 mg/L TP
- Levels 4-1, 4-2, 5-1, and 5-2: 0.1 mg/L TP (remaining TP to achieve <0.02 mg/L effluent target for Level 5 configurations will be achieved with RO)

In addition, ERG revised the default chemical dosage to two times the stoichiometric alum dose, as recommended by the *Municipal Nutrient Removal Technologies Reference Document* (U.S. EPA OWM, 2008b).

Additional key parameters and default design values for Chemical Phosphorous Removal include:

- Metal Precipitant: Equivalent Aluminum

E.1.9 Secondary Clarifier

The default Secondary Clarifier design values were modified as followed:

- Surface overflow rate: 600 gal/ft^2-d (instead of 500 gal/ft^2-d)
- Sidewater depth: 14.5 ft (instead of 9.0 ft)

The surface overflow rate was modified to match WERF's *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011). Note that this surface overflow rate is within CAPDETWorks^{TM}' recommended range (200 to 800 gal/ft^2-day) (Hydromantis, 2014). CAPDETWorks^{TM}' background documentation generally describes that lower overflow rates are more appropriate for smaller plants and higher overflow rates are more appropriate for larger plants (Hydromantis, 2014). The sidewater depth and underflow concentrations were modified to within ranges recommended in *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014). Note that the sidewater depth is within CAPDETWorks^{TM}'s recommended ranges (7-15 ft) (Hydromantis, 2014).

Additional key parameters and default design values for Secondary Clarifier include:

- Underflow concentration: 1%
- Weir Overflow Rate – Maximum 15,000 gal/ft-d
- Effluent Suspended Solids: 20 mg/L

E.1.10 Chlorination

Chlorination using liquid hypochlorite is more common that gaseous chlorine due to safety concern and regulations on the handling and storage of pressurized liquid chlorine (Tchobanoglous et al., 2014). However, this analysis assumes use of gaseous chlorine because that is the only disinfection alternative used by CAPDETWorks™ (Hydromantis, 2014).

When used for wastewater treatment configurations where solids removal is completed with clarifiers (Level 1, Level 2-1, and Level 2-2), the default Chlorination design values were modified as follows:

- Contact Time at Peak Flow: 30 min
- Chlorine Dose: 10 mg/L

When used for wastewater treatment configurations where solids removal is completed with a sand filter or membrane bioreactor (Level 3-1, Level 3-2, Level 4-1, and Level 4-2), the default Chlorination design values were modified as follows:

- Contact Time at Peak Flow: 30 min
- Chlorine Dose: 8 mg/L

When used for wastewater treatment configurations with the majority of the flow going through reverse osmosis (Level 5-1 and Level 5-2), the default Chlorination design values were modified as follows:

- Contact Time at Peak Flow: 30 min
- Chlorine Dose: 5 mg/L

ERG developed these design input value recommendations based on consideration of CAPDETWorks™ default design values (Hydromantis, 2014) and assumptions provided in *Striking the Balance Between Nutrient Removal in Wastewater Treatment and Sustainability* (Falk et al, 2011), which were further supported based on an evaluation of design information provided in EPA's *Onsite Wastewater Treatment Systems Manual* (EPA, 2002).

E.1.11 Gravity Thickener

The default Gravity Thickener design values were modified as follows:

- Based On: Mass Loading (instead of Settling)
- Mass Loading: 30 lb/ft^2-d (instead of 10 lb/ft^2-d)
- Underflow Concentration: 4.0% (instead of 5.0%)
- Depth: 11.5 ft (instead of 9 ft)
- Standard 90 ft Diameter Thickener: $1,000,000 (instead of $154,000)

Note that using the default Settling design basis returned a unit design with a HRT of 20.3 hr, well above recommended HRT values (maximum HRT of 6 hrs from CAPDETWorks™ (Hydromantis, 2014)). As a result, ERG used CAPDETWorks™ maximum recommended mass loading rate rather than the default design value of 10 lb/ft^2-d to reduce the gravity thickener HRT and the risk of creating anaerobic conditions that can lead to phosphorous release from the sludge. Using the recommended mass loading results in a HRT of 6.78 hrs, which is reasonable compared to CAPDETWorks™ recommended 6 hr maximum (Hydromantis, 2014).

The underflow concentration was modified to within the range in *Wastewater Engineering: Treatment and Resource Recovery* (Tchobanoglous et al., 2014). The depth was modified to within the range recommended in *Biosolids Technology Fact Sheet – Gravity Thickening* (U.S. EPA, 2003a). The standard 90 ft diameter thickener cost was modified to $1,000,000 so the gravity thickener purchased equipment cost was comparable to the costs in *Biosolids Technology Fact Sheet – Gravity Thickening* (U.S. EPA, 2003a).

E.1.12 Anaerobic Digestion

The default Anaerobic Digestion design values were modified to match the Gravity Thickener underflow concentration (see Section E.1.11) as follows:

- Concentration in Digester: 4.0% (instead of 5.0%)

Note that this concentration in digester is within CAPDETWorks™' recommended range (3 to 7%) (Hydromantis, 2014).

Additional key parameters and default design values for Anaerobic Digestion include:

- Percent Volatile Solids Destroyed: 50%
- Minimum Detention Time in Digester: 15 d
- Fraction of Influent Flow Returned as Supernatant: 2%
- Supernatant Concentrations:
  - — Suspended Solids: 6,250 mg/L
  - — BOD: 1,000 mg/L
  - — COD: 2,150 mg/L
  - — TKN: 950 mg/L
  - — Ammonia: 650 mg/L

E.1.13 Haul and Landfill - Sludge

ERG modified the following default design values as follows to correspond with the 25 mi one-way distance used in the ORCR CCR rule (ERG, 2013):

- Distance to Disposal Site: 25 mi one way

- Disposal Cost Based On: Sludge Disposal per Ton

E.1.14 Key Default Design Parameters for Select Unit Processes

Membrane Bioreactor

Key parameters and default design values for Membrane Bioreactor include:

- Average Net Flux: 20 L/m2-hr
- Effluent Suspended Solids: 1.0 mg/L
- Underflow Concentration: 1.2%
- Scour Air Cycle Time: 20 s
- Scour Air On Time: 10 s
- Physical Cleaning Interval: 9 min
- Physical Cleaning Duration: 1 min
- Chemical Cleaning Interval: 7 days
- Backflush Flow Factor: 1.25

Sand Filter

Key parameters and default design values for Sand Filter include:

- Number of Layers: 4
- Layer 1: Anthracite
- Layers 2, 3, and 4: Sand
- Loading Rate: 6 gpm/ft^2
- Backwash Time: 10 min

Centrifugation – Sludge

Key parameters and default design values for Centrifugation – Sludge include:

- Cake Solids Content: 9%
- Solids Capture: 90%
- Number of Units: 2
- Operation: 8 hr/d for 5 d/wk

E.2 Dechlorination

Listed below are the capital cost elements included for dechlorination using sodium bisulfite ($NaHSO_3$), with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate.

Capital Costs

1. Dechlorination Contact Tank, Dechlorination Building, Chemical Storage Building, and Miscellaneous Items (e.g., grass seeding, site cleanup, piping).

   Costed in 2014 $ using the CAPDETWorks™ chlorination unit process and selecting unit process input values to simulate dechlorination rather than chlorination.

   - Revised the CAPDETWorks™ input contact time at peak flow to 5 minutes to reflect the dechlorination unit contact time:
     - CAPDETWorks™ uses the contact time at peak flow to calculate the contact tank volume (Hydromantis, 2014).
     - EPA's Wastewater Technology Fact Sheet – Dechlorination recommends dechlorination contact times of one to five minutes to react with free chlorine and inorganic chloramines (U.S. EPA, 2000). ERG selected five minutes to ensure adequate dechlorination prior to discharge.
   - Revised the CAPDETWorks™ input chemical dose to 3.75 mg/L to reflect the sodium bisulfite solution dose:
     - CAPDETWorks™ uses the chemical dose to size the chemical feed storage building (Hydromantis, 2014).
     - ERG selected the input chlorine dose for each wastewater treatment configuration to achieve approximately 1 mg/L residual chlorine. Specifically, for the chlorination unit process, ERG used 10 mg/L for Levels 1, 2-1, and 2-2; 8 mg/L for levels 3-1, 3-2, 4-1, and 4-2; and 5 mg/L for Levels 5-1 and 5-2 (see Appendix E.1.8).
     - EPA's Wastewater Technology Fact Sheet – Dechlorination indicates that, on a mass basis, 1.46 parts of sodium bisulfite is required to dechlorinate 1.0 parts of residual chlorine (U.S. EPA, 2000), which ERG rounded to 1.5 parts of sodium bisulfite. Assuming a 40% by weight sodium bisulfide in solution results in a sodium bisulfite dose of 3.75 mg/L, as presented in Equation E-1.

$$3.75\ NaHSO_3\ 40\%\ \text{Solution}\ \left(\frac{mg}{L}\right) = 1.5\ NaHSO_3\ 100\%\ \text{Solution}\ \left(\frac{mg}{L}\right) \times \frac{100\%\ NaHSO_3\ \text{Solution}}{40\%\ NaHSO_3\ \text{Solution}}$$

Equation E-1

2. Sodium Bisulfite Liquid Feed System
   - See Table E-1 for calculation of sodium bisulfite liquid feed rates for each wastewater treatment configuration.
   - For sodium bisulfite liquid feed rates less than 100 gph, purchase cost of $5,000, plus $300 for transport, in 2011 $, based on telephone contact with EnPro Technologies (ERG, 2011b). Escalated to 2014 $ using RSMeans Construction Cost Index and the calculation presented in Section 3.2.1 (RSMeans, 2017).
   - Used the installation factor of 0.3 from CAPDETWorks™ for the installation of the dechlorination system to account for installation and other costs such as electrical, piping, painting, etc. associated with the sodium bisulfite system (Hydromatis, 2014).
3. Total capital costs were estimated by applying the CAPDETWorks™ direct and indirect cost factors to the purchase costs, using the factors and methodology described in Section 3.3 of this report.

Table E-1. Sodium Bisulfite Liquid Feed Rate Calculation

Level	$NaHSO_3$ Rate (gph) =	Sodium Bisulfite Dose (mg/L)	× Gram to Milligram Factor (g/mg)	× $NaHSO_3$ Dose Factor (calculated in Table E-2)	× Estimated Wastewater Treatment Flow (MGD)	× 1,000,000 gal/Mgal	× Day to Hour Factor (day/hr)
Level 1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 2-1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 2-2	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 3-1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 3-2	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 4-1	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 4-2	2.6	3.8	1.0E-3	1.7E-3	10	1.0E+6	0.04
Level 5-1	4.3	7.5	1.0E-3	1.7E-3	8.2	1.0E+6	0.04
Level 5-2	4.4	7.5	1.0E-3	1.7E-3	8.3	1.0E+6	0.04

Table E-2. Sodium Bisulfite Dose Factor Calculation

$NaHSO_3$ Dose Factor =	1	/ (NaHSO3 Concentration (%)	× NaHSO3 Density (kg/L)	× 1,000 g/kg)
0.00168919	1	0.4	1.48	1000

E.3 Annual Costs

1. Operating Labor, Maintenance Labor, Materials and Supplies[13]
    - Costed in 2014 $ using the CAPDETWorks™ chlorination unit process to simulate dechlorination rather than chlorination.
    - Revised the CAPDETWorks™ input contact time at peak flow to 5 minutes and chemical dose to 3.75 mg/L to reflect the dechlorination unit contact time and dose (see justification in the Capital Cost section item #1).

2. Energy
    - One 0.5 HP feed system pump operated continuously for a calculated annual electrical requirement of approximately 6,500 kWh/yr (ERG, 2011b).
    - Using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $) (Hydromantis, 2014), total energy costs are approximately $650/yr.

3. Sodium Bisulfite
    - Calculated using:
        - Dosage rate of:
            - 1.5 mg/L for Levels 1, 2-1, 2-2, 3-1, 3-2, 4-1, and 4-2 (see justification in the Capital Cost section #1)
            - 3.0 mg/L for Levels 5-1 and 5-2 to also account for the chemicals required for RO pretreatment.[14]
        - Effluent flow rate from the chlorination unit process for each wastewater treatment configuration modeled in CAPDETWorks™.
    - Assumed a 40% by weight sodium bisulfide in solution.
    - Chemical cost of $344/ton of 40% sodium bisulfide solution in 2010 $ (ERG, 2014). This cost includes freight and assumes the chemical will be delivered in drums or totes. Escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017.

E.4 Methanol Addition

Listed below are the capital cost elements included for dechlorination using sodium bisulfite ($NaHSO_3$), with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate.

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[13] Materials and supplies include materials and replacement parts required to keep the facilities in proper operating conditions.

[14] The RO system requires 1 mg/L chlorine pretreatment and a corresponding sodium bisulfite dechlorination. ERG assumed the majority of the 1 mg/L chlorine would remain as chlorine residual. Therefore, the dechlorination sodium bisulfite dose is 1.5 mg/L neat. Capital costs for the RO pretreatment sodium bisulfite system are included in Appendix E.5.

Capital Costs

1. Methanol Storage Tank, Feed Pump, Control System, and Miscellaneous Items (e.g., piping).

   Costed in 2014 $ using the CAPDETWorks™ denitrification – attached growth (i.e., denitrification filter) unit process that includes methanol addition. Selected unit process input values to match the required nitrate reduction and used only the output associated with the methanol system.

   - Revised the CAPDETWorks™ influent wastewater average and minimum flow rates to 10.1 MGD and maximum flow rate to 20.1 MGD to match the influent flow rates for the 4-stage Bardenpho. CAPDETWorks™ uses the influent wastewater flow rates to calculate the methanol system capital cost (Hydromantis, 2014).
   - Revised the CAPDETWorks™ influent nitrate concentration to 8.24 mg/L to match the effluent from the 4-stage Bardenpho and the denitrification – attached growth input allowable effluent nitrate to 1.95 mg/L to match the necessary effluent nitrate concentration to achieve 3 mg/L total nitrogen (TKN effluent is 1.05 mg/L) for Level 4-2, MBR. CAPDETWorks™ uses the difference between the influent and allowable effluent nitrate concentration to calculate the methanol feed rate, which is used to calculate the methanol system capital cost (Hydromantis, 2014).

2. Methanol feed system cost (2014 $) from the CAPDETWorks™ output were added to the 4-stage Bardenpho capital costs for the Level 4-2, MBR.

3. Total capital costs for the 4-stage Bardenpho were estimated by applying the CAPDETWorks™ direct and indirect cost factors to the purchase costs, using the factors and methodology described in Section 3.3 of this report.

Annual Costs

1. Operating Labor, Maintenance Labor, Materials and Supplies[15], and Energy
   - CAPDETWorks™ does not calculate costs for operating labor, maintenance labor, materials and supplies, and energy for the methanol feed system separately from the denitrification – attached growth unit process. As a result, assumed the 4-stage Bardenpho operating labor, maintenance labor, materials and supplies, and energy include costs for the methanol feed system.
2. Methanol
   - CAPDETWorks™ calculates the methanol cost based on the influent nitrate and allowable effluent nitrate concentrations, as discussed in the

[15] Materials and supplies include materials and replacement parts required to keep the facilities in proper operating conditions.

Capital Costs section above. Used the default methanol cost of \$0.60/lb from CAPDETWorks™.

E.5 Ultrafiltration

Listed below are the capital cost elements included for ultrafiltration, with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate. Table E-3 and Table E-4 summarize the capital and O&M cost calculations, respectively.

Capital Costs

1. Membrane Filtration System – cost basis obtained from email contacts with Evoqua Water Technologies LLC, 2015 (ERG, 2015a). Escalated to 2014 \$ using RSMeans Construction Cost Index (RSMeans, 2017). For a 9 MGD system for this project[16], purchase costs for membrane equipment and appurtenances are approximately \$3.7 million. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.
2. Membrane Filtration Building – using equipment dimensions provided by Evoqua (ERG, 2015a), calculated a required building footprint of 8,040 square feet to house the system. Using the CAPDETWorks™ building unit cost of \$110/square foot, calculated a total capital building cost of approximately \$880,000.

Operating and Maintenance Costs

1. Operating Labor – transferred the operating labor costs from reverse osmosis (RO) (see Appendix E.6).
2. Maintenance Labor – transferred the operating labor costs from RO (see Appendix E.6).
3. Materials – membrane replacement cost of \$1,650 per membrane times an estimated 768 membranes for a 9 MGD system based on Evoqua (ERG, 2015a). Assumed membranes have a 7-year life based on Evoqua (ERG, 2015a). Escalated to 2014 \$ using RSMeans Construction Cost Index (RSMeans, 2017). Calculated materials costs of approximately \$240,000/yr.
4. Chemicals – membrane cleaning chemical costs estimated using chemical usage rates and costs per Evoqua (ERG, 2015a) and a \$0.03/lb freight cost from FreightCenter.com (ERG, 2011a), which were escalated to 2014 \$ using RSMeans Construction Cost Index (RSMeans, 2017), resulting in a total annual chemicals cost of approximately \$91,000/yr. Cleaning chemicals include citric acid, sodium hypochlorite, sulfuric acid, sodium hydroxide, and sodium bisulfite.

[16] Based on side stream treatment of 90 percent of the 10 MGD flow for Level 5-1 5-Stage Bardenpho with Sidestream Reverse Osmosis.

5. Energy – energy usage equal to the average of estimates provided by two sources:

   - Evoqua (ERG, 2015a) estimated energy usage of 0.5 kWh/kgal
   - WateReuse Research Foundation, 2014 estimated energy usage ranging from 0.75 to 1.1 kWh/kgal (average of 0.925 kWh/kgal)

   Used the average of the average estimated energy usage from these two sources, 0.7125kWh/kgal (average of 0.5 kWh/kgal and 0.925 kWh/kgal). For a 9 MGD system, and using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total annual energy costs are approximately $230,000.

Table E-3. Ultrafiltration Capital Costs

Equipment Cost Item	Size or Number	Units	Unit Cost	Total Cost	Year	2014 Purchased Cost	Total Capital Cost	Source
Ultrafiltration	9	MGD		$3,750,000	2015	$3,717,344		Evoqua (ERG, 2015a).
Ultrafiltration Building	8,040	sq. foot	$110	$884,400	2014		$884,400	Evoqua, 2015; building unit cost from CAPDETWorks™.

Table E-4. Ultrafiltration Operating and Maintenance Costs

Operating Labor	Labor (hrs/day)	Labor Rate ($/hr)	Days/yr	Annual Operating Labor Cost ($/yr)	Source
Ultrafiltration	1	$51.50	365	$18,798	Evoqua (ERG, 2015a); transferred 1 hour/day operating labor from RO (see Table B.4-3); labor rate from CAPDETWorks™ for Operator.
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Maintenance Labor Cost ($/yr)**	**Source**
Ultrafiltration	1	$51.50	365	$18,798	Evoqua (ERG, 2015a); transferred 1 hour/day maintenance labor from RO (see Table B.4.3); labor rate from CAPDETWorks™ for Operator.
Material	**Annual Materials Cost ($/yr)**				**Source**
Membrane Replacement	$124,473				Evoqua (ERG, 2015a).

Table E-5. Ultrafiltration Operating and Maintenance Costs

Membrane Cleaning Chemicals	Usage (gal/yr)	Cost ($/gal)	Annual Chemicals Cost ($/yr)	Source
50% Citric Acid	4,551	$10.41	$47,369	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).
50% Sulfuric Acid	2,891	$4.56	$13,183	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).
12.5% Sodium Hypochlorite	2,997	$0.89	$2,674	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).
25% Sodium Hydroxide	10,366	$2.43	$25,176	Evoqua (ERG, 2015a) (multiplied usage by 2 as usage data based on 50% solution and cost data based on 25% solution); freight per FreightCenter.com (ERG, 2011a).
12.5% Sodium Bisulfite	1,223	$2.43	$2,970	Evoqua (ERG, 2015a); freight per FreightCenter.com (ERG, 2011a).

Table E-6. Ultrafiltration Operating and Maintenance Costs

Energy	Rate (kWh/day)	Annual Energy (kWh/yr)	Energy Rate ($/kWh)	Annual Energy Cost ($/yr)	Source
Ultrafiltration	6,413	2,340,563	$0.10	$234,056	Evoqua (ERG, 2015a); WateReuse, 2014; and CAPDETWorks™.

E.6 Reverse Osmosis (RO)

Listed below are the capital cost elements included for RO, with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate. Table E-7 and Table E-8 summarize the capital cost calculations for the 90 and 85 percent flow options, respectively (Levels 5-1 and 5-2), while Table E-9 and Table E-12 summarize the O&M cost calculations for the 90 and 85 percent flow options, respectively (Levels 5-1 and 5-2).

Capital Costs

1. RO System – cost basis obtained from telephone contacts with Wigen Water Technologies, 2015 (ERG, 2015b). Prepared a cost curve based on purchase costs provided for 2.5, 5, and 10 MGD systems (see Figure E-1).

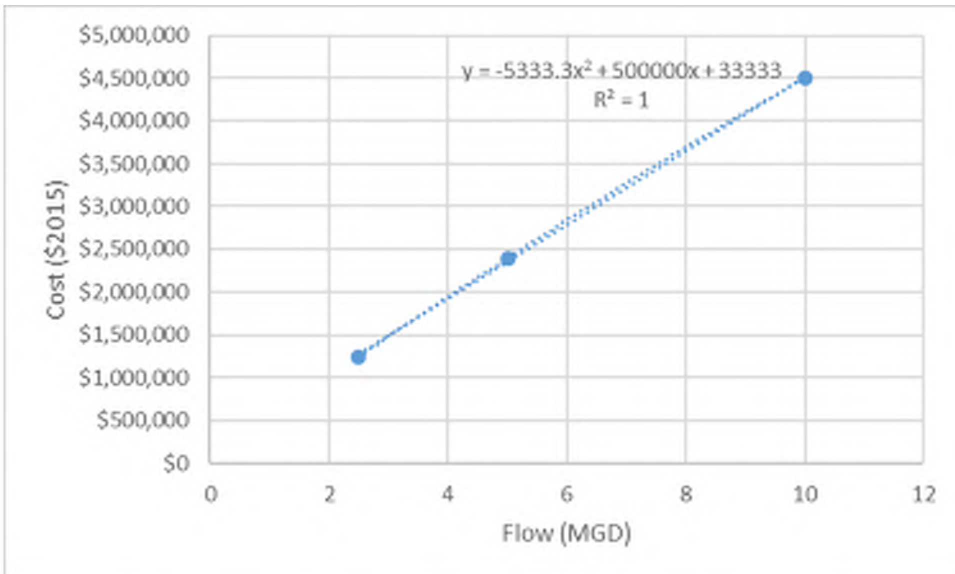

Figure E-1. RO Purchase Cost Curve

Escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). For a 9 MGD and 8.5 MGD system for this project[17], purchase costs for membrane equipment and appurtenances are approximately $4.4 million and $4.2 million, respectively. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.

2. RO Building – using equipment dimensions provided by Wigen (ERG, 2015b), calculated a required building footprint of 4,960 square feet to house the system.

[17] Based on side stream treatment of 85% and 90% of the 10 MGD flow for Level 5-1 5-Stage Bardenpho with Sidestream Reverse Osmosis and Level 5-2 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis, respectively.

Using the CAPDETWorks™ building unit cost of $110/square foot, calculated a total capital building cost of approximately $550,000.

3. Chlorine Feed System – assumed a single, shared chlorine feed system for the RO biofouling control pretreatment and final wastewater disinfection. Costs for the shared chlorine feed system were estimated as part of the CAPDETWorks™ chlorine wastewater disinfection module.

4. Dechlorination and Antiscalant Feed Systems – purchase cost of $5,000, plus $300 for transport, for each feed system based on telephone contact with EnProTechnologies (ERG, 2011b). Escalated to 2014 $ Using RSMeans Construction Cost Index (RSMeans, 2017), resulting in a 2014 purchase cost of approximately $5,900 for each of these two systems. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.

5. Brine Surge Sump – estimated an in-ground concrete brine collection sump volume based on an assumed 60-minute residence time (best professional judgement) and a RO rejection rate of 20 percent based on telephone contacts with Wigen (ERG, 2015b). Calculated a total capital cost of approximately $190,000 for the 90% side stream treatment option, and approximately $180,000 for the 85% side stream treatment option, using a concrete basin cost curve developed using *RSMeans Building Construction Cost Data* (see Figure E-2). Escalated from $2010 to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017).

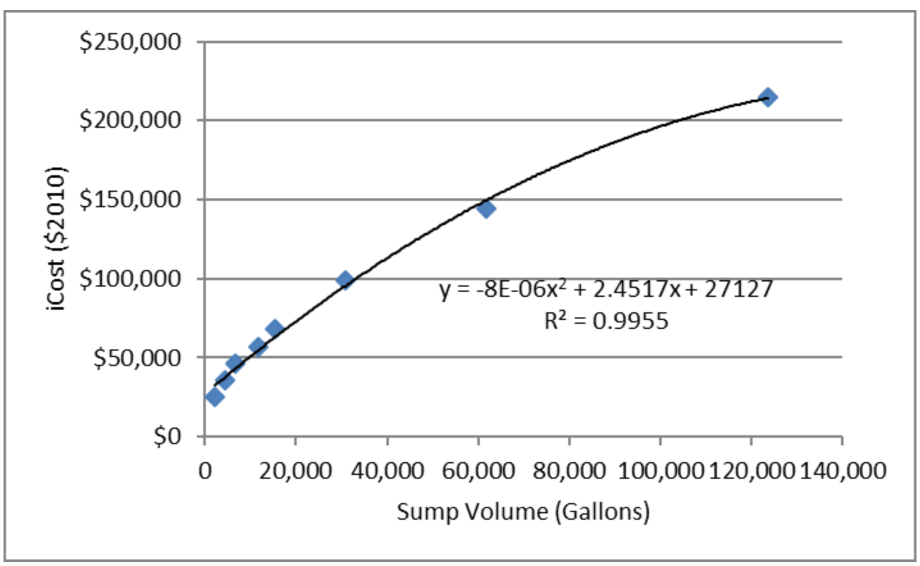

Figure E-2. Brine Surge Sump Total Capital Cost Curve

Operating and Maintenance Costs

1. Operating Labor – One labor hour per day based on Wigen (ERG, 2015b) and CAPDETWorks™ operator labor rate of $51.50/hour (2014 $) for a total operating labor cost of approximately $19,000/yr.
2. Maintenance Labor – One labor hour per day based on best professional judgement that maintenance labor requirements would be similar to, and not greater than, operating labor requirements, and sufficient for maintenance activities such as lubrication, troubleshooting, and installing replacement parts. Used the CAPDETWorks™ operator labor rate of $51.50/hour (2014 $), for a total annual maintenance labor cost of approximately $19,000/yr.
3. Materials – membrane replacement cost of $450 per membrane times an estimated 2,000 membranes for a 10 MGD system based on Wigen (ERG, 2015b), scaled to 9 MGD and 8.5 MGD systems for this project. Assumed membranes has a 4-year life based on Wigen (ERG, 2015b). Escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). Calculated materials costs of approximately $162,000/yr for the 90% side stream treatment option, and approximately $150,000/yr for the 85% side stream treatment option.
4. Antiscalant Chemicals – calculated using dosage rate of 3 mg/L of Vitec 3000 per Wigen (ERG, 2015b). Vitec 3000 chemical cost of approximately $1,300/500 lb provided by Water Surplus, 2015 and a $0.03/lb freight cost from FreightCenter.com (ERG, 2011a), for a total antiscalant chemicals cost of approximately $220,000/yr and $200,000/yr for the 90% and 85% side stream treatment options, respectively.
5. Membrane Cleaning Chemicals – per Wigen (ERG, 2015b), two cleaning chemicals are each 4,000 lb/yr for a 2.5 MGD system at a cost of $5/lb. Scaled to 9 MGD and 8.5 MGD for this project and added a $0.03/lb freight cost from FreightCenter.com (ERG, 2011a), for a total membrane cleaning chemicals cost of approximately $145,000/yr and $137,000/yr for the 90% and 85% side stream treatment options, respectively.
6. Chlorine and Sodium Bisulfite Pretreatment Chemicals – modified the CAPDETWorks™ chlorine wastewater disinfection module, and the supplemental dechlorination module developed for this project, to incorporate the additional chemical requirements associated with RO pretreatment. Assumed a 1 mg/L chlorine dosage rate per Wigen (ERG, 2015b) and a corresponding dechlorination dosage rate.
7. RO System Energy – energy usage equal to the average of estimates provided by two sources:
   - Wigen (ERG, 2015b) estimated energy usage ranging from 3,000 to 6,000 kWh/day for a 2.5 MGD system (average of 4,500 kWh for a 2.5 MGD system, or 1.8 kWh/kgal)
   - WateReuse Research Foundation, 2014 estimated energy usage ranging from 1.9 to 2.3 kWh/kgal (average of 2.1 kWh/kgal)

Used the average of the average estimated energy usage from these two sources, 1.95kWh/kgal (average of 1.8 kWh/kgal and 2.1 kWh/kgal). For a 9 MGD system, and using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total annual energy costs are approximately $640,000/yr and $600,000/yr for the 90% and 85% side stream treatment options, respectively.

8. Dechlorination and Antiscalant Feed System Energy – Two 0.5 HP feed system pumps operated continuously for a calculated annual electrical requirement of approximately 6,500 kWh/yr. Using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total energy costs are approximately $650/yr.

Table E-7. RO Capital Costs, 90 Percent of Flow

Equipment Cost Item	Size or number	Units	Unit Cost	Total Cost	Year	2014 Purchased Cost	Total Capital Cost	Source
RO System	9	MGD		$4,460,136	2015	$4,421,296		Wigen (ERG, 2015b).
RO System Building	4,960	sq. foot	$110	$545,600	2014		$545,600	Wigen (ERG, 2015b); building unit cost from CAPDETWorks™.
Chlorination Feed System						$0	$0	
Dechlorination Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Anti-Scale Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Brine Surge Sump	75,000	gallons		$166,005	2010		$185,364	RSMeans Building Construction Cost Data; RO rejection rate from Wigen (ERG, 2015b).

Table E-8. RO Capital Costs, 85 Percent of Flow

Equipment Cost Item	Size or number	Units	Unit Cost	Total Cost	Year	2014 Purchased Cost	Total Capital Cost	Source
RO System	8.5	MGD		$4,214,802	2015	$4,178,098		Wigen (ERG, 2015b).
RO System Building	4,960	sq. foot	$110	$545,600	2014		$545,600	Wigen (ERG, 2015b); building unit cost from CAPDETWorks™.
Chlorination Feed System						$0	$0	
Dechlorination Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Anti-Scale Feed System	1	Each	$5,300	$5,300	2010	$5,918		EnPro (ERG, 2011b).
Brine Surge Sump	70,833	gallons		$160,650	2010		$179,385	RSMeans Building Construction Cost Data; RO rejection rate from Wigen (ERG, 2015b).

Table E-9. RO Operating and Maintenance Costs, 90 Percent of Flow

Operating Labor	Labor (hrs/day)	Labor Rate ($/hr)	Days/yr	Annual Operating Labor Cost ($/yr)	Source
RO System	1	$51.50	365	$18,798	Wigen (ERG, 2015b).
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Maintenance Labor Cost ($/yr)**	**Source**
RO System	1	$51.50	365	$18,798	Best Professional Judgement and CAPDETWorks™
Materials	**Annual Materials Cost ($/yr)**				**Source**
RO System	$162,044				Wigen (ERG, 2015b).

Table E-10. RO Operating and Maintenance Costs, 90 Percent of Flow

Chemicals	Dose Rate (lbs/gal)	Total Flow (gal/yr)	Annual Anti-Scale Chemicals (lbs/yr)	Cost ($/lb)	Annual Chemicals Cost ($/yr)	Source	Chemical Consumption
Pretreatment Anti-Scale	0.00002	3,285,000,000	82,063	$2.64	$216,317	Dose per Wigen (ERG, 2015b); cost per Water Surplus, 2015; freight per FreightCenter.com (ERG, 2011a).	Annual Vitec 3000 Consumption: 91,181 lb/yr Annual Citric Acid Consumption: 16,000 lb/yr Annual Sodium Hypochlorite Consumption: 16,000 lb/yr
Membrane Cleaning	0.00001	3,285,000,000	28,800	$5.03	$144,864	Wigen (ERG, 2015b); freight per FreightCenter.com (ERG, 2011a).	
Pretreatment Chlorine					$0.00	Incorporated into wastewater disinfection module.	
Pretreatment Sodium Bisulfite					$0.00	Incorporated into wastewater dechlorination module.	

Table E-11. RO Operating and Maintenance Costs, 90 Percent of Flow

Energy	Rate (kWh/day)	Annual Electrical (kWh/yr)	Energy Rate ($/kWh)	Annual Energy Cost ($/yr)	Source
RO System	17,550	6,405,750	$0.10	$640,575	Wigen (ERG, 2015b); WateReuse, 2014; CAPDETWorks™.
Chemical Feed Systems	18	6,531	$0.10	$653	EnPro (ERG, 2011b); CAPDETWorks™.

Table E-12. RO Operating and Maintenance Costs, 85 Percent of Flow

Operating Labor	Labor (hrs/day)	Labor Rate ($/hr)	Days/yr	Annual Operating Labor Cost ($/yr)	Source
RO System	1	$51.50	365	$18,798	Wigen (ERG, 2015b).
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Maintenance Labor Cost ($/yr)**	**Source**
RO System	1	$51.50	365	$18,798	Best Professional Judgement and CAPDETWorks™
Materials	**Annual Materials Cost ($/yr)**				**Source**
RO System	$153,041				Wigen (ERG, 2015b).

Table E-13. RO Operating and Maintenance Costs, 85 Percent of Flow

Chemicals	Dose Rate (lbs/gal)	Total Flow (gal/yr)	Annual Anti-Scale Chemicals (lbs/yr)	Cost ($/lb)	Annual Chemicals Cost ($/yr)	Source	Chemical Consumption
Pretreatment Anti-Scale	0.00002	3,102,500,000	77,504	$2.64	$204,299	Dose per Wigen (ERG, 2015b); cost per Water Surplus, 2015; freight per FreightCenter.com (ERG, 2011a).	Annual Vitec 3000 Consumption: 91,181 lb/yr Annual Citric Acid Consumption: 16,000 lb/yr Annual Sodium Hypochlorite Consumption: 16,000 lb/yr
Membrane Cleaning	0.00001	3,102,500,000	27,200	$5.03	$136,816	Wigen (ERG, 2015b); freight per FreightCenter.com (ERG, 2011a).	
Pretreatment Chlorine					$0.00	Incorporated into wastewater disinfection module.	
Pretreatment Sodium Bisulfite					$0.00	Incorporated into wastewater dechlorination module.	

Table E-14. RO Operating and Maintenance Costs, 85 Percent of Flow

Energy	Rate (kWh/day)	Annual Electrical (kWh/yr)	Energy Rate ($/kWh)	Annual Energy Cost ($/yr)	Source
RO System	16,575	6,049,875	$0.10	$604,988	Wigen (ERG, 2015b); WateReuse, 2014; CAPDETWorks™.
Chemical Feed Systems	18	6,531	$0.10	$653	EnPro (ERG, 2011b) and CAPDETWorks™.

E.7 Deep Well Injection

Listed below are the capital cost elements included for deep well injection, with a general description of the basis of estimate, followed by the O&M cost elements and the basis of estimate. Table E-15 and Table E-16 summarize the capital and O&M cost calculations, respectively.

Capital Costs

1. Deep Injection Well – cost basis obtained from telephone contact with North Star Disposal, Inc (U.S. EPA, 2012a). Drilling a new underground injection well costs $3.5 million for a deep well, which was escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017), resulting in a 2014 total capital cost of approximately $3.7 million.
2. Injection Pump/Electrical Building – estimated pump house dimensions (12'x14') based on best professional judgement to house the 3 pumps and control panel, as informed by domestic wastewater deep well injection proposal prepared by the Santa Clarita Valley Sanitation District, 2015[18]. Using the CAPDETWorks™ building unit cost of $110/square foot, calculated a total capital building cost of approximately $18,000.
3. Injection Well Pumps – cost basis of approximately $49,000 for a 786 gpm multistate pump obtained from Water Surplus, 2015, which was escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). Assumed 2 pumps in operation and 1 spare for a total purchase cost of approximately $140,000. Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.
4. Injection Well Pumps Freight – cost basis of approximately $1,750 per flatbed truckload to transport all three pumps (total of 10 tons) obtained from Siemens (ERG, 2011c), which we escalated to 2014 $ using RSMeans Construction Cost Index (RSMeans, 2017). Total capital costs were estimated by applying the CAPDETWorks™ installation factor, and direct and indirect cost factors, to the purchase costs, after incorporating the purchase costs into the CAPDETWorks™ outputs.

Operating and Maintenance Costs

1. Operating Labor – 0.5 labor hour per day based on best professional judgement to inspect the pump motors and to record data, and CAPDETWorks™ operator labor rate of $51.50/hour (2014 $), for a total annual operating labor cost of approximately $9,400.

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[18] Santa Clarity Valley Sanitation District. 2015. *Information Sheet – Deep Well Injection Site for Brine Disposal*. DOC #2970311. Accessed from http://www.lacsd.org/civicax/filebank/blobdload.aspx?blobid=9556.

2. Maintenance Labor – 0.5 labor hour per day based on best professional judgement that maintenance labor requirements would be similar to, and not greater than, operating labor requirements, and sufficient for maintenance activities such as lubrication, troubleshooting, and installing replacement parts. Used the CAPDETWorks™ operator labor rate of $51.50/hour (2014 $), for a total annual maintenance labor cost of approximately $9,400/yr.
3. Materials – calculated total annual maintenance materials cost as 2 percent of injection well pump purchase cost based on CAPDETWorks™ methodology. Calculated a maintenance materials cost of approximately $3,000/yr.
4. Energy – Two 350 HP injection well pumps operated continuously for a calculated annual electrical requirement of approximately 4.5 million kWh/yr. Using the CAPDETWorks™ energy rate of $0.10/kWh (2014 $), total energy costs are approximately $460,000/yr.

Table E-15. Deep Well Injection Capital Costs

Equipment Cost Item	Number	Units	Unit Cost	Total Cost	Year	2014 Cost	Total Capital Cost	Data Source
Deep Injection Well	1	Each	$3,500,000	$3,500,000	2012		$3,685,252	North Star Disposal (U.S. EPA, 2012a).
Injection pump building to house pumps and electrical	168	square feet	$110	$18,480	2014		$18,480	Best professional judgement; building unit cost from CAPDETWorks™.
Injection Well Pumps	3	Each	$48,730	$146,190	2015	$144,917		Water Surplus, 2015.
Injection Well Pumps Freight	1	Flatbed Truck	$1,750	$1,750	2011	$1,875		Siemens (ERG, 2011c).

Table E-16. Deep Well Injection Operating and Maintenance Costs

Operating Labor	Labor (hrs/day)	Labor Rate ($/hr)	Days/yr	Annual Operating Labor Cost ($/yr)	Source
	0.5	$51.50	365	$9,399	Best Professional Judgement and CAPDETWorks™.
Maintenance Labor	**Labor (hrs/day)**	**Labor Rate ($/hr)**	**Days/yr**	**Annual Operating Labor Cost ($/yr)**	**Source**
	0.5	$51.50	365	$9,399	Best Professional Judgement and CAPDETWorks™.
Material	**Purchased Pump Cost**	**Rate (% of Purchase)**	**Annual Materials Cost ($/yr)**		**Source**
	$144,917	2	$2,898		CAPDETWorks™.
Chemicals	**Dose Rate (lbs/gal)**	**Total Flow (gallons/yr)**	**Annual Anti-Scale Chemicals (lbs/yr)**	**Cost ($/lb)**	**Annual Chemicals Cost ($/yr)**
No chemical requirements					
Energy	**Rate (kWh/day)**	**Annual Electrical (kWh/yr)**	**Energy Rate ($/kWh)**	**Annual Energy Cost ($/yr)**	**Source**
	12,526	4,572,019	$0.10	$457,202	Water Surplus, 2015 and CAPDETWorks™.

E.8 CAPDETWorks™ Direct Cost Factor Development

See Companion PDF File.

APPENDIX F
DETAILED AIR EMISSIONS METHODOLOGY

Appendix F: Detailed Air Emissions Methodology

F.1 Greenhouse Gas Analysis

This section details the calculations used to determine the process-level GHG emissions from the wastewater treatment and sludge handling stages, from the effluent, and from landfilled sludge. GHG emissions from background and upstream fuel and material processes already exist within the LCI databases used, and while incorporated in the study results, are not discussed here.

F.1.1 Methane Emissions from Biological Treatment

The methodology for calculating CH_4 emissions associated with the wastewater treatment configurations evaluated as part of this study is generally based on the guidance provided in the IPCC Guidelines for national inventories. CH_4 emissions are estimated based on the amount of organic material (i.e., BOD) entering the unit operations that may exhibit anaerobic activity, an estimate of the theoretical maximum amount of methane that can be generated from the organic material (B_o), and a methane correction factor that reflects the ability of the treatment system to achieve that theoretical maximum. In general, the IPCC does not estimate CH_4 emissions from well managed centralized aerobic treatment systems. However, there is acknowledgement that some CH_4 can be emitted from pockets of anaerobic activity, and more recent research suggests that dissolved CH_4 in the influent wastewater to the treatment system is emitted when the wastewater is aerated.

For this analysis, some of the wastewater treatment configurations include anaerobic zones within the treatment system. For these configurations, a methane correction factor (MCF) was used. The methodological equation is:

$$CH_{4\ PROCESS} = BOD\ (mg/L) \times Flow\ (MGD) \times 3.785\ L/gal \times 365.25\ days/yr \times 1x10^{-6}\ kg/mg \times B_o \times MCF$$

Equation F-1

where:

$CH_{4\ PROCESS}$	=	CH_4 emissions from wastewater treatment process (kg CH_4 /yr)
BOD	=	Concentration of BOD entering biological treatment process (mg/L)
Flow	=	Wastewater treatment flow entering biological treatment process (MGD)
B_o	=	maximum CH_4 producing capacity, kg CH_4/kg BOD
MCF	=	methane correction factor (fraction)

For this analysis, there was no relevant MCF provided in the IPCC guidance for centralized aerobic treatment with the wastewater treatment configurations included in this study. Instead, MCFs were developed based on GHG emission studies that were conducted at two U.S. WWTPs. The first study (Czepiel, 1995) evaluated emissions associated with a conventional activated sludge treatment plant, resulting in an MCF of 0.005, which was used for Level 1. The second study (Daelman et al., 2013) evaluated emissions associated with a municipal treatment plant with biological nutrient removal (specifically nitrification and denitrification), resulting in an MCF of 0.05, which was used for all other levels of treatment. No other studies were available and acceptable for use to allow differentiating CH_4 emissions between Levels 2 through 5.

The annual emissions per system were than translated to emissions per m^3 of wastewater treated, using the following calculation and displayed in Table F-1.

$$CH_4 \text{ Process Emissions (kg } CH_4/m^3 \text{ wastewater)} = CH_{4\ PROCESS} \div [10 \text{ MGD} \times 365 \text{ days/yr} \times 0.00378541 \ m^3/\text{gal}]$$

Equation F-2

Table F-1. Methane Emissions from Biological Treatment

System Configuration Level	Influent BOD to biotreatment, mg/L	Flow, MGD	MCF	CH_4 Emitted by Process, kg CH_4/yr	CH_4 Process Emissions, kg CH_4/m^3 wastewater
1	1.6E+2	10	5.0E-3	6.8E+3	5.0E-4
2-1	1.6E+2	10	0.05	6.6E+4	4.8E-3
2-2	1.6E+2	10	0.05	6.8E+4	4.9E-3
3-1	1.7E+2	10	0.05	7.1E+4	5.1E-3
3-2	1.7E+2	10	0.05	7.1E+4	5.1E-3
4-1	1.7E+2	10	0.05	7.1E+4	5.1E-3
4-2	1.6E+2	10	0.05	6.6E+4	4.8E-3
5-1	1.7E+2	10	0.05	7.1E+4	5.1E-3
5-2	1.7E+2	10	0.05	7.0E+4	5.1E-3

F.1.2 Nitrous Oxide Emissions from Biological Treatment

The methodology for calculating N_2O emissions associated with wastewater treatment is based on estimates of emissions reported in the literature. The guidance provided in the IPCC Guidelines for national inventories does not provide a sufficient basis to distinguish N_2O emissions from varying types of wastewater treatment configurations, particularly related to biological nutrient reduction. More recent research has highlighted the fact that emissions from these systems can be highly variable based on operational conditions, specific treatment configurations, and other factors (Chandran, 2012).

For this analysis, data collected from 12 WWTPs were reviewed to identify which wastewater treatment configuration they may best represent (Chandran, 2012). Using the emissions measured from these systems, an average emission factor (EF) was calculated and applied to the modeled data for the nine system configurations. The methodological equation is:

$$N_2O_{\ PROCESS} = \text{TKN (mg/L)} \times \text{Flow (MGD)} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times \text{EF\%} \times 44/14$$

Equation F-3

where:

$N_2O_{PROCESS}$ = N_2O emissions from wastewater treatment process (kg N_2O /yr)

TKN = Concentration of TKN entering biological treatment process (mg/L)

Flow = Wastewater treatment flow entering biological treatment process (MGD)

EF% = average measured % of TKN emitted as N_2O, %

44/14 = molecular weight conversion of N to N_2O

As displayed in Table F-2, the annual emissions per system were translated to emissions per m^3 of wastewater treated, using the following calculation.

$$N_2O \text{ Process Emissions (kg } N_2O/m^3 \text{ wastewater)} = N_2O_{PROCESS} \div [10 \text{ MGD x } 365 \text{ days/yr x } 0.00378541\ m^3/\text{gal}]$$

Equation F-4

Table F-2. Nitrous Oxide Emissions from Biological Treatment

System Configuration Level	Influent TKN to biotreatment, mg/L[a]	Flow, MGD[a]	EF%, % Emitted as N_2O	Source of EF	Unit Operation Basis	N_2O Emitted by Process, kg N_2O/yr	N_2O Process Emissions, kg N_2O/m^3 wastewater
1	43	10	0.035%	Czepiel (1995)	conventional activated sludge	6.6E+2	4.8E-5
2-1	41	10	0.160%	Chandran (2012)	MLE	2.9E+3	2.1E-4
2-2	43	10	0.020%	Chandran (2012)	separate stage BNR	3.9E+2	2.8E-5
3-1	42	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.8E+3	5.7E-4
3-2	42	10	0.160%	Chandran (2012)	MLE	3.0E+3	2.1E-4
4-1	43	10	0.425%	Chandran (2012)	4-stage Bardenpho	8.2E+3	5.9E-4
4-2	41	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.7E+3	5.6E-4
5-1	42	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.8E+3	5.7E-4
5-2	42	10	0.425%	Chandran (2012)	4-stage Bardenpho	7.7E+3	5.6E-4

a – Flow and influent TKN to biotreatment is based on CAPDETWorks™ modeling

F.1.3 Methane Emissions due to Anaerobic Digestion

The methodology for calculating CH_4 emissions associated with anaerobic sludge digestion is based on the guidance provided in the IPCC Guidelines for national inventories. CH_4 emissions from anaerobic digestion of sludge were estimated based on the amount of biogas generated by the digester, an estimation of the biogas composition, and an estimation of the amount of CH_4 destroyed through flaring.

CH_4 emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH_4 in digester biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4), and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99). For this analysis, ERG is assuming the biogas is flared, and not recovered for energy use. The methodological equation is:

$$CH_{4\ DIGESTER} = \text{Biogas Flow} \times \text{conversion to } m^3 \times (525960\ \text{min/year}) \times (FRAC\_CH_4) \times (\text{density of } CH_4) \times (1\text{-}DE) \times 1/10^{\wedge}3$$

Equation F-5

where:

$CH_{4\ DIGESTER}$	=	CH_4 emissions from anaerobic digestion (kg CH_4 /yr)
Biogas Flow	=	Cubic feet of digester gas produced by digester (ft^3/min)
conversion to m^3	=	Conversion factor, ft^3 to m^3 (0.0283)
FRAC_CH_4	=	Proportion CH_4 in biogas (0.65)
density of CH_4	=	662 (g CH_4/m^3 CH_4)
DE	=	CH_4 destruction efficiency from flaring (0.99 for enclosed flares)
1/10^3	=	Conversion factor, g to kg

As shown in Table F-3 the annual emissions per system were translated to emissions per m^3 of wastewater treated, using the following calculation.

$$CH_4 \text{ Digester Emissions (kg } CH_4/m^3 \text{ wastewater)} = CH_{4\ DIGESTER} \div [10\ \text{MGD} \times 365\ \text{days/yr} \times 0.00378541\ m^3/\text{gal}]$$

Equation F-6

Table F-3. Methane Emissions due to Anaerobic Digestion

System Configuration Level	Biogas Flow, ft^3/min[a]	CH_4 Generated by Digester, kg CH_4/yr	CH_4 Emitted by Digester, kg CH_4/yr	CH_4 Digester Emissions, kg CH_4/m^3 wastewater
1	1.1E+2	6.9E+5	6.9E+3	5.0E-4
2-1	88	5.6E+5	5.6E+3	4.1E-4
2-2	1.2E+2	7.6E+5	7.6E+3	5.5E-4
3-1	85	5.4E+5	5.4E+3	3.9E-4
3-2	85	5.4E+5	5.4E+3	3.9E-4
4-1	85	5.4E+5	5.4E+3	3.9E-4
4-2	87	5.6E+5	5.6E+3	4.1E-4
5-1	85	5.4E+5	5.4E+3	3.9E-4
5-2	82	5.2E+5	5.2E+3	3.8E-4

a – Biogas flow is based on CAPDETWorks™ modeling.

Air emissions other than CH_4 associated with flaring the digester biogas are covered at the end of this Appendix.

F.1.4 Nitrous Oxide Emissions from Effluent Discharged to Receiving Waters

The methodology for calculating nitrous oxide emissions associated with effluent discharge is based on the guidance provided in the IPCC Guidelines for national inventories. N_2O emissions from domestic wastewater (wastewater treatment) were estimated based on the amount of nitrogen discharged to aquatic environments from each of the system configurations, which accounts for nitrogen removed with sewage sludge.

$$N_2O_{EFFLUENT} = N_{EFFLUENT} \times Flow \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times EF_3 \times 44/28$$

Equation F-7

where:

$N_2O_{EFFLUENT}$	=	N_2O emissions from wastewater effluent discharged to aquatic environments (kg N_2O/yr)
$N_{EFFLUENT}$	=	N in wastewater discharged to receiving stream, mg/L
Flow	=	Effluent flow, MGD
EF_3	=	Emission factor (0.005 kg N_2O -N/kg sewage-N produced)
44/28	=	Molecular weight ratio of N_2O to N_2

As presented in Table F-4, the annual emissions per system were then translated to emissions per m^3 of wastewater treated, using the following calculation.

$$N_2O \text{ Effluent Emissions (kg } N_2O/m^3 \text{ wastewater)} = N_2O_{EFFLUENT} \div [10 \text{ MGD x } 365 \text{ days/yr x } 0.00378541 \text{ } m^3/\text{gal}]$$

Equation F-8

Table F-4. Nitrous Oxide Emissions from Effluent Discharged to Receiving Waters

System Configuration Level	Effluent Total Nitrogen, mg/L[a]	N_2O Effluent Emissions, kg N_2O /yr	N_2O Effluent Emissions, kg N_2O/m^3 wastewater
1	30	3.2E+3	2.3E-4
2-1	8.0	8.7E+2	6.3E-5
2-2	7.8	8.4E+2	6.1E-5
3-1	6.0	6.5E+2	4.7E-5
3-2	6.0	6.5E+2	4.7E-5
4-1	3.0	3.2E+2	2.4E-5
4-2	3.0	3.3E+2	2.4E-5
5-1	0.78	69	5.0E-6
5-2	1.9	1.7E+2	1.3E-5

a – Effluent nitrogen is based on CAPDETWorks™ modeling and calculated as TKN + nitrate + nitrite.

F.1.5 Methane Emissions and Energy Recovery from Sludge Disposal in Landfills

The methodology for calculating CH_4 emissions associated with landfill disposal are based on the general presumption that the portion of the landfill receiving anaerobic digester sludge operates as a "bioreactor landfill" due to the high BOD and water loading. As such, the anaerobic digestion process will reach steady state quickly. In addition, the anaerobic conversion of BOD to CH_4 will be very similar between anaerobic sludge digesters and anaerobic bioreactor landfills. As such, the ratio of CH_4 evolution to BOD removal in an anaerobic digester will also be applicable to sewage sludge degradation in anaerobic landfills. ERG calculated an emission factor for landfill emissions based on the conversion of organic material to CH_4, as seen in the anaerobic sludge digester. Using modeled outputs from Level 1, ERG calculated an emission factor of 0.61 kg CH_4 emitted per kg BOD added using the following equation:

$$CH_4EF_{LANDFILL} = \text{Digester } CH_4 \text{ Generated} \times [(\text{Digester BOD Inlet} – \text{Digester BOD Outlet}) \times 365.25 \text{ days/yr}]$$

Equation F-9

where:

$CH_4EF_{LANDFILL}$	=	CH_4 emission factor for landfills receiving municipal sludge (kg CH_4 /kg BOD removed)
Digester CH_4 Generated	=	CH_4 emissions generated in anaerobic sludge digester for Level 1 system, kg CH_4 /yr
Digester BOD Inlet	=	BOD entering the digester, kg/day
Digester BOD Outlet	=	BOD exiting the digester, kg/day

CH_4 emissions from domestic wastewater (wastewater treatment) were estimated based on the amount of BOD transferred to the landfill in digested sludge.

$$CH_{4\,LANDFILL} = \text{Sludge Volume} \times \text{BOD} \times 3.785 \text{ L/gal} \times 365.25 \text{ days/yr} \times 1\text{x}10^{-6} \text{ kg/mg} \times CH_4EF_{LANDFILL}$$

Equation F-10

where:

$CH_{4\,LANDFILL}$	=	CH_4 emissions from landfilled sludge (kg CH_4 /yr)
Sludge Volume	=	Volume of sludge transferred to landfill, MGD
BOD	=	BOD concentration in digested sludge, mg/L
$CH_4EF_{LANDFILL}$	=	CH_4 emission factor for landfills receiving municipal sludge (kg CH_4 /kg BOD)

As displayed in Table F-5, the annual emissions per system were then translated per m^3 of wastewater treated, using the following calculation. These values assume no capture of landfill gas.

$$CH_4 \text{ Landfill Emissions (kg } CH_4/m^3 \text{ wastewater)} = CH_{4\,LANDFILL} \div [10 \text{ MGD x 365 days/yr x 0.00378541 } m^3/\text{gal}]$$

Equation F-11

Table F-5. Raw Methane Emissions from Sludge Disposal in Landfills

System Configuration Level	Sludge Volume, MGD[a]	Sludge BOD, mg/L[a]	CH_4 Landfill Emissions, kg CH_4/yr	Raw CH_4 Landfill Emissions, kg CH_4 /m^3 wastewater
1	0.02	7.2E+3	1.2E+5	8.9E-3
2-1	0.02	7.0E+3	1.0E+5	7.3E-3
2-2	0.03	5.4E+3	1.4E+5	9.8E-3
3-1	0.02	5.6E+3	9.7E+4	7.0E-3
3-2	0.02	5.6E+3	9.7E+4	7.0E-3
4-1	0.02	5.5E+3	9.7E+4	7.0E-3
4-2	0.02	5.7E+3	1.0E+5	7.3E-3
5-1	0.02	5.5E+3	9.7E+4	7.0E-3
5-2	0.02	5.5E+3	9.4E+4	6.8E-3

a – Sludge volume and sludge BOD is based on CAPDETWorks™ modeling.

However, currently, about 71 percent of CH_4 generated from municipal solid waste landfills is converted to CO_2 before it is released to the environment. 10.6 percent is flared, 56.8 percent is burned with energy recovery, and about 3.8 percent is oxidized as it travels through the landfill cover based on the Inventory of U.S. GHG emissions and sinks (U.S. EPA, 2015b). Overall, only approximately 29 percent of the total CH_4 generated is released as methane without treatment. The net CH_4 emissions from sludge in a landfill, calculated by applying the percentage of CH_4 released without treatment to raw CH_4 emissions reported in Table F-5, is provided in Table F-6.

Table F-6. Methane Emissions from Sludge Disposal in Landfills after Treatment

System Configuration Level	Raw CH_4 Landfill Emissions, kg CH_4 /m^3 wastewater[a]	% CH_4 Released without Treatment	kg CH_4 Released without Treatment/m^3 wastewater
1	8.9E-3	29%	2.6E-3
2-1	7.3E-3	29%	2.1E-3
2-2	9.8E-3	29%	2.8E-3
3-1	7.0E-3	29%	2.0E-3
3-2	7.0E-3	29%	2.0E-3
4-1	7.0E-3	29%	2.0E-3
4-2	7.3E-3	29%	2.1E-3
5-1	7.0E-3	29%	2.0E-3
5-2	6.8E-3	29%	1.9E-3

a – Derived from Table F-5 results.

The U.S. EPA's Landfill Methane Outreach Program Landfill Database indicates that the majority of landfill gas burned with energy recovery is used to produce electricity (U.S. EPA, 2016). The gross energy recovered from combustion of sludge landfill is converted to displaced quantities of grid electricity using an efficiency factor of 1 kWh generated per 11,700 Btu (or 12.34 MJ) of landfill CH_4 burned (U.S. EPA, 2014). Each system configuration is credited with avoiding the GWP associated with production of the offset quantity of grid electricity. The calculations to derive this offset or avoided electricity per system configuration level are shown in Table F-7.

Table F-7. Electricity Generation from Landfill Methane Energy Recovery

System Configuration Level	Raw CH_4 Landfill Emissions, kg CH_4 /m^3 wastewater	% CH_4 Burned with Energy Recovery	kg CH_4 Burned with Energy Recovery/m^3 wastewater	Gross MJ from Landfill Gas Energy Recovery[a]/m^3 wastewater	Net kWh from Landfill CH_4 Energy Recovery/m^3 wastewater[b]
1	8.9E-3	57%	5.0E-3	0.28	0.02
2-1	7.3E-3	57%	4.1E-3	0.23	0.02
2-2	9.8E-3	57%	5.6E-3	0.31	0.03
3-1	7.0E-3	57%	4.0E-3	0.22	0.02
3-2	7.0E-3	57%	4.0E-3	0.22	0.02
4-1	7.0E-3	57%	4.0E-3	0.22	0.02
4-2	7.3E-3	57%	4.1E-3	0.23	0.02
5-1	7.0E-3	57%	4.0E-3	0.22	0.02
5-2	6.8E-3	57%	3.8E-3	0.21	0.02

a – HHV of methane = 11.47 MJ/kg

b – Modeled as avoided electricity with a negative value in the LCA.

F.2 Anaerobic Digester Biogas Flaring

Biogas production for each treatment level is a calculated based on the output of the CAPDETWorks™ model. Emissions inventory information for biogas flaring is compiled from three resources with the maximum reported emission value for each compound being taken as the emission factor for this project. Table F-8 shows the data extracted from each study with the last column displaying the emission factor selected for inclusion in this study. All emission factors in the table are included as kg of compound emitted per cubic meter of biogas flared. Emission factors from Levis and Barlaz 2013 are presented in the original study per cubic meter of biogas CH_4 content.

Table F-8. Biogas Flaring Emission Factors (All values are kg/m^3 Biogas Flared)

Compound	Levis & Barlaz [a]	Alberta Environment [b]	Environment Canada [c]	This Study (Max Value)
Nitrous Oxide	1.1E-5	3.5E-5	4.5E-4	4.5E-4
PM-Total	6.0E-5		8.5E-4	8.5E-4
PM10	1.0E-5		8.5E-4	8.5E-4
PM-2.5	4.7E-6		8.5E-4	8.5E-4
Nitrogen Oxides	0.01			0.01
NMVOCs	2.0E-5			2.0E-5

Table F-8. Biogas Flaring Emission Factors (All values are kg/m^3 Biogas Flared)

Compound	Levis & Barlaz [a]	Alberta Environment [b]	Environment Canada [c]	This Study (Max Value)
Sulfur Oxides	4.3E-4		9.2E-5	4.3E-4
Carbon Monoxide	6.2E-3		5.6E-5	6.2E-3
Ammonia	1.8E-5			1.8E-5
Hydrogen Sulfide	3.9E-6			3.9E-6
PAH			8.7E-6	8.7E-6

Sources:

a – Levis, J.W., and Barlaz, M.A. 2013. Anaerobic Digestion Process Model Documentation. North Carolina State University. http://www4.ncsu.edu/~jwlevis/AD.pdf. Accessed 5 April, 2016

b – Alberta Environment. 2007. Quantification Protocol for the Anaerobic Decomposition of Agricultural Materials Project: Excel Biogas Calculator. http://environment.gov.ab.ca/info/library/7917.pdf. Accessed 5 April, 2016.

c – Environment Canada. 2005. Biogas Flare. https://www.ec.gc.ca/inrp-npri/14618D02-387B-469D-B1CD-42BC61E51652/biogas_flare_e_04_02_2009.xls. Accessed 5 April, 2016

APPENDIX G
EXAMPLE LCI DATA CALCULATIONS

Appendix G: Example LCI Data Calculations

CAPDETWorks™ design and costing software (Hydromantis, 2014) provides the main source of LCI data for treatment plant unit process construction and operation. The relevant elements of the CAPDETWorks™ model output were imported into an Excel document where supplemental calculations were performed to standardize flows to be on the basis of physical units per cubic meter of treated wastewater. Calculation procedures were similar regardless of treatment level. Output LCI associated with the Level 1 treatment system is included in Table G-1 to provide an example of the procedure applied to all treatment levels. Supplementary LCI calculations not associated with CAPDETWorks™ output (e.g., process-level air emissions) are described elsewhere in the report.

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Table G-1. Example Standardization of CAPDETWorks™ Output to LCI per m3 of Treated Wastewater (Level 1)

Unit	*CAPDETWorks™ Model Output*				*Calculated LCI Values*			
	Description	**Value**	**Units**		**Calculated Flow**	**Units**	**Value**	**Assumptions**
Grit Removal	Energy cost	4,690	$/yr		Electricity	kwh/m^3	3.0E-3	$0.10/kWh
Primary Clarifier	Structural	40	years		Building	m^2/m^3	3.4E-8	structural lifespan 40 years
	Area of pump building	201	sqft					
	Electrical energy required	10,100	kWh/yr		Electricity, Total	kwh/m^3	8.4E-4	
	Electrical energy required	1,510	kWh/yr					
	Volume of earthwork required	129,000	cuft		Earthwork, Total	m^3/m^3	2.7E-6	plant lifespan of 100 years
	Volume of earthwork required	1,610	cuft					
	Volume of slab concrete required	10,700	cuft		Concrete, Total	m^3/m^3	9.5E-7	structural lifespan 40 years
	Volume of wall concrete required	7,810	cuft					
Plug Flow Activated Sludge	Electrical energy required	1,880,000	kWh/yr		Electricity, Total	kwh/m^3	0.14	
	Electrical energy required	113,000	kWh/yr					
	Volume of earthwork required	176,000	cuft		Earthwork, Total	m^3/m^3	3.7E-6	plant lifespan of 100 years
	Volume of earthwork required	2,670	cuft					
	Structural	40	years		Concrete	m^3/m^3	5.9E-6	structural lifespan 40 years
	Volume of slab concrete required	75,900	cuft					
	Volume of wall concrete required	38,200	cuft					
	Handrail length	1,290	ft		Steel	kg/m^3	6.4E-6	lifespan of 40 years
	Area of pump building	334	sqft		Building	m^2/m^3	5.6E-8	lifespan of 40 years
Secondary Clarifier	Electrical energy required	11,100	kWh/yr		Electricity, Total	kwh/m^3	1.0E-3	
	Electrical energy required	6,500	kWh/yr					
	Volume of earthwork required	216,000	cuft		Earthwork, Total	m^3/m^3	4.5E-6	plant lifespan of 100 years
	Volume of earthwork required	1,630	cuft					
	Structural	40	years		Concrete, Total	m^3/m^3	1.4E-7	structural lifespan 40 years
	Volume of slab concrete required	17,000	cuft					
	Volume of wall concrete required	9,830	cuft					
	Area of pump building	204	sqft		Building	m2/m3	3.4E-8	structural lifespan 40 years

Table G-1. Example Standardization of CAPDETWorks™ Output to LCI per m3 of Treated Wastewater (Level 1)

Unit	*CAPDETWorks™ Model Output*				*Calculated LCI Values*			
	Description	**Value**	**Units**		**Calculated Flow**	**Units**	**Value**	**Assumptions**
Chlorination	Average chlorine required	832	lb/d		Chlorine	kg/m^3	0.01	operates 365 days per year
	Electrical energy required	131,000	kWh/yr		Electricity	kwh/m^3	9.5E-3	
	Volume of earthwork required	11,900	cuft		Earthwork	m^3/m^3	2.4E-7	plant lifespan of 100 years
	Structural	40.0	years		Concrete, Total	m^3/m^3	4.0E-7	structural lifespan 40 years
	Volume of slab concrete required	2,790	cuft					
	Volume of wall concrete required	4,980	cuft					
	Chlorination building area	220	sqft		Building	m^2/m^3	3.4E-7	structural lifespan 40 years
	Area of chlorine storage building	1,820	sqft					
Dechlorination	Sodium Bisulfite 40% Solution	3.75	mg/L		Sodium bisulfite	kg/m^3	3.8E-3	
	Electrical energy required	131,000	kWh/yr		Electricity	kwh/m^3	9.5E-3	
	Volume of earthwork required	1,980	cuft		Earthwork	m^3/m^3	4.1E-8	plant lifespan of 100 years
	Structural	40.0	years		Concrete, Total	m^3/m^3	1.4E-7	structural lifespan 40 years
	Volume of slab concrete required	464	cuft					
	Volume of wall concrete required	2,330	cuft					
	Dechlorination building area	220	sqft		Building	m^2/m^3	1.5E-7	structural lifespan 40 years
	Area of sodium bisulfite 40% solution storage building	700	sqft					
Gravity Thickening	Electrical energy required	10,300	kWh/yr		Electricity	kwh/m^3	7.5E-4	
	Volume of earthwork required	14,400	cuft		Earthwork	m^3/m^3	3.0E-7	plant lifespan of 100 years
	Structural	40.0	years		Concrete, Total	m^3/m^3	1.6E-7	structural lifespan 40 years
	Volume of slab concrete required	1,260	cuft					
	Volume of wall concrete required	1,860	cuft					

Table G-1. Example Standardization of CAPDETWorks™ Output to LCI per m3 of Treated Wastewater (Level 1)

Unit	*CAPDETWorks™ Model Output*				*Calculated LCI Values*			
	Description	**Value**	**Units**		**Calculated Flow**	**Units**	**Value**	**Assumptions**
Anaerobic Digester	Gas produced	107	cuft/min		Biogas, production	m^3/m^3	0.12	continuous production
	Electrical energy required	253,000	kWh/yr		Electricity	kwh/m^3	0.02	
	Volume of earthwork required	196,000	cuft		Earthwork	m^3/m^3	4.0E-6	plant lifespan of 100 years
	Structural	40.0	years		Concrete, Total	m^3/m^3	1.8E-6	structural lifespan 40 years
	Volume of slab concrete required	6,860	cuft					
	Volume of wall concrete required	27,300	cuft					
	Length of total piping system	833	ft		Steel	kg/m^3	2.4E-5	8" steel pipe, 16.2 kg/ft, lifespan 40 years
	Surface area/floor of 2-story control bldg..	1,180	sqft		Building	m^2/m^3	2.0E-7	
	Heat required	1,350,000	BTU/hr		Natural Gas	m^3/m^3	0.02	38.4 MJ/m^3 Gas HHV
Centrifuge	Polymer dosage	248	lb/d		Polymer	kg/m^3	2.1E-3	operates 5 days per week
	Electrical energy required	237,000	kWh/yr		Electricity	kwh/m^3	0.02	
	Area of building	453	sqft		Building	m^2/m^3	7.6E-8	structural lifespan 40 years
Sludge Hauling & Landfill	Volume of earthwork required	26,700	cuft		Earthwork	m^3/m^3	5.5E-7	plant lifespan of 100 years
	Structural	40	years		Concrete	m^3/m^3	5.7E-7	structural lifespan 40 years
	Volume of slab concrete required	11,100	cuft					
	Sludge storage shed area	10,100	sqft		Building, Total	m^2/m^3	3.4E-6	structural lifespan 40 years
	Surface area of canopy roof	10,100	sqft					
	Sludge hauled	80,286	kg/day		Truck Transport	ton-km/m^3	0.09	25 km haul distance, 365 days per year

APPENDIX H
SUMMARY LCI RESULTS

Appendix H: Summary LCI Result

Table H-1. LCI for Level 1: Conventional Plug Flow Activated Sludge Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation										**Infrastructure**			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Truck Transport**	**Digester Gas, Flared [c]**	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m^3***	***m^3/m^3***	***kg/m^3***	***kg/m^3***	***kg/m^3***	***tkm/m^3 [b]***	***m^3/m^3***	***kg/m^3***	***kg/m3***	***kWh/m3***	***m^3/m^3***	***m^3/m^3***	***m^2/m^3***	***kg/m^3***
Screening and Grit Removal	3.4E-3													
Primary Clarifier	8.6E-4										2.7E-6	1.2E-6	3.4E-8	
Plug Flow Activated Sludge	0.14							3.3E-4	4.8E-5		3.7E-6	5.8E-6	5.6E-8	6.4E-6
Secondary Clarifier	1.3E-3										4.5E-6	1.9E-6	3.4E-8	
Chlorination	9.5E-3		1.0E-2								4.9E-7	7.0E-7	3.4E-7	
Dechlorination	9.5E-3				3.8E-3						8.1E-8	1.9E-7	1.5E-7	
Effluent Release [a]									2.4E-4					
Gravity Thickener	7.5E-4										3.0E-7	1.9E-7		
Anaerobic Digester	0.02	0.04					0.12	2.5E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5
Centrifuge	0.02			2.1E-3									8.4E-8	
Sludge Hauling and Landfill						0.09		2.6E-3		0.02	5.5E-7	5.7E-7	3.4E-6	
Totals	0.20	0.04	1.0E-2	2.1E-3	3.8E-3	**0.09**	**0.12**	5.4E-3	2.9E-4	0.02	1.7E-5	1.3E-5	4.4E-6	3.2E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8

Table H-2. LCI for Level 2-1: Anaerobic/Anoxic/Oxic Wastewater Treatment Configuration(per m3 wastewater treated)

	Operation										Infrastructure			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Truck Transport**	**Digester Gas, Flared [c]**	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m³***	***m³/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***tkm/m³ [b]***	***m³/m³***	***kg/m³***	***kg/m³***	***kWh/m³***	***m³/m³***	***m³/m³***	***m²/m³***	***kg/m³***
Screening and Grit Removal	3.4E-3													
Primary Clarifier	8.5E-4										2.6E-6	1.1E-6	3.4E-8	
Biological Nutrient Removal–3-Stage	0.43							3.3E-3	2.1E-4		9.5E-6	1.2E-5	1.2E-7	1.6E-5
Secondary Clarifier	1.1E-3										4.5E-6	1.9E-6	3.4E-8	
Chlorination	9.5E-3		1.0E-2								4.9E-7	7.0E-7	3.4E-7	
Dechlorination	9.5E-3				3.8E-3						8.1E-8	1.9E-7	1.5E-7	
Effluent Release [a]									6.3E-5					
Gravity Thickener	7.1E-4										2.6E-7	1.8E-7		
Anaerobic Digester	0.02	0.04					0.10	2.1E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5
Centrifuge	0.01			1.8E-3									7.8E-8	
Sludge Hauling and Landfill						0.07		2.1E-3		0.02	4.7E-7	4.9E-7	2.9E-6	
Totals	0.48	0.04	1.0E-2	1.8E-3	3.8E-3	0.07	0.10	7.5E-3	2.8E-4	0.02	2.3E-5	1.9E-5	3.9E-6	4.2E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-3. LCI for Level 2-2: Activated Sludge, 3-Sludge System Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation													Infrastructure			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Calcium Carbonate**	**Methanol**	**Truck Transport**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	*kWh/m^3*	*m^3/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*	*tkm/m^3* [b]	*m^3/m^3*	*kg/m^3*	*kg/m^3*	*kWh/m^3*	*m^3/m^3*	*m^3/m^3*	*m^2/m^3*	*kg/m^3*
Screening and Grit Removal	3.4E-3																
Primary Clarifier	8.8E-4													2.7E-6	1.2E-6	3.4E-8	
Plug Flow Activated Sludge	0.15										3.3E-3	2.8E-5		3.8E-6	6.1E-6	5.6E-8	6.6E-6
Chemical Phosphorus Removal						0.08											
Nitrification - Suspended Growth	0.16						0.21							3.8E-6	6.1E-6	5.6E-8	6.6E-6
Denitrification - Suspended Growth	0.13							0.05						2.3E-6	1.8E-6	5.6E-8	
Secondary Clarifier	1.3E-3													4.5E-6	1.9E-6	3.4E-8	
Tertiary Clarification (Nitrification)	8.3E-4													4.5E-6	1.9E-6	3.4E-8	
Tertiary Clarification (Denitrification)	1.0E-3													4.5E-6	1.9E-6	3.4E-8	
Chlorination	9.5E-3		1.0E-2											4.9E-7	7.0E-7	3.4E-7	
Dechlorination	9.5E-3				3.8E-3									8.1E-8	1.9E-7	1.5E-7	
Effluent Release [a]												6.1E-5					
Gravity Thickener	8.2E-4													3.8E-7	2.3E-7		
Anaerobic Digester	0.02	0.06								0.13	2.8E-3			6.6E-6	2.7E-6	3.0E-7	3.5E-5
Centrifuge	0.02			3.2E-3												9.0E-8	
Sludge Hauling and Landfill									0.13		2.8E-3		0.03	8.1E-7	8.4E-7	5.1E-6	
Totals	0.51	0.06	1.0E-2	3.2E-3	3.8E-3	0.08	0.21	0.05	0.13	0.13	8.9E-3	8.9E-5	0.03	3.4E-5	2.5E-5	6.3E-6	4.8E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-4. LCI for Level 3-1: 5-Stage Bardenpho System Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation											Infrastructure						
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Truck Transport**	**Digester Gas, Flared [c]**	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	*kWh/m³*	*m³/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*tkm/m³ [b]*	*m³/m³*	*kg/m³*	*kg/m³*	*kWh/m³*	*m³/m³*	*m³/m³*	*m²/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*
Screening and Grit Removal	3.4E-3																	
Primary Clarifier	8.5E-4											2.6E-6	1.1E-6	3.4E-8				
Fermenter	8.8E-4											2.1E-7	1.4E-7					
Biological Nutrient Removal–5-Stage	0.46								8.4E-3	5.7E-4		1.1E-5	1.4E-5	1.2E-7	1.9E-5			
Chemical Phosphorus Removal						4.2E-3												
Secondary Clarifier	1.2E-3											4.5E-6	1.9E-6	3.4E-8				
Filtration–Sand Filter	5.6E-3											2.7E-6	1.6E-6			1.1E-3	4.0E-4	2.7E-4
Chlorination	9.5E-3		8.0E-3									4.9E-7	7.0E-7	2.7E-7				
Dechlorination	9.5E-3				3.8E-3							8.1E-8	1.9E-7	1.5E-7				
Effluent Release [a]										4.7E-5								
Gravity Thickener	7.1E-4											2.6E-7	1.8E-7					
Anaerobic Digester	0.02	0.04						0.09	2.0E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge	0.01			1.8E-3										7.9E-8				
Sludge Hauling and Landfill							0.07		2.0E-3		0.02	4.7E-7	4.9E-7	2.9E-6				
Totals	0.52	0.04	8.0E-3	1.8E-3	3.8E-3	4.2E-3	0.07	0.09	0.01	6.2E-4	0.02	2.7E-5	2.2E-5	3.9E-6	4.5E-5	1.1E-3	4.0E-4	2.7E-4

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-5. LCI for Level 3-2: Modified University of Cape Town Process Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation											**Infrastructure**						
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Truck Transport**	**Digester Gas, Flared [c]**	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	***kWh/m³***	***m³/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***tkm/m³ [b]***	***m³/m³***	***kg/m³***	***kg/m³***	***kWh/m³***	***m³/m³***	***m³/m³***	***m²/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***kg/m³***
Screening and Grit Removal	3.4E-3											-	-	-	-			
Primary Clarifier	8.5E-4											2.6E-6	1.1E-6	3.4E-8	-			
Fermenter	8.8E-4											2.1E-7	1.4E-7	-	-			
Biological Nutrient Removal–4-Stage	0.51								8.4E-3	2.2E-4		1.1E-5	1.4E-5	1.1E-7	1.9E-5			
Chemical Phosphorus Removal						4.2E-3						-	-	-	-			
Secondary Clarifier	1.2E-3											4.5E-6	1.9E-6	3.4E-8	-			
Filtration–Sand Filter	5.6E-3											2.7E-6	1.6E-6	-	-	1.1E-3	4.0E-4	2.7E-4
Chlorination	9.5E-3		8.0E-3									4.9E-7	7.0E-7	2.7E-7	-			
Effluent Release [a]										4.7E-5								
Dechlorination	9.5E-3				3.8E-3							8.1E-8	1.9E-7	1.5E-7	-			
Gravity Thickener	7.1E-4											2.6E-7	1.8E-7	-	-			
Anaerobic Digester	0.02	0.04						0.09	2.0E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge	0.01			1.8E-3								-	-	7.9E-8	-			
Sludge Hauling and Landfill							0.07		2.0E-3		0.02	4.7E-7	4.9E-7	2.9E-6	-			
Totals	0.57	0.04	8.0E-3	1.8E-3	3.8E-3	4.2E-3	0.07	0.09	0.01	2.6E-4	0.02	2.7E-5	2.2E-5	3.9E-6	4.5E-5	1.1E-3	4.0E-4	2.7E-4

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table F-8.

Table H-6. LCI for Level 4-1: 5-Stage Bardenpho System with Denitrification Filter Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation												Infrastructure						
	Electr-icity	**Natu-ral Gas**	**Chlorine Gas**	**Polym-er**	**Sodium Bisulfite (40%)**	**Al Sulf-ate**	**Met-hanol**	**Truck Trans-port**	**Digester Gas, Flared [c]**	**CH_4 Emiss-ions**	**N_2O Emiss-ions**	**Elect-ricity (Avo-i-ded)**	**Earth-work**	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	*kWh/m³*	*m³/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*tkm/m³ [b]*	*m³/m³*	*kg/m³*	*kg/m³*	*kWh/m³*	*m³/m³*	*m³/m³*	*m²/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*
Screening and Grit Removal	3.4E-3																		
Primary Clarifier	8.5E-4												2.6E-6	1.1E-6	3.4E-8				
Fermenter	8.8E-4												2.1E-7	1.4E-7	-				
Biological Nutrient Removal–5-Stage	0.46									8.4E-3	5.7E-4		1.1E-5	1.4E-5	1.2E-7	1.9E-5			
Chemical Phosphorus Removal						4.2E-3													
Secondary Clarifier	1.2E-3												4.5E-6	1.9E-6	3.4E-8				
Denitrification - Attached Growth	0.13						0.02						1.5E-6	1.1E-6	1.9E-7		2.8E-4	1.2E-4	
Filtration–Sand Filter	5.6E-3												2.7E-6	1.6E-6			1.1E-3	4.0E-4	2.7E-4
Chlorination	9.5E-3		8.0E-3										4.9E-7	7.0E-7	2.7E-7				
Dechlorination	9.5E-3				3.8E-3								8.1E-8	1.9E-7	1.5E-7				
Effluent Release [a]											2.3E-5								
Gravity Thickener	7.1E-4												2.6E-7	1.8E-7					
Anaerobic Digester	0.02	0.04							0.09	2.0E-3			5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge	0.01			1.8E-3											7.9E-8				
Sludge Hauling and Landfill								0.07		2.0E-3		0.02	4.7E-7	4.9E-7	2.9E-6				
Totals	0.65	0.04	8.0E-3	1.8E-3	3.8E-3	4.2E-3	0.02	0.07	0.09	0.01	6.0E-4	0.02	2.9E-5	2.3E-5	4.1E-6	4.5E-5	1.4E-3	5.3E-4	2.7E-4

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table C-8.

Table H-7. LCI for Level 4-2: 4-Stage Bardenpho Membrane Bioreactor System Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation											Infrastructure			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Truck Transport**	**Digester Gas, Flared** [c]	**CH_4 Emissions**	**N_2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	***kWh/m³***	***m³/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***kg/m³***	***tkm/m³*** [b]	***m³/m³***	***kg/m³***	***kg/m³***	***kWh/m³***	***m³/m³***	***m³/m³***	***m²/m³***	***kg/m³***
Screening and Grit Removal	3.4E-3											-	-	-	-
Primary Clarifier	8.5E-4											2.6E-6	1.1E-6	3.4E-8	-
Biological Nutrient Removal–4-Stage	0.35								8.4E-3	5.6E-4		5.5E-6	7.8E-6	1.2E-7	9.4E-6
Chemical Phosphorus Removal						2.2E-3						-	-	-	-
Membrane Filter	0.23											1.5E-6	3.1E-6	8.2E-8	5.4E-6
Chlorination	9.5E-3		8.0E-3									4.9E-7	7.0E-7	2.7E-7	-
Dechlorination	9.5E-3				3.8E-3							8.1E-8	1.9E-7	1.5E-7	-
Effluent Release [a]										2.4E-5		-	-	-	-
Gravity Thickener	7.0E-4											2.6E-7	1.8E-7	-	-
Anaerobic Digester	0.02	0.03						0.09	2.0E-3			4.5E-6	1.9E-6	2.2E-7	2.5E-5
Centrifuge	0.01			1.8E-3								-	-	7.8E-8	-
Sludge Hauling and Landfill							0.07		2.1E-3		0.02	4.6E-7	4.8E-7	2.9E-6	-
Totals	0.64	0.03	8.0E-3	1.8E-3	3.8E-3	2.2E-3	0.07	0.09	0.01	5.9E-4	0.02	1.5E-5	1.5E-5	3.8E-6	4.0E-5

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table C-8.

Table H-8. Operational LCI for Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Wastewater Treatment Configuration (per m3 wastewater treated)

	Electricity	Natural Gas	Chlorine Gas	Polymer	Sodium Bisulfite (40%/12.5 %)	Al Sulfate	Methanol	Antiscalant	Brine Injection (Water Loss)	Truck Transport	Citric Acid	Sodium Hypochlorite	Sulfuric Acid	Sodium Hydroxide	Digester Gas, Flared [c]	CH_4 Emissions	N_2O Emissions	Electricity (Avoided)
Unit:	*kWh/m³*	*m³/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*m³/m³*	*tkm/m³ [b]*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*m³/m³*	*kg/m³*	*kg/m³*	*kWh/m³*
Screening and Grit Removal	3.4E-3																	
Primary Clarifier	8.5E-4																	
Fermenter	8.8E-4																	
Biological Nutrient Removal – 5-Stage	0.46															8.4E-3	5.7E-4	
Chemical Phosphorus Removal						4.2E-3												
Secondary Clarifier	1.2E-3																	
Denitrification – Attached Growth	0.01						2.3E-3											
Filtration – Sand Filter	5.9E-4																	
Chlorination	9.1E-3		4.9E-3															
Dechlorination	9.1E-3				7.5E-3													
Ultrafiltration	0.17				4.0E-4						1.6E-3	9.9E-4	1.2E-3	3.9E-3				
Reverse Osmosis	0.46							2.7E-3			9.5E-4							
Effluent Release [a]																	5.0E-6	
Gravity Thickener	7.1E-4																	
Anaerobic Digester	0.02	0.04													0.09	2.0E-3		
Centrifuge	0.01			1.8E-3														
Sludge Hauling and Landfill										0.07						2.0E-3		0.02
Underground Injection of Brine	0.33								0.18	2.7E-5								
Totals	1.5	0.04	4.9E-3	1.8E-3	7.9E-3	4.2E-3	2.3E-3	2.7E-3	0.18	0.07	2.5E-3	9.9E-4	1.2E-3	3.9E-3	0.09	0.01	5.8E-4	0.02

a – All effluent release emissions are presented in Table 1-4.

b – tkm is an abbreviation for ton-kilometers.

c – Biogas flaring emissions are presented in Table C-8.

Table H-9. Infrastructure LCI for Level 5-1: 5-Stage Bardenpho with Sidestream Reverse Osmosis Wastewater Treatment Configuration (per m3 wastewater treated)

	Earthwork	**Concrete**	**Building**	**Steel**	**Sand**	**Gravel**	**Anthracite**
Unit:	***m3/m3***	***m3/m3***	***m2/m3***	***kg/m3***	***kg/m3***	***kg/m3***	***kg/m3***
Screening and Grit Removal							
Primary Clarifier	2.6E-6	1.1E-6	3.4E-8				
Fermenter	2.1E-7	1.4E-7					
Biological Nutrient Removal – 5-Stage	1.1E-5	1.4E-5	1.2E-7	1.9E-5			
Chemical Phosphorus Removal							
Secondary Clarifier	4.5E-6	1.9E-6	3.4E-8				
Denitrification – Attached Growth	3.2E-7	4.1E-7	8.5E-8		2.8E-5	1.2E-5	
Filtration – Sand Filter	3.9E-7	2.2E-7			1.1E-4	4.0E-5	2.7E-5
Chlorination	4.0E-7	5.9E-7	2.0E-7				
Dechlorination	6.7E-8	1.8E-7	2.3E-7				
Ultrafiltration	2.6E-6	-	2.7E-6				
Reverse Osmosis	1.6E-6	-	1.7E-6				
Gravity Thickener	2.6E-7	1.8E-7					
Anaerobic Digester	5.0E-6	2.0E-6	2.4E-7	2.6E-5			
Centrifuge			7.9E-8				
Sludge Hauling and Landfill	4.7E-7	4.9E-7	2.9E-6				
Underground Injection of Brine			2.8E-8	2.7E-5			
Totals	2.9E-5	2.1E-5	8.4E-6	7.2E-5	1.4E-4	5.3E-5	2.7E-5

Table H-10. LCI for Level 5-2: 5-Stage Bardenpho Membrane Bioreactor with Sidestream Reverse Osmosis Wastewater Treatment Configuration (per m3 wastewater treated)

	Operation														Infrastructure			
	Electricity	**Natural Gas**	**Chlorine Gas**	**Polymer**	**Sodium Bisulfite (40%)**	**Al Sulfate**	**Antiscalant**	**Brine Injection (Water Loss)**	**Truck Transport**	**Citric Acid**	**Digester Gas, Flared [c]**	**CH4 Emissions**	**N2O Emissions**	**Electricity (Avoided)**	**Earthwork**	**Concrete**	**Building**	**Steel**
Unit:	*kWh/m³*	*m³/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*kg/m³*	*m³/m³*	*tkm/m³ [b]*	*kg/m³*	*m³/m³*	*kg/m³*	*kg/m³*	*kWh/m³*	*m³/m³*	*m³/m³*	*m²/m³*	*kg/m³*
Screening and Grit Removal	3.4E-3																	
Primary Clarifier	8.5E-4														2.6E-6	1.1E-6	3.4E-8	
Fermenter	8.8E-4														2.1E-7	1.4E-7		
Biological Nutrient Removal – 5-Stage	0.39											8.4E-3	5.7E-4		5.3E-6	7.6E-6	1.2E-7	9.1E-6
Chemical Phosphorus Removal						2.1E-3												
Membrane Filter	0.23														1.5E-6	3.1E-6	8.3E-8	5.4E-6
Chlorination	9.1E-3		5.0E-3												4.8E-7	6.9E-7	2.0E-7	
Dechlorination	9.1E-3				7.5E-3										8.0E-8	1.9E-7	2.3E-7	
Reverse Osmosis	0.44						2.5E-3			8.9E-4					1.6E-6	-	1.7E-6	
Effluent Release [a]													1.3E-5					
Gravity Thickener	7.0E-4														2.1E-7	1.5E-7		
Anaerobic Digester	0.02	0.03									0.09	1.9E-3			4.0E-6	1.8E-6	2.0E-7	2.4E-5
Centrifuge	0.01			1.7E-3													7.7E-8	
Sludge Hauling and Landfill									0.07			2.0E-3		0.02	4.5E-7	4.7E-7	2.8E-6	
Underground Injection of Brine	0.33							0.17	2.7E-5								2.8E-8	2.7E-5
Totals	1.4	0.03	5.0E-3	1.7E-3	7.5E-3	2.1E-3	2.5E-3	0.17	0.07	8.9E-4	0.09	0.01	5.8E-4	0.02	1.6E-5	1.5E-5	5.4E-6	6.6E-5

Table H-11. Sludge Quantity Produced by Wastewater Treatment Configuration

Wastewater Treatment Configuration	kg Sludge/m^3 Wastewater Treated[a]	% Change to Level 1, AS
Level 1, AS	0.26	-
Level 2-1, A2O	0.22	-15%
Level 2-2, AS3	0.38	48%
Level 3-1, B5	0.22	3%
Level 3-2, MUCT	0.22	3%
Level 4-1, B5/Denit	0.22	4%
Level 4-2, MBR	0.22	4%
Level 5-1, B5/RO	0.22	4%
Level 5-2, MBR/RO	0.21	0%

[a] 21 percent moisture

APPENDIX I
COST RESULTS BY UNIT PROCESS

Appendix I: Cost Results by Unit Process

This Appendix provides cost results by unit process using the 3% interest and discount rates. Table I-1 and Table I-2 display the detailed results for the total construction costs and total annual costs by unit process. Table I-3 through Table I-7 display the detailed results by total annual cost component (e.g., operational labor, maintenance labor) by unit process. Net present value was not calculated by unit process.

Table I-1. Total Construction Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$1,890,000	$1,890,000	$1,900,000	$1,890,000	$1,890,000	$1,888,000	$1,890,000	$1,888,000	$1,890,000
Primary clarifier	$1,260,000	$1,230,000	$1,260,000	$1,230,000	$1,230,000	$1,230,000	$1,230,000	$1,230,000	$1,230,000
Activated Sludge	$5,100,000		$5,260,000						
Biological nutrient removal-3-stage		$12,500,000							
Biological nutrient removal-4-stage					$14,800,000		$7,580,000		
Biological nutrient removal-5-stage				$13,800,000		$13,800,000		$13,800,000	$8,550,000
Blower System	$715,000	$770,000	$1,150,000	$787,000	$787,000	$787,000	$2,490,000	$787,000	$2,520,000
Secondary Clarifier	$1,880,000	$1,880,000	$1,890,000	$1,880,000	$1,880,000	$1,880,000		$1,880,000	
Membrane Filter							$13,300,000		$13,300,000
Nitrification, suspended growth			$5,330,000						
Tertiary clarification, nitrification			$1,860,000						
Denitrification, suspended growth			$1,830,000						
Tertiary clarification, denitrification			$1,880,000						
Fermenter				$788,000	$788,000	$788,000		$788,000	$788,000
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$302,000	$214,000	$214,000	$214,000	$214,000	$214,000	$214,000
Denitrification, attached growth						$2,580,000		$560,000	
Sand Filter				$3,810,000	$3,810,000	$3,810,000		$1,100,000	
Ultrafiltration								$11,430,000	
Reverse Osmosis								$12,990,000	$12,340,000
Chlorination	$977,000	$977,000	$977,000	$954,000	$954,000	$954,000	$955,000	$795,000	$860,000
$0Dechlorination	$213,000	$213,000	$213,000	$213,000	$213,000	$213,000	$213,000	$224,000	$235,000
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$1,090,000	$1,010,000	$1,240,000	$1,010,000	$1,010,000	$1,010,000	$1,010,000	$1,010,000	$901,000
Anaerobic Digester	$5,440,000	$5,320,000	$7,450,000	$5,320,000	$5,320,000	$5,320,000	$4,570,000	$5,320,000	$4,830,000
Centrifuge	$2,720,000	$2,370,000	$3,760,000	$2,380,000	$2,380,000	$2,380,000	$2,350,000	$2,390,000	$2,320,000
Sludge Hauling and Landfill	$988,000	$649,000	$1,320,000	$651,000	$651,000	$651,000	$644,000	$651,000	$639,000
Brine Injection Well								$7,790,000	$7,790,000
Other Costs	$33,000,000	$42,600,000	$55,500,000	$51,500,000	$53,000,000	$55,300,000	$53,700,000	$95,400,000	$86,000,000
Total	**$55,300,000**	**$71,400,000**	**$93,100,000**	**$86,400,000**	**$88,900,000**	**$92,800,000**	**$90,100,000**	**$160,000,000**	**$144,000,000**

Table I-2. Total Annual Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$170,000	$170,000	$174,000	$170,000	$171,000	$172,000	$171,000	$171,000	$171,000
Primary clarifier	$117,000	$117,000	$120,000	$120,000	$117,000	$118,000	$118,000	$118,000	$118,000
Activated Sludge	$518,000		$532,000						
Biological nutrient removal-3-stage		$1,300,000							
Biological nutrient removal-4-stage					$1,540,000		$1,120,000		
Biological nutrient removal-5-stage				$1,380,000		$1,380,000		$1,380,000	$1,140,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$157,000	$156,000	$160,000	$157,000	$157,000	$158,000		$158,000	
Membrane Filter							$1,230,000		$1,230,000
Nitrification, suspended growth			$554,000						
Tertiary clarification, nitrification			$148,000						
Denitrification, suspended growth			$1,370,000						
Tertiary clarification, denitrification			$155,000						
Fermenter				$72,000	$72,100	$72,800		$72,500	$72,400
Chemical Phosphorus Removal			$1,210,000	$61,500	$61,500	$61,500	$31,000	$61,500	$61,300
Alum Feed System			$124,000	$37,300	$37,300	$37,300	$35,200	$37,300	$37,300
Denitrification, attached growth						$1,030,000		$372,000	
Sand Filter				$128,000	$128,000	$129,000		$47,400	
Ultrafiltration								$487,000	
Reverse Osmosis								$1,200,000	$1,140,000
Chlorination	$313,000	$313,000	$313,000	$266,000	$267,000	$267,000	$267,000	$189,000	$193,000
Dechlorination	$121,000	$122,000	$122,000	$122,000	$122,000	$122,000	$122,000	$171,000	$173,000
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$75,000	$67,000	$92,800	$66,000	$66,600	$67,200	$66,800	$66,900	$64,900
Anaerobic Digester	$591,000	$526,000	$804,000	$523,000	$523,000	$525,000	$510,000	$524,000	$489,000
Centrifuge	$797,000	$717,000	$1,060,000	$720,000	$720,000	$721,000	$711,000	$720,000	$704,000
Sludge Hauling and Landfill	$1,990,000	$1,680,000	$2,910,000	$1,690,000	$1,690,000	$1,680,000	$1,660,000	$1,690,000	$1,640,000
Brine Injection Well								$479,000	$479,000
Other Costs	$288,000	$288,000	$290,000	$288,000	$288,000	$288,000	$288,000	$361,000	$360,000
Total	**$5,140,000**	**$5,470,000**	**$10,150,000**	**$5,800,000**	**$5,960,000**	**$6,840,000**	**$6,330,000**	**$8,320,000**	**$8,080,000**

Table I-3. Total Operational Labor Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$100,000	$100,000	$101,000	$100,000	$100,000	$100,000	$99,800	$100,000	$99,800
Primary clarifier	$68,900	$68,700	$69,500	$68,700	$68,700	$68,700	$68,600	$68,700	$68,600
Activated Sludge	$148,000		$149,000						
Biological nutrient removal-3-stage		$316,000							
Biological nutrient removal-4-stage					$348,000		$276,000		
Biological nutrient removal-5-stage				$320,000		$320,000		$320,000	$288,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$90,800	$89,800	$91,400	$90,300	$90,300	$90,300		$90,300	
Membrane Filter							$440,000		$440,000
Nitrification, suspended growth			$154,000						
Tertiary clarification, nitrification			$84,900						
Denitrification, suspended growth			$129,000						
Tertiary clarification, denitrification			$88,500						
Fermenter				$38,600	$38,600	$38,600		$38,600	$38,400
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$118,000	$33,000	$33,000	$33,000	$30,900	$33,000	$33,000
Denitrification, attached growth						$554,000		$221,000	
Sand Filter				$15,400	$15,400	$15,400		$4,140	
Ultrafiltration								$18,800	
Reverse Osmosis								$18,800	$18,800
Chlorination	$74,400	$74,400	$74,400	$66,100	$66,100	$66,100	$66,100	$51,000	$51,400
Dechlorination	$44,200	$44,200	$44,100	$44,200	$44,200	$44,200	$44,200	$57,400	$57,800
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$40,000	$34,900	$50,300	$34,700	$34,700	$34,700	$34,600	$34,700	$34,000
Anaerobic Digester	$134,000	$115,000	$171,000	$114,000	$114,000	$114,000	$113,000	$114,000	$111,000
Centrifuge	$570,000	$521,000	$730,000	$523,000	$523,000	$523,000	$517,000	$523,000	$512,000
Sludge Hauling and Landfill	$204,000	$173,000	$302,000	$174,000	$174,000	$173,000	$171,000	$174,000	$168,000
Brine Injection Well								$9,400	$9,400
Other Costs	$288,000	$288,000	$288,000	$288,000	$288,000	$288,000	$288,000	$361,000	$357,000
Total	**$1,760,000**	**$1,830,000**	**$2,650,000**	**$1,910,000**	**$1,940,000**	**$2,460,000**	**$2,150,000**	**$2,240,000**	**$2,290,000**

Table I-4. Total Maintenance Labor Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$41,700	$42,200	$44,100	$42,400	$42,500	$43,800	$43,300	$43,200	$43,400
Primary clarifier	$34,500	$34,900	$36,500	$35,100	$35,200	$36,200	$35,800	$35,700	$36,000
Activated Sludge	$74,100		$78,900						
Biological nutrient removal-3-stage		$168,000							
Biological nutrient removal-4-stage					$191,000		$149,000		
Biological nutrient removal-5-stage				$171,000		$176,000		$174,000	$158,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$45,500	$45,600	$48,000	$46,100	$46,200	$47,700		$47,000	
Membrane Filter							$239,000		$241,000
Nitrification, suspended growth			$81,300						
Tertiary clarification, nitrification			$43,300						
Denitrification, suspended growth			$70,200						
Tertiary clarification, denitrification			$46,100						
Fermenter				$24,300	$24,400	$25,100		$24,800	$24,900
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$0	$0	$0	$0	$0	$0	$0
Denitrification, attached growth						$216,000		$120,000	
Sand Filter				$9,090	$9,110	$9,390		$2,410	
Ultrafiltration								$18,800	
Reverse Osmosis								$18,800	$18,800
Chlorination	$15,600	$15,800	$16,300	$12,800	$12,900	$13,200	$13,100	$8,140	$8,310
Dechlorination	$6,020	$6,120	$6,310	$12,800	$6,160	$13,200	$6,290	$10,100	$10,300
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$22,900	$20,700	$29,000	$20,700	$20,800	$21,400	$21,100	$21,100	$20,900
Anaerobic Digester	$72,100	$63,600	$96,100	$63,500	$63,600	$65,500	$64,500	$64,700	$63,300
Centrifuge	$31,800	$29,800	$44,400	$30,100	$30,200	$31,000	$30,500	$30,600	$30,300
Sludge Hauling and Landfill	$0	$0	$0	$0	$0	$0	$0	$0	$0
Brine Injection Well								$9,400	$9,400
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$344,000**	**$427,000**	**$641,000**	**$461,000**	**$482,000**	**$692,000**	**$603,000**	**$629,000**	**$665,000**

Table I-5. Total Material Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$23,600	$23,600	$23,700	$23,600	$23,600	$23,600	$23,600	$23,600	$23,600
Primary clarifier	$12,500	$12,200	$12,500	$12,200	$12,200	$12,200	$12,200	$12,200	$12,200
Activated Sludge	$97,400		$100,000						
Biological nutrient removal-3-stage		$228,000							
Biological nutrient removal-4-stage					$259,000		$132,000		
Biological nutrient removal-5-stage				$253,000		$253,000		$253,000	$152,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$18,700	$18,700	$18,700	$18,700	$18,700	$18,700		$18,700	
Membrane Filter							$130,000		$130,000
Nitrification, suspended growth			$102,000						
Tertiary clarification, nitrification			$18,500						
Denitrification, suspended growth			$6,830						
Tertiary clarification, denitrification			$18,600						
Fermenter				$7,880	$7,880	$7,880		$7,875	$7,875
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$6,040	$4,280	$4,280	$4,280	$4,280	$4,280	$4,280
Denitrification, attached growth						$14,200		$3,270	
Sand Filter				$96,200	$96,200	$96,200		$40,000	
Ultrafiltration								$124,000	
Reverse Osmosis								$162,000	$153,000
Chlorination	$30,600	$30,600	$30,600	$31,400	$31,400	$31,400	$31,400	$29,300	$31,600
Dechlorination	$20,200	$20,200	$20,200	$20,200	$20,200	$20,200	$20,200	$20,600	$20,900
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$10,900	$10,100	$12,400	$10,100	$10,100	$10,100	$10,100	$10,100	$9,010
Anaerobic Digester	$42,400	$40,800	$59,400	$40,800	$40,800	$40,800	$39,100	$40,800	$37,400
Centrifuge	$86,400	$73,500	$128,000	$73,800	$73,800	$73,800	$72,300	$73,800	$71,400
Sludge Hauling and Landfill	$1,790,000	$1,510,000	$2,610,000	$1,520,000	$1,520,000	$1,510,000	$1,490,000	$1,520,000	$1,470,000
Brine Injection Well								$2,900	$2,900
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$2,130,000**	**$1,970,000**	**$3,170,000**	**$2,110,000**	**$2,120,000**	**$2,120,000**	**$1,970,000**	**$2,350,000**	**$2,130,000**

Table I-6. Total Chemical Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$0	$0	$0	$0	$0	$0	$0	$0	$0
Primary clarifier	$0	$0	$0	$0	$0	$0	$0	$0	$0
Activated Sludge	$0		$0						
Biological nutrient removal-3-stage		$0							
Biological nutrient removal-4-stage					$0		$77,300		
Biological nutrient removal-5-stage				$0		$0		$0	$0
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$0	$0	$0	$0	$0	$0		$0	
Membrane Filter							$103,000		$103,000
Nitrification, suspended growth			$0						
Tertiary clarification, nitrification			$0						
Denitrification, suspended growth			$991,000						
Tertiary clarification, denitrification			$0						
Fermenter				$0	$0	$0		$0	$0
Chemical Phosphorus Removal			$1,210,000	$61,500	$61,500	$61,500	$31,000	$61,500	$61,300
Alum Feed System			$0	$0	$0	$0	$0	$0	$0
Denitrification, attached growth						$74,300		$7,430	
Sand Filter				$0	$0	$0		$0	
Ultrafiltration								$91,400	
Reverse Osmosis								$361,000	$341,000
Chlorination	$179,000	$179,000	$179,000	$143,000	$143,000	$143,000	$143,000	$88,200	$89,300
Dechlorination	$50,400	$50,400	$50,400	$50,400	$50,400	$50,400	$50,400	$82,500	$83,500
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$0	$0	$0	$0	$0	$0	$0	$0	$0
Anaerobic Digester	$0	$0	$0	$0	$0	$0	$0	$0	$0
Centrifuge	$84,700	$71,800	$126,000	$72,100	$72,100	$72,100	$70,700	$72,200	$69,800
Sludge Hauling and Landfill	$0	$0	$0	$0	$0	$0	$0	$0	$0
Brine Injection Well								$0	$0
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$314,000**	**$301,000**	**$2,560,000**	**$327,000**	**$327,000**	**$401,000**	**$475,000**	**$764,000**	**$748,000**

Table I-7. Total Energy Costs by Detailed Unit Process (2014 $)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	$4,700	$4,680	$4,720	$4,690	$4,690	$4,690	$4,680	$4,690	$4,680
Primary clarifier	$1,190	$1,180	$1,210	$1,180	$1,180	$1,180	$1,180	$1,180	$1,180
Activated Sludge	$198,000		$204,000						
Biological nutrient removal-3-stage		$592,000							
Biological nutrient removal-4-stage					$737,000		$483,000		
Biological nutrient removal-5-stage				$635,000		$635,000		$635,000	$541,000
Blower System	$0	$0	$0	$0	$0	$0	$0	$0	$0
Secondary Clarifier	$1,760	$1,590	$1,820	$1,660	$1,660	$1,660		$1,660	
Membrane Filter							$319,000		$320,000
Nitrification, suspended growth			$217,000						
Tertiary clarification, nitrification			$1,140						
Denitrification, suspended growth			$175,000						
Tertiary clarification, denitrification			$1,400						
Fermenter				$1,220	$1,220	$1,220		$1,223	$1,220
Chemical Phosphorus Removal			$0	$0	$0	$0	$0	$0	$0
Alum Feed System			$0	$0	$0	$0	$0	$0	$0
Denitrification, attached growth						$174,000		$20,400	
Sand Filter				$7,690	$7,690	$7,690		$820	
Ultrafiltration								$234,000	
Reverse Osmosis								$641,000	$606,000
Chlorination	$13,100	$13,100	$13,100	$13,100	$13,100	$13,100	$13,100	$12,600	$12,600
Dechlorination	$650	$650	$650	$650	$650	$650	$650	$650	$650
Effluent Release	$0	$0	$0	$0	$0	$0	$0	$0	$0
Gravity Thickener	$1,030	$977	$1,130	$975	$975	$975	$972	$975	$965
Anaerobic Digester	$342,320	$306,861	$477,457	$304,875	$304,875	$304,875	$293,400	$304,875	$277,773
Centrifuge	$24,000	$20,500	$34,500	$20,600	$20,600	$20,600	$20,300	$20,600	$20,000
Sludge Hauling and Landfill	$0	$0	$0	$0	$0	$0	$0	$0	$0
Brine Injection Well								$457,000	$457,000
Other Costs	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total	**$587,000**	**$942,000**	**$1,130,000**	**$992,000**	**$1,090,000**	**$1,170,000**	**$1,140,000**	**$2,340,000**	**$2,240,000**

APPENDIX J
LCIA RESULTS BY UNIT PROCESS

Appendix J: LCIA Results by Unit Process

This Appendix provides LCIA results by unit process. Table J-1 through Table J-12 display the detailed results for the twelve impact categories by unit process on the basis of a cubic meter of wastewater treated.

Table J-1. Eutrophication Potential Results by Detailed Unit Process (kg N eq/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5
Primary clarifier	3.4E-6	3.4E-6	3.5E-6	3.4E-6	3.4E-6	3.3E-6	3.3E-6	3.4E-6	3.3E-6
Activated sludge	5.0E-4		5.1E-4						
Secondary clarifier	5.1E-6	4.6E-6	5.2E-6	4.8E-6	4.8E-6	4.8E-6		4.8E-6	
Biological nutrient removal-3-stage		1.5E-3							
Biological nutrient removal-4-stage					1.8E-3		1.2E-3		
Biological nutrient removal-5-stage				1.6E-3		1.6E-3		1.6E-3	1.4E-3
Filtration				2.2E-5	2.2E-5	2.2E-5		2.3E-6	
Tertiary clarification, denitrification			4.2E-6						
Tertiary clarification, nitrification			3.5E-6						
Chlorination	1.1E-4	1.0E-4	1.0E-4	9.0E-5	9.0E-5	9.0E-5	9.0E-5	6.7E-5	6.7E-5
Dechlorination	4.3E-5	4.3E-5	4.3E-5	4.3E-5	4.3E-5	4.3E-5	4.3E-5	5.1E-5	5.1E-5
Reverse osmosis								1.7E-3	1.6E-3
Denitrification, attached growth						4.5E-4		5.3E-5	
Denitrification, suspended growth			4.8E-4						
Nitrification, suspended growth			5.5E-4						
Ultrafiltration								6.7E-4	
Chemical phosphorus removal			2.5E-4	1.3E-5	1.3E-5	1.3E-5	6.4E-6	1.3E-5	6.3E-6
Membrane filter							8.3E-4		8.3E-4
Centrifuge	8.6E-5	7.3E-5	1.3E-4	7.4E-5	7.4E-5	7.4E-5	7.2E-5	7.4E-5	7.1E-5
Sludge hauling and landfill	1.7E-3	1.5E-3	2.6E-3	1.5E-3	1.5E-3	1.5E-3	1.4E-3	1.5E-3	1.4E-3
Anaerobic digester	1.4E-4	1.2E-4	1.7E-4	1.2E-4	1.2E-4	1.2E-4	1.2E-4	1.2E-4	1.1E-4
Fermentation				3.1E-6	3.1E-6	3.1E-6		3.1E-6	3.1E-6
Gravity thickener	2.6E-6	2.5E-6	2.9E-6	2.5E-6	2.5E-6	2.5E-6	2.5E-6	2.5E-6	2.5E-6
Effluent release	0.06	6.5E-3	0.01	3.3E-3	3.3E-3	2.2E-3	3.0E-3	5.9E-4	8.5E-4
Underground injection of brine								1.1E-3	1.1E-3
Total	0.07	9.8E-3	0.02	6.8E-3	6.9E-3	6.1E-3	6.8E-3	7.5E-3	7.5E-3

Table J-2. Cumulative Energy Demand Results by Detailed Unit Process (MJ/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Primary clarifier	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Activated sludge	2.0	-	2.1	-	-	-	-	-	-
Secondary clarifier	0.02	0.02	0.02	0.02	0.02	0.02		0.02	-
Biological nutrient removal-3-stage	-	6.1	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	7.2	-	5.0	-	-
Biological nutrient removal-5-stage	-	-	-	6.5	-	6.5	-	6.5	5.6
Filtration	-	-	-	0.09	0.09	0.09	-	9.2E-3	-
Tertiary clarification, denitrification	-	-	0.02	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	0.01	-	-	-	-	-	-
Chlorination	0.35	0.33	0.33	0.29	0.29	0.29	0.29	0.23	0.23
Dechlorination	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.20	0.20
Reverse osmosis	-	-	-	-	-	-	-	6.9	6.5
Denitrification, attached growth	-	-	-	-	-	2.7	-	0.30	-
Denitrification, suspended growth	-	-	3.8	-	-	-	-	-	-
Nitrification, suspended growth	-	-	2.3	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	2.8	-
Chemical phosphorus removal	-	-	0.79	0.04	0.04	0.04	0.02	0.04	0.02
Membrane filter	-	-	-	-	-	-	3.4	-	3.4
Centrifuge	0.39	0.33	0.57	0.33	0.33	0.33	0.33	0.33	0.32
Sludge hauling and landfill	0.51	0.44	0.88	0.45	0.45	0.45	0.43	0.45	0.43
Anaerobic digester	1.8	1.6	2.5	1.8	1.6	1.6	1.6	1.6	1.5
Fermentation	-	-	-	0.01	0.01	0.01	-	0.01	0.01
Gravity thickener	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	4.7	4.7
Total	5.4	9.1	14	9.7	10	12	11	24	23

Table J-3. Global Warming Potential Results by Detailed Unit Process (kg CO_2 eq/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3	2.7E-3
Primary clarifier	1.0E-3	1.0E-3	1.1E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3
Activated sludge	0.14	-	0.21	-	-	-	-	-	-
Secondary clarifier	1.6E-3	1.5E-3	1.6E-3	1.5E-3	1.5E-3	1.5E-3		1.5E-3	-
Biological nutrient removal-3-stage	-	0.49	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.68	-	0.66	-	-
Biological nutrient removal-5-stage	-	-	-	0.75	-	0.75	-	0.75	0.69
Filtration	-	-	-	4.5E-3	4.5E-3	4.5E-3	-	4.8E-4	-
Tertiary clarification, denitrification	-	-	1.4E-3	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	1.2E-3	-	-	-	-	-	-
Chlorination	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Dechlorination	9.4E-3	9.4E-3	9.4E-3	9.4E-3	9.4E-3	9.4E-3	9.4E-3	0.01	0.01
Reverse osmosis	-	-	-	-	-	-	-	0.39	0.36
Denitrification, attached growth	-	-	-	-	-	0.12	-	0.01	-
Denitrification, suspended growth	-	-	0.14	-	-	-	-	-	-
Nitrification, suspended growth	-	-	0.13	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.15	-
Chemical phosphorus removal	-	-	0.04	2.1E-3	2.1E-3	2.1E-3	1.0E-3	2.1E-3	1.0E-3
Membrane filter	-	-	-	-	-	-	0.19		0.19
Centrifuge	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Sludge hauling and landfill	0.07	0.06	0.09	0.06	0.06	0.06	0.06	0.06	0.05
Anaerobic digester	0.19	0.16	0.23	0.16	0.16	0.16	0.15	0.16	0.15
Fermentation	-	-	-	7.4E-4	7.4E-4	7.4E-4	-	7.4E-4	7.4E-4
Gravity thickener	6.5E-4	6.1E-4	7.2E-4	6.1E-4	6.1E-4	6.1E-4	6.1E-4	6.1E-4	6.0E-4
Effluent release	0.07	0.02	0.02	0.01	0.01	6.8E-3	7.0E-3	1.5E-3	3.9E-3
Underground injection of brine	-	-	-	-	-	-	-	0.26	0.26
Total	0.52	0.77	0.92	1.0	0.96	1.1	1.1	1.8	1.8

Table J-4. Acidification Potential Results by Detailed Unit Process (kg SO_2 eq/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4	2.1E-4
Primary clarifier	5.7E-5	5.7E-5	5.9E-5	5.7E-5	5.7E-5	5.7E-5	5.7E-5	5.7E-5	5.7E-5
Activated sludge	9.0E-3	-	9.2E-3	-	-	-	-	-	-
Secondary clarifier	8.6E-5	7.8E-5	8.8E-5	8.1E-5	8.2E-5	8.2E-5	-	8.2E-5	-
Biological nutrient removal-3-stage	-	0.03	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.03	-	0.02	-	-
Biological nutrient removal-5-stage	-	-	-	0.03	-	0.03	-	0.03	0.02
Filtration	-	-	-	3.5E-4	3.5E-4	3.5E-4	-	3.7E-5	-
Tertiary clarification, denitrification	-	-	6.9E-5	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	5.8E-5	-	-	-	-	-	-
Chlorination	6.5E-4	6.4E-4	6.4E-4	6.3E-4	6.3E-4	6.3E-4	6.3E-4	5.9E-4	5.9E-4
Dechlorination	6.0E-4	6.0E-4	6.0E-4	6.0E-4	6.0E-4	6.0E-4	6.0E-4	5.9E-4	5.9E-4
Reverse osmosis	-	-	-	-	-	-	-	0.03	0.03
Denitrification, attached growth	-	-	-	-	-	7.9E-3	-	9.2E-4	-
Denitrification, suspended growth	-	-	8.0E-3	-	-	-	-	-	-
Nitrification, suspended growth	-	-	9.8E-3	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.01	-
Chemical phosphorus removal	-	-	7.5E-4	3.8E-5	3.8E-5	3.8E-5	1.9E-5	3.8E-5	1.9E-5
Membrane filter	-	-	-	-	-	-	0.01	-	0.01
Centrifuge	1.1E-3	9.5E-4	1.6E-3	9.6E-4	9.6E-4	9.6E-4	9.4E-4	9.6E-4	9.2E-4
Sludge hauling and landfill	-	-	-	-9.6E-4	-9.7E-4	-9.7E-4	-9.8E-4	-9.7E-4	-9.3E-4
Anaerobic digester	2.4E-3	2.1E-3	3.0E-3	2.2E-3	2.0E-3	2.0E-3	2.0E-3	2.0E-3	2.0E-3
Fermentation	-	-	-	5.6E-5	5.6E-5	5.6E-5	-	5.6E-5	5.5E-5
Gravity thickener	4.7E-5	4.5E-5	5.2E-5	4.5E-5	4.5E-5	4.5E-5	4.4E-5	4.5E-5	4.4E-5
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	0.02	0.02
Total	0.01	0.03	0.03	0.03	0.04	0.04	0.04	0.09	0.09

Table J-5. Fossil Depletion Results by Detailed Unit Process (kg oil eq/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3	1.1E-3
Primary clarifier	3.1E-4	3.0E-4	3.1E-4	3.0E-4	3.0E-4	3.0E-4	3.0E-4	3.0E-4	3.0E-4
Activated sludge	0.05	-	0.05	-	-	-	-	-	-
Secondary clarifier	4.6E-4	4.2E-4	4.7E-4	4.4E-4	4.4E-4	4.4E-4	-	4.4E-4	-
Biological nutrient removal-3-stage	-	0.14	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.16		0.11	-	-
Biological nutrient removal-5-stage	-	-	-	0.15		0.15	-	0.15	0.12
Filtration	-	-	-	1.9E-3	1.9E-3	1.9E-3	-	2.1E-4	-
Tertiary clarification, denitrification	-	-	3.8E-4	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	3.2E-4	-	-	-	-	-	-
Chlorination	6.0E-3	5.7E-3	5.7E-3	5.2E-3	5.2E-3	5.2E-3	5.2E-3	4.2E-3	4.3E-3
Dechlorination	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3	3.6E-3	4.1E-3	4.1E-3
Reverse osmosis	-	-	-	-	-	-	-	0.15	0.14
Denitrification, attached growth	-	-	-	-	-	0.06	-	6.7E-3	-
Denitrification, suspended growth	-	-	0.09	-	-	-	-	-	-
Nitrification, suspended growth	-	-	0.05	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.06	-
Chemical phosphorus removal	-	-	0.01	6.3E-4	6.3E-4	6.3E-4	3.2E-4	6.3E-4	3.2E-4
Membrane filter	-	-	-	-	-	-	0.08	-	0.08
Centrifuge	8.8E-3	7.5E-3	0.01	7.6E-3	7.5E-3	7.5E-3	7.4E-3	7.5E-3	7.2E-3
Sludge hauling and landfill	0.01	9.2E-3	0.02	9.6E-3	9.5E-3	9.5E-3	9.1E-3	9.5E-3	9.0E-3
Anaerobic digester	0.04	0.04	0.06	0.04	0.04	0.04	0.04	0.04	0.03
Fermentation	-	-	-	2.8E-4	2.8E-4	2.8E-4	-	2.8E-4	2.8E-4
Gravity thickener	2.4E-4	2.3E-4	2.7E-4	2.3E-4	2.3E-4	2.3E-4	2.3E-4	2.3E-4	2.2E-4
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	0.10	0.10
Total	0.12	0.20	0.30	0.22	0.23	0.28	0.25	0.54	0.51

Table J-6. Smog Formation Potential Results by Detailed Unit Process (kg O_3 eq/m^3 Wastewater Treated)

Process	**Level 1, AS**	**Level 2-1, A2O**	**Level 2-2, AS3**	**Level 3-1, B5**	**Level 3-2, MUCT**	**Level 4-1, B5/Denit**	**Level 4-2, MBR**	**Level 5-1, B5/RO**	**Level 5-2, MBR/RO**
Screening and grit removal	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3
Primary clarifier	4.5E-4	4.5E-4	4.6E-4	4.5E-4	4.5E-4	4.5E-4	4.5E-4	4.5E-4	4.5E-4
Activated sludge	0.07	-	0.07	-	-	-	-	-	-
Secondary clarifier	6.8E-4	6.2E-4	7.0E-4	6.5E-4	6.5E-4	6.5E-4	-	6.5E-4	-
Biological nutrient removal-3-stage	-	0.21	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	0.25	-	0.17	-	-
Biological nutrient removal-5-stage	-	-	-	0.22	-	0.22	-	0.22	0.19
Filtration	-	-	-	2.7E-3	2.7E-3	2.7E-3	-	2.9E-4	-
Tertiary clarification, denitrification	-	-	5.5E-4	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	4.7E-4	-	-	-	-	-	-
Chlorination	5.1E-3	5.0E-3	5.0E-3	4.9E-3	4.9E-3	4.9E-3	4.9E-3	4.6E-3	4.6E-3
Dechlorination	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.0E-3	5.3E-3	5.3E-3
Reverse osmosis	-	-	-	-	-	-	-	0.22	0.21
Denitrification, attached growth	-	-	-	-	-	0.06	-	7.1E-3	-
Denitrification, suspended growth	-	-	0.06	-	-	-	-	-	-
Nitrification, suspended growth	-	-	0.08	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	0.08	-
Chemical phosphorus removal	-	-	3.0E-3	1.5E-4	1.5E-4	1.5E-4	7.6E-5	1.5E-4	7.5E-5
Membrane filter	-	-	-	-	-	-	0.11	-	0.11
Centrifuge	8.6E-3	7.3E-3	0.01	7.4E-3	7.4E-3	7.4E-3	7.2E-3	7.4E-3	7.1E-3
Sludge hauling and landfill	-	-	-7.1E-3	-5.9E-3	-5.9E-3	-5.9E-3	-6.0E-3	-5.9E-3	-5.7E-3
Anaerobic digester	0.05	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04
Fermentation	-	-	-	4.3E-4	4.3E-4	4.3E-4	-	4.3E-4	4.3E-4
Gravity thickener	3.7E-4	3.5E-4	4.0E-4	3.5E-4	3.5E-4	3.5E-4	3.4E-4	3.5E-4	3.4E-4
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	4.3E-4	-	0.16	0.16
Total	0.14	0.27	0.29	0.28	0.30	0.34	0.33	0.75	0.72

Table J-7. Human Health- Particulate Matter Formation Potential Results by Detailed Unit Process (kg PM2.5 eq/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5	2.4E-5
Primary clarifier	6.5E-6	6.5E-6	6.6E-6	6.5E-6	6.5E-6	6.5E-6	6.5E-6	6.5E-6	6.4E-6
Activated sludge	1.0E-3	-	1.0E-3	-	-	-	-	-	-
Secondary clarifier	9.8E-6	8.9E-6	1.0E-5	9.2E-6	9.3E-6	9.3E-6	-	9.3E-6	-
Biological nutrient removal-3-stage	-	3.0E-3	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	3.6E-3	-	2.5E-3	-	-
Biological nutrient removal-5-stage	-	-	-	3.2E-3	-	3.2E-3	-	3.2E-3	2.7E-3
Filtration	-	-	-	3.9E-5	3.9E-5	3.9E-5	-	4.1E-6	-
Tertiary clarification, denitrification	-	-	7.9E-6	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	6.6E-6	-	-	-	-	-	-
Chlorination	7.2E-5	7.1E-5	7.1E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	6.6E-5	6.6E-5
Dechlorination	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.0E-5	7.1E-5	7.1E-5
Reverse osmosis	-	-	-	-	-	-	-	3.2E-3	3.1E-3
Denitrification, attached growth	-	-	-	-	-	8.8E-4	-	1.0E-4	-
Denitrification, suspended growth	-	-	8.9E-4	-	-	-	-	-	-
Nitrification, suspended growth	-	-	1.1E-3	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.2E-3	-
Chemical phosphorus removal	-	-	6.6E-5	3.3E-6	3.3E-6	3.3E-6	1.7E-6	3.3E-6	1.7E-6
Membrane filter	-	-	-	-	-	-	1.6E-3	-	1.6E-3
Centrifuge	1.3E-4	1.1E-4	1.8E-4	1.1E-4	1.1E-4	1.1E-4	1.1E-4	1.1E-4	1.0E-4
Sludge hauling and landfill	-	-	-1.5E-4	-1.1E-4	-1.1E-4	-1.1E-4	-1.1E-4	-1.1E-4	-1.1E-4
Anaerobic digester	1.8E-4	1.6E-4	2.3E-4	1.7E-4	1.6E-4	1.6E-4	1.6E-4	1.6E-4	1.5E-4
Fermentation	-	-	-	6.2E-6	6.2E-6	6.2E-6	-	6.2E-6	6.2E-6
Gravity thickener	5.3E-6	5.0E-6	5.8E-6	5.0E-6	5.0E-6	5.0E-6	5.0E-6	5.0E-6	4.9E-6
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	2.3E-3	2.3E-3
Total	1.5E-3	3.4E-3	3.5E-3	3.6E-3	3.9E-3	4.5E-3	4.4E-3	0.01	0.01

Table J-8. Ozone Depletion Potential Results by Detailed Unit Process (kg CFC-11 eq/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9	1.8E-9
Primary clarifier	5.0E-10	5.0E-10	5.1E-10	5.0E-10	5.0E-10	5.0E-10	5.0E-10	5.0E-10	5.0E-10
Activated sludge	6.1E-7	-	3.9E-7	-	-	-	-	-	-
Secondary clarifier	7.6E-10	6.9E-10	7.8E-10	7.1E-10	7.2E-10	7.2E-10	-	7.2E-10	-
Biological nutrient removal-3-stage	-	2.6E-6	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	2.7E-6	-	6.4E-6	-	-
Biological nutrient removal-5-stage	-	-	-	6.6E-6	-	6.6E-6	-	6.6E-6	6.5E-6
Filtration	-	-	-	3.0E-9	3.0E-9	3.0E-9	-	3.2E-10	-
Tertiary clarification, denitrification	-	-	6.1E-10	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	5.1E-10	-	-	-	-	-	-
Chlorination	2.6E-8	2.5E-8	2.5E-8	2.1E-8	2.1E-8	2.1E-8	2.1E-8	1.5E-8	1.5E-8
Dechlorination	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.0E-9	6.7E-9	6.7E-9
Reverse osmosis	-	-	-	-	-	-	-	2.7E-7	2.5E-7
Denitrification, attached growth	-	-	-	-	-	7.4E-8	-	8.5E-9	-
Denitrification, suspended growth	-	-	8.2E-8	-	-	-	-	-	-
Nitrification, suspended growth	-	-	8.6E-8	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.1E-7	-
Chemical phosphorus removal	-	-	1.5E-8	7.7E-10	7.7E-10	7.7E-10	3.9E-10	7.7E-10	3.8E-10
Membrane filter	-	-	-	-	-	-	1.3E-7	-	1.3E-7
Centrifuge	1.1E-8	9.1E-9	1.5E-8	9.2E-9	9.1E-9	9.1E-9	9.0E-9	9.1E-9	8.8E-9
Sludge hauling and landfill	4.9E-9	4.4E-9	1.2E-8	4.9E-9	4.8E-9	4.8E-9	4.4E-9	4.8E-9	4.6E-9
Anaerobic digester	5.9E-7	4.9E-7	6.5E-7	4.7E-7	4.7E-7	4.7E-7	4.8E-7	4.7E-7	4.5E-7
Fermentation				4.8E-10	4.8E-10	4.8E-10	-	4.8E-10	4.8E-10
Gravity thickener	4.1E-10	3.9E-10	4.5E-10	3.9E-10	3.9E-10	3.9E-10	3.9E-10	3.9E-10	3.8E-10
Effluent release	2.6E-6	6.9E-7	6.7E-7	5.2E-7	5.2E-7	2.5E-7	2.6E-7	5.5E-8	1.4E-7
Underground injection of brine	-	-	-	-	-	-	-	1.8E-7	1.8E-7
Total	3.9E-6	3.8E-6	2.0E-6	7.6E-6	3.7E-6	7.4E-6	7.3E-6	7.7E-6	7.7E-6

Table J-9. Water Depletion Results by Detailed Unit Process (m^3 H_2O/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	8.2E-6	8.1E-6	8.2E-6	8.2E-6	8.2E-6	8.2E-6	8.1E-6	8.2E-6	8.1E-6
Primary clarifier	5.9E-6	5.8E-6	6.0E-6	5.8E-6	5.8E-6	5.8E-6	5.8E-6	5.8E-6	5.8E-6
Activated sludge	3.6E-4	-	3.8E-4	-	-	-	-	-	-
Secondary clarifier	9.4E-6	9.1E-6	9.5E-6	9.2E-6	9.2E-6	9.2E-6	-	9.2E-6	-
Biological nutrient removal-3-stage	-	1.1E-3	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	1.3E-3	-	8.7E-4	-	-
Biological nutrient removal-5-stage	-	-	-	1.2E-3	-	1.2E-3	-	1.2E-3	9.7E-4
Filtration	-	-	-	1.6E-5	1.6E-5	1.6E-5	-	1.7E-6	-
Tertiary clarification, denitrification	-	-	8.7E-6	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	8.3E-6	-	-	-	-	-	-
Chlorination	1.7E-4	1.6E-4	1.6E-4	1.3E-4	1.3E-4	1.3E-4	1.3E-4	9.0E-5	9.1E-5
Dechlorination	3.7E-5	3.7E-5	3.7E-5	3.7E-5	3.7E-5	3.7E-5	3.7E-5	4.9E-5	4.9E-5
Reverse osmosis	-	-	-	-	-	-	-	1.7E-3	1.6E-3
Denitrification, attached growth	-	-	-	-	-	3.5E-4	-	4.0E-5	-
Denitrification, suspended growth	-	-	4.1E-4	-	-	-	-	-	-
Nitrification, suspended growth	-	-	4.1E-4	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.4E-3	-
Chemical phosphorus removal	-	-	2.4E-3	1.2E-4	1.2E-4	1.2E-4	6.0E-5	1.2E-4	6.0E-5
Membrane filter	-	-	-	-	-	-	6.7E-4	-	6.7E-4
Centrifuge	6.3E-5	5.3E-5	9.1E-5	5.4E-5	5.4E-5	5.4E-5	5.3E-5	5.4E-5	5.1E-5
Sludge hauling and landfill	9.0E-5	7.8E-5	1.5E-4	8.0E-5	8.0E-5	8.0E-5	7.7E-5	8.0E-5	7.6E-5
Anaerobic digester	5.7E-5	5.1E-5	7.4E-5	5.5E-5	5.1E-5	5.1E-5	5.0E-5	5.1E-5	4.8E-5
Fermentation	-	-	-	2.6E-6	2.6E-6	2.6E-6	-	2.6E-6	2.6E-6
Gravity thickener	2.4E-6	2.3E-6	2.7E-6	2.3E-6	2.3E-6	2.3E-6	2.3E-6	2.3E-6	2.2E-6
Effluent release	-	-	-	-	-	-	-	-	-
Underground injection of brine	-	-	-	-	-	-	-	0.18	0.17
Total	8.0E-4	1.5E-3	4.1E-3	1.7E-3	1.8E-3	2.0E-3	2.0E-3	0.19	0.17

Table J-10. Human Health-Cancer Results by Detailed Unit Process (CTU_h/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11	1.1E-11
Primary clarifier	5.0E-12	4.9E-12	5.1E-12	4.9E-12	4.9E-12	4.9E-12	4.9E-12	4.9E-12	4.9E-12
Activated sludge	4.8E-10	-	5.0E-10	-	-	-	-	-	-
Secondary clarifier	7.5E-12	7.1E-12	7.6E-12	7.2E-12	7.2E-12	7.2E-12	-	7.2E-12	-
Biological nutrient removal-3-stage	-	1.4E-9	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	1.7E-9	-	1.2E-9	-	-
Biological nutrient removal-5-stage	-	-	-	1.5E-9	-	1.5E-9	-	1.5E-9	1.3E-9
Filtration	-	-	-	1.9E-11	1.9E-11	1.9E-11	-	2.0E-12	-
Tertiary clarification, denitrification	-	-	6.6E-12	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	6.0E-12	-	-	-	-	-	-
Chlorination	1.9E-10	1.4E-10	1.4E-10	1.2E-10	1.2E-10	1.2E-10	1.2E-10	8.4E-11	8.5E-11
Dechlorination	5.4E-11	5.4E-11	5.4E-11	5.4E-11	5.4E-11	5.4E-11	5.4E-11	7.3E-11	7.4E-11
Reverse osmosis	-	-	-	-	-	-	-	1.7E-9	1.6E-9
Denitrification, attached growth	-	-	-	-	-	4.8E-10	-	5.6E-11	-
Denitrification, suspended growth	-	-	5.6E-10	-	-	-	-	-	-
Nitrification, suspended growth	-	-	5.6E-10	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	7.6E-10	-
Chemical phosphorus removal	-	-	4.9E-9	2.4E-10	2.4E-10	2.4E-10	1.2E-10	2.4E-10	1.2E-10
Membrane filter	-	-	-	-	-	-	8.1E-10	-	8.1E-10
Centrifuge	8.8E-11	7.5E-11	1.3E-10	7.6E-11	7.6E-11	7.6E-11	7.4E-11	7.6E-11	7.3E-11
Sludge hauling and landfill	2.6E-10	2.3E-10	3.8E-10	2.4E-10	2.5E-10	2.4E-10	2.7E-10	2.8E-10	2.8E-10
Anaerobic digester	9.0E-11	8.1E-11	1.2E-10	8.7E-11	8.1E-11	8.1E-11	7.9E-11	8.1E-11	7.6E-11
Fermentation	-	-	-	3.1E-12	3.1E-12	3.1E-12	-	3.1E-12	3.1E-12
Gravity thickener	2.7E-12	2.6E-12	3.0E-12	2.6E-12	2.6E-12	2.6E-12	2.6E-12	2.6E-12	2.5E-12
Effluent release	3.1E-9	3.1E-9	2.5E-9	2.1E-9	1.5E-9	2.4E-9	1.0E-9	4.0E-10	1.7E-10
Underground injection of brine	-	-	-	-	-	-	-	1.1E-9	1.1E-9
Total	4.3E-9	5.1E-9	9.9E-9	4.5E-9	4.1E-9	5.2E-9	3.7E-9	6.4E-9	5.7E-9

Table J-11. Human Health-NonCancer Results by Detailed Unit Process (CTU_h/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10	1.1E-10
Primary clarifier	6.1E-11	6.0E-11	6.1E-11	6.0E-11	6.0E-11	6.0E-11	6.0E-11	6.0E-11	6.0E-11
Activated sludge	4.8E-9	-	4.9E-9	-	-	-	-	-	-
Secondary clarifier	9.3E-11	8.9E-11	9.4E-11	9.1E-11	9.1E-11	9.1E-11	-	9.1E-11	-
Biological nutrient removal-3-stage	-	1.4E-8	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	1.7E-8	-	1.2E-8	-	-
Biological nutrient removal-5-stage	-	-	-	1.5E-8	-	1.5E-8	-	1.5E-8	1.3E-8
Filtration	-	-	-	1.8E-10	1.8E-10	1.8E-10	-	2.0E-11	-
Tertiary clarification, denitrification	-	-	8.4E-11	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	7.8E-11	-	-	-	-	-	-
Chlorination	2.0E-9	1.6E-9	1.6E-9	1.3E-9	1.3E-9	1.3E-9	1.3E-9	9.2E-10	9.3E-10
Dechlorination	9.6E-10	9.6E-10	9.6E-10	9.6E-10	9.6E-10	9.6E-10	9.6E-10	1.6E-9	1.6E-9
Reverse osmosis	-	-	-	-	-	-	-	1.6E-8	1.5E-8
Denitrification, attached growth	-	-	-	-	-	4.5E-9	-	5.3E-10	-
Denitrification, suspended growth	-	-	5.1E-9	-	-	-	-	-	-
Nitrification, suspended growth	-	-	5.4E-9	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	1.1E-8	-
Chemical phosphorus removal	-	-	1.2E-8	5.8E-10	5.8E-10	5.8E-10	3.0E-10	5.8E-10	2.9E-10
Membrane filter	-	-	-	-	-	-	8.0E-9	-	8.0E-9
Centrifuge	9.3E-10	7.9E-10	1.3E-9	8.0E-10	8.0E-10	8.0E-10	7.8E-10	8.0E-10	7.7E-10
Sludge hauling and landfill	4.5E-9	4.2E-9	5.8E-9	4.9E-9	5.3E-9	4.9E-9	6.3E-9	6.6E-9	6.7E-9
Anaerobic digester	2.1E-9	1.9E-9	2.9E-9	2.1E-9	1.9E-9	1.9E-9	1.8E-9	1.9E-9	1.8E-9
Fermentation	-	-	-	3.2E-11	3.2E-11	3.2E-11	-	3.2E-11	3.2E-11
Gravity thickener	2.9E-11	2.7E-11	3.2E-11	2.7E-11	2.7E-11	2.7E-11	2.7E-11	2.7E-11	2.6E-11
Effluent release	1.0E-7	1.0E-7	1.0E-7	7.6E-8	6.2E-8	7.6E-8	1.9E-8	1.1E-8	2.1E-9
Underground injection of brine	-	-	-	-	-	-	-	1.1E-8	1.1E-8
Total	1.2E-7	1.3E-7	1.4E-7	1.0E-7	9.0E-8	1.1E-7	5.0E-8	7.7E-8	6.1E-8

Table J-12. Ecotoxicity Results by Detailed Unit Process (CTU_e/m^3 Wastewater Treated)

Process	Level 1, AS	Level 2-1, A2O	Level 2-2, AS3	Level 3-1, B5	Level 3-2, MUCT	Level 4-1, B5/Denit	Level 4-2, MBR	Level 5-1, B5/RO	Level 5-2, MBR/RO
Screening and grit removal	0.59	0.58	0.59	0.59	0.59	0.59	0.58	0.59	0.58
Primary clarifier	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Activated sludge	25	-	26	-	-	-	-	-	-
Secondary clarifier	0.29	0.27	0.29	0.28	0.28	0.28	-	0.28	-
Biological nutrient removal-3-stage	-	74	-	-	-	-	-	-	-
Biological nutrient removal-4-stage	-	-	-	-	88	-	61	-	-
Biological nutrient removal-5-stage	-	-	-	80	-	80	-	80	68
Filtration	-	-	-	1.0	1.0	1.0	-	0.11	-
Tertiary clarification, denitrification	-	-	0.24	-	-	-	-	-	-
Tertiary clarification, nitrification	-	-	0.21	-	-	-	-	-	-
Chlorination	5.2	4.9	4.9	4.3	4.3	4.3	4.3	3.2	3.2
Dechlorination	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.5	2.6
Reverse osmosis	-	-	-	-	-	-	-	83	78
Denitrification, attached growth	-	-	-	-	-	23	-	2.7	-
Denitrification, suspended growth	-	-	25	-	-	-	-	-	-
Nitrification, suspended growth	-	-	28	-	-	-	-	-	-
Ultrafiltration	-	-	-	-	-	-	-	34	-
Chemical phosphorus removal	-	-	14	0.68	0.68	0.68	0.35	0.68	0.34
Membrane filter	-	-	-	-	-	-	42	-	42
Centrifuge	3.5	3.0	5.1	3.0	3.0	3.0	3.0	3.0	2.9
Sludge hauling and landfill	11	11	12	14	14	14	17	18	18
Anaerobic digester	7.3	6.4	9.7	7.0	6.4	6.4	6.2	6.4	6.0
Fermentation	-	-	-	0.16	0.16	0.16	-	0.16	0.16
Gravity thickener	0.14	0.13	0.15	0.13	0.13	0.13	0.13	0.13	0.13
Effluent release	2.8E+2	2.8E+2	2.8E+2	1.6E+2	1.6E+2	1.6E+2	72	25	6.0
Underground injection of brine	-	-	-	-	-	-	-	57	57
Total	3.4E+2	3.9E+2	4.1E+2	2.7E+2	2.8E+2	2.9E+2	2.1E+2	3.2E+2	2.9E+2

Performance-based approach methods document: marine dissolved oxygen

Public workshop and hearing

May 15, 2025

Today's Agenda

1. Meeting logistics
2. Presentation on the Performance-based approach methods document
3. Question and answer session
4. Public hearing

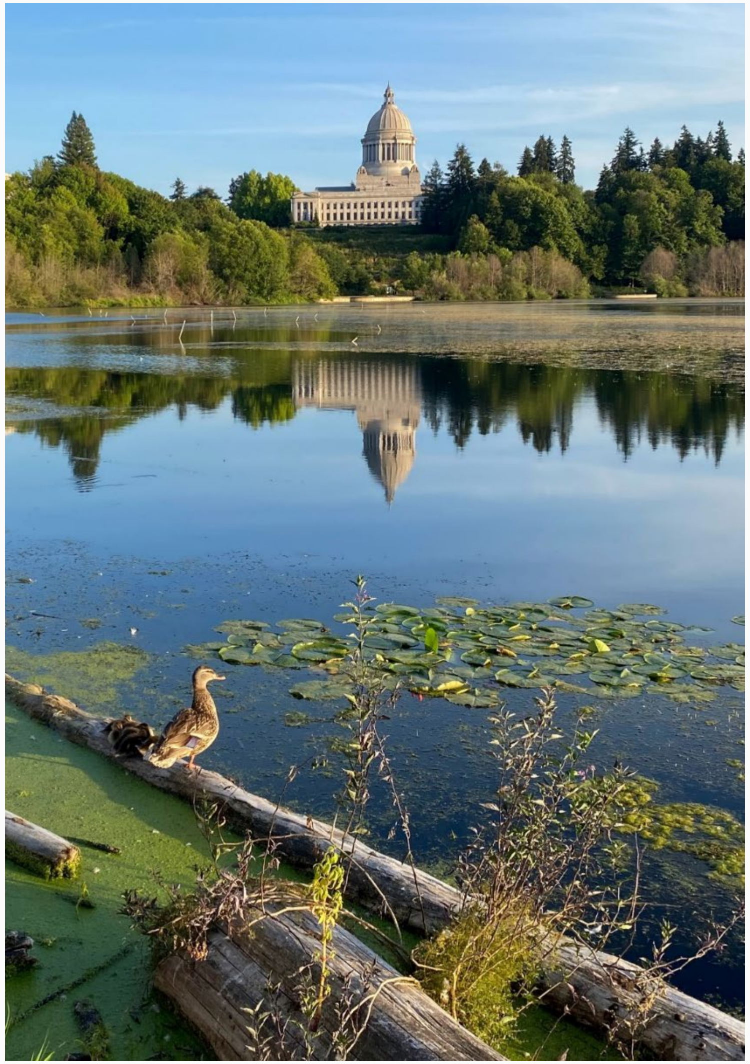
DEPARTMENT OF ECOLOGY
State of Washington

Performance-Based Approach Methodology for Marine DO Natural Conditions Criteria
May 15, 2025

1. Updates on our Natural Conditions Rulemaking

Natural Conditions Rulemaking Status

- November 2024 -- We adopted natural conditions provisions into Washington's standards, including:
  - General provision.
  - Human-use allowances.
  - Methods to establishing site-specific criteria, including new performance-based approach (PBA).
- We did not finalize the draft Performance-Based Approach (PBA) methods document.



Natural Conditions Rulemaking Next Steps

- We anticipate submitting the rule package to EPA this summer.
  - Will include finalized PBA methodology for marine DO.
- EPA will review and take action on our rulemaking.
- EPA will evaluate impact on endangered species and critical habitat.
  - Process will also likely require consultation with ESA-listing agencies (USFWS, NOAA NMFS)

2. A recap of the Performance-Based Approach and methods document

When We Traditionally Propose Site-Specific Criteria…

DEPARTMENT OF ECOLOGY
State of Washington

- We submit everything to the public and EPA, including:
  - The site-specific criteria (cookies)
  - All the data used, scientific support, and methods (recipe and ingredients)
- EPA reviews our process (recipe), our data (ingredients), what we did (mixing and baking), and our final criteria (cookies).
- EPA makes approval decision per submission (batch of cookies)

CHOCOLATE CHIP COOKIES

YIELD: 24 COOKIES
PREP TIME: 20 MINUTES
BAKE TIME: 10 MINUTES

INGREDIENTS

- 360 g All-purpose Flour
- 5 g Baking Soda
- 5 g Salt
- 230 g Unsalted Butter (Softened)
- 200 g Granulated Sugar
- 200 g Light Brown Sugar
- 10 g Vanilla Extract
- 2 Large Eggs
- 350 g Chocolate Chips/Chunks

TOOLS

- (2) Mixing Bowls
- Kitchen Scale
- Spatula
- Cookie Scoop
- Hand/Stand Mixer or Spoon
- (1) Full Size Sheet Pan

46 cm x 66 cm

DIRECTIONS

1. Pre-heat oven to 180 °C
2. In a mixing bowl, combine room-temperature butter, both types of sugar, and vanilla until smooth. Beat in the eggs
3. Combine the flour, baking soda, and salt into the butter mixture with a spatula until combined, then set aside
4. Gradually add flour mixture to the butter mixture and combine well
5. Stir in chocolate chips/chunks
6. Spoon dough from the mixing bowl onto a full size sheet pan using a cookie scoop (or spoon). Allow sufficient space between each cookie for spreading to occur during the baking process
7. Place the pan into preheated oven on the middle rack and bake for about 10 minutes. Cookies are done when the edges are lightly browned
8. Serve warm or cold. Enjoy!

NIST OFFICE OF WEIGHTS AND MEASURES

But In A Performance-Based Approach…

- We submit our recipe (methods) to the public and EPA.
  - Recipe needs to be repeatable and contain sufficient, detailed information.
- EPA may also want to see how we plan on using approach during review.
- EPA approval of a performance-based approach (recipe) means approval of the criteria (batch of cookies) as well.

CHOCOLATE CHIP COOKIES

YIELD: 24 COOKIES

PREP TIME: 20 MINUTES BAKE TIME: 10 MINUTES

INGREDIENTS

- 360 g All-purpose Flour
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NIST OFFICE OF WEIGHTS AND MEASURES

February 2023 nist.gov/metric

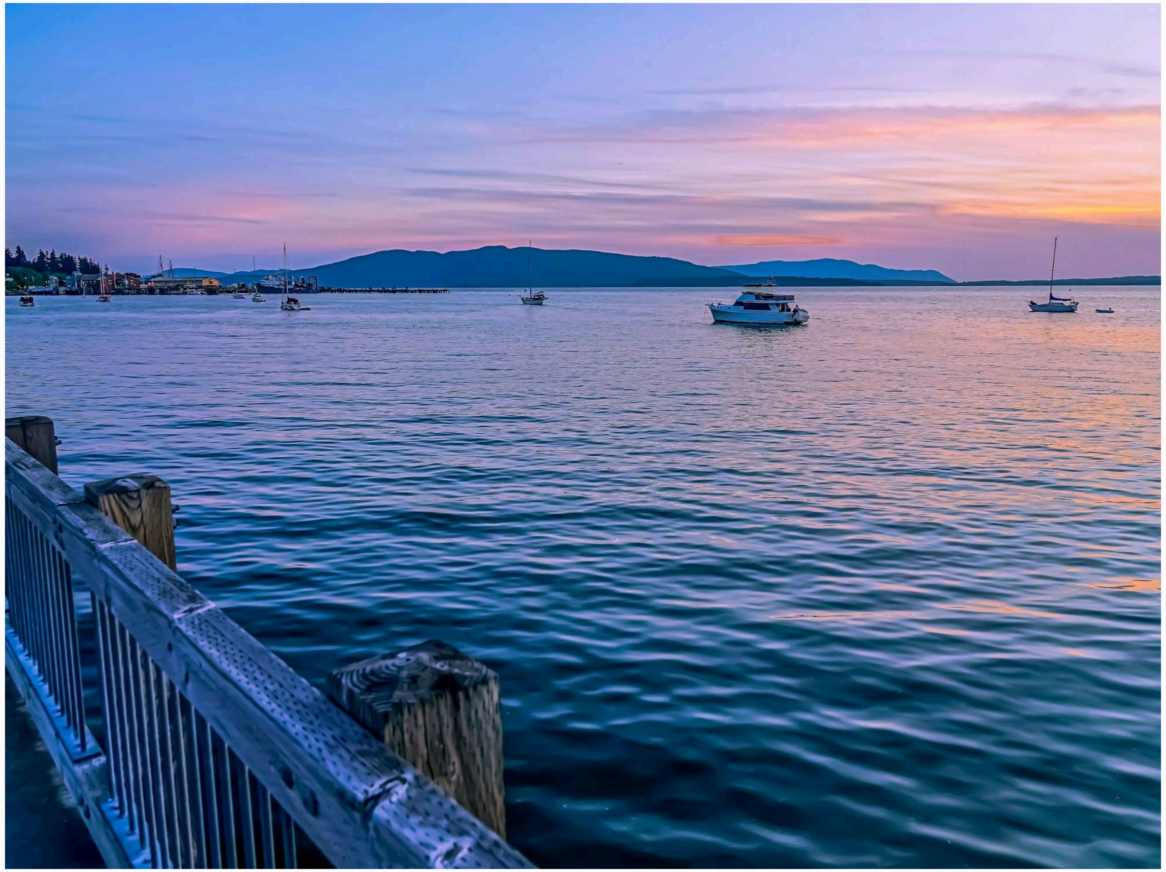
This publication is available free of charge https://doi.org/10.6028/NIST.MetricRecipes-2023

Site-specific criteria development is **Ecology's role and responsibility.**

The PBA methods document is a tool for the agency to use in its Clean Water Act responsibilities and actions.

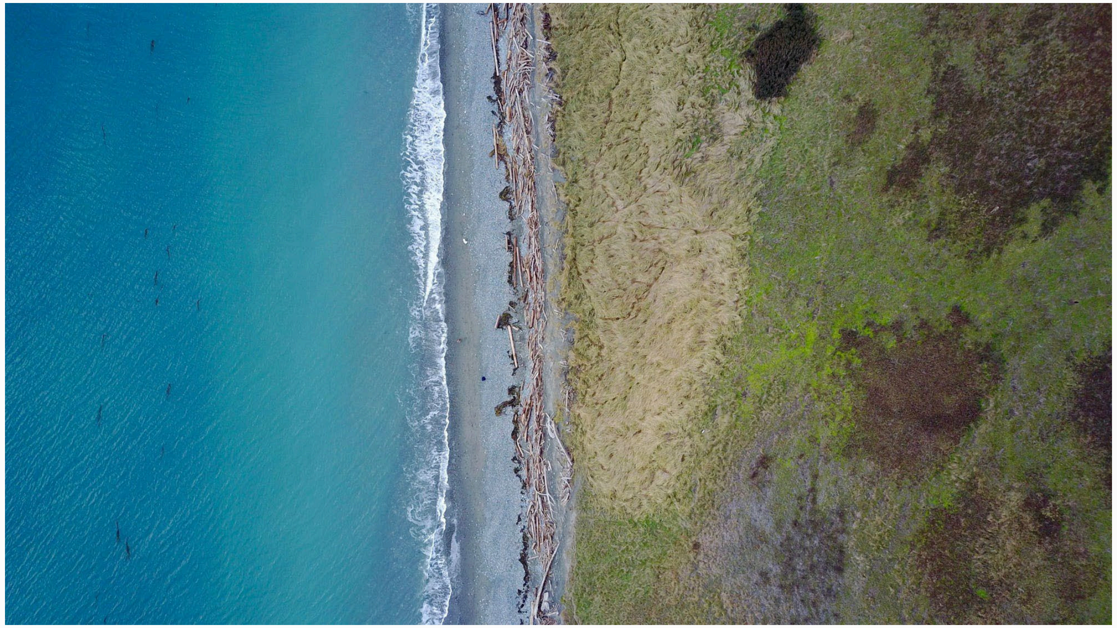
Our First Focus: Marine Dissolved Oxygen

- During natural conditions rulemaking, we received comments, including from EPA, that requested we add more detail.
- To do so, significant work and changes were required that we were unable to complete before a rulemaking decision needed to be made.
- So, we first focused crafting methods for marine DO natural conditions criteria.



Marine Dissolved Oxygen PBA Methodology

- Regular meetings with EPA have clarified EPA's previous comments.
- EPA's recommendation: more "like a permit"
  - Just the facts and requirements.
- EPA would also want to see how we plan on using this approach (e.g., Salish Sea Model) during their review of our PBA methods document.



3. What did we change and improve from the first draft?

Reorganization and Data Discussion

- We reorganized the document to ensure it flowed better as a step-wise approach.
- Added a new table (Step 2) to showcase data categories (like hydrology), and what sort of data types we use for modeling current conditions and estimating natural conditions.

Table 1. Data needs for modeling current and natural conditions.

Category	Current Conditions	Natural Conditions
Water Quality Observations, Marine Water	Marine water quality observations (e.g., salinity, temperature, photosynthetically active radiation, chlorophyll-*a*, dissolved oxygen, dissolved and particulate fractions of speciated nutrients, density)	--
Water Quality Observations, Fresh Water	Freshwater quality observations (e.g., nutrients, temperature)	Freshwater quality observations (e.g., nutrients)
Hydrodynamics	Hydrodynamic data (tides and currents)	--

Collecting New Data and Model Requirements

- After we start project, we may find out that current data are insufficient and impede estimating natural conditions.
- Two new sections in document (Step 4 and Step 5) describe how Ecology will collect these data and ensure they are credible.
- For model requirements (Step 6), we provided additional details, such as what key processes (e.g., phytoplankton dynamics) the model must be able to simulate.

Estimating Natural Conditions and Determining Criteria Values

- We expanded on the required elements (Step 8) that must be considered, accounted for, and removed when estimating natural conditions.
  - E.g., establishing oceanic open boundary conditions, accounting for climate change.
- We specified more clearly how we will go from model outputs to criteria values (Step 9).

Step 9 Updates: Aggregating Model Outputs to Determine Criteria

- We first aggregate horizontally within the assessment unit (AU).
- We next take the daily minimum value (same as biological criteria).
- No vertical aggregation.
- The final criteria: One DO concentration per day per assessment unit per depth layer (e.g., 10 layers in Salish Sea).

4. How will Ecology use this methodology?

General Use

- Following the PBA methodology will require time, investment, research, and modeling of a site.
- We anticipate this being an option for waters that have already been identified as impaired *and* some of the non-compliance is due to natural water quality.
- Therefore, we anticipate use of the PBA methodology, when needed, in our water clean up plans.

Public Involvement

- If Ecology develops natural conditions criteria using an EPA-approved PBA method, no additional rulemaking for the criteria is required.
  - There may still be other required public processes for the project.
- Ecology is committed to providing the documentation for developing these natural conditions criteria to the public for review.
  - Could be part of a public process (e.g., draft TMDL), or a separate public review.
- Ecology is committed to providing resources for identifying where we developed natural conditions criteria and where they are in effect.

5. What about other water quality parameters, like temperature in fresh waters?

Next Chapter: Freshwater Temperature

- We are in exploration stage.
- We will need to consider available models and scope compared to marine DO chapter.
  - This chapter may require a lot more and different work and information compared to marine DO.
- Early considerations include ensuring there are sufficient cold-water refugia options.

Other Parameter PBA Methodologies

- Consideration:
  We may wait for additional EPA feedback and after EPA action on our marine DO PBA.
- Will go through same process as marine DO PBA methodology.
- Other parameters being considered:
  - Freshwater Temperature
  - Freshwater DO
  - Freshwater pH
  - Marine Temperature

6. These are our next steps.

Marine Dissolved Oxygen PBA Next Steps

- March 25
  Release of second public draft.
- May 22
  Comment period ends.
- May-July
  Finalize document, respond to comments, and have AGO certify as water quality standard.
- Not a rulemaking for the state.
  - Still requires us to follow federal regulations for public process and receive EPA approval before CWA use.

7. Thank you! If you have questions, ask or reach out anytime.

kalman.bugica@ecy.wa.gov

Q&A Session

- Raise your hand to ask a question or type your questions in chat
- Calling from a phone? Press *9 to raise your hand and *6 to unmute

Contact Kalman if you have more questions: Kalman.bugica@ecy.wa.gov

Public Hearing
Hearings officer: Andrew Luymes

If you would like to provide comment at this hearing, please use the Raise Hand feature to identify yourself, or press ***9** from your phone

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Other ways to provide your comments, due May 22, 2025:

Online: https://wq.ecology.commentinput.com/?id=6EfTCSi5B

By mail: Marla Koberstein
Washington State Department of Ecology
PO BOX 47696
Olympia, WA 98504-7696

Thank you!

Kalman Bugica

Kalman.bugica@ecy.wa.gov

Puget Sound Nutrient Source Reduction Project

Volume 1: Model Updates and Bounding Scenarios

DEPARTMENT OF
ECOLOGY
State of Washington

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Cover image: Salish Sea Model grid and domain.

Puget Sound
Nutrient Source Reduction Project

Volume 1:
Model Updates and Bounding Scenarios

by

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Executive Summary

Low levels of dissolved oxygen have been measured throughout Puget Sound and the Salish Sea. In numerous places, seasonal oxygen levels are below those needed for fish and other marine life to thrive, and water quality standards are not being met. Nutrient pollution from human activities is worsening the region's naturally low oxygen levels. Areas most affected are poorly flushed inlets, including Penn Cove, Quartermaster Harbor, and Case, Carr, Budd, Sinclair, and Dyes Inlets.

Many Puget Sound locations are listed on the U.S. Environmental Protection Agency's Clean Water Act Section 303(d) list as "impaired." Federal law requires states to identify sources of pollution and develop water quality improvement plans for waters listed as impaired.

Excessive nutrients flowing into marine waters can lead to profound consequences for the ecosystem. In addition to low levels of oxygen, some effects include:

- Acidification, which can prevent shellfish and other marine organisms from forming shells.
- Shifts in the number and types of bottom-dwelling invertebrates.
- Increases in abundance of macroalgae, which can impair the health of eelgrass beds.
- Seasonal reductions in fish habitat and intensification of fish kill events.
- Potential disruption of the food web.

Figure ES1. Salish Sea Model area (orange grid).

Washington State Department of Ecology (Ecology) recognizes the need to manage human sources of nutrients in the Puget Sound region. To understand the significance of these sources and identify potential solutions, Ecology used a peer-reviewed, state-of-the-science computer modeling tool called the Salish Sea Model. It models conditions in the Salish Sea, extending into the coastal waters of southwest British Columbia, Washington, and northwest Oregon (Figure ES1). This report shares the findings of the first set of modeled scenarios; it will inform discussions and guide the next round of modeling, to begin in 2019.

Excessive nutrients in rivers and from point sources flowing into the Sound, such as municipal wastewater treatment plants, deplete dissolved oxygen below the water quality standards.

In this report, Ecology evaluated changes in marine dissolved oxygen due to reducing nitrogen and carbon at municipal wastewater plants.

The years 2006, 2008, and 2014 were modeled to represent a range of climate and ocean conditions affecting Puget Sound. Model scenarios tested the impacts of:

- Current levels of nutrient pollution from rivers and wastewater treatment plants discharging directly to marine waters.
- Reduced nitrogen and carbon at all municipal wastewater treatment plants discharging to marine waters.
- Reduced nitrogen and carbon at only midsize and large municipal wastewater treatment plants discharging to marine waters.
- Reduced nitrogen and carbon at only large municipal wastewater treatment plants discharging to marine waters.

Only the 79 municipal wastewater treatment plants that discharge directly into the United States portion of the Salish Sea were simulated with lower nutrient levels. Canadian and industrial treatment plants remained at current loadings in all the scenarios tested. Plants were grouped into three categories: all plants, midsize, and large. Midsize plants include Chambers Creek, Tacoma Central, Brightwater, Everett outfall in the Snohomish River, Everett-Marysville, and Bellingham. Large plants are South King County and West Point.

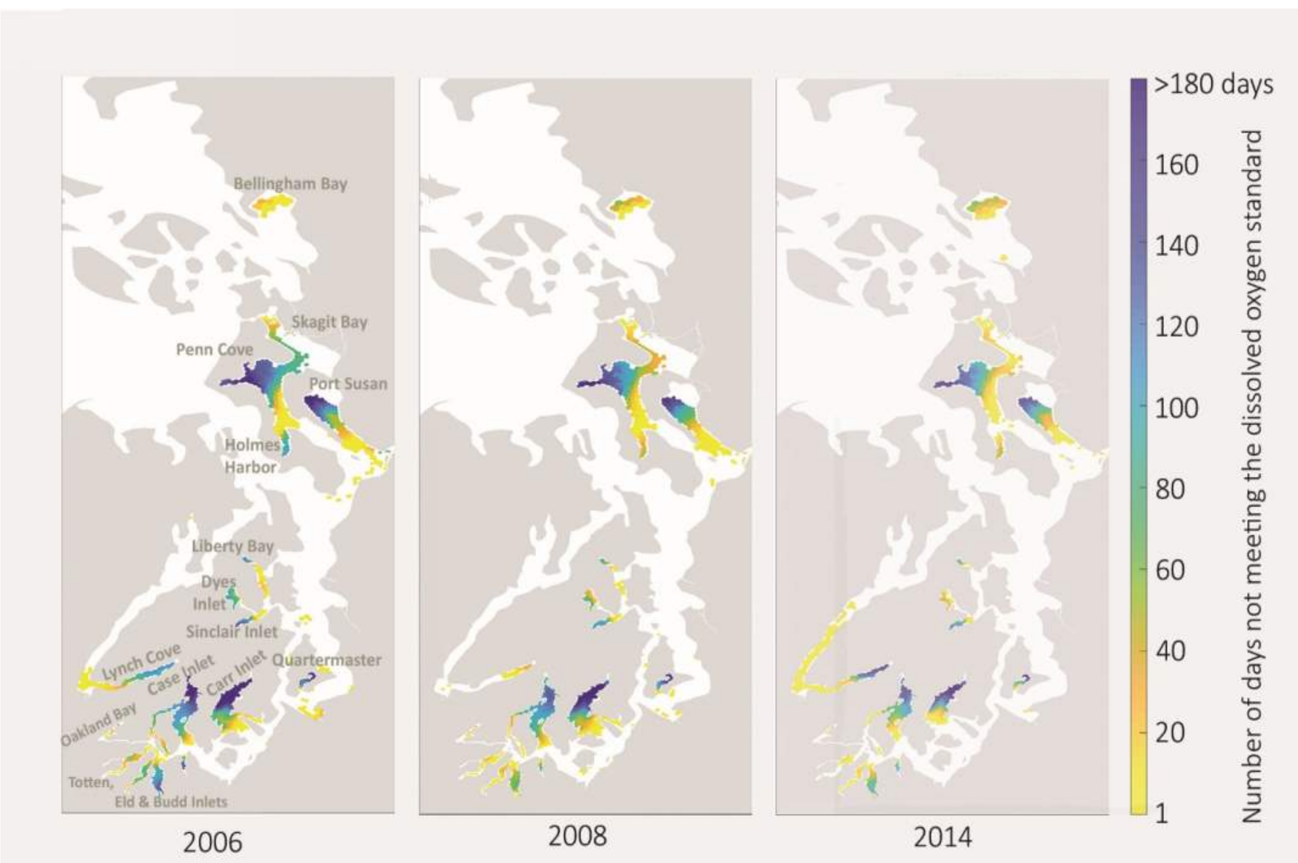


Figure ES2. Number of days not meeting the dissolved oxygen water quality standards for the years 2006, 2008, and 2014.

During all three years under the current nutrient loads, dissolved oxygen standards were not met. For example, Figure ES2 shows the number of days per year that water quality standards were not met, and where the noncompliance occurred. Complete details and results of the scenarios are complex and begin on page 72 of this report.

Ecology found that implementing nutrient reduction at wastewater treatment plants would achieve significant improvements toward meeting the dissolved oxygen water quality standards. The model estimates improvements in the number of days (Table ES1) and area (Table ES2) not meeting the standards.

Table ES1. Improvement in the number of noncompliant days due to nutrient reduction at wastewater treatment plants.

Year	Improvement in dissolved oxygen (% reduction in noncompliant days)		
	All plants	**Mid & large plants**	**Large plants**
2006	51%	43%	31%
2008	61%	49%	33%
2014	51%	42%	22%

Table ES2. Improvement in noncompliant area due to nutrient reduction at wastewater treatment plants.

Year	Improvement in dissolved oxygen (% reduction in noncompliant area)		
	All plants	**Mid & large plants**	**Large plants**
2006	47%	37%	23%
2008	51%	41%	24%
2014	42%	33%	13%

Under existing conditions, approximately 20% of the area in the greater Puget Sound does not meet the dissolved oxygen standards. If reductions are made at all municipal wastewater treatment plants as modeled, approximately 10% of the greater Puget Sound would not meet the standards. This represents roughly a 50% improvement in compliance area for the dissolved oxygen standards.

The results of the first phase of modeling conducted in 2018 confirm that human sources of nutrients are having a significant impact on dissolved oxygen in multiple Puget Sound embayments. It is clear from the modeling study that it will take a combination of nutrient reductions from wastewater treatment plants and other sources of nutrient pollution in watersheds to meet marine water quality standards.

Therefore, future evaluations of nutrient reduction strategies will need to include a comprehensive suite of measures. These measures should include nutrient load reductions from both wastewater treatment plants and watersheds to comply fully with Washington's marine water quality standards for dissolved oxygen.

To address this complex issue, evaluations of different combinations of marine and watershed source reductions are planned for the next phase of modeling, beginning in early 2019.

Abstract

Low dissolved oxygen (DO) levels have been observed throughout the Salish Sea,[1] and recent studies[2] have shown that nutrient inputs from anthropogenic sources influence these low DO events in Puget Sound. This work is the first in a series of technical studies to inform the Puget Sound Nutrient Source Reduction Project (PSNSRP). The PSNSRP is an effort to guide regional investments in nutrient reductions with the goal of meeting Washington State marine water quality standards for DO in Puget Sound.

The Washington State Department of Ecology (Ecology) conducted hydrodynamic and water quality simulations using a peer-reviewed, state-of-the-science regional biogeochemical model. We applied the model to a set of hypothetical (or bounding) scenarios to test the effects of major changes in nutrient loadings to the system. In addition, we implemented model enhancements to watershed hydrology and anthropogenic loading inputs, checked model calibration, explored alternative parametrizations, assessed model performance, evaluated the existing water quality conditions throughout Puget Sound for multiple years to better understand interannual variability, and determined human contributions to low DO concentrations.

Results from this project confirm that regional nutrient contributions from humans exacerbate low DO, especially in poorly flushed areas, such as inlets. *Hypoxic events*, when DO levels dip to between 2 and 3 mg/L or lower, can have severe ecosystem consequences. Hypoxic area varies temporally, and during 2006 it was estimated to peak around 52,500 acres (212 km^2) within the greater Puget Sound, out of which approximately 19% (around 10,000 acres) are attributable to human nutrient loadings. Furthermore, model results show that Puget Sound's cumulative annual hypoxic volumes for 2006, 2008, and 2014 were between 28% and 35% higher than under reference (pre-industrial) conditions.

Washington State's DO water quality standards are set at levels above hypoxic to protect healthy, robust aquatic communities, including the most sensitive species. We found the following when applying the standards to the model results:

- The total area of greater Puget Sound waters not meeting the marine DO standard was estimated to be around 151,000 acres (612 km^2) in 2006, 132,000 acres (536 km^2) in 2008, and 126,000 acres (511 km^2) in 2014. These areas correspond roughly to about 23%, 20%, and 19% of greater Puget Sound in each year, respectively, excluding the intertidal zone.
- Noncompliant areas are located within all Puget Sound basins except Admiralty Inlet. All areas not meeting the water quality standard have depleted levels of DO in the water column as a result of human loadings from Washington State. Model computations take into account multiple oceanographic, hydrographic, and climatological drivers, so that depletions due to human activity alone can be computed by excluding other influences, such as that of the Pacific Ocean.

[1] The Salish Sea includes the Strait of Juan de Fuca, the Strait of Georgia, Puget Sound, and all of their connecting channels and adjoining waters, such as Haro Strait, Rosario Strait, Bellingham Bay, Hood Canal, and the waters around and between the San Juan Islands in Washington State and the Gulf Islands in British Columbia, Canada.
[2] Ahmed et al. (2014); Albertson et al. (2002); Roberts et al. (2014).

- Extreme DO depletions of almost 2 mg/L below the water quality standard are predicted to occur at specific poorly flushed locations, with an overall mean around 0.3 mg/L below the standard.
- Portions of Puget Sound, primarily in South Sound and Whidbey Basin, experience a large number of days per year when the marine DO standards are not met. The number of noncompliant days varies by year and location. For instance, the maximum number of noncompliant days occurred in 2006 (Carr Inlet, 250 days), followed by 2008 (Carr Inlet, 216 days), and 2014 (Quartermaster Harbor, 198 days). The average cumulative number of noncompliant days computed over all areas not meeting the standard was 63, 50, and 46 in each of those years, respectively.

We modeled three scenarios consisting of hypothetical reductions in both dissolved inorganic nitrogen and organic carbon loadings from Washington State municipal wastewater treatment plants (WWTPs) discharging into the Salish Sea. These bounding scenarios were based on load reductions that could occur if seasonal biological nitrogen removal (BNR) technology were applied, as follows:

- At all municipal WWTPs.
- Only at WWTPs with dissolved inorganic nitrogen loading of 1000 kg/day or higher.
- Only at WWTPs with dissolved inorganic nitrogen loading of 8000 kg/day or higher.

This modeling study confirmed that the inner basins of Puget Sound share a portion of their waters, so that discharges in one basin can affect the water quality in other basins. Model simulations for 2006 show that the selected hypothetical nutrient reductions diminish the impacted areas by 47%, 37%, and 23% for each of the scenarios listed above, respectively. Similar reductions were observed for 2008 and 2014. The nutrient load reductions also resulted in significant improvements in the total number of noncompliant days (up to 61% reduction when applying seasonal BNR to all WWTPs).

These hypothetical wastewater treatment reductions could return marine water quality to a level that complies with the DO standard at many locations and considerably reduce the number of noncompliant days. However, full compliance with the standards at all locations cannot be achieved through these actions alone. This analysis compares the relative influence of all marine point sources to human activities in watersheds. When all anthropogenic watershed sources were set to reference conditions and marine point source discharges remained as they are, the water quality noncompliant area was about 31% of the actual noncompliant area computed for 2006.

It is clear that a comprehensive suite of measures, including watershed load reductions, is needed to fully comply with water quality standards in Puget Sound. Evaluation of different combinations of marine and watershed nutrient source reductions will begin in the next phase of modeling in 2019.

Introduction

Background

The Salish Sea is a network of coastal waterways spanning southwest British Columbia (Canada) and northwest Washington State (United States). It includes three major waterbodies: Strait of Juan de Fuca, Strait of Georgia, and Puget Sound (Figure 1). It also includes their connecting channels and adjoining waters, such as Haro Strait, Rosario Strait, Bellingham Bay, Hood Canal, and the waters surrounding the San Juan Islands in Washington State and the Gulf Islands in British Columbia (Figure 1).

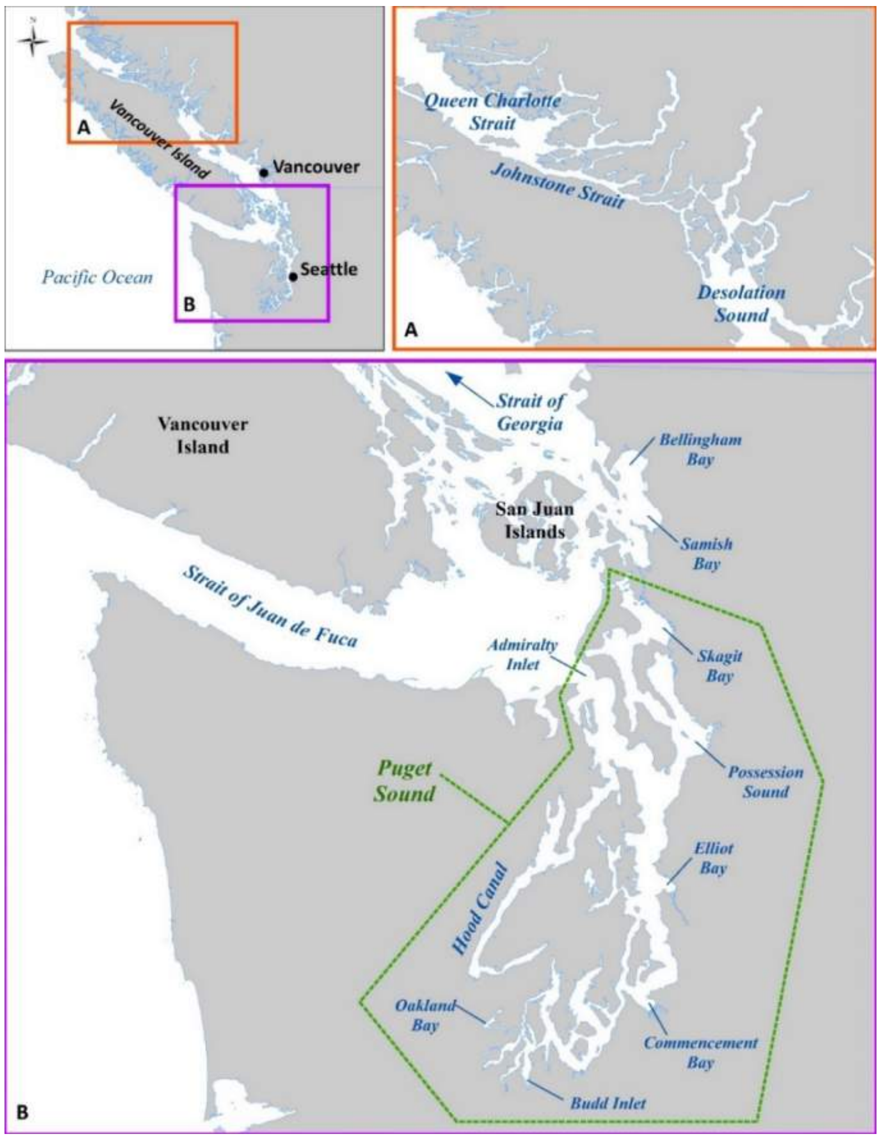


Figure 1. Regions of the Salish Sea (Strait of Juan de Fuca, Strait of Georgia, and Puget Sound), including Johnstone and Queen Charlotte Straits.

Low dissolved oxygen (DO) levels have been observed throughout the Salish Sea, and recent studies have shown that nutrient inputs from anthropogenic sources have influenced low DO in

Puget Sound (Ahmed et al., 2014; Albertson et al., 2002; Roberts et al., 2014). Recent sensitivity assessments of nutrient pollution in the Salish Sea have also shown that land-based nutrient sources may be responsible for most of the exposure to bottom-layer hypoxic waters (Khangaonkar et al., 2018).

Nitrogen acts like a fertilizer, causing algae to grow, and it is a limiting nutrient in Puget Sound (Newton and Van Voorhis, 2002). Nitrogen is a naturally occurring nutrient. However, too much nitrogen results in excessive algal growth. Algal growth generates organic carbon. Organic carbon may also be present in the form of detritus from terrestrial loads. Organic carbon decomposes and consumes oxygen. In some cases, due to excessive nutrient inflows, oxygen is depleted to low levels, which prompts shifts in the form and function of the ecosystem and its ability to support aquatic life (Diaz and Rosenberg, 2008; Glibert et al., 2005). This process is referred to as *eutrophication*.

Nutrient over-enrichment can result in additional eutrophication indicators, beyond increases in phytoplankton and biomass. This report does not include an assessment of other potential impacts from nutrient over-enrichment, but it is important to recognize the connection to other chemical and biological responses. These include:

- Production of carbon dioxide from remineralization of organic carbon, which lowers the pH, contributing to acidification of the water column (Wallace et al., 2014; Feely et al., 2010; Pelletier et al., 2017b). As water becomes acidic, less calcium carbonate is available for marine organisms to form shells (Bednarsek et al., 2017, and references therein).
- Changes to the benthic (bottom-dwelling) macroinvertebrate community structure and species diversity, habitat compression, and shifts to microbial-dominated energy flow, resulting in changes to the food chain (Diaz and Rosenberg, 2008, and references therein).
- Changes to micronutrient availability that can lead to increased incidence and duration of harmful algal blooms (Howarth et al., 2011, and references therein).
- Increased growth and abundance of opportunistic and ephemeral macroalgae, in particular, species of *Ulva* (Teichberg et al., 2010, and references therein).
- Deleterious effects to eelgrass meadows (Burkholder et al., 2007; Hessing-Lewis et al., 2011). Declines in eelgrass shoot density with increasing macroalgal abundance have been demonstrated (Bittick et al., 2018; Nelson and Lee, 2001).

Specific parts of the Salish Sea, such as the shallow inlets and bays in southern Puget Sound, are more sensitive to eutrophication, due to reduced flushing compared to the Main Basin and more open marine waters (Ahmed et al., 2017; Khangaonkar et al., 2012; Sutherland et al., 2011). In addition, future population growth in the Salish Sea region will likely increase human nutrient loads, including excess nitrogen and carbon from wastewater, stormwater, agricultural runoff, and other land-use activities. Regional population growth will contribute to further DO concentration reductions if no actions are taken to reduce human nutrient sources (Roberts et al., 2014). Figure 2 shows the DO numeric criteria that apply in the marine waters of the United States and Puget Sound, where water quality data indicates that waterbody segments are not meeting the numeric part of the standards (based on Washington's Water Quality Assessment that was approved by EPA in 2016 [Ecology, 2018]).

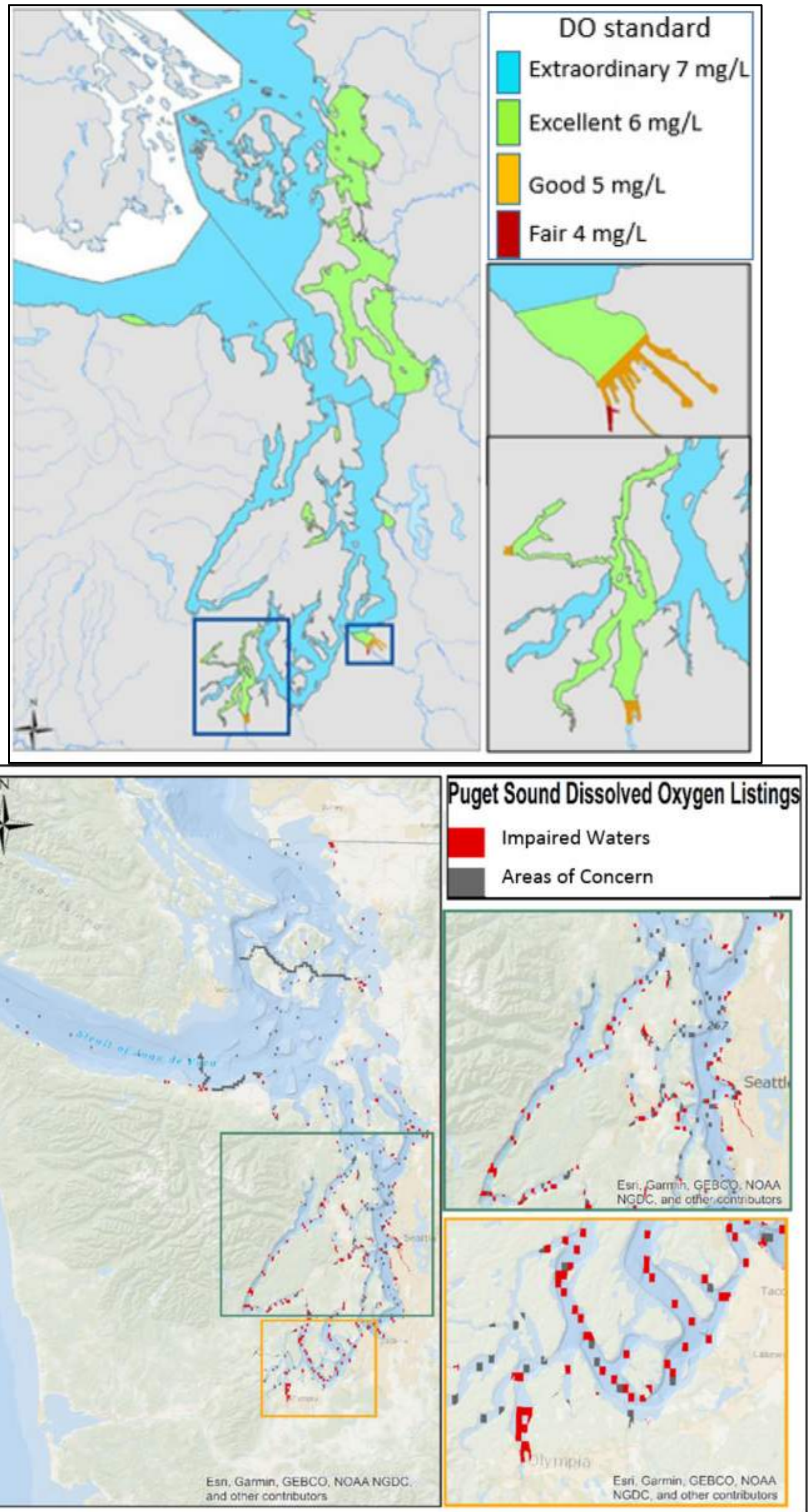


Figure 2. Dissolved oxygen (DO) in Puget Sound.
Above, numeric water quality standards for dissolved oxygen. *Below*, results from Washington's Water Quality Assessment for dissolved oxygen in Puget Sound. Red indicates Category 5 impaired waters, and blue-gray represents Category 2 areas of concern for 2016.

The Water Quality Assessment for DO is based only on the numeric part of the standard. Although a waterbody segment may be included in Category 5 as impaired or Category 2 as an area of concern, that listing process does not consider the 0.2 mg/L human allowance from natural conditions that is part of the DO standards. We use an estimated reference condition computed for each model year to measure anthropogenic change.

Areas vulnerable to eutrophication in Puget Sound are thought to share three key characteristics: poor vertical mixing of the water column that may lead to stratification, dissolved inorganic nitrogen (DIN) limitations on phytoplankton growth, and long residence times (Encyclopedia of Puget Sound, 2018a). Yet, the complexity of the system is remarkable, necessitating the aid of mechanistic models to reveal causes and effects, and sources and sinks. For instance, using a circulation model, Banas et al. (2015) showed that local salinity is not a reliable indicator of the influence of the nearest rivers on Puget Sound water quality. Khangaonkar et al. (2018), using a biogeochemical model, showed that land-based sources of nutrients have a significant impact on water quality.

Although large-scale climatological, meteorological, and hydrological drivers produce large variabilities in Puget Sound water quality (PSEMP, 2012–2017), sensitivity to anthropogenic nutrient additions within the Salish Sea is heightened in locations that have low flushing rates and adjoin urbanized shorelines (Mackas and Harrison, 1997). Albertson et al. (2007) qualified South Puget Sound as relatively more “sluggish and stratified” and highlighted the importance of wind patterns and magnitude to water circulation in the region. EPA (1992) also identified several restricted bays, inlets, and passages in Puget Sound as potentially sensitive to eutrophication based on their frequency of DIN depletion in surface waters and low DO.

Thom et al. (1988) demonstrated that Fauntleroy Cove, in southwest Seattle, has experienced localized eutrophication. They recommended studies on the freshwater nutrient contributions to Puget Sound and the degree of “nutrient trapping” in embayments. Other observational studies have identified various Puget Sound inlets that experience persistent or seasonal stratification, depletion of nitrogen at the surface, and substantial enhancement of primary production due to nutrient addition, consequently making these locations vulnerable to eutrophication (Newton and Reynolds, 2002; Eisner and Newton, 1997; Newton et al., 1998). Mechanistic modeling studies associated those same locations that experience poor flushing, such as South Puget Sound inlets, with human-influenced low DO conditions (Ahmed et al., 2014, 2017; Roberts et al., 2014).

The deteriorating quality of Puget Sound benthic assemblages, as shown via a decline in the overall area of unaffected benthos, along with observations of adversely affected communities in terminal inlets, are suggestive of biogeochemical ecosystem changes potentially related to low oxygen episodes (Weakland et al., 2018). Such changes in the benthic community composition can occur in estuaries at varying low DO levels (Howarth et al., 2011, and references therein), and can be synergistically confounded by the presence of sulfide in the sediments, which can occur under low-oxygen conditions (Vaquer-Sunyer and Duarte, 2010). While implications of benthic community changes to Puget Sound food webs have not yet been studied, Macdonald et al. (2012) discuss the profound effect of the makeup of benthic communities in the Salish Sea’s ecosystem function.

In recent years, late summer aerial observations and photography reveal intense algal blooms, copious jellyfish patches, and remnants of floating macroalgal mats in terminal inlets of Puget Sound (Krembs et al., 2012; Krembs, 2014–2018). The significance of the latter observations and their potential linkages to eutrophic processes and food web changes are yet to be elucidated. Nelson et al. (2003) found that macroalgal blooms peaked in summer and autumn at various Puget Sound sites, and biomass was greatest at sites with the highest water column nitrogen concentrations, suggesting that additional anthropogenic nitrogen can increase macroalgal biomass in the region. Van Alstyne (2016) conducted research in Penn Cove and showed, via isotopic analyses, that nitrogen from oceanic origin is the primary nitrogen source for macroalgal (genus *Ulva*) biomass, but anthropogenic sources also contribute. The most likely sources of additional nitrogen for *Ulva* samples collected in September were wastewater treatment plants.

The Washington State Department of Ecology (Ecology) has undertaken a Puget Sound Nutrient Source Reduction Project (PSNSRP) to address these water quality concerns in Puget Sound. This is a collaborative process aimed at reducing nutrients from point and nonpoint sources. The PSNSRP will guide regional investments in point and nonpoint source nutrient controls so that Puget Sound will meet DO water quality criteria and aquatic life designated uses by 2040.

To commence the PSNSRP, Ecology aims to establish an initial framework for improvements in water quality that can be achieved through reductions in current source conditions. These are referred to as "bounding scenarios." One scenario is designed to assess the overall impact of watershed loads and marine point sources. A subset of the bounding scenarios are based on achievable technological upgrades, where seasonal biological nitrogen removal (BNR) is added to secondary treatment at municipal wastewater treatment plants (WWTPs). BNR effluent limits are set to be 8 mg/L for both dissolved inorganic nitrogen (DIN) and carbonaceous biological oxygen demand ($CBOD_5$), based on a study (Tetra Tech, 2011) that consisted of a technical and economic evaluation of nutrient removal at WWTPs. These effluent limits were applied on a seasonal basis, from April through October.

A mechanistic model is essential to cover complex interactions that affect marine water quality. Processes that contribute nutrients include atmospheric deposition, river and stream inflows, point source discharges, nonpoint source inputs, nutrient fluxes into and out of the oceanic boundary, and sediment–water exchanges. Hydrodynamic characteristics such as tides, stratification, mixing, and freshwater inflows govern transport of nutrients and other variables. Photosynthesis and respiration rates govern biological nutrient transformations and DO dynamics. Light, nutrient availability, temperature, and phytoplankton influence photosynthesis rates as well as algal growth, respiration, death, and settling. The Salish Sea Model simulates all of these processes, and it was identified as the tool that will help in developing the Puget Sound Nutrient Management Strategy. As results from other biogeochemical models for the Puget Sound become available, comparison of output from diverse models may further our understanding of system dynamics.

The Salish Sea Model

The Salish Sea Model[3] (SSM) was developed by Pacific Northwest National Laboratory in collaboration with Ecology, with funding from the United States Environmental Protection Agency (EPA). The SSM is a state-of-the-science computer modeling tool used to simulate the complex physical, chemical, and biological patterns inherent in this system. It has been developed over the past decade to analyze regional hypoxia, with continuous improvements over that time period. It has been the basis for over 20 peer-reviewed publications. This tool will be used to assess marine water quality standards and evaluate nutrient reduction options for improving and restoring Puget Sound (the Sound) to meet our water quality goals.

A first generation of the SSM was named "Puget Sound Model" (PSM), with ocean boundaries established near the mouths of the Strait of Juan de Fuca and Georgia Strait, while inner boundaries extended to all estuarine waters south and east of these open boundaries, culminating in Oakland Bay in the southernmost inner region of the model domain (see Figure 1). The model is based on the coupled hydrodynamic (Finite Volume Coastal Ocean Model, FVCOM) and water quality (CE-QUAL-ICM) models as implemented by Kim and Khangaonkar (2012). The hydrodynamics and water quality calibration of the first-generation PSM has been documented previously in Khangaonkar et al. (2011, 2012).

A second generation of the model included the addition of sediment diagenesis and carbonate systems as reported by Pelletier et al. (2017a, 2017b) and Bianucci et al. (2018). These first- and second-generation PSMs required open boundary adjustments for model calibration to accurately simulate estuarine exchange, due to the fact that the open boundary was close to entrances to the Strait of Juan de Fuca and the north boundary of Georgia Strait (Khangaonkar et al., 2018). Also, the secondary pathway for estuarine exchange through Johnstone Strait at the north end of Georgia Strait was found to be significant (Khangaonkar et al., 2017). Therefore, the model domain was expanded westward to the continental shelf in the Pacific Ocean, northward to include Johnstone Strait, and southward to Oregon's Waldport (south of Yaquina Bay), while retaining the previously developed sediment diagenesis and ocean acidification modules as described by Khangaonkar et al. (2018). This is the third-generation model, named simply the Salish Sea Model or SSM. The PSM and the SSM domains are shown in Figure 3.

In building the SSM, the grid of the older PSM was expanded out to the new model domain extent, primarily to improve handling of boundary conditions. The bathymetry of the additional area through Discovery Islands and Johnstone Strait were based on the Cascadia grid employed by the Department of Fisheries and Oceans, Canada (DFO) tsunami propagation research. The continental shelf expansion was based on bathymetry of the Advanced Circulation (ADCIRC) model of the Eastern North Pacific (ENPAC) (Spargo et al., 2003), as reported by Khangaonkar et al. (2018). The model grid also includes ten vertical layers, distributed with greater layer density near the surface (Khangaonkar et al., 2017).

[3] https://ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Salish-Sea-modeling

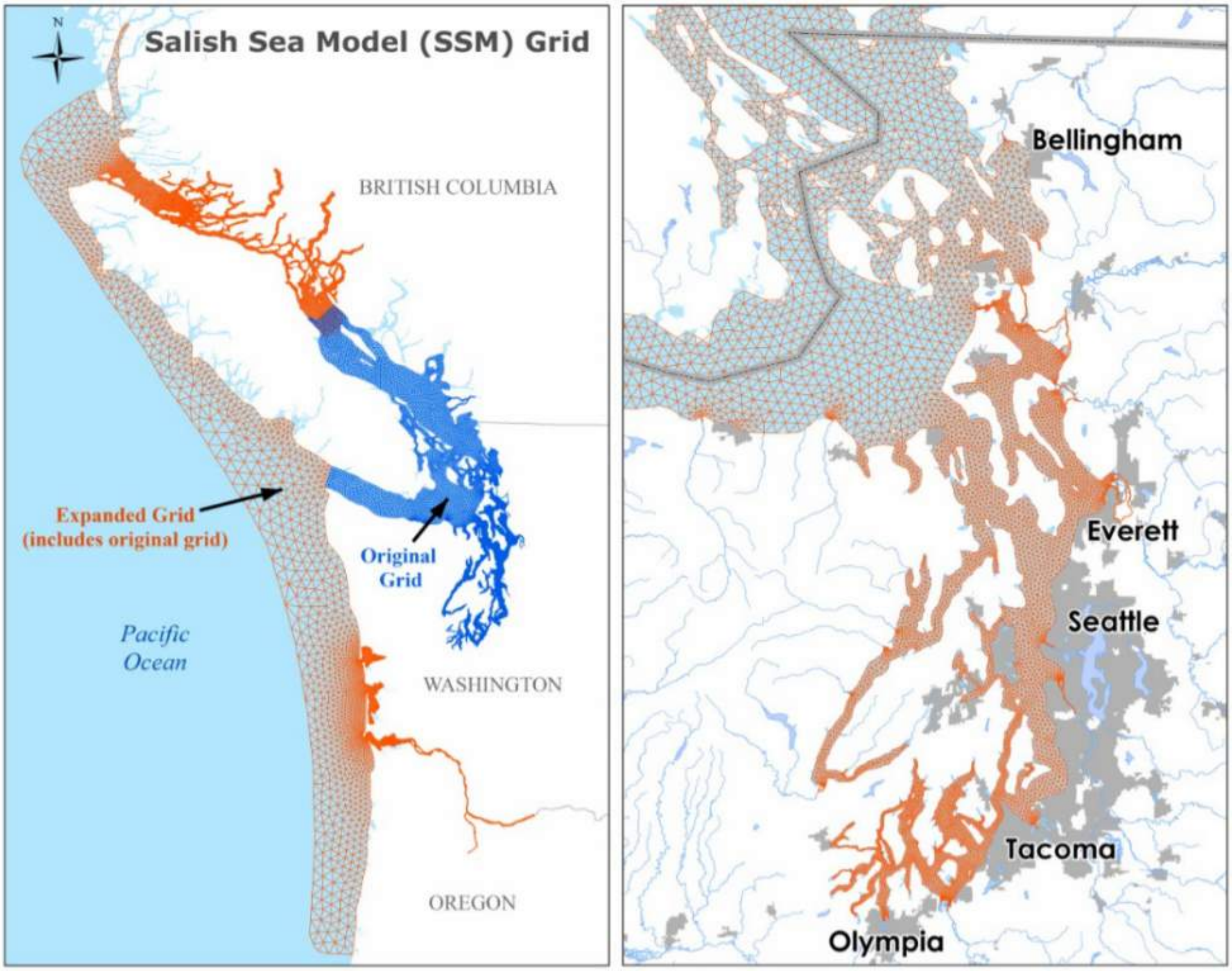


Figure 3. Domain and resolution of both the expanded Salish Sea Model (left) and original Puget Sound Model (right).

Bathymetry smoothing procedures and hydrodynamic formulations such as horizontal and vertical mixing schemes and bottom friction are discussed in Khangaonkar et al. (2018). The SSM grid consists of 16,012 nodes and 25,019 triangular elements. Grid resolution in the expanded grid (but within the old model domain) remains the same as before, while the grid resolution becomes coarser towards the continental shelf. The SSM hydrodynamics and water quality calibration is described for 2014 conditions by Khangaonkar et al. (2018). Figure 4 depicts the three-dimensional model with its nodes and elements, as well as vertical layers. Also shown in Figure 4 is the area of influence (grid cell) surrounding each node. The model predicts average water quality concentrations for each grid cell and layer for each time step.

Regions of Puget Sound that do not meet the DO standard are expressed in terms of area (e.g., acres or km^2). Since the model is three dimensional, each vertical column of water is represented by ten layered grid cells. Area, in this context, refers to the surface area of the vertical column (which is equivalent to the area represented by the grid cell in Figure 4). If DO levels in one or more layers in the water column does not meet the DO standard, the surface area of that water column is counted towards the total noncompliant area.

This report describes improved estimates of current watershed and marine point source inputs to the SSM. A finer resolution was used to delineate watersheds, which allowed for distributed flows from sub-watersheds into multiple model nodes instead of large watersheds discharging to a single model node. This refinement was limited to freshwater inflows entering South and Central Puget Sound. An additional freshwater flow input was also included to represent flow from the North Fork Skokomish River via Lake Cushman, which is used for generating electricity by Tacoma Public Utility, and which enters Hood Canal at the "great bend." This was previously missing.

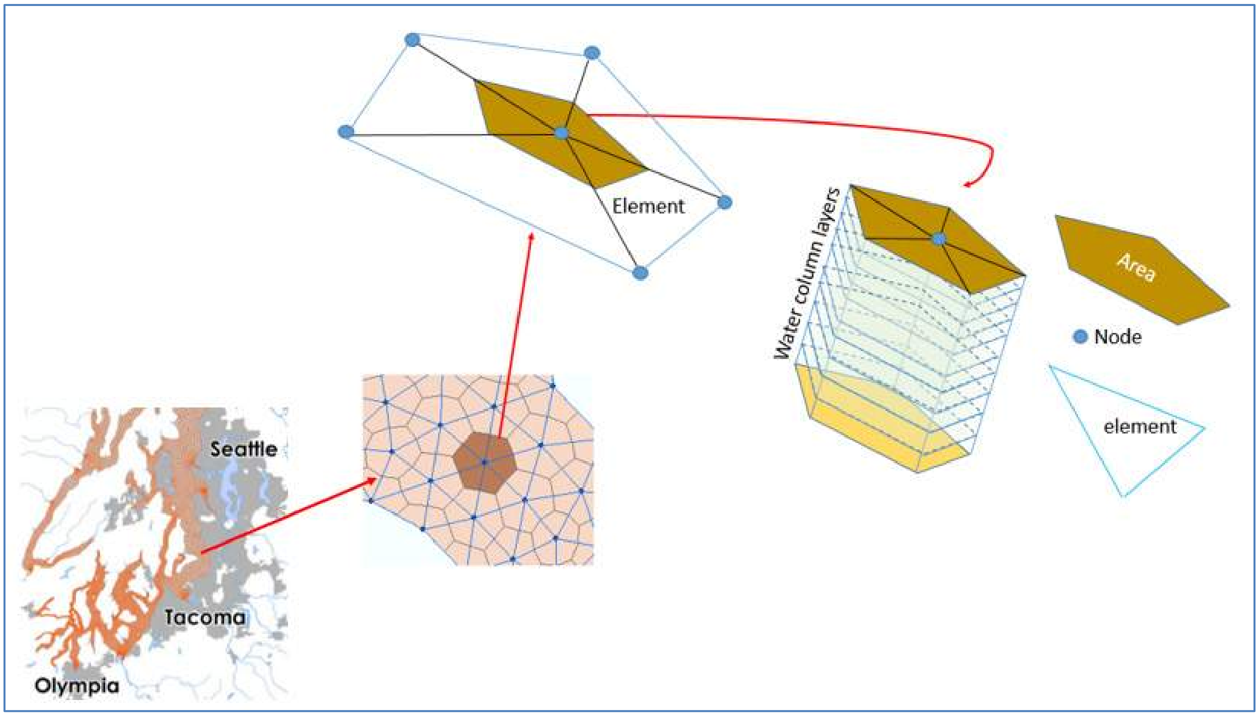


Figure 4. Model nodes, elements, layers, and area of influence of each node.

Also, flow and water quality to represent the Lake Washington inflow into Puget Sound was updated with data obtained from the Corps of Engineers and King County. In addition, new watersheds were added in northern Vancouver Island and mainland British Columbia to represent freshwater inflows to the SSM in this region. Four major watershed inflows along the Washington–Oregon Coast — Willapa, Chehalis, Columbia, and Willamette — were previously added as part of the grid expansion (Khangaonkar et al., 2018).

Water quality inputs into the model from point sources were also improved through new regressions using a larger set of data, available since 2006. Model simulations will be presented for 2006, 2008, and 2014, and calibrations checked to observed data for these years. This report will supply information for Ecology's PSNSRP, which will design management strategies for anthropogenic nutrient inputs affecting DO.

Project Description

Project goal

The project goals are to (1) run the SSM with improvements and updates to model inputs and check calibration of the model, and (2) use the calibrated model to run and evaluate bounding scenarios, which will be used to inform and develop the nutrient management strategy for Puget Sound. This report is the first in a series of modeling reports that will aid in development of a nutrient management strategy. Volume 1 provides information that will be used to guide further optimization modeling runs.

Project objectives

The project objectives include the following:

- Update the database (river and marine point source flows and water quality, and marine observations).
- Refine existing river and stream inputs and incorporate additional surface flow for the expanded grid.
- Check calibration of the expanded model to observed data for the years 2006, 2008, and 2014.
- Evaluate the relative impacts of regional anthropogenic nutrient sources on DO both spatially and temporally for 2006, 2008, and 2014 through broad perturbations in the SSM (bounding scenarios).

Methods

Boundary Conditions

Tidal forcings for the years 2006, 2008, and 2014 for the open boundary along the continental shelf were based on tidal constituents derived from the ENPAC model (Spargo et al., 2003). These include S2 (principal solar semidiurnal), M2 (principal lunar semidiurnal), N2 (larger lunar elliptic semidiurnal), K2 (lunisolar semidiurnal), K1 (lunisolar declinational diurnal), P1 (solar diurnal), O1 (lunar declinational diurnal), Q1 (larger lunar elliptic diurnal), M4 (shallow water over tides of principal lunar), and M6 (shallow water sixth diurnal constituent). Each of these tidal components has an amplitude and phase angle for each of the 87 nodes at the model open boundary at the continental shelf. An input file with these components for the open boundary model nodes was generated and included in Appendix A1.

Water quality at the open boundary for 2006, 2008, and 2014 was established using data from the Department of Fisheries and Oceans, Canada (DFO) and interpolated and extrapolated to the model ocean boundary over space and time using the procedure developed by Pacific Northwest National Laboratory (Khangaonkar et al., 2018). Appendix A2 contains the model open boundary water quality generated with this procedure.

The model is also forced with wind and heat flux at the water surface. These meteorological forcings are based on Weather Research and Forecasting model reanalysis data generated by the University of Washington Mesoscale Analysis and Forecasting Group.

The atmospheric carbon dioxide mixing ratio (xCO_2, or mole fraction of CO_2) was measured at the National Oceanic and Atmospheric Administration (NOAA) buoy at Cape Elizabeth, Washington (Table 1), and reported in NOAA's Puget Sound Ecosystem Monitoring Program (PSEMP) report for the year 2016 (PSEMP, 2017). Khangaonkar et al. (2018) used a pCO_2 value of 400 µatm for the 2014 SSM run. Since the partial pressure of carbon dioxide (pCO_2) input is currently spatially and temporally uniform in the Salish Sea Model (SSM), an annual average value reflective of measurements at Cape Elizabeth was used for model input. These values are 386 µatm and 390 µatm for 2006 and 2008, respectively.

Table 1. Atmospheric carbon dioxide mixing ratio (xCO_2) annual average concentrations (ppm) (± SD) at Cape Elizabeth, Washington (PSEMP, 2017).

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
xCO_2 (ppm)	386 ± 8	390 ± 7	390 ± 6	389 ± 7	393 ± 6	394 ± 8	397 ± 8	402 ± 7	403 ± 8	402 ± 8	406 ± 6

The model is driven with freshwater inflows from 161 watersheds and 99 municipal and industrial point sources. Appendix A3 contains a list of the watersheds, and Appendix A4 contains plots of inflows for these watersheds for the years 2006, 2008, and 2014. Appendix A5 identifies all of the marine point sources included in the model, and Appendix A6 contains plots of inflows for these marine point sources for the years 2006, 2008, and 2014. Concentrations of water quality parameters for the years 2006, 2008, and 2014 for watershed and marine point source inflows are presented in Appendices A7 and A8.

Watershed Updates

The updated SSM version used for this project included:

- Refinement of watershed inflows into South and Central Puget Sound.
- Addition of watershed inflows in coastal areas, northwest British Columbia, and Lake Cushman.
- Other watershed flows and water quality updates.

There are now a total of 161 freshwater inputs entering the model with the refined watershed delineation and addition of new watersheds, while the previous models had fewer freshwater inputs with 64 and 69 for the Puget Sound Model (PSM) (Bianucci et al., 2018) and SSM (Khangaonkar et al., 2018), respectively. These inputs represent the loading of nutrients entering marine waters in the SSM domain at the mouth of each of these rivers. In this context, river inflows into SSM are integrated and do not distinguish between all upstream watershed sources.

River inflows into South and Central Puget Sound were refined relative to the previous representation in the first-generation PSM. Previous studies identified embayments in South and Central Puget Sound as vulnerable to eutrophication and low DO conditions, so we focused on freshwater refinements in these regions. Higher resolution of watershed inflow data is now available. The refinement involved subdividing the original watersheds into smaller hydrologic units. This resulted in more freshwater inflows entering South and Central Puget Sound, but did not change the total amount of freshwater being added. Figure 5 illustrates some of these updates.

Flow and water quality estimates for the refined watersheds were originally developed for a different model of South and Central Puget Sound as part of the South and Central Puget Sound Dissolved Oxygen (SPSDO) study. These methods are described in more detail by Mohamedali et al. (2011a, 2011b). The process involved a multiple linear regression technique to create a daily time series of water quality constituents using daily USGS flows and monthly water quality data collected between 2006 and 2007 as part of the SPSDO study (Roberts et al., 2008).

The refined watershed delineations for the SSM remained consistent with the ones developed for the SPSDO study, except that a few watersheds (e.g., Sinclair/Dyes Inlet) were refined further. This refinement was done by superimposing 12-digit USGS Hydrologic Unit Code (HUC12) watershed delineations over the original PSM watersheds and using that as a basis of subdividing larger watersheds into smaller catchments.

Freshwater inflows entering the expanded model domain were also added, as described in Appendix B. These included inflows in coastal areas, northwest British Columbia, Vancouver Island, and from Lake Cushman.

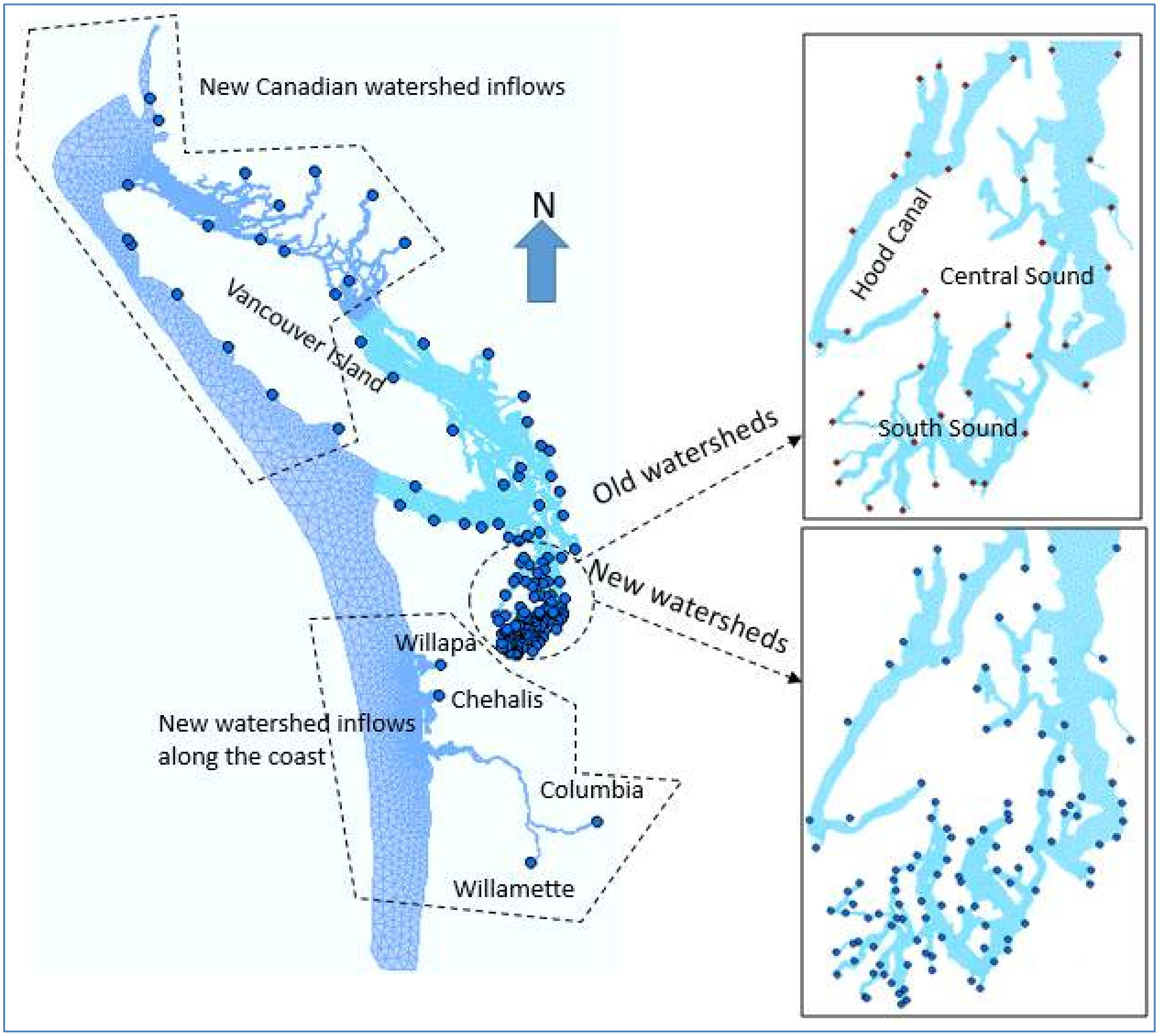


Figure 5. The new Salish Sea Model (SSM), with its refined watershed inflow nodes in South and Central Puget Sound, new Canadian watershed inflow nodes, and new watershed inflows along the Pacific Ocean coastline.

Marine Point Source Flows and Water Quality

A total of 99 marine point source inputs are included in the SSM. These include both municipal wastewater treatment plants (WWTPs) and industrial discharges that are under Washington State jurisdiction, as well as WWTPs under U.S. federal government and Canadian jurisdiction. The original marine point source flow and water quality time series described in Mohamedali at al. (2011a) were developed for the years 1999 through 2008. These time series were created using a multiple linear regression approach analogous to that used for the watershed inflows, thus creating a continuous time series for each year of input for the SSM using mostly monthly water quality data. We have now extended these time series to more recent years, through June 2017. The updated time series also include new WWTPs that have come online since 2008. Data for this recent time period were obtained from a combination of sources. Quality control procedures, data quality, and representativeness objectives are found in the Quality Assurance Project Plan or quality assurance/quality control document of each organization from which we used data, as cited in McCarthy et al. (2018).

Data for marine point sources under Washington State jurisdiction were obtained primarily from Ecology's Water Quality Permitting and Reporting Information System (PARIS), which houses monthly discharge monitoring reports for all point sources under the National Pollutant Discharge Elimination System (NPDES) program. Data for WWTPs under federal jurisdiction were obtained through the EPA Region 10 NPDES Program (R. Grandinetti, EPA Region 10, pers. comm., 2018).

Annual reports for all WWTPs in Canada for the period 1999 to 2016 were obtained from Capitol Regional District (2018) and Metro Vancouver (2018). Raw data for the WWTPs were also obtained for 2017 to complete the long-term database.

Marine point sources were reviewed for any process or outfall location changes. If there was a change in the treatment process, a new regression was developed and applied to the time period following the treatment change. Previous regressions were used where no new data were available. New regressions were also developed if a particular facility started monitoring for parameter(s) not previously monitored. Any changes in outfall locations were noted and a new model grid node closest to the new outfall was selected. Also, treatment plant shutdowns and new sources coming online were noted.

Summary of Nutrient Influx

Oceanic

Mackas and Harrison (1997) estimated the ocean input of nitrogen to Puget Sound to be around 408,000 kg/day, or about 88% of the total nitrogen entering Puget Sound. This oceanic influx of nitrogen enters as the inflowing branch of the estuarine exchange flow. However, the rate of algal inorganic nitrogen consumption in the euphotic zone (between the surface and about 30 m depth) is much greater than the advective flux of inorganic nitrogen to the surface from the lower layers (Khangaonkar et al., 2018). So, a significant portion of the oceanic nitrogen input is not expected to penetrate the euphotic zone, but instead flows back out to the outer coast. Davis et al. (2014) estimated that about 98% of the water exiting the Strait of Juan the Fuca is of oceanic origin.

Understanding the impact of oceanic nitrogen within Puget Sound is further complicated by the large estimated percentage (60%–66%) of the water at Admiralty Inlet that is refluxed back into Puget Sound (Ebbesmeyer and Barnes, 1980; Khangaonkar et al., 2017). The magnitude of the average oceanic flux of nutrients at Admiralty Inlet does not fully characterize the dynamics of nutrient movements *within* the entire Puget Sound, as the relative contribution from terrestrial sources varies between basins, and it appears to be much higher in poorly flushed inlets. The model's hydrodynamic solution accounts for the spatial and temporal variations of this oceanic input as described in Khangaonkar et al. (2018).

Land-based inflows

Land-based or terrestrial inputs of nutrients include both marine point sources and watershed sources:

- Marine point sources include all facilities with outfalls in marine waters, such as WWTPs and industrial facilities.
- Watershed sources of nutrients enter the model domain at the point where rivers or streams meet the Salish Sea (i.e., at the mouth or downstream end of each river or stream). Rivers are pathways for both point and nonpoint sources upstream. The model includes loads from rivers, streams, and their watersheds, as well as flows from shoreline fringes. Watershed loads include base flow (which is predominantly fed by groundwater). Groundwater contributions are discussed in Mohamedali et al. (2011a, 2011b).

On an annual basis, rivers account for approximately 45% and 95% of the incoming terrestrial organic nitrogen and carbon load, respectively. Figure 6 shows the seasonal variation of the dissolved inorganic nitrogen (DIN) and dissolved organic carbon (DOC) loadings from point sources and rivers into Puget Sound. While rivers dominate the seasonal DOC loads, marine point sources are the dominant land-based DIN source during the summer. Figure 7 shows the breakdown of terrestrial loads of DIN, total organic nitrogen (TON), and total organic carbon (TOC) flowing into different Puget Sound basins. Appendix A9 contains tables with annual average DIN load for 2006, 2008, and 2014. The largest proportion of nitrogen inflows are discharged into the Main Basin, whereas the largest proportion of carbon is discharged into Whidbey Basin.

Other sources

The biochemical processes occurring in the sediments constitute a significant source of DIN to the water column. Sinking particles remove organic nitrogen from the water column. As accumulated organic matter in the sediment is remineralized, decomposition of proteins in organic detritus produces a flux of DIN (primarily in the form of ammonium) to the bottom layer of the water column. A relatively small portion of DIN (as nitrate) is removed from the water column at the water–sediment boundary, but a much larger fraction of DIN returns to the water column from the sediments in the form of ammonium ions. Appendix C contains a map of the modeled ammonium sediment flux delivered to the water column for 2006, 2008, and 2014.

Direct atmospheric deposition into the Salish Sea is estimated to be a minor contributor of nitrogen to the system, at a flux of approximately 1 kg/ha/yr (based on AIRPACT, a regional atmospheric modeling system). This estimate does not include the atmospheric deposition into watersheds, which is already indirectly accounted for in the inflows from rivers. Appendix C contains further information about atmospheric deposition estimates.

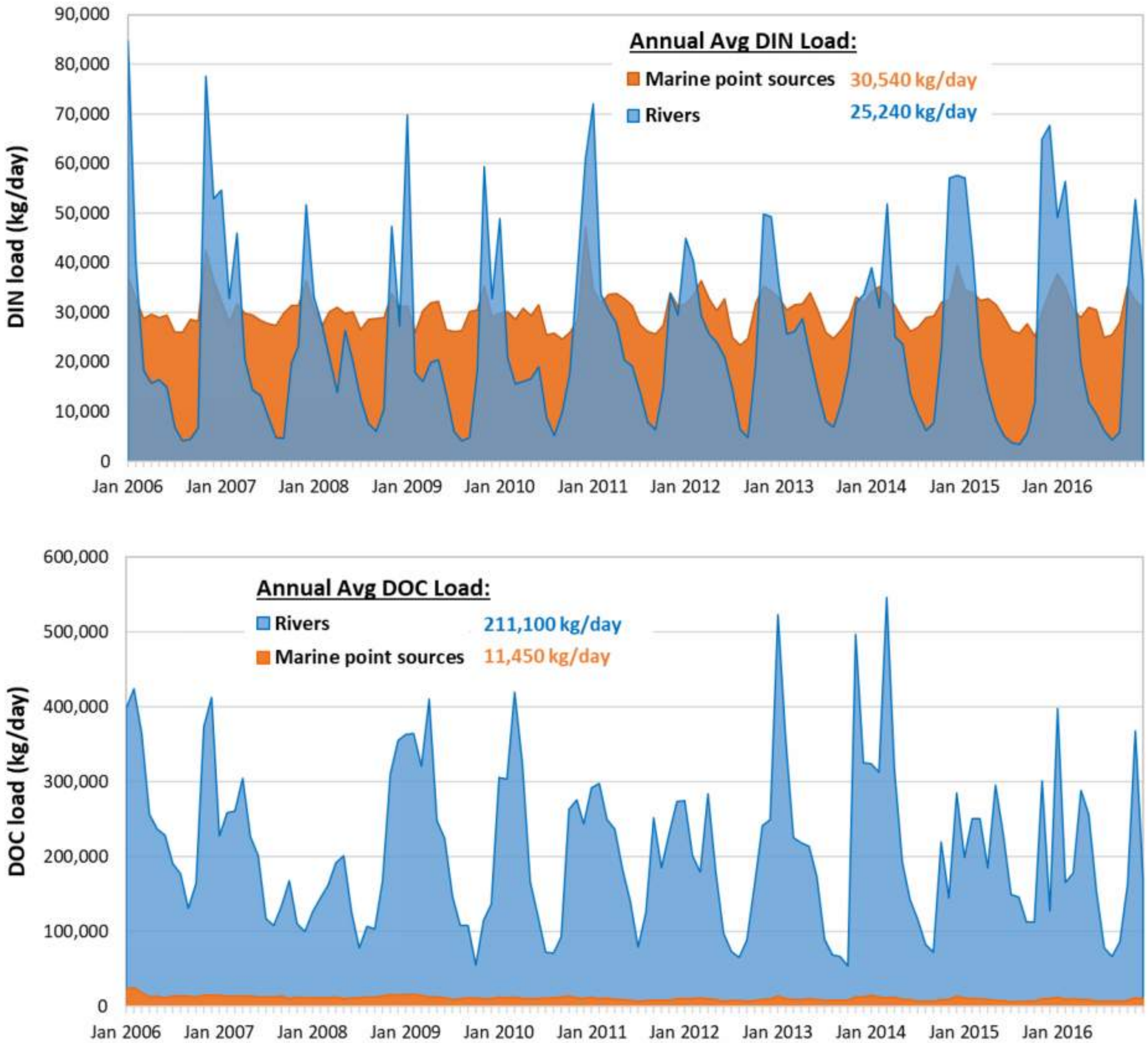


Figure 6. Dissolved inorganic nitrogen (DIN, above) and dissolved organic carbon (DOC, below) loading estimates for Puget Sound land-based sources.

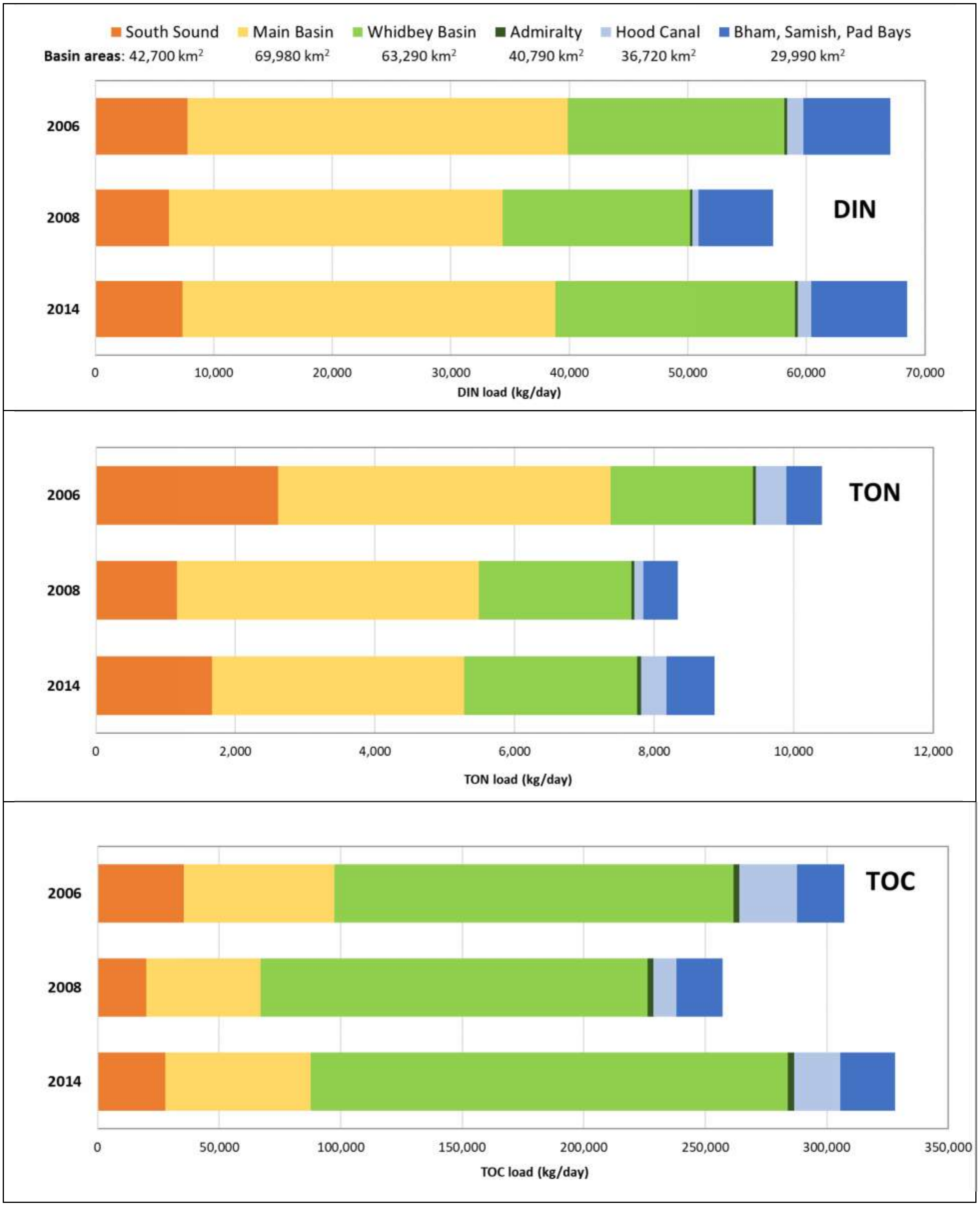


Figure 7. Comparison of dissolved inorganic nitrogen (DIN, above), total organic nitrogen (TON, center), and total organic carbon (TOC, below) loading into different regions of Puget Sound from terrestrial sources (rivers + point sources discharging into marine waters) under 2006, 2008, and 2014 existing conditions.

Figure 8 shows the estimated relative contributions of the non-oceanic DIN loads into Puget Sound.[4] Table 2 shows the average estimated daily loads from non-oceanic sources. It is important to note that each of these loads enters the system at different points in space and time. Therefore, the impact that each load has on localized biogeochemical processes is markedly different, non-linear, and cannot be gauged by this overall comparison. Rather, it is through the model computations at each time step, grid node, and vertical layer that we understand the complex interrelationship of these loadings.

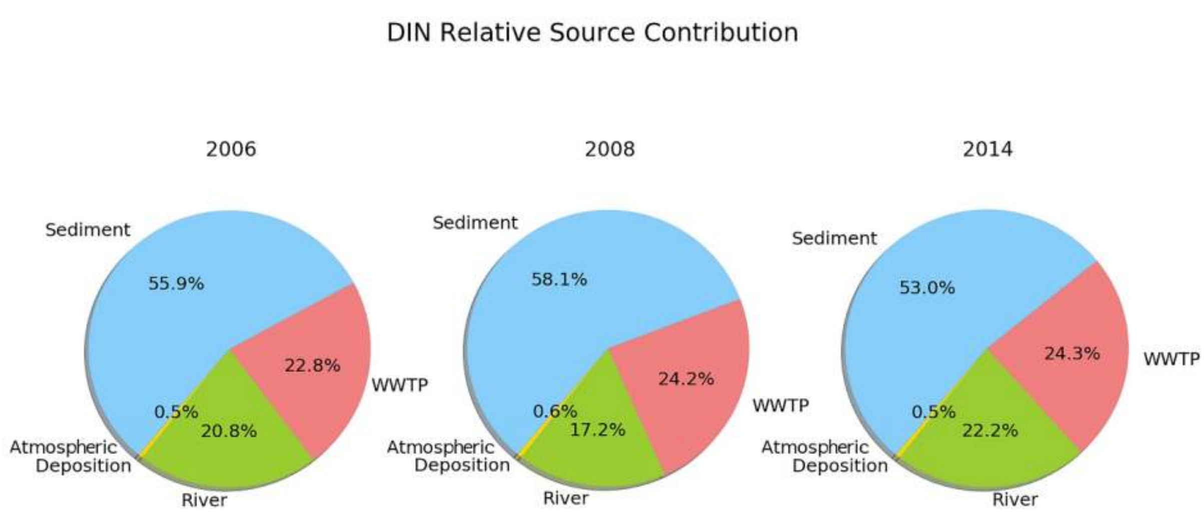


Figure 8. Relative contributions of dissolved inorganic nitrogen (DIN) to Puget Sound from rivers, marine point sources (WWTPs), sediment, and direct atmospheric deposition to marine waters.

Table 2. Average annual non-oceanic inorganic nitrogen loads (kg/day) entering Puget Sound's water column.

Source	2006 (kg/day)	2008 (kg/day)	2014 (kg/day)
Sediment	77,000	72,000	70,000
Direct atmospheric deposition to marine waters	700	700	700
Rivers	28,500	21,100	29,000
Marine point sources (wastewater treatment plants)	31,200	30,000	32,000

[4] Puget Sound refers to only South Sound, Main Basin, Whidbey Basin, Admiralty Inlet, and Hood Canal.

Water Quality Observations Database

Marine water quality monitoring data were obtained from Ecology's Marine Monitoring Unit, King County, NOAA, and the University of Washington (UW). Figure 9 shows the locations of these stations. These data were primarily used to check the calibration (i.e., to compare simulated values with observed data for the years 2006, 2008, and 2014). Appendix D contains details on how the observed database was developed. Since the model grid has ten layers and CTD (conductivity, temperature, and depth instrument) casts result in more than one data point corresponding to each layer, error statistics were based on comparing model-predicted concentration to individual observed data in a given layer for a particular time window.

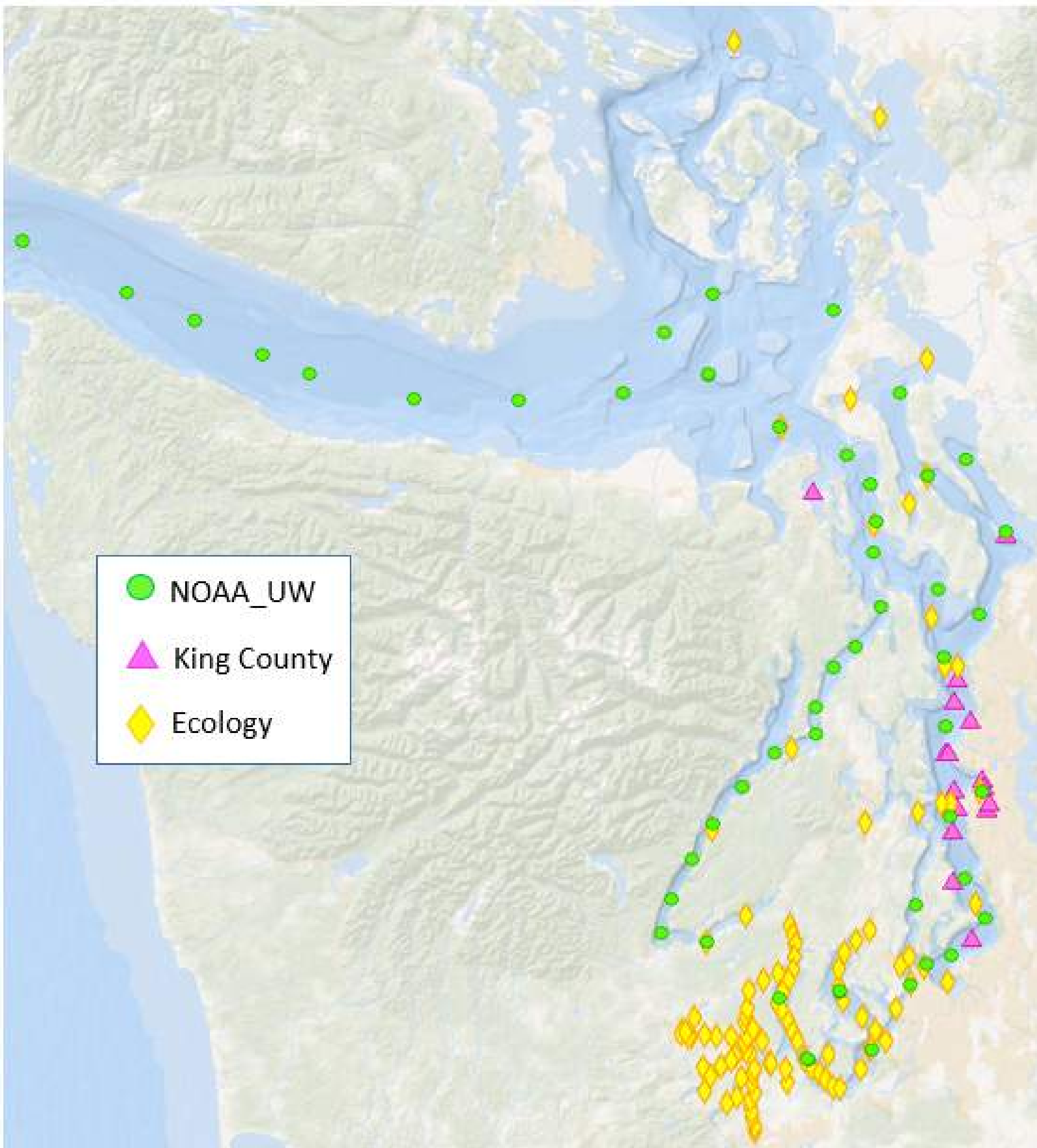


Figure 9. Locations of marine monitoring stations used for water quality calibration checks.

After checking data qualifiers, we discarded data that did not meet quality objectives. In the case of moorings or buoy data, if quality control procedures were not complete (as is often the case with this type of data), we used them only in a qualitative sense to examine overall patterns and trends.

Model Parameters

The SSM contains model parameters, including rates and constants, used to govern hydrodynamic and biogeochemical processes. The majority of parameter values for the SSM are commonly accepted to be the same constant values across a large number of studies (e.g., Martin and Wool, 2013; Di Toro, 2001; and Testa et al., 2013).

We reviewed two model calibration sets for DO and pH: Khangaonkar et al. (2018) and Bianucci et al. (2018). Khangaonkar et al. (2018) improved the DO calibration compared to that of Bianucci et al. (2018). However, as noted by Khangaonkar et al. (2018), further improvement to pH calibration was necessary. In the current project, year 2008 was selected to see if pH calibration could be improved while maintaining the DO calibration. We started with the rates and constants used in Khangaonkar et al. (2018), along with the updates in watershed and marine point source inputs as discussed in this report, and performed a calibration check. Alternative rates and constants were explored through sensitivity analyses and are further discussed in Appendix E, but the final set of parameters used for the bounding scenarios remained consistent with those published in Khangaonkar et al. (2018).

The SSM is continually undergoing evaluation and refinement, and there may be future refinements that improve performance. At this time, the SSM is at a state of maturity where we believe that differences in estimated impacts due to model refinements will be small moving forward.

Model Calibration Check

Model calibration was checked to confirm adequacy of model performance for two reasons: (1) modifications were made to watershed inflows, as well as other changes as described earlier, and (2) Khangaonkar et al. (2018) used the year 2014 for calibration, rather than 2006 and 2008, which are additional years included in this report.

The hydrodynamic calibration check included a comparison of model predictions to observed data at NOAA stations for water surface elevations. Model-predicted currents were compared with observed Acoustic Doppler Current Profiler (ADCP) data for the year 2006 at Pickering and Dana Passages in South Puget Sound. Figure 10 illustrates the locations of both NOAA and ADCP stations.

Temperature, salinity, and other water quality variables predicted by the model were also compared with observed data at marine stations discussed above and shown in Figure 9. Both time series plots as well as scatter plots were used to establish model skill. Model skill statistics were compared with values presented by Khangaonkar et al. (2018) for year 2014 and with those presented for year 2008 by Bianucci et al. (2018). In addition, predicted primary production and sediment oxygen demand (SOD) were compared with observed data, where available.

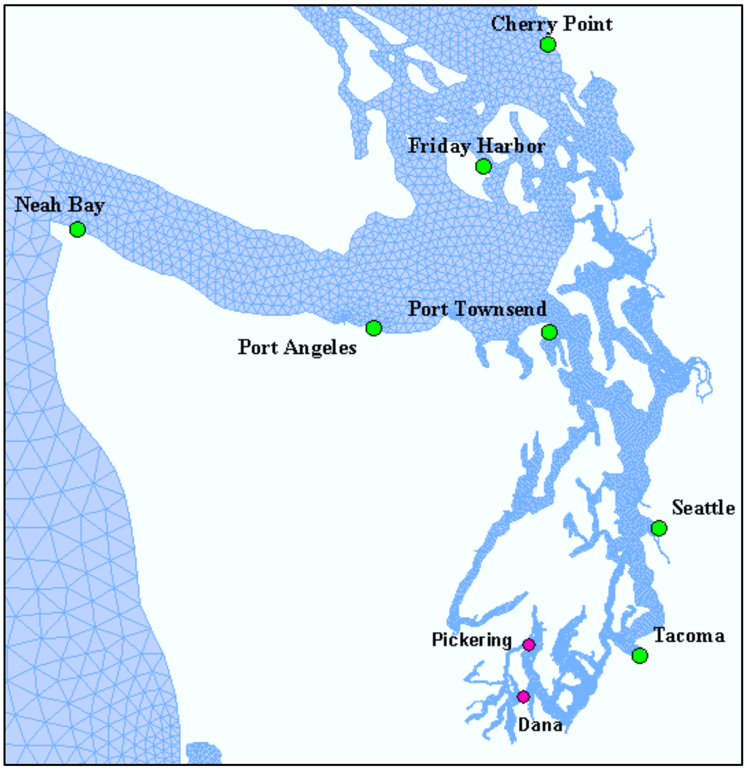


Figure 10. National Oceanic and Atmospheric Administration (NOAA) stations (green dots), where model-predicted water surface elevations were compared with observed data, and Acoustic Doppler Current Profiler (ADCP) stations (red dots), where model-predicted currents were compared with observed data.

Sensitivity runs

Sensitivity runs involved varying key water quality parameters and rates to understand their impact on model predictions, with the goal of optimizing model performance. A different set of rates and constants was evaluated that resulted in similar performance. Output from an alternative parametrization was used to compare the root mean square error (RMSE) of DO depletions between existing and reference conditions with output from the optimized and selected parametrization from Khangaonkar et al. (2018).

Reference Conditions

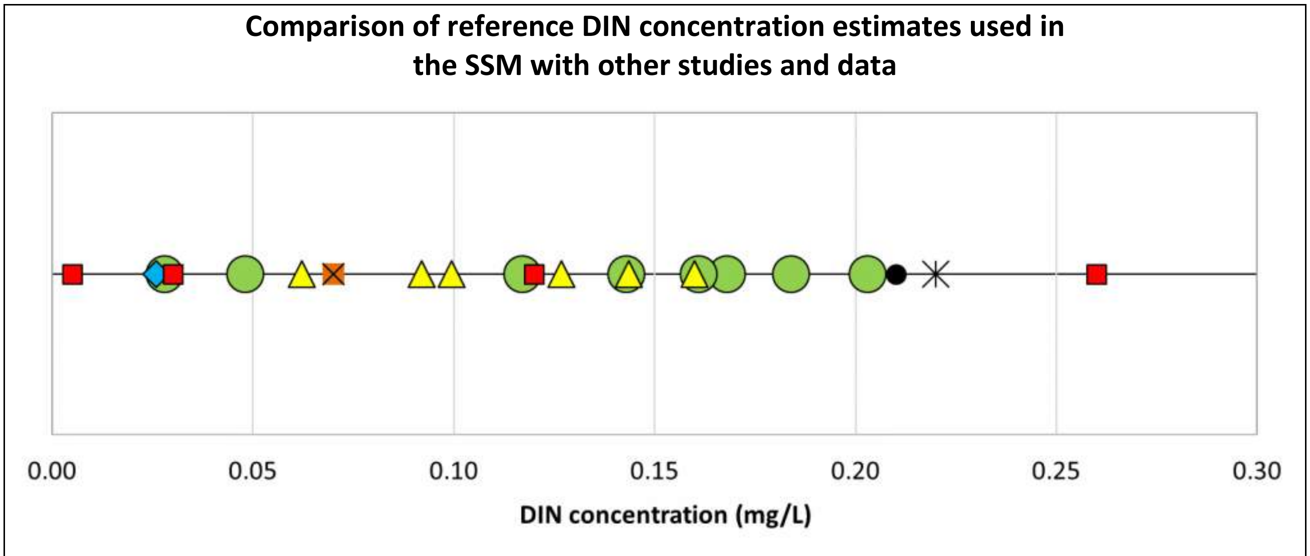
In order to isolate the effect of human sources on marine water quality, we compared the model year existing (hindcast) conditions to a reference condition for the same model year. We created the reference condition scenario by setting watershed inputs and marine source inputs to an estimated natural load of nitrogen and carbon while keeping the model year climate, hydrology, and ocean boundary conditions the same as the existing conditions scenario. The reference condition is our best estimate of natural conditions and is specific to each model year. Reference conditions were used to calculate DO depletion due to human influence, and they were derived by excluding estimated anthropogenic inputs of nutrients from contemporary loadings used in hindcast model runs.

A key aspect of the reference conditions used in this report is that all of Washington's WWTP effluent and river concentrations are set to reference river concentrations. However, there is no change in ocean boundary conditions, Canadian point sources, or Canadian river inputs in the reference condition scenario. Thus, in the reference condition, significant loadings from external sources such as the Fraser River (which is the largest freshwater flow into the Salish Sea) and from the Pacific Ocean remain unchanged. As a result, differences between the existing model year condition and its reference condition reflect changes due only to estimated anthropogenic nutrient inputs in the Washington portion of the Salish Sea.

Methods used to calculate reference conditions using the SSM are described in previous reports (Mohamedali et al., 2011a, 2011b; Pelletier et al., 2017b). Monthly reference condition loads for rivers were estimated by taking the 10th percentile of measured monthly nutrient concentrations at monitored locations, and in some cases, using atmospheric concentrations during the wetter months (if these were lower). The 50th percentile was used for rivers in the Olympic Peninsula that do not have significant human nutrient sources in their watersheds. This approach follows one of the three options in EPA's nutrient criteria guidance manual (EPA, 2000). For the SSM, reference concentration estimates vary seasonally by month, and regionally to account for spatial variation. The reason we aggregated reference concentrations regionally was to have a larger dataset from which to calculate the 10th percentiles. Also, there are a lot of smaller rivers and streams that are unmonitored, so having a regional approach enabled the establishment of reference conditions for unmonitored freshwater inputs that enter the SSM. This regional approach has the following limitations:

- Reference condition estimates still contain an anthropogenic signal because they are based on contemporary data, and watersheds with more development have higher reference concentrations. Also, atmospheric data used to develop the reference condition include the influence of anthropogenic regional and global nitrogen emissions.
- The regional aggregation of rivers averages natural spatial differences between rivers grouped in the same region. For example, Skagit River's reference concentrations are likely overestimated, since the 10th percentile reference concentrations for other rivers entering the Whidbey Basin region turn out to be close in value to current Skagit River concentrations.

Because of these limitations and uncertainties around what the "true" natural or reference conditions are, we performed a meta-analysis to corroborate and compare our reference condition estimates with other studies and data. This comparison is presented in Figure 11 and illustrates that our estimates are within the same range as other estimates developed using different methods and analyses.



1. Our estimates (Mohamedali et al., 2011; Pelletier et al., 2017b)	Reference DIN concentration estimates used in the SSM. Each green circle represents the annual average DIN concentrations for rivers and streams entering the following regions in Puget Sound (from left to right on the plot: Strait of Juan de Fuca, Hood Canal, Whidbey Basin, Commencement Bay, Puget Main, South Puget Sound, Strait of Georgia, and Elliott Bay).
2. Toxics study -forested basins (Herrera Environmental Consultants, 2011)	DIN concentrations in surface runoff (base flow and stormwater events) measured as part of the Puget Sound Toxics Loading study. The value here is the median of data collected from predominantly forested subbasins in the Puyallup and Snohomish watersheds.
3. Hood -forested basins (Steinberg et al., 2010)	The Hood Canal Dissolved Oxygen Program estimated natural background concentrations for streams entering Hood Canal based on the annual average DIN concentrations for the least impacted rivers in the Olympic Peninsula.
4. USGS background (Smith et al., 2003)	The estimate on the plot is the 75th percentile of background concentrations predicted from an empirical model developed by the USGS. This particular estimate is for the "Western Forested Mountains," which includes the Puget Sound area.
5. EMAP Cascades Data available at: www.epa.gov/emap	EPA's Environmental Monitoring & Assessment Program (EMAP) data are available online. This estimate is the 50th percentile of DIN data measured in streams in the Cascades region for the period 1999 to 2000.
6. Upstream data	Annual means of monthly 10th percentiles of ambient data (WY 2002–2009) collected at Ecology's long-term ambient monitoring stations located in the upper reaches of Puget Sound watershed (from left to right on the plot: Skagit, Green, Stillaguamish, Nooksack, Cedar, and Snoqualmie).
7. EPA ecoregional criteria (EPA, 2001, Appendix B)	EPA developed nutrient criteria based on various data sources collected between 1990 and 1999. The red squares represent the 25th percentile of the criteria for each ecoregion (from left to right on the plot: Cascades, N. Cascades, and Puget Lowlands).

Figure 11. Reference dissolved inorganic nitrogen (DIN) concentration estimates used in the Salish Sea Model compared with other studies and data.

We also reviewed our original reference condition methodology described in Mohamedali et al. (2011a, 2011b) based on EPA's nutrient criteria guidance manual (EPA, 2000). First, we expanded the current data set used to estimate reference condition percentiles (2001–2009) to include newer ambient water quality data (2010–2015). The expanded data set resulted in similar reference condition estimates, and in most regions, the current reference concentration estimates were lower. We also compared our reference conditions using data from reference streams, which are sampling sites located in areas of minimal human impact (EPA, 2000; Von Prause, 2014). Data from reference sites are spatially and temporally limited. Thus, while this approach helped to provide a comparison for select rivers, our current approach uses more data available at a higher spatial and temporal resolution throughout all regions. This review supports our continued use of the current methods for estimating reference conditions. However, we plan to continue to review our methodology as new data become available.

Another limitation of the current reference condition is a consequence of sparse organic carbon observations. This results in the use of regressions primarily based on data sets collected in smaller rivers and streams in South Puget Sound from 2006 to 2007. To remedy this data paucity, Ecology began monitoring organic carbon at freshwater monitoring stations in October 2017. We also have compiled recent USGS data, and we are pursuing other event-based measurements that could be conducted if funding becomes available. These data sets will improve our freshwater organic carbon loadings estimates, and they will also expand the data set from which improved reference condition estimates can be derived.

Bounding Scenarios

Among other benefits, Ecology's Puget Sound Nutrient Source Reduction Project (PSNSRP) aims to achieve DO and carbonate system improvements from optimum reductions in anthropogenic nutrient and carbon loads in marine point source and watershed discharges. The bounding scenarios represent the range of the response of water quality in Puget Sound to major hypothetical loading changes focused on reductions to marine point source inputs from municipal WWTPs.

To choose model years that represent the range of interannual variability, we considered the residence time index for Central Puget Sound as presented in the Puget Sound Ecosystem Monitoring Program report for the year 2015 (PSEMP, 2016) and reproduced in Figure 12. The residence time index was estimated by a Knudsen relationship using river flow and observational marine data for the upper 30 meters (Albertson et al., 2016; Knudsen, 1900). Residence time is displayed as an index relative to a 16-year baseline (the dotted line in Figure 12). The residence time index for 2014 appears to be at the baseline, while 2008 is slightly higher and 2006 is much higher than the baseline value. Years with a positive index reflect higher residence times than the baseline.

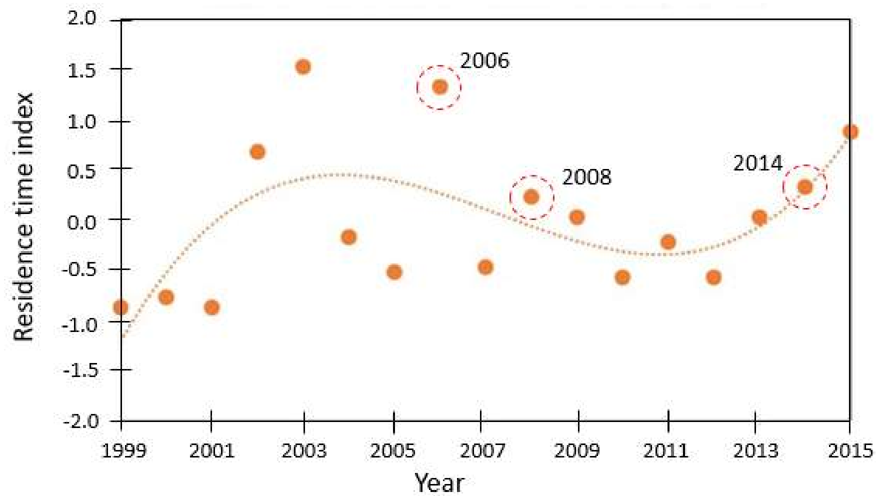


Figure 12. Index of residence time relative to normal in the top 0–30 m in Central Puget Sound, 1999–2015 (PSEMP, 2016).

The residence time index reflects different hydrodynamic characteristics in each of these years. These characteristics are also reflected in the differences in annual average flows, as shown in Table 3.

Table 3. Annual average flows (m^3/s).

River	2006	2008	2014
Fraser	2364	2750	3185
Skagit	548	515	669
Stillaguamish	135	122	149
Nisqually	62	59	61
Skokomish	57	30	39

A virtual dye study was conducted previously, using the PSM model for the years 2006, 2008, and 2014. An initial dye concentration was input to the model at the start of the model run. The dye concentration at each model grid cell was tracked with time. The time it took for the concentration to reach 37% of the initial concentration (also known as *e-folding time*) was noted for each grid cell.

These e-folding times are relative to the open boundary at the mouths of the Straits of Juan de Fuca and Georgia. E-folding times are plotted in Figure 13 for 2006, 2008, and 2014. The e-folding times (considered as indicative of residence times) varied between the years. For example, e-folding times in Penn Cove (red circles in Figure 13) varied between approximately 270 days in 2006, 250 days in 2008, and 170 days in 2014.

Longer residence times promote stagnation and buildup of pollutant concentrations, increase primary productivity and depletion of nutrients, increase nitrification (oxidation of ammonia to nitrate, which depletes oxygen), increase settling of particulate organic matter (e.g., dead algae), and increase decomposition of organic carbon (which depletes oxygen). Higher residence times are indicative of where the potential hot spots are for biogeochemical stressors. Thus, consideration of interannual variability is important when evaluating anthropogenic nutrient reductions on DO concentrations.

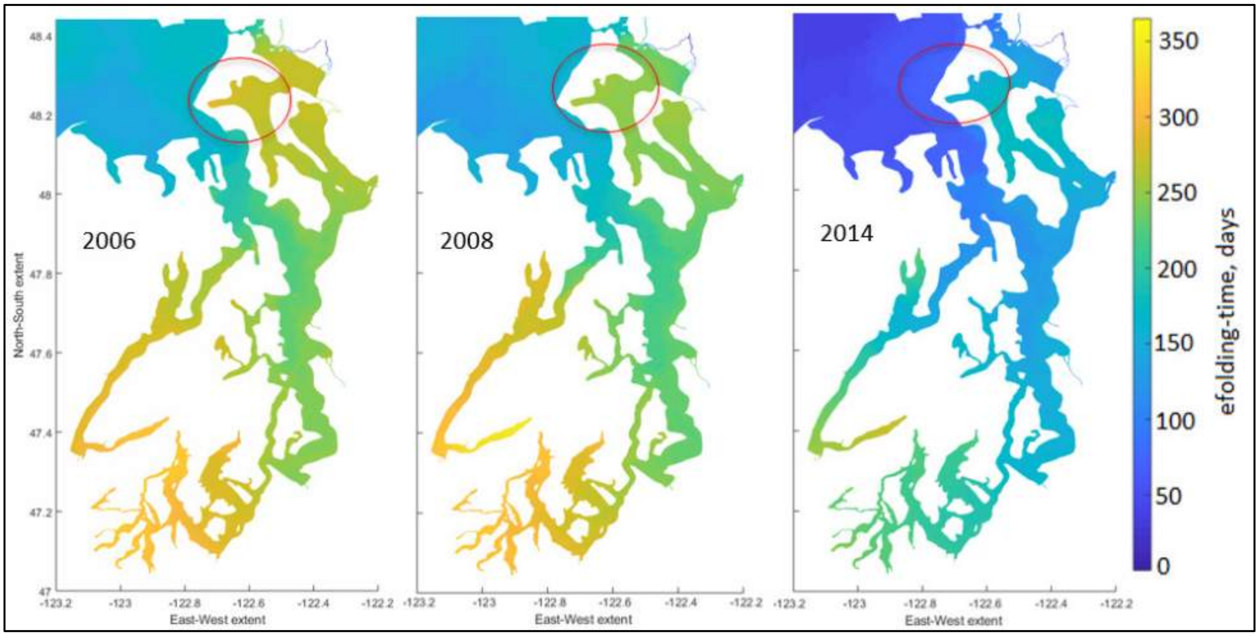


Figure 13. E-folding times (indicative of residence times) in Puget Sound for 2006, 2008, and 2014.

Hindcast model runs for the years 2006, 2008, and 2014 were conducted. Throughout this report, the term "existing condition" refers to the model output derived for each year from those hindcast runs. Table 4 shows the various bounding scenarios considered in this report. Seasonal biological nitrogen removal (BNR) indicated in the table refers to wastewater treatment technology that achieves dissolved inorganic nitrogen (DIN = NH^{4+} + NO^{3-}/NO^{2-}) and carbonaceous biological oxygen demand ($CBOD_5$) at levels equal to or less than 8 mg/L from April through October, per Tetra Tech (2011). The impact of each of the scenarios listed in Table 4 was obtained from computing the difference between each scenario and reference conditions.

Table 4. List of bounding scenarios.

Scenarios for 2006, 2008, and 2014	
1	Impact of all anthropogenic sources
2	Impact of marine point sources only (watershed sources set at reference conditions)
3	Improvement with BNR at all Washington municipal WWTPs discharging into Salish Sea waters
4	Improvement with BNR at Washington municipal WWTPs that discharge DIN >1000 kg/day into Salish Sea waters
5	Improvement with BNR at Washington municipal WWTPs that discharge DIN >8000 kg/day into Salish Sea waters

BNR: Biological nitrogen removal

Marine point sources with DIN loads greater than 1000 kg/day include the municipal WWTPs Chambers Creek, Tacoma Central, Brightwater, South King County, West Point, Everett outfall in the Snohomish River, Everett-Marysville combined outfall in Port Gardner, and Bellingham. Brightwater WWTP was not included in the 2006 or 2008 loading scenarios, because it came online in 2012. Brightwater WWTP is included in the 2014 runs. Marine point sources with DIN loads of 8000 kg/day or greater include the South King County and West Point municipal WWTPs.

Each scenario was compared to the reference condition. For instance, the impact of the total anthropogenic sources (item 1 in Table 4) during the years studied was assessed by subtracting the modeled reference condition from the existing condition for each years' result. Likewise, the impact of marine point sources (item 2 in Table 4) was assessed by comparing the effect of the discharges from all marine point sources alone to the effect of the reference loads. Note that this scenario involves the removal of the anthropogenic river loads.

Results and Discussion

Model Performance: Hydrodynamics

Hydrodynamic model evaluation included comparing model predictions with observed data for salinity, temperature, water surface elevations, tidal harmonics, and currents. Salinity and temperature statistics are presented under the section “Model Performance: Water Quality.”

Water surface elevations

Model-predicted water surface elevations were compared with those observed at seven National Oceanic and Atmospheric Administration (NOAA) stations. Relative error in water surface elevation predictions (as a percentage of the tidal range) were compared for 2006 and 2014 with those previously published by Khangaonkar et al. (2017 and 2018, respectively) and are presented in Table 5. The relative errors in predictions are comparable to the published values within Puget Sound, but they are slightly higher at Cherry Point and Friday Harbor. Khangaonkar et al. (2017) used a Salish Sea model expanded farther than the one we are employing in this report, with grids extending beyond the continental shelf. In addition, changes and updates to the model described in Khangaonkar et al. (2018) were made, as explained in this report.

Table 5. Relative error in predictions of water surface elevations (% of tidal range) at National Oceanic and Atmospheric Administration monitoring stations.

Station	2014	2008	2006	2006 Extended SSM, Khangaonkar et al. (2017)	2014 SSM, Khangaonkar et al. (2018)
Cherry Point	11.6	12.4	12.0	9.8	≤10
Friday Harbor	10.9	11.4	11.4	7.7	≤10
Port Angeles	6.8	7.5	7.3	7.7	≤10
Port Townsend	8.2	8.7	8.6	7.9	≤10
Seattle	8.0	8.5	8.5	8.6	≤10
Tacoma	8.6	8.8	8.9	8.7	≤10
Neah Bay	10.6	10.7	10.7	NA	NA

Appendix F includes scatter plots of water surface elevation for the seven NOAA stations, showing overall statistics for paired 2006, 2008, and 2014 predicted and observed data sets, as well as time series plots of water surface elevations for the last two weeks of May.

Figure 14 shows a typical scatter plot and time series plot at NOAA’s Seattle station. The model does well at predicting the different phases of the tidal cycle.

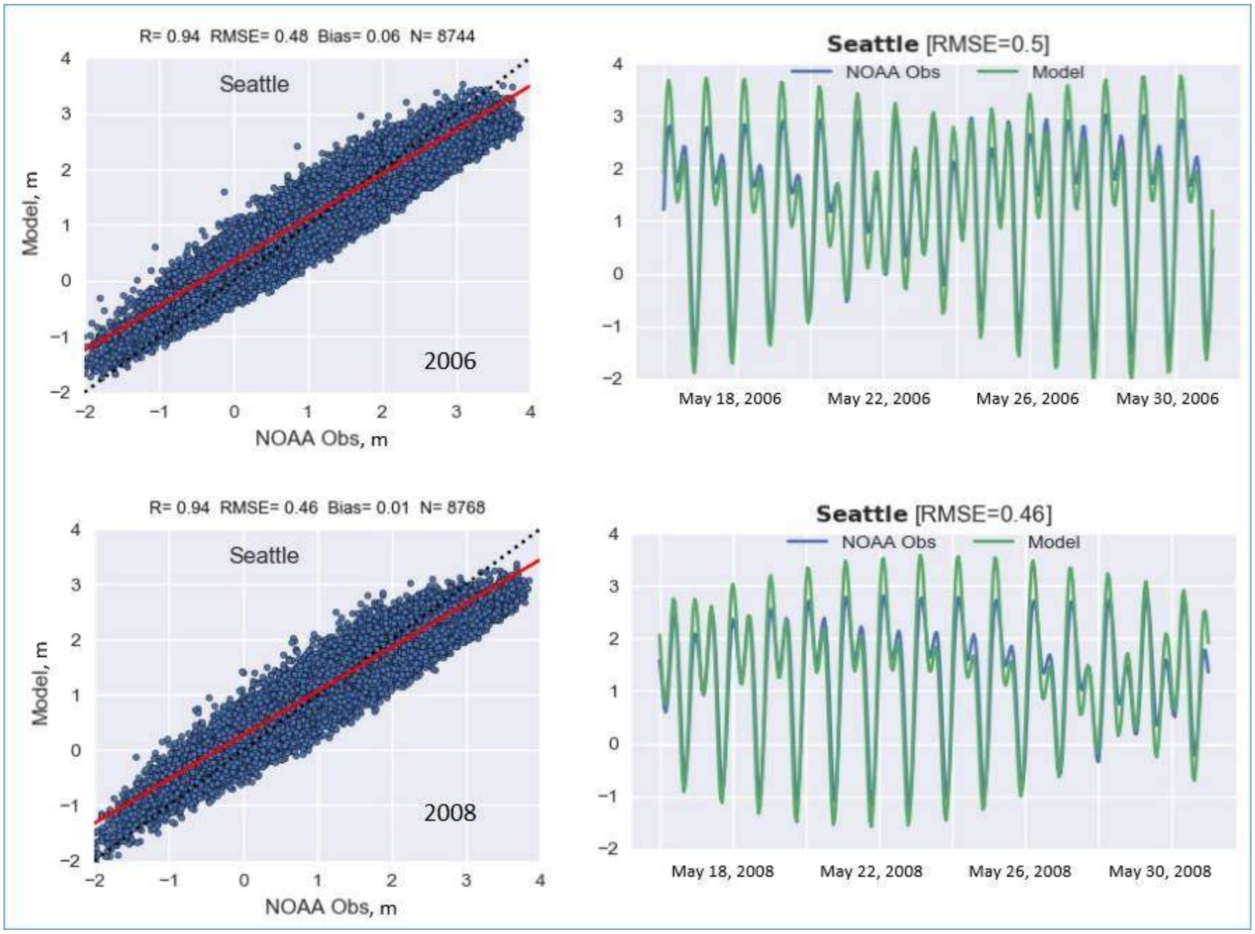


Figure 14. Model predictions and observed data for water surface elevations.
Left panel, typical scatter plots for 2006 (above) and 2008 (below). *Right panel*, time series for the month of May 2006 (above) and May 2008 (below).

Currents

Observed current data are available at two stations (Pickering and Dana Passages) for 2006 only. Table 6 shows the average root mean square error (RMSE) statistic at these stations. The RMSE compares well with those presented by Khangaonkar et al. (2011).

Table 6. Root mean square error (RMSE) (m/s) of predicted and observed currents for October 2006.

Source	Location	Pickering Passage	Dana Passage
Khangaonkar et al., 2011	Surface	0.20	0.34
	Bottom	0.12	0.28
Salish Sea Model predictions	Surface	0.11	0.21
	Bottom	0.06	0.20

Appendix F contains a detailed analysis of the eastward and northward current components for all layers, as well as depth-averaged currents at the Pickering and Dana Passages stations. Figure 15 shows the depth-averaged time series plot of predicted and observed eastward (U, cm/s) and northward (V, cm/s) currents at Dana and Pickering Passages.

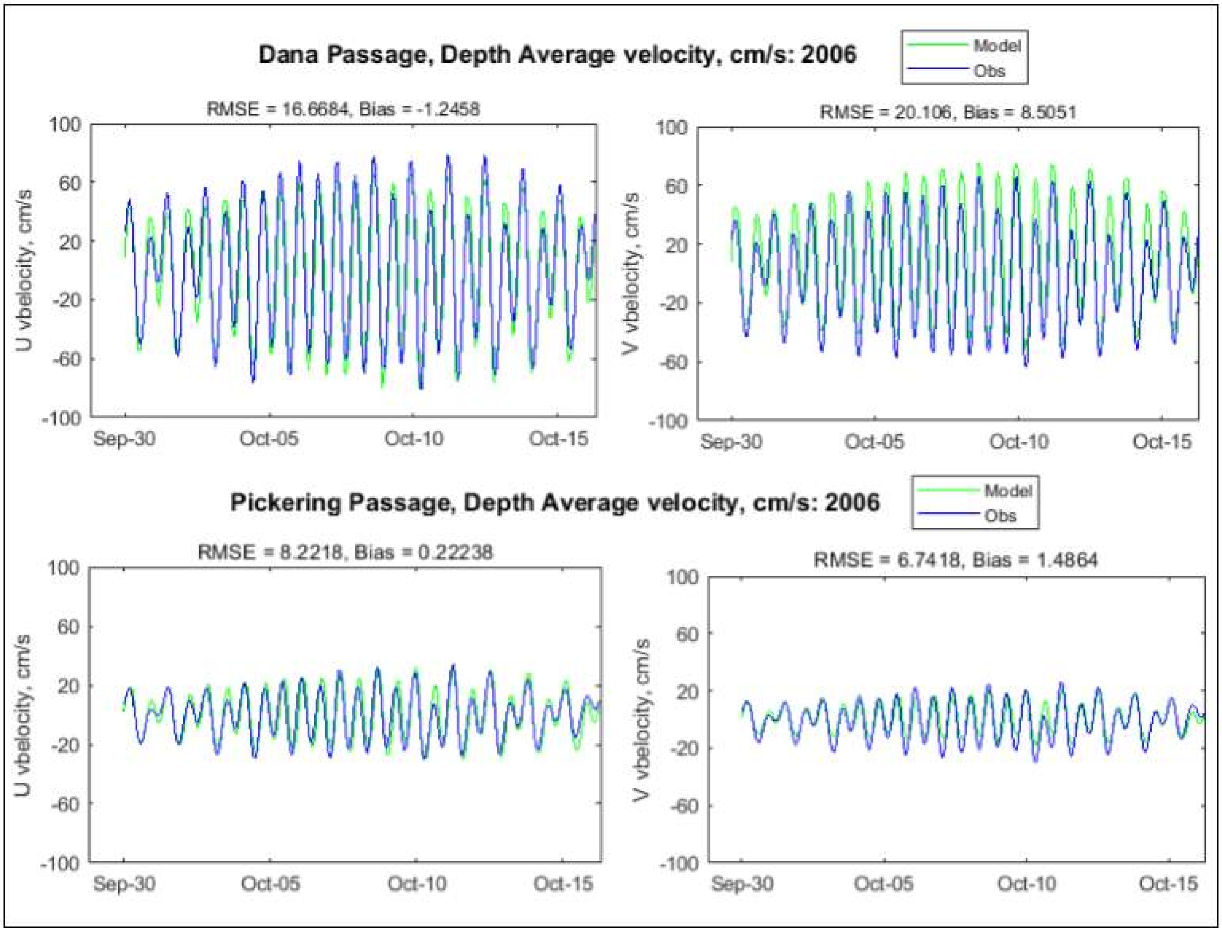


Figure 15. Eastward (left, U velocity) and northward (right, V velocity) depth-averaged current comparison between model prediction and observed data for Dana Passage (above) and Pickering Passage (below).

Model Performance: Water Quality

Model performance quality objectives described in McCarthy et al. (2018) were met. We used the root mean square error (RMSE), correlation coefficient (R), and bias as indicators of goodness of fit. These measures of goodness of fit to observed data reveal the model's overall high level of skill for predicting DO and its capability to accurately predict DO response to nutrient reduction scenarios. Model performance statistics, as shown below, are about the same or better than previous SSM studies. Additionally, the performance statistics presented here are similar to those reported for other biogeochemical modeling efforts focused on hypoxia (Cerco and Noel, 2013; Irby et al., 2016).

The overall statistics for 2008 and 2006 for the SSM are shown in Table 7 with a comparison of statistics for the intermediate-scale Puget Sound Model (PSM) as per Bianucci et al. (2018). Statistics for 2014 for the SSM are also included to compare with the statistics presented by Khangaonkar et al. (2018).

The current model setup improves the overall temperature and salinity predictions for 2006, 2008, and 2014. This is demonstrated by the relative increase in correlation coefficient (R), relative reduction in RMSE compared to those presented by Bianucci et al. (2018) for the intermediate-scale PSM for 2008, and compared to those presented by Khangaonkar et al. (2018) for the expanded SSM for 2014 (Table 7). With respect to DO predictions, RMSE values are much improved compared to those reported by Bianucci et al. (2018) and are similar to those reported by Khangaonkar et al. (2018).

Table 7 also shows that the statistics for pH have not generally improved compared to Bianucci et al. (2018). Improvement to the pH calibration for the SSM is underway at Pacific Northwest National Laboratory .

Appendix G presents model performance for overall water quality and for each station, for the years 2006, 2008, and 2014. Appendix G1 contains a map of all the station locations where model performance was evaluated for water quality. Appendix G2 contains an explanation of how to read time-depth plots. Appendices G3, G4, and G5 contain model performance plots for 2006, 2008, and 2014, respectively.

Table 7. Overall performance statistics for 2006, 2008, and 2014 for the updated SSM and two previous versions. R = correlation coefficient; RMSE = root mean square error; n = number of observations.

Temperature (°C)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.90	1.48	1.28	67858
2008 SSM	0.95	0.56	-0.05	67857
2006 SSM	0.95	0.69	0.39	140080
2014 SSM	0.95	0.87	-0.41	89222
2014 SSM (Khangaonkar et al. 2018)	0.93	0.76	-0.28	38218
Salinity (psu)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.61	1.33	-0.68	66934
2008 SSM	0.76	0.81	0.03	66958
2006 SSM	0.84	0.77	-0.47	138845
2014 SSM	0.75	0.88	-0.37	89025
2014 SSM (Khangaonkar et al. 2018)	0.75	0.97	-0.12	38043
Dissolved oxygen (mg/L)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.80	1.8	-1.56	66538
2008 SSM	0.85	0.98	-0.53	66931
2006 SSM	0.80	1.09	-0.57	135115
2014 SSM	0.81	0.96	-0.34	87725
2014 SSM (Khangaonkar et al. 2018)	0.83	0.99	-0.24	26082

NO_3 (mg/L)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.80	0.08	-0.001	1902
2008 SSM	0.78	0.09	-0.04	1381
2006 SSM	0.81	0.07	-0.02	678
2014 SSM	0.84	0.07	0.00	1849
2014 SSM (Khangaonkar et al. 2018)	0.82	0.09	0.013	1187
Chlorophyll (µg/L)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.50	2.78	-0.3	66041
2008 SSM	0.49	3.10	0.33	66941
2006 SSM	0.52	4.48	0.19	112567
2014 SSM	0.52	3.48	-0.13	89338
2014 SSM (Khangaonkar et al. 2018)	0.54	4.37	0.83	26940
pH (total scale)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.64	0.14	-0.07	584
2008 SSM	0.74	0.18	0.15	589
2006 SSM	NA	NA	NA	NA
2014 SSM	0.60	0.28	0.14	622

Time-depth plots

Figures 16, 17, and 18 show typical time-depth plots for temperature, salinity, and DO for observed and predicted data for year 2006 at selected stations in South Puget Sound (Ecology station D001 in Dana Passage), Central Puget Sound (King County Station KSBP01), Hood Canal (Ecology station HCB003), Admiralty Inlet (Ecology station ADM001), and Bellingham Bay (Ecology station BLL009). Specific error statistics for each station are included.

The background color in Figures 16–18 is indicative of the model prediction for each parameter at each station, while the circles indicate multiple observations at depth at the same location. The color within the circles has the same scale as that for model predictions (see Appendix G2 for an explanation on how to read the time-depth plots). Time-depth plots for all stations and for years 2006, 2008, and 2014 are presented in Appendix G3 through G5, respectively.

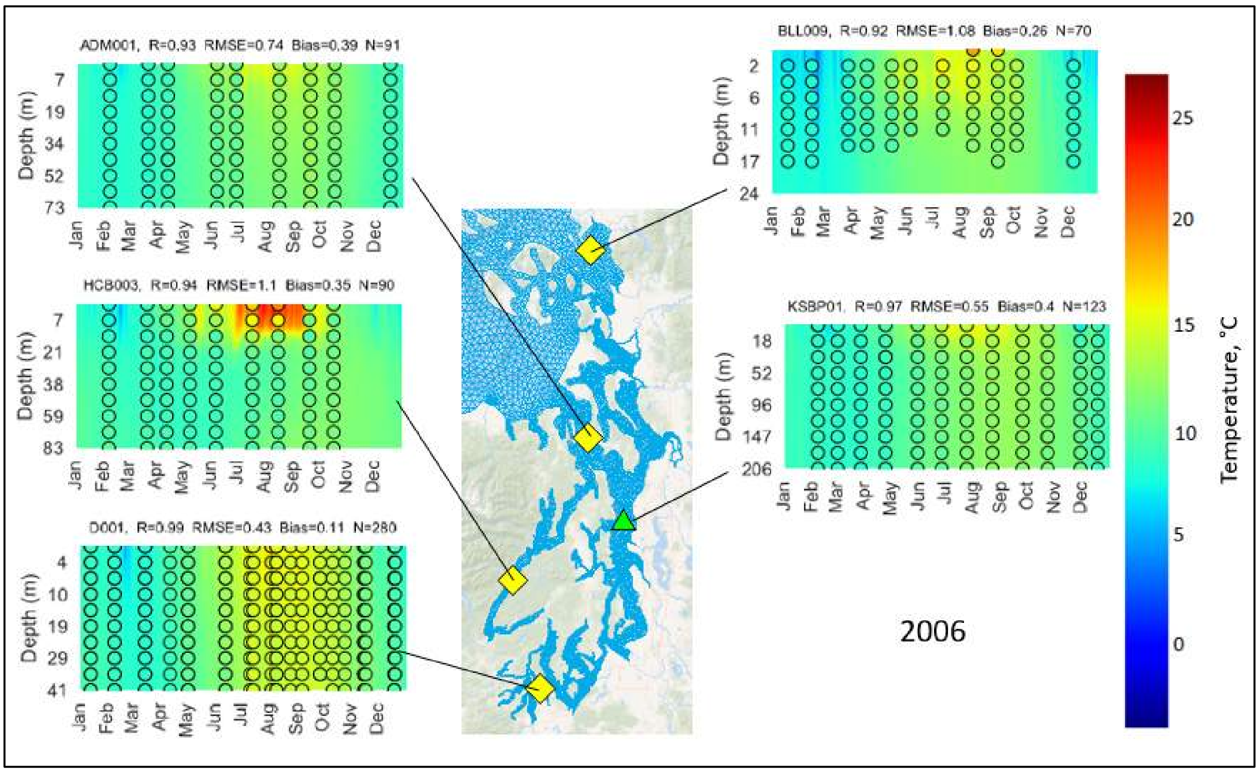


Figure 16. Time-depth plots of observed and predicted temperatures at selected stations for 2006. The colors inside the circles represent observed measurements taken at a particular depth and time, while the colors in the background represent model-simulated values.

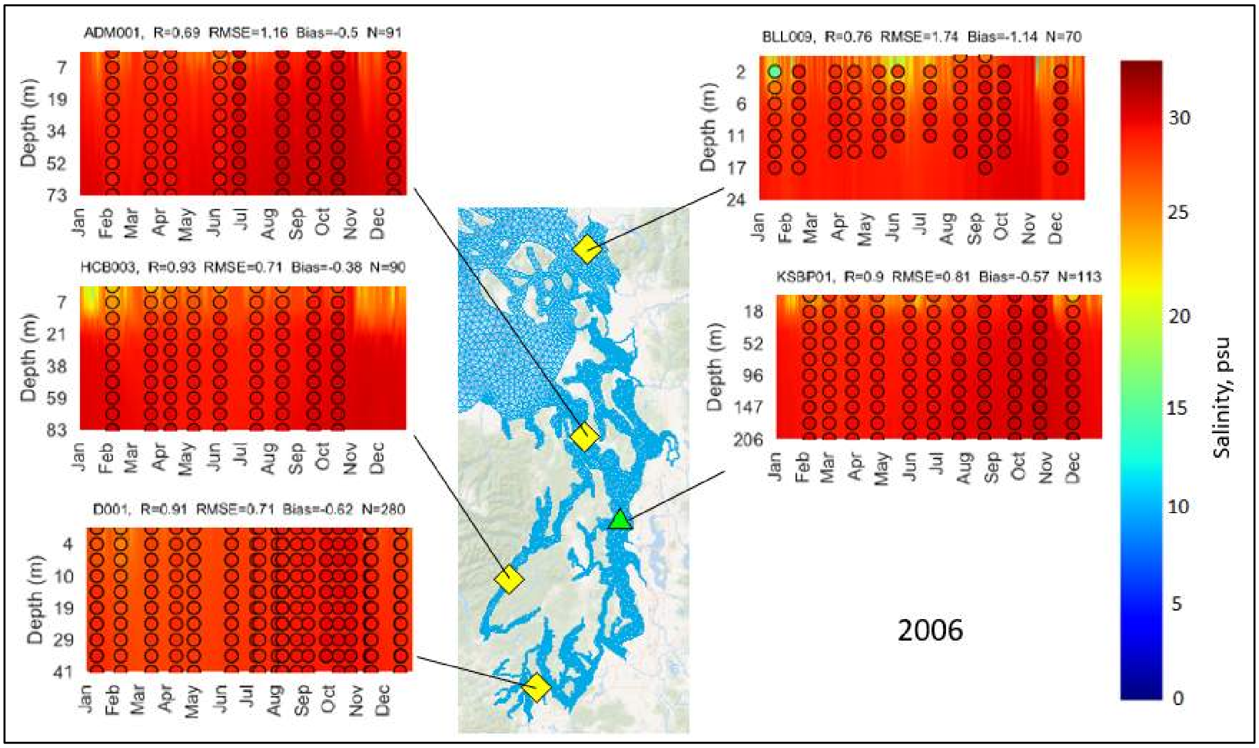


Figure 17. Time-depth plots of observed and predicted salinities at selected stations for 2006.

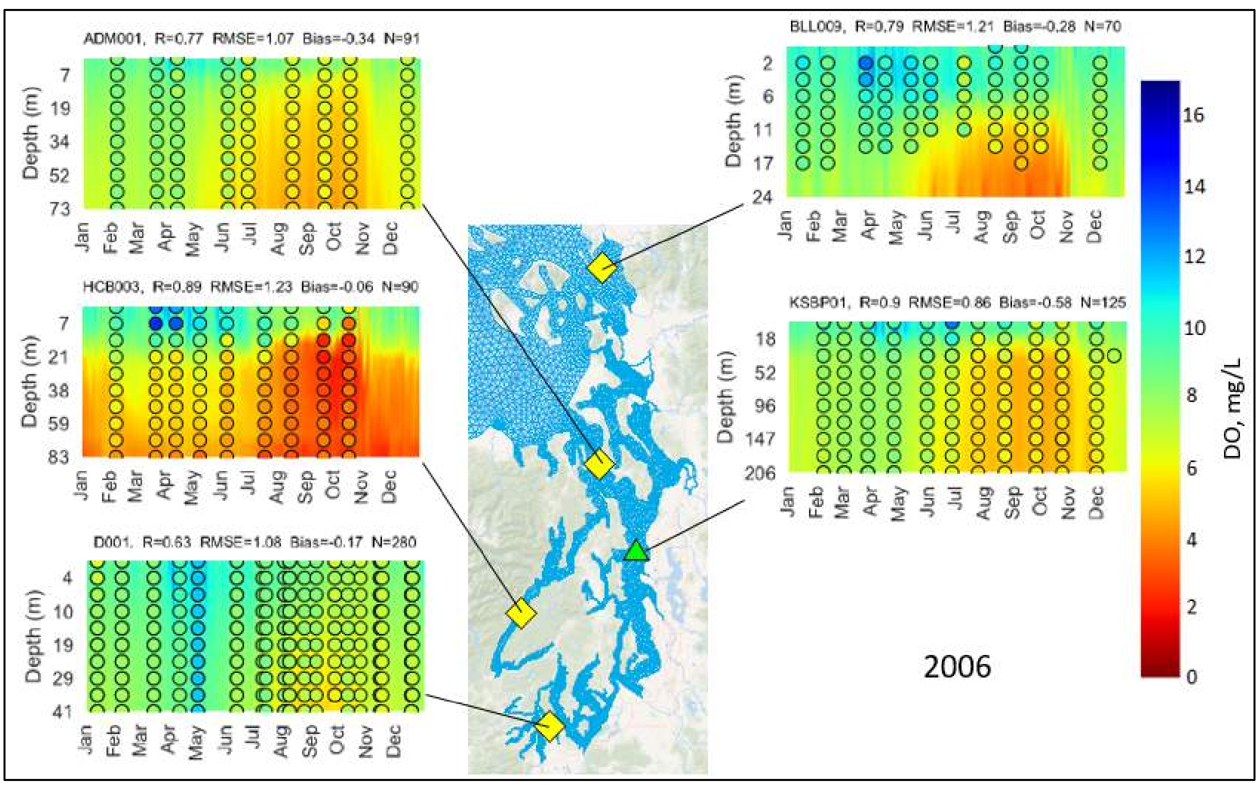


Figure 18. Time-depth plots of observed and predicted dissolved oxygen (DO) at selected stations for 2006.

Time series plots

Figures 19, 20, and 21 show the time series plots for temperature, salinity, and DO for observed and predicted data for 2006 at selected stations in South Puget Sound (Ecology station D001 in Dana Passage), Central Puget Sound (King County station KSBP01), Hood Canal (Ecology station HCB003), Admiralty Inlet (Ecology station ADM001), and Bellingham Bay (Ecology station BLL009) at the surface and bottom layers. Specific error statistics for each station are also included for the surface and bottom layers. Time series plots for all stations for 2006, 2008, and 2014 are presented in Appendices G3 through G5.

In general, model performance as measured by root mean square error (RMSE) is better for the bottom layer relative to the surface layer. Observed data at the Bellingham station for surface and bottom layers is scant, so error statistics for this station cannot be adequately estimated.

The model performs well in predicting the warming of the surface layer in Hood Canal, as seen in observed data. The distinct salinity difference between surface and bottom layer is also well predicted by the model at the Hood Canal Station. Observed data at other stations for surface and bottom layers show little stratification. The model also performs well in predicting the observed hypoxia in Hood Canal.

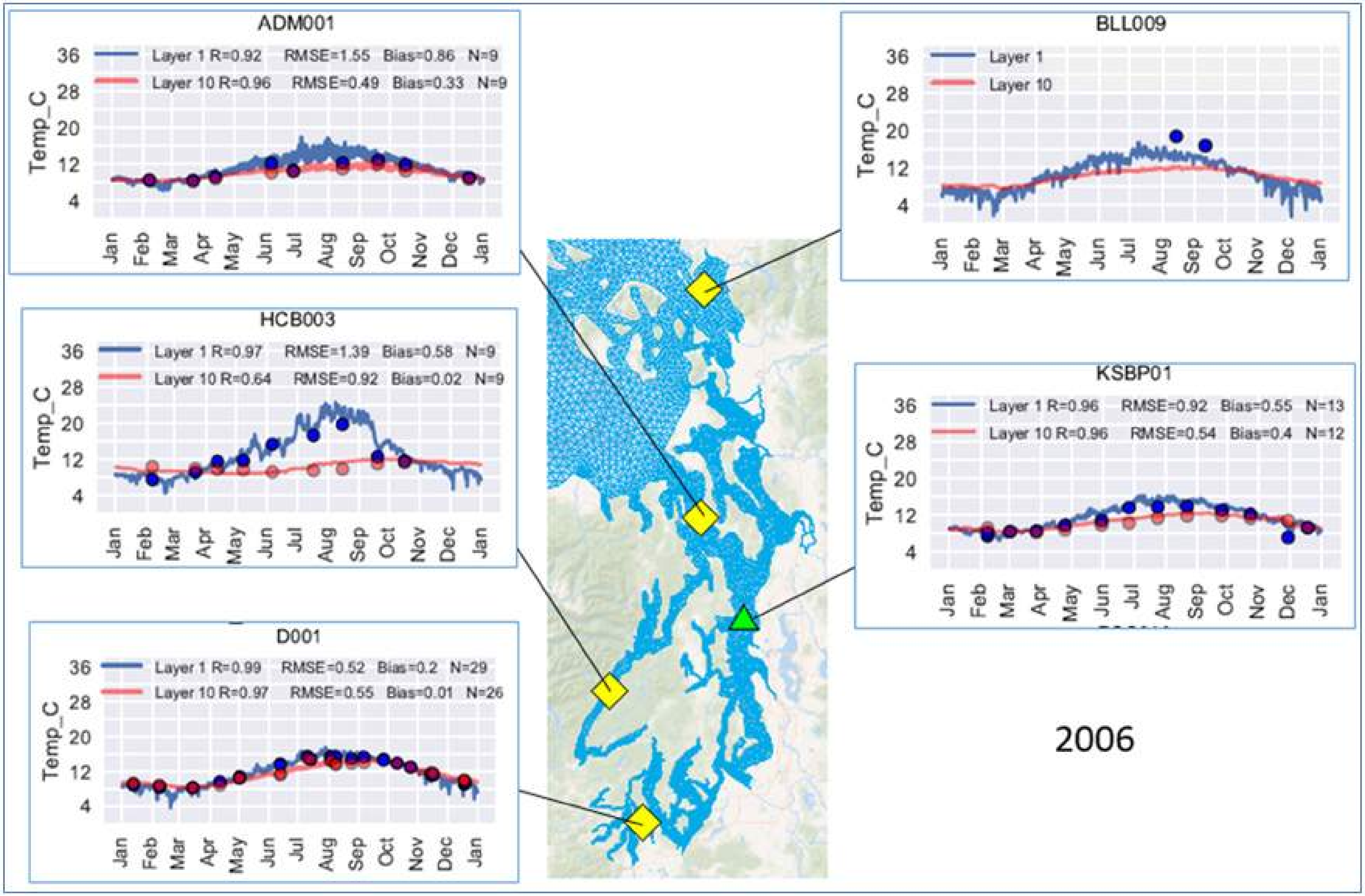


Figure 19. Time series plots for temperature (°C) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

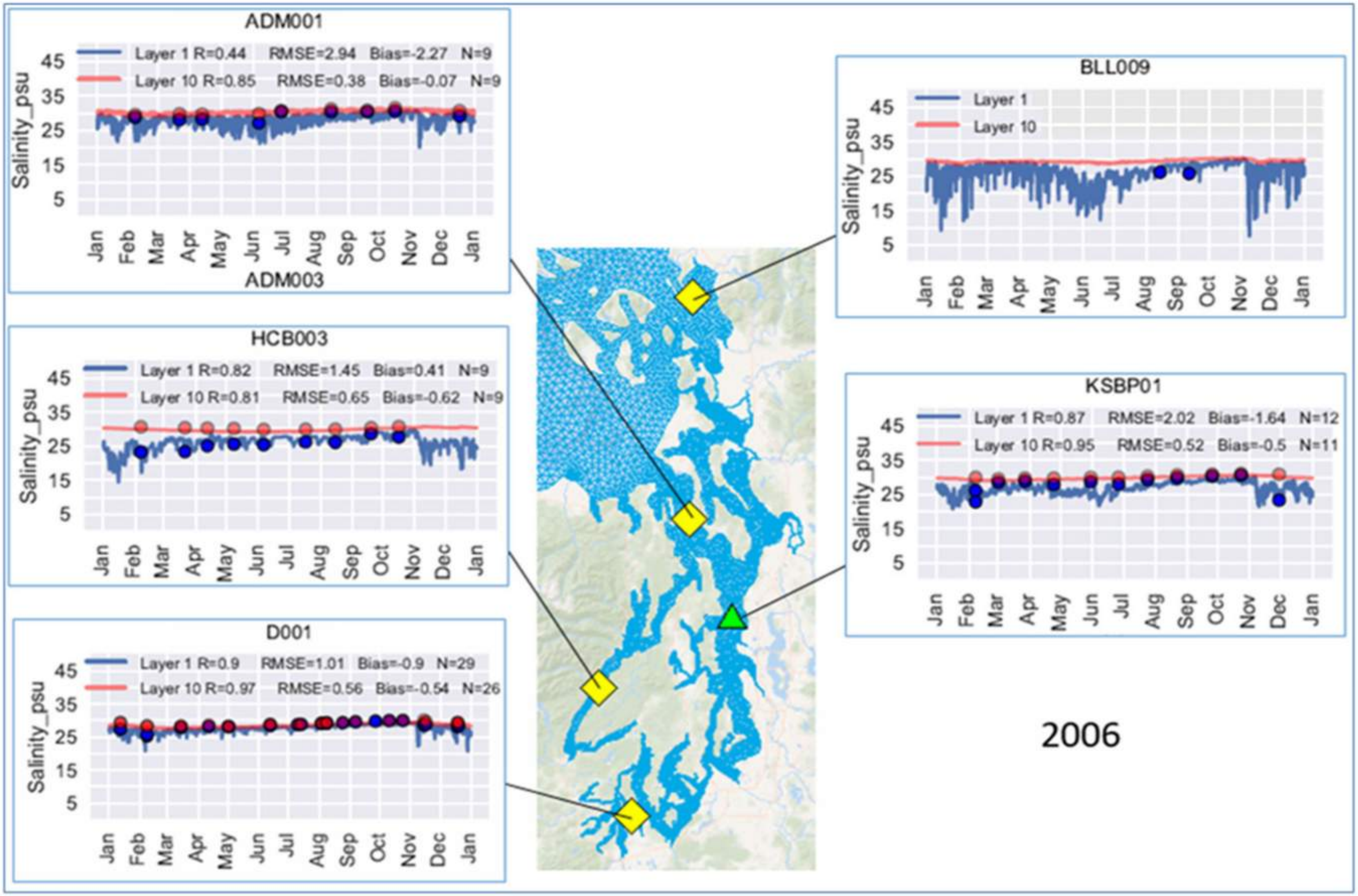


Figure 20. Time series plots for salinity (psu) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

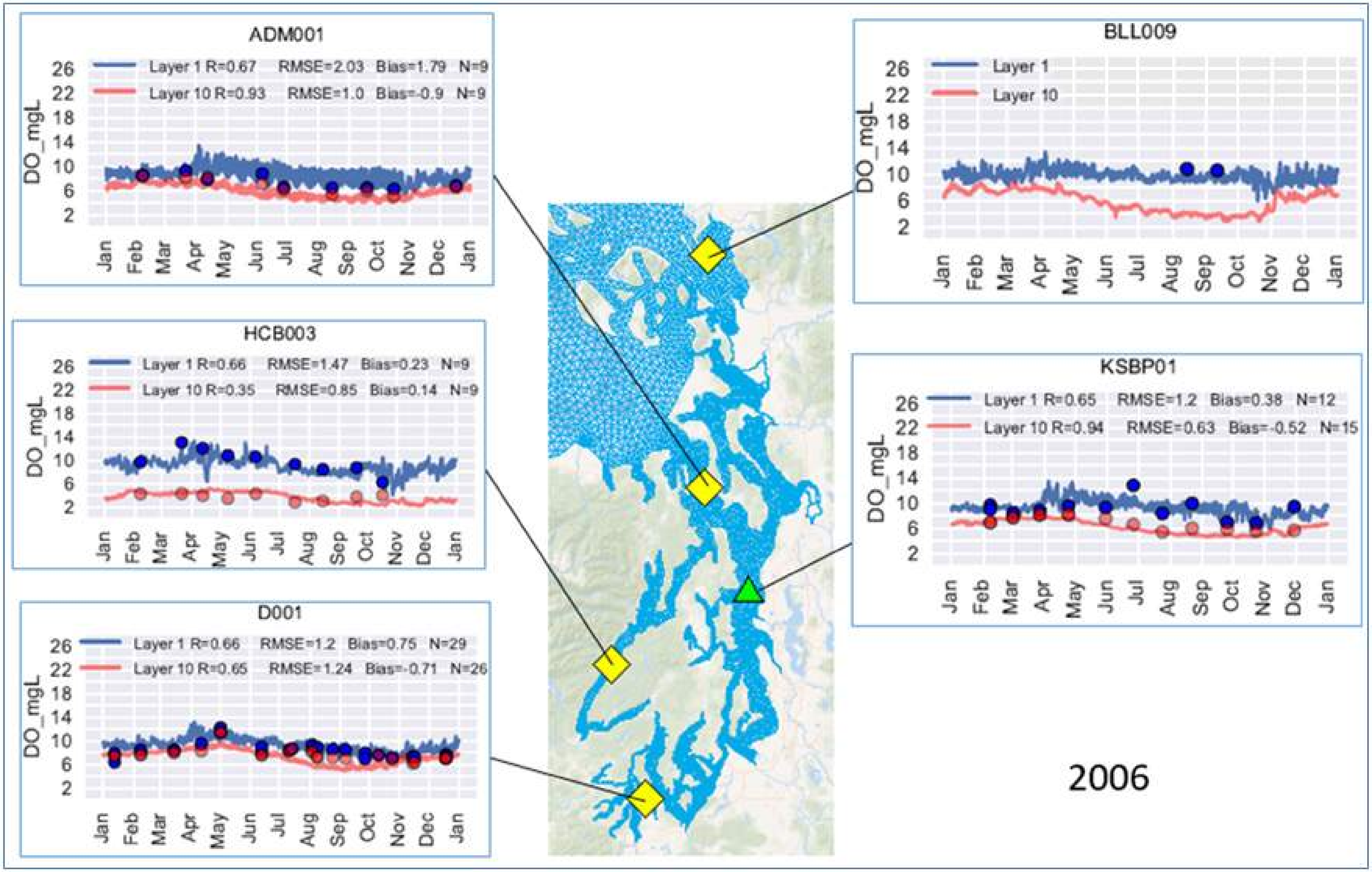


Figure 21. Time series plots for dissolved oxygen (DO, mg/L) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

Profile plots

Figures 22, 23, and 24 show profile plots for temperature, salinity, and oxygen for observed and predicted data for 2006 at selected stations in South Puget Sound (Ecology station D001 in Dana Passage), Central Puget Sound (King County Station KSBP01), Hood Canal (Ecology station HCB003), Admiralty Inlet (Ecology station ADM003), and Bellingham Bay (Ecology station BLL009). Specific error statistics for each station are included for each of the profile plots. Profile plots for all stations and for 2006, 2008, and 2014 are presented in Appendices G3 through G5, respectively.

In addition to model performance in predicting observed data, the profile plots also show how well the model predicts the stratification in the water column. Figures 22, 23, and 24 reveal stations where thermal, salinity, and oxygen stratification is relatively more pronounced, such as Hood Canal. These figures also show that the model does a good job in simulating the stratification and the shallow thermocline, halocline, and oxycline, respectively.

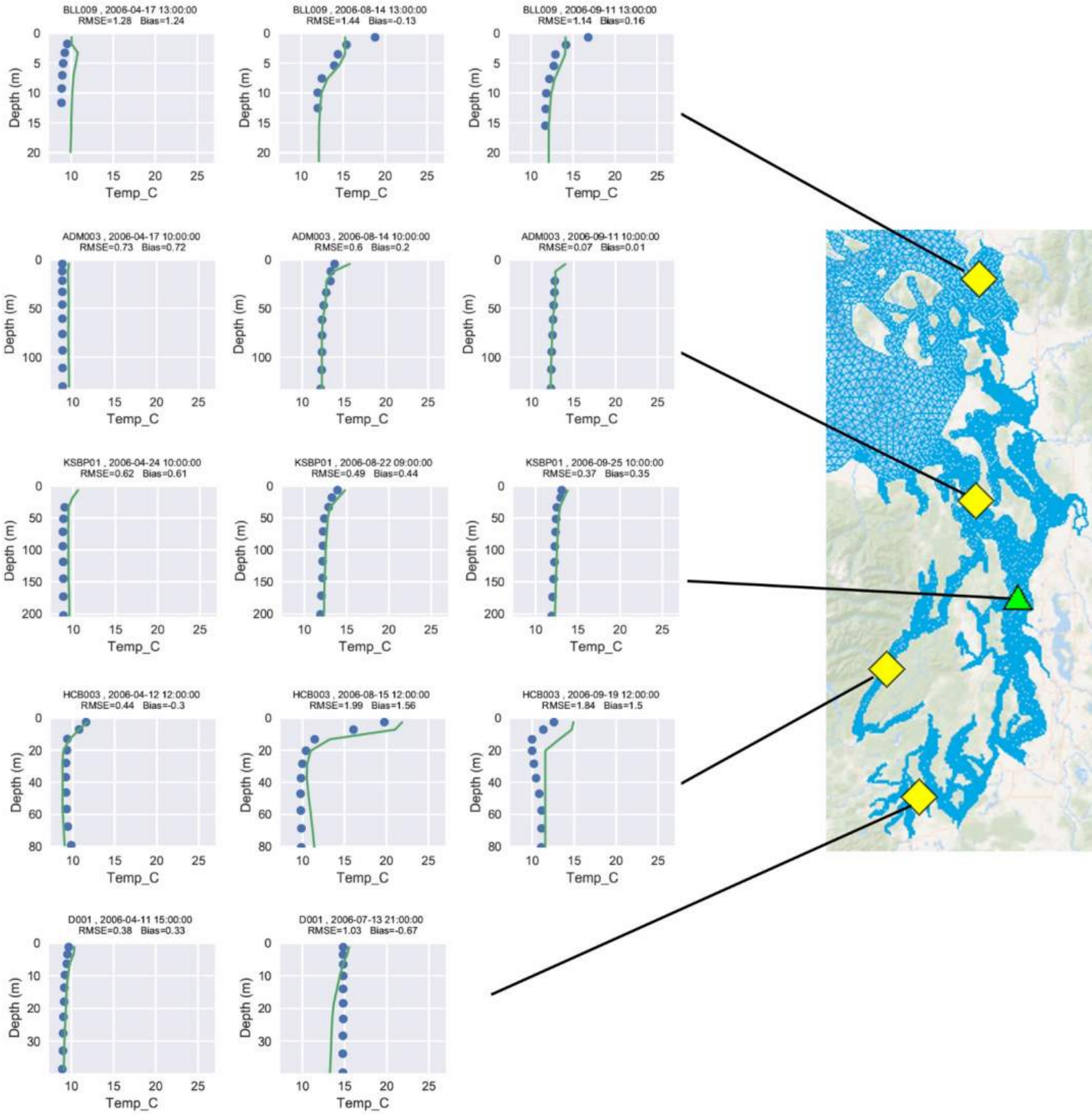


Figure 22. Year 2006 temperature profiles (°C) at selected stations for spring (left column), summer (center column), and fall (right column) conditions.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County Station KSBP01). Fourth row: Hood Canal (Ecology station HCB003). Fifth row: South Puget Sound (Ecology station D001 in Dana Passage).

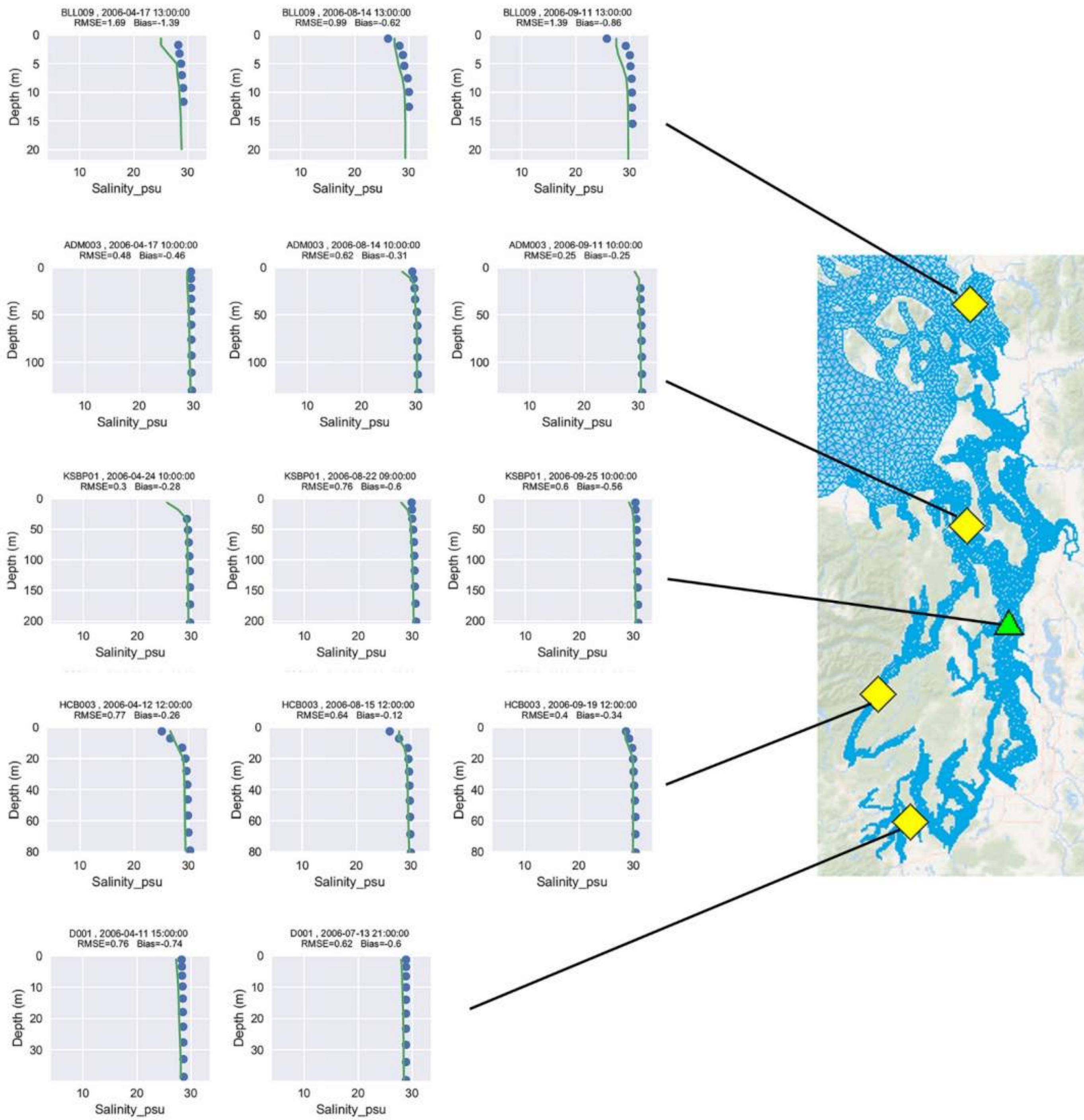


Figure 23. Year 2006 salinity profiles at selected stations for spring (left column), summer (center column), and fall (right column) conditions.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County Station KSBP01). Fourth row: Hood Canal (Ecology station HCB003). Fifth row: South Puget Sound (Ecology station D001 in Dana Passage).

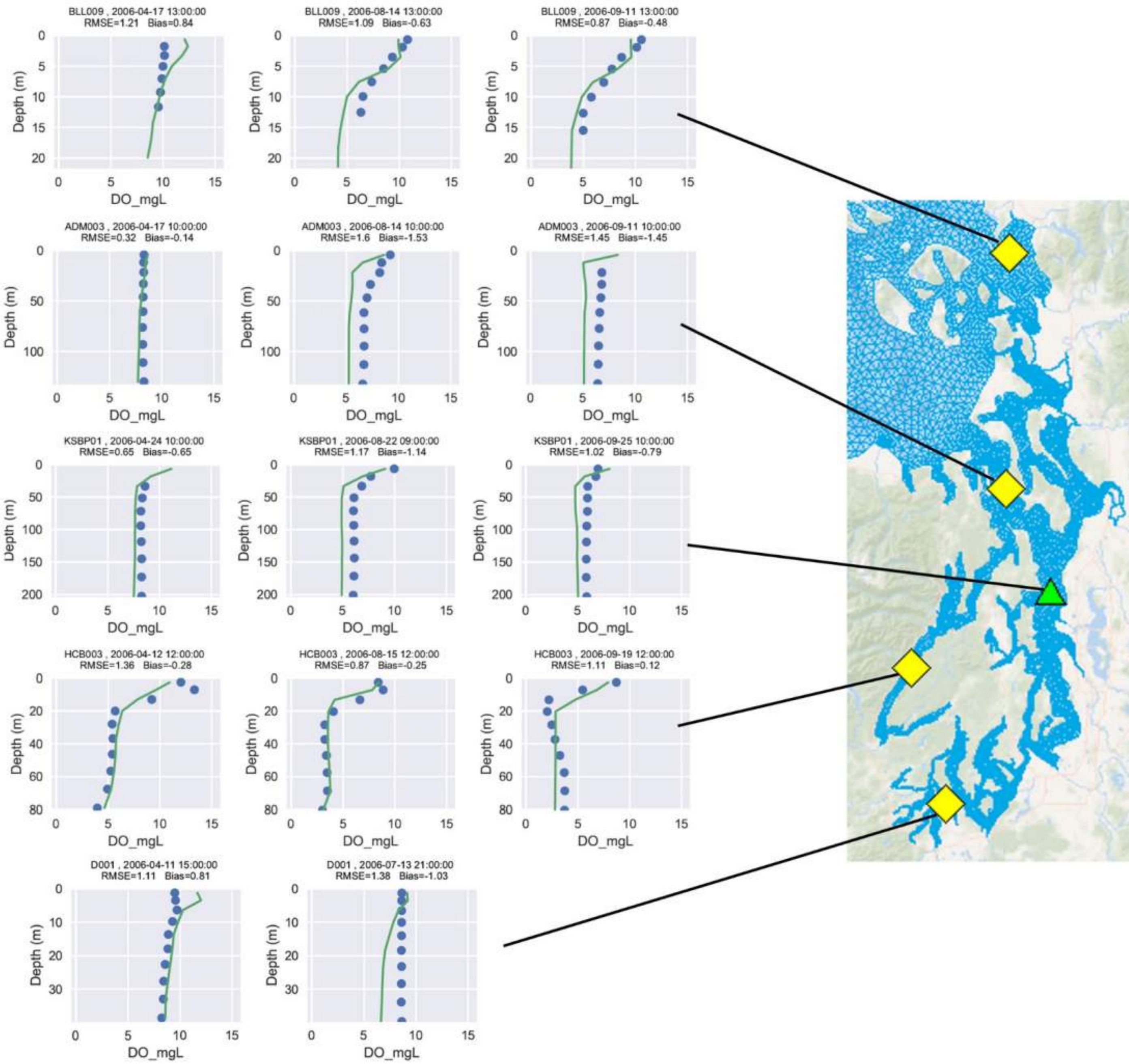


Figure 24. Year 2006 dissolved oxygen (DO, mg/L) profiles at selected stations for spring (left column), summer (center column), and fall (right column) conditions for 2006.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County Station KSBP01). Fourth row: Hood Canal (Ecology station HCB003). Fifth row: South Puget Sound (Ecology station D001 in Dana Passage).

Phytoplankton productivity

Overall model performance can also be gauged when comparing model predictions with observed phytoplankton productivity. However, since productivity observations are not available for the modeled years, only a qualitative comparison with available observations from different time periods is possible. Appendix H contains a comparison of available gross primary productivity between observed and modeled data. Predicted values for 2008, both average and peak, are significantly lower than measured values in the Main Basin from 1999 to 2001. Nonetheless, available chlorophyll data (Jaeger and Stark, 2017) imply that lower productivity was prevalent in 2008 when compared to the years 1999 to 2001, suggesting that predicted values may reflect the expected lower productivity for that model year. Since phytoplankton productivity is a key ecosystem function, it is necessary to conduct more model runs for different years to assess whether the model predicts peak and average daily gross primary productivity reflective of years in which observations are available.

Sediment oxygen demand

Sediment oxygen demand (SOD) is another parameter we used to qualitatively assess model performance. The range of predicted SOD is very similar between 2006 and 2008: from 0.2 to 1.4 and 1.3 g/m^2/day of O_2, respectively. The peak difference in O_2 between the existing and reference scenarios in both years is about 0.4 g/m^2/day. The difference between annual mean SOD among model years is relatively small (within 1%), and the spatial pattern of the SOD distribution in the model domain is almost identical from one year to the next. Appendix I contains 2006 and 2008 SOD maps for the existing and reference scenarios and their difference.

Pelletier et al. (2017a) compared predicted annual SOD means with observed means available at various locations in Puget Sound in 2006, albeit collected at different times and durations. Upon conducting a similar comparison, including predictions for 2006, 2008, and 2014 and using a new observational data set (Merritt, 2017), we obtained analogous statistics. The large difference (about 51%) between predictions and observations is expected and generally considered reasonable (Brady et al., 2013). These differences may be due to a combination of the following factors: model bias, incongruent temporal or spatial scales, or potential biases associated with measuring sediment fluxes (Engel and Macko, 1993).

Most of the SOD observations in our region prior to 2017 were conducted with flux chambers. A new data set is available using sediment core incubation methods (Merritt, 2017). The average difference between the predicted and observed means of the older data sets (Pelletier et al., 2017a) used for comparison remains virtually unchanged (about 87%), but with a slight improvement — the predicted mean is about 3% lower at the observed locations with the latest model updates. However, the average difference between the predicted and observed means using the Merritt data set alone is significantly lower (23%), suggesting that the sediment core incubation method more closely matches model output. This highlights the challenges associated with field measurements of sediment fluxes and the resulting variability in observed data.

Furthermore, the Merritt (2017) data provide higher spatial resolution. This data set consists of sediment flux measurements at locations within Bellingham Bay, with observational clusters in which samples collected were close enough to each other that, in some instances, they fall within the same model grid cell. While the data demonstrate large SOD spatial variability (with a coefficient of variation up to 30% within the same grid cell), the data are not temporally rich. Three grid cells with more than one observation were selected for a closer comparison with model output. Predicted June means for two boundary grid cells during each of the three years modeled (2006, 2008, and 2014) were slightly statistically significantly higher than the observational mean for June 2017. On the other hand, the predicted means and observational mean for June 2017 for a grid cell away from the shoreline are statistically the same, with overlapping 95th percentile confidence intervals. Table I2 in Appendix I contains the results of a nonparametric analysis comparing these means.

Merritt (2017) suggests that a high organic carbon depositional environment may be changing the remineralization dynamics at some locations, lowering the sediment oxygen uptake, and leading to formation of sulfides. This possibility merits investigation, because Bellingham Bay is cataloged as having adversely affected benthic communities (Weakland et al., 2018). Higher temporal resolution of river load observations may lead to improvements in SOD predictions, particularly in areas near river mouths or at sheltered embayments. Appendix I contains further details about comparisons conducted, as well as potential future directions in terms of model and sediment flux comparisons and improvements.

Comparison of model predictions with high-resolution temporal data

Another qualitative measure of model performance is comparison of predictions to high-resolution temporal data available for the time periods that were modeled. Often, data from moorings or buoys have only partially undergone quality assurance and quality control procedures, and so quantitative comparisons are not possible. Another shortcoming is that available mooring data were collected at intertidal locations, which this version of the SSM is not designed to adequately address. Nonetheless, these qualitative comparisons do provide insights into potential model limitations and biases.

A qualitative comparison of predictions and observations at buoy locations revealed congruence in patterns and overall magnitudes in temperature, salinity, and DO. In the bottom layer, plots of model predictions and observations show an almost perfect visual fit. Appendix J contains these plots, as well as a discussion regarding data and model limitations and insights from the comparisons.

A comparison with model nodes next to, but not co-located with, data from moorings show that the model missed the chlorophyll peaks at these nearshore locations, and thus missed both the DO extremes (peaks and minima), but predicted levels in the mean value range. Appendix J contains plots showing model predictions compared to data collected from moorings. As discussed in McCarthy et al. (2018), one of the limitations of the current version of the SSM is that it does not adequately resolve tidally influenced areas. Improving nearshore predictions involves higher grid resolution, with more accurate bathymetry and simulation of key location-specific biogeochemical forcings. For example, incorporation of eelgrass meadows, in locations where they exist, is a step towards adequately modeling the water quality in the nearshore.

Model performance statistics are not computed including areas that consist of intertidal or very shallow subtidal areas, such as Padilla Bay, as discussed in McCarthy et al. (2018). In addition, model results in tidally influenced areas were not used in the water quality noncompliance computations.

Model performance improvements

Overall, while the differences between model and observations suggest that there is room for model improvements (e.g., increase resolution in narrow inlets, very shallow subtidal/intertidal regions, and around islands), the statistical metrics are definitely within reasonable ranges. At the model's intermediate scale, improvements in terrestrial nutrient loadings can also make a difference. The question of variability of DIN and DOC loads from rivers is an important one, because the monthly data (used to develop daily time series river inputs into the model using a regression approach) may not adequately reflect peak loads or loading during specific rainfall events. Thus, a more frequent or continuous temporal record could improve inputs and model quality to address that question. Biogeochemistry at inlets and bays could be somewhat modulated by influx of overland allochthonous carbon loadings, which are not well resolved in the model. More marine and freshwater organic carbon observational data are needed to improve our understanding. In addition, the effect of settling rates on both dissolved and particulate organic carbon, and subsequent remineralization dynamics through respiration, is a topic that deserves more focus, as discussed in Appendix E.

Sensitivity Tests

Sensitivity runs were made for 2008 with changes to rates and constants as shown in Table 8. This table also shows the associated RMSE, correlation coefficient (R), and bias. These tests were conducted to examine the model's response to changes in potentially key parameters, but this work did not result in modifications to the baseline parameter set. We continue to use the Khangaonkar et al. (2018) parameter set for all bounding scenario runs.

Table 8. Variables used in sensitivity test runs for 2008 and resulting skill metrics.

Item	Variable	Description	Current value	Sensitivity test	DO RMSE	R	Bias
1	Existing	Using rates and constants from Khangaonkar et al. (2018)			0.98	0.85	-0.53
2	ALPHMN1, ALPHMN2	Initial slope of photosynthetic production vs. irradiance (alpha) for algal group 1 and 2	12, 12	8, 10	0.99	0.84	-0.51
3	KHN1	Half-saturation concentration for nitrogen uptake for algal group 1	0.06 g/m^3	0.02 g/m^3	0.98	0.85	-0.55
4	KHNNT	Half-saturation concentration of NH_4 required for nitrification	0.5 g/m^3	1 g/m^3	0.95	0.85	-0.5
5	OBC150	Open boundary depth truncation	200 m	150 m	0.79	0.86	-0.16
6	Item 2 through 4 combined	ALPHA1, ALPHA2, KHN1, KHNNT	12, 12, 0.06, 0.5	8,10, 0.02, 1	1.1	0.83	-0.67

ALPHMN is the initial slope of the primary production versus irradiance relationship, and it impacts the light limitation for algal growth. A large value of ALPHMN increases the algal growth rate under lower irradiance conditions. We conducted a sensitivity run to quantify DO response to changes in ALPHMN and ensuing variations in phytoplankton growth. The ALPHMN was changed from 12 for both algal groups to 8 for algal group 1 and 10 for algal group 2. The resultant DO predictions had a slightly higher RMSE and a lower R, even though there was a slight improvement in the bias. This sensitivity test showed no significant change in DO predictions from current values of ALPHMN.

KHN1 is the half-saturation constant for nitrogen uptake for algal group 1. Smaller values of KHN1 reduce the nitrogen limitation on algal growth. We conducted a sensitivity run to test if the half-saturation for nitrogen uptake value at a lower concentration would improve performance. In the sensitivity test, KHN1 was reduced from 0.06 g/m^3 to 0.02 g/m^3. The resulting DO predictions with the lower KHN1 had similar statistics compared to the higher KHN1, but the bias increased with the lower KHN1 value. Appendix E contains a detailed analysis regarding KHN parametrization.

The process of nitrification involves the conversion of ammonia to nitrate. DO is consumed during nitrification. KHNNT is the half-saturation constant for ammonia uptake for nitrification. A higher value would be more limiting. We conducted a sensitivity run to test whether model performance would improve with a higher KHNNT value. KHNNT was increased from 0.5 g/m^3 to 1 g/m^3, which resulted in a slight improvement in RMSE and bias, while the R remained the same.

OBC150 refers to the truncation of the depth at 150 meters at the coastal open boundary, below which water quality remains constant. A depth of 200 m was used by Khangaonkar et al. (2018). The truncation depth was used as a calibration switch pertaining to the homogeneity of deeper waters off the continental shelf. These deeper waters were represented using the Canadian Department of Fisheries and Oceans (DFO) data to generate open boundary water quality. However, this data set is also sparse, with quarterly profiles and stations limited to the northern portion of the model. The DFO data was both temporally and spatially interpolated to generate the open boundary water quality. This test examines how sensitive the open boundary water quality is in DO predictions. The results show sensitivity to the OBC change, with RMSE, R, and bias significantly improving. One recommendation resulting from this test is to use the water quality predictions from larger ocean models, for example, the U.S. Navy's Hybrid Coordinate Ocean Model (HYCOM).

The last sensitivity test was done with a combination of lower ALPHMN, KHN1, and higher KHNNT, plus other variations detailed in Appendix E. This run showed a slight worsening of RMSE, R, and bias for DO predictions compared to the run using the rates and constants from Khangaonkar et al. (2018), and slight improvements to carbonate system parameter statistics.

Uncertainty in Dissolved Oxygen Depletion Estimates

The RMSE of differences is calculated to understand the uncertainty associated with the result of subtracting one model scenario from another model scenario (i.e., the difference between two model scenarios). In this case, we calculated the error associated with the DO depletions computed from the difference between the existing and reference model scenarios.

The following equations (Snedecor and Cochran, 1989) were used to estimate the RMSE of differences, and are based on first calculating the variance of the difference between existing and reference conditions. We are using the variance of the existing condition as an estimate of the variance of the reference condition.

VAR_{exist} = variance of predictions under existing conditions = $(RMSE_{exist})^2$
VAR_{ref} = variance of predictions under reference conditions, assumed equal to VAR_{exist}
R = Pearson's correlation coefficient between existing and reference conditions
VAR_{diff} = variance of the difference between existing and reference predictions
$= VAR_{exist} + VAR_{ref} - 2 \times R \times RMSE_{exist} \times RMSE_{ref}$

$$RMSE_{diff} = \sqrt{VAR_{diff}}$$

Using the Khangaonkar et al. (2018) parametrization, the resulting $RMSE_{diff}$ for the difference of existing and reference conditions for 2006, 2008, and 2014 is 0.049, 0.030, and 0.041 mg/L of DO, respectively. This is much smaller than the RMSE of 1.1, 0.98, and 0.96 mg/L of DO for existing conditions in 2006, 2008, and 2014, respectively. For the alternate parametrization described in this report in row 6 of Table 8, which was used for model year 2008 (but not used for bounding scenarios), the $RMSE_{diff}$ was found to be 0.030 mg/L of DO. This suggests that the $RMSE_{diff}$ is small when reasonable sets of parametrizations are used for calibration.

Dissolved Oxygen Depletions Due to Anthropogenic Loading

The applicable water quality standard requires that when a waterbody's DO concentration is lower than the established numeric criteria and the condition is due to natural conditions, then human actions considered cumulatively may not cause the DO of that waterbody to decrease more than 0.2 mg/L below natural conditions. This is referred to as the human allowance. On the other hand, if the natural condition (in this case our estimated reference scenario) is above the water quality criteria, then human actions considered cumulatively may not cause the DO of that waterbody to decrease below the numeric criteria.

The cumulative impact of all human activities causes DO concentrations to decrease by more than 0.2 mg/L at multiple locations in Puget Sound. Figure 25 shows the spatial distribution of minimum water column DO for both existing and reference conditions, along with the difference between the two, for 2006, 2008, and 2014. Spatial patterns in minimum DO under the reference scenario closely resemble the existing condition patterns. The difference plot shows that maximum DO depletions (depletions below the reference condition DO levels) are predicted to occur in inlets where flushing is relatively poor compared to the main channel, such as Case, Carr, Dyes, Sinclair, Budd, and Henderson Inlets. Well-mixed basins, on the other hand, are predicted to experience smaller DO depletions relative to the reference scenario. Most of the central Main Basin, for instance, is predicted to experience close to, but less than, a 0.2 mg/L reduction in DO.

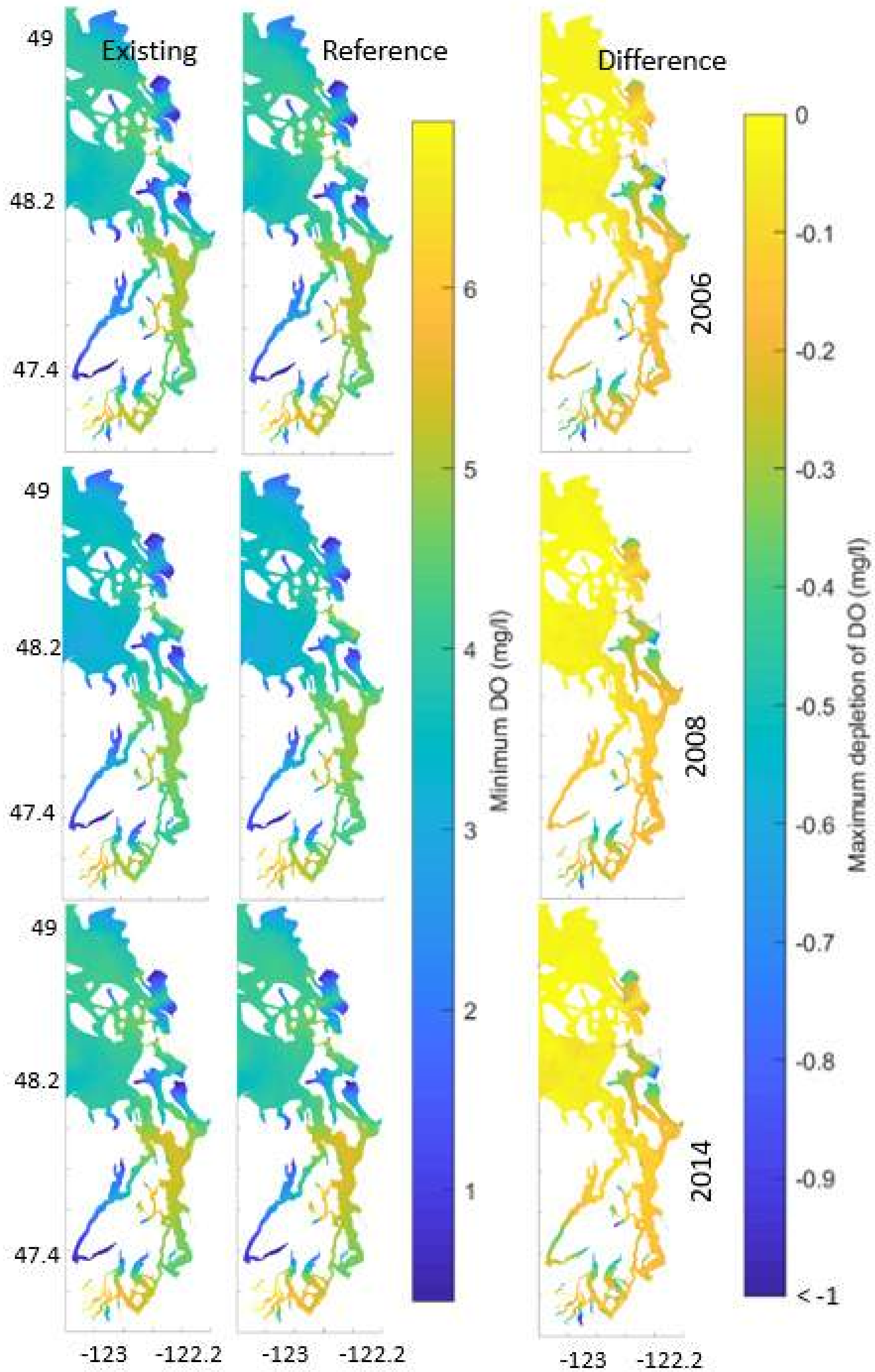


Figure 25. Comparison of the spatial distribution of predicted 2006, 2008, and 2014 minimum dissolved oxygen (DO) concentrations, corresponding reference condition scenarios, and the difference between them.
Areas that are green to blue are most sensitive to DO depletion from all human sources in Washington.

Since the DO standard incorporates a human allowance, depletions equal to or less than the allowance are not shown in subsequent maps. In addition, subsequent maps also do not show tidally influenced regions not appropriately resolved in this model version, as discussed in McCarthy et al. (2018).

The range of magnitude of anthropogenic DO depletions that cause water quality standard noncompliance varies for each model grid layer in each cell. Both Tier 1 (when the natural condition is above the numeric standard) as well as Tier 2 (when the natural/reference condition is below the numeric standard, and the human allowance must be met) were evaluated for each grid layer of each model cell. The maximum temporal depletions (either Tier 1 or Tier 2) were computed for each layer of each model cell. Finally, the maximum depletion among vertical layers for each cell was computed. We also computed the depths below modeled water surface elevations where DO depletions do not meet the water quality standards. The median depths (and maximum depths in parentheses) where the standard was not met were: 19.7 m (92.8 m) in 2006, 22 m (87.5 m) in 2008, and 17 m (88 m) in 2014.

The total area of greater Puget Sound waters not meeting the marine DO standard was estimated to be 151,000 acres (612 km^2), 132,000 acres (536 km^2), and 126,000 acres (511 km^2) in 2006, 2008, and 2014, respectively. These areas correspond roughly to about 23%, 20%, and 19% of greater Puget Sound, excluding the intertidal zone. Tables 9 and 10 contain the breakdown of the above noncompliant areas with respect to their corresponding levels of human-induced DO depletions, as well as summary statistics for minimum DO levels and cumulative number of noncompliant days for each depletion bracket. The median minimum DO levels in noncompliant areas are less than 4 mg/L, indicating that anthropogenic depletions often exacerbate already low oxygen events that result as a consequence of physical basin configuration and oceanographic, climatological, hydrologic, and meteorological drivers.

Table 9. Anthropogenic maximum dissolved oxygen (DO) depletions causing standard noncompliance, total area of noncompliance, minimum DO, and number of cumulative noncompliant days in greater Puget Sound for 2006.

Maximum DO depletions (mg/L)		Noncompliant area		Minimum DO in noncompliant area (mg/L)		Cumulative noncompliance (days)	
from	to	acres	km^2	median	95th percentile	median	95th percentile
-0.2	-0.4	124,900	505.5	3.42	5.13	39	146
-0.4	-0.6	20,400	82.5	2.02	4.2	169	243
-0.6	-0.8	2,900	11.8	2.03	3.4	107	182
-0.8	-1	1,400	5.7	1.53	2.68	118	139
-1	-1.2	670	2.7	1.3	2.62	126	161
-1.2	-1.4	440	1.8	1.34	1.75	102	147
-1.4	-1.6	360	1.5	1.29	1.93	108	162
-1.6	-1.8	150	0.6	0.54	0.69	152	160
-1.8	-2	50	0.2	0.39	0.5	157	163

Table 10. Anthropogenic maximum dissolved oxygen (DO) depletions causing standard noncompliance, total area of noncompliance, minimum DO, and number of cumulative noncompliant days in greater Puget Sound for 2008.

Maximum DO depletions (mg/L)		Noncompliant area		Minimum DO in noncompliant area (mg/L)		Cumulative noncompliance (days)	
from	to	acres	km^2	median	95th percentile	median	95th percentile
-0.2	-0.4	116,400	471.1	3.96	5.58	29	151
-0.4	-0.6	12,800	51.7	2.23	4.7	136	210
-0.6	-0.8	1,800	7.4	3.88	4.58	59	91
-0.8	-1	1,100	4.6	3.79	4.37	54	111
-1	-1.2	140	0.6	3.93	3.93	7	67
-1.2	-1.4	30	0.1	3.35	3.95	15	29
-1.4	-1.6	30	0.1	1.91	2.05	44	61
-1.6	-1.8	0	0	NA	NA	0	0
-1.8	-2	0	0	NA	NA	0	0

Figure 26 shows the spatial distribution of maximum DO depletions that cause water quality standard noncompliance. These DO depletions may occur in any vertical layer. Locations with larger DO depletions are reflective of longer residence times in these areas. For example, in the Penn Cove area, the e-folding times were longest in 2006 and shortest in 2014 (see Figure 13), thus depletions are largest in 2006 and smallest in 2014. For Lynch Cove, the e-folding times are longest in 2014 and shortest in 2008, thus the depletions are largest in 2014 and smallest in 2008. The maximum DO depletions below the water quality standards for the years 2006, 2008, and 2014 were –1.9 mg/L, –1.5 mg/L, and –2 mg/L, respectively, all occurring in the East Bay of Budd Inlet. The overall median DO depletions for 2006, 2008, and 2014 were –0.29 mg/L, –0.27 mg/L, and –0.28 mg/L, respectively.

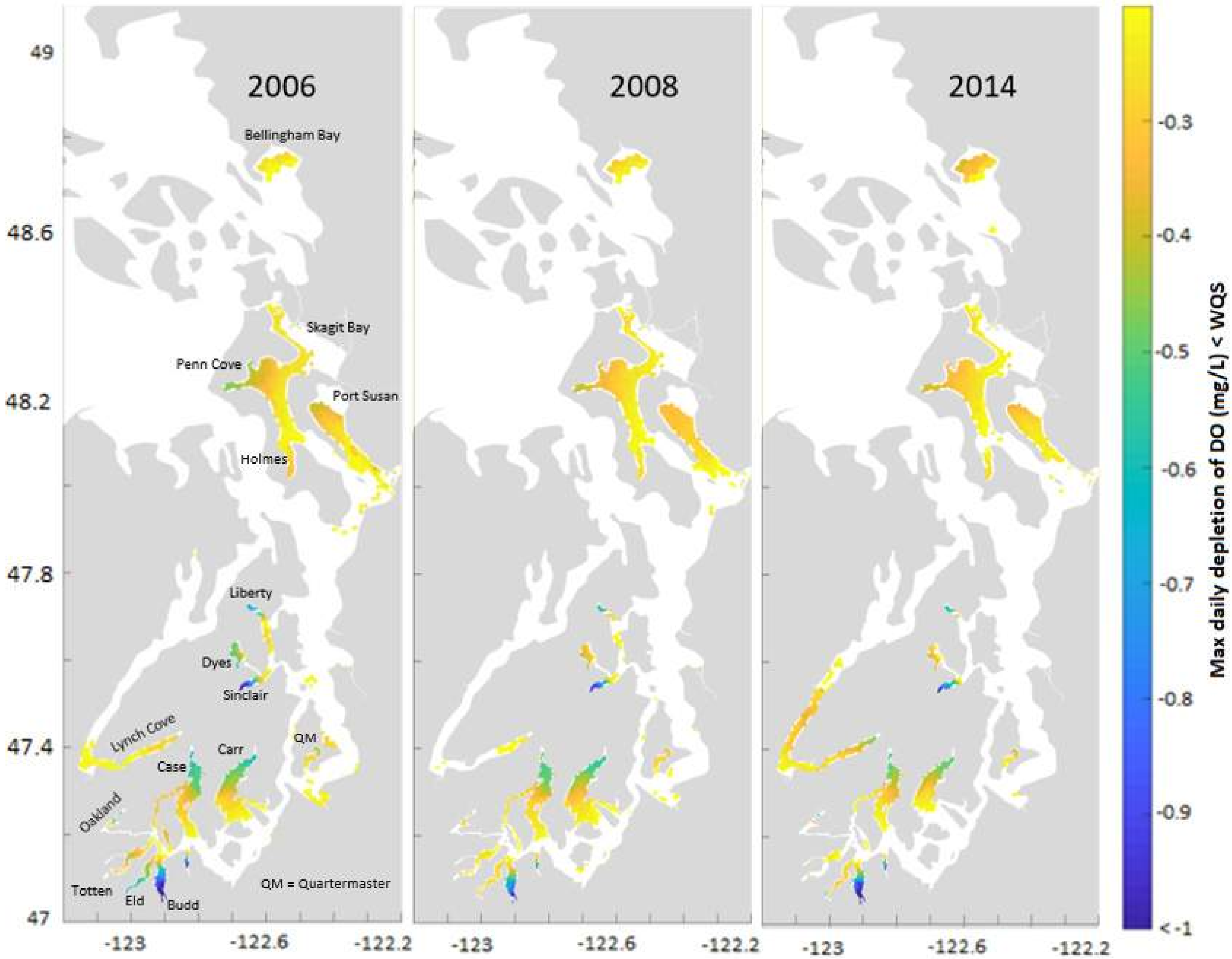


Figure 26. Maximum dissolved oxygen (DO) depletions from anthropogenic sources in 2006, 2008, and 2014, leading to noncompliance with the water quality standards (WQS).

Figure 27 shows the spatial distribution of the cumulative number of days that the DO concentrations were below the water quality standards for 2006, 2008, and 2014. Various locations during 2006, such as Lynch Cove, Holmes Harbor, and parts of Skagit Bay, are predicted to have experienced a significantly higher number of days below the standard compared to 2008 or 2014. Other locations such as Penn Cove, portions of Port Susan, Quartermaster Harbor, Case, Carr, Sinclair and Dyes Inlets, and Liberty Bay are predicted to have experienced a cumulative three months or more of noncompliance with the water quality standard during each of the three years. The maximum number of cumulative noncompliant days occurred in Carr Inlet in 2006 and 2008, where for 250 and 216 days, respectively, water quality standards were not met. In 2014, however, the maximum number of cumulative noncompliant days (198) occurred in Quartermaster Harbor.

The locations with the maximum number of cumulative noncompliant days does not coincide with the locations where the largest DO depletions occurred. The maximum DO depletions in Carr Inlet and Quartermaster Harbor were between –0.4 and –0.5 mg/L. At Budd Inlet, the location of maximum DO depletions in 2006, 2008, and 2014, the cumulative number of noncompliant days were 142, 33, and 95 days for each of those years, respectively.

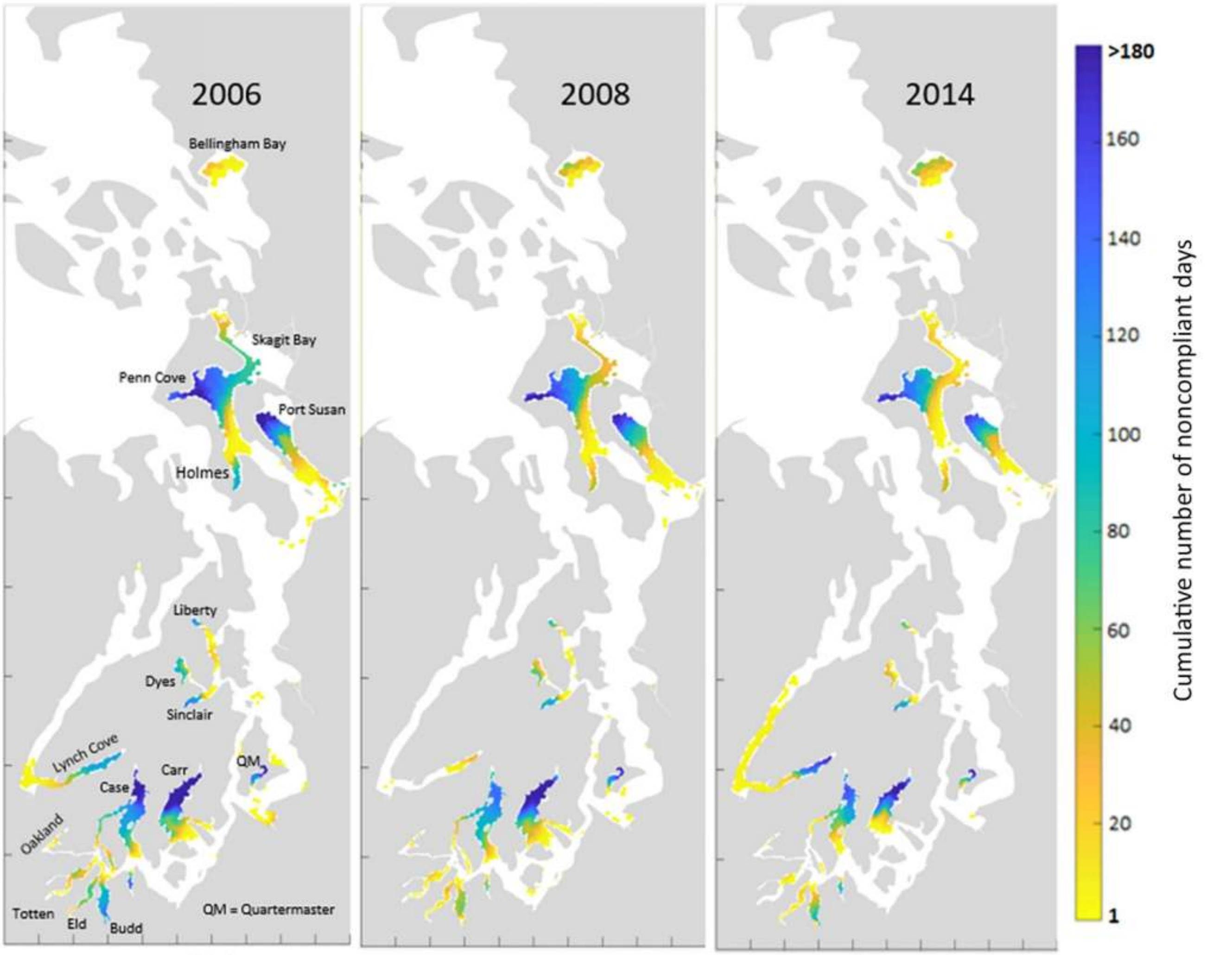


Figure 27. Spatial distribution of cumulative noncompliant days in 2006, 2008, and 2014, showing where depletion of dissolved oxygen (DO) results in noncompliance with water quality standards.

The differences in water quality in the three study years are likely due to multiple factors. Key factors that influence those differences include (1) hydrodynamics that affect residence times, (2) nitrogen loading that affects nutrient availability, and (3) organic carbon loading that depletes DO through heterotrophic bacterial decomposition of organic matter.

Regional factors may also play a role in differences between years. For example, the average e-folding times (as defined and discussed earlier, see Figure 13) for South Sound (which includes Budd Inlet, where maximum DO depletions occurred) were 289 days, 289 days, and 222 days, respectively, for 2006, 2008 and 2014. Annual average DIN loadings for South Sound were 7,800 kg/day, 6,200 kg/day, and 7,400 kg/day for the three years, respectively, and total organic carbon (TOC) loadings were 35,300 kg/day, 20,000 kg/day, and 27,900 kg/day, respectively. So, while residence times for South Sound in 2006 and 2008 were the same, both DIN and TOC loadings in South Sound were significantly higher in 2006 compared to 2008. Also, the Salish Sea as a whole had longer residence times in 2006 compared to 2008, even though regional differences were present. As a result, we see significantly larger maximum DO depletions, as well as a greater number of days with DO depletions, in Budd Inlet and overall in 2006 compared to 2008.

On the other hand, residence times throughout Puget Sound were shorter in 2014 compared to 2006. Thus, even though overall loadings in 2014 were higher, the cumulative number of noncompliant days was much higher in 2006 compared to 2014, while maximum depletions were similar.

Figure 28 shows the outline of the various basins in the greater Puget Sound, separated by shallow sills. These regions will be referenced in the following discussion.

Figure 29 shows the spatial distribution of the maximum DO depletions below the water quality standard in 2006 from (1) all anthropogenic sources, (2) only marine point sources, and (3) only anthropogenic watershed sources. Other years are not shown here because the distributions are similar. Maximum depletions refer to the largest predicted magnitude of DO water column reductions experienced during the year within any vertical layer in each model grid cell. At every impacted location, the effect of all anthropogenic loads results in larger DO depletions than those due to either marine point sources or anthropogenic watershed sources alone (Figure 29).

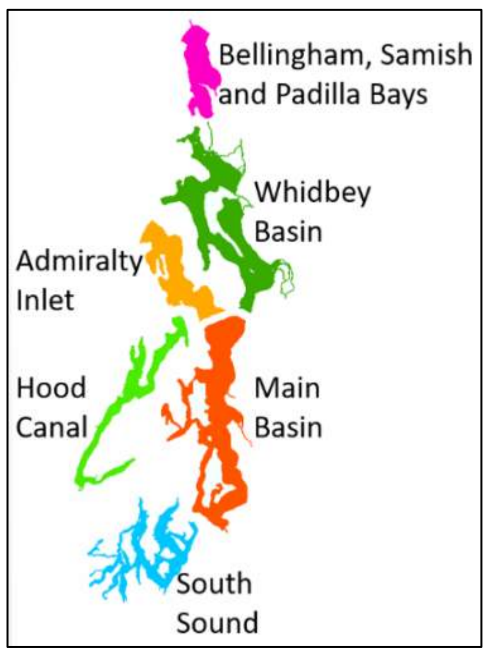


Figure 28. Basins in the greater Puget Sound.

It is noteworthy that the regions with the greatest impact from marine and anthropogenic watershed sources vary. Anthropogenic watershed sources alone produce DO depletions in Bellingham Bay, Whidbey Basin, South Sound, Hood Canal, and Main Basin, with a median of –0.22 mg/L and a peak depletion of –1.2

mg/L in East Bay of Budd Inlet. On the other hand, marine point sources alone produce some DO depletions in Whidbey Basin, and multiple depletions in South Sound and Main Basin, with a median of –0.28 mg/L and peak depletion of –1.4 mg/L in Sinclair Inlet. The combined effect of marine point and watershed sources can exacerbate DO depletions much more than either of the sources alone. Note this phenomenon in Penn Cove, Liberty Bay, Sinclair and Dyes Inlets, and Budd Inlet (e.g., with a median depletion of –0.29 mg/L and a peak depletion of –1.9 mg/L in East Bay of Budd Inlet).

Figure 30 shows the cumulative number of noncompliant days attributable to marine point sources if anthropogenic watershed sources were turned off, and the corresponding magnitude of noncompliant days for anthropogenic watershed sources only. There are significant differences between the two, with anthropogenic watershed sources creating a much larger number of noncompliant days in the domain, spread over a larger area. In terms of noncompliant area, if all anthropogenic watershed sources were turned off and marine point source emissions remained as they are, the water quality noncompliant area would be about 31% of the actual noncompliant area computed for 2006.

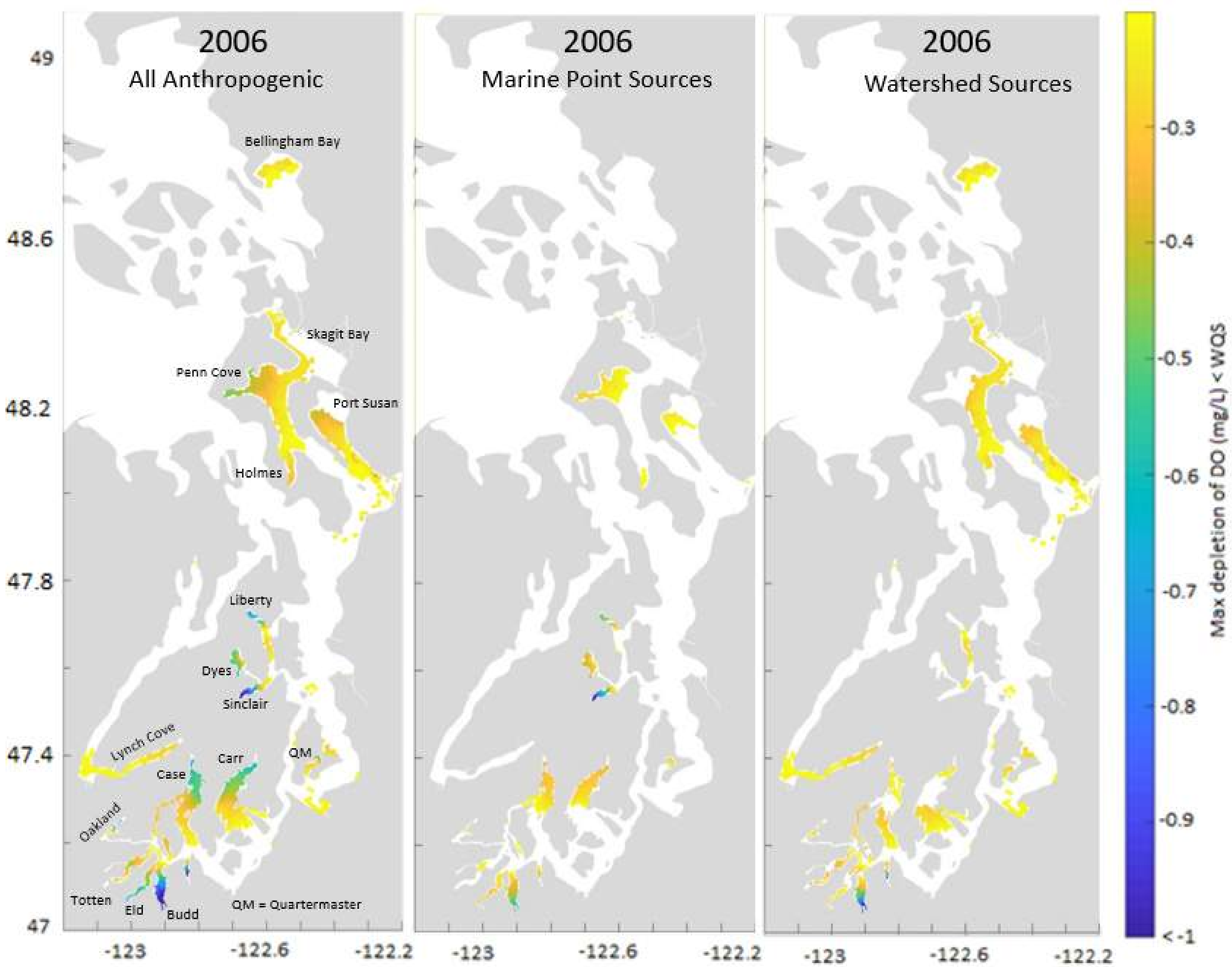


Figure 29. Year 2006 maximum dissolved oxygen (DO) depletions below the water quality standard due to all anthropogenic sources (left), marine point sources (center), and watershed sources (right).

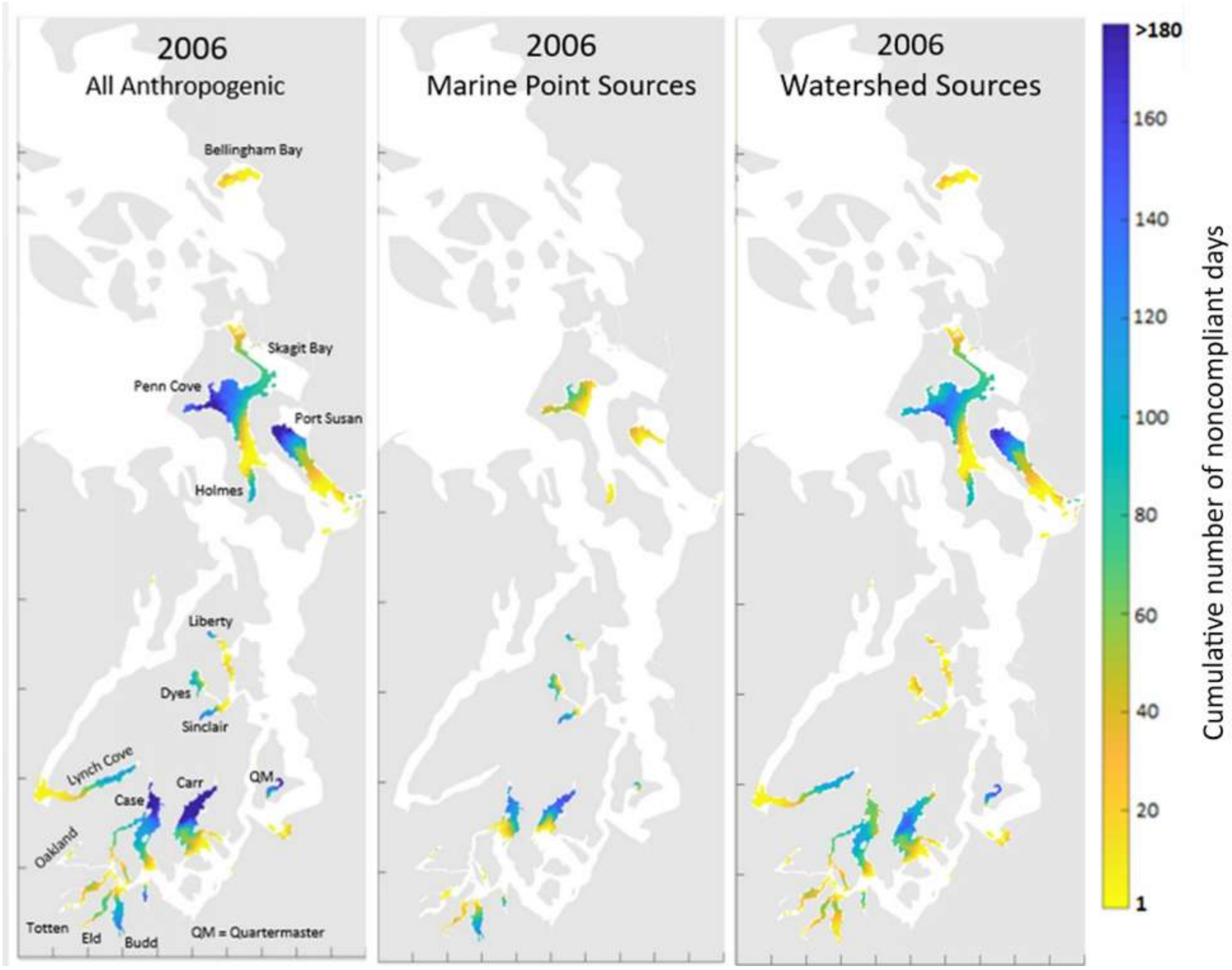


Figure 30. Cumulative number of days in 2006 when dissolved oxygen (DO) did not meet water quality standards due to all anthropogenic sources (left), marine point sources (center), and watershed sources (right).

At embayments where large depletions occur, the DO levels in the reference condition can dip significantly below the standard, which is 5 or 6 mg/L at several inlets and bays within Puget Sound. The large predicted depletions in these areas further exacerbate, in some cases down to anoxic conditions, already low DO reference levels. To illustrate this point, Figure 31 plots changes in DO concentrations (ΔDO) and the corresponding reference DO concentrations at which they occur in model nodes within two inlets that are strongly affected by low DO: Budd and Sinclair Inlets. Positive values for ΔDO, which indicate an increase in DO due to added nutrients, tend to occur mainly at high concentrations of DO, because added nutrients increase photosynthesis in the euphotic zone when DO is already high due to increased photosynthetic rates. On the other hand, negative values for ΔDO tend to occur mainly at low concentrations of DO, because added nutrients will also increase respiration in portions of the water column during times when DO is lowest due to increased respiration rates. Appendix K contains more plots at different locations that show the relationships between the DO depletions and the corresponding reference scenarios.

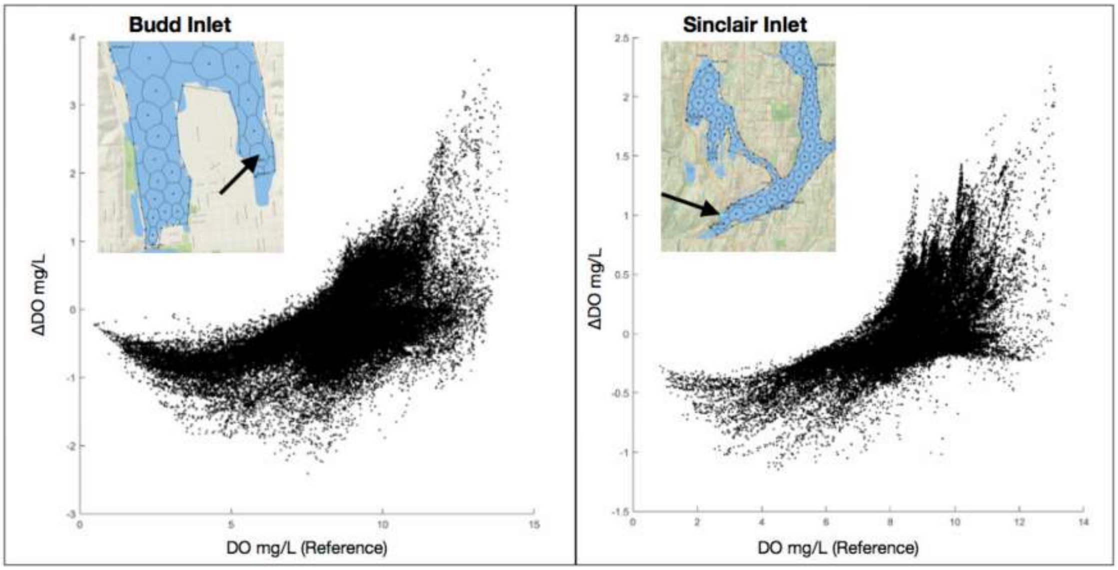


Figure 31. Difference between 2006 existing and reference dissolved oxygen (Δ DO) plotted against the corresponding reference DO concentrations at a model node in Budd Inlet (left) and Sinclair Inlet (right).

In order to assess water quality spatial trends from the open ocean to inner inlets in Puget Sound, two transects were selected. The first transect is along the thalweg from the mouth of the Strait of Juan de Fuca to Carr Inlet, and the other extends from the mouth of the Strait of Juan de Fuca to Whidbey Basin (Figure 32).

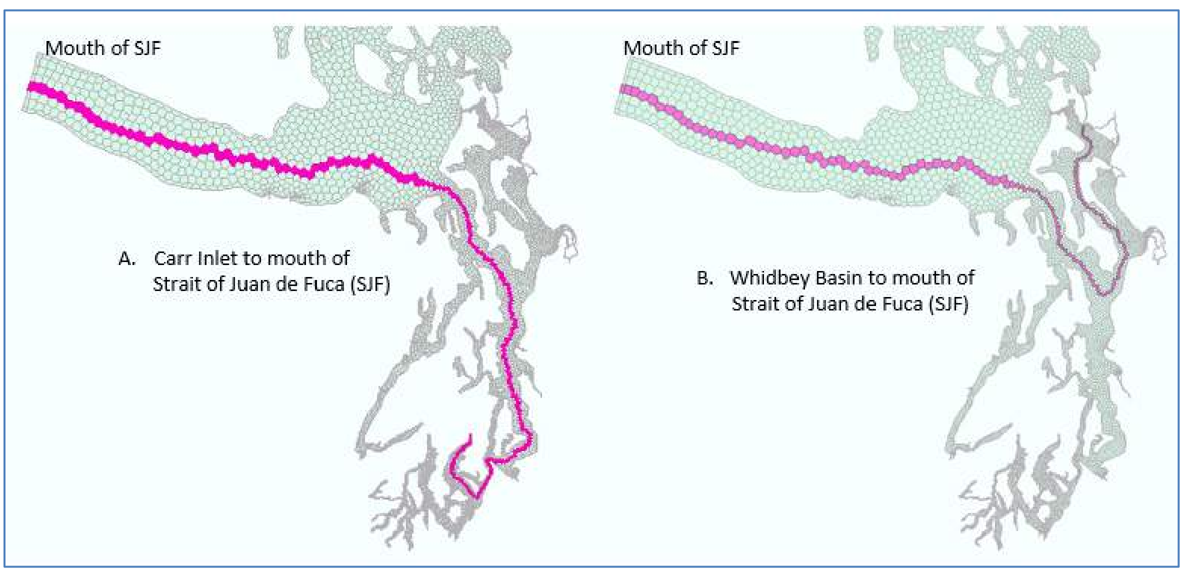


Figure 32. Thalweg transects: (A) mouth of the Strait of Juan de Fuca (SJF) to Carr Inlet, and (B) mouth of the Strait of Juan de Fuca to Whidbey Basin.

Thalwegs of annually averaged DO depletions along the transect from the Strait of Juan de Fuca to Whidbey Basin are shown in Figure 33. Depletions are generally vertically uniform within well-mixed areas below approximately 30 m, and depletions diminish in magnitude longitudinally away from inlets and bays until they become imperceptible. The overall magnitude of average annual depletion varies more noticeably in the innermost portions of the basins.

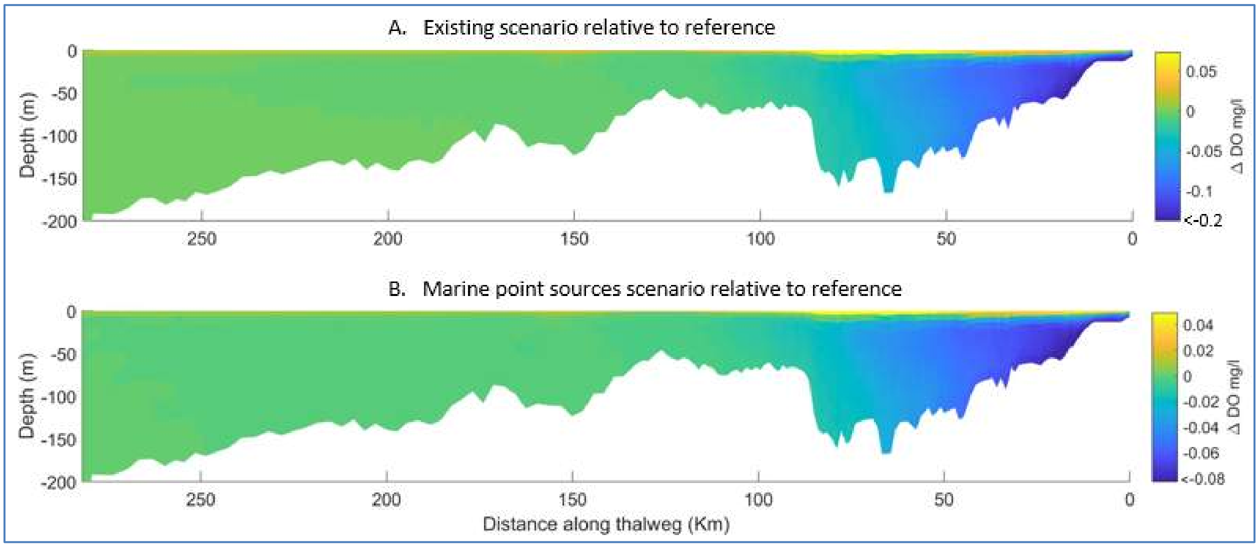


Figure 33. Year 2006 difference in dissolved oxygen (Δ DO, mg/L) between (A) all anthropogenic loading and reference conditions, and (B) marine point source loading and reference conditions computed along a thalweg from the mouth of the Strait of Juan de Fuca (left) to Whidbey Basin (right).

Figure 34 shows the relative increases between reference and existing conditions in average annual DIN and DOC, as well as changes in DO, along a transect from the Strait of Juan de Fuca to Carr Inlet. Near the ocean boundary, on the left side of Figure 34, there is very little increase in DIN or DOC due to anthropogenic sources. Larger increases are apparent in the portion of the transect corresponding to the Main Basin and South Puget Sound. For example, at around 90 km horizontal distance and a depth of about 50 m, there is a noticeable increase in DIN. This increase is probably due to a point source outfall near that location.

Greater DOC increases in the surface layer are likely tied to the "leakage" of DOC from increased algal growth and metabolism in the euphotic zone (above approximately 30 m). Below the euphotic zone, increases in DOC are uniform in the Main Basin, and within Carr Inlet increases in DOC are also more pronounced at the surface and closest to the terminus of the inlet. Dissolved oxygen depletions appear well mixed below the euphotic zone in most of the Main Basin and increase in magnitude closest to the terminus of the inlet.

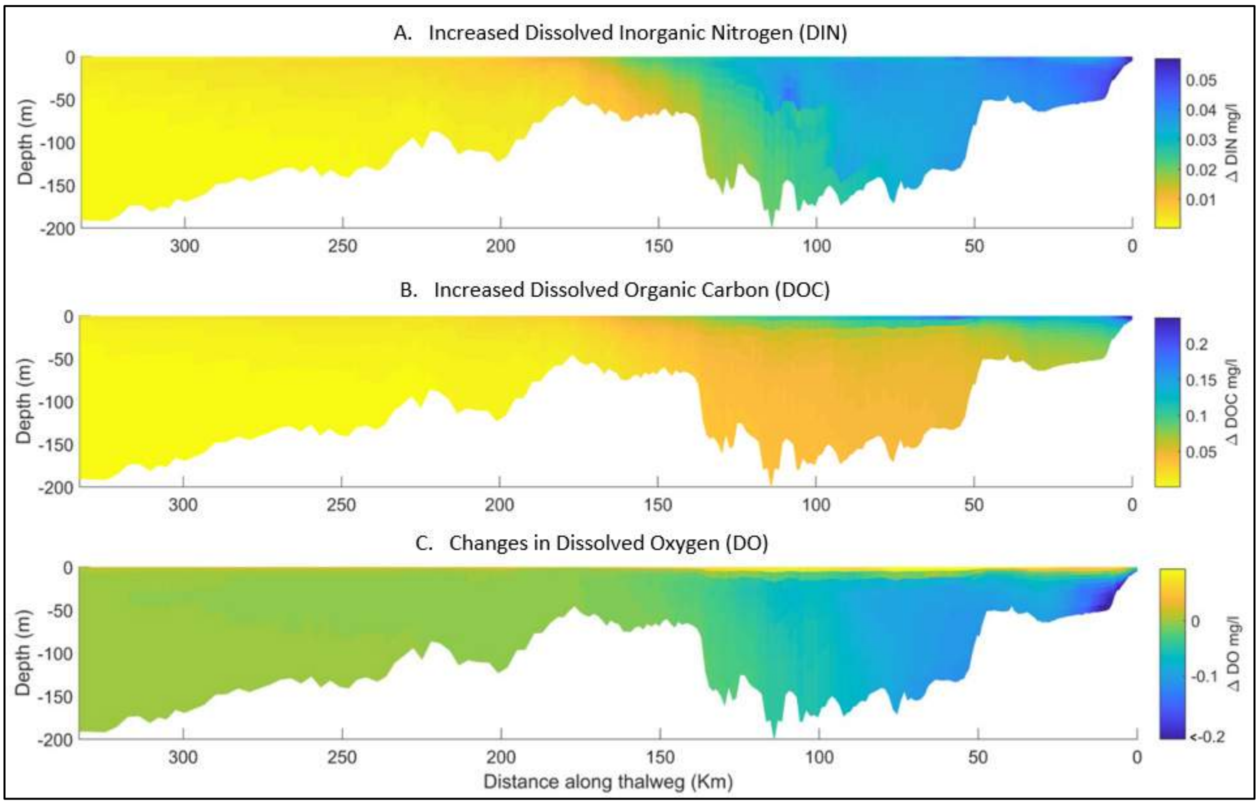


Figure 34. Changes due to anthropogenic loads of dissolved inorganic nitrogen (DIN, above), dissolved organic carbon (DOC, center), and dissolved oxygen (DO, below) along a thalweg from the mouth of Strait of Juan de Fuca (left) to Carr Inlet (right). .

Bounding Scenario Results

This section portrays the improvements and impacts associated with each of the last three scenarios listed in Table 4, considered bounding scenarios. These improvements are calculated using the hindcast model runs for the years 2006, 2008, and 2014 as baselines.

When conducting DO modeling scenarios, the relative proportion of estimated source contributions will be different depending on the order in which each source is added to or subtracted from the whole load. This nonlinearity occurs because reducing from the high end of the total nutrient loads does not reduce the availability of nutrients as much as when nutrient levels are lower. Therefore, the first sources removed can have less of an effect on phytoplankton growth because nutrient limitation is less when the loading is higher. However, reducing nutrients when loading is just above reference conditions would have a stronger influence on phytoplankton growth, because nutrient limitation is greater when loading is less. Thus, the improvements described below may vary upon the order of implementation of source reductions, and in this case, the improvements represent the result of a single category of the source reductions provided in Table 4. Evaluating individual scenarios is an important step in understanding the relative impacts of different existing nutrient sources. As further hypothetical management scenarios to achieve the water quality standards are tested, these scenarios should consider the full oxygen benefit of combined reductions from multiple sources, including the nonlinear relationship between nutrient load reduction and oxygen benefit.

Significant temporal and spatial improvements towards meeting the DO standard were realized with all three hypothetical treatment scenarios:

- BNR: Seasonal biological nitrogen removal at all municipal WWTPs discharging effluent to marine waters.
- BNR1000: Seasonal biological nitrogen removal at municipal WWTPs discharging effluent to marine waters with DIN loads of 1000 kg/day or greater.
- BNR8000: Seasonal biological nitrogen removal at municipal WWTPs discharging effluent to marine waters with DIN loads of 8000 kg/day or greater.

For each of these three scenarios, all river loads were kept at existing conditions. These scenarios result in improvements via reductions of the noncompliant area and the cumulative number of noncompliant days, as shown in Figure 35 and further described below.

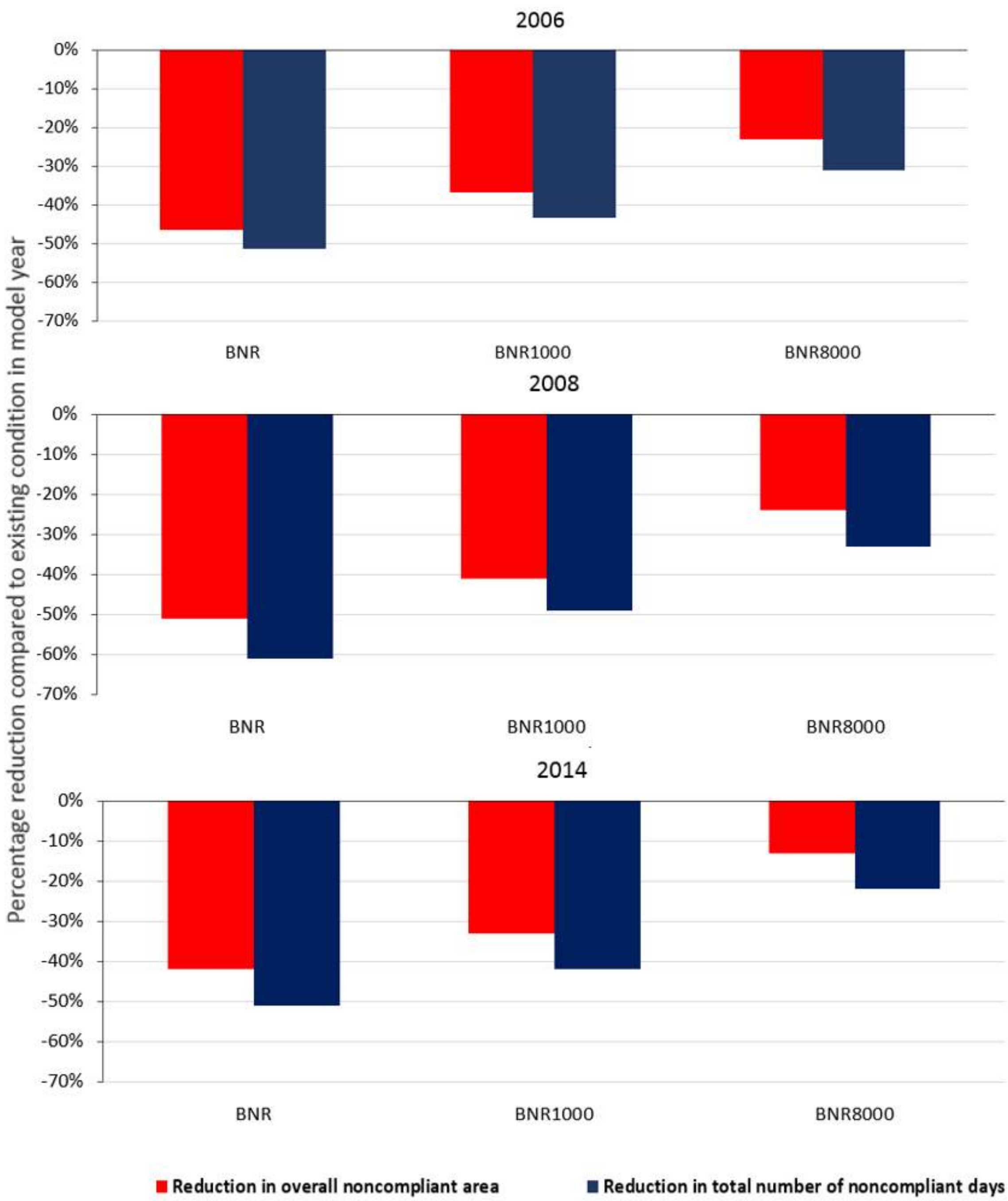


Figure 35. Plots of percent reduction in overall noncompliant area and total noncompliant days for 2006 (above), 2008 (center), and 2014 (below) under different hypothetical biological nitrogen removal (BNR) scenarios.

Improvements in maximum dissolved oxygen depletions and noncompliant area

Maximum DO depletions not meeting the standard when all anthropogenic sources are present were compared with those occurring in the same model grid cells under each of the BNR scenarios. The difference is the improvement in maximum DO depletions from reduced loadings.

Figure 36 shows the maximum depletions (calculated over the entire year for each model grid cell area) below water quality standards for 2006 when all anthropogenic sources are present, and when each of the three scenarios outlined above (BNR, BNR1000, and BNR8000) were applied. Appendix G contains similar maps for years 2008 and 2014.

All three scenarios show improvements, and standards are met at many locations, particularly where a relatively small magnitude of enhancement is needed to meet the standards. However, large DO deficits remain at several locations, including Budd and Sinclair Inlets (Figure 36).

Large improvements in maximum DO depletions in some areas are due to nutrient reductions from local, nearby point sources. For example, depletions in Sinclair Inlet are reduced the most when local WWTPs (Bremerton and Port Orchard WWTPs) apply BNR. Nutrient removal under BNR1000 and BNR8000 scenarios include the nearby King County WWTPs; however, their impact in Sinclair Inlet appears to be lower compared to those of the local WWTPs discharging to Sinclair Inlet. Another example of the influence of local point sources is in Budd Inlet, where improvement in DO depletions under the BNR scenario is low compared to the other two scenarios. That is because the largest local WWTP in Budd Inlet, LOTT, is currently already removing nitrogen from its effluent through nitrification and denitrification processes. So, in contrast to Sinclair Inlet, the BNR scenario does not change nutrient loadings *within* Budd Inlet significantly.

Table 11 shows the percent reduction in impacted area for 2006, 2008, and 2014 from the three nutrient removal scenarios. Across all years, BNR gives the best overall improvement, followed by BNR1000 and then BNR8000. However, relatively lower improvements were observed in the year 2014 for all treatment scenarios.

Table 11. Model scenario improvements, measured as percent reduction of noncompliant area where maximum dissolved oxygen depletions did not meet the water quality standard.

Scenario	**Improvement (% reduction in noncompliant area)**		
	2006	**2008**	**2014**
BNR	47%	51%	42%
BNR1000	37%	41%	33%
BNR8000	23%	24%	13%

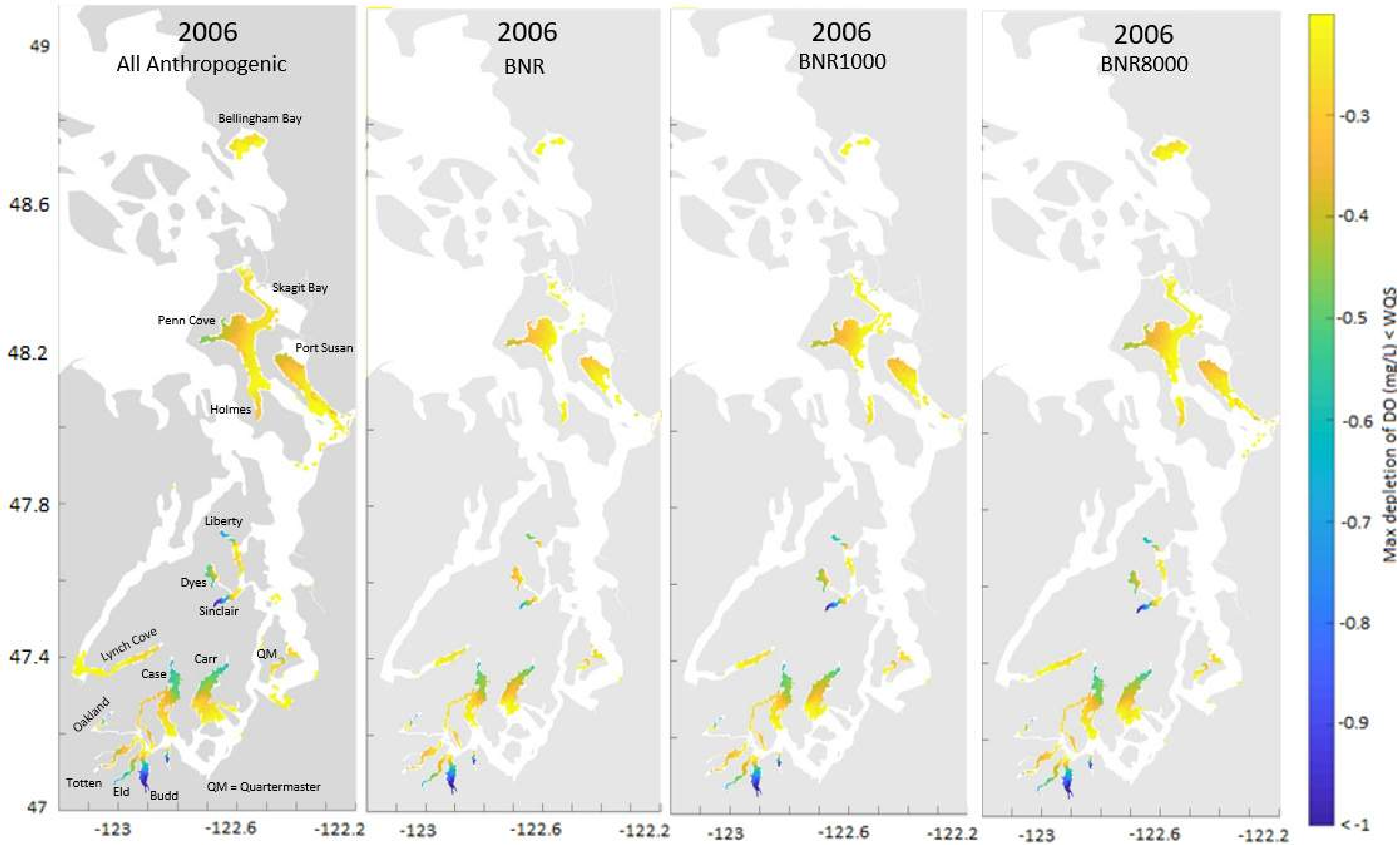


Figure 36. Four scenarios for maximum dissolved oxygen depletions for 2006.
Far left, due to all anthropogenic sources. *Center left*, with biological nitrogen removal (BNR) for all WWTPs discharging into marine waters. *Center right*, with BNR for WWTPs discharging dissolved inorganic nitrogen (DIN) >1000 kg/day (BNR1000). *Far right*, with BNR for WWTPs discharging DIN >8000 kg/day (BNR8000).

Improvements in cumulative number of days of DO depletions

To assess improvements in number of cumulative days in which DO depletions do not meet the standard, the total number of noncompliant days computed for each model grid cell were summed up for each scenario and compared to the sum of noncompliant days predicted in all cells for existing conditions in 2006, 2008, and 2014. The sum of the cumulative number of noncompliant days in all grid cells turns out to be large in 2014 (51,367 days), larger in 2008 (65,025), and even larger in 2006 (93,955). Percent improvements were computed relative to these numbers for each of the scenarios (shown in Table 12). The BNR scenario (all municipal WWTPs discharging into marine waters implementing biological nitrogen removal) consistently shows the greatest improvement in the number of days when DO depletions cause noncompliance with water quality standards.

Table 12. Three model scenario improvements (% reduction) in the number of days dissolved oxygen is below water quality standards.

Scenario	**Improvement (% reduction) in total number of noncompliant days**		
	2006	**2008**	**2014**
BNR	51%	61%	51%
BNR1000	43%	49%	42%
BNR8000	31%	33%	22%

Figure 37 shows the spatial distribution of the cumulative number of noncompliant days not meeting the water quality standards for 2006 under each BNR scenario. Maps for 2008 and 2014 are similar to those shown in Figure 36 and are included in Appendix G6.

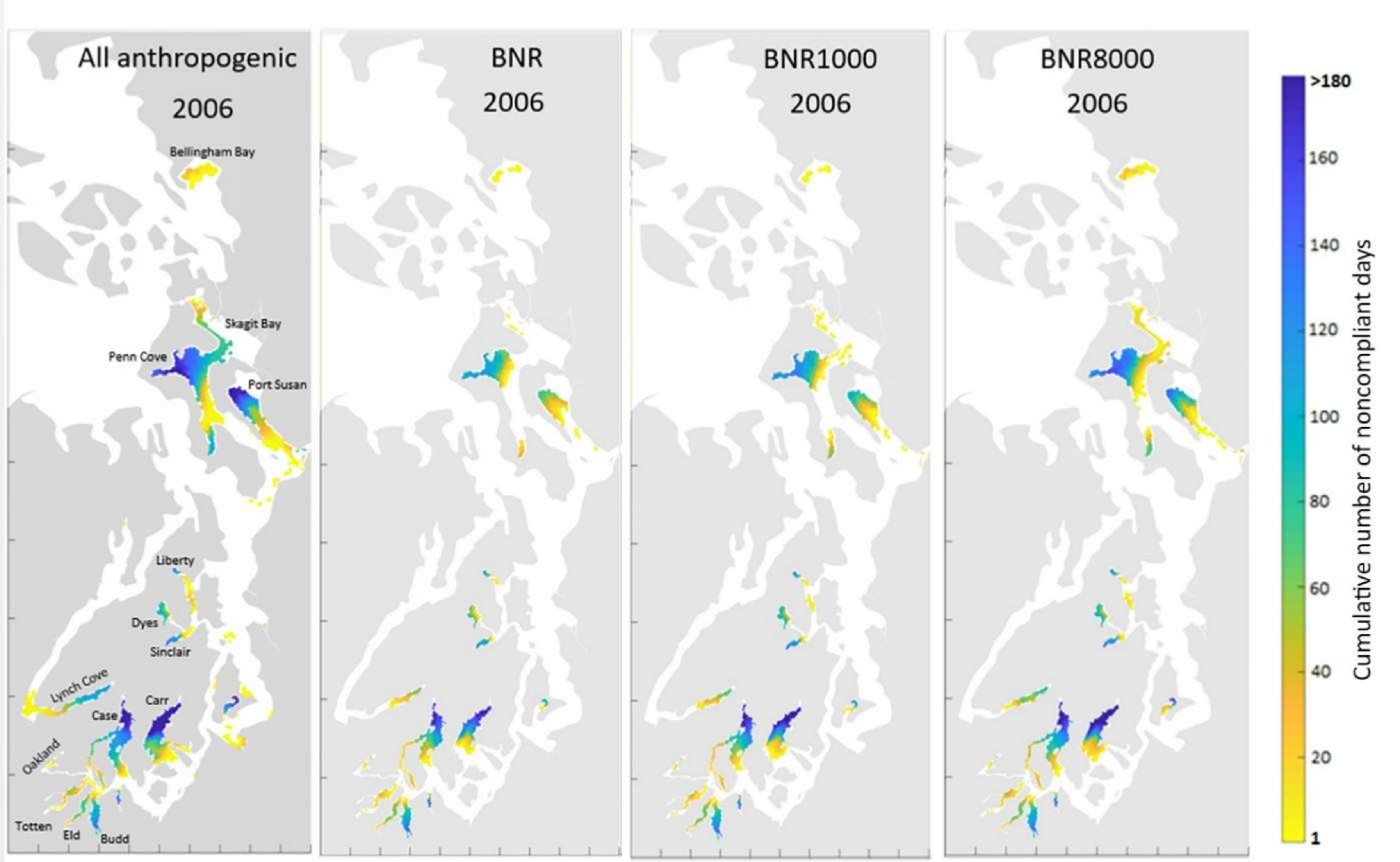


Figure 37. Four scenarios for cumulative number of days with depletions of dissolved oxygen for 2006.
Far left, due to all anthropogenic sources. *Center left*, with biological nitrogen removal (BNR) for all WWTPs discharging into marine waters. *Center right*, with BNR for WWTPs discharging dissolved inorganic nitrogen (DIN) >1000 kg/day (BNR1000). *Far right*, with BNR for WWTPs discharging DIN >8000 kg/day (BNR8000).

Hypoxic volume

The Ecological Society of America defines hypoxia as falling within the range of 2 to 3 mg/L of DO (ESA, 2018). When hypoxic levels in the Salish Sea occur, these very low oxygen regions consist of a relatively small but significant volume of water, with well-documented consequences for aquatic life. Hypoxia can change the biotic structure of bottom habitats, because the benthic communities living in them are generally immobile (Diaz and Rosenberg, 2008). A more noticeable impact of hypoxia occurs when there are fish kills, which happened in 2006. In that year, a severe fish kill event was documented in southern Hood Canal (Encyclopedia of Puget Sound, 2018b), corresponding with a rapid vertical displacement of hypoxic water, such that even mobile organisms such as fish were unable to avoid exposure. Hypoxic area varies temporally, and during 2006 it was estimated to peak around 52,500 acres (212 km^2) within greater Puget Sound, out of which approximately 19% (around 10,000 acres) was attributable to human nutrient loadings.

Figure 38 shows a comparison of existing and reference hypoxic volumes for 2006, when the SSM predicts the peak hypoxic volume occurred in September (at less than 2 mg/L of DO). Peak volume at less than 3 mg/L occurred in October that year. The volume less than 2 mg/L was much smaller (2.97 km^3) than the volume less than 3 mg/L (126 km^3). These comprised about 0.2% and 7.6%, respectively, of the entire Puget Sound Model domain volume, which includes the Strait of Juan de Fuca and a portion of the Strait of Georgia (see Figure 3).

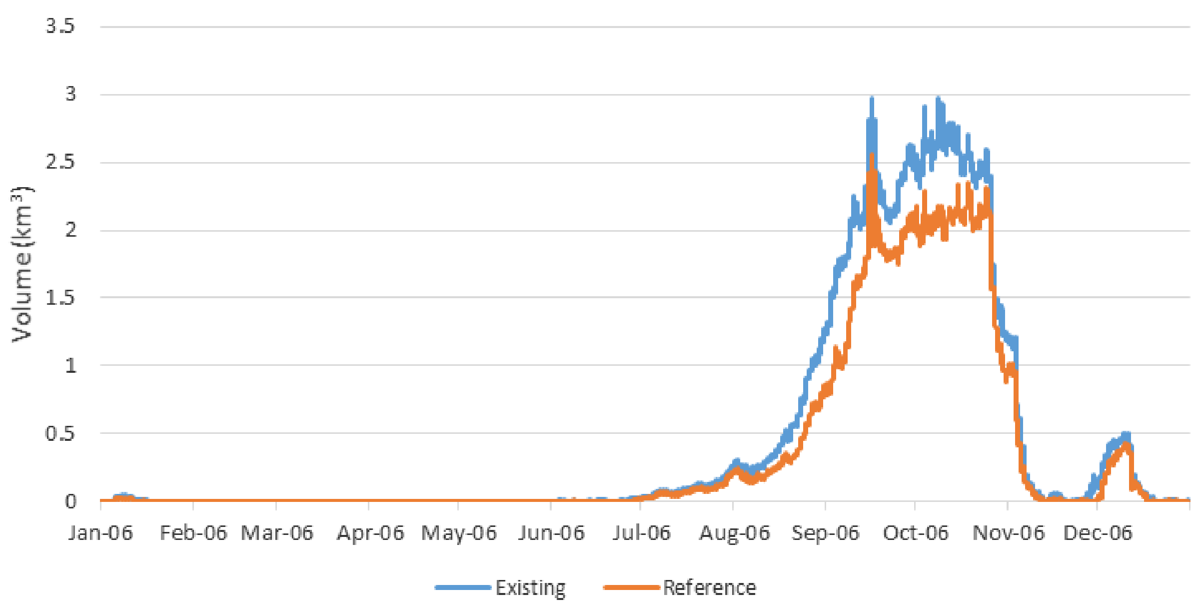


Figure 38. Hypoxic volume in Puget Sound (dissolved oxygen less than 2 mg/L) predicted for existing and reference conditions in 2006.

Annual cumulative hypoxic volume was calculated as the sum of volumes under the hypoxic threshold during each hour over the year. Model simulations for 2006, 2008, and 2014 show that for these years the annual cumulative hypoxic volume under existing loadings was 28%, 35%, and 28% higher, respectively, than the cumulative hypoxic volume Puget Sound would have experienced under reference conditions. During those years, reference conditions ranged from

1640 km^3-hrs to 3120 km^3-hrs. Table 13 shows the percent increase in annual cumulative hypoxic volume for each of the scenarios conducted relative to reference conditions. Note that under all scenarios there is a significantly higher cumulative hypoxic volume relative to reference conditions, which indicates that a comprehensive suite of measures, including watershed load reduction, is needed to fully address human-caused hypoxia in Puget Sound.

Table 13. Percent increase in annual cumulative hypoxic volume associated with each model scenario relative to the reference condition.

Scenario	2006	2008	2014
Total existing load (all sources)	28%	35%	28%
Watershed existing anthropogenic loads only	12%	14%	14%
Marine existing anthropogenic point sources only	16%	21%	14%
BNR8000	25%	30%	26%
BNR1000	23%	28%	23%
BNR	22%	27%	22%

Regional improvements in dissolved oxygen with seasonal biological nutrient reduction

For each of the bounding scenarios (BNR, BNR1000, and BNR8000), and for each of the three years (2006, 2008, and 2014), improvements in DO depletions were estimated using:

- percent reduction in the area experiencing DO standard noncompliance.
- percent reduction in the number of days of noncompliance.
- percent reduction in the maximum regional DO depletion.
- percent reduction in the mean regional DO depletion.

Reduction in noncompliant area

The percent reduction in area where the DO standard was not met for each of the six basins is presented in Table 14. As shown previously, BNR resulted in the largest reduction in area where noncompliances with the water quality standards were originally computed, followed by BNR1000, and then BNR8000. Other observations are as follows:

- Since *Admiralty Inlet* met the DO standard under anthropogenic nutrient loads for all three years, the improvement from the three treatment levels were labeled "not applicable."
- In *Bellingham Bay*, two treatment levels (BNR and BNR1000) resulted in similar percent reduction in area of DO standard noncompliance and almost no improvement for the BNR8000 scenario. This is because BNR was applied to the Bellingham WWTP under both BNR and BNR1000 scenarios, but not for the BNR8000 scenario. On an interannual basis, 2006 shows a larger reduction in affected area compared with 2008 or 2014.
- In *Hood Canal*, improvements were observed under all treatment levels and in all years. However, the largest improvements were in year 2008, followed by 2006, and then 2014. The

average DO depletions below the water quality standard in Hood Canal for these three years from all anthropogenic sources were low and close to the 0.2 mg/L human allowance (–0.23 mg/L in 2006, –0.21 mg/L in 2008, and –0.28 mg/L in 2014). Thus, it takes slight improvements in DO to bring this area to within DO standards. Nutrient reductions outside Hood Canal have an impact on DO depletions within Hood Canal. This is consistent with the work of Banas et al. (2015), who found 1%–3% of the volume of the Main Basin transported to Hood Canal in a 20-day period.

- In the *Main Basin*, *South Sound*, and *Whidbey Basin*, reductions in the DO noncompliant area were observed for all treatment levels and years. Banas et al. (2015) found that 6%–8% of the volume of Main Basin is transported to South Sound and 15%–31% is transported to Whidbey Basin, while 45%–54% is retained in the Main Basin during a 20-day period. Biological nitrogen removal was applied in the Main Basin under all treatment levels, though there was a variation in the number of facilities implementing it within the hypothetical scenarios.

Table 14. Percent reduction in area where the water quality standards were not met.

Region	Year	Noncompliant area (existing conditions, km^2)	Reduction in noncompliant area (%)		
			BNR	BNR1000	BNR8000
Admiralty Inlet	2006	NA	NA	NA	NA
	2008	NA	NA	NA	NA
	2014	NA	NA	NA	NA
Bellingham Bay	2006	31.4	66	66	7
	2008	31.4	51	51	0
	2014	42.4	26	26	0
Hood Canal	2006	44.7	70	67	57
	2008	11.8	86	86	75
	2014	83.5	14	12	7
Main Basin	2006	71.7	57	44	39
	2008	44.4	54	39	38
	2014	26.3	38	29	12
South Sound	2006	193	25	20	13
	2008	119	36	29	18
	2014	137	34	28	12
Whidbey Basin	2006	272	53	38	22
	2008	260	60	46	27
	2014	222	60	46	18

Reduction in number of noncompliant days

The percent reduction in the number of noncompliant days for each of the six basins is presented in Table 15. Again, as expected, BNR resulted in the highest reduction in the number of noncompliant days. This was followed by BNR1000 and then BNR8000. Other observations are as follows:

- *Admiralty Inlet* met the DO standards.
- *Bellingham Bay* showed similar reductions in the number of noncompliant days from BNR and BNR1000 treatment level for reasons discussed earlier, with little improvement from the BNR8000 treatment scenario.
- *Hood Canal* showed some of the largest reductions in noncompliant days, primarily because in this basin, slight improvements cause noncompliances to disappear.
- *Main Basin*, *South Sound*, and *Whidbey Basin* showed some of the same characteristics in percent reduction of the number of noncompliant days as percent reduction in impacted area discussed earlier.

Table 15. Percent reductions in total number of days not meeting the dissolved oxygen water quality standards.

Region	year	Total number of noncompliant days (existing condition)	Reduction in noncompliant days (%)		
			BNR	BNR1000	BNR8000
Admiralty	2006	NA	NA	NA	NA
	2008	NA	NA	NA	NA
	2014	NA	NA	NA	NA
Bellingham Bay	2006	98	87	87	6
	2008	292	77	77	5
	2014	464	59	59	2
Hood Canal	2006	3620	83	77	62
	2008	245	99	97	88
	2014	3469	36	32	20
Main Basin	2006	7572	57	43	33
	2008	5482	71	49	30
	2014	4237	62	47	24
South Sound	2006	57861	39	33	23
	2008	40767	49	42	27
	2014	28850	38	33	15
Whidbey Basin	2006	24804	73	63	46
	2008	18239	82	66	47
	2014	14347	77	63	36

Reduction in the maximum and mean DO depletion

Percent reduction in the maximum and mean regional DO depletion for each of the six basins is presented in Table 16. Biological nitrogen removal at all WWTPs (BNR) resulted in the largest improvement in DO depletion. The conclusions are similar to those discussed for the two previous tables. However, for the Main Basin, BNR shows a relatively higher reduction in maximum DO depletion in 2006 (56%) compared to that for BNR1000 and BNR8000 (3% and 2%, respectively). The maximum depletion in Main Basin occurs in Sinclair Inlet; the highest reduction in DO depletion from BNR reflects the impact of BNR at local municipal WWTPs discharging there.

Table 16. Regional percent reduction in the maximum and mean daily dissolved oxygen depletion.

Region	year	Maximum depletion (existing condition, mg/L)	Mean depletion (existing condition, mg/L)	Reduction in maximum depletion (%)			Reduction in mean depletion (%)		
				BNR	BNR1000	BNR8000	BNR	BNR1000	BNR8000
Admiralty	2006	NA	NA	NA	NA	NA	NA	NA	NA
	2008	NA	NA	NA	NA	NA	NA	NA	NA
	2014	NA	NA	NA	NA	NA	NA	NA	NA
Bellingham Bay	2006	-0.27	-0.23	19	18	1	70	69	8
	2008	-0.31	-0.25	19	18	0.8	54	54	0.9
	2014	-0.40	-0.30	16	16	0.4	33	33	0.5
Hood Canal	2006	-0.29	-0.23	11	9	7	74	70	58
	2008	-0.24	-0.21	13	12	8	85	85	74
	2014	-0.46	-0.28	8	7	3	16	14	8
Main Basin	2006	-1.49	-0.34	56	3	2	57	36	31
	2008	-1.07	-0.34	51	5	4	59	34	29
	2014	-1.30	-0.41	52	3	2	48	25	11
South Sound	2006	-1.90	-0.44	3	2	1.6	24	20	13
	2008	-1.50	-0.36	4.6	3.7	2	36	30	19
	2014	-2.11	-0.42	4	3	1	29	24	12
Whidbey Basin	2006	-1.16	-0.28	3	2.6	1.8	57	42	26
	2008	-0.52	-0.27	10	7	4	66	52	32
	2014	-0.40	-0.26	21	14	7	66	52	24

Conclusions

Improvements to the Salish Sea Model's (SSM's) performance were achieved via refinements to river and stream loadings and hydrology, as well as updates to point source flows and nutrient loadings. To consider interannual variability, three years (2006, 2008, and 2014) with distinct hydrodynamic conditions were chosen based on the residence time index for Central Puget Sound. A robust field database was compiled to assess model performance for these years, including monthly casts, seasonal cruises, and moorings of multiple water quality parameters. The model (1) demonstrated high skill in reproducing dissolved oxygen (DO) concentrations in space and time, and (2) met model quality expectations. The uncertainty of model predictions for DO depletions (from 0.03 to 0.05 mg/L) is well below the anthropogenic allowance in the Washington State water quality standard (0.2 mg/L). Further enhancements will be needed to improve DO predictions in nearshore (intertidal and very shallow subtidal) areas.

An alternative parametrization was developed after dozens of sensitivity tests were performed to assess parameters and rates. The SSM was most sensitive to changes in reaeration coefficients and the truncation depth at which the incoming ocean water quality is held constant. We showed that increased model performance is feasible via improvements to oceanic boundary conditions, and we plan to pursue the use of a global ocean model (the U.S. Navy's Hybrid Coordinate Ocean Model, or HYCOM) to improve these boundary conditions. The model is moderately sensitive to settling rates, organic carbon dissolution and respiration rates, and nitrification rates. Model output using the alternative parametrization reveals similar spatial and temporal patterns as the baseline parametrization from Khangaonkar et al. (2018), which was used for all model scenarios.

Modeling scenarios compared DO levels under existing nutrient loadings in 2006, 2008, and 2014 to estimated reference conditions for these years. The results of these scenarios confirmed that the cumulative impact of all human activities causes DO concentrations to decrease by more than the 0.2 mg/L human allowance established in the DO water quality standards. This decrease in DO concentration occurs at multiple locations in greater Puget Sound. Maximum DO depletions of 1.9 mg/L (mean of 0.36 mg/L), 1.5 mg/L (mean of 0.32 mg/L), and 2 mg/L (mean of 0.35 mg/L) were predicted for 2006, 2008, and 2014, respectively. These depletions are highly variable throughout Puget Sound.

The total area of greater Puget Sound waters not meeting the marine DO standard was estimated to be around 151,000 acres (612 km^2), 132,000 acres (536 km^2), and 126,000 acres (511 km^2) in 2006, 2008, and 2014, respectively. The locations most impacted consist of poorly flushed inlets and bays, such as Penn Cove; Quartermaster Harbor; Case, Carr, Budd, Sinclair, and Dyes Inlets; and Liberty Bay.

The cumulative annual hypoxic (DO less than 2 mg/L) volume in Puget Sound was 28%, 35%, and 28% higher than under reference conditions for 2006, 2008, and 2014, respectively. Anthropogenic depletions often exacerbate already low oxygen events that result as a consequence of physical basin configuration and oceanographic, climatological, hydrologic, and meteorological drivers.

Modeling results show that portions of Puget Sound, primarily South Sound and Whidbey Basin, experience a large number of days when the marine DO water quality standard is not met. In multiple locations within these two regions, the total number of noncompliant days is over three months. This number varies by year and location. For instance, the largest total number of noncompliant days (250) occurred in 2006, followed by 2008 (216 days) and 2014 (198 days). The average cumulative number of noncompliant days computed over all areas not meeting the water quality standard was 63, 50, and 46 days in each of those years, respectively.

We examined hypothetical modifications representing major (or "bounding") changes to Washington's marine point sources of nutrients by comparing various point source reduction scenarios with estimated reference conditions. Spatial analysis of the regional impact of each scenario confirmed that the inner basins of Puget Sound do share a certain portion of their waters, so that discharges in one basin can affect the water quality in others. Significant reduction of the total number of days of noncompliance with the DO water quality standard can be achieved with each of the three seasonal BNR scenarios. For example, BNR at all wastewater treatment plants (WWTPs), BNR1000, and BNR8000 result in a 61%, 49%, and 33% reduction in the total number of noncompliant days for 2008, with slightly lower improvements in 2006 and 2014. Approximately 47%, 51%, and 42% of the impacted area came into compliance with water quality standards with seasonal BNR at all WWTPs in 2006, 2008, and 2014, respectively. Additionally, modeling results indicated that each of the three scenarios led to improvements in DO at most or all locations where water quality noncompliance was identified in the existing condition.

The largest estimated improvements occurred with implementation of seasonal BNR at all WWTPs. Some embayments (e.g., Sinclair Inlet and Bellingham Bay) showed improvements in DO depletions most likely due to enhanced treatment at local WWTPs that discharge to that embayment, rather than because of enhanced treatment at WWTPs in different basins. However, basin-wide or interbasin improvements also add to such local improvements in DO. It is important to note that due to nonlinearities of the biogeochemical system, the estimated magnitude of improvements may vary depending on the order of potential nutrient source reductions evaluated, so these results cannot be construed as definitive, but rather as a first estimate based on the hypothetical scenarios posed.

In summary, under existing conditions, approximately 20% of the area in the greater Puget Sound, excluding intertidal areas, does not meet the dissolved oxygen standards. If reductions are made at all municipal wastewater treatment plants discharging into marine waters, approximately 10% of the greater Puget Sound would not meet the standards. This represents roughly a 50% improvement in compliance area for the dissolved oxygen standards.

It is clear from these scenario tests that anthropogenic watershed loads also contributed significantly to DO depletions in 2006, 2008, and 2014. Thus, a successful nutrient reduction strategy will need to include reductions to loads and sources within the watersheds to achieve full compliance with Washington's marine water quality standards.

Next Steps

Future modeling work will respond to the policy questions posed within the context of the Puget Sound Nutrient Source Reduction Project (PSNSRP). The next phase of the project is the *optimization phase*, which involves extensive input from stakeholders to help determine the different modeling scenarios needed to address the costs and benefits of different combinations of nutrient source reductions. Ecology plans to conduct model runs for hypothetical scenarios derived from those stakeholder consultations. In addition, we plan to conduct the following next steps:

- Review and improve river loadings as new data become available. This will include (1) reviewing the multiple linear regression equations developed primarily on data collected during 2006 and 2007, and (2) analyzing how well these equations represent conditions during more recent years.
- Conduct modeling to incorporate new marine and freshwater observations, as they become available, including freshwater nitrogen and carbon data, marine organic carbon concentrations, sediment flux data, and respiration rates. Consider modeling a year for which productivity data are available.
- Collaborate in the development of hypothetical scenarios that represent future conditions in the Salish Sea, including new and future projected discharges; projected future meteorological, hydrological, and oceanographic inputs; and regional population growth.
- Incorporate output from the U.S. Navy's Hybrid Coordinate Ocean Model into the Salish Sea Model to improve the oceanic boundary condition where limited or no observations are available.
- Review reference conditions as new data sets become available, and update or improve these estimates, as appropriate.
- Incorporate updates, when available, to SSM parametrization that result in improvements to model performance.

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Glossary, Acronyms, and Abbreviations

Glossary

Advective flux: Transport with bulk fluid flow.

Allochthonous carbon: Organic compounds originating from terrestrial sources, in this case, outside of the Salish Sea aquatic system.

Anoxic: Dissolved oxygen in the water column is at 0 mg/L.

Anthropogenic: Human-caused.

Biological Nitrogen Removal (BNR): General term for a wastewater treatment process that removes nitrogen through the manipulation of oxygen within the treatment train to drive nitrification and denitrification. Nitrogen removal efficiency depends on site-specific conditions, such as treatment processes, climate, and the overall strength of the raw wastewater.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Euphotic zone: Vertical layer in the water column where light is available and photosynthesis takes place.

Greater Puget Sound: Includes Samish, Padilla, and Bellingham Bays, as well as South Sound, Main Basin, Whidbey Basin, Admiralty Inlet, and Hood Canal (see also Puget Sound).

Hindcast: Historical model run.

Hypoxic: Dissolved oxygen in the water column is lower than 2 to 3 mg/L.

Marine point source: Point sources (see "point source" definition below) that discharge specifically to, or in close proximity to, marine waters. In this report, marine point sources are included as inputs into the Salish Sea Model.

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of “point source” in section 502(14) of the Clean Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Point source: Pollution from a single, identifiable discharge at a specific location into the natural environment. This includes water discharged from pipes, outfalls, or any other discrete discharge with a direct conveyance to surface water. It also includes a discharge to ground where pollutants reach a surface water where there is direct hydraulic pollutant conveyance. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, and industrial waste treatment facilities.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Primary production: Biomass production due to photosynthesis by phytoplankton.

Puget Sound: Includes South Sound, Main Basin, Whidbey Basin, Admiralty Inlet, and Hood Canal (see also greater Puget Sound).

Rivers/streams: A freshwater pathway that delivers nutrients and drains watershed areas. In the context of this report, “rivers inputs” and “river inflows” are used interchangeably with “watersheds,” “watershed inputs,” and “watershed inflows” to represent the delivery of flow and nutrient inputs into the Salish Sea Model. In the model, these estimates are for the mouth of each river, stream, or watershed and represent loading at the point at which the freshwater inflow enters the Salish Sea. These estimates include but do not distinguish between various upstream point and nonpoint sources in the watersheds that contribute to the loading at the mouth.

Salish Sea: Puget Sound, Strait of Georgia, and Strait of Juan de Fuca, including their connecting channels and adjoining waters (Figure 1).

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Thalweg: The deepest portion of a stream or navigable channel.

Tidal forcing: Tidal elevation time series at open boundary.

Tidal range: The difference between NOAA's minimum and maximum water surface elevations for a given year.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting water quality standards. A TMDL is equal to the sum of all of the following: (1) individual waste load allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a margin of safety to allow for uncertainty in the waste load determination. A reserve for future growth is also generally provided.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

Watershed inflows: See definition of "rivers" above.

Watershed load: Nutrient inputs originating in a watershed and primarily discharged into the Salish Sea via rivers and streams. Watershed loads can be composed of both point and nonpoint sources.

303(d) list: Section 303(d) of the federal Clean Water Act requires Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water — such as for drinking, recreation, aquatic habitat, and industrial use — are impaired by pollutants. These are water quality–limited estuaries, lakes, and streams that fall short of state surface water quality standards and are not expected to improve within the next two years.

Acronyms and Abbreviations

Ω_{arag}	Aragonite saturation state
ADCP	Acoustic Doppler Current Profiler
BC	British Columbia
BNR	biological nitrogen removal
C	carbon
$CBOD_5$	five-day carbonaceous biological oxygen demand
Chl-a	chlorophyll-a
CO_2	carbon dioxide
CTD	conductivity, temperature, and depth
DFO	Department of Fisheries and Oceans, Canada
DIC	dissolved inorganic carbon
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
DOC	dissolved organic carbon
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
et al.	and others
Lat	latitude
Lon	longitude
NH_4	ammonium
NO_3	nitrate
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
O_2	molecular oxygen composed of two atoms of oxygen
PARIS	Ecology's Water Quality Permitting and Reporting Information System
pCO_2	partial pressure of carbon dioxide
PNNL	Pacific Northwest National Laboratory
PO_4	phosphate
PRISM	Puget Sound Regional Synthesis Model
PSM	Puget Sound Model
PSNSRP	Puget Sound Nutrient Source Reduction Project
RMSE	root mean square error
S	salinity
SJF	Strait of Juan de Fuca
SOD	sediment oxygen demand
SOG	Strait of Georgia
SPSDO	South and Central Puget Sound Dissolved Oxygen
SSM	Salish Sea Model
T	temperature
TA	total alkalinity
TOC	total organic carbon

TON	total organic nitrogen
UW	University of Washington
WA	Washington State
WAC	Washington Administrative Code
WQS	water quality standard
WWTP	wastewater treatment plant
xCO_2	mixing ratio of carbon dioxide (mole fraction), expressed in ppm

Units of Measurement

ft	feet
g	gram, a unit of mass
$g/m^2/day$	gram per meter squared per day
kg	kilograms, a unit of mass equal to 1,000 grams
kg/day	kilograms per day
kg/ha/yr	kilograms per hectare per year
km	kilometer, a unit of length equal to 1,000 meters
km^3-hrs	cubic kilometer-hours
m	meter
mg	milligram
ppm	parts per million
psu	practical salinity units
s.u.	standard units
µatm	microatmospheres
yr	year

Appendices

Appendices A through K are available only on the internet, linked to this report at https://fortress.wa.gov/ecy/publications/SummaryPages/1903001.html.

Appendix A. Boundary Conditions

Appendix A1. Tidal Components at Open Boundary for 2006, 2008, and 2014

Appendix A2. Open Boundary Water Quality for 2006, 2008, and 2014

Appendix A3. List of Rivers Entering the Salish Sea

Appendix A4. Watershed Inflows for 2006, 2008, and 2014

Appendix A5. List of Marine Point Sources Entering the Salish Sea

Appendix A6. Marine Point Source Inflows for 2006, 2008, and 2014

Appendix A7. Watershed Inflow Water Quality for 2006, 2008, and 2014

Appendix A8. Marine Point Source Inflow Water Quality for 2006, 2008, and 2014

Appendix A9. Annual Average Dissolved Inorganic Nitrogen Loads for 2006, 2008, and 2014

Appendix B. Updated Watershed Flows and Water Quality

Appendix C. Other Sources of Nitrogen Influx to the Salish Sea

Appendix D. Observed Water Quality Databases

Appendix E. Parameters and Rates

Appendix E1. Parameters and Rates

Appendix E2. Parameters and Rates for Sensitivity Analyses

Appendix F. Comparison of Observed and Predicted Water Surface Elevations and Currents

Appendix G. Water Quality Binder for 2006, 2008, 2014, and Bounding Scenario Plots

Appendix G1. Marine Station Locations

Appendix G2. How to Read Time-Depth Plots

Appendix G3. Water Quality Binder for 2006

Appendix G4. Water Quality Binder for 2008

Appendix G5. Water Quality Binder for 2014

Appendix G6. Bounding Scenario Planview Maps

Appendix H. Comparison of Observed and Predicted Phytoplankton Primary Productivity

Appendix I. Sediment Oxygen Demand

Appendix J. ORCA Buoys and Moorings

Appendix K. Change in Dissolved Oxygen versus Reference Dissolved Oxygen

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Technical Memorandum

Salish Sea Model Evaluation and Proposed Actions to Improve Confidence in Model Application

June 26, 2024

Contributing Authors: Stefano Mazzilli, Joel Baker, and Marielle Larson, with model analysis provided by Rachael Mueller (PSI). Input and review provided by the PSI Modeling Evaluation Group members: Bill Dennison, Jacob Carstensen, Jeremy Testa, Kevin Farley, and Peter Vanrolleghem.

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EXECUTIVE SUMMARY

Puget Sound and the broader Salish Sea region have extensive ongoing monitoring and modeling efforts and world-class scientists engaged in addressing regional water quality recovery targets. The Salish Sea Model has been developed as part of this effort and is used by Washington State to evaluate regulatory compliance and the effectiveness of nutrient reduction scenarios and their targets. New regulation using the model may result in historic investments in nutrient management, including billion-dollar wastewater treatment plant upgrades. The decisions made now regarding nutrient management have the potential to shape the future of wastewater treatment, water quality, and communities for generations to come. Consequently, there is heightened interest in assessing the Salish Sea Model's performance, particularly related to the dissolved oxygen outputs used to determine the extent of regulatory compliance and the efficacy of nutrient management actions.

Purpose of the Model Evaluation Group

In addressing complex environmental challenges such as managing nutrients in Puget Sound, valuable insights can be gained from the experience of scientists in other regions. For example, scientists investigating the Chesapeake Bay and the Baltic Sea have applied models in nutrient management scenarios for decades. The University of Washington Puget Sound Institute convened global experts to advise on how to improve confidence in the current and future applications of the Salish Sea Model. The Model Evaluation Group[1] included scientists who have led cutting-edge research and advised regional managers on the application of modeling and monitoring in nutrient management programs in other regions. Like in Puget Sound, these programs include a focus on reducing human-induced low dissolved oxygen events and biological impacts. Furthermore, as is the case with the Baltic, modeling efforts must also address the challenge of quantifying the change in dissolved oxygen in areas where bottom-water oxygen concentrations are naturally so low that they are expected to not support species found elsewhere – even in modeled estimations of times before human influence from Washington State.

Puget Sound Model Evaluation Group	
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The Model Evaluation Group and PSI staff worked together to produce this literature review, whose purpose was two-fold. First, to summarize the Salish Sea Model development and evaluation to date, including the documentation of key parameters and model processes, as well as model performance, sensitivity and uncertainty analysis of model results (Section 1). Second, to describe additional evaluation actions recommended by the Model Evaluation Group focused on improving confidence in model application supporting Puget Sound's recovery goals on water quality and the regulatory application (Section 2). Many of these topics were presented and discussed at the Science of Puget Sound regional workshops[1], and recommendations build on research actions and scientific uncertainties defined by participants in the earlier Puget Sound Partnership Marine Water Quality Implementation Strategy workshops.

Key Takeaways

Overall, the Salish Sea-wide model simulations have comparable performance to other models used to inform nutrient reduction management elsewhere in the USA. Furthermore, Salish Sea-wide (or domain-wide) error and uncertainty analysis are well documented in the literature. In contrast, there is a paucity of analysis regarding model-observation comparisons available for the cell areas (i.e., Salish Sea locations) that represent places where low dissolved oxygen predictions are used to determine regulatory non-compliance in Washington State.

One of the most important long-term improvements to model output and accuracy is advancing model scale and resolution, supported by increased monitoring. In particular, there should be more fine-scale representation of shallow water embayments that are either adjacent to, or in, areas where low dissolved oxygen outputs are used in the determination of non-compliance.

Currently, the regulatory application excludes outputs from a buffer of cells representing nearshore habitats where model resolution and outputs are considered unsatisfactory but can be improved in the future with available data. The exclusion buffer borders non-compliant cells in all embayments where low dissolved oxygen is identified as a concern.

In considering the model at its current resolution, the MEG identified four key points (in bold below) and several recommendations (bulleted following) that were also identified across the modeled physical and biogeochemical processes reviewed in this report. Recommendations may improve confidence in the nutrient reduction scenarios and regulatory application of both current and future versions of the model, as well as the scientific understanding of what's driving lower dissolved oxygen and other impacts on water quality.

Washington uses both model outputs and measured data to determine 303(d) listings of impaired water bodies. This regulatory application places greater interest and demand on the accuracy and skill of the model used, and the communication of uncertainty and sensitivity implications for decision makers.

In comparison, while other states use models to set water quality standards and nutrient discharge limits, to our knowledge, they only use monitoring data to assess compliance with nutrient and dissolved oxygen water quality standards (see grey call-out box for examples).

[1] www.pugetsoundinstitute.org/about/waterquality/

Additionally, Washington state also uses the model to predict non-compliance with Washington's water quality standards, and these predictions are used to inform effluent limits.

The assessment of skill and uncertainty has so far concentrated on domain-wide analysis, and on the three specific years when the model calibrated by the state and its outputs used. There is an opportunity to use available measured data for additional independent validation runs for periods other than those used for calibration. Furthermore, analysis of multi-year runs is only available in later versions of a research version of the model, and sensitivity and uncertainty analysis of interannual variability of inputs is limited.

At a domain-wide scale, the skill and error of the Salish Sea model have been extensively addressed in the literature for each model version published, with deviations from the observations typically < 1 mg/L Root Mean Square Error (RMSE) for dissolved oxygen (DO), < 1 degree C for temperature, < 1.2 PPT for salinity, and < 6% tides for each year the model was calibrated and skill assessed. For the applied version of the model, analysis has primarily focused on one-year runs for the years 2014 as well as 2006 and 2008e, for those specific years calibrated. A multi-year domain-wide analysis for 2013-17 using research versions of the model was also completed. Assessment of skill and error at the domain-wide scale supports the model's general ability to represent and investigate hydrodynamic and biogeochemical processes for the years the model has been calibrated. For example, an RMSE of 1 DO mg/L means that 95% of the model outputs statistically fall within +/-2 mg/L of the measured DO values across all data used in the domain-wide evaluation. For context, ocean DO concentrations range from approximately 0-10 mg/L and are often considered to be of concern when they fall below 2 or 3 mg/L for sustained periods, which is referred to as hypoxia.

Regulatory application in Washington State, and use of the model
The Department of Ecology uses monitoring data and the Salish Sea Model to determine compliance with Washington's dissolved oxygen water quality standard and establish each 303(d) listing. The Salish Sea Model simulates both existing conditions and reference conditions; i.e., an approximation of conditions before western settlement. The reference condition removes nitrogen and carbon loads from Washington's wastewater treatment plants and rivers and is estimated from observations in current pristine watersheds. All other nutrient inputs and forcing are kept the same. Based on these model results there are two steps to predict whether each of the over 16,000 cells in the model are compliant under the existing conditions or any scenario of wastewater or river reduction investigated:

- **Part A: Numeric Criteria -** A cell is predicted to be non-compliant for the day, if the minimum dissolved oxygen modeled in any of the 10 layers is less than the numeric criteria for that location for at least an hour (e.g. 7 mg/L)
- **Part B: Natural Conditions Provision* -** A cell is predicted to be non-compliant if the existing condition /nutrient reduction scenario is **also** at least 0.2 mg/L lower than the reference condition in any layer for an hour.

** EPA disallowed the natural conditions allowance. Ecology recently proposed updated rule language for comment.*

Learn more about the Puget Sound Nutrient Source Reduction Project & General Permit

Regulatory application using models in other states:
While other states use models to set nutrient discharge limits, only monitoring data is used to assess compliance with nutrient and dissolved oxygen water quality standards. Examples include:

- Chesapeake Bay used a similar model to set discharge limits for wastewater treatment plants and non-point sources like agriculture as part of their TMDL process. However, compliance with the water quality standards driving these discharge limits is based on monitoring data. The Chesapeake's water quality standard tries to protect marine life by considering:
    - Lethal and chronic risks to key species with instantaneous and monthly criteria
    - The duration, extent, and seasonal timing of key species' exposure in five distinct habitats
- Pensacola Bay, Florida used a similar model-to-model comparison of existing and reference conditions to understand the influence of nutrient loads and other stressors on water quality outcomes, including chlorophyll a, bottom light levels, and dissolved oxygen. Ultimately, compliance with their water quality standards is determined by average daily, weekly, and monthly percent dissolved oxygen saturation measurements.

Dissolved oxygen non-compliance for Puget Sound occurs mostly within 16 shallow-water embayments and areas of Hood Canal when applying the state's 0.2 mg/L natural conditions threshold to model outputs. Looking within these specific geographic areas, a larger model error is reported in Ahmed et al. (2019) than for domain-wide results (1.04 - 3.05 mg/L DO RMSE) for the calibrated model results for 2014. This highlights the value of looking at model

performance analysis specifically in the places and at the times where model outputs are used in regulatory decision-making.

Model results suggest there are at least 16 areas where human activities may further decrease dissolved oxygen (DO), especially during late summer and early fall. Compared to domain-wide analysis, there has been less model performance assessment at a scale relevant to these areas and times of concern. In this review analyzing a subset of available data in the literature, a mean of 1.64, and a range of 1.04 - 3.05 mg/L DO RMSE was calculated for 28 model-to-measured comparisons across 22 sites in these embayments. This error calculation is based on existing condition results (not the difference between existing and reference scenarios) as the error for the pre-anthropogenic reference condition is inherently unknowable. However, for context, these RMSE results are approximately an order of magnitude greater than the natural condition threshold of 0.2 mg/L DO that has been used to determine regulatory compliance. Furthermore, the current regulatory determination of non-compliance was found to be quite sensitive to the natural conditions threshold defined by the state's water quality standards. For example, in 2014, 58% of the non-compliant area had a predicted change of 0.2-0.3 mg/L.

Levels of confidence in scenario results are not currently communicated as context to model predictions, and there is a lack of clarity as to the propagation of error especially considering model-to-model comparison used to determine regulatory compliance.

The propagation of error in model results has thus far been calculated in different ways for the regulatory application of the model, with two conflicting results, and varying approaches suggested to resolve uncertainty. An earlier research action recommendation of the Marine Water Quality (MWQ) Interdisciplinary Team (PSI, 2022) prioritized addressing this uncertainty and offering decision-makers more context regarding the acceptable margin of error on reduction scenarios they are willing to consider. The errors from the two model runs cancel each other out as proposed in one of the approaches used to calculate error for the regulatory application of the model. However, it is also possible that this approach may have the consequence of underestimating the uncertainty of deviations between the two scenarios applied in each calculation of non-compliance. Without additional analysis, it is unclear to what extent model prediction uncertainty may be compounded in the model-to-model comparisons. The confidence level for assessing deviations between the two model runs should also be considered for assessing compliance in relation to the 0.2 mg/L threshold used in the model's regulatory application.

RECOMMENDATIONS

The Model Evaluation Group identified the following to improve broader confidence in the model results and strengthen a process-based approach to understanding water quality drivers of change. Recommendations included data access and further analysis that would be required to further determine confidence in the current regulatory application of the model:

- Facilitate broader model performance assessment by the scientific community through direct online access to both modeled and measured data utilized in prior or new analyses. Model performance assessment of independent validation and calibration runs, and multi-year outputs can be prioritized. Currently, the majority of the datasets underlying the model-to-measured statistics presented in this review are not readily downable. Furthermore, the continuous profile datasets that can address more process-based validation throughout the water column have only been evaluated qualitatively in the current model reporting. Ready access to underlying data will enable other scientists to contribute to further analysis that will improve understanding and wider confidence in future applications.

- Perform additional validation studies specific to shallow water embayments and Hood Canal, where low Dissolved Oxygen (DO) outputs are used in non-compliance calculations, and at times of the year when phytoplankton and sediment/water processes have a high impact on oxygen reduction.
- Perform further validation studies using sub-sets of data above/below the pycnocline using available continuous profile data, towards better understanding the model skill related to processes such as vertical mixing, stratification, phytoplankton growth, and water-sediment interactions. In other words, validate oxygen data at various depths in the water column.
- Use newly and prior available data to analyze model performance for non-calibration years and across multiple years that better represent the "water cycle" year and range of interannual variability. Validation of key parameters over a wider range of years would further increase confidence in the model's ability to predict and respond to changes influencing dissolved oxygen beyond the three existing single-year runs applied.
- Perform further sensitivity scenarios and input parameter variability assessment considering model years and model inputs that are at opposite ends of the spectrum of interannual variability for key processes affecting DO. For example, considering interannual variabilities and extremes of available longer-term ocean and river loading inputs beyond the existing three model years.
- Undertake model performance analysis of Sediment Oxygen Demand (SOD) in embayments. Assessment of seasonal-specific nitrogen and SOD is now also possible, as well as validation of related processes/drivers using available measurements of carbon and other fluxes, and estimates of denitrification.
- Where appropriate, investigate and employ theoretically-founded probabilistic approaches to quantify associated uncertainty as context provided to future model scenario outputs and sensitivity analysis presented to stakeholders.

The Model Evaluation Group also identified the following recommendations on combined modeling and monitoring efforts in the region to further support transparency, trust, collaboration, and independent scientific input on the use and development of water quality models:

- Establish a systematic, collaborative process to develop and adapt new versions of the research model for regulatory applications. There are notable advances in versions of the model applied in research (e.g. multi-year runs, refined phytoplankton dynamics, etc.), however, a process has not yet been undertaken with stakeholders to establish timelines for adoption of these advancements in a regulatory version.
- Support systematic ensemble model development and assessment, including direct access to standardized validation and input data sets. In particular, the accessibility of subsets of key measured and modeled data for comparison across model versions and platforms.
- Support systematic integration and analysis across monitoring programs to better understand long-term water quality trends and variability, advancing combined model and measured analysis.

- Overall, there are many new observations of high spatial and temporal resolution that have become increasingly available in recent years. In particular, data from automated samplers of physical and biogeochemical processes should be used to support further model development and validation for years outside of those used for calibration. That said, there are key gaps to address in monitoring data that were identified as priorities by scientists in the region to support model advancement. In particular, efforts should be focused on further measurements and analysis of phytoplankton and sediment processes.

INTRODUCTION AND OBJECTIVES

The University of Washington Puget Sound Institute convened global experts to contribute to this literature review and analysis, advising on how to improve confidence in the current and future applications of the Salish Sea Model. It was not within the group's scope to provide a full audit of the model or evaluate regulatory standards. However, it is expected that recommendations can improve confidence in the regulatory application and will be relevant to the wider eutrophication and water quality targets of Puget Sound Partnership's Recovery goals. The Partnership's Marine Water Quality Vital Signs were recently updated from a dissolved oxygen focus to one including a wider range of anthropogenic measures of eutrophication (e.g. nutrient balances), and measures of multi-stressors (e.g. climate change).

The literature review includes the following in Section 1:

- Development and application of the Salish Sea Model in Washington State
- Salish Sea Model error, uncertainty, and sensitivity analysis undertaken
- Sediment/water column fluxes
- Phytoplankton and primary production

Statistics that are presented in this report are limited to the methods and results in the original sources cited, which in most cases did not include access to the data used. Therefore, review of these skill and error statistics are made at face value, without validation of the results or further reanalysis of underlying datasets.

Based on a review of the available literature, Puget Sound Institute and the Model Evaluation Group have defined an initial set of recommendations presented here. They are expected to be revisited and revised over time. Recommendations focus in the short term on further model-related analysis and/or validation using available measured data and existing model outputs or run input files. These consider the modeling capacity currently available with collaborating partners. Longer-term recommendations require more complex investigation and are intended to be integrated with wider regional collaboration on planned monitoring and modeling efforts. Further investigation of the following topics (*in italics*) covered in the literature review (Section 1) provide an opportunity to improve confidence in the application of the Salish Sea Model through specific modeling-related recommendations for each topic (Section 2):

Sediment/water fluxes:

- Rec. 1 Examination of modeled sediment flux responses to changing nutrient loading
- Rec. 2 Further validation of the sediment module using measured data
- Rec. 3 Analysis of Salish Sea Model sediment exchange model spin-up and stability

Primary production and phytoplankton:

- Rec. 4 Monthly budgets of primary production, N and C in selected embayments, and analysis of the role of ocean loading and riverine discharge variability in limiting primary production

Interannual variability and consideration of SSM versions and multi-model approaches:

- Rec. 5 Observed riverine, wastewater treatment plant, and ocean long-term variability and regional analysis
- Rec. 6 Comparison of two versions of the Salish Sea Model, and available model year outputs
- Rec. 7 1999-2019 data for longer model runs using multiple models, and further analysis of interannual variability of available forcing data

1 LITERATURE REVIEW

1.1 DEVELOPMENT AND APPLICATION OF THE SALISH SEA MODEL IN WASHINGTON STATE

Washington State determines the extent of dissolved oxygen non-compliance in Puget Sound by using the Salish Sea Model (SSM) to compare existing conditions and reference (estimated pre-industrial condition inputs from watersheds in Washington State) model scenario runs. Based on this method, parts of Puget Sound are determined as non-compliant under the Clean Water Act. Additionally, results of nutrient reduction scenarios are also used in planning decisions in support of the Puget Sound Partnership (PSP) Marine Water Quality Vital Sign targets. Strategies are being proposed to address non-compliance, including those reducing nitrogen loading at wastewater treatment plants and throughout the watershed.

Reference Condition Scenario

What is changed from existing conditions?

- Natural loads of nitrogen and carbon for Washington's wastewater treatment plants and rivers are estimated from observations in pristine watersheds. These represent a pre-anthropogenic or pre-industrial nutrient loading.

What is kept the same?

- Nutrient inputs from:
  - Canadian sources including the Fraser River
  - Washington's industrial treatment plants and those not under the general permit
- Climate, hydrology, and ocean, and all other boundary and forcing conditions
- A unique reference condition is created for each year the model is run

The Salish Sea Model has been developed for more than 10 years. The model has been calibrated with considerable hydrodynamic, salinity, and temperature data and has known model performance statistics that have been published in peer-reviewed literature. The development and evaluation of the model is summarized in Table 1. Model development was led by the Pacific North West National Laboratory through a joint initiative with the Washington State Department of Ecology, and more recently also through the University of Washington Salish Sea Modeling Center (SSMC) which was set up for the purpose. The evolution of the model and specific functions/modules are presented sequentially (columns 1 and 2), with relevant scientific publications and reports that document the model development and evaluation assigned to each (column 3). The model phasing and nomenclature follow that defined by the SSMC at the time of writing (https://ssmc-uw.org/) and a further summary of the differences in the model applied by the State of Washington, and the various branches of the research model are included in the PSP Marine Water Quality State of Knowledge (PSI, 2022).

The version of the model that is of particular focus for this model evaluation is that "applied" by the state in the Puget Sound Nutrient Source Reduction Project[2] (referred to here as the applied model - PSM/SSM 2017 -FVCOM v2.7ecy/FVCOM-ICMv2 – in bold in Table 1), as well as reviewing aspects of the current "research model" (SSM 2021-FVCOM v4.3a/FVCOM-ICMv4) where further development and performance assessment has been undertaken on specific modules, and across a number of sequential years.

The applied model has several additional Quality Assurance Project Plans (QAPPs), and stakeholder engagement steps that are commonly undertaken with model development and evaluation plans (see call-out box). The model was developed iteratively with different versions applied to different years the model was calibrated, assessed, and used. Key steps undertaken in model development are summarized as follows indicating source documents, with further detail in the following section reviewing error, sensitivity and uncertainty analysis:

- Ahmed et al. (2019) and the Ahmed et al. (2021) update, provide results of the Bounding Scenarios nutrient reduction model runs undertaken by the state, as well as summaries of model development, model performance, sensitivity analysis, and associated publications.
- In addition to the reports and publications listed in Table 1, Ecology undertook further QAPPs, model performance, and sensitivity analysis specific to the development of the model and application in the Puget Sound Nutrient Source Reduction Project; as described in Ahmed et al. (2019) and summarized in slides of the Puget Sound Nutrient Forum, September 20, 2018[3]). The QAPP for the current model applied by the state (McCarthy et al., 2018) is based on the procedure outlined in EPA (2002).
- Development of the sediment diagenesis model to improve sediment-water column interactions included nutrient exchange and sediment oxygen demand and pH modules (Pelletier et al., 2017a and 2017b describing model version FVCOM_v2.7ecy/FVCOM-ICMv2 in Table 1), and further model evaluation specific to this development is described in the literature review following, along with all sensitivity and uncertainty analysis undertaken.
- The assessment of skill and uncertainty has thus far focused on statistical comparison of domain-wide analyses, and for three specific years where the applied model simulations were presented (2006, 2008, and 2014) - with "calibration checks" against observed data for those years (Ahmed et al., 2019 and 2021).
- Finally, it should be noted that the model version used and evaluated by the state in Ahmed et al. (2019) subsequently included recalibration and harmonization of pH and DO using the parameters consistent with Khangaonkar et al. (2018b) for all three years (similar to SSM 2018 (v2.7d/v2) in Table 1). In addition, the ocean boundary forcing was also updated to use HYCOM (year 2014 only); similar in forcing to the later research models, and described in the Ahmed et al., (2021) update report, along with other model changes made.

[2] https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Helping-Puget-Sound/Reducing-Puget-Sound-nutrients/Puget-Sound-Nutrient-Reduction-Project
[3] www.ezview.wa.gov/Portals/_1962/Documents/PSNSRP/2018_09_20_ModelUpdates_BoundingScen_Anise.pdf

Table 1. Development of the Salish Sea Model including additional capabilities, and associated references and publications describing the application and model evaluation (originally from the Salish Sea Modelling Center website and reproduced from PSI, 2022 with further detail on the applied version of the model sown in bold.

Model, Year (and FVCOM / FVCOM-ICM versions)	Description, Features, and Domain Extent	Code Development and evaluation documentation
PSM 2012 (v2.7/v1)	Original model also referred to as the Puget Sound Model. Domain: Puget Sound and Georgia Basin	Khangaonkar et al. (ECSS 2011, Ocean Dynamics. 2012) & Kim and Khangaonkar (2012) for FVCOM-ICM_v1 specifically
PSM 2013 (v2.7a/v1)	+ floating structure/bridge module	Khangaonkar and Wang (Applied Ocean. Res. 2013)
PSM 2014 (v2.7b/v1)	+ kelp module	Wang and Khangaonkar et al. (JMSE 2014)
Fine-resolution PSM 2016 (v2.7c/v1)	+ embedded fine-resolution + wetting and drying Improved: intertidal nearshore salinity and temperature	Khangaonkar et al. (Northwest Science 2016)
PSM/SSM 2017* (v2.7ecy/v2)	+ sediment diagenesis and +pH modules (documentation in Pelletier et al. (2017a) and (2017b) respectively), + expanded freshwater (161) and marine point source (99) inputs in the **applied version*** with further additions in Ahmed et al. (2019) and (2021)	Bianucci, Long, Khangaonkar et al. (Elementa Science of the Anthropocene, 2018a)
SSM 2017 (v2.7d/v2)	Domain: extended past continental shelf + Exchange flow and circulation computation	Khangaonkar et al. (Ocean Modelling 2017)
SSM 2018 (v2.7d/v2)	Domain: extended to shelf break + hypoxia and net heat flux calibration	Khangaonkar et al. (JGR 2018b)
SSM 2021 (v2.7d/v3&4)	Improved: ocean boundary forcing to HYCOM, new re-aeration formulation Recalibration for harmonization of pH and DO (v3) + turbidity, zooplankton, and submerged aquatic vegetation modules (V4)	Khangaonkar et al. (Ecological Modelling 2021)
SSM 2021 (v4.3a/v4)	Improved: currents and water surface elevation calibration using distributed bed friction and meteorology and FVCOM version upgrade	Publications in Progress.

* Applied version of the model used by Washington State. This included a branch of further improvements described in Ahmed (2019) and (2021), summarized in the accompanying text.

Guidance on model development and community engagement building stakeholder confidence

Guidance by the EPA, the National Research Council (NRC), and others summarize the common components that would be reasonably anticipated in model development and evaluation plans, and to build further stakeholder confidence in the appropriate use of models such as the Salish Sea Model. For example: EPA (2002); EPA (2009); NRC (2007); Thacker et al. (2004); Harmel et al. (2014), and a recent model uncertainty webinar series co-hosted by the research institutes and water agencies in California. Based on this guidance, the common components and processes can be grouped into seven activities that are largely sequential and presented below. There is some expected overlap and iteration of phases, particularly during further model development and review:

1. **Dialogue and consensus** with the broader community on; a) end-points of concern, b) consequences and risk of action/inaction, and c) scientific data for both
2. **Monitoring the states and rates for forcing** (e.g. land, ocean, atmospheric) and transformation constants and end-points
3. **Rationale for model selection and open access** to the model and results
4. **Metrics and broader framework for interpreting phenomena of interest**
5. **Error and skill assessment** at relevant spatial and temporal scales addressing state and rate of variables vs observations as part of model performance, or "quantitative corroboration" (EPA, 2009), evaluating calibration and validation outputs.
6. **Sensitivity linking key drivers to phenomena of interest** through scenario analysis, including a) parameterization of key processes and b) forcing
7. **Uncertainty communicated and used by stakeholders**, e.g. community engagement in confidence interval development and case studies

The focus of this review is primarily on model performance considering *error and skill assessment (5)*, and *sensitivity and uncertainty analysis (6)* for the application of the Salish Sea Model, and does not evaluate stakeholder engagement in any of the seven activities. However, references are provided to the reader in this section documenting quality assurance undertaken by the state, and other reports and workshops covering activities 1-4 above.

On guidance on model performance assessment, sensitivity and uncertainty the EPA (2009) also defines terms important to guidance on model development specific to error, skill and uncertainty analysis of both calibration and validation phases of development:

Corroboration and model performance: *comparison of model results with data collected in the field or laboratory to assess the model's accuracy and improve its performance …. when corroboration data are significantly different from calibration data, the corroboration exercise provides a measure of both model performance and robustness.* Guidance specific to hydrodynamic estuarine models, further specifies the role of validation in corroboration, for example: *running the model using data covering an alternative period and/or a different location without making any additional adjustment to the model parameter* (Williams and Esteves, 2017), which is similarly prioritized in guidance on regulatory applications (e.g. NRC, 2007).
Uncertainty and variability: *... describes the extent to which the variability and uncertainty (quantitative and qualitative) in the information or in the procedures, measures, methods, or models are evaluated and characterized (EPA 2003).*

Sensitivity analysis: *the computation of the effect of changes in input values or assumptions (including boundaries and model functional form) on the outputs (Morgan and Henrion 1990); the study of how uncertainty in a model output can be systematically apportioned to different sources of uncertainty in the model input (Saltelli et al. 2000). By investigating the "relative sensitivity" of model parameters, a user can become knowledgeable of the relative importance of parameters in the model.*

Uncertainty analysis: *investigation of the effects of lack of knowledge or potential errors on the model (e.g., the "uncertainty" associated with parameter values). When combined with sensitivity analysis (see definition), uncertainty analysis allows a model user to be more informed about the confidence that can be placed in model results.*

On stakeholder engagement in uncertainty analysis for models used in regulatory activities, the National Research Committee (2007) highlighted that: *effective uncertainty communication requires a high level of interaction with the relevant decision makers to ensure that they have the necessary information about the nature and sources of uncertainty and their consequences. Thus, performing uncertainty analysis for environmental regulatory activities requires extensive discussion between analysts and decision-makers*.
Some specific recommendations for this include:

- *… It also is important for modelers to involve decision makers in the development of uncertainty analysis to ensure that decision makers incorporate their policy expertise and preferences into such assessments*.
- *…. Effective decision making will require providing policy makers with more than a single probability distribution for a model result (and certainly more than just a single number, such as the expected net benefit, with no indication of uncertainty). Such summaries obscure the sensitivities of the outcome to individual sources of uncertainty, thus undermining the ability of policy makers to make informed decisions and constraining the efforts of stakeholders to understand the basis for the decisions.*
- Further guidance on approaches relevant to complex numerical models where full probabilistic assessment is not possible include*: …the committee recommends that various approaches be used to communicate the results of the analysis. These include hybrid approaches in which some unknown quantities are treated probabilistically and others are explored in scenario-assessment mode by decision makers through a range of plausible values.* Detailing further information specifically on *scenario assessment and/or sensitivity analysis*, the example is provided where a *scenario assessment might consider model results for a relatively small number of plausible cases (for example, "pessimistic," "neutral," and "optimistic" scenarios).*

Subsequent versions of the research model developed by PNNL/SSMC include turbidity, zooplankton, and submerged aquatic vegetation modules (SSM 2021 - FVCOM v2.7d/FVCOM-ICMv4; Table 1), and recent applications include multi-year runs examining the last marine heat wave (Khangaonkar, et al., 2021b), and refined quantification of residence and flushing times of embayments using a higher resolution bathymetric grid with approximately 100m nearshore resolution (Premathilake and Khangaonkar, 2022). The many scenarios completed for nutrient reduction and other investigations also have value for re-use in wider water-quality management and Puget Sound recovery goals. For example, model inputs, and state variables are relevant to the majority of the PSP Marine Water Quality Vital Sign (e.g. parameters related to nutrient and phytoplankton change, such as nitrate concentrations and net primary production rates). Parameters are outputted at each location within the domain and are accessible from existing output files of each nutrient scenario run that has been undertaken in Washington State.

1.2 SALISH SEA MODEL ERROR, UNCERTAINTY, AND SENSITIVITY ANALYSIS UNDERTAKEN

Hydrodynamic and biogeochemistry parameters have been systematically evaluated for error and skill assessment in all key Salish Sea Model versions and module development phases, providing results mainly at a Salish Sea-wide basis in peer-reviewed literature (Table 1). For the model versions applied in the Puget Sound Nutrient Source Reduction Project, calibrations were "checked" (Ahmed et al. 2019) to observed data for 2006, 2008, and 2014 with model performance statistics provided for each year. Resulting skill and uncertainty statistical are what are considered in the assessment of applied model performance in this review. Currently, no further delineation or description of independent validation runs are available for time periods other than the three calibration and simulation periods.

Geographic and temporally specific statistical analyses of measured to modeled data is provided throughout Puget Sound (bounding scenarios reports of Ahmed et al., (2019) and Ahmed et al. (2021)). These reports also provide model evaluation and sensitivity analysis of key parameters for processes and advancement of model modules such as sediments and phytoplankton (discussed in the following sections). However, the focus on the synthesis of statistical assessment of skill and error results in the bounding scenarios reports is on a modeled domain-wide basis. Therefore, there is an opportunity to use these extensive geographic and temporally specific statistics and plots for further analysis and synthesis of regional and inlet-specific skill and error assessment.

Here, we review three areas of skill and error assessment undertaken for the Salish Sea Model:

- **Model domain-wide skill and error assessment**: summarizing the existing statistics and analysis published in journals and the state's bounding scenarios report
- **Geographic and temporal specific skill and error assessment**: synthesizing statistical analysis of model-to-measured results in regions and inlets of Puget Sound using available results from Appendix H of the Bounding Scenarios Report.
- **Process-based evaluation and other skill and error considerations**

Model domain/Sound-wide skill and error assessment

A synthesis of comparative error and skill results on biogeochemistry parameters from the year 2014 model outputs across different model versions is provided in Table 2. Sources include journal articles, and the Bounding Scenario reports published specifically on the model applied by the state in the Nutrient Source Reduction Project. Model year 2006 results are also included for the applied model. In the more recent versions of the research model, a further relaxation of the calibration was required to run the model for the longer time period for the years 2013-17. Statistics are therefore included for the average of the 5-year run as well as specifically for the year 2014 during that 5-year run period.

Table 2. A synthesis of comparative error and skill results on biogeochemistry parameters from the year 2014 model outputs across different model versions (sources are in the footnote). The model applied by the state is compared to the same year's results from the later research model, including the version with relaxed calibration to provide multi-year outputs. Statistics include the root-mean-square-error (RMSE), mean error (ME), and Willmott Skill Score (WSS). The sets of measured data used in statistical analysis for the state versus research model are understood to be different subsets of the same available 2014 measured data; different both in terms of a number of sites and specific locations selected. In both analyses, all available data from throughout the water column and for each time period were used (see gray call-out box following for examples and further details on measured data used).

Parameters	**State Applied Model: Year 2006[1]**		**State Applied Model: Year 2014[1]**		**Single-year Research Model: Year 2014[2]**			**Multi-year Research Model: Years 2013 – 2017[3]**		**Multi-year Research Model: Years 2014 only[3]**		
	RMSE	WSS	RMSE	WSS	ME	RMSE	WSS	ME	RMSE	ME	RMSE	WSS
Temperature (°C)	0.69	0.96	0.78	0.94	-0.27	0.76	0.96	-0.03	0.71	0.20	0.74	0.96
Salinity (PPT)	0.74	0.88	0.84	0.87	-0.12	0.97	0.84	0.07	0.88	-0.04	0.92	0.86
Dissolved Oxygen (mg/L)	1.13	0.85	0.98	0.89	-0.07	0.92	0.92	0.08	0.98	0.06	0.95	0.92
Nitrate*: $NO_3 + NO_2$ (mg/L)	0.08	0.90	0.07	0.90	< -0.01	0.08	0.91	0.02	0.09	< 0.01	0.09	0.90
Chlorophyll a (µg /L)	4.48	0.64	3.42	0.67	0.60	4.32	0.70	0.29	3.84	0.64	4.49	0.70
Ammonium*: NH_4 (mg/L)	0.02	0.66	0.02	0.56	< 0.01	0.02	0.67	0.01	0.02	0.01	0.02	0.64
Phosphate*: PO_4 (mg/L)					-0.01	0.02	0.69	< -0.01	0.02	-0.01	0.02	0.69
pH					0.02	0.16	0.67	0.08	0.26	0.03	0.16	0.71
					-0.03	0.14	0.81					
TA (µ mol/kg)					39.8	86.4	0.74					
DIC (µ mol/kg)					49.7	102.5	0.8[a]					
PAR (E/m^2/Day)	4.09	0.69	6.00	0.66								

*Published results for the research version of the model were in µ mol/L for Nitrate, Ammonium, and Phosphate, converted here presuming a molecular weight of N and P respectively rather than for the molecule (e.g. N versus NO3).

Web links included to key sources reports and publications for the three model versions:

[1] State Applied Model: Year 2014 – Ap. H, Ahmed et al. (2021) Bounding Scenarios update

[2] Research Model: applied to the Year 2014 – Khangaonkar et al. (2021a)

[3] Research Model: calibrated for a multi-year run. Statistics provided for the Year 2014 versus the average of Years 2013 – 2017 – Khangaonkar et al. (2021b) for Puget Sound and the Strait of Juan de Fuca were used. Separate skill numbers are provided for pH to distinguish between the two data sets collected and analyzed using different techniques.

Table 3 and Table 4 provide a summary of all available skill and error statistics for the most recent version of the model results published by the state for the modeled years 2006 and 2014, respectively (Ahmed et al., 2021). The earlier version of the Bounding Scenarios Report (Ahmed, et al., 2019) provides model performance on all three years run. However, results in the 2021 report improved quality control and added additional sites, and therefore superseded the earlier statistics for the years 2006/14 – in addition to improvements to the model noted earlier. Overall, using the Ahmed et al. (2021) results, R, RMSE, and other statistics are better for DO for the year 2014 versus 2006, with varying goodness of fit across other parameters. Two considerations are identified when comparing the 2006 and 2014 results. First, 2006 exhibits a longer residence time and a larger non-compliant area based on DO. Second, 2014 also used an improved model configuration compared to 2006, with updated ocean boundary condition forcing. When tested for the same model year (2014), the updated boundary condition version of the model performed with improved domain-wide RMSE and bias for temperature (Appendix D of Ahmed, et al., 2021). The model maintained similar RMSE results across most other parameters, with slightly more negative bias (overestimation by the model). It was noted that future regional exploration model skills should be considered. These could focus on areas where hydrodynamics, stratification, and resulting DO may be more sensitive to ocean forcing.

Table 3. Detailed skill metrics for the State Applied Model: Year 2006 from Table D2, Appendix H1, of the Bounding Scenarios Update Report (Ahmed et al., 2021). RMSEc is the centered root-mean-square error.

Parameter	**R**	**WSS**	**RMSE**	**RMSEc**	**RE**	**MAE**	**Bias**	**n**
	correlation coefficient	Wilmott Skill Score	square root of the variance of the residuals		relative error (%)	mean absolute error	mean of the residuals	no. of observati ons
Temperature (°C)	0.95	0.96	0.69	0.58	5%	0.53	0.38	145919
Salinity (psu)	0.86	0.88	0.74	0.57	2%	0.53	-0.47	144850
Dissolved Oxygen (mg/L)	0.80	0.85	1.13	0.94	14%	0.92	-0.62	134591
Chlorophyll a (µg /L)	0.51	0.64	4.48	4.47	72%	1.70	0.20	110580
NO_3 (mg/L)	0.82	0.90	0.08	0.08	16%	0.05	0	2356
Ammonium: NH_4 (mg/L)	0.51	0.66	0.02	0.02	102%	0.01	0.01	3034
PAR (E/m^2/Day)	0.60	0.69	4.09	4.06	85%	0.76	-0.51	47791

Table 4. Detailed skill metrics for the State Applied Model: Year 2014 from Table D3, Appendix H1, of the bounding scenarios update report (Ahmed et al., 2021). RMSEc is the centered root-mean-square error.

Parameter	R	WSS	RMSE	RMSEc	RE	MAE	Bias	n
	correlation coefficient	Wilmott Skill Score	square root of the variance of the residuals		relative error	mean absolute error	mean of the residuals	no. of observations
Temperature (°C)	0.95	0.94	0.78	0.74	6%	0.62	-0.23	97687
Salinity (psu)	0.82	0.87	0.84	0.71	2%	0.51	-0.44	97487
Dissolved Oxygen (mg/L)	0.83	0.89	0.98	0.89	11%	0.74	-0.43	96152
Chlorophyll a (µg /L)	0.52	0.67	3.42	3.42	71%	1.41	-0.11	87671
Nitrate/Nitrite (mg/L)	0.84	0.9	0.07	0.07	15%	0.05	0	1934
Ammonium: NH_4 (mg/L)	0.35	0.56	0.02	0.02	58%	0.01	0	1595
PAR (E/m^2/Day)	0.61	0.66	6.00	5.94	78%	1.08	-0.81	82178

In summary, key points are as follows considering the skill and error analysis of Salish Sea Model calibrated outputs at a domain-wide scales:

- Domain-wide, the model performance is reasonably consistent for different versions of the model reviewed, and for key physical and biogeochemical parameters. The Salish Sea Model has consistently shown a RMSE of approximately DO < 1 mg/L and temperature < 1 degree C (Table 2), with earlier analysis of RMSE for salinity < 1.2 PPT, and tides < 6% relative RMSE (Khangaonkar, Pers. Comm., 2 Dec. 2022). It would be expected that results may be poorer than presented in Tables 2 to 4 if independent validation was done using data from years other than those that were used in calibration.
- For the 2014 condition scenario of the applied model (Table 4), the RMSE of 0.98 mg/L DO shows a lower error, in comparison to 2006 domain-wide results. A bias of -0.43 mg/L indicates a systematic overestimation of modeled DO relative to the measured data, which would contribute a portion of this total error across the aggregated results. The relative error of 11% DO suggests that oxygen values used in the inputs for this aggregated analysis are around 10 mg/L, and are not likely oxygen-deficient waters.
- The number and selection of sites for skill assessment are not standardized between the applied and research model, contributing to differences in comparative results.
- To our knowledge none of the datasets prepared for the statistical analyses of model performance described in Table 2 are available publicly for download from the cited sources.
- Where possible, further model validation and skill and error assessment should be undertaken for both the hydrodynamic and biogeochemical model components for years other than 2006/8/14 that were used in model calibration (Appendix D, Ahmed et al., 2019). The application of the research model for the years 2013-17 is a step towards addressing this gap in measured/modeled validation - at least at a domain-wide-analysis level presented in Table 2. Making available multi-year model outputs from this (or newer studies), and providing the associated measured data used in the evaluation of all statistical analysis in Table 2, would support this gap, and results may improve confidence in the model application. These datasets would also enable analysis specifically of shallow-water embayments and other areas of concern at the times of the year when DO is low, as described following, for the year 2014.

Geographic and temporal specific skill and error assessment:
A synthesis is provided here of all available statistical analyses of the model to measured results in regions and embayments of Puget Sound (Table 5), using available results from Appendix H of the Bounding Scenarios Report produced by the state. The methodology applied and example plots are summarized in the gray call-out box. The reader is encouraged to examine the synthesis by embayment in Appendix 1 which includes all available plots and statistical results as well as maps providing orientation of sample locations and extent of non-compliance in each.

Inlet-scale review of measured to modeled dissolved oxygen goodness of fit in areas identified as non-compliant in Washington State
The **purpose** of this review is to use the extensive analysis undertaken by the state, providing further detail on the skill and error specific to model performance in shallow water embayments where low DO is a concern, and to the time period and depths within these locations that significantly contribute to low DO for the regions and wider Puget Sound. The **methodology** includes three steps: First, sub-sampling from the plots available (Appendix H, Ahmed et al. 2019), selecting all that fall within the geographic area identified by the state as non-compliant in inlets and embayments of Puget Sound using just the 2014 delineation for simplicity. All analysis compares the same time period of the year and location. Second, selecting from these, only those that had ≥ 3 months of measured data in the typical period of lowest dissolved oxygen (July – November). Appendix 1 provides all selected plots and statistical analysis as well as maps and further details on methodologies. An example for Hood Canal in 2014 is below. Third, presenting the range of model error and skill for each site here in Table 5, including all available statistics. The best- and worst-case goodness of fit based on RMSE are presented for each year, where available, for each embayment/region totaling 28 samples across 22 sites in 11 geographic areas.

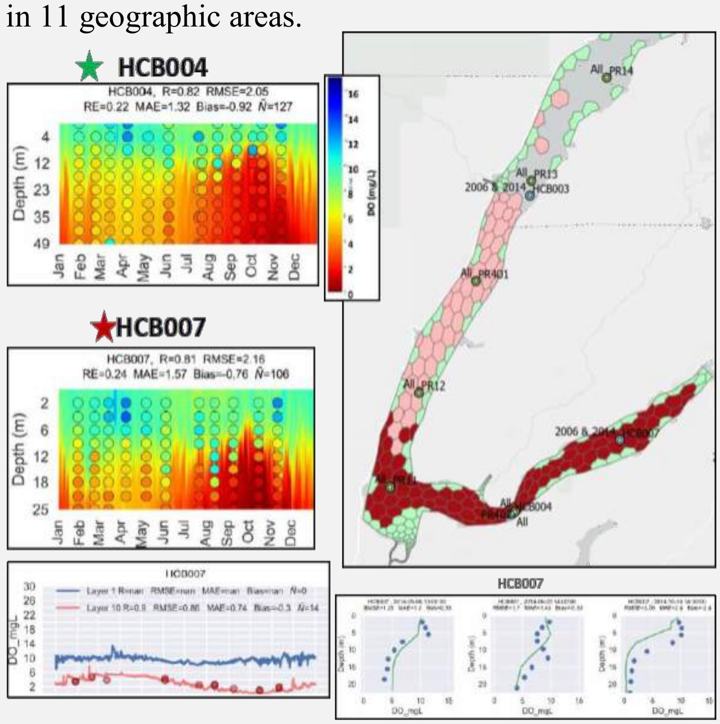

Table 5. Skill metrics on dissolved oxygen results (mg/L) for the state's Applied Model for specific regions, and inlets within them. All sites where results are presented fall within the geographic areas identified by the state as DO non-compliant. Multiple sites and samples are included to represent the range of goodness of fit. The grey call-out box provides further details, including methodology. Appendix 1 provides all plots and results examined within all inlets examined. The domain-wide statistics are drawn from Table 3 and Table 4.

Monitoring Station	R	RMSE	RE	MAE	Bias	n	Depth[b] (m)
Domain Wide							
2014	0.83	0.98	11%	0.74	-0.43	96152	n/a
2006	0.80	1.13	14%	0.92	-0.62	134591	n/a
Hood Canal							
HCB007 2014	0.81	2.16	24%	1.57	-0.76	106	19
HCB004 2014	0.82	2.05	22%	1.32	-0.92	127	45
HCB007 2006	0.90	1.93	22%	1.34	-0.57	63	19
HCB004 2006	0.90	1.6	26%	1.32	0.16	115	45
Whidbey							
SKG003 2014	0.87	1.19	11%	0.86	0.30	84	16
SKG003 2006	0.83	1.64	20%	1.51	0.23	14	16
PR2 2006	0.93	1.05	13%	0.92	-0.73	20	84
Bellingham Bay			0%				
BLL0009 2014 [a1]	0.79	1.19	10%	0.81	0.11	69	21
BLL0009 2006 [a1]	0.80	1.2	11%	0.98	-0.28	70	21
Main Basin							
CMB003 2014[a2]	0.79	1.12	10%	0.78	-0.5	119	107
SIN001 2014	0.61	1.92	15%	1.52	-0.93	90	9
CMB003 2006 [a2]	0.87	1.06	11%	0.83	-0.52	121	107
SIN001 2006	0.60	1.64	14%	1.33	-0.57	72	9
South Sound region, and inlets and embayments							
Carr Inlet							
CRR001 2014*	0.83	1.23	12%	0.98	-0.65	104	56
SS74 2006	0.68	2.12	23%	1.72	-1.16	36	28
SS70 2006	0.84	1.15	14%	1.00	-0.77	40	55
Case Inlet							
PR37a 2014*	0.96	1.69	17%	1.27	-1.27	6	51
SS45 2006	0.2	3.05	38%	2.57	1.18	36	5
SS51 2006	0.84	1.04	13%	0.91	-0.57	55	44
Budd Inlet							
BUD005 2014*	0.64	2.1	15%	1.42	-0.15	101	10
SS07 2006	0.28	2.77	30%	2.10	1.05	27	7
SS13 2006	0.40	1.23	12%	0.98	-0.66	36	32
Totten Inlet							
TOT002 2014*[a3]	0.49	1.56	15%	1.36	0.48	88	5
SS25 2006	0	1.28	13%	1.13	-0.67	36	8
SS21 2006	-0.53	2.01	19%	1.73	-1.30	48	24
Eld Inlet							
SS16 2006	0.31	1.93	18%	1.53	-0.76	31	13
SS15 2006	0.18	1.9	18%	1.54	-1.19	66	21
Oakland Bay							
SS36 2006*	0.24	1.16	12%	0.96	0.39	44	6

a1-3 Included as the only available min/max RMSE, even though it does not meet criteria as the measured site is located outside of, but near, modeled non-compliant grid cells: a1) 1 km south, and missing deep water measured data during Jul-Nov where DO would be the lowest; a2) 750m south-west, and a3) 125 m south of each embayment.
b Interpolated model depth drawn from nearest value from bathymetry model input data files used in SSM
** Included as the only station in the embayment for the given year. No range of RMSE to present.*

Existing data are synthesized to provide context to the statistical analysis of the modeled to measured results in regions and embayments of Puget Sound (Table 5). Additionally, the modeled minimum dissolved oxygen concentration is analyzed for each related embayment in 2014 in Figure 1. Figure 2 presents the greatest difference in daily dissolved oxygen between existing and reference conditions for non-compliant cells by embayment, presented as the cumulative area over a year. Using Bellingham Bay as an example of how to interpret these results, there are approximately 29 km^2 where non-compliance was identified in the existing conditions scenario throughout 2014 (Figure 1). Of this, the model predicts about half the area had a minimum dissolved oxygen concentration of <1 mg/L and the other half was between 1 to 2 mg/L (red and orange respectively). Minimum dissolved oxygen is identified here as the annual minimum occurring in any one of the 10 layers in each of the cells identified in the corresponding areas presented. When compared to the reference (or pre-anthropogenic) scenario, the greatest difference in daily dissolved oxygen for existing conditions is 0.3 mg/L for approximately 21 km^2 of Bellingham Bay and a 0.4 mg/L difference for the remaining 8 km^2 (Figure 2). Appendix 2 also includes further comparative plots by region and embayment for 2014 and 2006 model outputs.

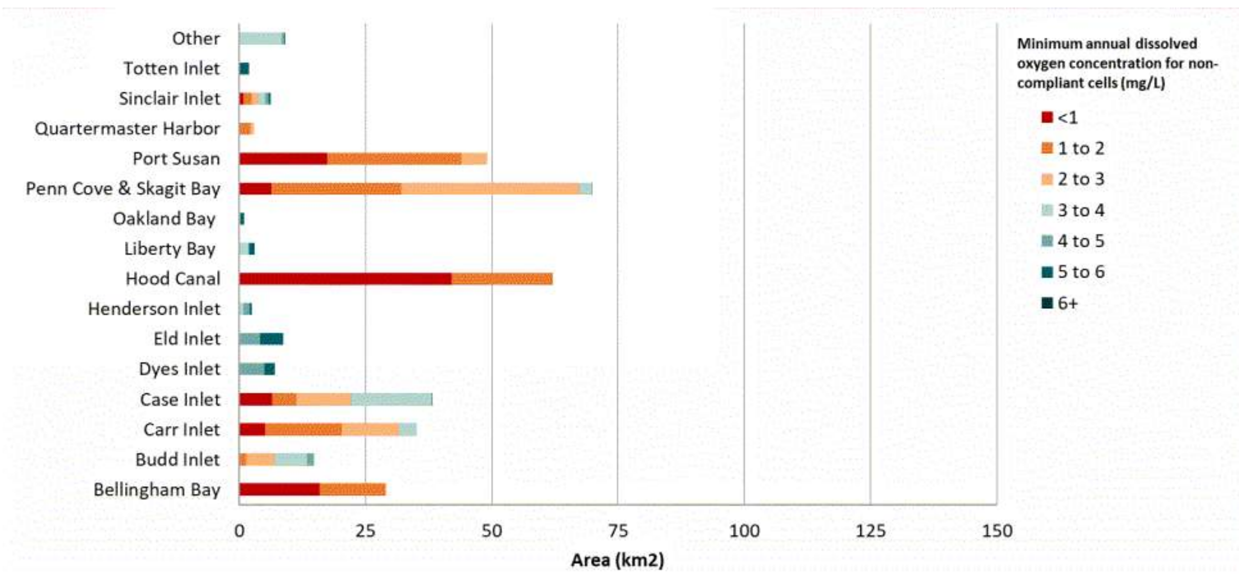

Figure 1. Minimum annual dissolved oxygen concentration for non-compliant areas by embayment for 2014. Sources and details on methodologies are included in Appendix 2. Figures 1 and 2 include all cells in Washington State waters that are calculated to have non-compliance for at least 1 hour for 2014, and it is from these areas that the sub-selection of statistics presented for embayments in Table 5 and the gray inset box above are drawn). See Ahmed et al. (2019) for details on the state's non-compliance calculations.

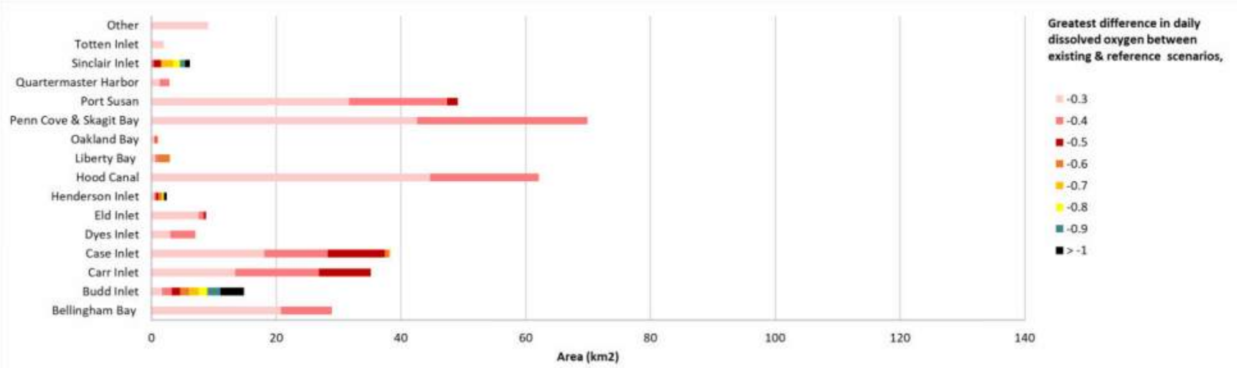

Figure 2. Calculated greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by embayment for 2014. Sources and details on methodologies are included in Appendix 2.

Overall, key points for consideration on the geographic and temporal specific skill and error assessment of the Salish Sea Model include:

- A mean of 1.64, and a range of 1.04-3.05 mg/L DO for the RMSE was calculated across all 28 model-to-measured comparisons made in embayments and areas of concern in each region (Table 5). For context, the range of RMSE calculated is an order of magnitude greater than the current natural condition threshold of 0.2 mg/L DO.
- Table 5 includes the best and worst RMSE identified at each embayment for each year in the subset of data used. Taking an example at one embayment, Case Inlet has both the best and worst goodness of fit of all embayments examined: 1.04 -3.05 mg/L RMSE respectively. 2014 results were consistently higher at all sites than the aggregated global RMSE of 0.98 mg/L calculated domain-wide for 2014.
- Model bias varied for different embayments and years. Where there was an overestimation of DO for 20 of these model results, the mean was -0.75 (range: -0.15 to -1.30). Where DO was underestimated for the remaining 8 of these model results, the mean was 0.49 (range: 1.18 to 0.11).
- The model appears to have better predictive capacity based on R^2 in those embayments with larger areas of low DO. Consistently higher predictive R^2 values ($\gtrsim$0.8) were determined for most of the sites from regions and embayments with large areas of low DO (Figure 1), and consistently lower R^2 at some of the embayments with no annual DO minimum <0.3 mg/L (e.g. Tottenham and Eld Inlet and Oakland Bay).
- Context is provided in Figure 2 to consider the relative model skill (Table 5) calculated at these embayments which are generally non-compliant. Figure 2 highlights the differences in areas of Puget Sound that will be close to the current 0.2 mg/l natural conditions or other thresholds that might be used to calculate non-compliance and DO impacts:
    - A maximum difference between the existing and reference (pre-anthropogenic) scenarios of 0.3-0.49 mg/L DO is calculated for most cells in most embayments (shown by area in km2 in Figure 2), while a few inlets have areas with greater differences greater than 0.5 mg/L (e.g. Budd, Sinclair, and Henderson).
    - Results represent the maximum envelope of nutrient reduction possible in these locations if all human sources of nitrogen were eliminated from Washington State rivers and wastewater treatment plants.

- Figure 2 results also highlight the importance and role of the threshold used in such calculations using existing and reference model results. For example, 58% of the non-compliant area in 2014 had a predicted change of 0.2-0.3 mg/L.

Process-based evaluation and other skill and error considerations

Propagation of error with model-to-model calculations: The modeled error calculation propagated in DO non-compliance calculations may require further consideration as prioritized by the Marine Water Quality (MWQ) Interdisciplinary Team (PSI, 2022). Research action recommendations included applying a probabilistic approach to quantify associated uncertainty providing context for model scenario outputs and sensitivity analysis presented to stakeholders. Examples provided were in the form of Monte Carlo analysis, which is beyond the scope of this review and current analysis. Earlier, Ahmed et al. (2019) provided a statistical calculation of RMSE that considered the differences in model runs following the equations of Snedecor and Cochran (1989) to ascertain uncertainty in dissolved oxygen non-compliance calculations. For the 2014 model year scenarios the authors calculated a RMSE of 0.041mg/L DO. This was much smaller than the 0.96 mg/L calculated for the existing conditions scenario alone and implies that errors are reduced overall in the process. Holtgrieve and Scheuerell (University of Washington) provided a review of the above method and alternative options for analysis as part of a written input requested from scientists in the region for a Puget Sound Workshop help in 2020. A number of statistical analysis methodologies were also proposed for consideration, and further potential challenges were identified in the current approach presented in Ahmed et al. (2019) for this calculation.

It is possible that the errors from the two model runs cancel out each other out in approaches used to calculate error for the regulatory application of the model. The consequence of this may be an underestimation of the uncertainty of deviations between the two scenarios applied in each calculation of non-compliance. However, without additional analysis, it is unclear to what extent model prediction uncertainty may be compounded in the model-to-model comparisons. The confidence level for assessing deviations between the two model runs should also be considered for assessing compliance in relation to the 0.2 mg/L threshold.

Future probabilistic approach to quantify associated uncertainty can provide context for model scenario outputs and sensitivity analysis presented to stakeholders. For example, the same maps and tables of results can be presented to stakeholders to quantify non-compliance for a nutrient reduction scenario - with the addition of associated levels of confidence a decision maker may want to consider as an acceptable level of error on each (e.g. differences between a 95 vs 80% confidence interval).

Process-specific error and sensitivity analysis: Processes of sediment/water column fluxes, carbon chemistry, and phytoplankton have a considerable impact on model results, and further error and sensitivity analysis of key parameters has been undertaken by the state and are considered in the following sections. Continuous monitoring data from buoys are one type of data set that has been underutilized in statistical analysis of model performance and may be beneficial for future process-specific error and sensitivity analysis (Figure 3). Furthermore, additional buoys have come online over the last few years in other parts of the region. Qualitative comparisons of measured buoy and modeled results are provided in Appendix J of

Ahmed et al. (2019) and include temperature, salinity, dissolved oxygen, and chlorophyll at the surface or bottom in 2008 or 2014 (e.g. Figure 3). However, statistical comparisons were not available in this report. Observations include three ORCA buoy stations in Hood Canal (Dabob Bay, Hoodsport, and Twanoh), one in South Puget Sound (Carr Inlet), and one in Puget Sound's Main Basin (Point Wells). Further qualitative comparisons are made at King County's moorings at Quartermaster Harbor, the Tacoma Yacht Club (QMH), and the Seattle Aquarium in the Main Basin.

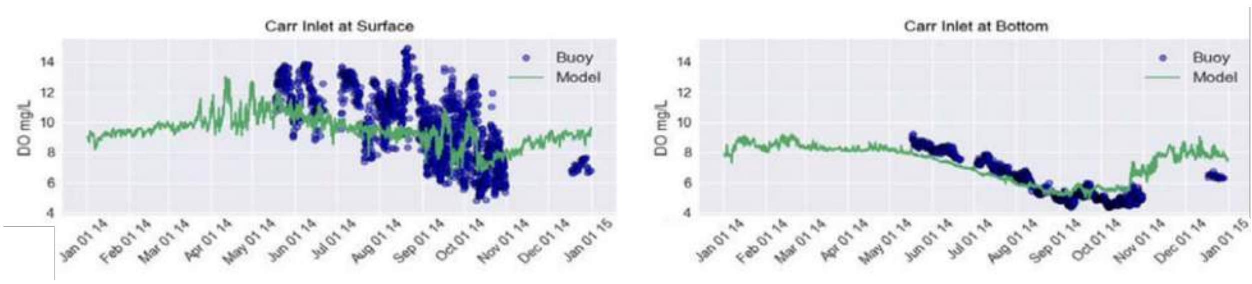

Figure 3. Example from Ahmed et al. (2019) of one of the plots comparing model predictions for 2014 overlaid on continuous monitoring data from the same year.

Several process-specific recommendations can be drawn from these results for future consideration in model performance and advancement:

- Given that the model seems to underestimate surface DO in certain embayments (Appendix 1), it is worth investigating contributing processes impacting these results. For example, if: (i) primary production and associated algal blooms are too low; (ii) air-sea exchange is too high; (iii) the representation of temperature, salinity, and stratification is adequate, and (iv) what related impacts there might be on vertical mixing with oxygen-deplete bottom waters during certain periods or events.
- Statistical investigation of vertical mixing and stratification would be readily addressable if the data that was used to produce D.O. profile plots were available and used for the purpose.
- Evaluation of model skill specific to the sediment/water column processes and exchange across the pycnocline to determine if the model resolution in embayments and regions of concern is high enough to resolve processes.
- In addition to temporal and embayment-specific analyses, comparisons specific to either above or below the pycnocline will be beneficial in future analysis. As will evaluation of the model's ability to predict observed changes across years that are different in loading and response.
- Levels of confidence in scenario results are not currently communicated as context to model predictions, and there is a lack of clarity as to the propagation of error especially considering model-to-model comparison used to determine regulatory compliance. Future approach to quantify associated uncertainty can provide context for model scenario outputs and sensitivity analysis presented to stakeholders, including associated levels of confidence a decision maker may want to consider as an acceptable level of error.

1.3 SEDIMENT/WATER COLUMN FLUXES

The Sediment Diagenesis Module structure and function are summarized on the Salish Sea Modelling Centre (SSMC) website, and detailed in Pelletier et al. (2017a) and Bianucci et al. (2018). The module is based on the Di Toro et al. (2001) model of Sediment Oxygen Demand

(SOD) and was integrated into the ICM portion of the Salish Sea Model (SSM) code (FVCOM-ICM). A review of the module and associated skill, error, and sensitivity analyses are presented here in three sequential sections:

- Sediment/water exchange parameterization, calibration, and model response
- Skill and error analysis and sensitivity testing from annualized data
- Seasonal specific skill and error analysis and sensitivity testing

Sediment/water exchange parameterization, calibration, and model response

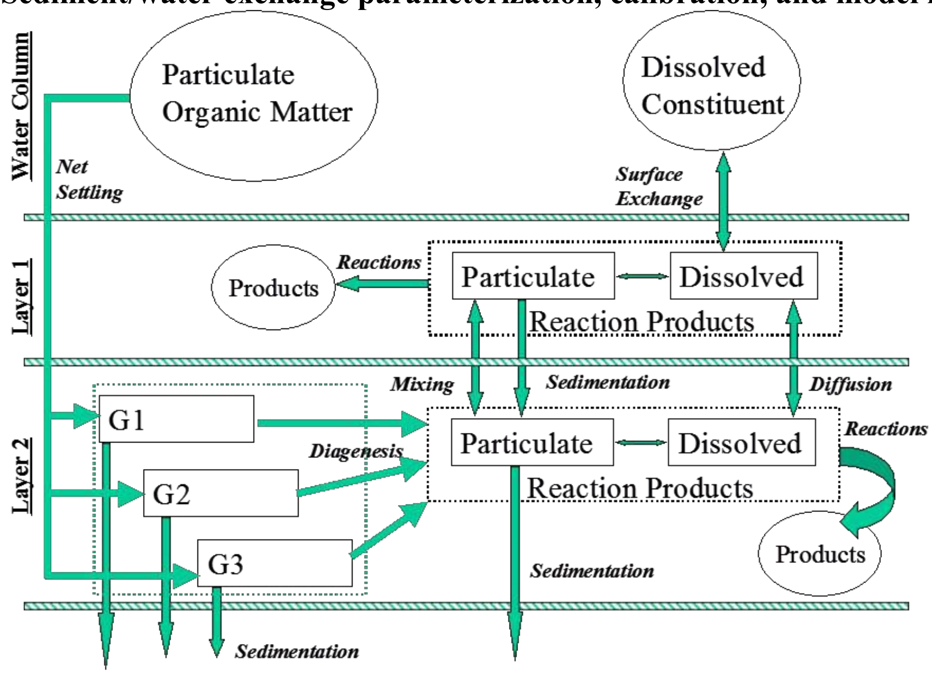

Figure 4. Basic Structure of the Sediment Diagenesis module of the Salish Sea Model (reproduced from Martin and Wool, 2013 and further described in the SSMC website documentation).

The model structure for the sediment diagenesis module involves 5 general processes: (1) the sediment receives depositional fluxes of POM (Particulate Organic Matter), as well as detrital phosphorus from the overlying water, (2) the decomposition of POM produces soluble intermediates that are quantified as diagenesis fluxes, (3) solutes react, transfer between solid and dissolved phases, and are transported between the aerobic and anaerobic layers of the sediment, or are released as gases (CH_4, N_2), (4) solutes are returned to the overlying water as sediment-water fluxes (NH_4, $NO_{2/3}$, PO_4, O_2), and (5) POM leaving the module through sedimentation and burial. FVCOM-ICM numerically integrates mass-balance equations for chemical constituents in two functional layers: an aerobic layer near the sediment–water interface of variable depth (Layer 1) and an anaerobic layer (Layer 2) below that is equal to the total modeled sediment depth (0.1 m) minus the depth of Layer 1. The model includes an algorithm that continually updates the thickness of the aerobic layer. The diagenesis of POM is modeled by partitioning the settling POM into 3 reactivity classes, termed the G model, where each class represents a fixed portion of the organic material that reacts at a specific rate. Oxygen levels in sediments impact nitrogen cycling, where nitrification only occurs in the aerobic layer (where oxygen is available), but denitrification can occur in both layers, with the assumption that anoxic micro-zones can occur in otherwise aerobic environments. In the aerobic layer, nitrification sensitivity to oxygen is modeled as a saturating function, where the nitrification rate declines with oxygen depletion (Testa et al. 2013). The model includes an oxygen-sensitive partitioning coefficient for phosphate sorption to particles, allowing high partitioning under oxygenated conditions (i.e., high P sorption) and low P sorption under low-oxygen conditions, allowing for sediment P release when hypoxia and anoxia occur (Testa et al. 2013). For further details on the sediment model used here, refer to Bianucci et al. (2018) and Pelletier et al. (2017a).

The annual proportion of sediment flux attributed to reductions in land-based nutrient loads for the year 2014 has been estimated for three flux parameters of the Sediment Diagenesis Module of the Salish Sea Model (Figure 5; Khangaonkar et al., 2018). In the absence of land-based loads, the authors found:

- -17% Sediment Oxygen Demand (SOD); a reduction in sediment oxygen consumption
- -10% NH_4; a reduction in the NH_4 efflux from sediments
- +20% Nitrate influx; the sediments consumed less Nitrate when loads were reduced

Results show a reduction of NH_4 efflux and SOD (i.e. oxygen consumption) from the sediment (e.g. less sediment recycling of NH_4), which would be expected at this domain-wide, annual scale with an elimination of all modeled land-based loads to the Salish Sea. In other words, lower nutrient loads lead to less algal growth and less organic deposition to sediments, thereby reducing oxygen consumption and NH_4 production associated with the breakdown of organic material. Furthermore, the modeled Nitrate influxes were lower (i.e., less negative) with this load reduction, which may indicate the model is responding to either (a) lower water-column Nitrate and thus less influx from the water column (i.e., smaller concentration gradient), and/or (b) more nitrification in sediment due to deeper oxygen penetration. Changes in sediment flux response for all three parameters were greatest within Puget Sound as well as near the mouth of the Frazer and Nooksack Rivers. In particular, responses were largest in the shallow waters of South Sound and Whidbey Basin. Terminal inlets in South Sound also show the most extensive contiguous areas of SOD and NH_4 reductions (e.g. NH_4 between approximately -0.2 and -0.4 $g/m^2/d$ in parts of Budd and Case inlet). The analysis included all cells within the domain including the shallow waters to the land boundary that are excluded in calculations of water quality non-compliance by Washington State.

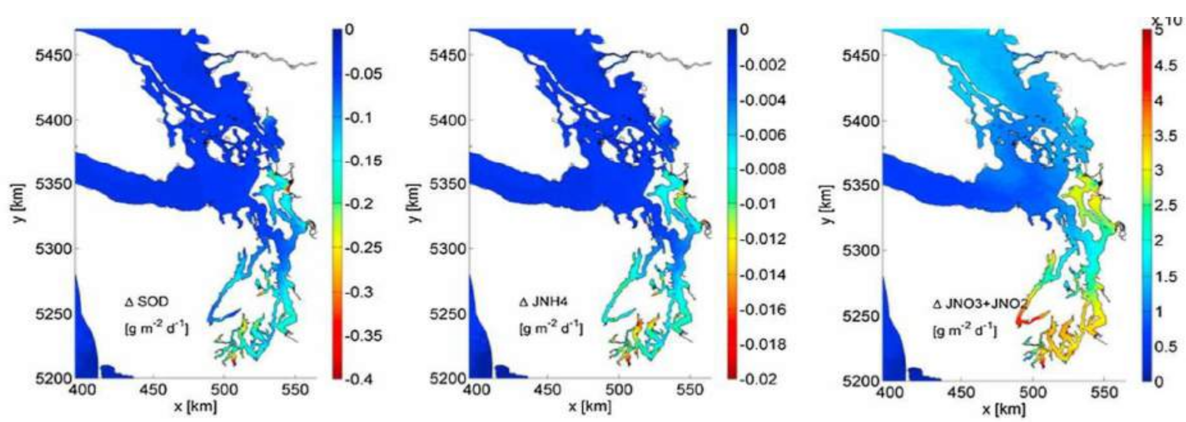

Figure 5. Change in sediment fluxes of DO, ammonium, and nitrate between the baseline 2014 conditions and the hypothetical scenarios without land-based loads (reproduced from Figure 15 of Khangaonkar et al. (2018)).

Sensitivity analysis and calibration of parameters of the Sediment Diagenesis Module
A number of sensitivity analyses and calibration steps for the sediment module have been undertaken and results are presented in Appendix E1 of Ahmed et. al. (2019) and Bianucci et al. (2018). Model parameterization remained the same across the operational version of the model used by the state (SSM v2.7ecy/v2, described in Table 1) through to the current Research Model (SSM v2.7d/v4), with parameters further described in Appendix E1 of Ahmed et al. (2019) matching Khangaonkar et al. (2018). Model parameters tested, and those finally used in the operational model, are summarized in Table 6 and Table 7.

Table 6. Parameters and rates for sensitivity analyses used in the states' operational model reproduced from Appendix E1 of Ahmed et al. (2019).

Parameter	**Currently Used**[1]	**Comparison for Sensitivity**
Settling Rates		
Labile (WSLAB) and refractory (WSREF)	5 m/day	10 m/day
For Diatoms (WS1)	0.4 m/d	0.6 m/d
For Dinoflagellates (WS2)	0.2 m/d	0.3 m/d
Nitrification: Half-saturation concentration of ammonium ion required for nitrification (KHNNT)	0.5 g/N/m3	1 g/N/m3
Mineralization: Minimum heterotrophic respiration rate (KLDC)	0.025 d	0.05 d

[1] Matching that published in Khangaonkar et al. (2018)

Table 7. Parameters and rates for sensitivity analyses used in the development of the states' operational model, reproduced from earlier work in Bianucci et al. (2018).

Parameter	**Currently used**	**Comparison for Sensitivity**
Freshwater at ambient seawater concentration	Including Freshwater (FW) in FVCOM and ICM (baseline)	Including FW only in FVCOM
High DIC at the Ocean Boundary	Baseline	DIC at SJF Ocean Boundary 2% from baseline (+40mmol m-3)
High DIC in freshwater	Baseline	High DIC in FW 2%

In summary, key points for consideration on the **sediment/water exchange parameterization, calibration, and nutrient loading response** include**:**

- Parameters in the sediment module are applied uniformly throughout the model domain using default values of the original sediment oxygen model adapted from Di Toro et al. (2001). These values are similar to those applied in Chesapeake Bay (Testa et. al., 2013).
- Calibration and sensitivity tests of key settling, nitrification, and mineralization rates were undertaken and applied with uniform rates across the domain (Table 6). Further sensitivity testing included salinity and carbon loadings (Table 7). In these studies, the authors examined results at a domain-wide, annual scale, and did not find improvements in the global model performance of DO, concluding default values from Khangaonkar et

al. (2018) should be used going forward. Analysis of model performance results specific to shallow water areas where low DO is of concern, and for times of the year with high sediment/water flux activity, may further verify and build confidence in the current application of the model for calculating load reduction scenarios on DO.

- The Sediment Diagenesis component of the Salish Sea Model responded as expected to modeled reductions in land-based nutrient loads in terms of the direction of change of key parameter fluxes when examined domain-wide and at an annual scale. Modeled elimination of loads from the 2014 existing conditions scenario resulted in decreased oxygen consumption and ammonium efflux. Furthermore, responses were greatest in terminal inlets and near river mouths where differences would be expected to be more pronounced. Nitrate influx was also lower (less negative in this case) domain-wide, with the greatest reductions in shallow waters and parts of the Hood Canal.

Skill and error analysis and sensitivity testing from annualized data
Domain-wide comparison of model results across years:
A comparison by Ahmed et al. (2019) of modeled outputs for 2006 and 2008 yielded the following annual range in SOD fluxes across the model domain:

- 2006 existing conditions: 0.2-1.4 O_2 $g/m^2/d$
- 2008 conditions: 0.2-1.3 O_2 $g/m^2/d$
- Approximate 0.4 O_2 $g/m^2/d$ peak difference between existing and reference conditions at across both years (presumed to be the direct difference in daily or monthly output rather than the annual range in outputs presented above).

Results appear similar domain-wide for 2006 and 2008, however, additional analysis would be required to quantify how representative these years are of the spectrum of inter-annual variability of loading across a wider range of conditions. This would require further investigation. Ahmed et al. (2019) further assessed modeled SOD for the years 2006, 2008, and 2014, comparing to measured data in a reassessment of annual comparisons an earlier synthesis of work done by the authors in Pelletier et al. (2017a), and using additional seasonal data at three locations at Bellingham Bay (Merritt 2017). For the updated review of annual model outputs, little change was seen for different modeled years Sound-wide (Figure 3.1 in Appendix 3), although differences were noted in comparison to site- and seasonal-specific measured data available in Merritt (2017), discussed following.

Modeled to measured comparisons at sites, and aggregated domain-wide:
Annual comparisons of measured and modeled data (Pelletier et al., 2017a) are summarized in Table 8 and presented in Table 9. The analysis included 25 sites across a range of depths, mainly derived from flux chamber measurements. Data was drawn from the synthesis of regional measurements of O_2 and N fluxes published earlier in Sheibley & Paulson (2014).

Table 8. Summary statistics across 24 locations where model-predicted and observed sediment/water column fluxes were compared in Pelletier et al. (2017a).

Parameter	**Modeled predictions 2006 (Pelletier et al. 2017a) – annual**			**Observed data (Sheibley and Paulson, 2014) – specific time period**			**Compared annually to a specific time period means at each site**
	Mean	Min	Max	Mean	Min	Max	RMSE
SOD (O_2) g O_2/m^2/d	1.23	0.32	4.41	0.63	-0.03	1.72	0.73
Ammonium (NH_4) g N/m^2/d	0.060	0.000	0.180	0.056	-0.004	0.189	0.038
Nitrate + Nitrite (NO_3) g N/m^2/d	-0.015	-0.025	0.008	-0.009	-0.081	0.021	0.014

Table 9. Comparison of model-predicted and observed sediment oxygen demand. Reproduced from Table 2 of Pelletier et al. (2017a).

		Model predictions (gO2/m^2/d)				**Observed data (gO2/m^2/d)**			
Stations	Node	Year	Mean	Min	Max	Year (Month)	Mean	Min	Max
BUDD05	8615	2006	1.60	0.93	2.00	2007 (Sep-Oct)	0.44	0.08	0.99
BUDD15	8374	2006	1.54	0.95	1.89	2007 (Sep-Oct)	0.82	0.63	1.13
BUDD25	8372	2006	1.43	0.91	1.75	2007 (Sep-Oct)	0.62	0.50	0.70
CARR05	8016	2006	1.01	0.73	1.33	2007 (Sep-Oct)	0.51	0.33	0.79
CARR15	7950	2006	1.05	0.82	1.37	2007 (Sep-Oct)	0.69	0.64	0.77
CARR25	7846	2006	1.26	1.06	1.45	2007 (Sep-Oct)	0.25	0.21	0.27
CASE05	8858	2006	0.88	0.59	1.07	2007 (Sep-Oct)	0.33	-0.03	0.69
CASE15	8756	2006	1.08	0.73	1.29	2007 (Sep-Oct)	0.53	0.39	0.62
CASE25	8656	2006	1.28	0.84	1.54	2007 (Sep-Oct)	0.70	0.49	1.03
ELD05	8741	2006	1.34	0.66	1.89	2007 (Sep-Oct)	1.49	1.23	1.71
ELD15	8579	2006	1.48	0.78	2.01	2007 (Sep-Oct)	0.94	0.89	1.02
ELD25	8397	2006	1.60	1.00	1.99	2007 (Sep-Oct)	0.74	0.22	1.08
QMH_A	6817	2006	1.30	0.94	1.69	2010 (Sep)	1.72	1.72	1.72
QMH_B	6783	2006	1.19	0.89	1.44	2010 (Sep)	0.72	0.72	0.72
QMH_C	6684	2006	1.16	0.97	1.29	2010 (Sep)	0.64	0.64	0.64
QMH_D	6645	2006	1.14	0.99	1.25	2010 (Sep)	0.95	0.95	0.95
QMH_E	6574	2006	1.20	1.05	1.27	2010 (Sep)	0.16	0.16	0.16
BD-2	8374	2006	1.03	0.36	1.96	1996-7 (Sep-Sep)	0.57	0.26	0.92
LOON-1	8492	2006	1.03	0.41	1.87	1996-7 (Sep-Sep)	0.59	0.36	1.01
BA-1	8615	2006	1.24	0.54	2.24	1996-7 (Sep-Sep)	0.57	0.32	0.87
BI-5	8775	2006	2.37	1.26	4.41	1996-7 (Sep-Sep)	0.58	0.17	1.14
DABOB	5380	2006	0.61	0.32	0.97	1981-2 (Jan-Jan)	0.17	0.07	0.36
HOLMES	4786	2006	0.95	0.94	0.97	1993 (Aug)	0.14	0.12	0.16
CARKEEK	4276	2006	0.64	0.52	0.74	1982 (Jun)	0.17	0.17	0.17
All stations mean, min, or max			1.23	0.32	4.41		0.63	-0.03	1.72

[1] The stations in this table are located in:
Budd Inlet (BUDD05, BUDD15, BUDD25, BD-2, LOON-1, BA-1, BI-5)
Carr Inlet (CARR05, CARR15, CARR25)
Case Inlet (CASE05, CASE15, CASE25)
Eld Inlet (ELD05, ELD15, ELD25)
Quartermaster Harbor (QMH_A, QMH_B, QMH_C, QMH_D, QMH_E)
Dabob Bay (DABOB)
Holmes Harbor (HOLMES)
Near Carkeek (CARKEEK)

Limited regional comparisons of measured to modeled sediment N fluxes have been available thus far for the Salish Sea Model, with the most comprehensive analysis undertaken at the same 24 sites as was done for DO in Pelletier et al. (2017a). The annual aggregate model results from this study (Table 8), show reasonably small RMSE results for the NH_4 mean fluxes of 0.06 Ng/m^2/d (RMSE = 0.038), and NO_3 mean of -0.015 Ng/m^2/d (RMSE = 0.014). Sediment incubation data from Rigby (2019) are available across 41 sites in 2018 for many key sediment/water flux parameters. These data are reproduced here in Appendix 3, and now published by Santana and Shull (2023). Measured data from all sites from Rigby (2019) are compared to annual aggregated model results (Table 10). Similar, but slightly lower, annual mean and range of all fluxes are observed for the 2014 model year, compared to 2006 (Table 8).

As expected, measured data specifically for April and early May aggregated across the 41 sites are considerably lower than annual measurements for SOD and Ammonium, indicating the importance of a seasonally-specific model performance assessment. For example, the model prediction of sediment-water fluxes is relatively close to observations if just the spring period is considered (Figure 7). A subset of the 2018 observations are compared to the 2014 model output in the following section on seasonal-specific skill and error analysis and sensitivity testing.

Table 10. Summary statistics across 41 locations where model-predicted sediment/water column fluxes were compared to data available from Rigby (2019). Appendix 3 includes site source data.

Parameter	**Modeled predictions 2014 (Current study) – annual mean**			**Observed data (Rigby, 2019)* - April/early May**		
	Mean	Min	Max	Mean	Min	Max
SOD (O_2) g/m^2/d	0.821	0.134	3.709	0.426	0.167	1.227
Ammonium (JNH_4) g/m^2/d	0.040	0.002	0.233	0.003	-0.006	0.017
Nitrate + Nitrite (JNO_3) g/m^2/d	-0.011	-0.022	0.007	-0.006	-0.027	0.0001

*Measured data from April and early May 2018. SOD was originally presented as a negative number in Rigby (2019), representing a net negative sediment-water O_2 flux (i.e., sediment uptake). Here, the Rigby (2019) values are multiplied by -1 to present those data in the convention of SOD consistent with the other values we present.

In summary, key points for consideration on **skill and error analysis and sensitivity testing from annualized data** include:

- Across the results reviewed here comparing annual modeled SOD to measured observations, modeled results were within a reasonable expected range of approximately 0.1 to 4 O_2 g/m^2/d across the domain, and showed a consistent overestimation of mean and gradient of SOD (O_2 consumption):
    - o The most extensive comparison of modeled to measured SOD consumption in Puget Sound (Pelletier et al., 2017a) reflected this bias across the mean calculated at 22 of the 24 sites, and in the system-wide aggregation of mean SOD. A modeled mean of 1.23 vs 0.63 O_2 g/m^2/d observed mean was calculated across all sites; Table 8). The associated RMSE was 0.64 g O_2 /m^2/day.
    - o Later analysis by Ahmed et al. (2019) comparing modeled 2006, 2008, and 2014 results with an expanded observation data set (including Merritt, 2017), again

showed similar results, and a model overestimation of annual SOD compared to measured (approximately +30%; Figure 3.1 in Appendix 3).
  - In all cases observed data was drawn from a specific number of days, or in the best case a month of measurements, and from different years to the modeled annual data compared, which almost certainly drives the bias in annual aggregate model results compared to observations from a specific season. Thus, more refined, seasonally-specific model evaluations are needed.
- Comparison of annual modeled SOD response for different years, and scenarios of nutrient load reductions for those years, showed a very similar domain-wide response (<1% difference 2006/8), and 0.4 O_2 g/m^2/d peak difference in SOD when nutrient loads were reduced to estimated pre-anthropogenic levels. It is unclear how well these two years represent the spectrum of inter-annual variability of loading longer-term. However, looking at the modeled loadings for these two years, 200 has approximately 25% lower DIC and 15% lower DIN loading than 2006. The two years have a <5% difference in wastewater treatment plant DIN (Table 4.1, Appendix 4).
- Sensitivity analysis comparing and quantifying the impact of inter-annual variability on biogeochemical processes will further support the verification of the Salish Sea Model, and in particular the representation of sediment/water fluxes. Ideally, sensitivity testing could include model years or sensitivity scenarios where loadings are at opposite ends of the spectrum of interannual variability for key inputs/processes affecting DO, such as nutrients and hydrodynamic differences in ocean loading and rivers.

Seasonal-specific skill and error analysis and sensitivity testing

Comparison of seasonally specific observations to modeled data for the same time period has been undertaken at three locations in Puget Sound. The results from the comparison at these three relatively shallow-water (<40 m) sites in Bellingham Bay (Figure 6; Merritt, 2017) showed a difference of -13.66 to 42.62% across all three model years compared to observations in 2017 from the same month (Table 11). The site located further from the shore had a smaller predicted difference of mean modeled results relative to observed data when compared to the two sites closer to the shore which further over-predicted observed Sediment Oxygen consumption. At the time of writing, newly available sediment incubation data from Rigby (2019) were available across 41 sites for many key sediment/water flux parameters (reproduced in Appendix 3). A subset of 2018 observations for SOD, NH_4, and NO_3 at sites in three Puget Sound inlets was compared to 2014 model outputs from the same time period, and throughout the year (Figure 7). Annual aggregated results are presented in Table 10.

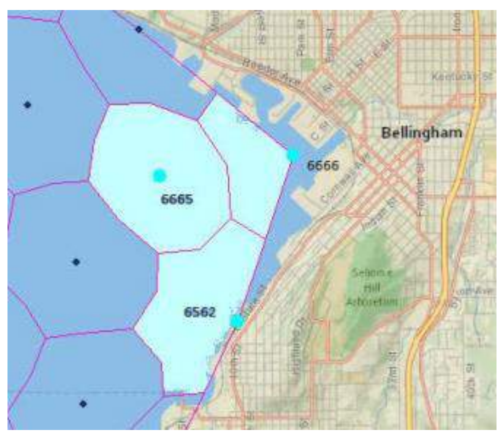

Figure 6. Map of Bellingham Bay showing model grid cells (light blue) that were compared to Merritt (2017) observations (reproduced from Figure I3 of Appendix I of Ahmed et al. (2019)).

Table 11. Comparison of observed and predicted sediment oxygen demand (O_2 g/m2/day) at model grid cells in Bellingham Bay. Reproduced from Table I1 of Appendix I of Ahmed et al. (2019) which provides details on the method and further statistical analysis applied.

Model grid cell identifiers	**6562**	**6666**	**6665**
June 2017 Observations			
Mean	0.71	0.88	1.25
Standard deviation	0.21	0.07	0.28
Coefficient of variation	29.97%	8.28%	22.02%
June-2006 Predictions			
Mean	1.01	1.15	1.21
Standard deviation	0.04	0.05	0.05
Percent difference of means compared to observations	42.62%	31.29%	-3.66%
June-2008 Predictions			
Mean	0.94	1.06	1.12
Standard deviation	0.05	0.07	0.07
Percent difference of means compared to observations	32.84%	21.41%	-10.74%
June-2014 Predictions			
Mean	0.88	1.05	1.08
Standard deviation	0.05	0.07	0.07
Percent difference of means compared to observations	24.19%	19.62%	-13.66%

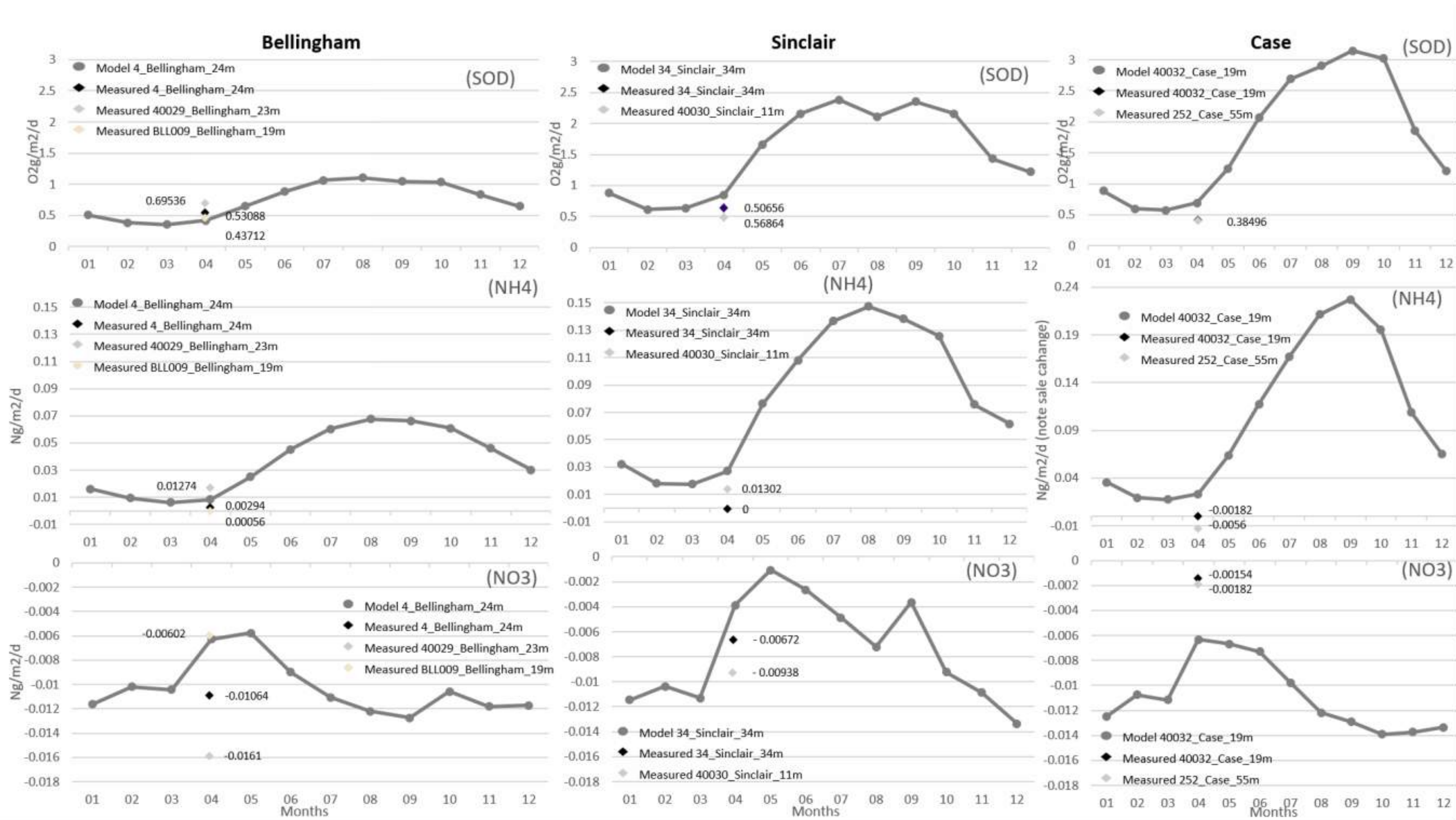

Figure 7. Modeled 2014 sediment/water fluxes at inlets over the year 2014, overlaid with Rigby (2019) site measurements taken for the same time of year in 2018.

In summary, key points for consideration on the **seasonal-specific skill and error analysis and sensitivity testing**, include:

- Validation of modeled results to measured data for specific seasons and locations has thus far been limited to three nearshore sites in Bellingham Bay for SOD. Results show a variation in response of SOD ranging from -13.66 to +42.62% across all three sites and three model years (2006, 2008, 2014) compared to observations in 2017; with better results at the deeper versus shallow-water sites (Table 11). Despite differences in the magnitude of modeled and observed flux, the spatial gradient of the fluxes is consistent between the model and the observations. Ahmed et al. (2019) indicated the following for further model improvement and evaluation consideration, particularly in shallower waters:
    - Examination of high organic carbon depositional environments (that may influence remineralization dynamics and lower SOD), as well as settling and burial rates in these locations, which are currently parameterized uniformly across the model domain.
    - Once observational data are available to improve model parameterization, then *…resuspension of particulates to the water column is another important factor, but not separately resolved in the model.*
    - Improving river loading observations may… *lead to improvements in SOD predictions, particularly in areas near river mouths or at sheltered embayments*
- No seasonal-specific evaluation of measured to modeled data has been undertaken for NH_4 and NO_3 fluxes, though measured data has been compared to annual model outputs from different years (described earlier).
- Given the availability of seasonal and site-specific SOD, NH_4, and NO_3 flux data in Santana and Shull (2023) and Rigby (2019), further model runs and performance assessments for different years can utilize this data set (reproduced in Appendix 3 for 41 sites in Puget Sound). This can additionally include Merritt (2017) and earlier Sound-wide data compiled in Sheibley & Paulson (2014) (summarized in Appendix 5):
    - Analysis can address three current model performance assessment gaps: First, seasonal and spatial-specific validation of SOD (including many of the shallow water areas where low-DO is a concern). Second, validation of N fluxes (NH_4 and NO_3) at those times and locations. Third, validation of any further related parameters and processes with available measures of carbon, phosphate, silicate, pH, and estimates of denitrification available.
    - Although Rigby (2019) provides a substantial step forward in sediment-water observations in Puget Sound, further sampling campaigns are critical to fill observation gaps. In particular in further nearshore locations, and over the year with high levels of sediment flux activity.
- Initial comparisons presented here (Figure 7) for Rigby (2019) observations in 2018 and modeled outputs in 2014 show the following across three inlets:
    - Modeled and measured SOD results for each inlet are reasonably similar, for the early April time period where observed data is available.
    - As planned by the researchers, observations were made just before the period of high productivity across all sites (spring through late autumn). Higher sustained productivity is represented in modeled results during this later period for each of the three embayments examined here, ranging in both timing and magnitude of

SOD response. Daily mean SOD ranges from Bellingham Bay (≈ 0.4 to 1 O_2 g/ m^2/d) to Sinclair inlet (≈ 0.5 to 3 O_2 g/m^2/d).
  - The large variation in modeled SOD and sustained period of predicted high productivity may contribute to the model bias identified in earlier comparisons to annualized measured data from a single season (Tables 8 and 10). This is illustrated in the overlaying of measured to modeled outputs in Figure 7. Further seasonal-specific skill assessment with available datasets may address the source of model bias identified in results thus far.

1.4 PHYTOPLANKTON AND PRIMARY PRODUCTION

Ahmed et al. (2019), Appendix H, summarized primary productivity data published in Puget Sound, and the key papers that explore the driving influences on temporal and spatial variability; namely vertical mixing and density-driven stratification, the influence of bathymetric features and local winds, and variations in solar radiation (e.g. Winter et al., 1975). Very little Gross Primary Production (GPP) data is available to assess the performance of the model. Of the data reviewed, spring peaks ranged from 4.8-10 g C/m^2/day, and were summarized as follows: *Welch (1968) reported 4 to 5 g C/m^2/day during the peak annual bloom in 1965 near the mouth of the Duwamish. Newton et al. (1998) reported almost 6 g C/m^2/day peak GPP in Budd Inlet. Campbell et al. (1977) reports spring peaks equivalent to 5.6, 5.8, and 4.8 g C/m^2/day during 1975, 1966, and 1967, respectively, in a main basin station off of West Point. The highest peak value reported at that station occurred at the end of August in 1975 and was close to 10 g C/m^2/day.*

Ahmed et al, (2019) further compared Salish Sea Model outputs in 2008 to observed data at three locations (Admiralty Inlet, Possession Sound, and West Point) for the years 1999 to 2001, published by Newton and Van Voorhis (2002), identifying:

- An average annual range of 1.89g to 3.36 g/m^2/day across all sites and years
- Annual peaks of observed data were approximately two times greater for all years (Figure 5), compared to the modeled data for the same time period in 2008 which was noted as ranging from 6.8-11.3 g C/m^2/day). The authors stated this may reflect lower productivity in 2008 indicated in longer-term chlorophyll data sets examined for the Central Basin (Figure 9).
- Measured and modeled data at the West Point site in Central Sound were higher than the other two stations further to the north.

The

Table 12. Comparison of Observed and Predicted Annual Average Daily Gross Primary Production (mg C/m^2/day) at Central Puget Sound Sites. All observations cited in this table are from Newton and Van Voorhis (2002). Reproduced from Table H1 of Appendix H of Ahmed et al. (2019).

Years	Admiralty Inlet	Possession Sound	Main Basin-West Point
1999 (C-14 uptake Observations)	1886	2127	2559
2000 (C-14 uptake Observations)	2694	2135	3460
2001 (C-14 uptake Observations)	3356	3525	3551
2008 Salish Sea Model	1894	1330	1970

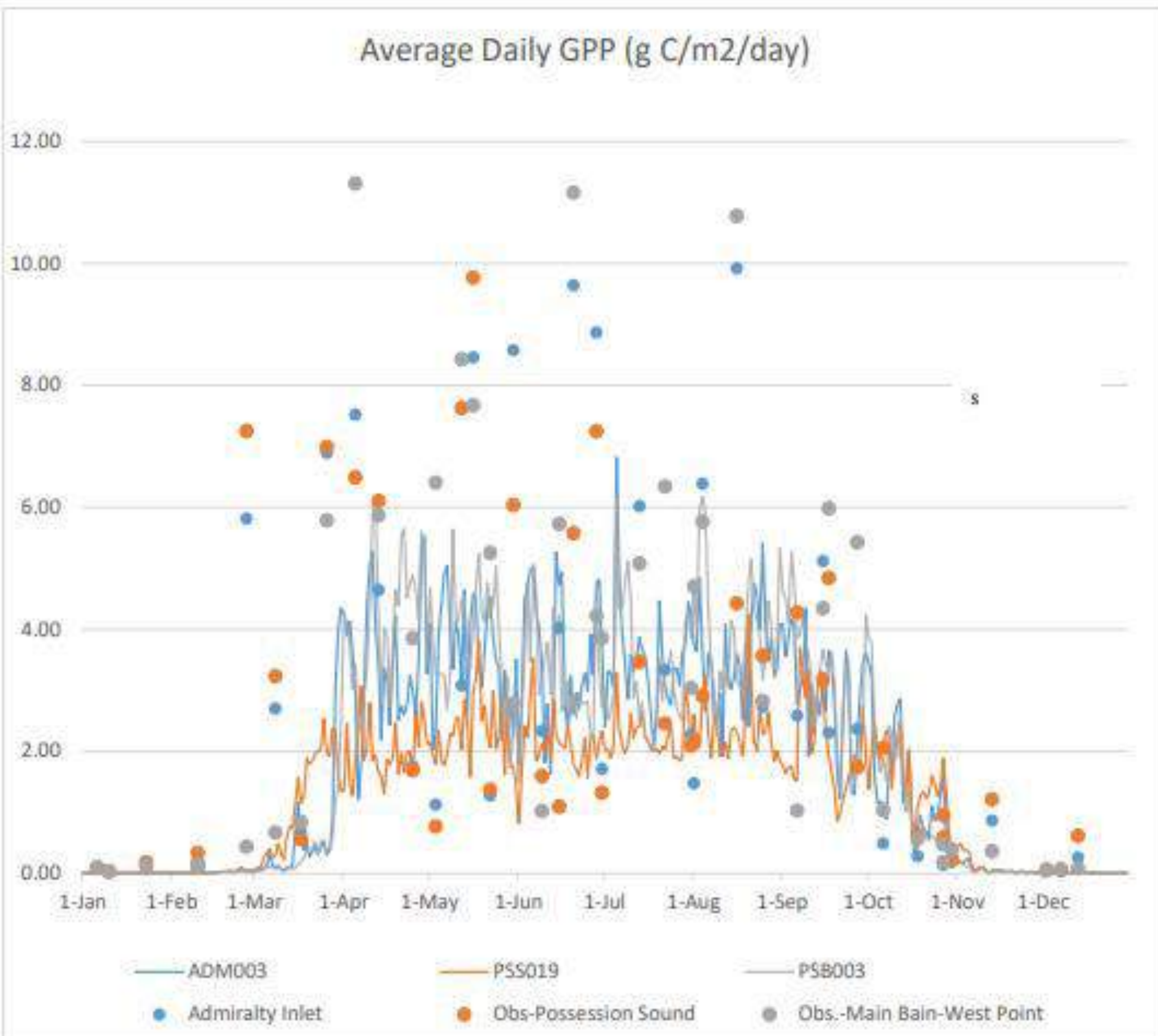

Figure 8. Comparison of 2008 average daily GPP Salish Sea Model output for Admiralty Inlet (blue line), Possession Sound (orange line), and Main Basin-West Point (grey line), with observations from 1999 to 2011 at Admiralty Inlet (blue circle), Possession Sound (orange circle), and Main Basin-West Point) grey circle). Reproduced from Figure H2 of Appendix H of Ahmed et al. (2019).

Very little longer-term data on primary production is available. Chlorophyll-a data from Central Puget Sound showed variation from year to year (Figure 9) and across the years 1998-2016 (approximately 3.5 ug/L in 2008 to 10 ug/L in 2014).

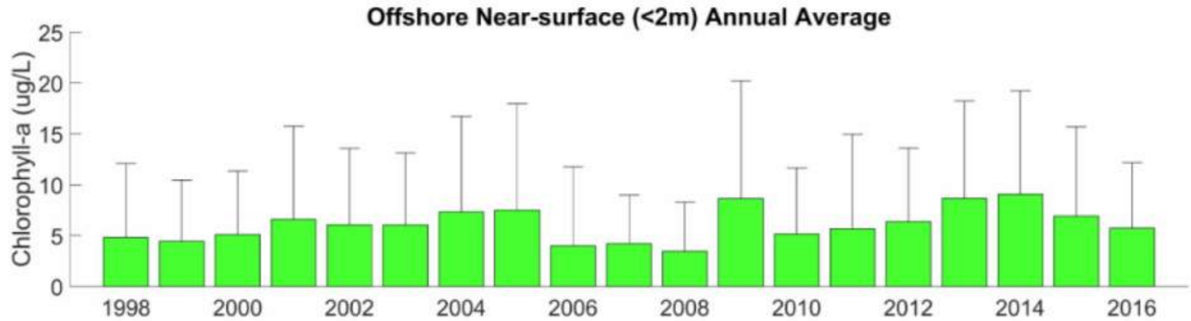

Figure 9. Annual average chlorophyll based on monthly data from Central Puget Sound (Jaeger and Stark, 2017). Reproduced from Figure H1 of Appendix H of Ahmed et al. (2019).

Further sensitivity analysis by Ahmed (2019) was undertaken specifically to phytoplankton dynamics and role in biogeochemical cycling, including:

- Aeration coefficients
- Algal kinetics: Light limitation
- Algal kinetics: Half-saturation rate for Nitrogen uptake (KHn)
- Fractionation of particulate organic matter due to predation
- Settling rates for diatoms and dinoflagellates

Earlier, sensitivity analysis was undertaken by the state on algal and organic particle settling rates, nitrification, and mineralization (Table 13) – all of which largely were left with the same parameterization published in Khangaonkar et al. (2018).

Table 13. Variables used in sensitivity test runs for 2008 and resulting skill metrics. Reproduced from Table 8 of Ahmed et al. (2019).

Item	Variable	Description	Current value	Sensitivity test	DO RMSE	R	Bias
1	Existing	Using rates and constants from Khangaonkar et al. (2018)			0.98	0.85	-0.53
2	ALPHMN1, ALPHMN2	Initial slope of photosynthetic production vs. irradiance (alpha) for algal group 1 and 2	12, 12	8, 10	0.99	0.84	-0.51
3	KHN1	Half-saturation concentration for nitrogen uptake for algal group 1	0.06 g/m^3	0.02 g/m^3	0.98	0.85	-0.55
4	KHNNT	Half-saturation concentration of NH_4 required for nitrification	0.5 g/m^3	1 g/m^3	0.95	0.85	-0.5
5	OBC150	Open boundary depth truncation	200 m	150 m	0.79	0.86	-0.16
6	Item 2 through 4 combined	ALPHA1, ALPHA2, KHN1, KHNNT	12, 12, 0.06, 0.5	8,10, 0.02, 1	1.1	0.83	-0.67

In summary, key points for consideration on the phytoplankton and primary production model performance and sensitivity analyses include**:**

- As the measured and modeled data are from different years, inter-annual differences may contribute to the lower annual modeled results for 2008 vs the observed annual average in 1999-2001 (Table 12). This is supported by the lower annual average chlorophyll data observed for 2008 vs the longer time series of 2008-2016 in the Central basin (Figure 9). Future work might consider:
    - Comparisons of existing or future Gross Primary Production (GPP) data from the same years, where available
    - If inner-annual differences are nutrient load dependent, and if a simplified relationship of loading to productivity can be approximated. The 35-80% higher GPP in measured years 2000/2001 to the year 1999 may be due to higher nutrient inputs, as indicated by the higher chlorophyll biomass (Figure 8).
- GPP peaks for observed data appear higher than the modeled results, while summer lows are also lower (Figure 8). Re-analysis of results from different years such as the existing observed (1999-2001) to modeled (2008) GPP data in Figure 8, could also consider a comparison of integrated calculation of measured outputs (i.e. area under the curve) across the years.
- Much of the variation in the GPP observed over the year (Figure 8) is likely due to differences in biomass. If possible, future comparisons of GPP could be biomass specific to remove this part of the variation. For example, if GPP uses chlorophyll, then use the ratio of GPP/chlorophyll in the model to the observed time series.
- Re-assessing the domain-wide sensitivity analysis results (Table 13) to determine season and location-specific statistics for areas where low DO is a concern may further increase confidence in application in those areas and times of the year. Furthermore, this analysis may identify data gaps in monitoring data and priorities for model development.

2 RECOMMENDATIONS: UNCERTAINTIES AND OPPORTUNITIES TO IMPROVE CONFIDENCE IN THE APPLICATION OF THE SALISH SEA MODEL

The Model Evaluation Group (MEG) and Puget Sound Institute (PSI) identified recommendations that can improve stakeholder confidence in both the regulatory model application and the wider eutrophication and water quality targets of Puget Sound Partnership's Recovery Actions. Recommendations are based on the available literature and analysis presented in Section 1, priorities identified in a series of regional workshops on scientific uncertainties, as well as ongoing and planned activities by the local science community.
Recommendations are intended to define a need and expected outcome of further scientific investigation within each of the modeling-related topics below (*in italics).* By prioritizing these opportunities by topic, our hope is it will make it easier for scientists and managers in the region to collaborate on advancing the recommendations. Depending on resources, Puget Sound Institute may be able to further collaborate.

The short-term recommendations focus on further model-related analysis and/or model performance, sensitivity and uncertainty assessment using available measured data and existing model outputs or run input files. These consider the modeling capacity currently available with collaborating partners and suggest specific activities. Longer-term recommendations are broader, requiring more complex investigation and longer time frames to define potential project leads and work plans. They focus on building on wider monitoring and modeling efforts, and stakeholder engagement processes.

Sediment/water fluxes:
- Rec. 1 Examination of modeled sediment flux responses to changing nutrient loading
- Rec. 2 Further validation of the sediment module using measured data
- Rec. 3 Analysis of Salish Sea Model sediment exchange model spin-up and stability

Primary production and phytoplankton:
- Rec. 4 Monthly budgets of primary production, N and C in inlets, and role of ocean loading and riverine discharge variability in limiting primary production

Interannual variability and consideration of Salish Sea Model versions and multi-model approaches:
- Rec. 5 Observed riverine, wastewater treatment plant, and ocean long-term variability and regional analysis
- Rec. 6 Comparison of two versions of the Salish Sea Model and available model year outputs
- Rec. 7 1999-2019 data for longer model runs using multiple models, and further analysis of interannual variability of available forcing data

2.1 SEDIMENT-WATER FLUXES

2.1.1 Rec. 1 Examination of modeled sediment flux responses to changing nutrient loading

Purpose and outputs: The purpose of this proposed analysis is two-fold. First to quantify the sediment-water exchange component of N and C in seasonal and annual budgets based on available Salish Sea Model scenario runs. Second, using results from scenario runs, further quantify the temporal and spatial variability of modeled flux response through the Sound. Modeled sediment-water column nitrate, ammonium, and SOD fluxes can first be investigated for two model scenarios following and expanding on the analysis of Khangaonkar et al. (2018); comparing the existing conditions in 2014, and the modeled pre-anthropogenic loading estimates (reference scenario) shown in Figure 5. A comparison of results can further verify the model's capacity to represent the range of sediment flux response to loading and forcing conditions that might be expected both spatially and temporally between these two scenarios. Further, modeled sediment-water column fluxes can also be compared to bottom water nitrate, indicators of phytoplankton in overlying waters (Net Primary Production), and circulation and physical forcing (temperature and salinity). Where available, modeled nutrient loads from terrestrial sources should also be summarized monthly at a basin scale (discussed following), and considered in the examination of sediment flux response to changing loadings.

Proposed methodology: Using the initialization files for the existing and reference condition scenarios in Ahmed et al. (2021), the Salish Sea Model can be run for the year 2014, saving daily averaged sediment-water flux concentration outputs for dissolved oxygen, dissolved N, particulate C and N, and sulfide, among others. The proposed analysis will examine three sediment-water fluxes processes important to nutrient budgets, each with a set of parameters within the Salish Sea Model:

i) Organic sediment settling
ii) Sedimentation (or burial)
iii) Sediment-water fluxes including remineralization

(i) <u>Organic Sediment Settling</u>: deposition from the water column to sediments of all Particulate Organic Matter (POM) including nitrogen carbon and silicate from all forms of detritus and POC, and algal biomass that leaves the water column and reaches the sediment. In this analysis, we propose examining the 10 identified terms of net settling of POM representing the liability fractions of each species of organic N, C, P, and Si accounted for in the model (Table 6.1 in Appendix 6).

(ii) <u>Sedimentation of POC and PON</u>*:* The Salish Sea Model computes a total PON and POC in layer 2 that can be coupled to the prescribed sedimentation rate parameter to calculate what permanently leaves the system through burial (Table 6.1 in Appendix 6).

(iii) <u>Sediment-water fluxes</u> of SOD, NO_3, and NH_4 as well as sulfide, and methane (Table 6.1 in Appendix 6).

2.1.2 Rec. 2 Further validation of the sediment module using measured data

Purpose and outputs: Ideally, the SSM would be run for periods other than the three years calibrated, and performance assessed against the measured data for all modeling processes, including those identified for the sediment fluxes following. However, as an initial phase of work using newly available measured data, the following proposed skill assessment of sediment modeling outputs for the current calibrated model would extend the earlier studies by Ahmed et al. (2019) and Pelletier et al. (2017) through:

a) Expansion and provision of a geo-referenced regional validation data set readily available for download in a format useful for further analysis by the wider scientific community. This can include both N and DO, adding new sites for validation of the SSM.
b) Seasonal variations in N fluxes, investigating three locations from available the literature.
c) Spring-time DO and N fluxes observations and model outputs across 40 shallow water embayments and deep-water sites.
d) Embayment-wide delineations added to the geo-referenced regional validation data set (a) and used for model output comparison to measured DO and N, seasonally and for springtime.

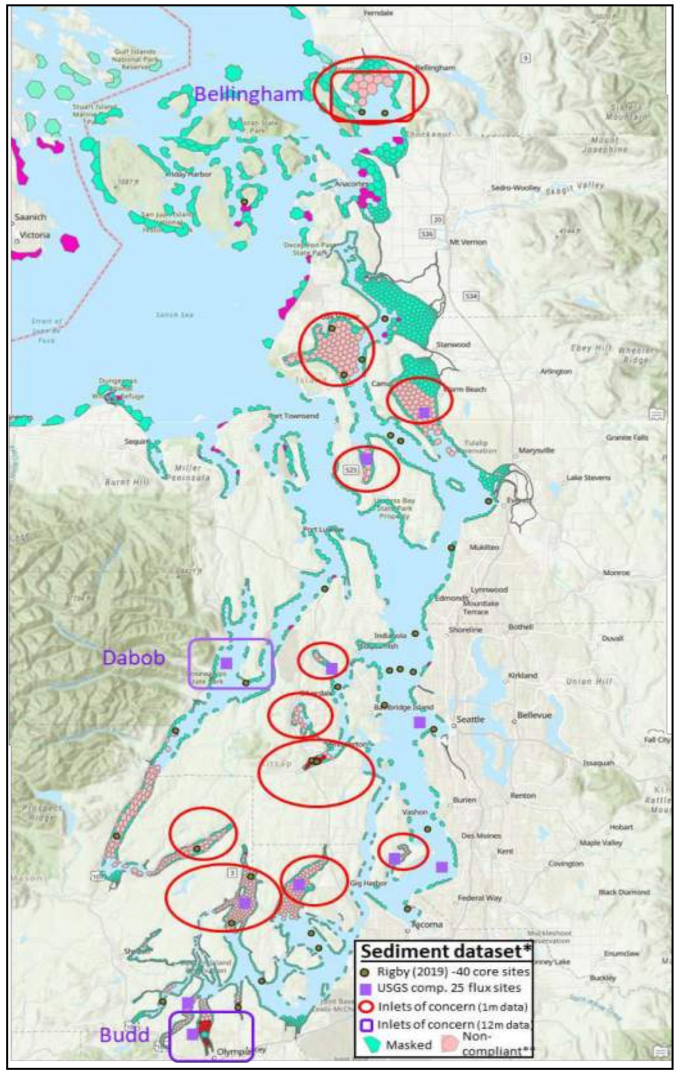

Figure 10. Locations selected for: Rec. 1a, expanded regional flux site validation (purple squares); Rec. 2b further seasonal validation (3 purple boxes); Rec. 2c Spring time comparisons (brown circles), and Rec 2d embayment wide comparisons (3 red ovals, including Bellingham). Reproduced from slides presented at the Science of Puget Sound Water Quality Sediment Exchange Workshop, October 17, 2022. See presentation for further details.

Although observed-to-modeled comparisons proposed here are for different years given the available SSM outputs, the intended outcome is to understand the model's behavior and ability to represent seasonal and spatial differences in sediment-water fluxes.

Proposed methodology: For each of these outputs, a methodology is proposed below, concluding with planned data provision for potential follow-up multi-model comparisons and further measured/modeled sediment exchange analysis.

a) Expanded regional validation dataset: This analysis builds on the annual model-to-measured comparison of DO by Pelletier et al. (2017), to (i) compare 2014 modeled averaged monthly data matching the same month that measured data was collected, and (ii) include comparison of both N and DO at these locations. As with Pelletier et al. (2017), measured data is primarily from the synthesis in Sheibley & Paulson (2014) which forms the basis of the dataset. All relevant data will be collated into a sediment/water column flux geo-referenced dataset pairing measured and modeled data from the same location. Data should be available to download as Geographic Information System (GIS) data layers, and text files where appropriate.

b) Seasonal variation in N: Very little validation exists for the seasonal variation in Salish Sea Model nitrogen fluxes. Seasonal variation of measured nitrate and ammonium in Dabob Bay, Budd Inlet (Sheibley & Paulson., 2014; Appendix 5), and Bellingham Bay (Merritt, 2017) will be compared to monthly averaged model data for the same time period in 2014. For simplicity, a monthly modeled average will be computed from daily averages and measured data compared to the closest monthly modeled average. Further methodology for preparing model outputs for each of the analysis in Rec. 2 is described earlier in Rec. 1. Paired measured and modeled data will be added to the sediment/water column flux validation dataset (a).

c) Spring-time comparison of DO and DIN in shallow water embayment, and selected deep water sites, with measured nutrient data: Pelletier et al. (2017a) compared averaged annual model outputs for DO to data collected at a number of sites throughout Puget Sound. However, until now, no data has been available for analysis of Salish Sea Model outputs across both DO and N fluxes for the same season, and considering a wider range of shallower water sites identified as impaired in Ahmed et al. (2019). This analysis will compare the 40+ sites measuring DO and DIN in shallow water embayments (and selected deep water sites) in April and early May 2018 (Rigby, 2019; Appendix 4), to modeled data for the same time period in 2014. Measured and modeled phosphate and silicate are also available to examine. Where measured fluxes fall within the areas of the model domain that are masked and excluded from the Salish Sea Model results, then the nearest adjacent seaward model cell output that is not excluded will also be compared. Although observed and

d) Embayment-wide comparisons of sediment flux seasonally and for springtime: Using results from a and b, the analysis will be extended to embayment-wide calculations. Three embayments in each from a different sub-region of Puget Sound have been identified where there is low DO and measured data availability (Figure 10). In each case, GIS data layers can be made available that delineates delineate these areas for modelers in the region to use for comparative analysis. Model results for all unmasked cells in an embayment will be compared to measured data.
In addition, future work should consider:

- SSM runs for periods other than the current three years calibrated, and performance assessed against available measured data for all modeling processes, including those identified for the sediment fluxes here.
- Future measured/modeled analysis and multi-model comparisons: It has been discussed in the Model Evaluation Group, and in regional forums that multiple model comparisons and monitoring validation can advance our understanding of key processes and the level of confidence in their model representation. Towards this, results should be made available to

graduate students at UW and UBC for further performance assessment and cross-model comparisons with the LiveOcean and SalishSeaCast models.

- Further assessment and advancement of modeled sediment/water column fluxes: Dr. David Shull (Western Washington University) is leading work in this area focused on measured data. These may provide readily accessible input on potential improvements to the nearshore parameterization of the Salish Sea Model, among others. It is proposed that model outputs will be provided for further measured-to-modeled analysis with graduate students and collaboration on publications.
- Exploration of available erosion and sedimentation basins and sediment type information that can provide context to sediment-water flux analyses in the Salish Sea.

2.1.3 Rec. 3 Analysis of Salish Sea Model sediment exchange spin-up and stability

Note: this is a longer-term recommendation that could be addressed relatively quickly after completion of those prior above. The necessary model run files are available to adapt for this work in prior PSI/SSMC activities.

Outputs and methodology: The proposed analysis of sediment exchange spin-up and stability includes the following stepwise activities, illustrated in Figure 11:

- Using the initialization files for the existing and reference condition runs in Ahmed et al. (2021), the Salish Sea Model will be run for the year 2014, saving sediment flux concentration described in Rec. 1.
- At the end of that year, the results are used as initial conditions for a second annual run of the same year.
- Repeat 5 times and if possible 10-15 times. In the Chesapeake coupled hydro and bio-geochemical models have been undertaken for 5 years while stand-sediment models have been done for 15 years (Testa et al., 2014).
- Plot the sediment conditions for all of the warm-up years in sequence and quantify the change in the stability of sediment concentrations over time.
- Examine where there are significant differences in the context of the measured-to-model comparison planned in Rec. 2.

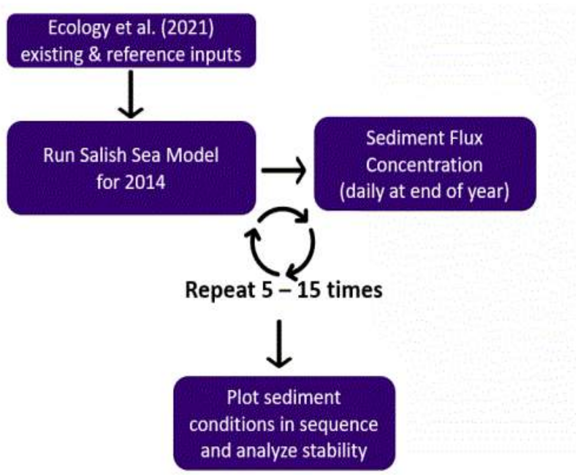

Figure 11. Analysis of Salish Sea Model sediment exchange spin up and stability. Reproduced from slides presented at the Science of Puget Sound Water Quality Sediment Exchange Workshop, October 17, 2022. See the presentation for further details.

2.2 PRIMARY PRODUCTION AND PHYTOPLANKTON

2.2.1 Rec. 4 Monthly budgets of primary production, N and C in selected embayments, and analysis of the role of ocean loading and riverine discharge variability in limiting primary production

Proposed Outputs: Establish components of a nitrogen, carbon, and phytoplankton budget in selected inlets, and undertake initial characterization of seasonal response in nitrogen to changes in light, or other limitations to phytoplankton. In a second phase, it is proposed to expand budgets to address more complex components such as exchange flow, which supports the investigation of the role of ocean loading and riverine discharge variability on the limits and controls of primary production**.** Some preliminary results data were presented on this recommendation in the associated phytoplankton workshop. Discussion with stakeholders included addressing broader questions that this work may contribute to, such as: *considering future climate change, how do changes in density structure in response to the relative timing of coastal upwelling and earlier river discharge alter growth conditions for phytoplankton productivity?*

Proposed Methodology:

Phase 1: Budget components on primary production in selected inlets:

Note: Phase 1 is a short-term recommendation that can be undertaken relatively quickly following those earlier, and using the associated model and GIS outputs to understand regional budgets.

- Parameters and time scale: Extract daily and monthly averages for key processes, extending the earlier sediment budget analysis to phytoplankton e.g. (i.e., POM and phytoplankton loss, standing mass of diatoms and dinoflagellates, growth rate in Table 6.1 in Appendix 6). Partial sediment N and C budget components can use parameters identified in Rec. 1 and Table 6.1 in Appendix 6.
- Inlet locations:
  - Starting with the same three inlets delineated where the partial sediment N and C budgets are planned (Figure 10) in the earlier recommendation: Bellingham Bay, Sinclair, and Case Inlet.
  - Followed by the locations where monthly data is available for N and DO: again, Bellingham Bay, with the potential addition of Dabob Bay and Budd Inlet
- Spatial and temporal extent: first phase single box model components without exchange flow:
  - Consider photic zone in this first phase delineating simple box models: For example, fixed layers matching approximate euphotic zone and/or delineating single box model where seaward side matches 30 or 50m depth.
  - Horizontal exchange across the sea-ward boundary of this box model will need to be considered in phase 2.
  - A transect profile showing the change in results from 5 or more cells from deep to shallow water.
  - Future advancement might also consider a simple Knudsen theorem approach using salinity differences for annual exchange flows (e.g. Burchard et al., 2018).
- Analysis: Quantify the availability of light, nutrients, and phytoplankton mass in the euphotic zone monthly in selected inlets considering:

- a) total mass, and b) change over time, considering a base rate of phytoplankton loss
- Quantify relative change seasonally in nutrient availability to the euphotic zone from different sources, including sediment recirculation and all nutrients entering inlet vs rivers (where applicable).
- Consider additional metrics such as carbon to chlorophyll ratio and other analysis relevant to primary production and sediment budgets and changes seasonally.

<u>Phase 2: Budget on primary production and loss in selected inlets considering exchange flow:</u>
Note: This is a longer-term recommendation that extends the single-box approach to address the challenge of exchange flow, and further characterize the euphotic zone. A number of alternative modeling approaches are available and some of these are included here from workshop *presentations and/or discussions with Tarang Khangaonkar, Parker MacCready, Ben Roberts, and Michael Brett.*

Extension of work in phase 2:

- Further defining the euphotic zone within inlets using the Salish Sea Model:
  - Consider a variable depth box model that is based on light attenuation, if relevant for inlets of interest. One opportunity that is already available is to build on Ben Roberts (UW Engineering Ph.D. Candidate) ongoing coding efforts and approach addressing this: https://github.com/bedaro/ssm-analysis/blob/main/misc/PhoticZone.ipynb
- Quantify exchange flow and/or vertical fluxes from deep water to the euphotic zone at inlets of interest. Multiple approaches and models should be considered and some that were discussed at the phytoplankton workshop and other forums are included here for consideration:
  - Direct tidally averaged approaches to calculate exchange flow on a specified vertical boundary, as has been used by Tarang Khangaonkar and colleagues, requiring the setup of specific Salish Sea Model input files before running them. At the phytoplankton workshop results from Khangaonkar and colleagues were presented, which at a systems level characterized the multi-year responsiveness of the hydrodynamics and higher-level processes to interannual changes in hydrology and meteorology (Khangaonkar et al., 2021b).
  - Calculation and approach of exchange flow can consider options like that applied by MacCready (2021) in Live Ocean and also currently being adapted by Ben Roberts for the FVCOM grid for use in the Salish Sea Model: https://github.com/bedaro/ssm-analysis/tree/main/transport This approach and status of this work was also presented at the associated phytoplankton workshop.
- Extend the quantification of relative change seasonally in nutrient availability to the euphotic zone from different sources, including marine vs riverine input (were possible), and provide comparison/context using the longer-term river and WWTP data by region (see following recommendation).
- Given the above results for existing and reference conditions runs, consider further model scenario runs and analysis addressing the scientific questions and research priorities discussed in the associated phytoplankton workshop. For example, how well the model reproduced primary production rates and then see how much of this was respired in the water column versus sediments.

See Appendix 7 for additional information and examples of initial results provided by Ben Roberts (UW Engineering) that were available at the time of writing.

2.3 INTERANNUAL VARIABILITY AND CONSIDERATION OF SALISH SEA MODEL VERSIONS AND MULTI-MODEL APPROACHES

2.3.1 Rec. 5 Observed riverine, wastewater treatment plant, and ocean long-term variability and regional analysis

Note: At the time of publication, this short-term recommendation builds on specific outputs currently under consideration with the researchers identified.

Proposed Output and Methodology: Further characterization of the interannual variability of riverine and wastewater data presented in Ahmed et al. (2019), considering model years 2006, 2008, and 2014 which are the focus of regional modeling efforts. Newly updated data from Ahmed et al. (2019) is now available. This can be synthesized relatively quickly to address scientific uncertainties regarding the interannual variability of datasets used as Salish Sea Model inputs to nutrient reduction scenarios. Furthermore, further work on ocean forcing and the long-term response of nutrients and DO in the waters of Puget Sound has been examined by Parker MacCready and will inform any additional sensitivity analysis considering interannual variability. Many of the model-related uncertainties raised by the PSP Marine Water Quality Interdisciplinary Team focused on understanding the interannual variability of physical processes, forcing the model, and how these influence hydrodynamics and biogeochemistry. For example, how do the stratification, mixing, residence time, and nutrient loading in the three years the state's modeled compare to the range and interannual variability?

At the time of writing, University of Washington (UW) researchers Aurora Leeson, Dakota Mascarenas, Parker MacCready, Liz Elmstrom, and Gordon Holtgrieve were planning to address elements of the following, and PSI is engaging with these and other researchers in the region interested in undertaking aligned analysis. Example steps discussed include:

- Characterize the interannual variability for the most current riverine dataset for the region. The expanded and improved 1999-2017 daily time series applied by the state was made available in October 2022 on the Ecology web pages. Unlike the prior version, the interannual variability has not yet been analyzed. The dataset includes the daily flow, nitrogen, and other biogeochemistry parameters for the wastewater treatment plant and riverine inputs that were used to force the Ahmed et al. (2021) nutrient reduction scenarios. This dataset was created by Ecology from direct measurements where available and used regression analysis to fill temporal gaps and between locations where data was not available for rivers (Ahmed et al., 2019).
- Combine the recently updated 1999-2017 riverine dataset that is used for the Salish Sea Model with additional datasets used by other regional modeling efforts including Live Ocean[4] and SalishSeaCast[5].
- Characterize the interannual variability of available ocean biogeochemistry and hydrodynamic forcing data.
- Where possible, time-series analysis of nitrogen on dissolved oxygen and other observations of water quality change should be further investigated. Analysis of longer-term

[4] https://faculty.washington.edu/pmacc/LO/LiveOcean.html
[5] https://salishsea.eos.ubc.ca/nemo/

observational-data covariance may provide additional lines of evidence for interannual change in the effects of natural or anthropogenic N loading on dissolved oxygen. Future work can expand to the analysis of riverine budgets and isotopic studies (e.g. Gordon Holtgrieve), sediment records (e.g. Sophia Johannessen), and remote sensing observations of changes in eutrophication and water quality (e.g., Maycira Costa), with examples from this and other regions presented in the Sediment Exchange workshop on October 17, 2022.

Further definition of the methodology and project activities regarding wastewater treatment plants should consider utility interest and engagement in the validation process of the wastewater treatment plant inputs. For example, a number of utilities have shared an interest and willingness to review their specific plant loading data in the updated input files. As required, PSI can facilitate this review for the model years where nutrient reduction scenarios have been run by the state. See Appendix 8 for additional information on approach and preliminary data provided by UW students.

2.3.2 Rec. 6 Comparison of two versions of the Salish Sea Model and available model year outputs

Note: This longer-term recommendation is dependent on the provision of data and code which is noted as available on request in Khangaonkar et al. (2021). With this code, the activity can begin relatively quickly with phase 1.

Proposed Outputs and Methodology: The purpose of this activity is to provide further confidence in the applied model, adopted methodologies, and model years selected (2006, 2008, and 2014); comparing the results from the research model with the applied model for the same years and corroborating results. The research model has been calibrated and run across multiple years (2014-19) and includes advanced modules on higher-level processes (e.g., phytoplankton and Submerged Aquatic Vegetation, among others - see Table 1). All activities should be considered with the input, guidance, and review of the Ecology modeling team and Tarang Khangaonkar. The Ecology modeling team is responsible for decisions regarding the timing and sequencing of any future updates to the operational model applied by the state and these outputs may inform the process.

<u>Phase 1: Initial comparison of model outputs for the year 2014 and review of 5-year output</u>
The methodology could consider:

- Comparison of the two available versions of the Salish Sea Model, and additional model year outputs also available as solution files. This might include a comparison of the existing and reference outputs for 2014 from both Ahmed et al. (2019) and the more advanced version of the research model, which used multi-year runs (Khangaonkar et al. 2021). Note that:
    - If solution files are not readily available for the research model, this would require first running the available Khangaonkar et al. (2021) run and input files to process solutions.
    - If the advanced model input file used significantly different wastewater inputs to that used in Ahmed et al. (2019), then additional steps to update and rerun both models with the same wastewater treatment plant inputs might need to be considered (Recommendation 7).
- Results would inform the consideration of phase 2 of this work.

Phase 2: In-depth comparison of multi-year model outputs:

- More detailed investigation of all model outputs and the models themselves with the engagement of the Ecology modeling team. This may potentially inform decision-making on any future updates to the operational model applied by the state, and more immediately the use of the research version of the Salish Sea Model by multiple users.
- Specifically, this can include consideration of how important multiple-year runs are as an approach, compared to the current "hot-start/cold-start" approach to running a single year.

2.3.3 Rec. 7 1999-2019 data for longer model runs using multiple models and further analysis of interannual variability of available forcing data

Note: The following longer-term recommendation is envisaged as a larger endeavor toward providing a standard set of input data for a multi-year model ensemble approach to nutrient scenario analysis in the region. It is well suited to engage and support the outputs of King County, and other, currently funded PhD students utilizing multiple modeling platforms, including: the Salish Sea Model (UW), Live Ocean (UW), and SalishSeaCast (UBC). On initial examination, there appears to be a relatively extensive set of data that is available for consideration on key forcing data (some extending back to the 80s). However, this has not been synthesized in a format for ready access across these platforms.

Draft Purpose and Method: Facilitate the collaborative curation of a multi-year model dataset for nutrient modeling for the Salish Sea that the major numerical modeling platforms can all share. Additionally, to provide a robust dataset of inputs to other modeling and analysis efforts as they are developed. The following model-to-model comparison steps and model-forcing data sources could be considered, in addition to model validation datasets identified in this report:

- Consideration of models calibrated for multi-year runs across multiple models: a later research version of the Salish Sea Model has been calibrated and validated for multiple-year runs, and the source code and data outputs are available for public use (Khangaonkar et al. 2021). However, input data and initialization files for all years 2014-19 are not currently publicly available and may require further consideration regarding inputs used (Rec. 6). On initial review of Live Ocean, hindcast solution files are available from 2019 onwards, and relatively quickly able to be configured to run for years 2013 onwards.
- 1999-2017 wastewater treatment plant and riverine nutrients and flow: datasets from Ecology are currently available (Rec. 5 -see potential collaborators). Wastewater treatment plant data is available on an ongoing basis for further collation into model input data sets. Furthermore, improved provision by Ecology of measured river gauge data is expected within the next few years.
- Ocean boundary biogeochemistry:
    - Currently biogeochemical forcing for all three regional models uses the same regression analysis of cruise data to HYCOM data, developed by Ryan McCabe in 2015 with Parker McCready.
    - Newly available modeled data pre-2000 onwards is also now available at a resolution and locations relevant to the Salish Sea ocean boundary forcing; from a number of modeling groups, and on an ongoing basis. In some cases, hindcasts of these data start in the 80s. Greg Pelletier provided some initial review of these data sources showing relatively good accuracy of these modeled sources compared to the regression data used currently for biogeochemistry forcing. Greg Pelletier can be contacted for the

advancement of the proposed ocean boundary biochemistry and hydrodynamics activities defined here. Greg, with input from Parker McCready, has provided this initial review of data inputs and some suggested methodologies and could be contacted for further input and details.

- Ocean boundary hydrodynamics: HYCOM data is currently used for physical parameter forcing of all models as ocean boundary conditions. On initial investigation, it appears that HYCOM extends back to at least 1999. However, the quality of the data pre-2012 needs further consideration
- Atmospheric forcing: All models use atmospheric forcing from UW's Department of Atmospheric Sciences advanced research core of the Weather Research and Forecasting Model (WRF) - (WRF-ARW v3.7.1) This is expected to extend back in hindcast to 2019, however, the resolution of earlier years requires further investigation.
- Ocean and climate change predictions and sensitivity: future scenarios can draw on the range of ensemble ocean model analysis that has been undertaken, and requires further consideration. The exploration of this topic is ongoing in various regional forums. However, ensembles of models for consideration, and best practices, can be identified now. Future scenarios of climate change impacts on both terrestrial and marine environments are being addressed through the Puget Sound Integrated Modeling Framework project.
- A nearshore higher resolution grid has been developed and published in Premathilake and Khangaonkar (2022), which can be considered for any further SSM advancement.

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APPENDIX 1: EMBAYMENT-SCALE REVIEW OF MEASURED TO MODELED DISSOLVED OXYGEN GOODNESS OF FIT IN AREAS IDENTIFIED AS NON-COMPLIANT IN WASHINGTON STATE

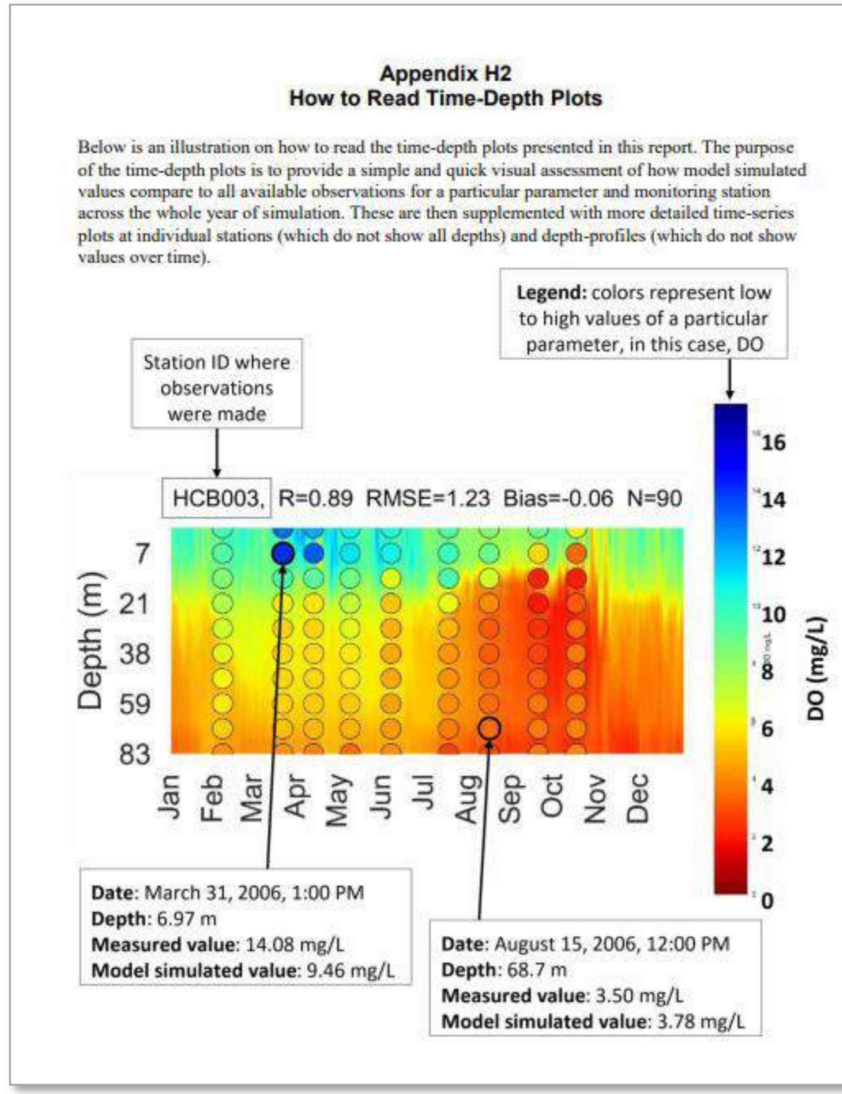
Appendix 1: Inlet-scale review of measured to modeled dissolved oxygen goodness of fit in areas identified as non-compliant in Washington State

Methods

The **purpose** of this review is to use the extensive analysis undertaken by the state[1], providing further detail on the relative skill and error specific to model performance in shallow water inlets/embayments where low DO is a concern, and to the time period and specific depths within these locations that contribute the majority of low DO identified across Puget Sound.

This review sub-samples and summarizes model skill analysis by the Department of Ecology, sequentially:

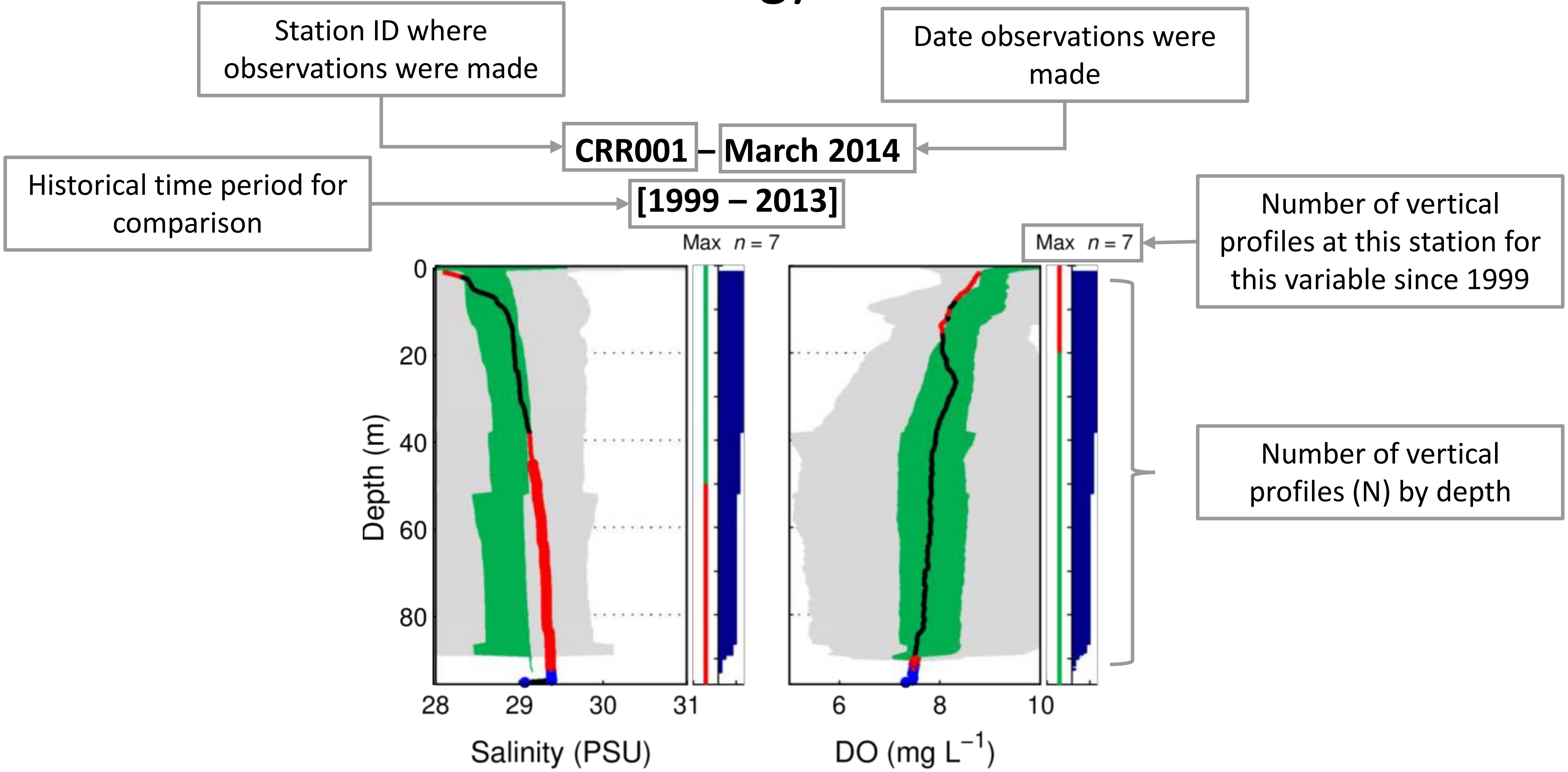
- Including only model to CTD measured validation for sites falling within the contiguous model cells counted as non-compliant within and extending from each embayment/region[2]. Geographic delineation is defined in recent Bounding Scenarios Update report by the State (Ahmed et al., 2021), using the 2014 delineation of non compliance. All plots and statistics available for all sites[1] falling in this geographic range in 2006/14 CTD casts are included sequentially in this Appendix. Additional longer term synthesis of CTD results are included with each site, where available
- Further sub-selection of representative sites for embayment-scale comparison, selecting only sites were the CTD casts for the year cover at least $\geq$ 3 months of measured data in the typical period of lowest dissolved oxygen (July – November), and throughout the water-column.
- Summarizing the range of model skill in the inlet-scale comparison:
    - Present the range of model skill in the main report - tabulated model skill and error statistics(Table 5), for each station in each embayment with the highest(★) and lowest (★) RMSE for 2006 and 2014.
    - In the Appendix, provide an overall review on goodness of fit by region/inlet, maps of sites within inlets, and addition notes on methodology, including where additional sites are the only available and included but do not meet all of the above selection criteria, or where only a single site matches (E.g.★ =only 1 site meeting criteria and is tabulated in report).



[1] Technical Memorandum: Puget Sound Nutrient Source Reduction Project Phase II - Optimization Scenarios (Year 1)

[2] *Explore the non compliance model results & monitoring locations with Ecology's interactive map*

How to read measured data from Ecology CTD casts



Legend

- Interquartile range for 25th – 75th percentile
- 1.5 times the interquartile range to estimate the 5th and 95th percentile
- Falls onto the historical interquartile range
- Falls outside the historical interquartile range
- Deeper than previously measured
- Outside the historical data range

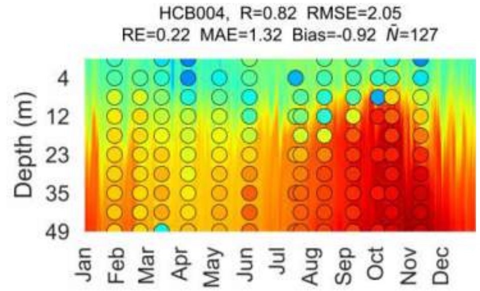
Measured data for 20 year period of CTD casts (not for circulation): results from the year 2014 (overlayed against the range of prior long-term results) are included with each measured/modeled statistical analysis presented following

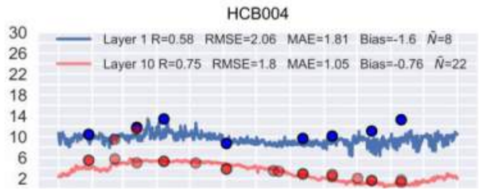
Hood Canal | 2014

Context

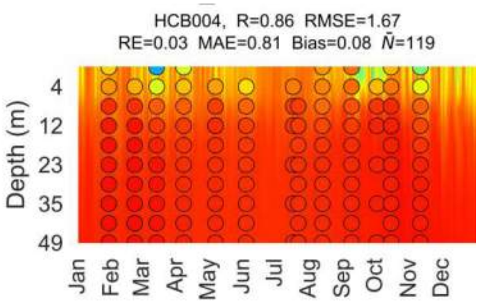
- Salinity plots included for comparison here for HCB004/007

★ HCB004

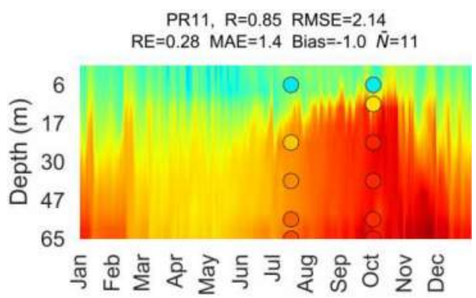


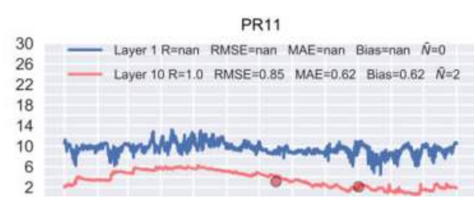


Salinity

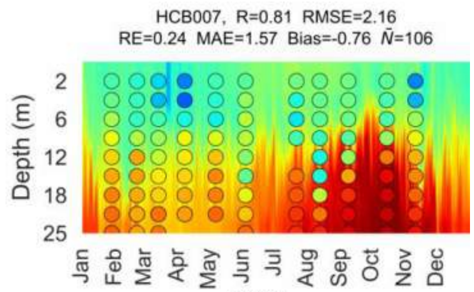


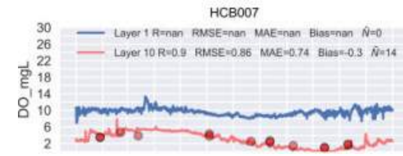
PR11

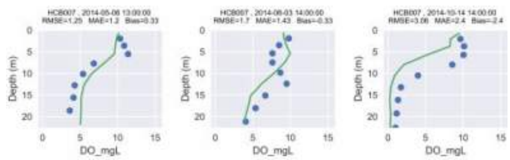




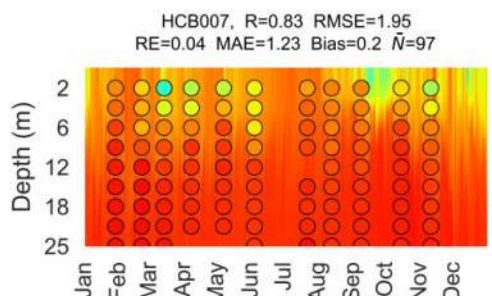
★HCB007



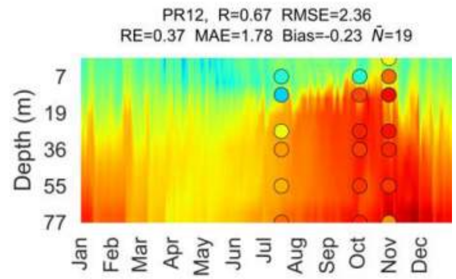


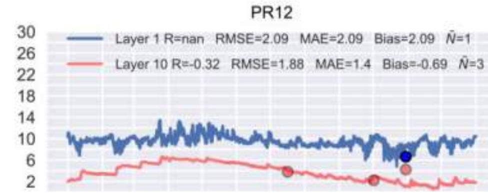


Salinity

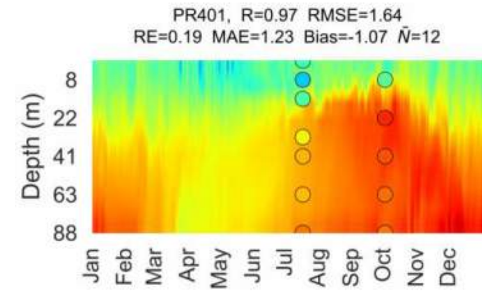


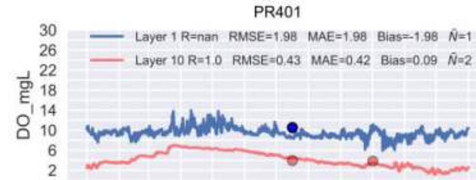
PR12





PR401



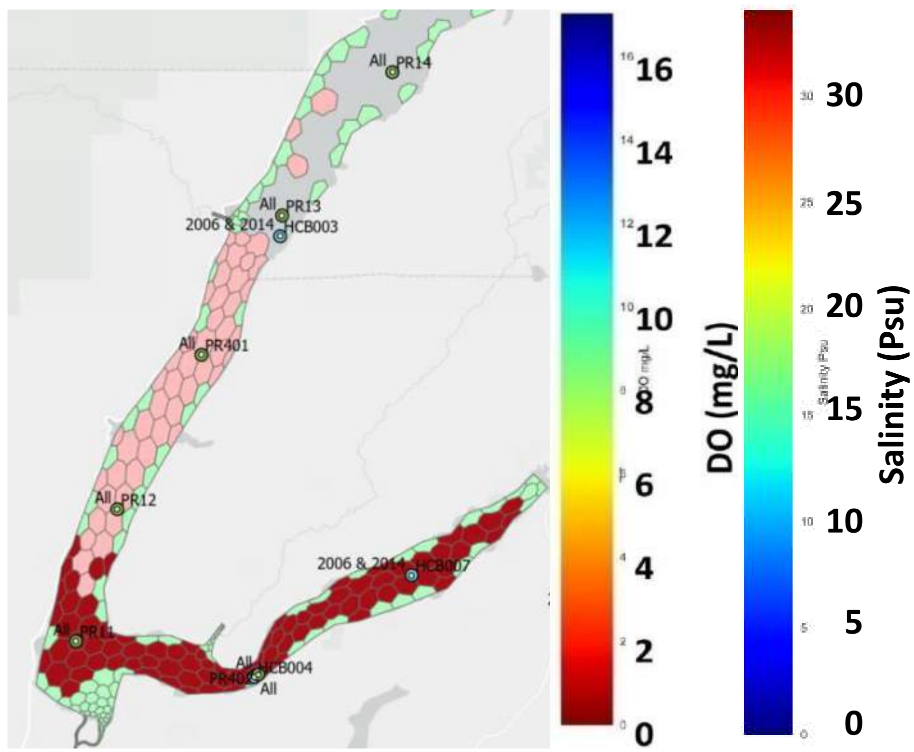


Context

- PR402 isn't included and is within the same cell as HCB004

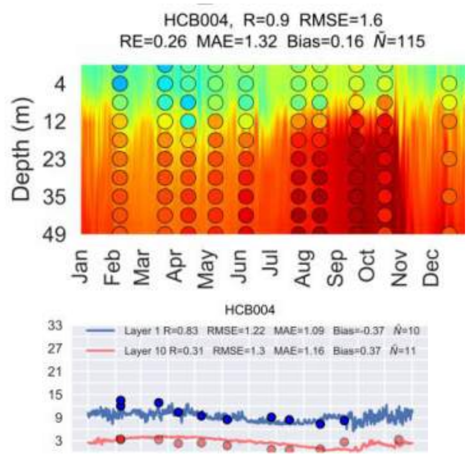
Reflections

July–Nov: Modeled match measures results in deepest waters with greatest presence of low DO. Layer ten shows slightly lower modeled DO in HCB004/7. Some over estimation of DO nearer to the line of vertical stratification of DO in shallow waters, as well the shallowest waters above this however this varies month to month. For example, in Oct 2014 where the difference is plotted and discernable, **the modeled result ranges from 0.5 to 7mg/l less than measured.**

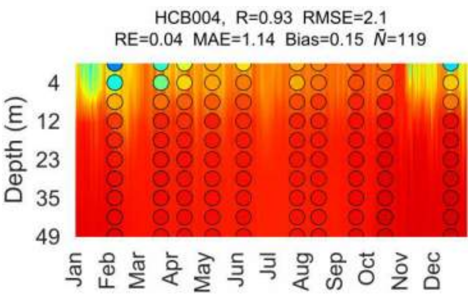


Hood Canal | 2006

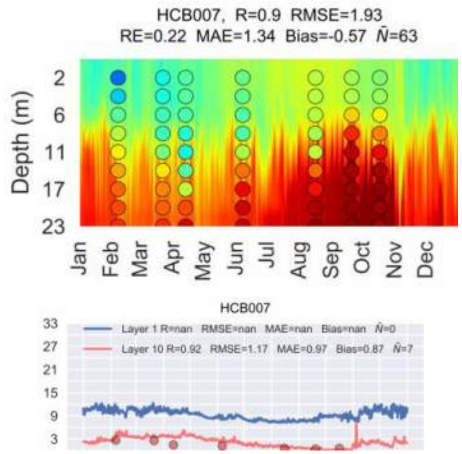
★HCB004

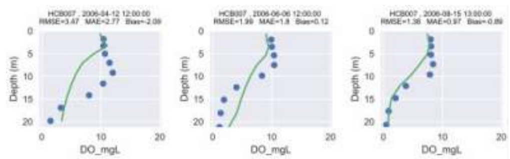


Salinity

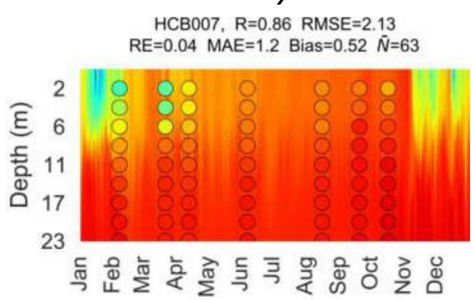


★HCB007

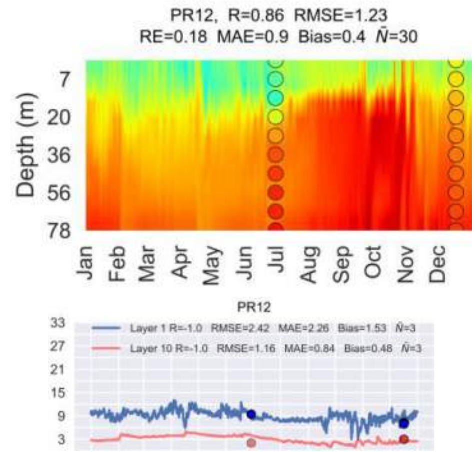




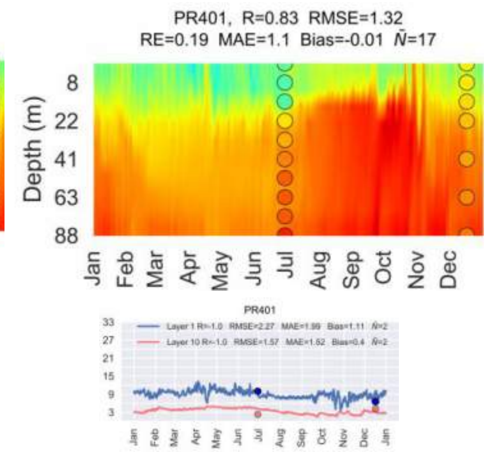
Salinity



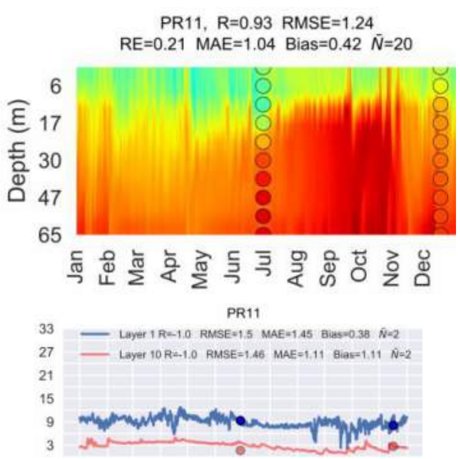
PR12



PR401



PR11

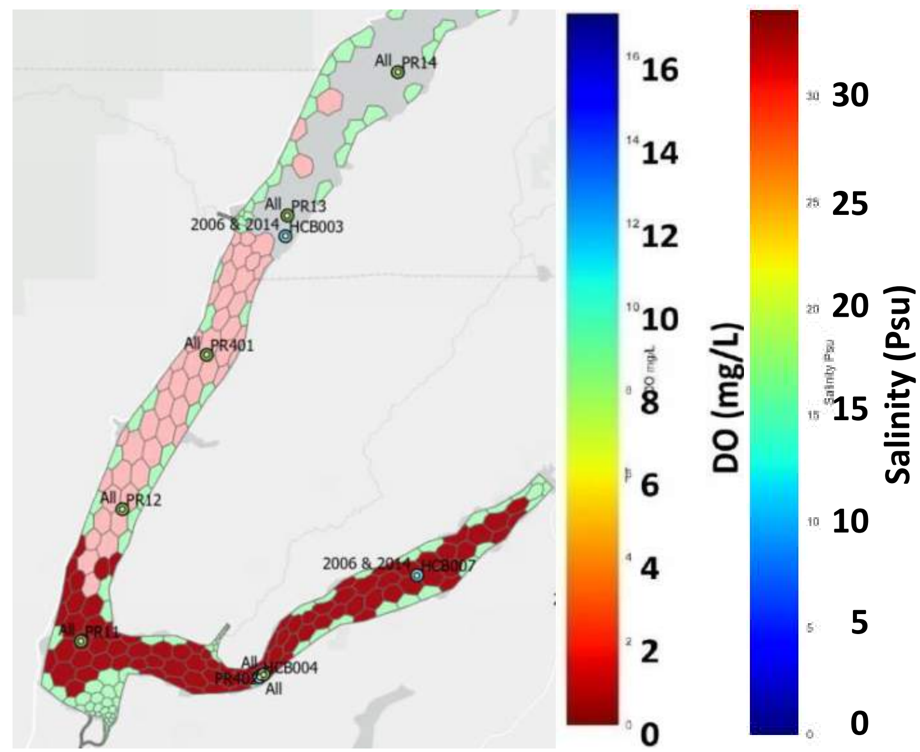


Context

- PR402 isn't included and is within the same cell as HCB004

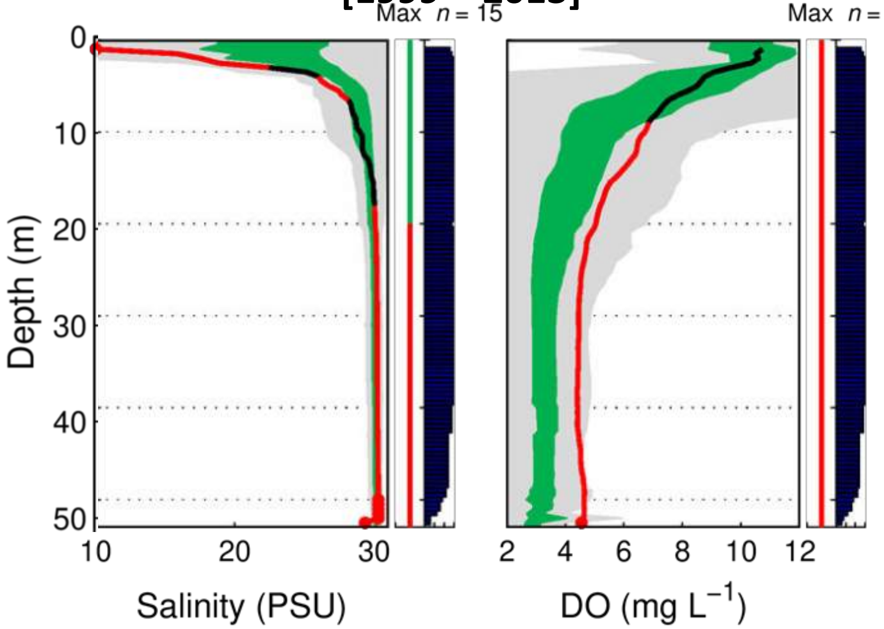
Reflections

July–Nov: Modeled match measures results in deepest waters, and is better than 2014 in shallow waters. Layer ten shows both higher and lower modeled DO, which is also shown throughout the water-column profile at HCB007 were data are presented (**approximately 3mg/l maximum at 10m at HCB007 in August.**)

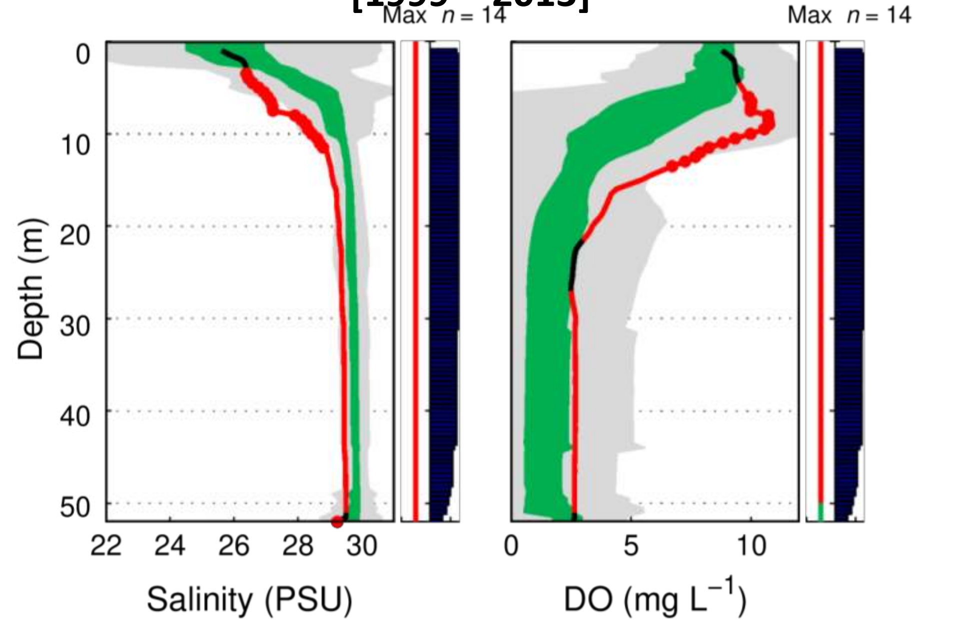


Hood Canal

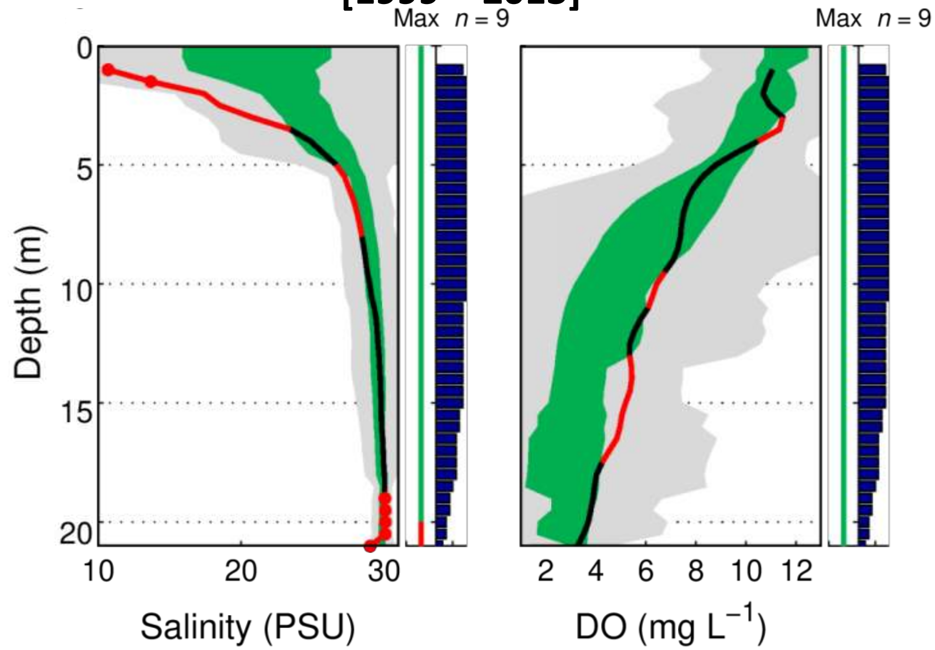
HCB004 – March 2014
[1999 – 2013]



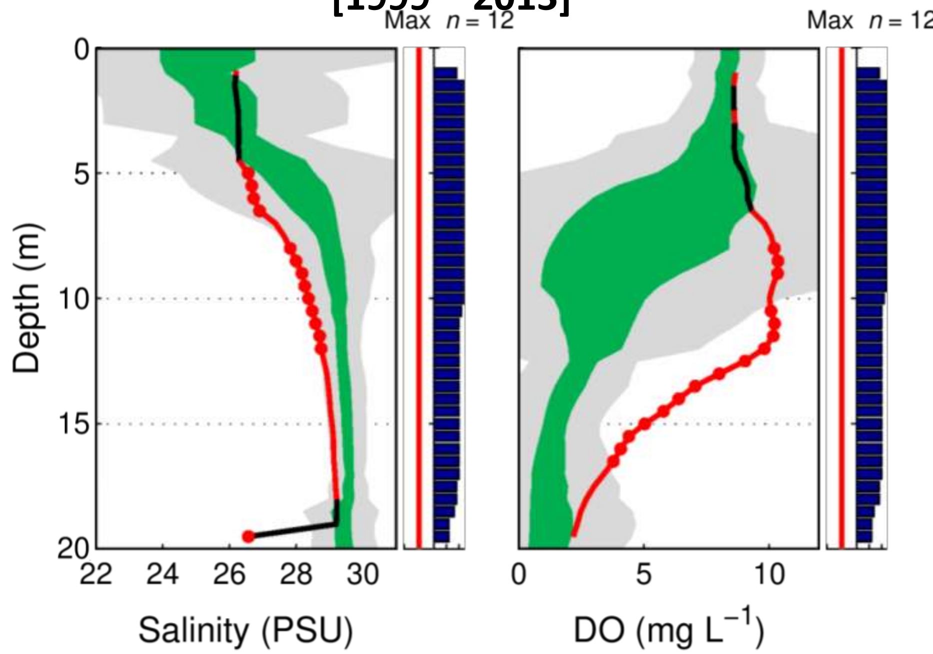
HCB004 – August 2014
[1999 – 2013]



HCB007 – March 2014
[1999 – 2013]

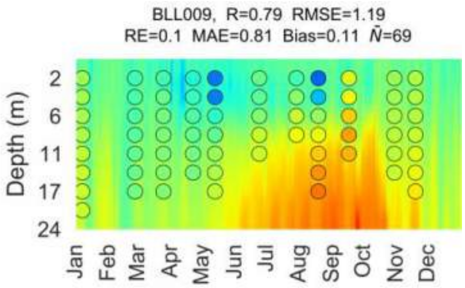


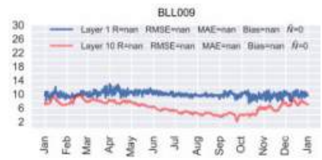
HCB007 – August 2014
[1999 – 2013]

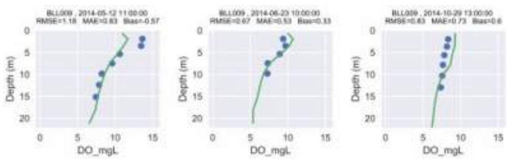


Bellingham Bay | 2006 & 2014

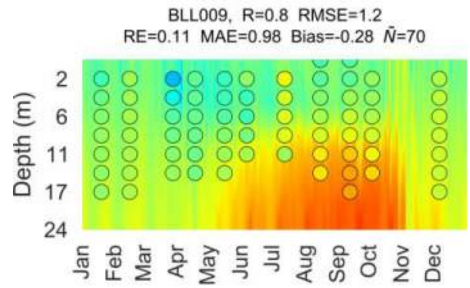
★BLL009 (2014)

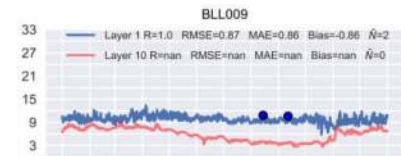


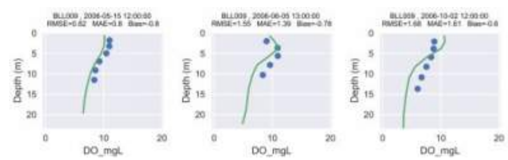


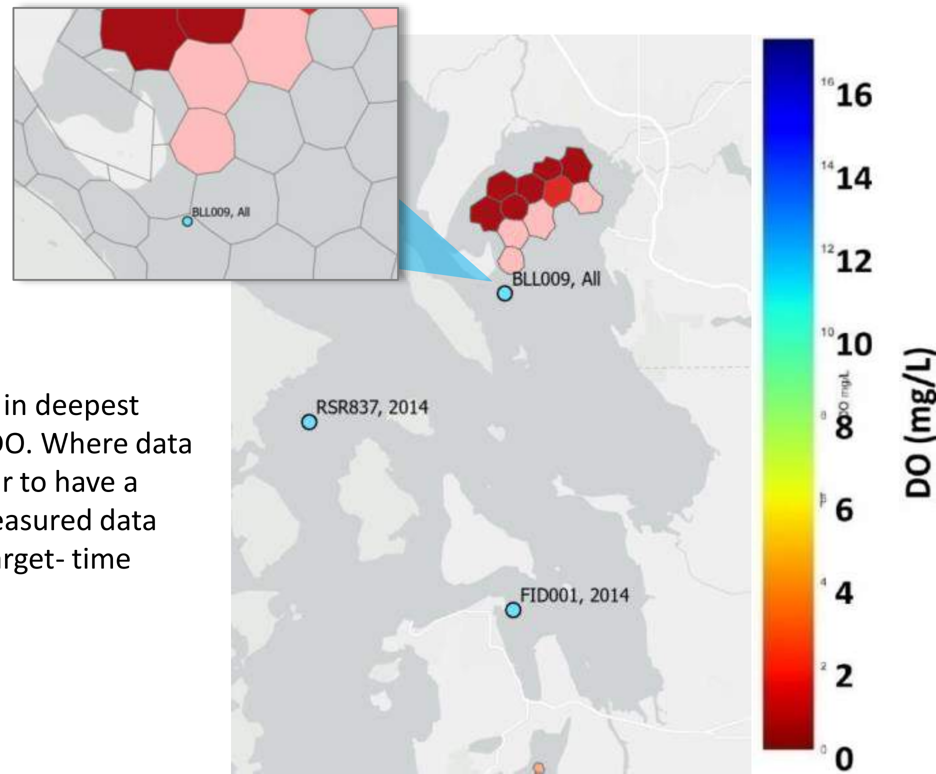


★BLL009 (2006)









Context

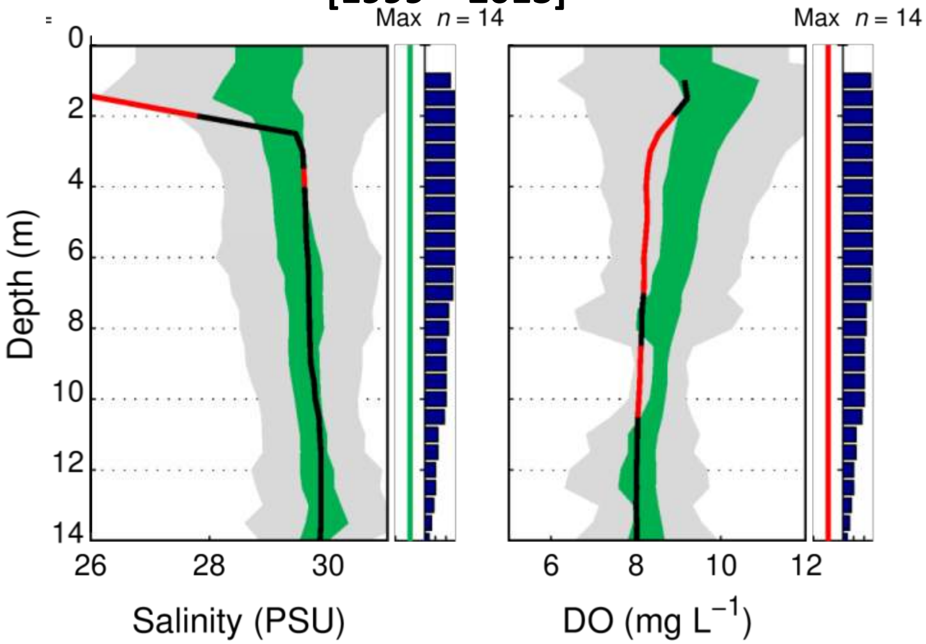
- BLL009 is the closest monitoring station. No other stations are near an area of non-compliance for any years
- BLL009 is located approximately 1km south with one cell of separation from the nearest non-compliant cell
- BLL009 is missing deep water data for comparison during Jul-Nov where DO would be the lowest

Reflections

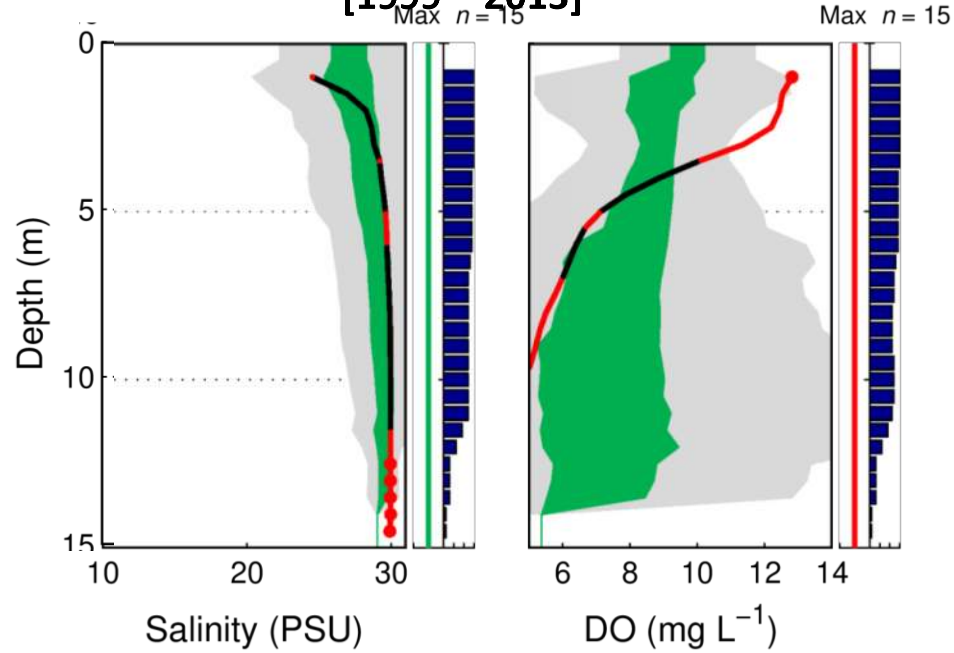
July–Nov: Modeled data not available in deepest waters with greatest presence of low DO. Where data is available, the modeled results appear to have a maximum difference of 2mg/l from measured data within the 0-15m depth range at the target- time period.

Bellingham Bay

BLL009 – March 2014
[1999 – 2013]

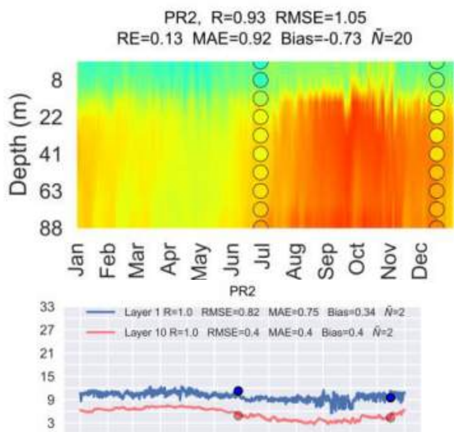


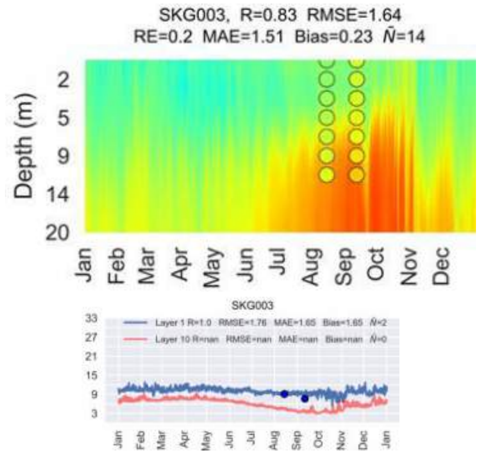
BLL009 – August 2014
[1999 – 2013]

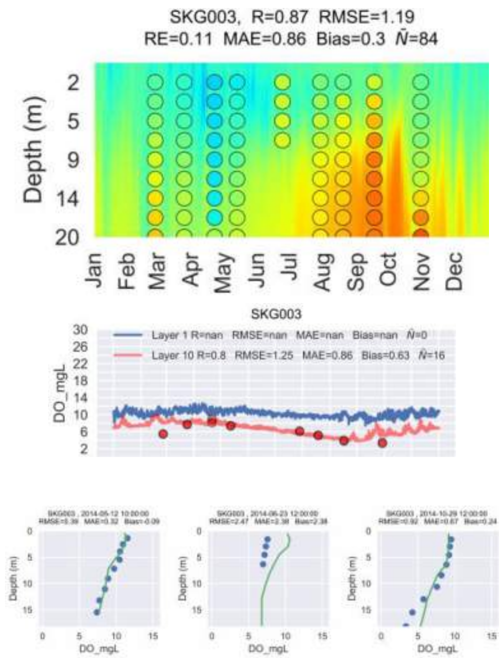


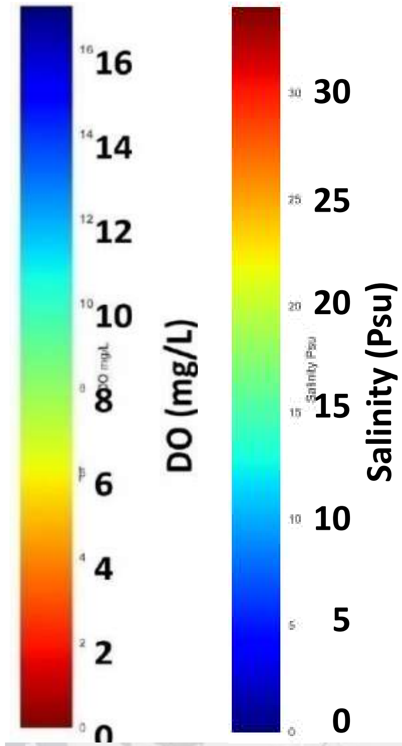
Whidbey Basin| 2006 & 2014

★Near Port Susan PR2 (2006) **★S. Skagit Bay: SKG003 (2006)** **★ SKG003 (2014)**

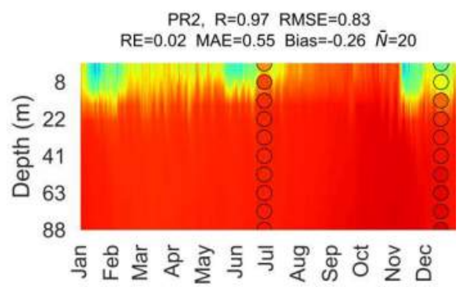




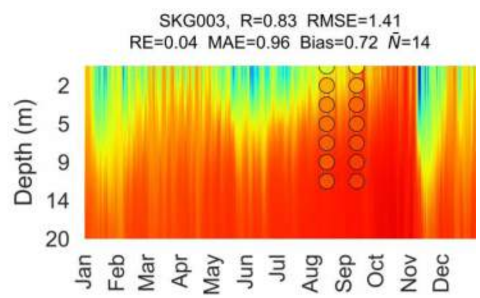




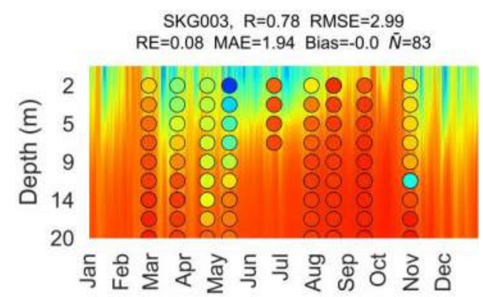
Salinity

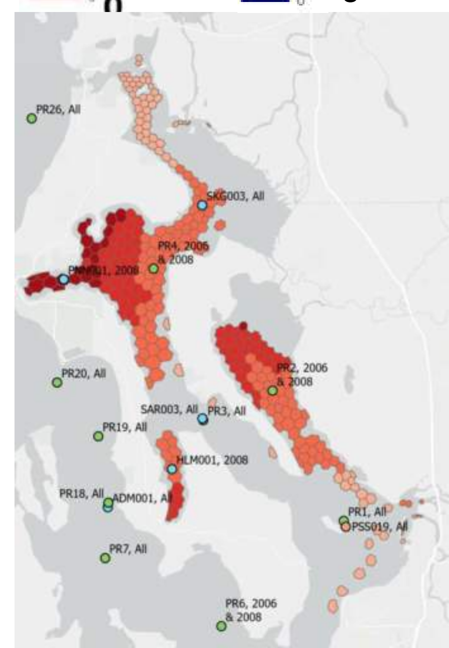


Salinity



Salinity





Context

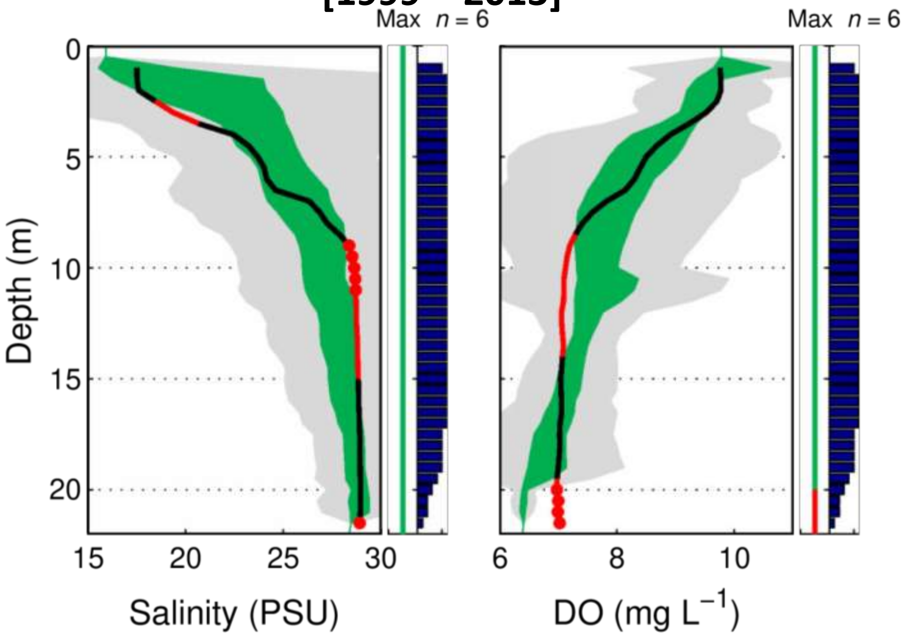
- Measured data not available for Port Susan in 2014
- PR4 isn't plotted in Appendix for 2006

Reflections

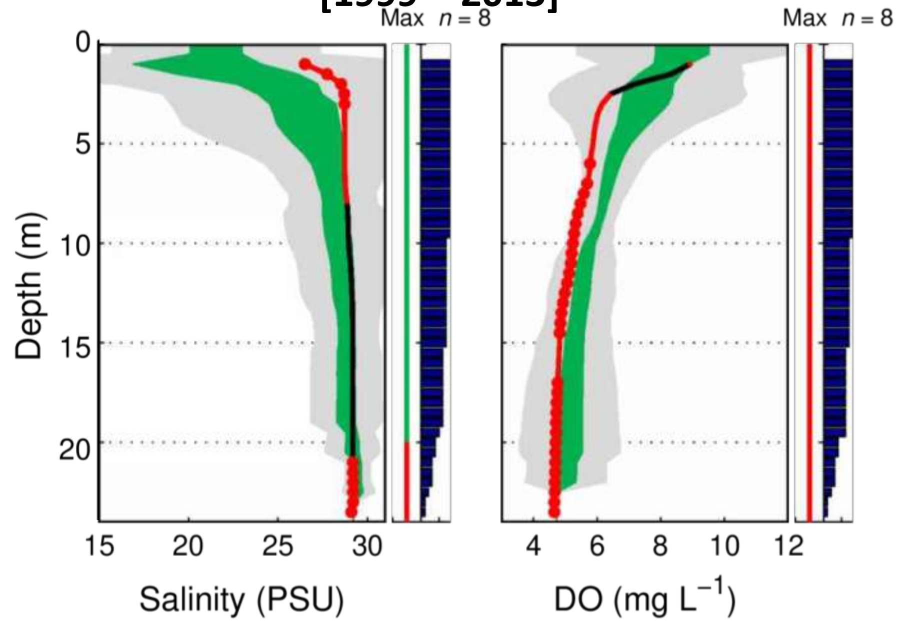
July–Nov: Measured data not available in deepest waters with greatest presence of low DO in Port Susan. Layer ten shows reasonable match of modeled DO for July-Nov, where data is available except Sep-Nov 2014 in Skagit Bay where modeled DO is over estimated for 2 of the 4 months. Similarly, some over estimation of DO is exhibited at 5-15m depths below the line delineating vertical stratification, as well as shallow waters above (**at least +2mg/l in worst case** for deepest layer and shallow waters).

Whidbey Basin

SKG003 – March 2014
[1999 – 2013]

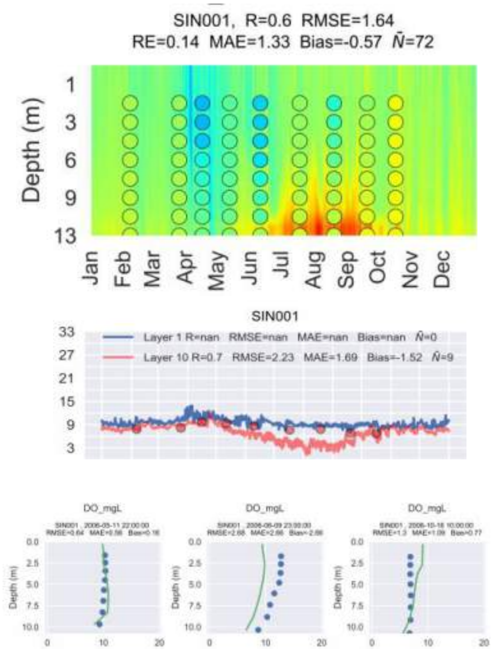


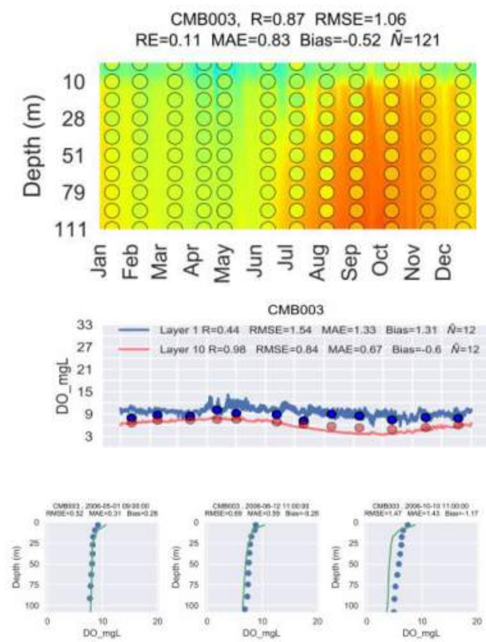
SKG003 – August 2014
[1999 – 2013]



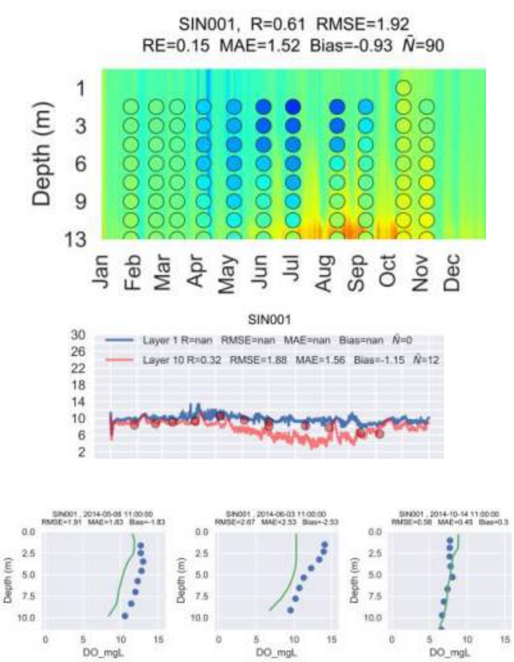
Main Basin | 2006 & 2014

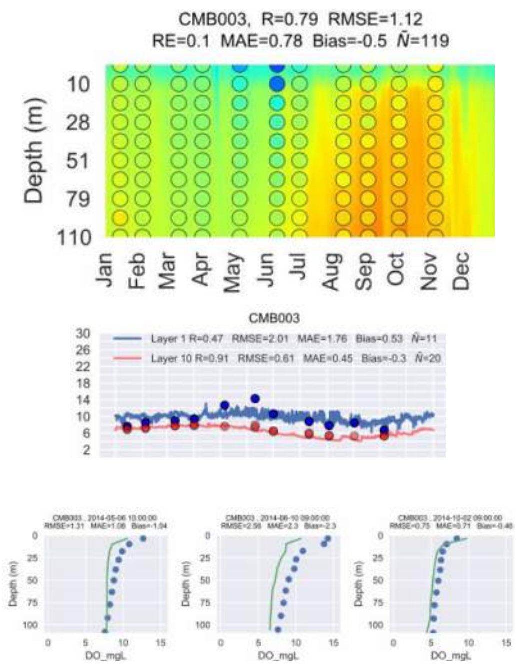
★Sinclair: SIN001 (2006) ★Commencement: CMB003 (2006)





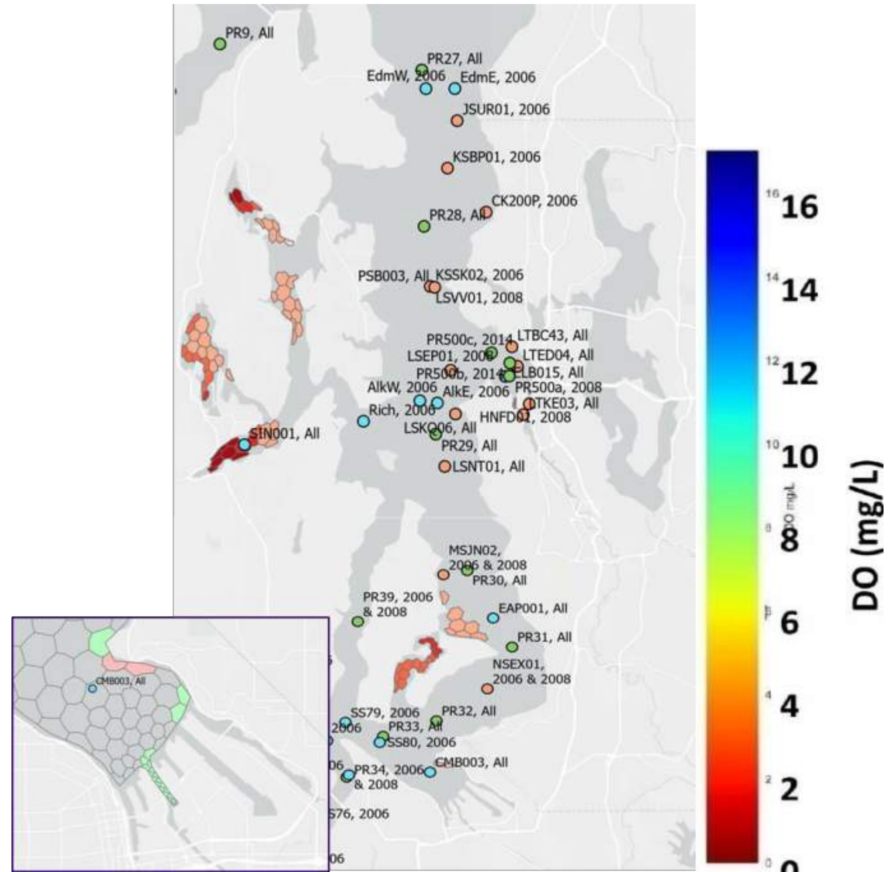
★SIN001 (2014) ★CMB003 (2014)





Context

- CMB003 is the next closet monitoring station outside of area of non-compliance.
- No other stations outputs are available in no-compliant cells for any years. It is located approximately 750m south-west with one cell of separation from the nearest non-compliant cell.

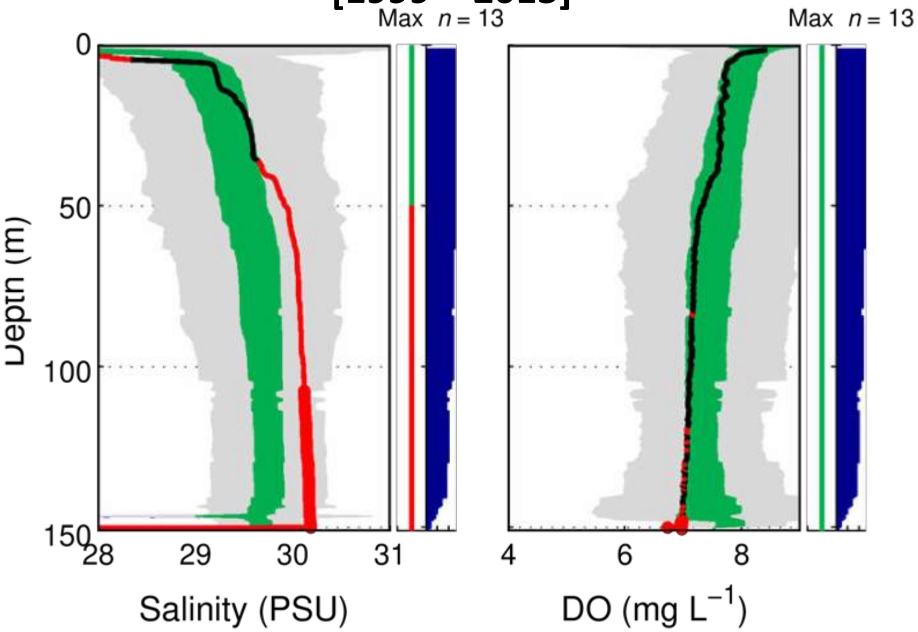


Reflections

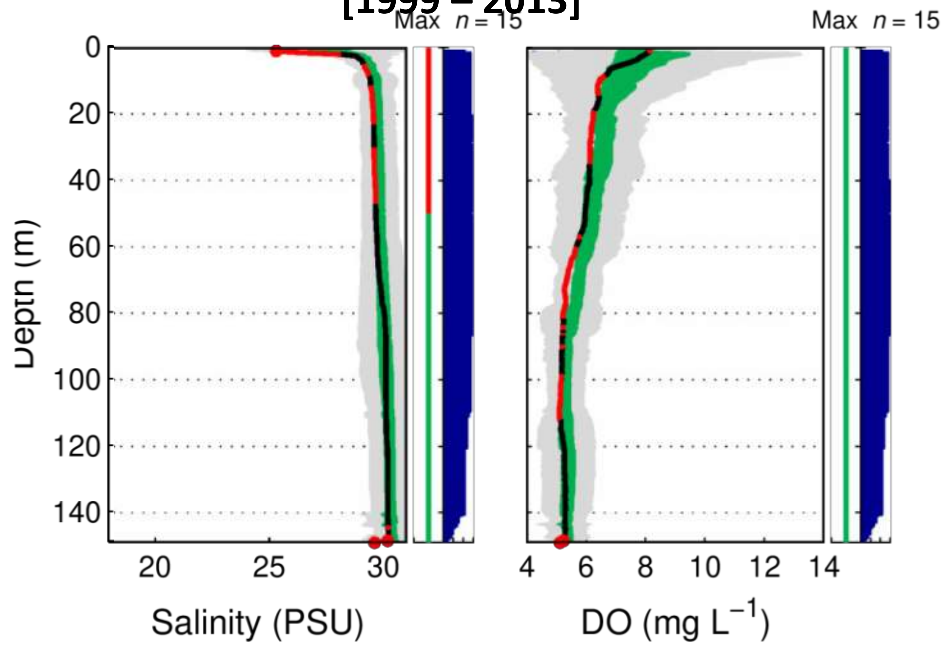
July–Nov: Deeper waters varies in modeled/measured match, however lower modeled than measured DO Jul-Nov is observed throughout most of water column for most months sampled at both stations in the target time-period. For Sinclair, the deepest layer appear 3mg/l lower or more modeled DO for most targeted months but is a good fit for Oct/Nov. The rest of the water column exhibits similar lower DO than measured on certain months but not sequential (e.g. at least -4mg/l in worse case). Commencement bay shows a better match of modeled to measured data with only 8 of the 10 target months with greater than 0.5-1mg/l or more modeled DO across both years.

Main Basin

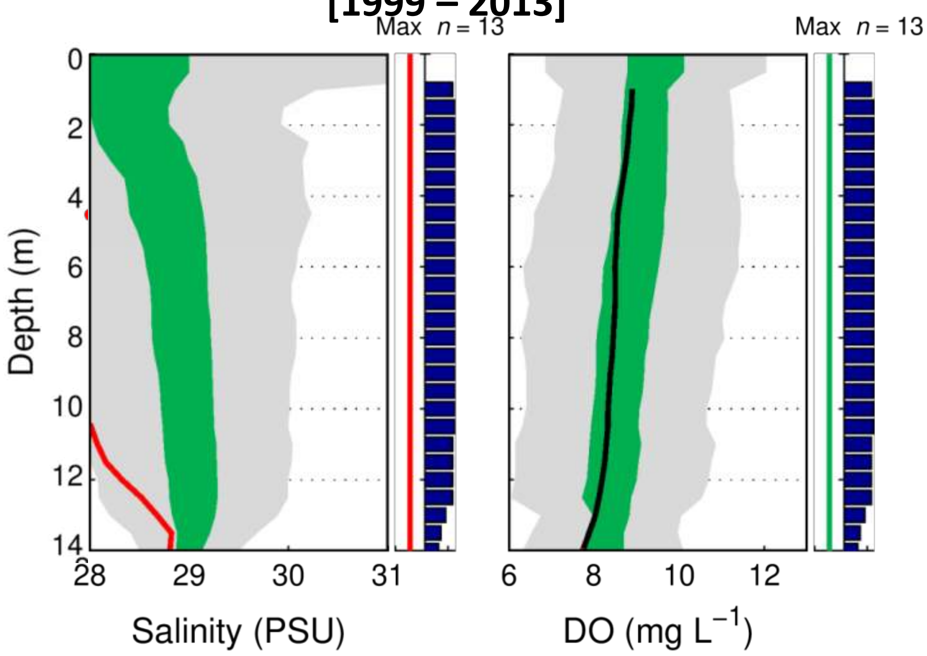
CMB003 – March 2014
[1999 – 2013]



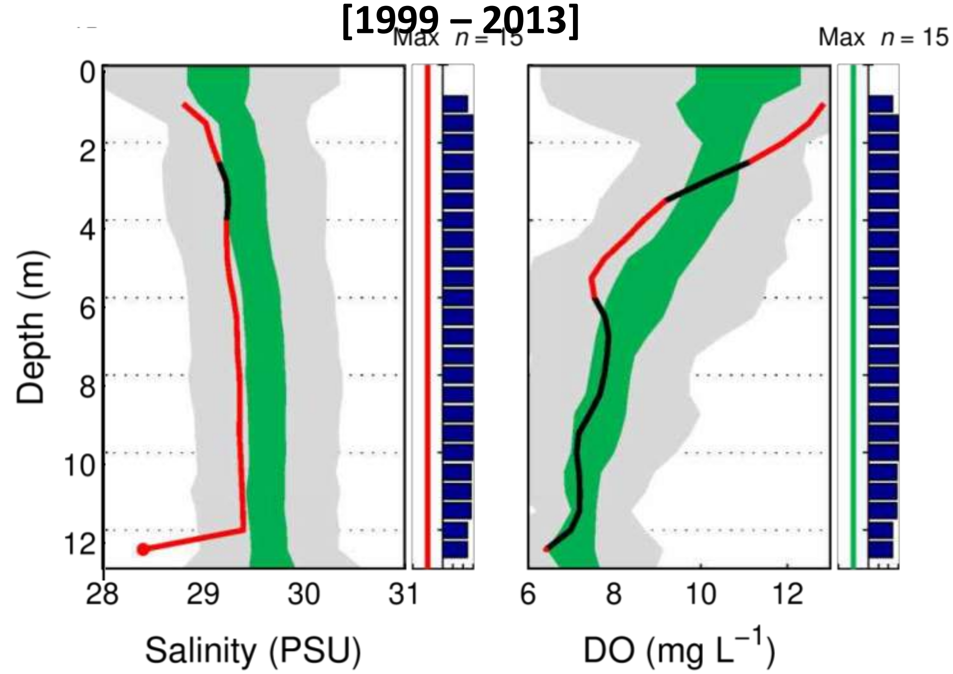
CMB003 – August 2014
[1999 – 2013]



SIN001 – March 2014
[1999 – 2013]

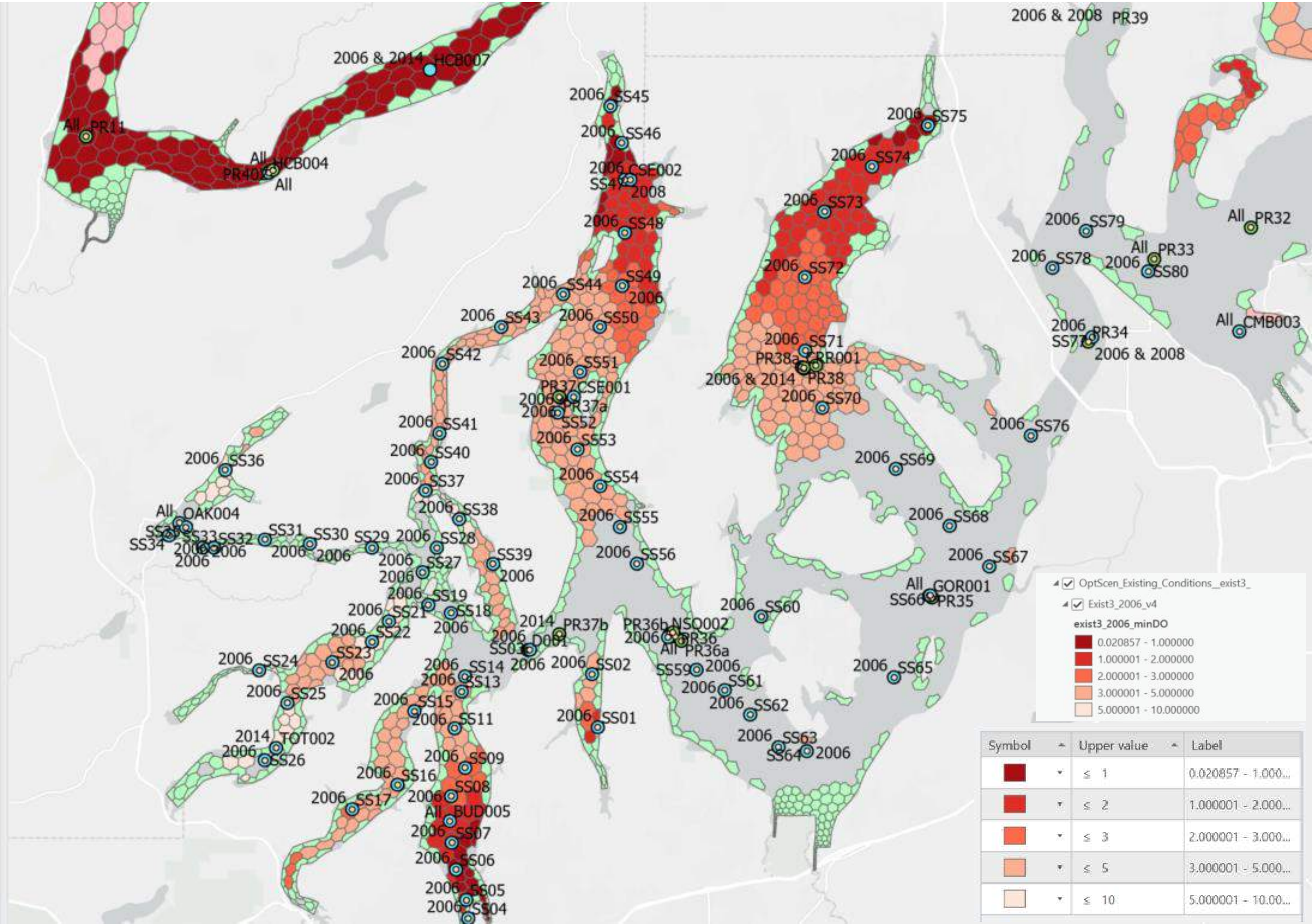


SIN001 – August 2014
[1999 – 2013]



South Sound

- Each inlet is assessed individually following where data are available
- Henderson Inlet: SS02 and SS01 aren't included in the comparison

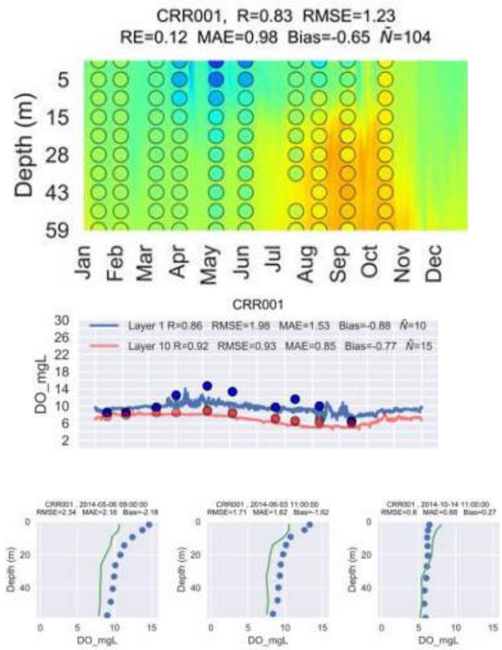


South Sound | 2014

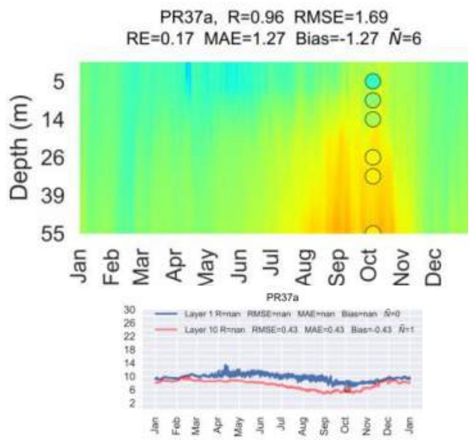
Context

- CSE001 isn't included and is within the same cell as PR37a
- CRR001 and PR38a are in the same cell

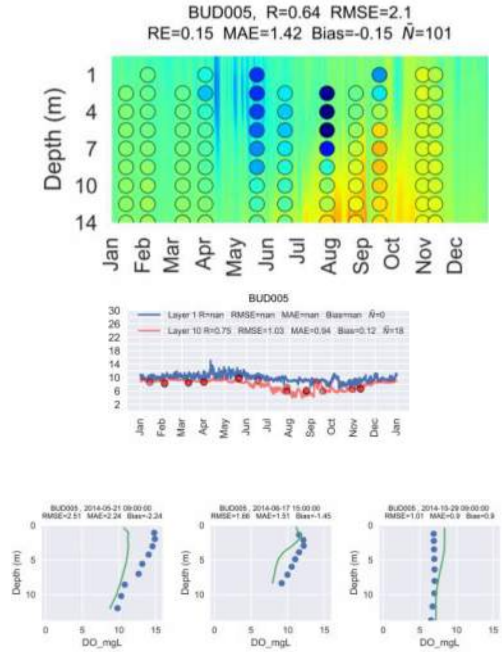
★ CRR001 (Carr Inlet)



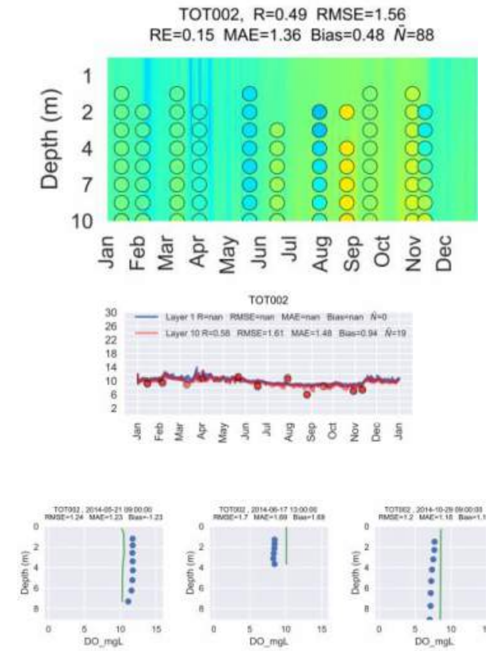
★ PR37a (Case Inlet)



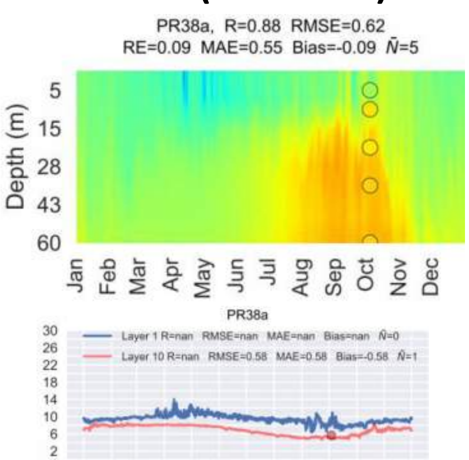
★ BUD005 (Bud Inlet)



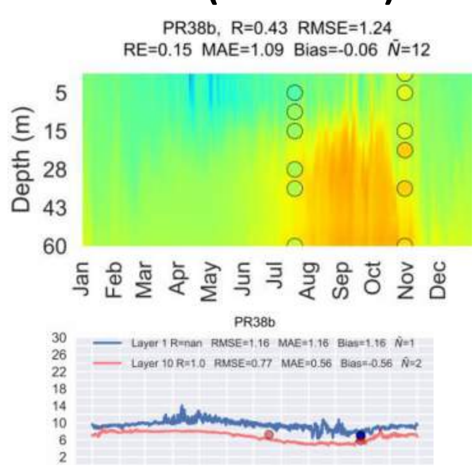
★ TOT002* (Totten Inlet)



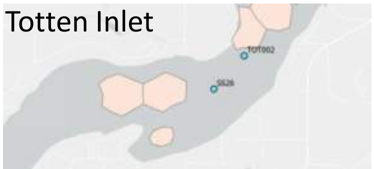
PR38a (Carr Inlet)

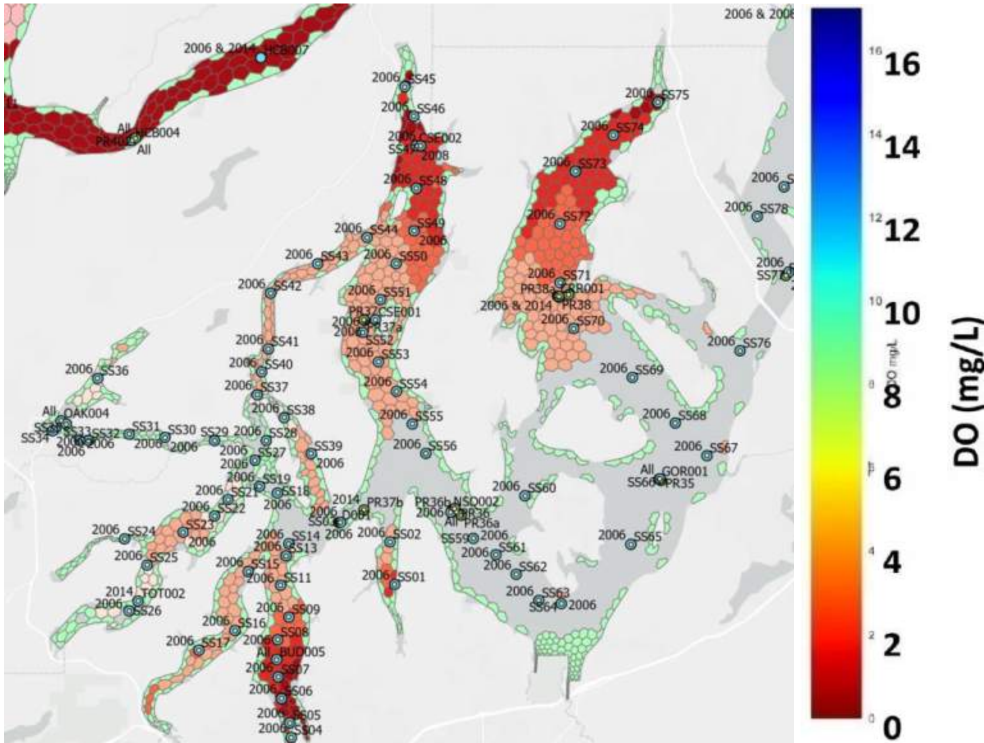


PR38b (Carr Inlet)



*TOT002 is located 130m south of the nearest adjacent model cell with non-compliance. See South Sound| 2006 figures for enlarged maps of non-compliance for each inlet

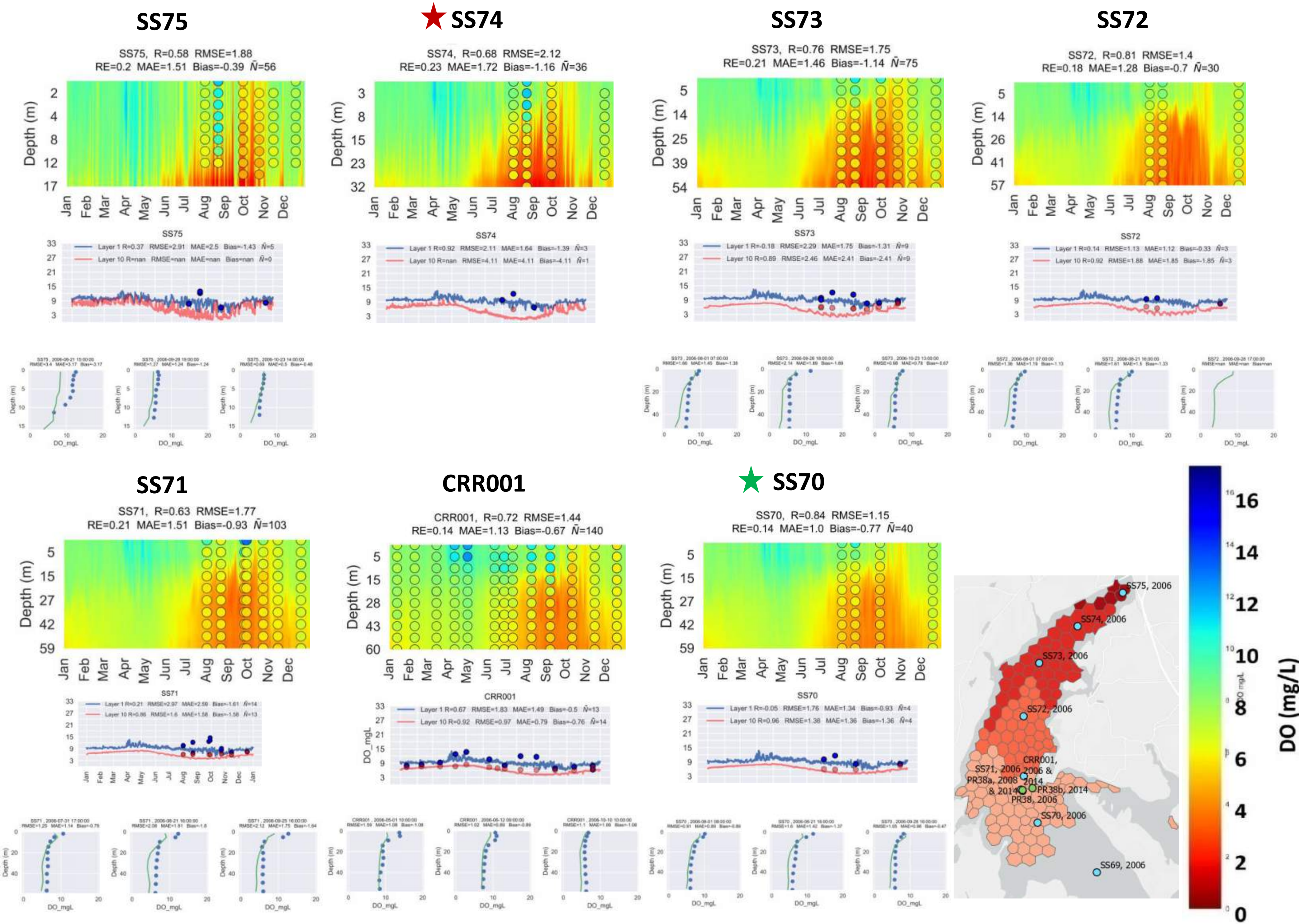




Carr Inlet | 2006

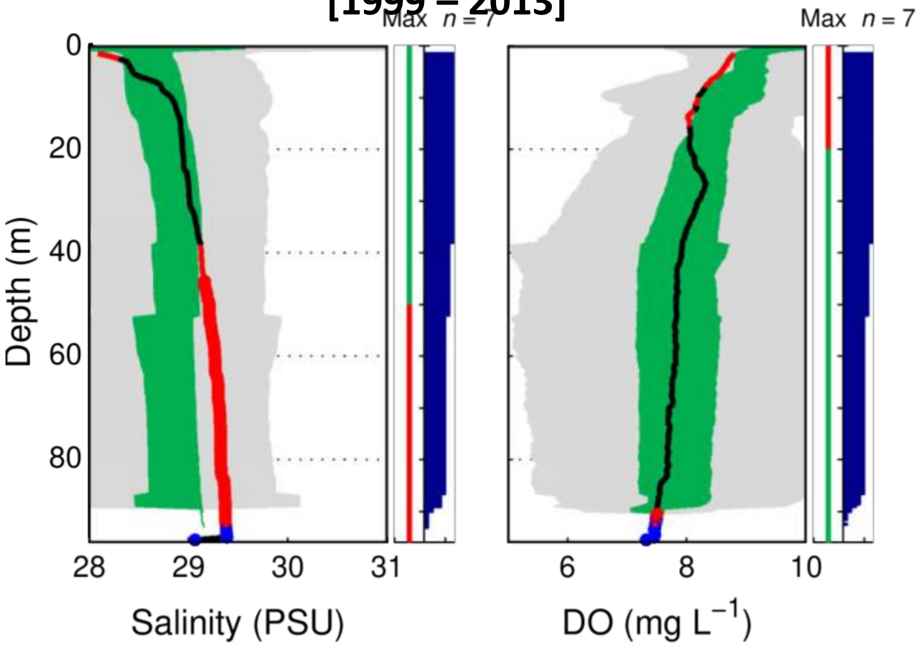
Context

- Located in South Sound
- PR38 isn't included and is within the same cell as CRR001

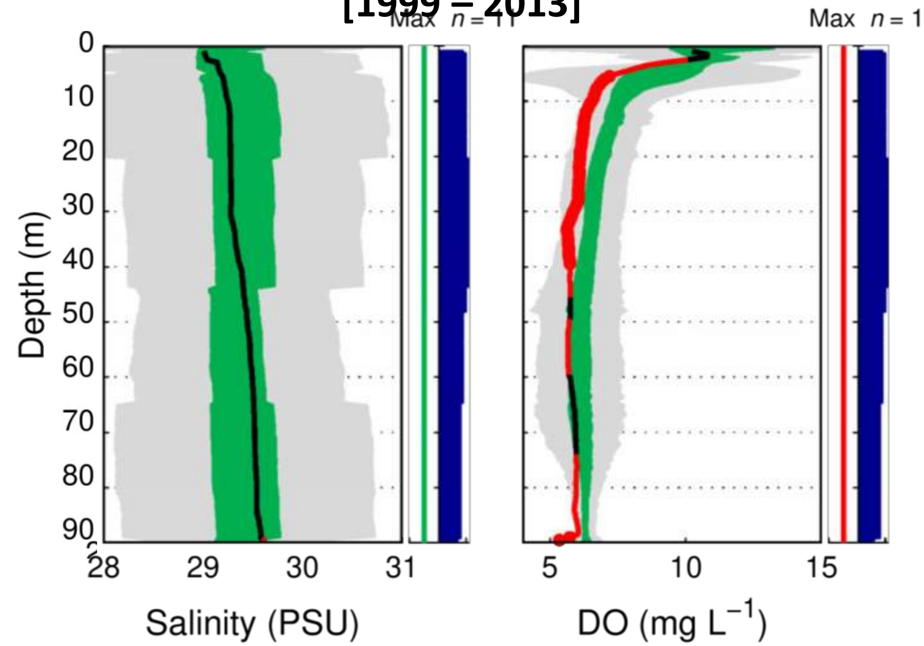


Carr Inlet

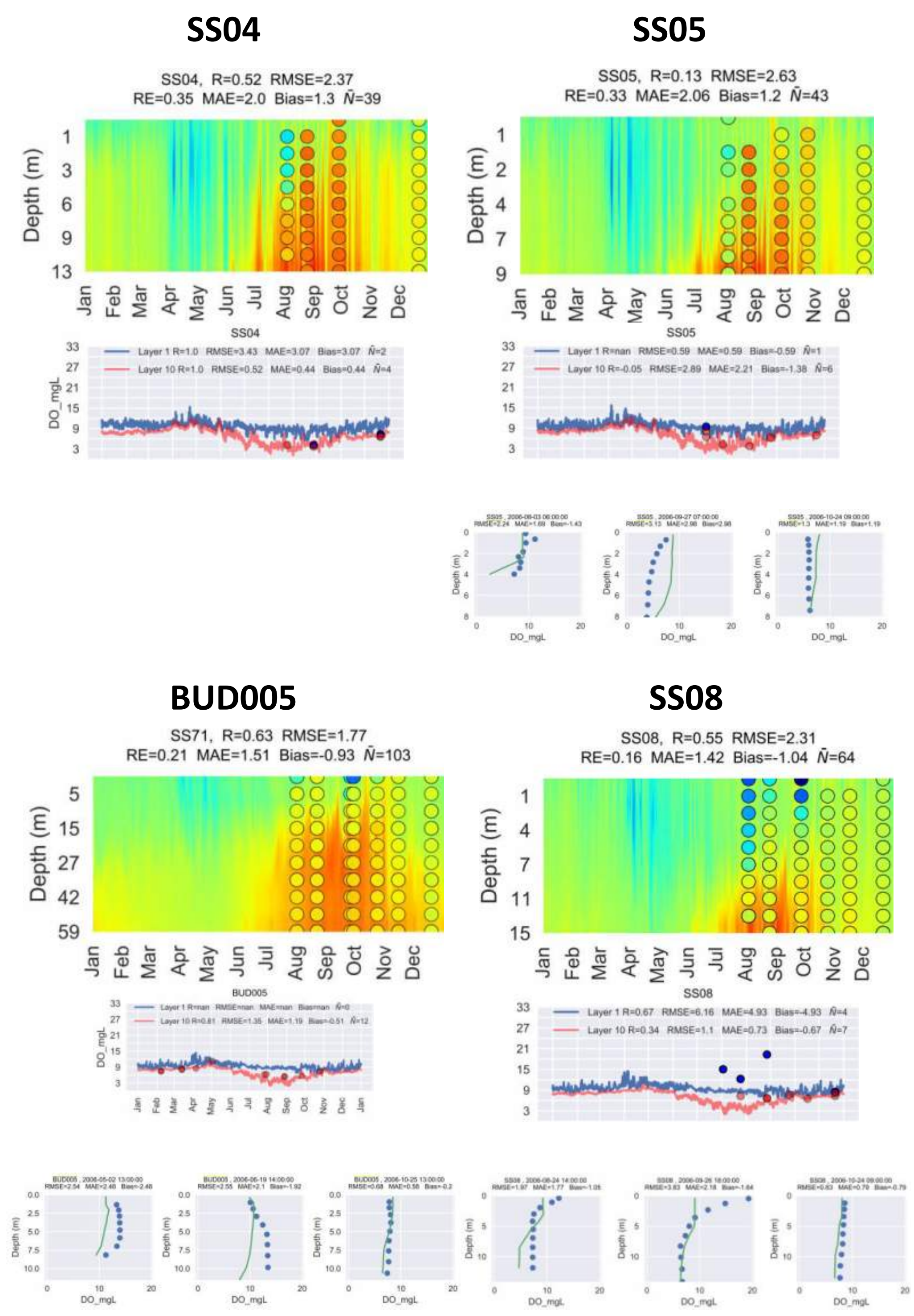
CRR001 – March 2014
[1999 – 2013]

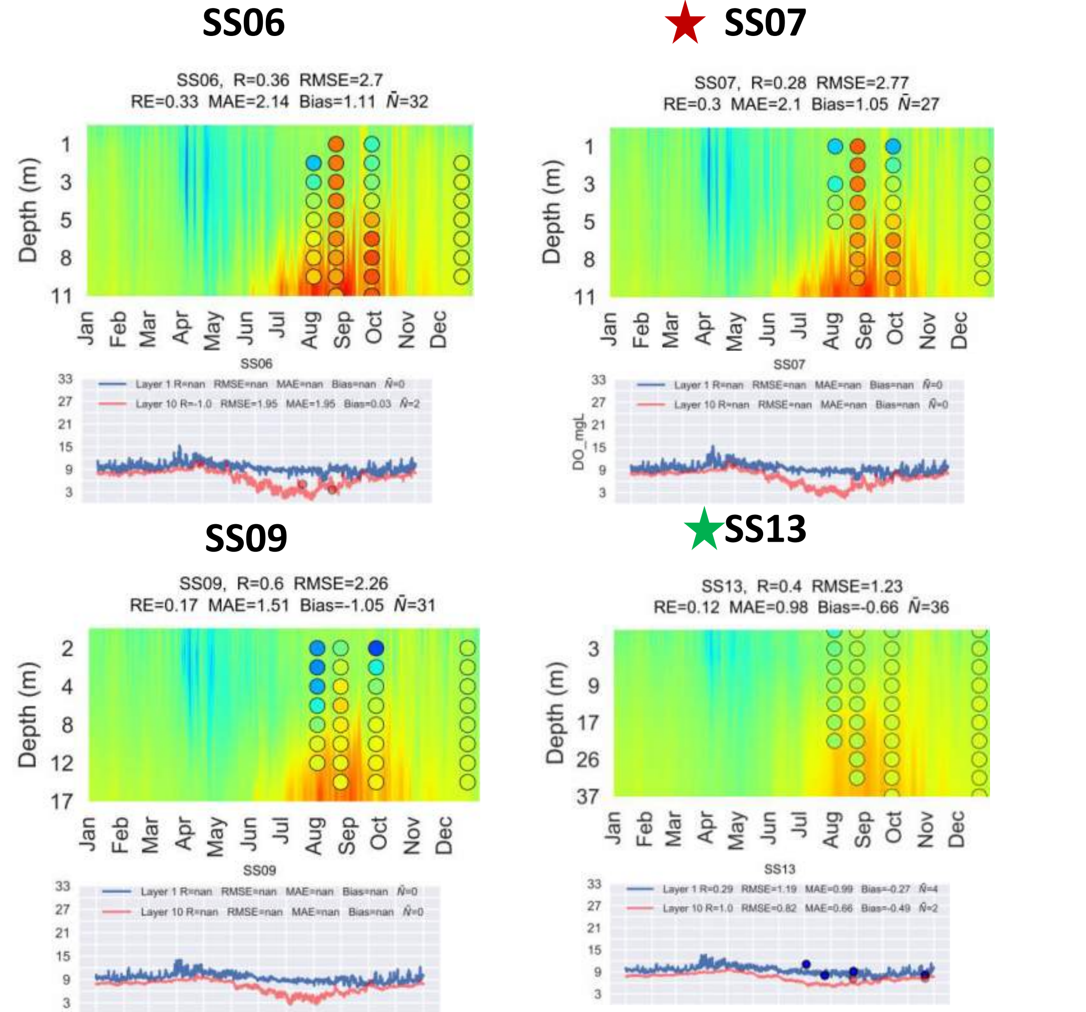


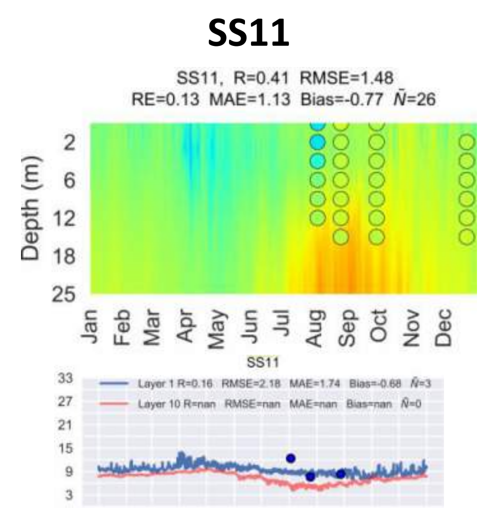
CRR001 – August 2014
[1999 – 2013]

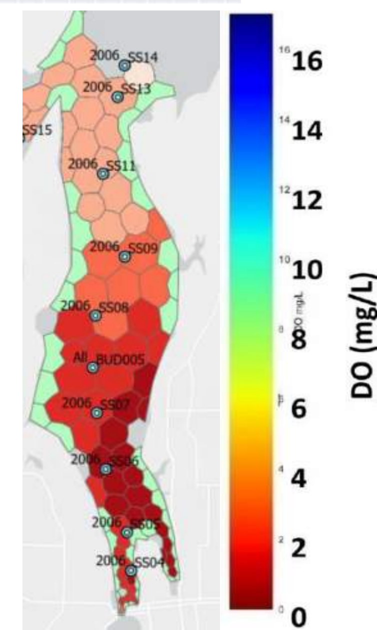


Budd Inlet | 2006





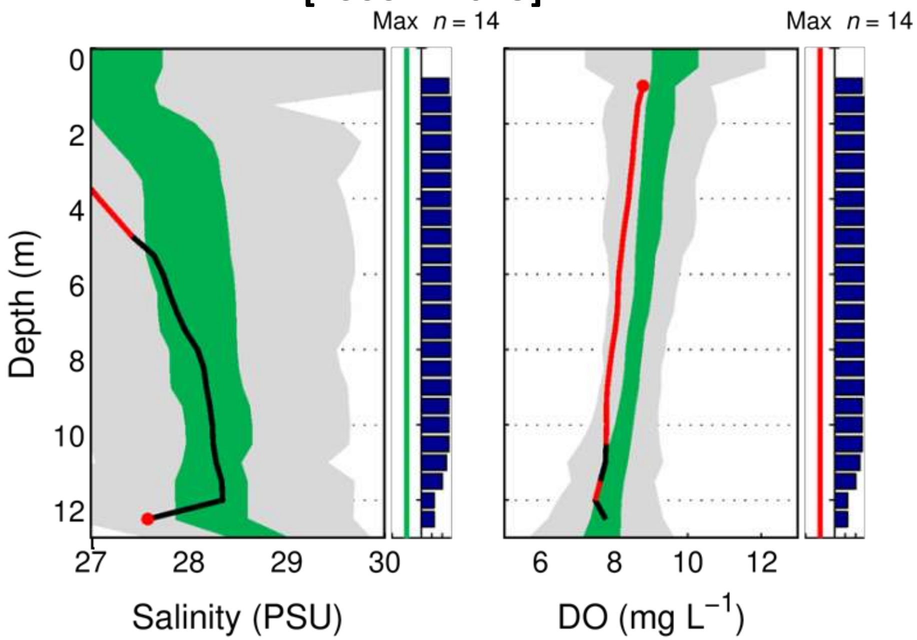




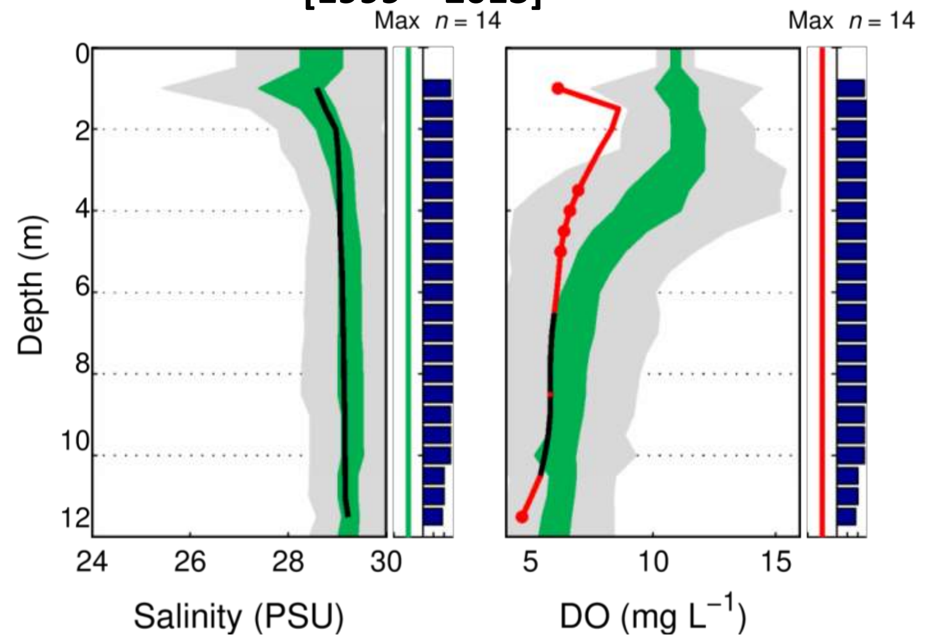
- Located in South Sound

Budd Inlet

BUD005 – March 2014
[1999 – 2013]



BUD005 – August 2014
[1999 – 2013]

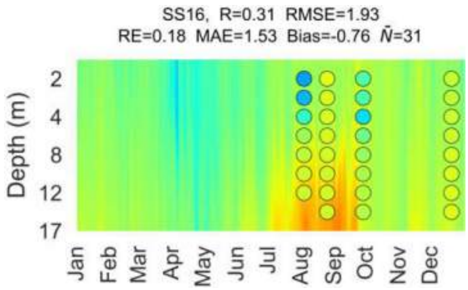


Eld Inlet | 2006

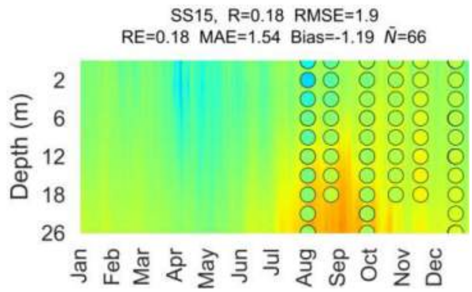
- Located in South Sound
- SS17 isn't included

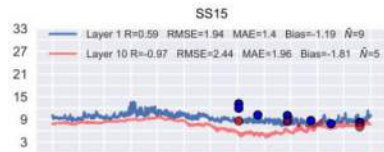
Context

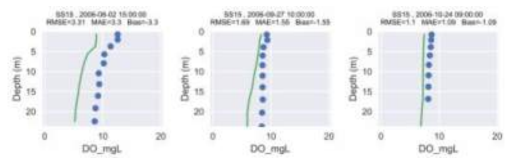
SS16

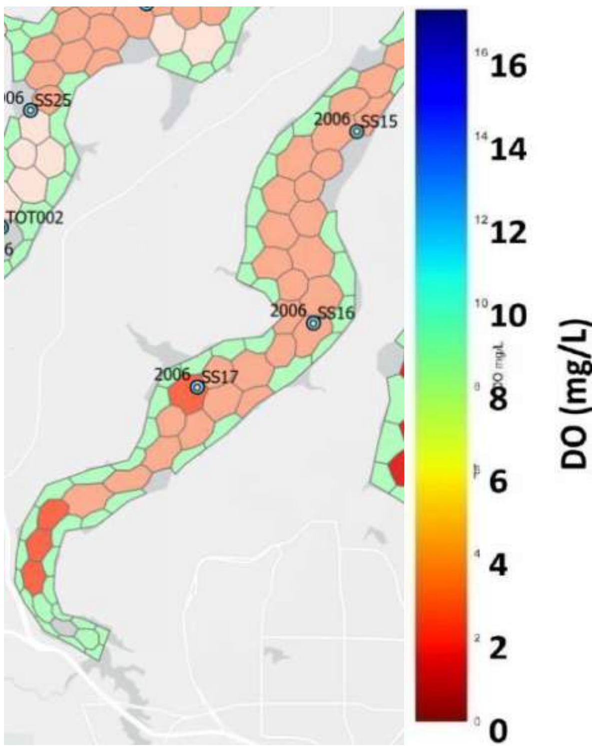


SS15







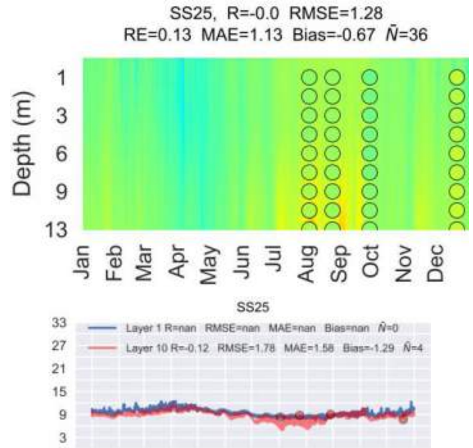


Totten Inlet | 2006

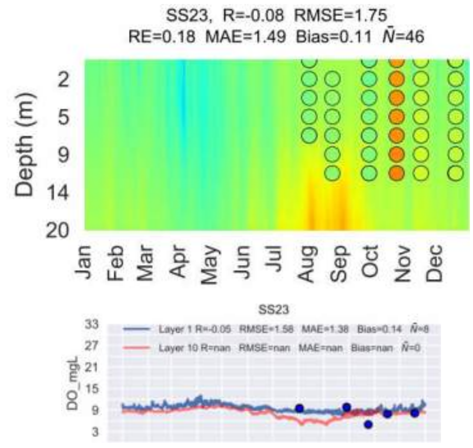
Context

- Located in South Sound
- SS26 is at the farthest end of the inlet, but compliant

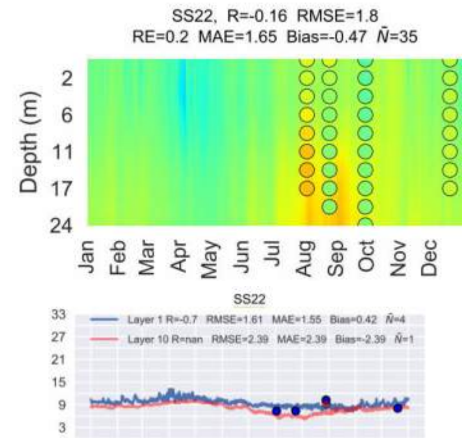
★ SS25



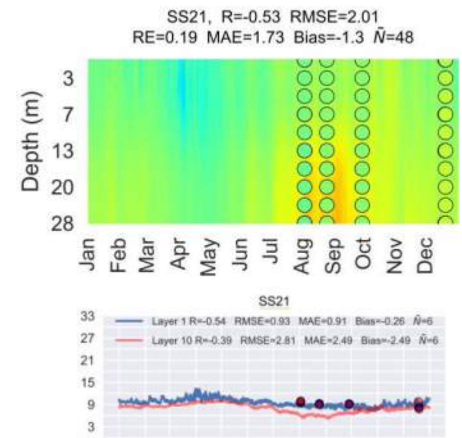
SS23

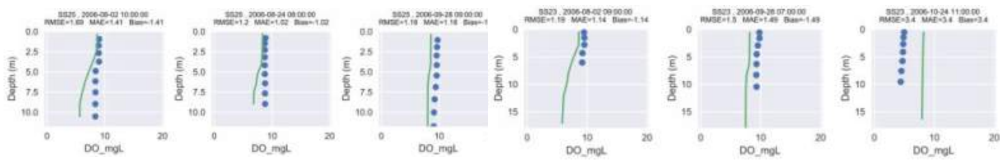


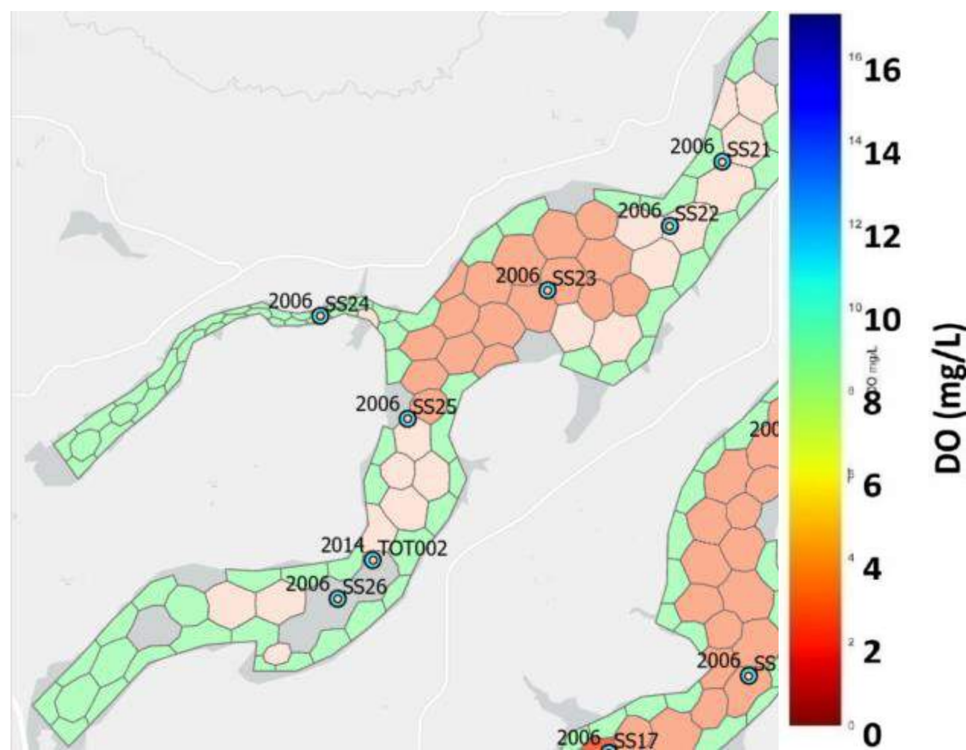
SS22



★ SS21

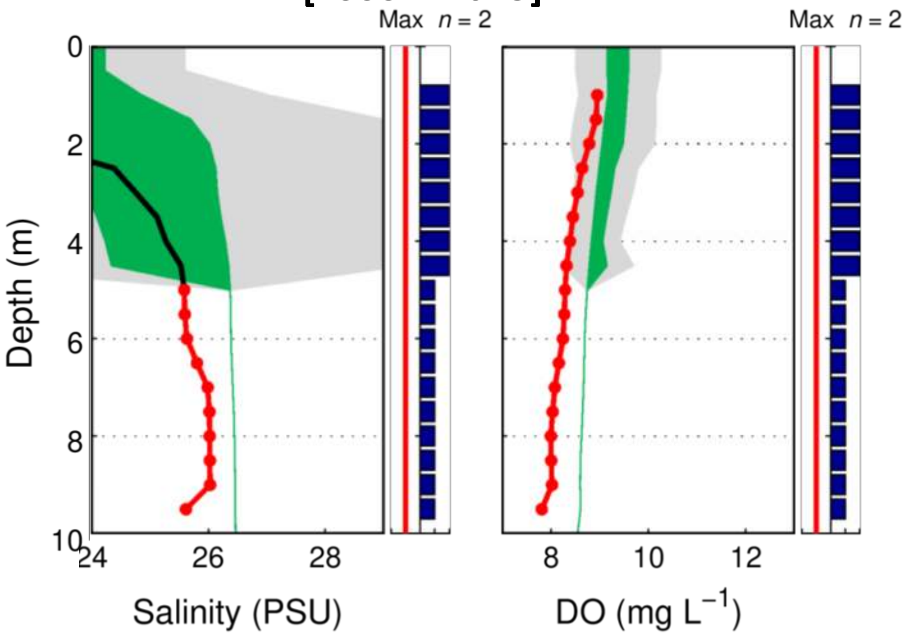




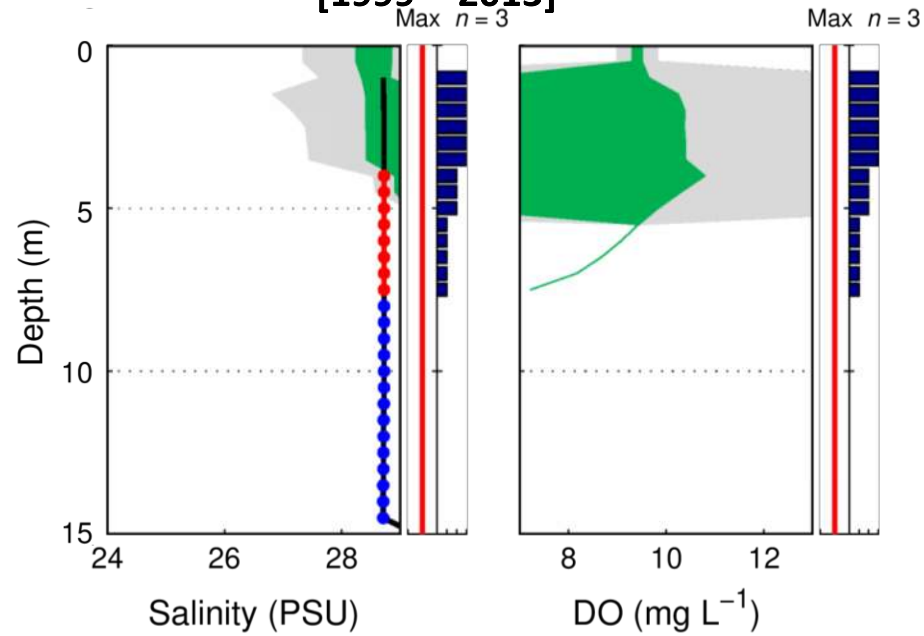


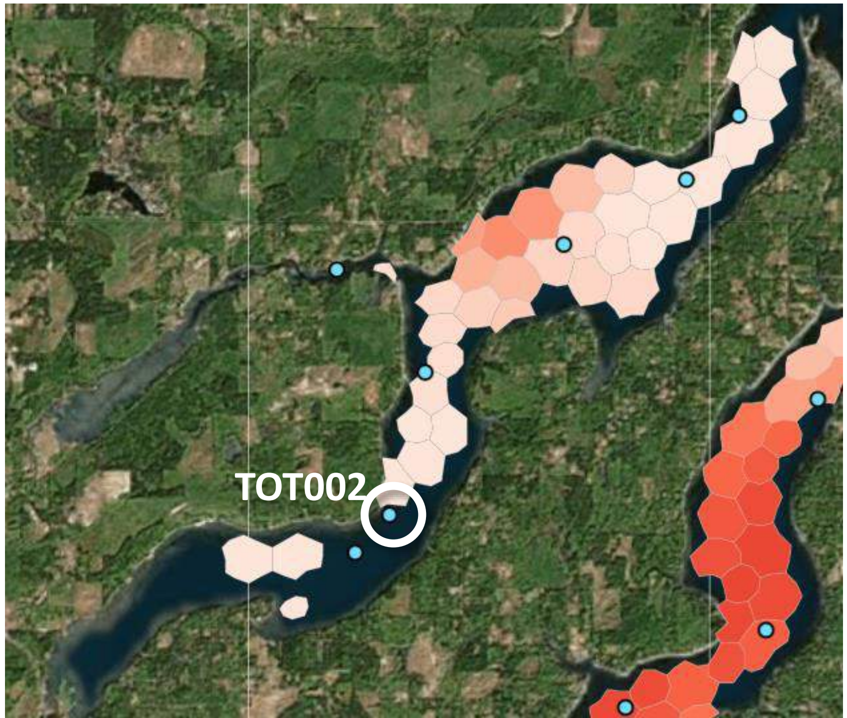
Totten Inlet

TOT002* – March 2014
[1999 – 2013]



TOT002* – August 2014
[1999 – 2013]





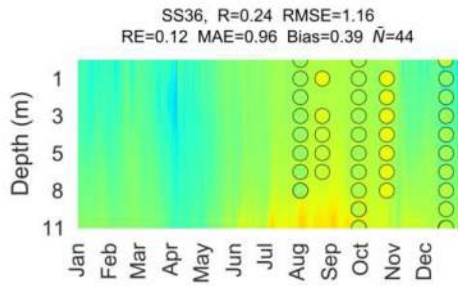
*While the monitoring station is compliant, it’s the closest long-term monitoring station to the non-compliant inlet

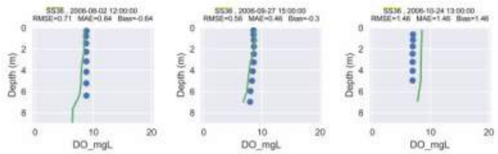
Oakland Bay | 2006

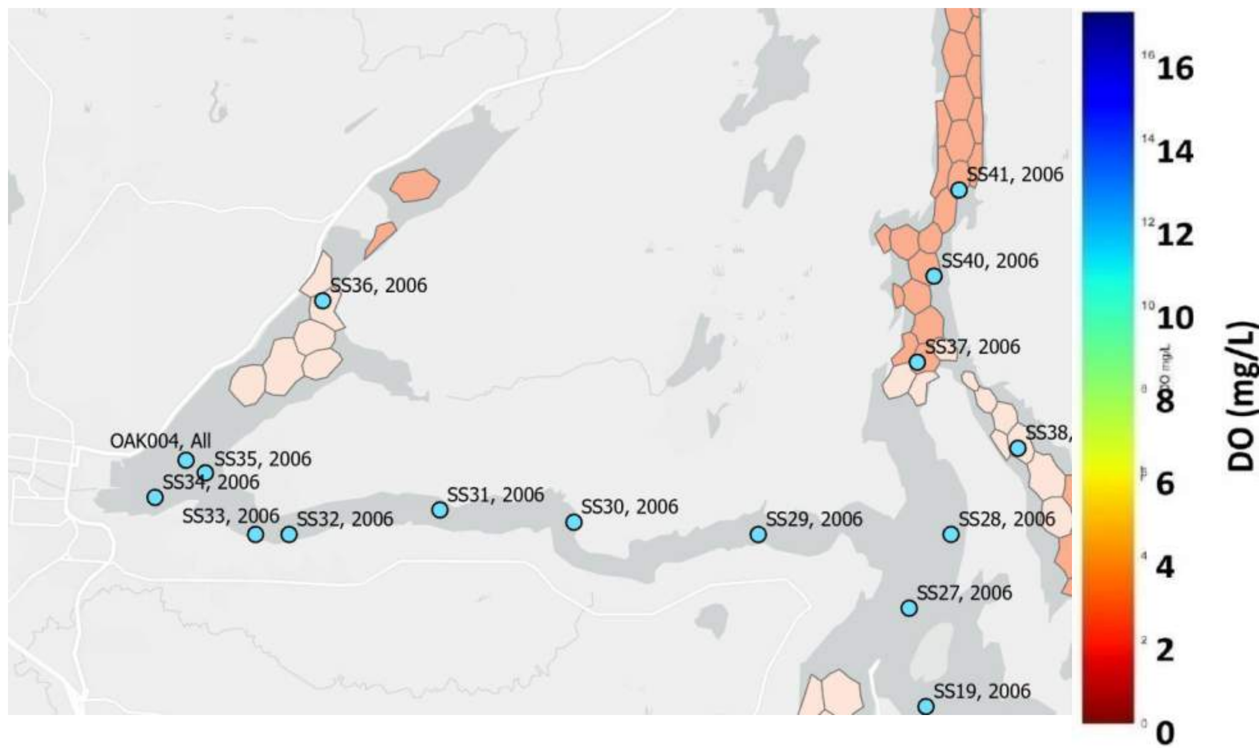
Context

- Located in South Sound

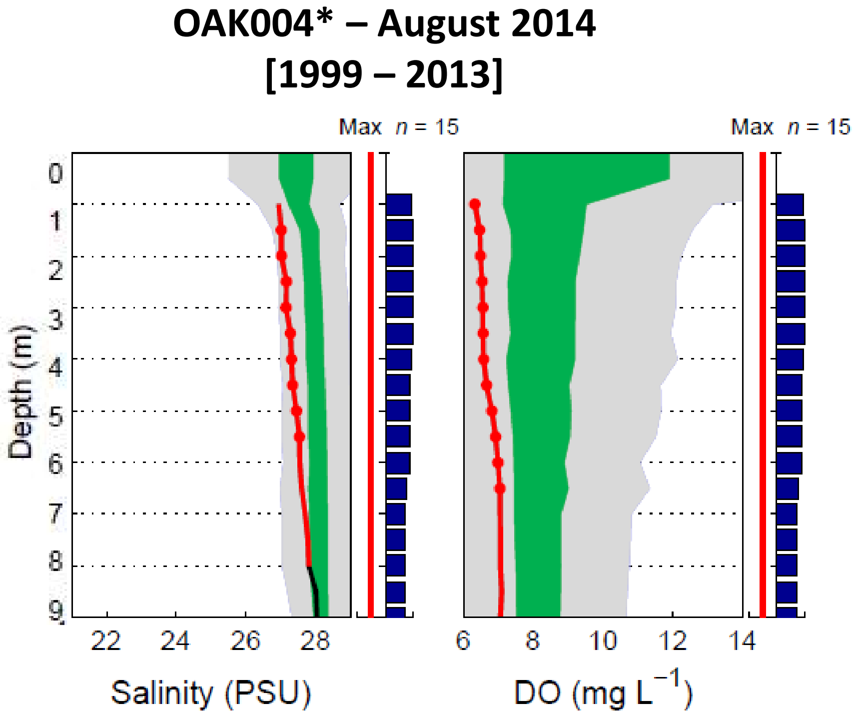
★ **SS36**







Oakland Bay



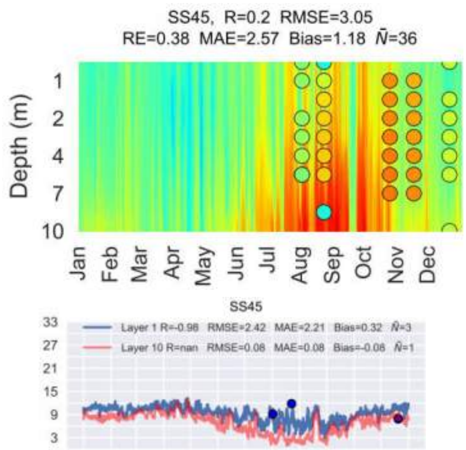
*While the monitoring station is compliant, it's the closest long-term monitoring station to the non-compliant inlet

Case Inlet | 2006

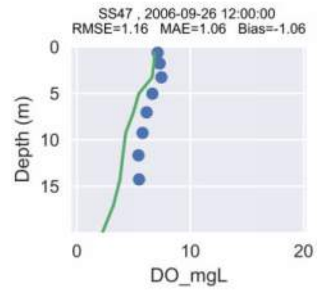
Context

- Located in South Sound
- SS46 is also available, but falls within the masked area
- SS47 only has a partial comparison

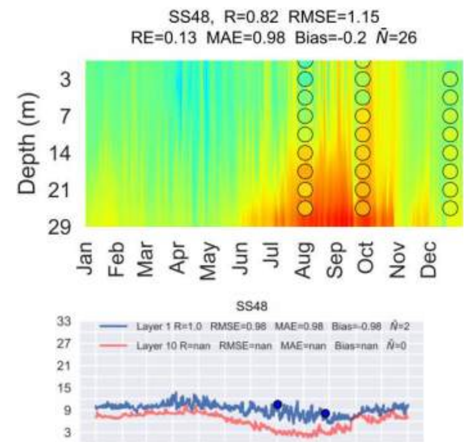
★ SS45



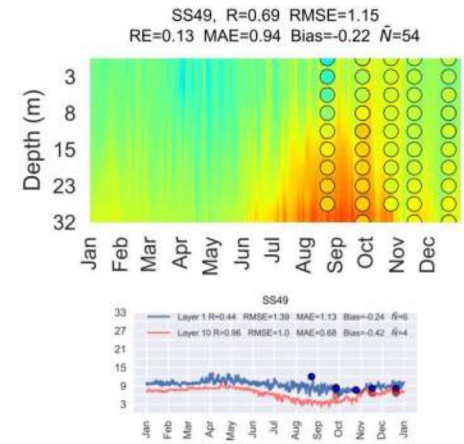
SS47

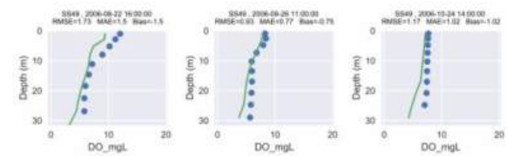


SS48

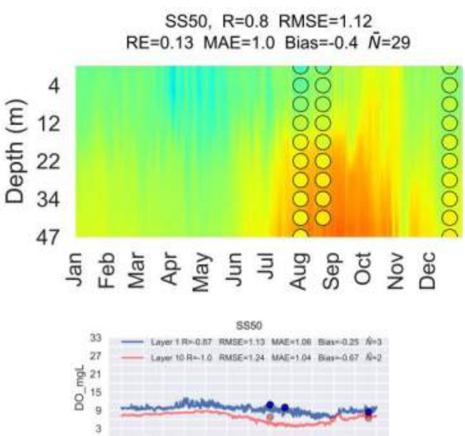


SS49

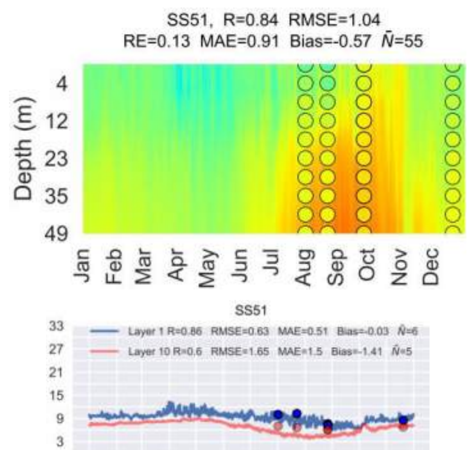


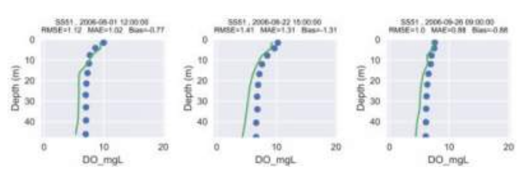


SS50

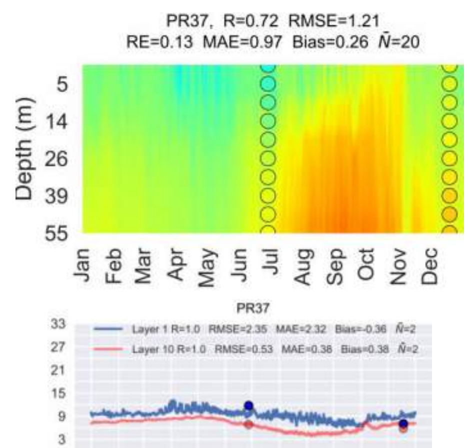


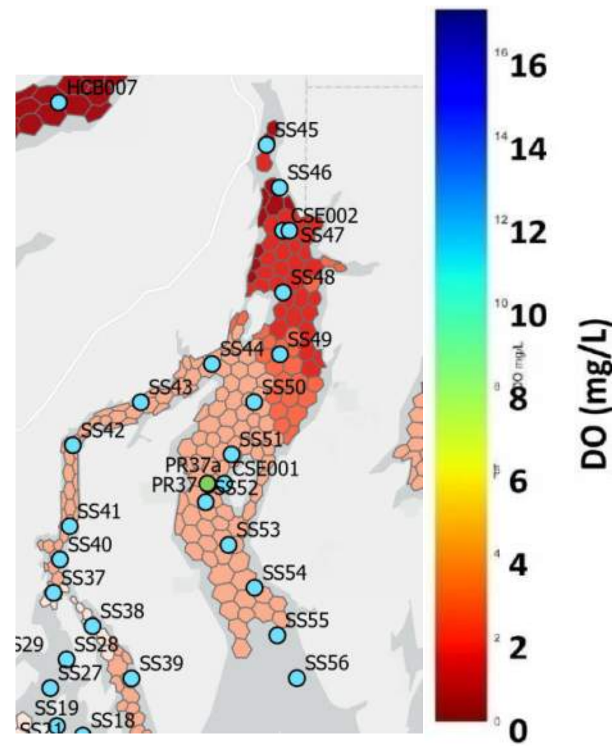
★ SS51





PR37



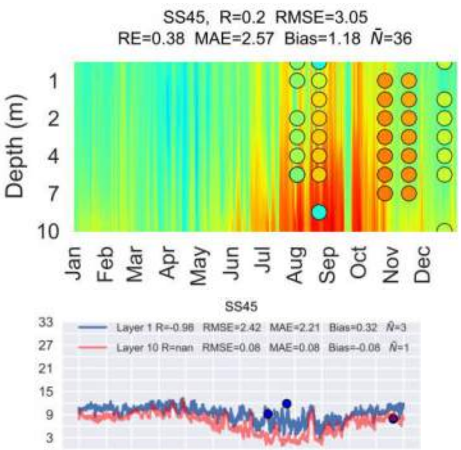


Case Inlet | 2006

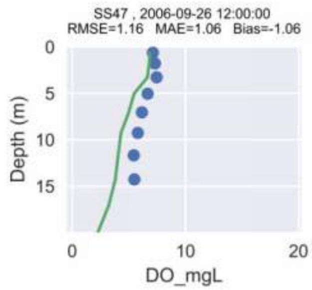
Context

- Located in South Sound
- SS46 is also available, but falls within the masked area
- SS47 only has a partial comparison

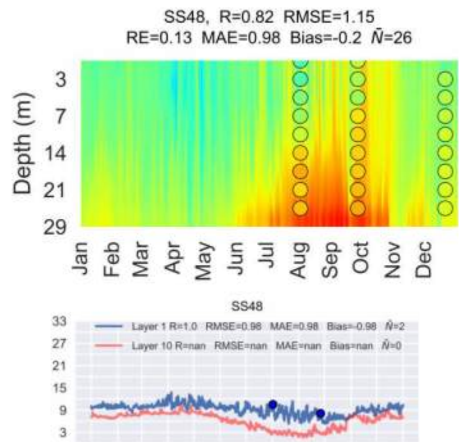
★ SS45



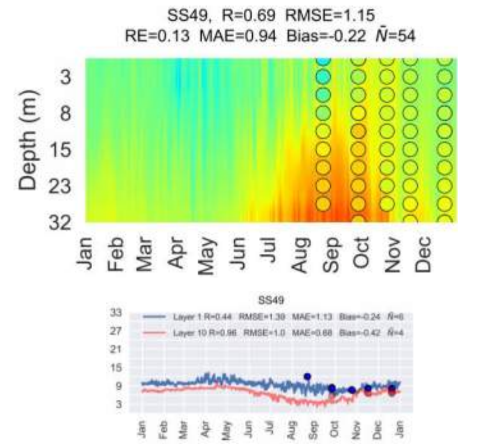
SS47

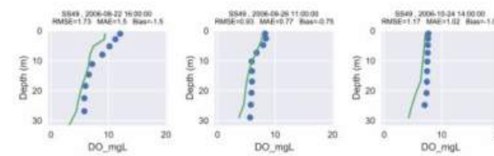


SS48

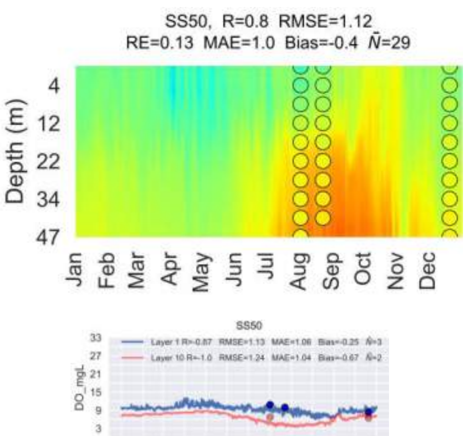


SS49

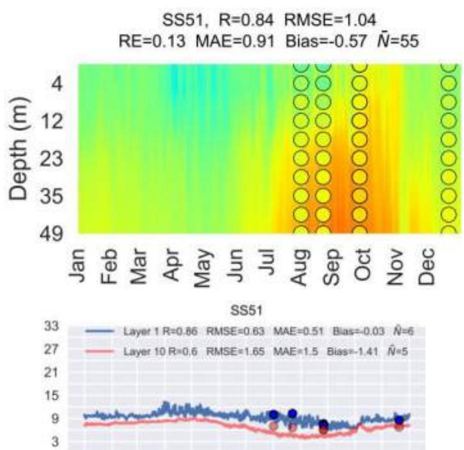


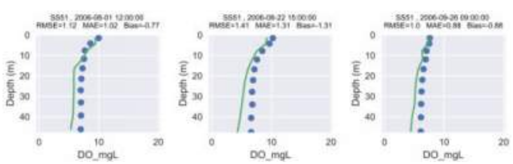


SS50

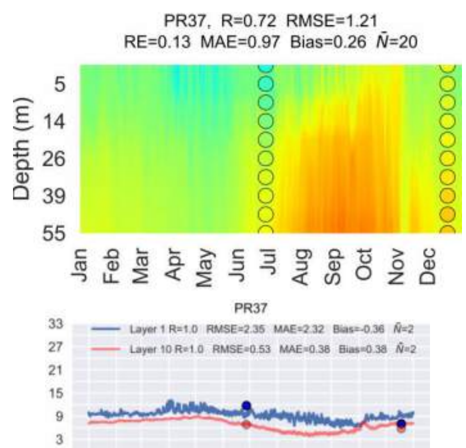


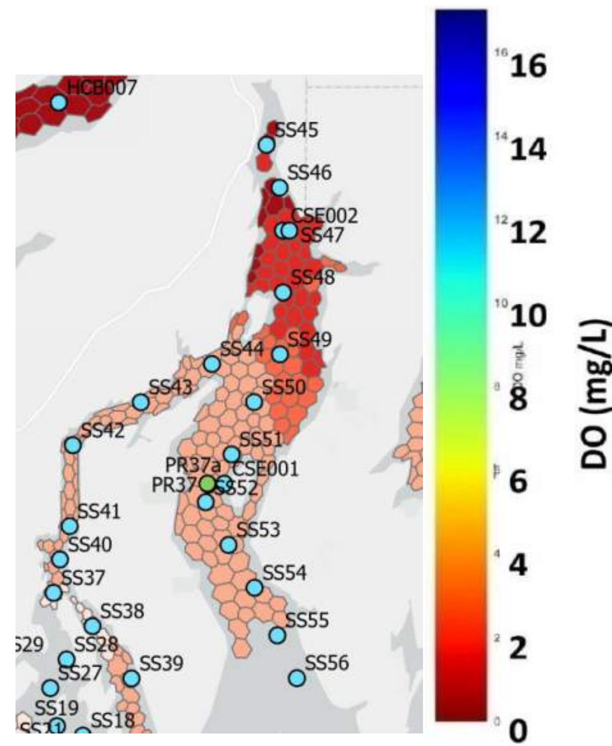
★ SS51





PR37



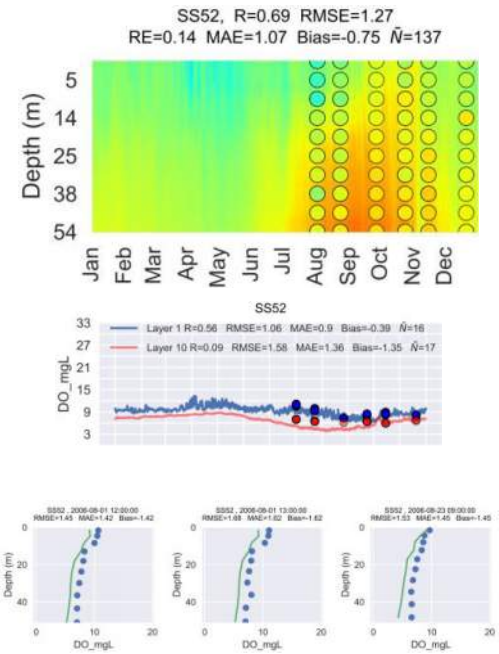


Case Inlet cont.| 2006

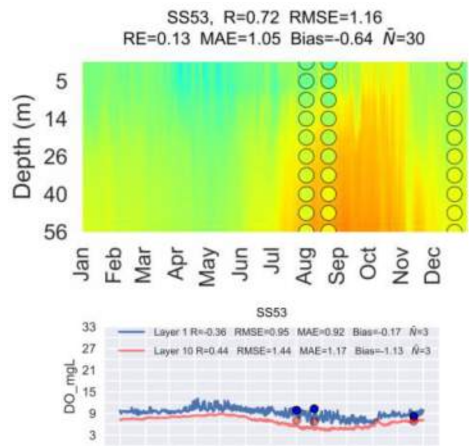
Context

- Located in South Sound
- SS43 is also available, but falls within the masked area

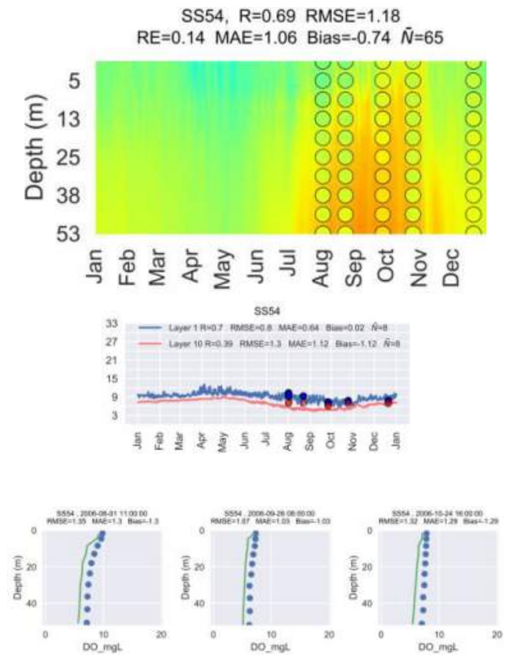
SS52



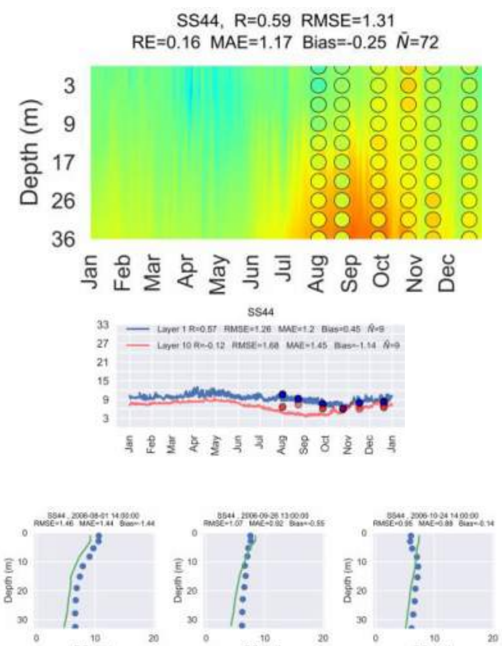
SS53



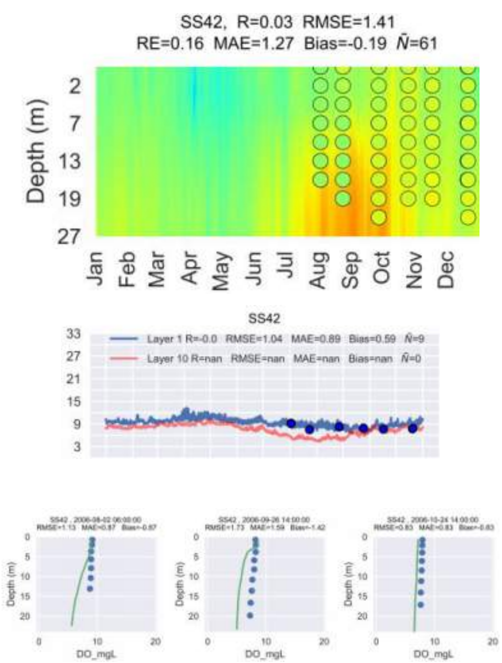
SS54



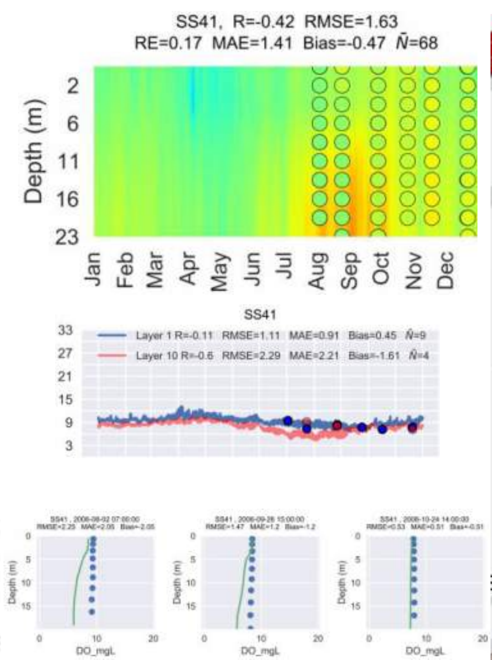
SS44

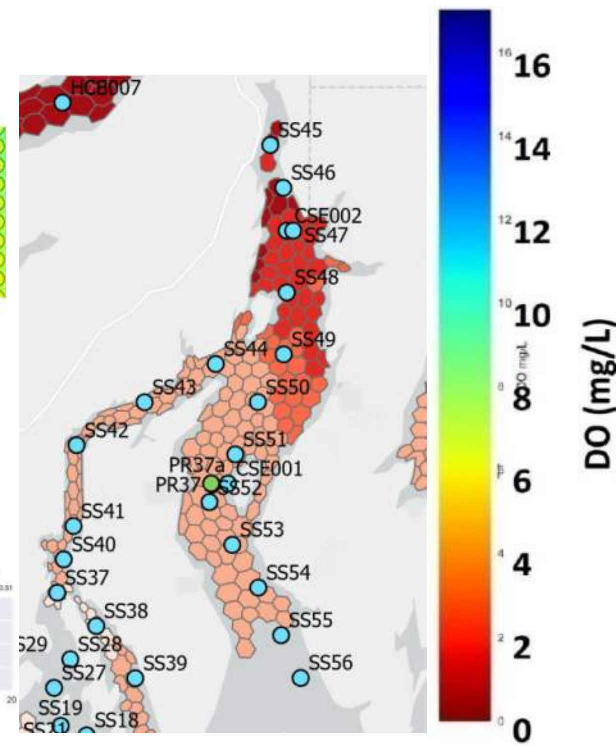


SS42



SS41



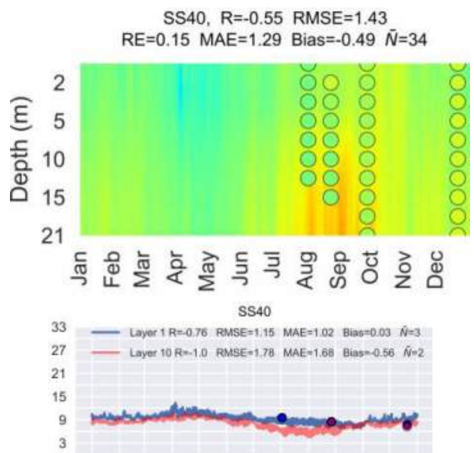


Case Inlet cont.| 2006

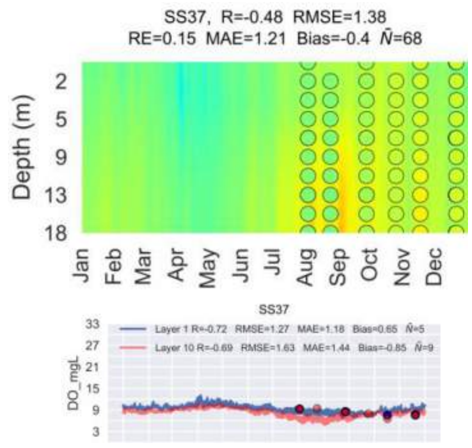
- Located in South Sound

Context

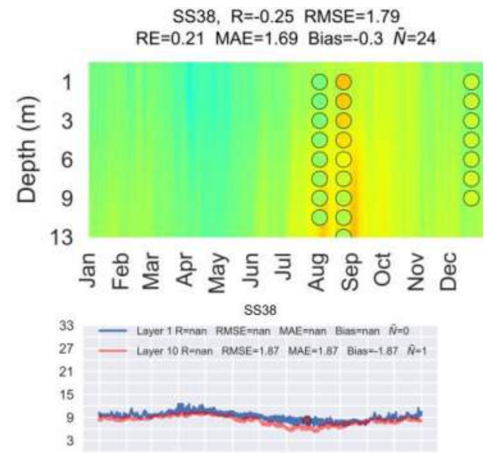
SS40



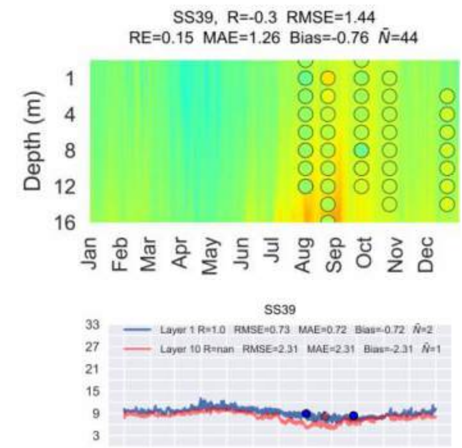
SS37

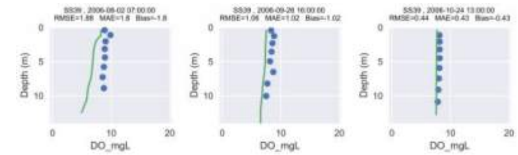


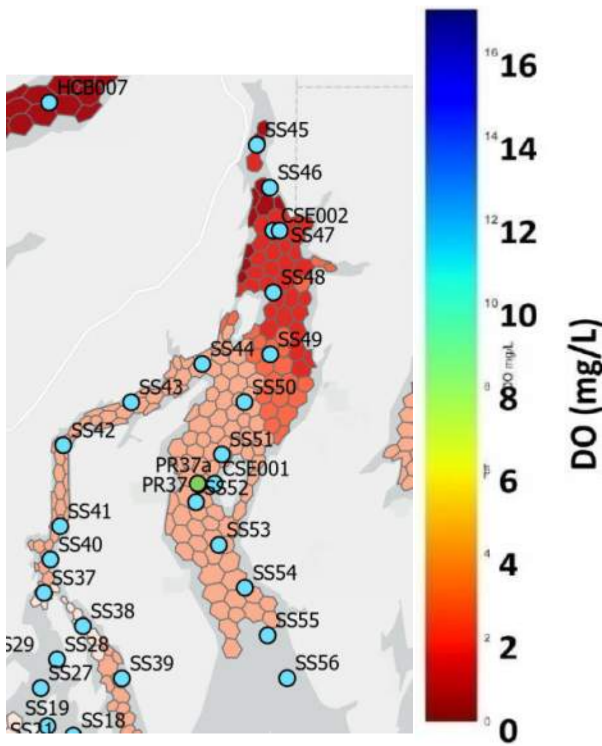
SS38



SS39

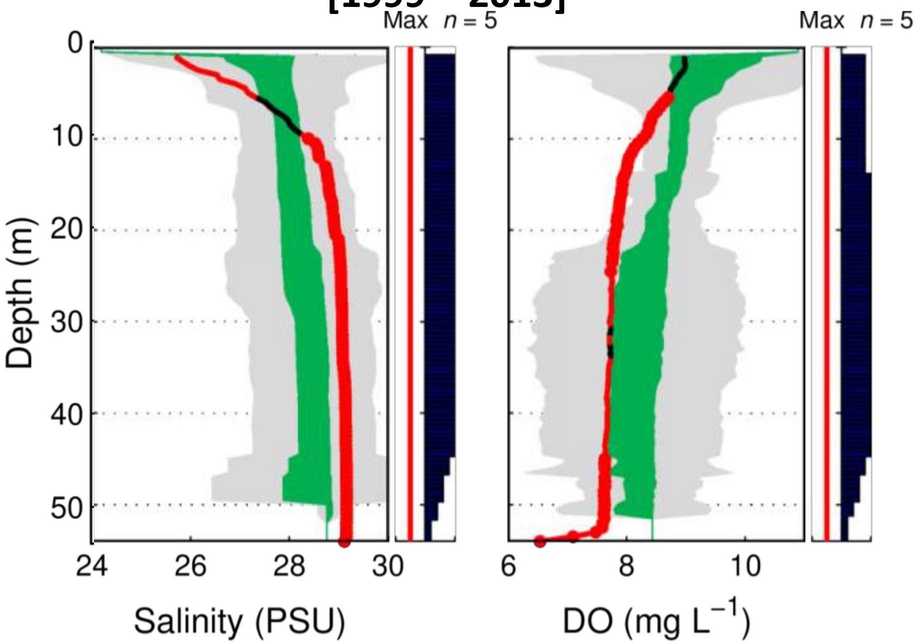




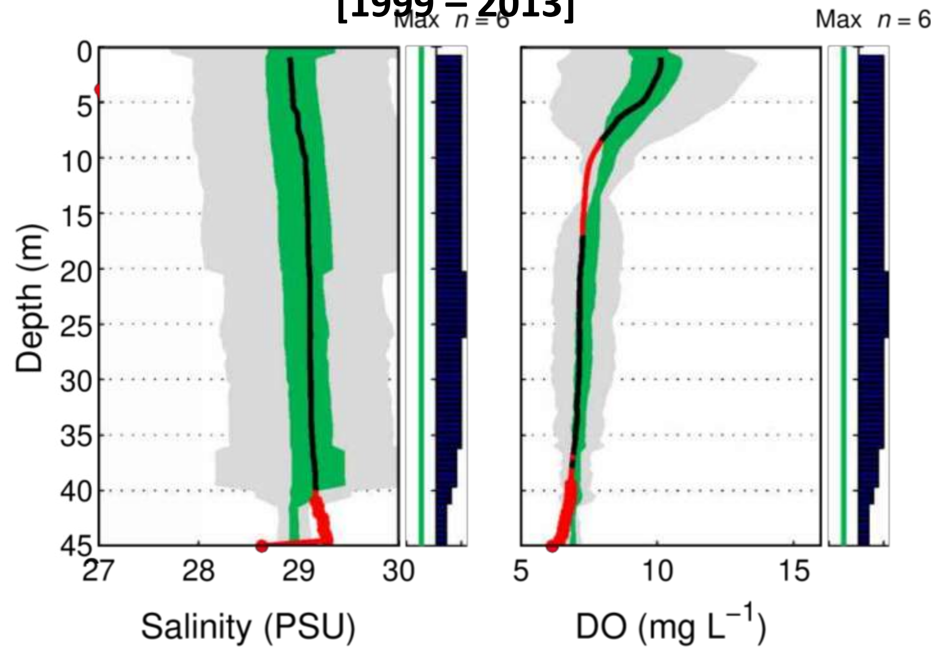


Case Inlet

CSE001* – March 2014
[1999 – 2013]



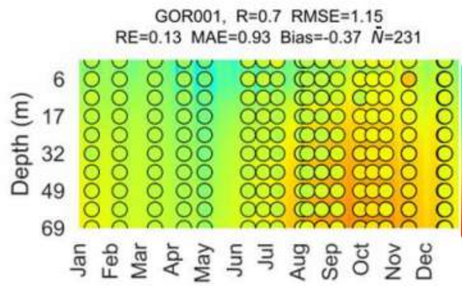
CSE001* – August 2014
[1999 – 2013]

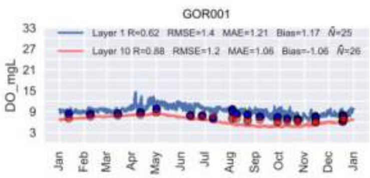


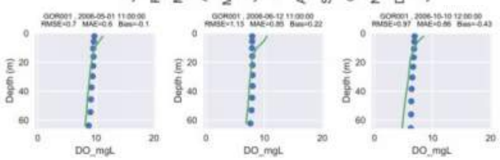
*Ecology et al. 2021 did not compare the model predictions to this monitoring station. However, it falls within the same non-compliant model cell as monitoring station PR37a which was compared.

Deep Location for Comparison | South Sound

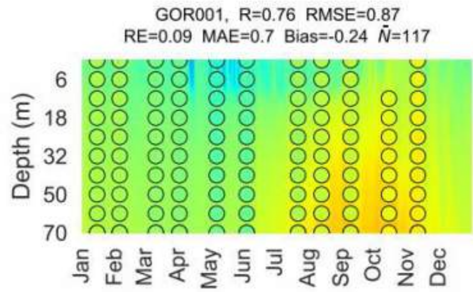
GOR001 - 2006

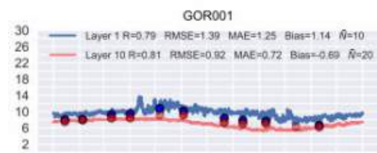


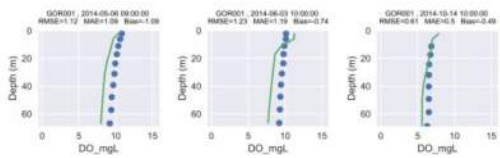




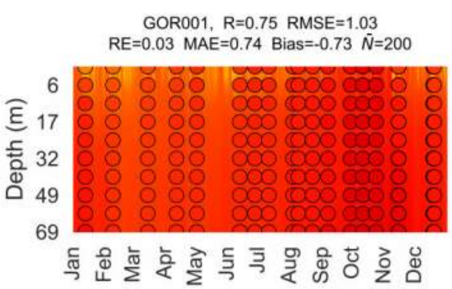
GOR001 - 2014







Salinity



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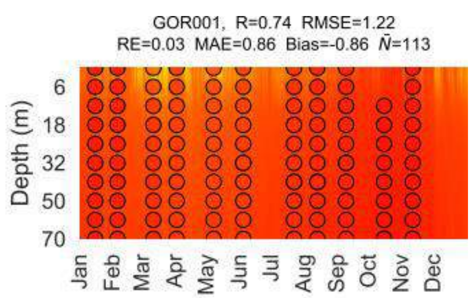
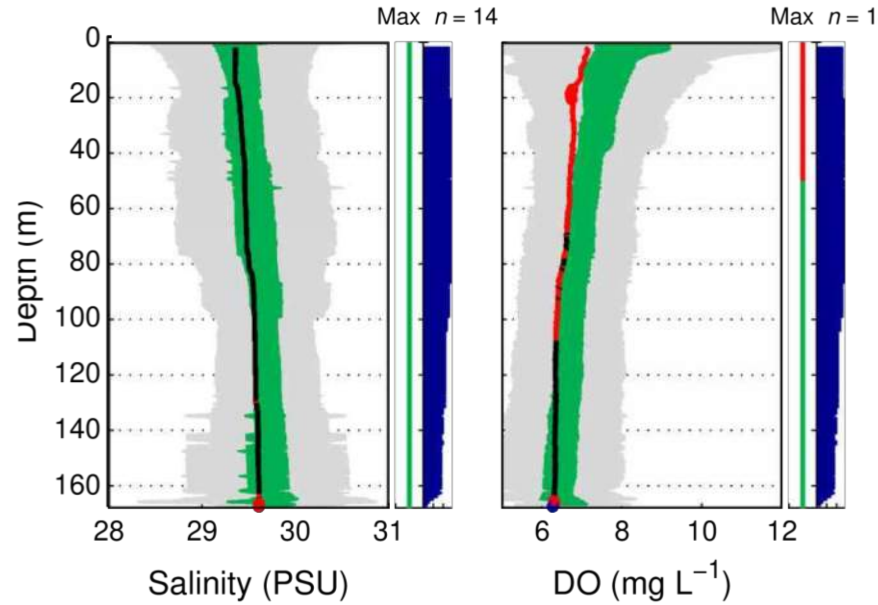
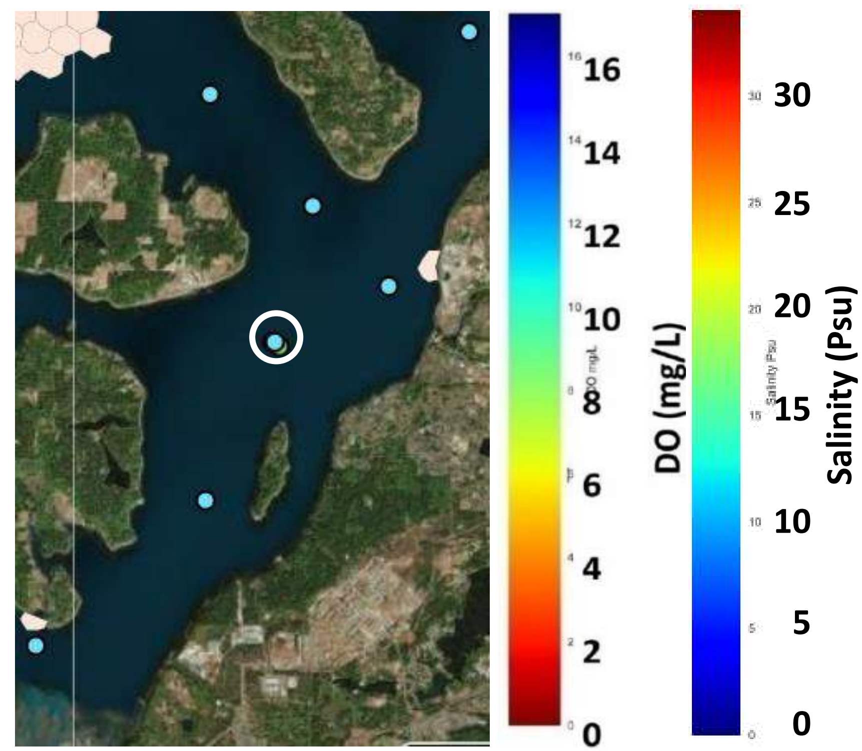


GOR001 – August 2014 (1999 – 2013)

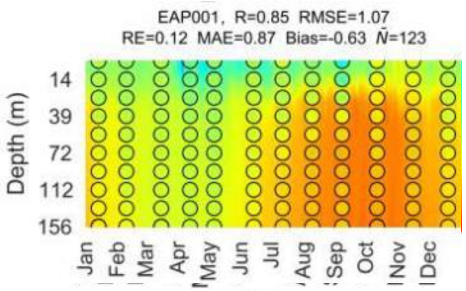


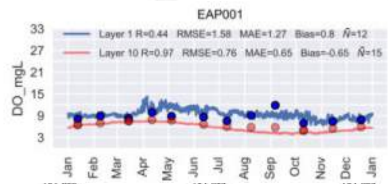


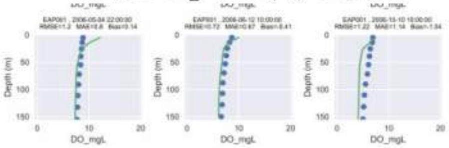
*Note this location has a modeled depth of approximately **65m** and is compliant*

Deep Location for Comparison | Main Basin

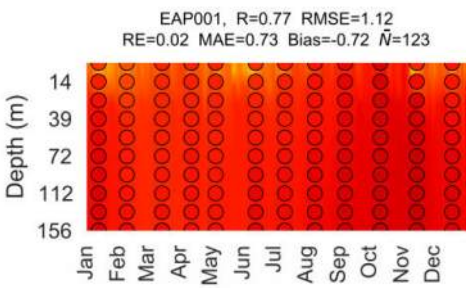
EAP001 - 2006







Salinity



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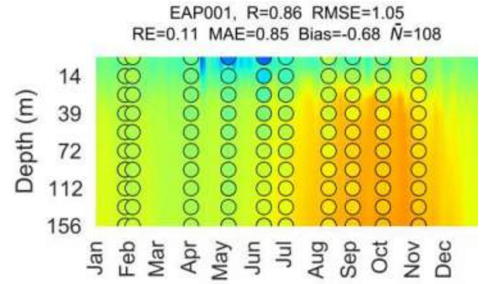
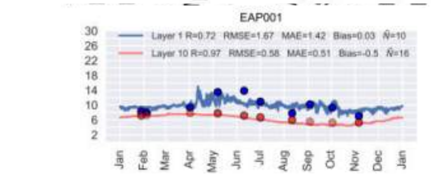
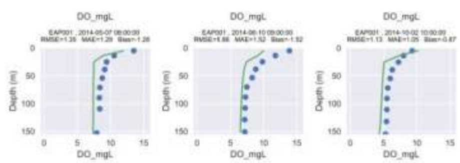
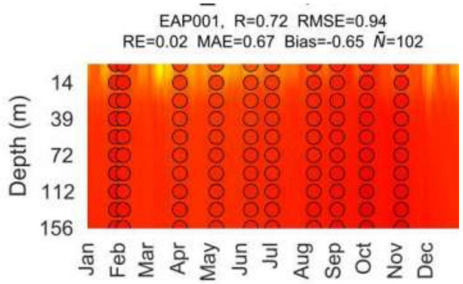


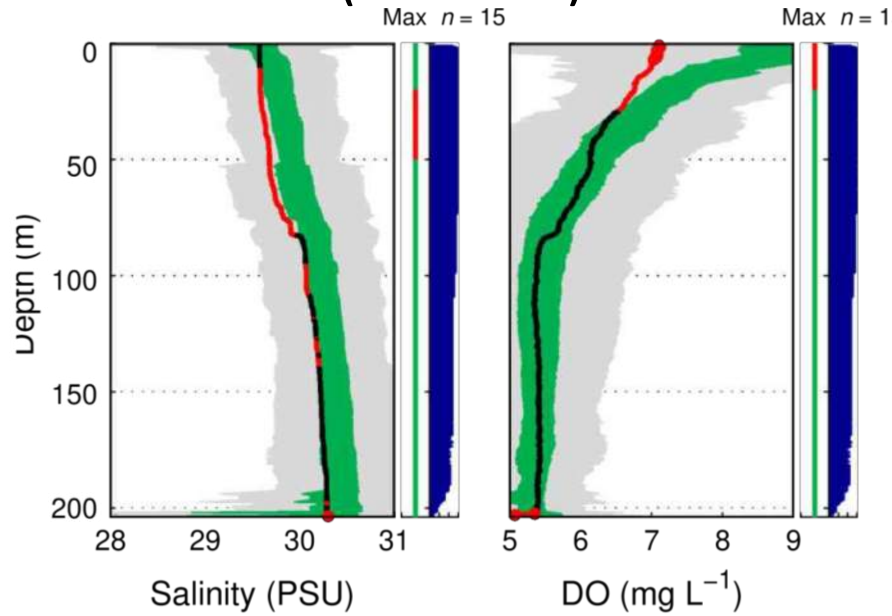


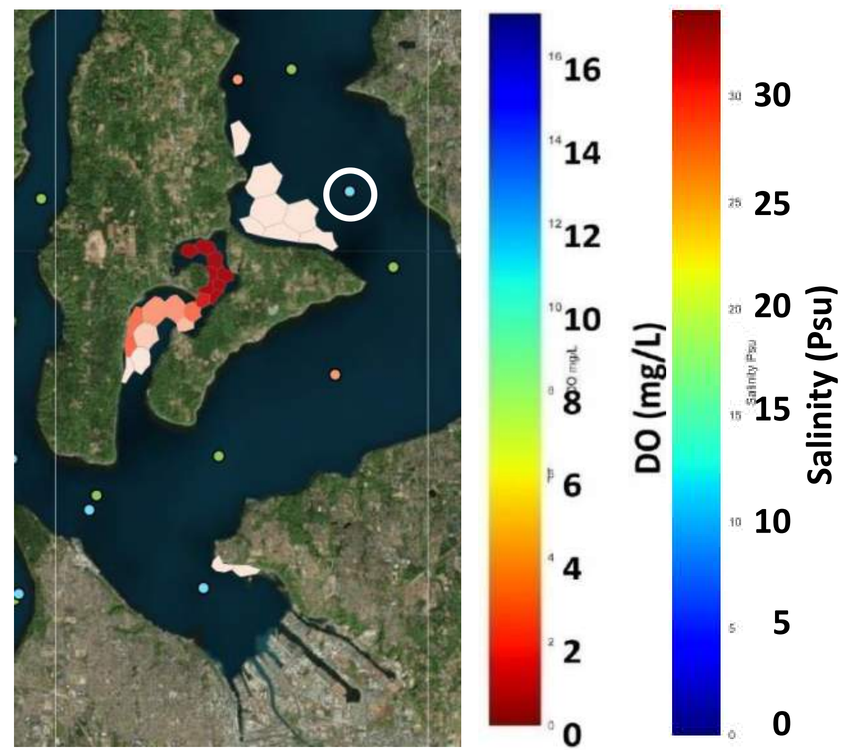


Salinity



EAP001 – August 2014
(1999 – 2013)





*Note this location has a modeled depth of approximately **150m** and is compliant*

APPENDIX 2: MINIMUM DISSOLVED OXYGEN AND GREATEST DIFFERENCE ANNUALLY FOR NON-COMPLIANT CELLS

Source Data: Ecology Puget Sound Nutrient Source Reduction Project: Salish Sea Model Results

Minimum annual dissolved oxygen concentration for non-compliant areas (mg/L)

Ecology calculates the dissolved oxygen concentration for each layer in each cell and rolls it up to a daily minimum. Then, they summarize the minimum dissolved oxygen for each cell, annually.

In producing the plots presented below, the University of Washington Puget Sound Institute then:

1. Extracted data for cells that are predicted to be non-compliant at least once during 2014 and 2006 existing conditions, respectively.
2. Delineated the embayment (e.g., Budd Inlet) where each non-compliant cell is located. The regions (e.g., Whidbey Basin) are already defined in the source data.
3. Binned the minimum dissolved oxygen concentrations into integer ranges (e.g., 3 to 4 mg/L).
4. Used the area of each non-compliant cell to calculate the area for each minimum concentration range in each embayment.

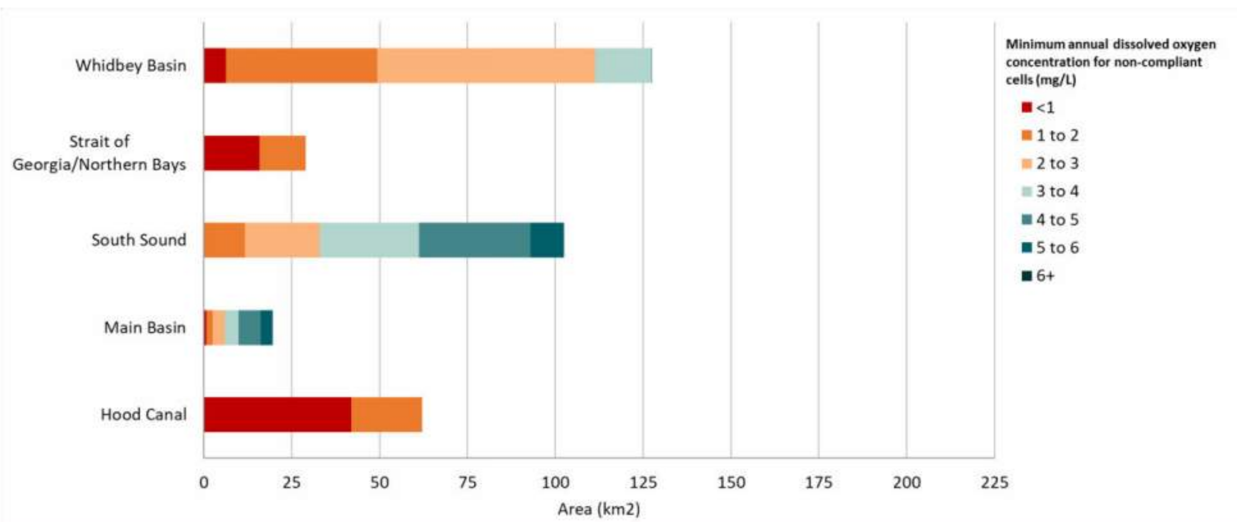


Figure 2.1 2014: Minimum annual dissolved oxygen concentration for non-compliant areas by region
Note that the plot for 2014 minimum annual dissolved oxygen concentration for non-compliant areas by embayment is included in the main body of the report.

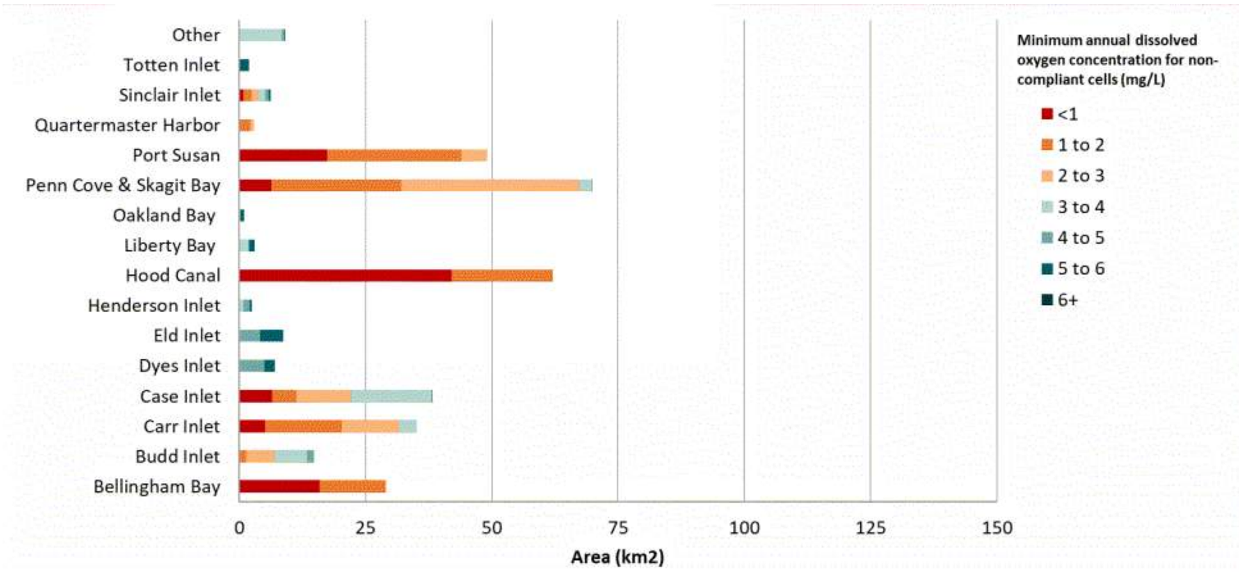


Figure 2.2 2014: Minimum annual dissolved oxygen concentration for non-compliant areas by embayment

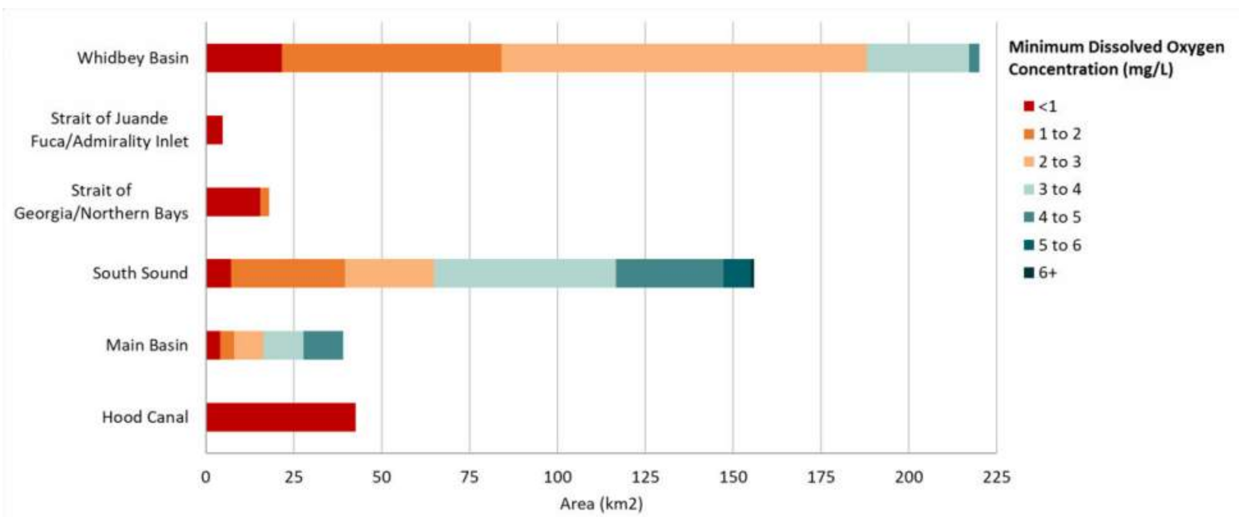


Figure 2.3 2006: Minimum annual dissolved oxygen concentration for non-compliant areas by region

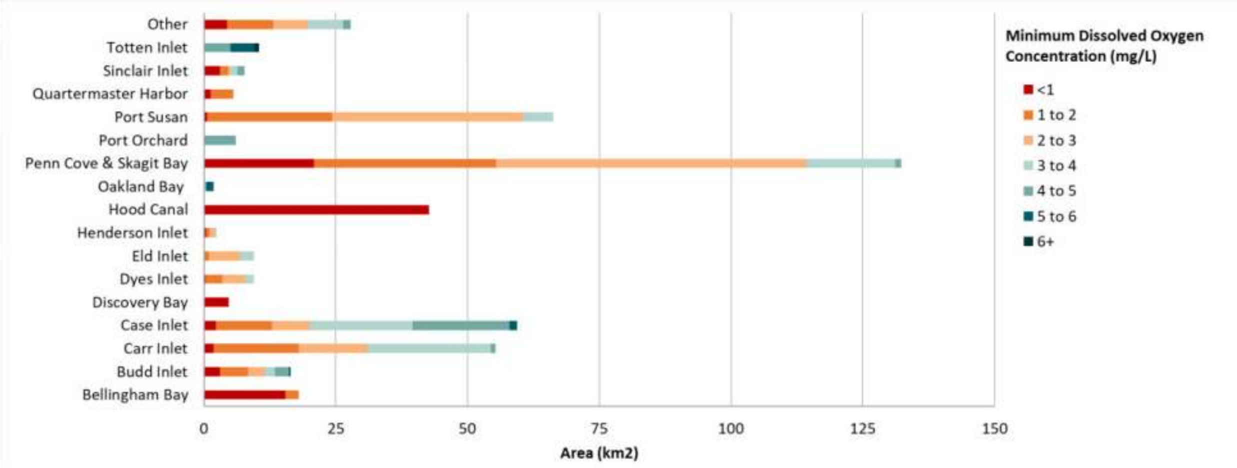


Figure 2.4 2006: Minimum annual dissolved oxygen concentration for non-compliant areas by embayment

Greatest difference in daily Dissolved Oxygen between existing & reference (mg/L) for Non-Compliant Cells

1. The way the Washington State Department of Ecology calculates the greatest non-compliance magnitude for the year in each cell is based on the daily magnitude of non-compliance for each cell and each layer (see Ahmed et al. 2019 for further detail). In summary, the magnitude of non-compliance represents the difference between the existing and reference conditions above and beyond the 0.2 mg/L natural conditions provision. The magnitude of noncompliance is rounded to the nearest tenth (0.1 mg/L).

University of Washington Puget Sound Institute then:

1. Extracted data for cells that are non-compliant at least once for 2014 and 2006 existing conditions, respectively.
2. Delineated the embayment (e.g., Budd Inlet) where each non-compliant cell is located. The regions (e.g., Whidbey Basin) are already defined in the source data.
3. Added 0.2 mg/L to the predicted magnitude of non-compliance to calculate an estimated total depletion from reference conditions (i.e., reference minus existing conditions) for each cell.
    - As Ecology notes, "The dissolved oxygen noncompliance of -0.1 to -0.2 mg/L is analogous to total dissolved oxygen depletions between -0.3 and - 0.4 mg/L" (Ahmed et al., 2021)
    - As cell areas are non-compliant (implying a 0.2 mg difference) cell areas less than -0.3 greatest difference in daily dissolved oxygen are not included in these calculations and plots
4. Used the area of each non-compliant cell to calculate the area for the greatest difference in each embayment.

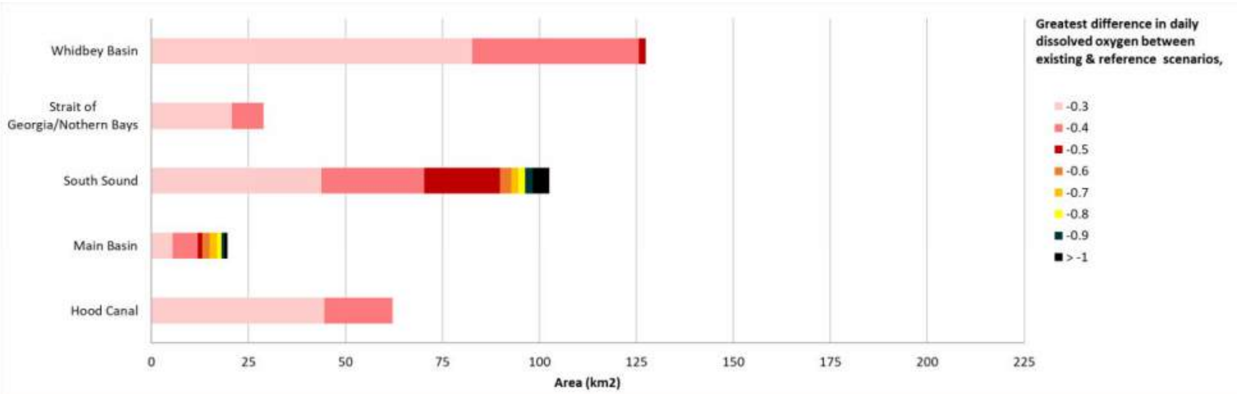


Figure 2.5 2014: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by region

Note that the plot for 2014 difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by embayment is included in the main body of the report.

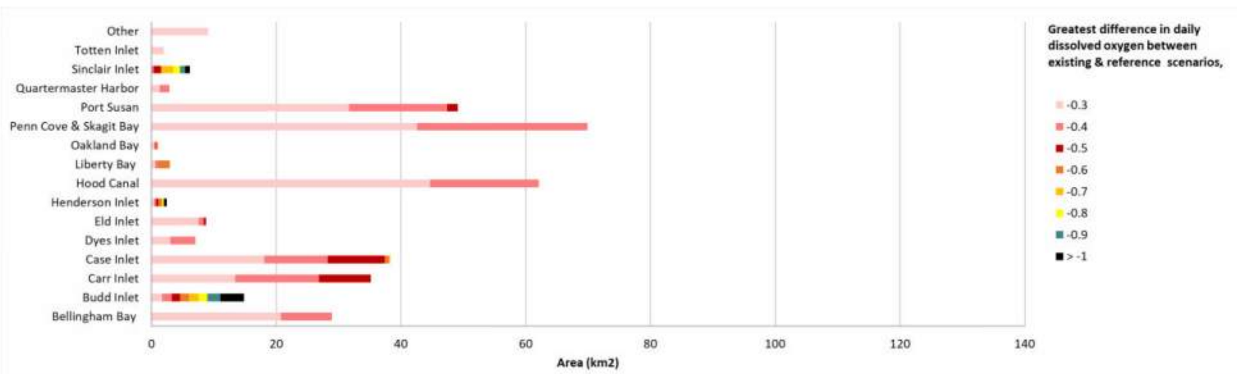


Figure 2.6 2014: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by embayment

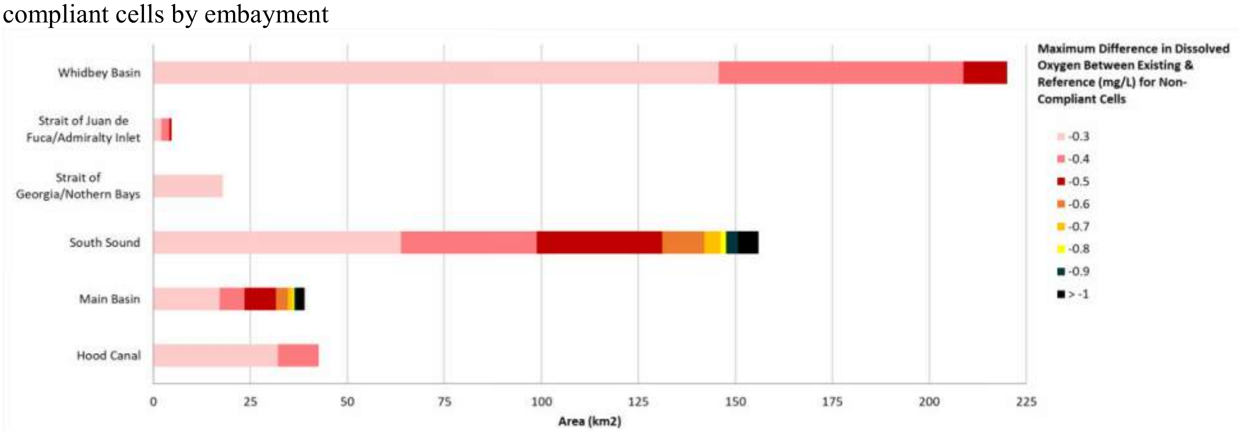


Figure 2.7 2006: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by region

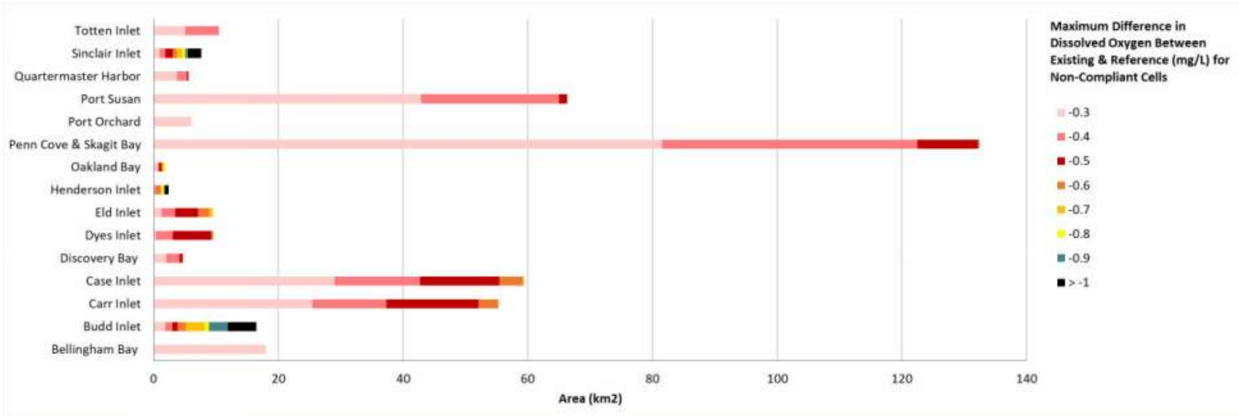


Figure 2.8 2006: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by embayment

APPENDIX 3: SPRINGTIME FLUX WORK UNDERTAKEN BY THE SHULL LABORATORY (WWU)

Selected data from Rigby (2019):

The most recently published work used at the time of writing this report was from Rigby, Emma I 2019. Springtime Benthic Fluxes in the Salish Sea: Environmental Parameters Driving Spatial Variation in the Exchange of Dissolved Oxygen, Inorganic Carbon, Nutrients, and Alkalinity Between the Sediments and Overlying Water. MS Thesis, Western Washington University (available at: https://cedar.wwu.edu/wwuet/903/). Results were subsequently published by collaborators in Santana and Shull (2023).

Table 4.1. Springtime benthic fluxes and estimated denitrification rates (removal of DIN via nitrate reduction + anammox) measured in mmol m^{-2} d^{-1} and hydrogen ion fluxes reported in µmol m^{-2} d^{-1}. Standard error is included in parentheses. If no standard error is included, only one core was successfully collected and sampled. Bolded values indicate fluxes that have standard errors larger than the flux.

Station	Dissolved Oxygen (DO)	Dissolved Inorganic Carbon (DIC)	Hydrogen ion (H^+)	Total Alkalinity (TA)	Ammonium (NH_4^+)	Nitrate +Nitrite (NO_3^-+$NO_2^=$)	Silicate (Si)	Phosphate (PO_4^3)	Estimated Denitrification
4	-16.59 ± 2.31	12.89 ± 3.24	0.76 +/- 0.47	5.73 ± 0.47	0.21 ± 0.14	-0.76 ± 0.27	12.40 ± 0.11	-0.08 ± 0.02	2.23
13	-11.78 ± 1.36	6.93 ± 0.80	0.44 +/- 0.03	1.88 ± 0.17	0.10 ± 0.21	-0.04 ± 0.10	7.16 ± 2.06	-0.01 ± 0.03	0.96
19	-9.17 ± 0.68	4.08 ± 8.87	0.57 +/- 0.02	-0.21 ± 9.24	-0.01 ± 0.00	-0.49 ± 0.04	6.56 ± 0.11	0.01 ± 0.04	0.86
21	-6.71 ± 0.10	1.02 ± 20.68	0.23 +/- 0.06	3.68 ± 12.14	0.11 ± 0.01	-0.34 ± 0.12	1.80 ± 0.38	-0.02 ± 0.00	0.31
29	-8.49	5.23	-0.04	5.80	-0.30	-0.31	4.19	0.01	1.22
34	-17.77 ± 0.96	1.39	1.10	-12.01	0.00 ± 0.21	-0.48± 0.10	3.38 ± 0.98	0.01 ± 0.06	0.66
38	-6.10	3.78	0.45	-0.90	-0.19	-0.21	5.57	0.01	0.81
49	-26.48 ± 2.16	7.24 ± 5.54	1.03 +/- 0.22	-5.18 ± 3.32	0.42 ± 0.04	-0.68 ± 0.06	-1.16 ± 1.46	-0.06 ± 0.03	1.14
52	-9.61 ± 1.05	-1.10 ± 0.08	1.1 +/- 0.52	-13.10 ± 5.83	0.05 ± 0.10	-0.27 ± 0.04	2.62 ± 0.41	-0.01 ± 0.00	-
191	-11.05 ± 0.70	3.67 ± 0.59	0.42 +/- 0.07	-0.92 ± 0.02	-0.06 ± 0.13	-0.23 ± 0.01	5.93 ± 1.37	0.04 ± 0.06	0.53
209	-9.70 ± 0.74	12.72 ± 0.03	0.91 +/- 0.23	7.49 ± 1.24	0.31 ± 0.20	-0.26 ± 0.23	2.43 ± 0.50	-0.04 ± 0.02	0.96
222	-6.18 ± 0.12	4.67 ± 0.18	0.67 +/- 0.09	0.56 ± 0.34	0.29 ± 0.09	-0.40 ± 0.06	3.41 ± 2.30	0.03 ± 0.07	0.61
252	-11.86 ± 1.05	11.18 ± 10.37	0.73 +/- 0.09	4.09 ± 12.92	-0.40 ± 0.09	-0.13 ± 0.04	7.71 ± 2.32	-0.02 ± 0.03	1.65
265	-11.27	16.21	1.13	5.26	0.28	-0.02	5.34	-0.02	1.34
281	-5.22 ± 0.19	2.69 ± 4.24	0.51 +/- 0.03	-2.29 ± 3.89	-0.23 ± 0.14	0.01 ± 0.19	-0.61 ± 3.53	-0.01 ± 0.03	0.44
305R	-8.99 ± 0.16	6.36 ± 0.37	0.73 +/- 0.12	1.26 ± 0.38	-0.02 ± 0.20	-0.45 ± 0.25	4.31 ± 1.36	-0.09 ± 0.01	1.13
40005	-21.44 ± 1.29	15.46 ± 7.25	1.28 +/- 0.28	2.47 ± 6.02	1.00 ± 0.61	-0.90 ± 0.06	14.15 ± 3.93	0.03 ± 0.08	1.52
40006	-9.00	2.52	0.35	-1.12	0.13	0.00	4.72	0.01	0.15
40007	-11.89 ± 1.28	8.99 ± 3.28	1.06 +/- 0.09	-2.01 ± 4.01	-0.17 ± 0.10	-0.42 ± 0.01	6.59 ± 0.05	0.01 ± 0.02	1.33
40008	-12.54	13.14	0.67	7.80	0.65	-0.47	8.70	-0.02	1.25
40009	-18.28	12.96	0.37	8.34	0.70	-0.37	6.73	-0.05	0.95
40010	-5.41	4.27	0.37	0.68	-0.20	-0.49	3.81	-0.01	1.14

Station	Dissolved Oxygen (DO)	Dissolved Inorganic Carbon (DIC)	Hydrogen ion (H^+)	Total Alkalinity (TA)	Ammonium (NH_4^+)	Nitrate +Nitrite ($NO_3^- + NO_2^=$)	Silicate (Si)	Phosphate (PO_4^3)	Estimated Denitrification
40011	-14.47 ± 1.18	8.58 ± 0.28	0.73 +/- 0.16	0.69 ± 1.14	0.04 ± 0.09	-0.18 ± 0.18	11.46 ± 1.94	-0.06 ± 0.02	1.14
40013	-38.33 ± 0.87	26.05 ± 0.73	0.93 +/- 0.93	5.68 ± 0.04	0.49 ± 0.05	-1.94 ± 0.19	9.14 ± 0.09	-0.17 ± 0.00	4.07
40015	-10.54 ± 0.06	10.83 ± 17.00	-0.12 +/- 0.56	2.52 ± 22.95	-0.07 ± 0.09	-0.31 ± 0.13	8.26 ± 0.07	0.04 ± 0.02	1.40
40016	-13.17	3.57	1.02	-6.48	0.21	-0.34	-0.61	-0.04	0.50
40017	-15.35 ± 0.23	5.40 ± 0.04	0.67 +/- 0.07	-1.35 ± 0.14	0.25 ± 0.04	-0.43 ± 0.17	2.95 ± 0.09	-0.10 ± 0.03	0.72
40018	-10.41 ± 1.95	34.31 ± 27.87	0.56 +/- 0.17	29.38 ± 30.83	-0.11 ± 0.02	-0.34 ± 0.00	5.48 ± 1.96	0.00 ± 0.01	3.26
40019	-10.38	1.81	0.75	-1.40	1.04	-0.63	3.21	-0.02	-0.21
40020	-9.18 ± 2.22	4.76 ± 0.92	0.24 +/- 0.19	2.21 ± 1.09	0.19 ± 0.01	0.00 ± 0.04	4.07 ± 1.14	0.06 ± 0.01	0.51
40021	-16.87 ± 1.13	23.73 ± 26.91	1.25 +/- 0.11	15.69 ± 26.37	0.92 ± 0.46	-0.67 ± 0.37	9.39 ± 0.35	0.04 ± 0.00	1.94
40022	-21.57	8.63	1.05	-2.48	1.23	-1.24	14.20	-0.09	1.29
40025	-19.84 ± 1.85	0.11 ± 0.01	0.04 +/- 0.04	-8.60 ± 1.06	0.80 ± 0.15	-0.18 ± 0.01	2.85 ± 0.92	0.01 ± 0.00	-0.61
40028	-23.19 ± 0.79	3.32 ± 8.83	0.93 +/- 0.10	-9.12 ± 8.62	0.32 ± 0.10	-0.25 ± 0.25	3.86 ± 2.35	-0.05 ± 0.02	0.28
40029	-21.73 ± 1.88	31.83 ± 0.14	0.75 +/- 0.11	24.10 ± 0.34	0.91 ± 0.19	-1.15 ± 0.39	20.29 ± 3.17	0.05 ± 0.06	4.05
40030	-15.83 ± 0.16	6.65 ± 1.84	0.87 +/- 0.13	-1.25 ± 2.70	0.93 ± 0.07	-0.67 ± 0.22	3.42 ± 0.10	-0.08 ± 0.02	0.44
40032	-12.03 ± 0.32	4.49 ± 0.05	0.89 +/- 0.08	-2.98 ± 0.68	-0.13 ± 0.38	-0.11 ± 0.05	2.55 ± 0.55	-0.01 ± 0.05	0.69
40037	-5.81	11.98	1.12	5.27	0.07	-0.64	4.42	0.01	1.68
40038	-9.31 ± 0.50	7.51 ± 2.06	0.57 +/- 0.07	1.59 ± 1.39	0.00 ± 0.10	-0.21 ± 0.06	7.76 ± 2.36	-0.02 ± 0.01	1.31
BLL009	-13.66 ± 1.90	12.99 ± 0.57	0.66 +/- 0.13	5.26 ± 0.45	0.04 ± 0.02	-0.43 ± 0.22	6.64 ± 1.74	0.03 ± 0.01	2.09
HCB003	-8.72	5.94	0.43	1.79	0.05	-0.12	6.24	0.03	0.59

Table 4.2. Sampling station coordinates and environmental variables measured at each station in April and early May 2018. BW = bottom water, DO = dissolved oxygen, DIC = dissolved inorganic carbon, TA = total alkalinity, TOC = total organic carbon, TOC:N = total organic carbon to nitrogen ratio.

Station	Latitude (°N)	Longitude (°W)	Depth (m)	BW Temp. (°C)	Salinity (psu)	BW DO (µM)	BW DIC (µM)	BW TA (µM)	BW pH	Total Fines (%)	TOC (%)	TOC:N
4	48.68394	-122.53811	24	9.6	31	259.6	2050.6	2158.2	7.917	82.6	2.1	8.2
13	47.83758	-122.62896	20	10.5	30	252.2	2023.2	2130.2	7.918	11.2	0.2	5.7
19	48.09793	-122.47129	124	9.2	25	212.1	2061.7	2117.2	7.763	65.6	2.0	9.3
21	47.98545	-122.24292	27	9.9	28	261.0	2037.2	2122.7	7.856	61.7	1.2	15.3
29	47.70072	-122.45405	202	9.8	30	249.6	2062.0	2141.8	7.826	73.2	1.8	7.4
34	47.54703	-122.66205	11	9.1	30	286.9	-	-	-	78.2	2.4	9.2
38	47.42835	-122.39361	203	9.3	30	249.4	2056.2	2190.1	7.987	87.6	2.3	7.9
49	47.07997	-122.91353	7	10.0	27	326.7	1925.1	2020.1	7.923	61.7	2.5	9.9
52	47.17059	-122.78061	107	11.0	30	264.7	2021.1	2150.7	7.983	21.8	0.5	8.6
191	47.59842	-122.37578	101	9.0	30	267.5	2022.1	2119.3	7.909	53.5	1.6	11.4

Station	Latitude (°N)	Longitude (°W)	Depth (m)	BW Temp. (°C)	Salinity (psu)	BW DO (µM)	BW DIC (µM)	BW TA (µM)	BW pH	Total Fines (%)	TOC (%)	TO C:N
209	48.29534	-122.48857	20	9.5	23	224.6	-	-	-	27.6	0.4	11.4
222	47.67819	-122.81464	127	10.4	30	176.1	2126.6	2161.2	7.659	77.2	1.8	8.4
252	47.26959	-122.85094	55	9.4	30	267.5	2001.7	2086.1	7.876	83.9	2.2	7.7
265	47.25244	-122.66566	108	8.5	31	253.7	2026.4	2105.4	7.868	73.7	2.2	8.1
281	47.29235	-122.44195	140	8.7	30	243.9	2048.4	2130.5	7.860	88.4	1.3	10.8
305R	47.39713	-122.93123	21	11.1	30	123.3	2031.7	2077.9	7.719	76.4	3.6	8.4
40005	48.13872	-123.44985	25	11.0	32	248.8	2079.6	2235.9	8.009	72.0	4.7	17.5
40006	47.63968	-122.49041	81	9.4	31	261.2	2034.5	2122.5	7.874	11.3	0.6	16.5
40007	48.22611	-122.5437	54	9.3	26	233.3	-	-	-	11.9	0.2	10.1
40008	47.22686	-122.64787	125	8.8	30	261.4	1950.3	2023.0	7.859	72.9	2.2	8.1
40009	48.90624	-122.82633	28	9.0	32	-	2031.4	2136.1	7.919	12.1	0.3	6.7
40010	47.59744	-122.97823	134	10.5	27	164.4	2123.4	2175.8	7.720	80.4	2.6	10.7
40011	47.76106	-122.41765	201	9.4	30	242.6	2052.7	2135.1	7.837	67.2	1.6	7.6
40013	48.49623	-122.8214	11	10.5	32	278.8	2031.2	2174.6	8.004	62.9	1.1	8.3
40015	48.08878	-122.44857	108	9.2	25	300.4	2053.8	2181.3	7.991	76.0	2.0	8.7
40016	47.1255	-122.83639	7	10.0	29	325.5	1930.4	2019.5	7.903	83.3	2.7	9.5
40017	48.99472	-122.9678	17	9.0	28	-	2032.4	2155.4	7.972	6.0	0.4	7.1
40018	47.41788	-123.11741	128	12.0	27	91.9	2059.2	2077.8	7.609	86.2	2.3	9.2
40019	47.90608	-122.33067	89	9.3	25	256	2028.0	2117.1	7.885	17.7	0.5	11.1
40020	47.69586	-122.42253	88	9.0	30	255.8	2037.9	2125.0	7.874	6.2	0.3	11.0
40021	48.27946	-122.61512	13	10.3	28	211.5	1970.8	2025.7	7.777	81.0	1.7	9.5
40022	47.67157	-122.59949	20	9.6	30	265.8	2011.0	2101.0	7.893	92.4	2.9	8.1
40025	48.6245	-122.96328	23	10.1	32	284	2026.0	2104.1	7.821	89.6	1.8	8.9
40028	47.13601	-123.01005	7	10.3	28	395.3	1788.2	1830.5	7.748	85.3	2.7	7.6
40029	48.63714	-122.55224	23	9.6	30	263.1	2041.7	2126.5	7.861	81.8	1.4	7.6
40030	47.54499	-122.65119	11	10.4	29	280.6	2043.1	2147.8	7.910	79.2	3.3	8.7
40032	47.34951	-122.80543	19	9.6	29	244.2	1976.7	2084.5	7.938	14.0	0.4	7.4
40037	48.19993	-122.58646	54	9.4	23	216.3	2055.1	2143.5	7.872	84.9	1.8	9.2
40038	47.69895	-122.47833	187	9.6	29	280.5	2053.9	2146.2	7.864	71.0	1.7	8.2
BLL009	48.68589	-122.59418	19	9.4	29	252.5	2047.3	2148.8	7.912	29.2	0.5	6.0
HCB003	47.59842	-122.37578	101	11.9	29	138.3	2022.1	2119.3	7.909	14.0	1.6	11.4

Selected data from Merritt (2017):

Merritt, E. 2017. The influence of sedimentary biogeochemistry on oxygen consumption and nutrient cycling in Bellingham Bay, Washington. Thesis, Western Washington University, NSF REU at Shannon Point Marine Center. Anacortes, Washington.

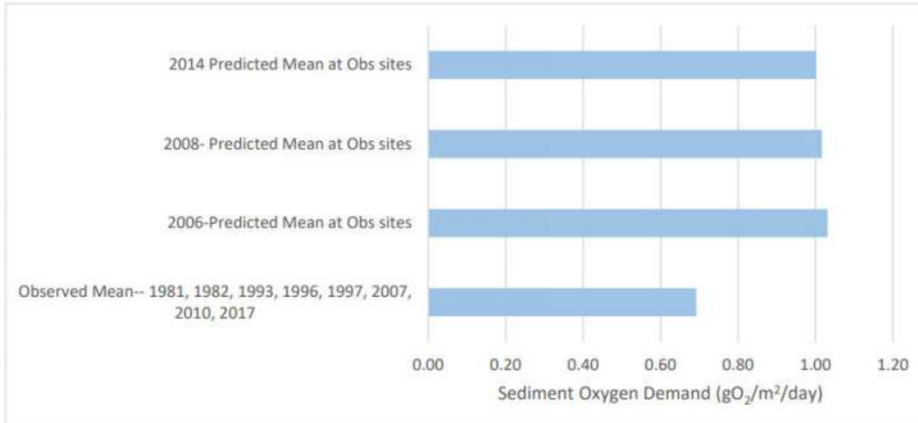


Figure 3.1. Comparison of predicted and observed sediment oxygen demand at multiple locations, but at different times. Reproduced from Figure I2 of Appendix I of Ahmed et al. (2019)

APPENDIX 4: SALISH SEA MODEL LOADING INPUTS FOR THE STATE'S OPTIMIZATION SCENARIOS (AHMED ET AL. 2021) AND BOUNDING SCENARIOS (AHMED ET AL. 2019)

Note: The following tables 4.1 and 4.2 summarize Salish Sea Model input data available from the Department of Ecology website, downloaded for each year and scenario run:*

Inputs*	Used In
2014	Optimization Scenarios
2006	Optimization Scenarios & Bounding Scenarios
2008 & 2014 (old)**	Bounding Scenarios

*All of Ecology's downloadable files are available here, the following tables were produced using "*Region Loads Exist v3 files*" (see: *Read Me*).
**2008 and the 2014 (old) data use the "old" regional delineations from the Bounding Scenarios, which are different to those "new" delineations used in the later Optimization Scenario updates.

Table 4.1 Annual dissolved organic carbon and dissolved inorganic nitrogen inputs for 2006, 2008, and 2014 for Puget Sound and the Salish Sea, respectively.

Scope	2006	2008	2014 (new)	2014 (old)
Annual Dissolved Organic Carbon (DOC)				
Puget Sound Total	124,564,690	96,427,557	110,165,721	125,602,890
Salish Sea Total	529,549,524	493,298,128	602,334,795	573,618,723
Annual Dissolved Inorganic Nitrogen (DIN)				
Puget Sound Total	25,196,416	21,425,660	25,332,759	25,666,013
Salish Sea Total	43,952,717	40,683,249	51,607,580	52,026,108

Table 4.2 Daily river and wastewater treatment plant inputs for flow, dissolved inorganic nitrogen (DIN), total nitrogen (TN), total organic nitrogen (TON), dissolved organic carbon (DOC), particulate organic carbon (POC), and total organic carbon (TOC). Results are presented for model years 2006, 2008, and 2014 for Puget Sound and the Salish Sea, respectively.

Year	Source	Region	Flow	DIN	TN	TON	DOC	POC	TOC
2006	Rivers	Puget Sound Total	1,868	36,075	41,687	5,612	330,070	39,029	369,099
2006	Rivers	Salish Sea Total	5,996	62,088	129,747	67,659	1,398,251	39,382	1,437,633
2006	Wastewater treatment plants	Puget Sound Total	20	32,957	37,927	4,970	11,203	7,767	18,970
2006	Wastewater treatment plants	Salish Sea Total	36	58,330	69,986	11,655	52,570	13,689	66,259
2006	**Rivers & Wastewater treatment plants**	**Puget Sound Total**	**1,889**	**69,031**	**79,614**	**10,583**	**341,273**	**46,796**	**388,069**
2006	**Rivers & Wastewater treatment plants**	**Salish Sea Total**	**6,032**	**120,418**	**199,732**	**79,314**	**1,450,821**	**53,071**	**1,503,892**
2008	Rivers	Puget Sound Total	1,611	27,200	n/a	n/a	254,740	n/a	n/a
2008	Rivers	Salish Sea Total	9,479	53,028	n/a	n/a	1,303,352	n/a	n/a
2008	Wastewater treatment plants	Puget Sound Total	18	31,500	n/a	n/a	9,445	n/a	n/a
2008	Wastewater treatment plants	Salish Sea Total	33	58,433	n/a	n/a	48,150	n/a	n/a
2008	**Rivers & Wastewater treatment plants**	**Puget Sound Total**	**1,628**	**58,700**	**n/a**	**n/a**	**264,185**	**n/a**	**n/a**
2008	**Rivers & Wastewater treatment plants**	**Salish Sea Total**	**9,511**	**111,461**	**n/a**	**n/a**	**1,351,502**	**n/a**	**n/a**
2014	Rivers	Puget Sound Total	2,019	36,248	42,755	6,507	293,440	18,487	311,927
2014	Rivers	Salish Sea Total	6,946	69,703	131,988	62,285	1,605,583	18,909	1,624,492
2014	Wastewater treatment plants	Puget Sound Total	18	33,157	36,463	3,306	8,384	6,184	14,569
2014	Wastewater treatment plants	Salish Sea Total	33	71,688	82,106	10,418	44,649	12,194	56,843

Year	Source	Region	Flow	DIN	TN	TON	DOC	POC	TOC
2014	**Rivers & Wastewater treatment plants**	**Puget Sound Total**	**2,038**	**69,405**	**79,218**	**9,813**	**301,824**	**24,672**	**326,496**
2014	**Rivers & Wastewater treatment plants**	**Salish Sea Total**	**6,980**	**141,391**	**214,094**	**72,703**	**1,650,232**	**31,102**	**1,681,335**
2014 (old)	Wastewater treatment plants	Puget Sound Total	18	33,161	n/a	n/a	8,411	n/a	n/a
2014 (old)	Wastewater treatment plants	Salish Sea Total	33	71,795	n/a	n/a	44,736	n/a	n/a
2014 (old)	Rivers	Puget Sound Total	2,020	37,157	n/a	n/a	335,707	n/a	n/a
2014 (old)	Rivers	Salish Sea Total	10,969	70,743	n/a	n/a	1,526,822	n/a	n/a
2014 (old)	**Rivers & Wastewater treatment plants**	**Puget Sound Total**	**2,039**	**70,318**	**n/a**	**n/a**	**344,118**	**n/a**	**n/a**
2014 (old)	**Rivers & Wastewater treatment plants**	**Salish Sea Total**	**11,002**	**142,537**	**n/a**	**n/a**	**1,571,558**	**n/a**	**n/a**

APPENDIX 5: USGS SYNTHESIS OF SEDIMENT-WATER FLUX SELECTED FIGURES AND TABLES

Sheibley, Richard W. & Paulson, Anthony J. 2014. Quantifying Benthic Nitrogen Fluxes in Puget Sound, Washington—A Review of Available Data (USGS) sir20145033.pdf (usgs.gov)

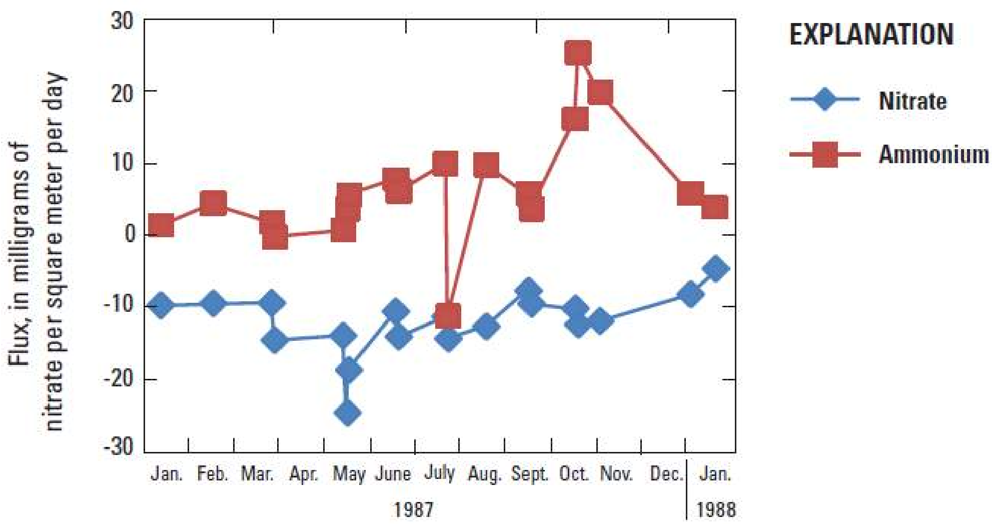


Figure 4. Time-series plot showing nitrate (NO_3^-) and ammonium (NH_4^+) benthic flux in Dabob Bay, Puget Sound, Washington. Negative values indicate flux into the sediment. Data from Colbert and others, University of Washington, unpub. data, 2010.

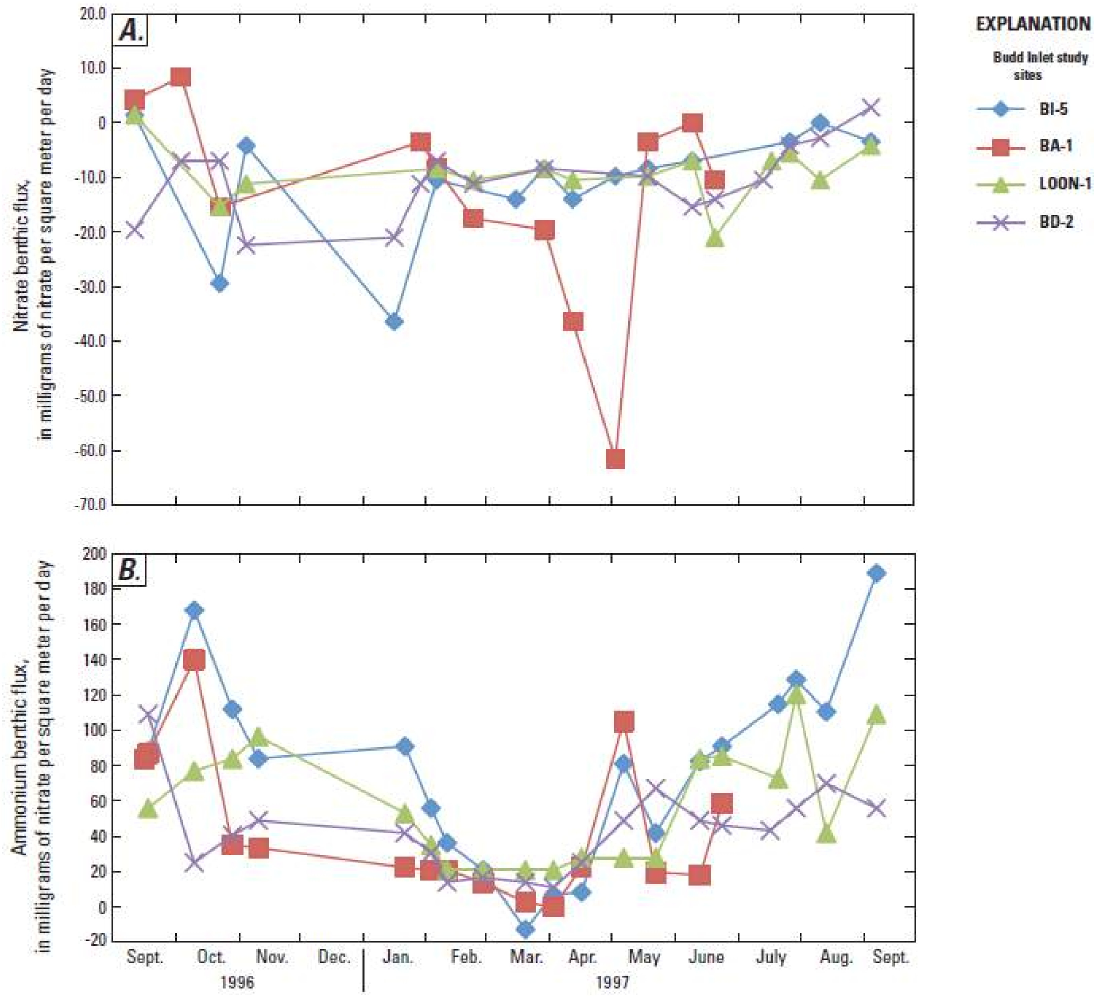


Figure 5. Time-series plot showing (*A*) nitrate and (*B*) ammonium chamber benthic flux from four sites in Budd Inlet, Puget Sound, Washington. Data from Aura Nova Consultants and others, 1998.

A total of 138 individual flux chamber measurements and 38 sets of diffusive fluxes were compiled for this study

Table 1. General site information for benthic chamber sites in Puget Sound, Washington.

[For detailed site metadata, see table A1]

Station/site identifier	Date sampled	Depth (meters)	Study details	Reference
Carkeek pelagic site (PS17)	June 8–9, 1982	175	Single site, measured once	Murray (1982)
Carkeek pelagic site	Unknown	200	Single site, measured once	Grundmanis (1989)
Holmes Harbor	August 1993	50–70	Three sites, measured once	Brandes and Devol (1997)
Dabob Bay	January 1987–January 1988	110	Single site, measured 20 times during the year	Colbert and others, unpub. data (2010)
Budd Inlet	September 1996–September 1997	5–15	Four sites measured 17–19 times during the year	Aura Nova Consultants and others (1998)
Case Inlet	September–October 2007	5–25	Three depths measured 3 times	Roberts and others (2008)
Carr Inlet	September–October 2007	5–25	Three depths measured 3 times	Roberts and others (2008)
Eld Inlet	September–October 2007	5–25	Three depths measured 3 times	Roberts and others (2008)
Budd Inlet	September–October 2007	3–25	Three depths measured 3 times	Roberts and others (2008)
Quartermaster Harbor	September 1–2, 2010	4–17	Five sites measured once	King County (2012)

Table 2. Average benthic flux estimates from benthic flux chamber measurement sites, Puget Sound, Washington.

[Negative values indicate fluxes into the sediments. **Abbreviations**: (mg N/m^2)/d, milligrams of nitrogen per square meter per day; –, no data]

Station/site identifier	Number of measurements	Depth (meters)	Benthic fluxes [(mg N/m^2)/d]		
			Nitrate	Nitrite	Ammonium
Carkeek pelagic site	2	175–200	–	–	4.5
Holmes Harbor	3	50–70	-8.4	–	6.4
Dabob Bay	19	110	-12.0	–	6.3
Budd Inlet (BI-5)	19	5–15	-10.6	–	78.9
Budd Inlet (BA-1)	16	5–15	-13.7	–	42.8
Budd Inlet (LOON-1)	19	5–15	-9.2	–	57.0
Budd Inlet (BD-2)	19	5–15	-10.5	–	42.9
Case Inlet	9	5–25	-15.8	0.2	52.8
Carr Inlet	9	5–25	-8.0	2.9	47.2
Eld Inlet	9	5–25	-9.0	-0.9	68.6
Budd Inlet	9	5–25	-13.3	-1.4	115.1
Quartermaster Harbor	5	4–17	-1.0	–	53.0
Overall average			-10.1	0.2	48.0

APPENDIX 6: SEDIMENT AND PHYTOPLANKTON PARAMETERS OF THE SALISH SEA MODEL IDENTIFIED IN THE DEVELOPMENT OF RECOMMENDATIONS

Table 6.1. Sediment and phytoplankton parameters of the Salish Sea Model. For each, PSI has identified available details including variable names, code details, and documentation.

Parameter name and description	Fortran code output No.[1]	Fortran code name and details	Variable list name	Closest matching documentation from Pelletier et al. (2017) etc.
Organic Sediment Settling				
POC sum (C in oxygen equivalents)	46	(JPOC_GL(I, 1)/1000.0*2.667, I=1, MGL)		JPOC = total particulate organic carbon flux into sediments from water column (gO2/m2/day)
POC sum (C in oxygen equivalents)	47	(JPOC_GL(I, 2)/1000.0*2.667, I=1, MGL)		*As above*
POC sum (C in oxygen equivalents)	48	(JPOC_GL(I, 3)/1000.0*2.667, I=1, MGL)		*As above*
PON sum	49	(JPON_GL(I, 1)/1000.0, I=1, MGL)	JPON1: Sed particulate organic nitrogen (gN/m2/day)	JPON = total particulate organic nitrogen flux into sediments from water column (gN/ m2/day)
PON sum	50	(JPON_GL(I, 2)/1000.0, I=1, MGL)	JPON2: Sed particulate organic nitrogen (gN/m2/day)	*As above*
PON sum	51	(JPON_GL(I, 3)/1000.0, I=1, MGL)	JPON3: Sed particulate organic nitrogen (gN/m2/day)	JPON = total particulate organic nitrogen flux into sediments from water column (gN/ m2/day)
POP sum	52	(JPOP_GL(I, 1)/1000.0, I=1, MGL)		JPOP = total particulate organic phosphorus flux into sediments from water column (gP/ m2/day)
POP sum	53	(JPOP_GL(I, 2)/1000.0, I=1, MGL)		*As above*
POP sum	54	(JPOP_GL(I, 3)/1000.0, I=1, MGL)		*As above*
POSi	55	(JPOS_GL(I)/1000.0, I=1,MGL)		JPOS = total particulate organic silicate flux into sediments from water column (gSi/ m2/day)
Sediment-water fluxes				
	64	(S_GL(I, KBM1), I=1, MGL)	S: Surface Diffusion velocity (m/day) = SOD1/O20 (mgO2/m2/day)/(mgO2/m3)	
Oxygen	65	(SODTM1S_GL(I), I=1, MGL)	SODTM1S: Sediment oxygen demand (gO2/m2/day)	

Parameter name and description	Fortran code output No.[1]	Fortran code name and details	Variable list name	Closest matching documentation from Pelletier et al. (2017) etc.
Ammonium	66	(JNH4_GL(I)/1000.0, I=1, MGL)	JNH4: Sediment dissolved ammonia flux (gN/m2/day)	JNH4 = sediment to water column ammonia flux (gN/ m2/day)
Nitrate	67	(JNO3_GL(I)/1000.0, I=1, MGL)	JNO3: Sediment dissolved nitrate flux (gN/m2/day)	JNO3 = sediment to water column nitrate flux (gN/ m2/day)
Denitrification	68	(BENDEN_GL(I), I=1, MGL)	Denit(1) * NO3(1) + Denit(2) * NO3(2) (gN/m2/day)	JDenitT in documentation, but unclear if this is benthic denitrification or matches BENDEN in model code
Methane -dissolved	69	(JCH4_GL(I), I=1, MGL)		JCH4 = sediment to water column dissolved methane flux (gO2/ m2/day)
Methane -gas phase	70	(JCH4G_GL(I), I=1, MGL)		JCH4g = sediment to water column gas-phase methane flux (gO2/ m2/day)
Hydrogen Sulfide	71	(JHS_GL(I), I=1, MGL)	gO2/m2/day	JHS = sediment to water column hydrogen sulfide flux (gO2/ m2/day
Phosphate	72	(JPO4_GL(I)/1000.0, I=1, MGL)	gP/m2/day	JPO4 figure B-4 : gP/m2/day
Silicate	73	(JSI_GL(I)/1000.0, I=1, MGL)	gSi/m2/day	JSI = sediment to water column silicate flux (gSi/ m2/day)
Sedimentation of POC and PON				
C sedimentation sum layer 2	82	(CH41TM1S_GL(I), I=1, MGL)		
C sedimentation sum layer 2	83	(CH42_GL(I), I=1, MGL)		
C sedimentation sum layer 2	86	(CPOC_GL(I, 1)/1000.0*2.667, I=1, MGL)		POC1 = G1 particulate organic carbon in layer 2 (mgO2/L)
C sedimentation sum layer 2	87	(CPOC_GL(I, 2)/1000.0*2.667, I=1, MGL)		POC2 = G2 particulate organic carbon in layer 2 (mgO2/L)
C sedimentation sum layer 2	88	(CPOC_GL(I, 3)/1000.0*2.667, I=1, MGL)		POC3 = G3 particulate organic carbon in layer 2 (mgO2/L)
N sedimentation sum	76	(NO31_GL(I)/1000.0, I=1, MGL)	sed_NO31: sed layer 1 dissolved nitrate (gN/m3)	NO31 = sediment dissolved nitrate concentration in layer 1 (mg-N/L)
N sedimentation sum layer 2	74	(NH41_GL(I)/1000.0, I=1, MGL)	sed_NH41: Sediment layer 1 dissolved ammonia (gN/m3)	NH41 = sediment dissolved ammonia concentration in layer 1 (mg-N/L)
N sedimentation sum layer 2	75	(NH42_GL(I)/1000.0, I=1, MGL)	sed_NH42: Sediment layer 2 dissolved ammonia (gN/m3)	“
N sedimentation sum layer 2	77	(NO32_GL(I)/1000.0, I=1, MGL)	sed_NO32: sed layer 2 dissolved nitrate (gN/m3)	NO32 = sediment dissolved nitrate concentration in layer 2 (mg-N/L)

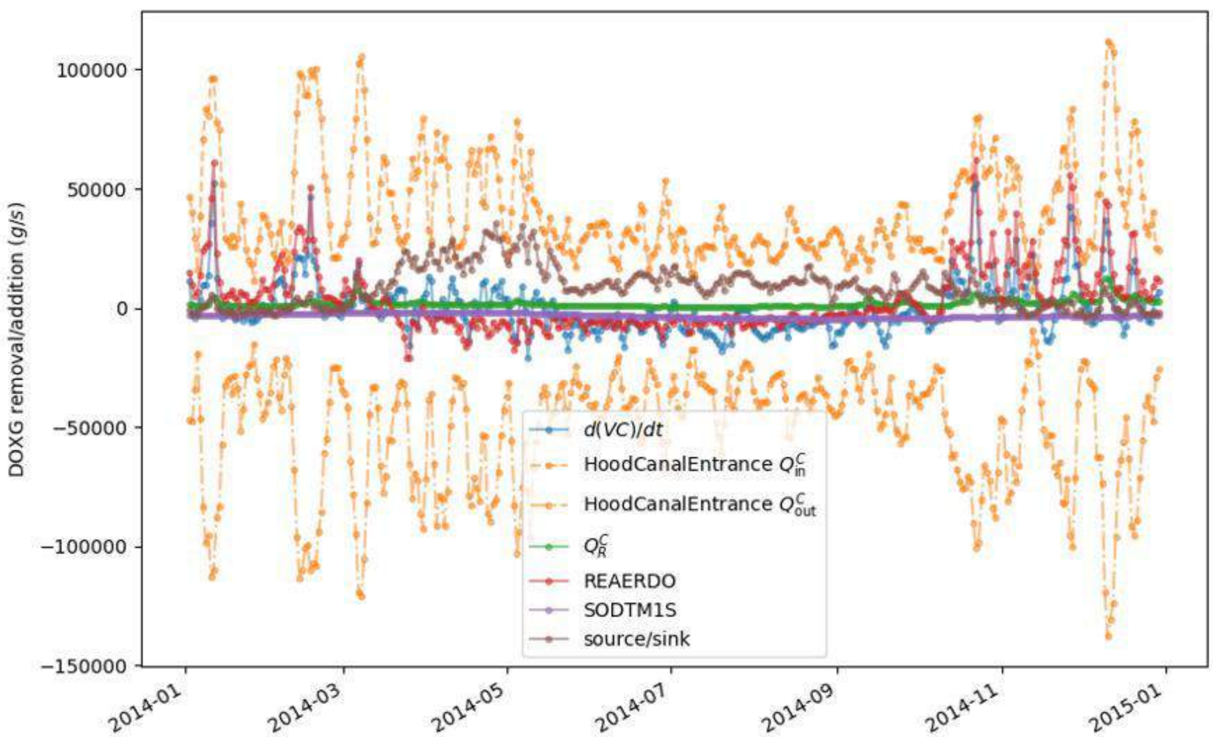
Parameter name and description	Fortran code output No.[1]	Fortran code name and details	Variable list name	Closest matching documentation from Pelletier et al. (2017) etc.
N sedimentation sum layer 2	89	(CPON_GL(I, 1)/1000.0, I=1, MGL)	sed_CPON1: sed particulate organic nitrogen 1 (gN/m3)	PON1 = G1 particulate organic nitrogen in layer 2 (mg-N/L)
N sedimentation sum layer 2	90	(CPON_GL(I, 2)/1000.0, I=1, MGL)	sed_CPON2: sed particulate organic nitrogen 2 (gN/m3)	PON2 = G2 particulate organic nitrogen in layer 2 (mg-N/L)
N sedimentation sum layer 2	91	(CPON_GL(I, 3)/1000.0, I=1, MGL)	sed_CPON3: sed particulate organic nitrogen 3 (gN/m3)	PON3 = G3 particulate organic nitrogen in layer 2 (mg-N/L)
		W1	W1: Net sedimentation velocity (input variable named as VSED in early documentation	W1 =Net Sediment Velocity
		W2	W2: Net sedimentation velocity (input variable named as VSED in early documentation	W2 = net sedimentation velocity (input variable). In documentation of variables the following is noted as sedimentation rate: VSED =0.2502 cm/yr equaling what is shown in a model testing a value = 6.85x10-6 m/d
Phytoplankton budget in inlets				
Total NPP change	11	(total_netPP_GL(I), I=1, MGL)	NPP: total net primary production gC/m2	
Total diatom change		FVCOM_Name: Conc of I_GAM1_C mg/L	B1: algal group 1 (gC/m3)	B1 (ALG1): representing diatoms - have not found these in model parameters as yet and unclear of unit
Total dinoflagellates change		FVCOM_Name: Conc of I_GAM2_C mg/L	B2: algal group 2 (gC/m3)	B2 (ALG2): representing dinoflagellates
Loss of diatom and dinoflagellates			Settling rates for: Labile (WSLAB) and refractory (WSREF) particulates and Diatoms (WS1) and Dinoflagellates (WS2)	

[1]FVCOM ICM4

APPENDIX 7: EXCHANGE FLOW, CONTROL VOLUME BUDGETS

Lead: Ben Roberts (UW)

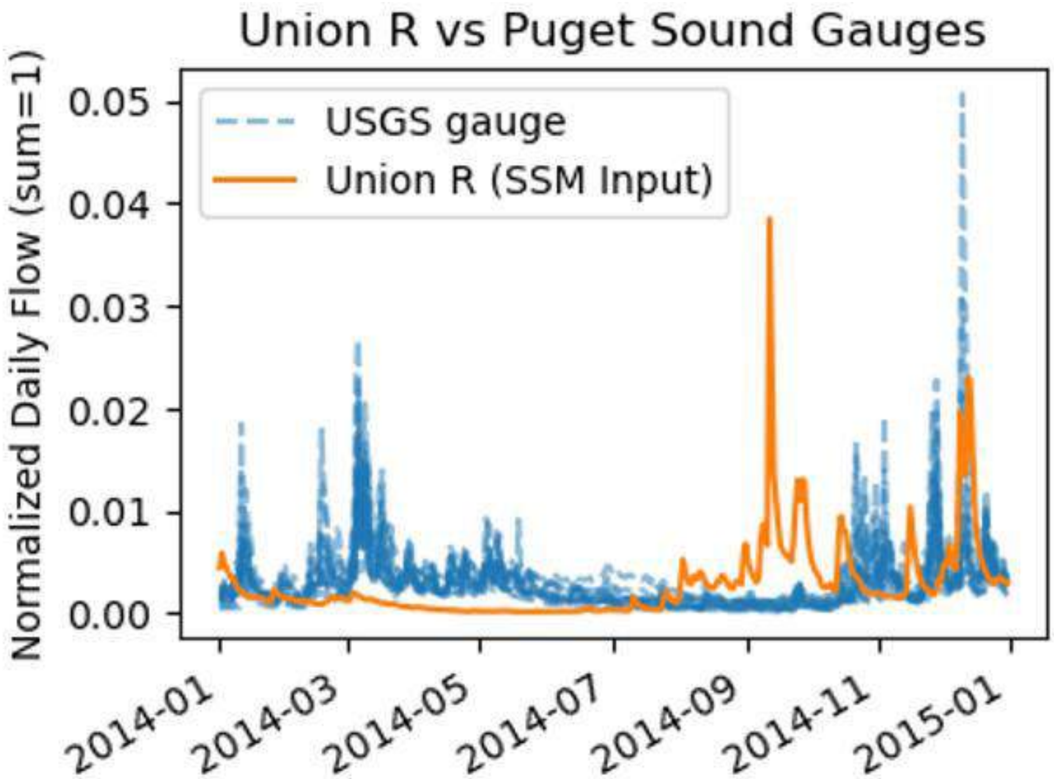
- Total exchange flow approach (ref MacCready 2011, Lorenz et al 2019, MacCready et al 2020)
- Purpose: quantifying inflow/outflow of constituents with an ocean influence, and how those rates change under different hydrological scenarios (e.g. interannual variability, changes in freshwater loading)
- Building control volumes in an unstructured grid (ref Conroy 2020)
- Validation with volume and salt budgets
- Constituent budgets and bracketing the net biogeochemical influence



APPENDIX 8: FRESHWATER BOUNDARY CONDITIONS

Lead: Ben Roberts in collaboration with Aurora Leeson (UW)

- Methods for assembling boundary conditions (example plot below)
- Emphasis has been on total annual flow rather than timing
- Possible errors and mistakes in data set



Researchers zero in on low-oxygen areas of concern in Puget Sound

Coupeville Wharf at Penn Cove, Whidbey Island. Penn Cove is one of the most productive shellfish-growing locations on the U.S. West Coast. Scientists are monitoring oxygen levels here as the climate warms and pressures from human development continue. Photo: Jason Walsh (CC BY 2.0)

KEYWORDS: EUTROPHICATION, HARMFUL ALGAL BLOOMS, HYPOXIA, MODELING, MONITORING, NUTRIENT POLLUTION, SALISH SEA CURRENTS MAGAZINE, WATER QUALITY

By Sarah DeWeerdt

Published April 21, 2025

Low dissolved oxygen levels put aquatic life in Puget Sound at risk – but not everywhere. A combination of careful monitoring efforts and powerful computer models are now enabling scientists to identify which areas of our regional waters are most prone to low oxygen levels, when, and why. This article is part of a series of reports funded by King County about the quest to define healthy oxygen levels in Puget Sound.

Late one afternoon in the middle of March, a gray whale dives in Penn Cove off Whidbey Island. On the right underside of its tail fluke, three large, irregularly shaped pale spots mark this whale as CRC2356 or Stalwart, one of a dozen or so gray whales known as "Sounders" who descend on Puget Sound each spring to feast on ghost shrimp. The whales scoop great mouthfuls of mud from shallow tidal flats and force it out through their baleen plates, gulping down the tasty four-inch crustaceans that remain.

In front of the whale and a little to the west lies the grid of wooden rafts belonging to Penn Cove Shellfish, which at this time of year will be hung with lines coiled at the top of the water to catch mussel spat from the spring spawn. Penn Cove is one of the most productive shellfish-growing locations on the U.S. West Coast, rich in nutrients that fuel the growth of the plankton that mussels and other filter-feeders depend on.

Beneath this idyllic scene, at the bottom of the cove on the seafloor, water trickles into the cove from the Pacific Ocean. The ever-so-faint current might be barely registered by the knobby papillae on the bodies of sea cucumbers that hang out below the rafts and feed on the bonanza of mussel waste that sifts down from above.

Mussel rafts in Penn Cove, Whidbey Island. Photo: AdobeStock

The ocean water has traveled along the Strait of Juan de Fuca, through Admiralty Inlet and around the southern tip of Whidbey Island then up through Saratoga Passage, sluicing through glacier-carved channels and tipping headlong over sills to reach Penn Cove. Its arrival will establish how well the local ecosystem “breathes” and whether life can continue to thrive here. This springtime inflow will shape dissolved oxygen (DO) levels in the cove until sometime in the fall.

It is a simple fact that almost all living things need oxygen to survive — from whales to shellfish — and diminished levels of dissolved oxygen can make marine organisms more vulnerable to disease, interfere with their sensory perception, impair their reproduction, and may even be fatal. In Penn Cove, for example, oxygen levels at the bottom of the water can fall as low as 0.18 mg/L in the late summer and early fall.

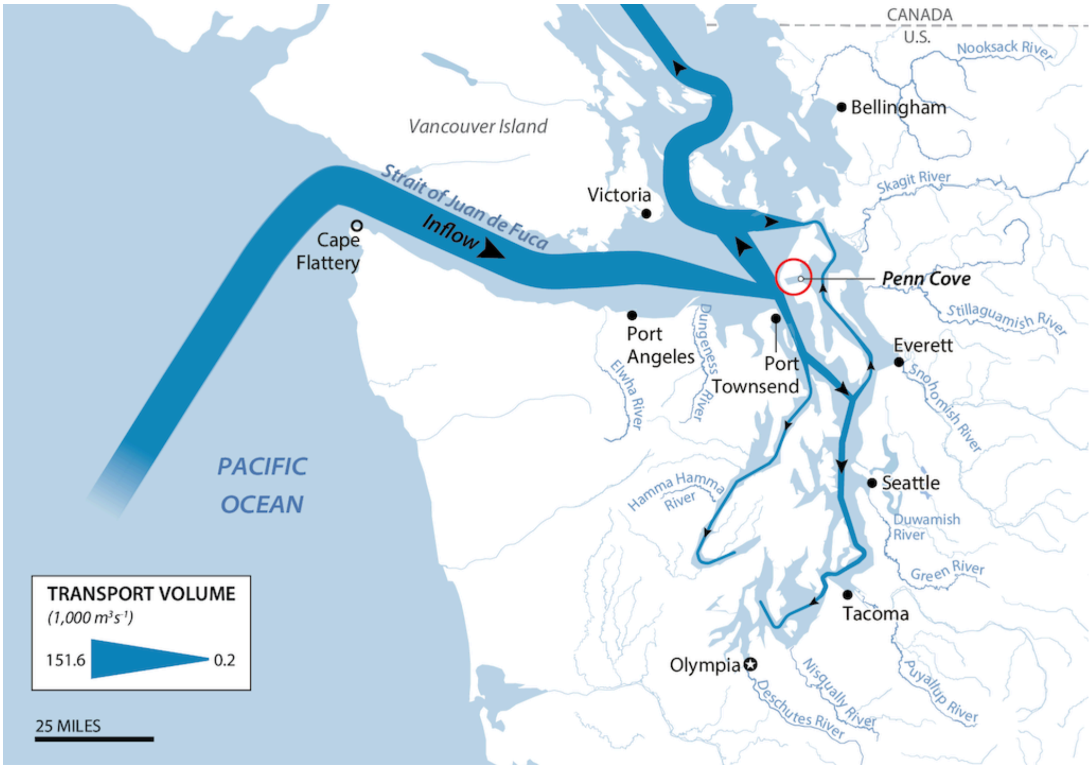
Among other consequences, low oxygen may weaken mussels’ byssal threads, which they use to attach themselves to the rocks, ropes, or other substrates on which they live. Although there have been no dramatic consequences of low oxygen in Penn Cove so far, such as fish kills that have occurred in some parts of Puget Sound, scientists are closely monitoring trends in oxygen levels here and elsewhere as the climate warms and pressures from human development continue.

This is why scientists consider dissolved oxygen to be a critical measure of an area's water quality, and it's why a pair of sleek, white, two-foot-long cylinders are attached to a piling on the Coupeville Wharf. The cylinders contain sensors that log water temperature, salinity, pressure, pH, dissolved oxygen, chlorophyll, turbidity, and nitrogen every 15 minutes as part of a King Country program to monitor water quality in the Whidbey Basin of Puget Sound.

The scene at Penn Cove is the backdrop to an effort to understand which parts of Puget Sound suffer from low levels of dissolved oxygen, when, and why. Problems with dissolved oxygen in Puget Sound vary both by location and by season, this research is revealing. But many questions remain – and the answers could have multi-billion-dollar stakes.

ELEMENTS OF THE PROBLEM

Penn Cove, like many parts of Puget Sound is naturally prone to low oxygen due to circulation patterns and bathymetry, or the shape of the underwater terrain. The question of what exactly constitutes natural conditions in Puget Sound has been contentious. But the broad strokes of oxygen dynamics are well understood. Waters of different temperature or salinity tend not to mix, so fresher, more oxygenated water pouring into Puget Sound from rivers tends to sit on top of saltier, oxygen-poor marine waters from the Pacific Ocean. This phenomenon, known as stratification, worsens the depletion of oxygen in bottom waters. Long, narrow, and shallow bays and inlets are especially prone to this issue because their waters are slow to be exchanged with water from larger water bodies. Penn Cove, which pushes more than three miles into the eastern shore of Whidbey Island like a finger making a deep dimple in soft bread dough, is a typical example.



Penn Cove (circled in red), like many parts of Puget Sound is naturally prone to low oxygen due to circulation patterns. The volume of ocean water that enters Puget Sound diminishes as it reaches the end of narrow bays and inlets like Penn Cove taking longer to flush out excess nutrients and pollutants. Map: Puget Sound Institute; Data source: MacCready et al. 2021

While some parts of Puget Sound are prone to low oxygen year-round, the problem tends to be worse and more widespread in late summer and fall. This is partly because warm weather during summer makes stratification more pronounced. In addition, summer’s long, sunny days drive the growth of photosynthetic organisms including microscopic cyanobacteria and algae. When the blooms die back, the remains of these organisms fall to the bottom and are broken down by bacteria, a process that consumes oxygen.

Human activities can also worsen oxygen depletion, chiefly by increasing the level of nutrients, especially nitrogen, entering Puget Sound. Excess nitrogen comes from agricultural runoff, fossil fuel burning, and especially discharges from wastewater treatment plants serving the region’s burgeoning human population.

The large majority of human-caused nutrient pollution comes from wastewater treatment plants, according to Colleen Keltz, Communications Manager for the Water Quality Program at the Washington State Department of Ecology. "[It] doesn't mean they generate the pollution," she says. “It means we, as humans, pee and flush the toilet.” When that happens, nitrogen-rich effluent from wastewater treatment plants can act as a fertilizer, turbocharging summer algal blooms and making the subsequent fall in dissolved oxygen more acute.

Most of the nitrogen found in Puget Sound comes from natural sources, the vast majority of that from the ocean. An estimated 9% of the nitrogen can be traced to human activities in Washington State. While the anthropogenic contribution is small overall, nitrogen is normally a limiting nutrient in Puget Sound waters, so just a little extra may result in substantial overgrowth of phytoplankton blooms and subsequent lack of oxygen.

Just how much that amount might tip the balance has become a matter of debate that is driving scientific research and has set off a series of legal battles over what should be done about it.

AREAS OF CONCERN

Excess human-caused nutrients are a widespread problem affecting waterways worldwide. Nutrient reduction strategies have yielded success in cleaning up the Chesapeake Bay and waters around Denmark. In Puget Sound, some Native tribes and local communities, especially in areas with waters affected by low oxygen, argue that technology to remove nutrients from wastewater should be added to treatment plants around the region. But this strategy could cost billions of dollars, costs that would be passed on to utility ratepayers. And it’s important to know exactly where nutrient pollution needs to be reduced and by how much.

Some guidance on that question comes from water quality standards. The Washington State Department of Ecology regulates dissolved oxygen levels in marine waters as part of its responsibility for implementing the federal Clean Water Act. Standards range from 4 to 7 milligrams of oxygen per liter, depending on the needs of the species that live (or could live) in a particular location. For most of Puget Sound this so-called biologically based or numeric standard is 6 or 7 mg/L; in Penn Cove it is 6.

Waters can fall afoul of state dissolved oxygen standards without being hypoxic, a term that most commonly indicates dissolved oxygen levels of less than 2 mg/L. But state officials say these higher standards are necessary to protect the health of aquatic life. “These are the oxygen concentrations that we know the fish that are existing in these specific parts of Puget Sound and other critters need to thrive,” says Jeremy Reiman, an environmental planner at the Department of Ecology working on water quality standards.

Washington State is currently in the process of re-establishing water quality standards based on the dissolved oxygen levels that would have historically, prior to European settlement, prevailed at a particular location. Once such “natural conditions” criteria are in place, they will replace the numeric standard wherever they apply. Under the natural conditions regime, state regulations include an “anthropogenic allowance” for human impacts. Human activities cannot reduce dissolved oxygen by more than 0.2 mg/L or 10% (whichever decrease is smaller).

A primary tool for understanding the human influence on oxygen levels in Puget Sound is the Salish Sea Model (SSM), a state-of-the-art computer simulation developed by the Pacific Northwest National Laboratory in collaboration with the Washington Department of Ecology. The SSM can also provide a more detailed, high-resolution picture of current oxygen conditions than is available from on-the-water monitoring data – and thus point to areas where greater monitoring efforts are needed.

An algal bloom in Hood Canal on August 21, 2022 turns the water bright turquoise and can be seen from space. Photo: NASA Operational Land Imager-2 on Landsat 9

In one SSM analysis, the model revealed roughly a dozen and a half areas around Puget Sound that may be out of compliance with state dissolved oxygen standards due to human activities and where more information is needed about local oxygen dynamics. The areas of concern include parts of Hood Canal, a long, narrow, deep arm of the sea that has what researchers in a 2018 paper on hypoxia in Puget Sound dubbed a “classic fjord-type circulation” with strong stratification and a “nearly stagnant” bottom layer, and regularly becomes depleted of oxygen in the summer. The list also includes many shallow terminal bays and inlets around the region. Some of the places on the list have long been known as areas prone to low oxygen. Budd Inlet, in the far southern reaches of Puget Sound near Olympia, has been the subject of nutrient cleanup efforts since the 1990s. But the list also includes some new areas of concern, including Penn Cove. The analysis provides a focus for concern about low oxygen levels in Puget Sound: the problem isn’t everywhere, says Stefano Mazzilli, senior research scientist at the University of Washington Puget Sound Institute who has been working with the model. “There is only a finite number of places,” he says, “So we can start by focusing on what’s driving change in those places.” *[Editor's note: The Puget Sound Institute is the parent organization of the Encyclopedia of Puget Sound.]*

A TALE OF TWO MODELS

More clues about when, where, and why low oxygen levels occur in Puget Sound come from a second computer model, known as LiveOcean. An analysis presented at the Science of Puget Sound Water Quality workshop series in February focused on six inlets in Puget Sound where LiveOcean predicts that average daily oxygen levels at the bottom of the water fall below 2 mg/L – that is, become hypoxic – during the late summer and early fall. That list includes Penn Cove.

Researchers analyzed these six hypoxic inlets compared to seven better-oxygenated inlets in Puget Sound to understand what processes contribute most to the development of low oxygen levels during August and September. According to the prevailing model of coastal oxygen dynamics, hypoxia might develop in a particular area because the water there starts out with relatively low oxygen levels, that is, at the beginning of the growing season in spring; because biological processes such as the breakdown of phytoplankton blooms deplete oxygen quickly; or because water sticks around in the area for a long time before being replaced with more oxygenated water from elsewhere.

The first and third of those factors are the main determinants of susceptibility to hypoxia in Puget Sound's inlets, the analysis showed. "The most hypoxic inlets in Puget Sound are not ones that act as isolated hotspots of high DO consumption or high DO depletion rates," Aurora Leeson, a graduate student in the laboratory of University of Washington oceanographer Parker MacCready, which developed and maintains LiveOcean, told the workshop. "Instead, deep DO concentrations in terminal inlets of Puget Sound are strongly influenced by what flows into the inlets and how long it takes to flush the inlet."

This analysis is based on 2017 data and represents current conditions, Leeson says. A next step is to analyze a reference scenario without anthropogenic nutrient inputs, then compare the two to determine how wastewater treatment plants and other human activities may be contributing to the dynamics that produce hypoxia in these inlets.

The two models have many differences: SSM divides Puget Sound into a landscape of triangles, while LiveOcean uses a grid of squares; SSM offers greater resolution at the surface of the water while LiveOcean divides the depth of the water column into finer layers; SSM focuses on minimum oxygen concentrations to LiveOcean's tidally-averaged daily values; and so on.

But while some details of the analyses conducted and results obtained may differ, in broad strokes the two models paint a similar picture of the problem of hypoxia in Puget Sound: The areas most affected are Hood Canal and many shallow bays and inlets with long flushing times. But the causes of hypoxia can't be localized just to those affected areas; "Puget Sound is so interconnected," Leeson told Salish Sea Currents.

This means it's necessary to reduce nutrient inputs not just near hypoxia hotspots but throughout Puget Sound, says Ecology's Colleen Keltz. The agency has sought to incorporate these insights into regulations with its Puget Sound Nutrient General Permit, issued in December 2021 and covering 58 wastewater treatment plants that discharge into different parts of Puget Sound.

But on February 28, the Washington State Pollution Control Hearings Board struck down this approach, ruling that the general permit cannot be a mandatory overlay on existing individual permits. Ecology decided not to appeal the ruling and is shifting to a voluntary general permit approach.

TRENDS AND TINKERING

Meanwhile, efforts continue to both refine the models and build a better understanding of actual conditions in the water. Shallow terminal embayments – precisely the sorts of areas that are prone to low oxygen levels – are also difficult to render precisely in large-scale ocean models, says Taylor Martin, an oceanographer with King County.

Spurred by SSM results suggesting that nutrient discharges from King County wastewater treatment plants could contribute to low oxygen levels in Penn Cove and nearby areas, the county has launched a water quality monitoring program in the Whidbey Basin. “A lot of the water that comes from King County flows back North,” Martin explains. “A lot of it goes back out Admiralty Inlet. But not all of it. Some of it does slosh around to the East side of Whidbey.”

King County began sampling water quality at 10 locations in Whidbey Basin in 2022, initially collecting data twice and now once monthly. In 2023 they installed continuous monitoring instruments at three locations – near Port Susan, near the mouth of Penn Cove, and at Coupeville Wharf – that record data every 15 minutes.

So far in Penn Cove, “I think we've seen basically exactly what we expected to see,” Martin reports. “Dissolved oxygen does get quite low in the late summer and fall.” The county plans to continue monitoring these areas to see if there are any trends in the timing or duration of hypoxia – which can be difficult to establish because patterns of dissolved oxygen can vary so much from year to year, Martin says.

The Department of Ecology has been continuing to tinker with the SSM to find the best strategies for nutrient reduction, looking for scenarios in which the model predicts the highest compliance with dissolved oxygen standards throughout Puget Sound. Its modeling team teased the latest results at a meeting of the Puget Sound Nutrient Forum on March 27, and the agency plans to release the results along with an Advance Restoration Plan to reduce nutrients in Puget Sound in June.

This article was funded in part by King County in conjunction with a series of online workshops exploring Puget Sound water quality. Its content does not necessarily represent the views of King County or its employees.

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salish sea currents magazine

'Natural conditions' are at the center of disputes over dissolved oxygen standards

Questions over water quality standards have centered around nutrients that can lead to algal blooms and low oxygen levels. (Above) An algal bloom in Liberty Bay, WA in 2016. Photo: Ecology

KEYWORDS: EUTROPHICATION, HYPOXIA, SALISH SEA CURRENTS MAGAZINE, WATER QUALITY

By Christopher Dunagan

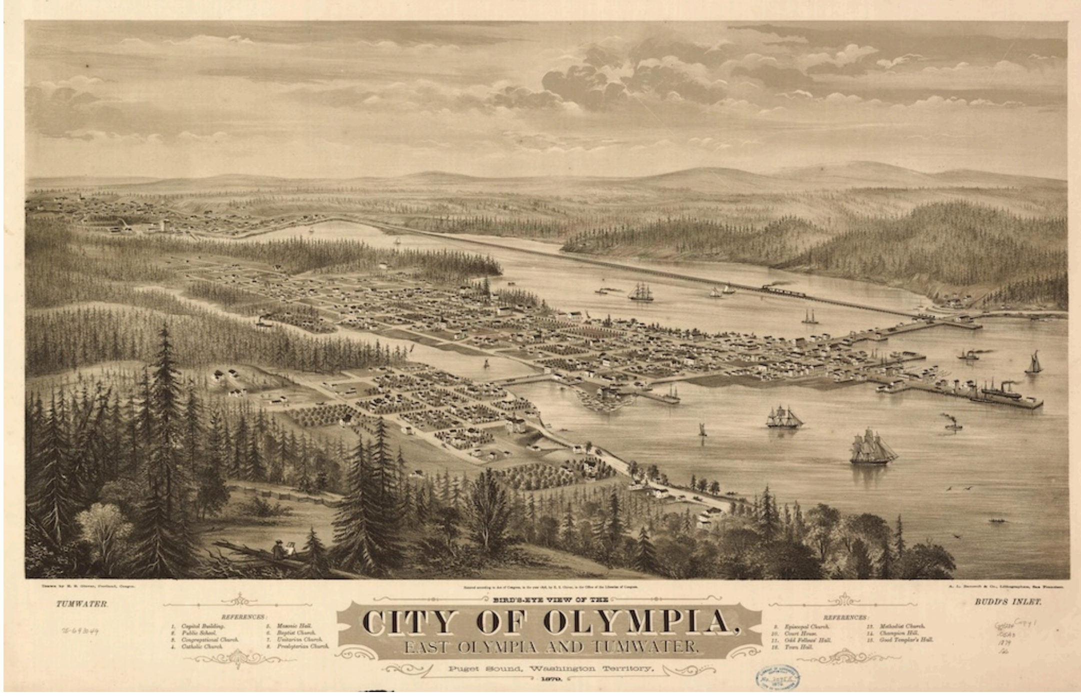
Published March 25, 2025

Oxygen is indisputably essential to aquatic life, but conflicts are brewing over water quality standards mandated in state regulations. This article is part of a series of reports funded by King County about the quest to define healthy oxygen levels in Puget Sound. By some estimates, those definitions could affect billions of dollars in state and local spending. [Editor's note: King County is currently in litigation with the Washington State Department of Ecology over the issue of dissolved oxygen water quality standards.]

Before early settlers built the region's first sawmill at Tumwater in 1848, before Arthur Denny and his party settled the future city of Seattle in 1851, and before the federal government created Washington Territory in 1853, the waters of Puget Sound and its freshwater streams were as clean as nature could provide. Fish and wildlife were abundant, having adapted to local conditions alongside native people of the area.

Needless to say, things have changed since those days. In the parlance of today's water-quality regulations, the clean waters of yesteryear are known as "natural conditions." Nobody believes that we will ever see those conditions again, but the term "natural conditions" has taken on a profound meaning as a point of reference. How far do we humans want to go in restoring polluted waters and limiting unhealthy discharges of wastewater into Puget Sound?

Washington Department of Ecology is currently struggling to establish a regulatory system involving natural conditions, based on the idea that it makes no sense to set cleanup goals beyond the best that nature has ever provided. The federal Environmental Protection Agency, which maintains ultimate authority over the nation's waterways, overturned



Illustrated view of the city of Olympia, East Olympia and Tumwater, Puget Sound, Washington Territory, 1879. Image: Illustrated perspective map: Library of Congress, Geography and Map Division

Ecology's existing natural conditions rule in 2021. Since then, Ecology has been working on a revision, particularly addressing water-quality goals for temperature and dissolved oxygen.

The agency recently completed limited rules for setting cleanup standards in defined locations. The ongoing effort is to create an enduring "performance-based" program that would empower experts to identify natural conditions anywhere in Puget Sound, along with an approved allowance for human degradation. The first draft received rather harsh comments from the EPA. A revised proposal that addresses only dissolved oxygen for marine waters was released for public comment this week.

In a letter to Ecology about the first draft, Rebecca Garnett, manager of standards and assessment for EPA's Region 10, said any new water quality criteria must meet scientific standards, be spelled out in sufficient detail, and fully protect aquatic creatures. "As currently proposed," she wrote, "the EPA is concerned that Ecology's performance-based approach for developing site-specific natural conditions criteria is not sufficiently 'binding, clear, predictable, and transparent.'"

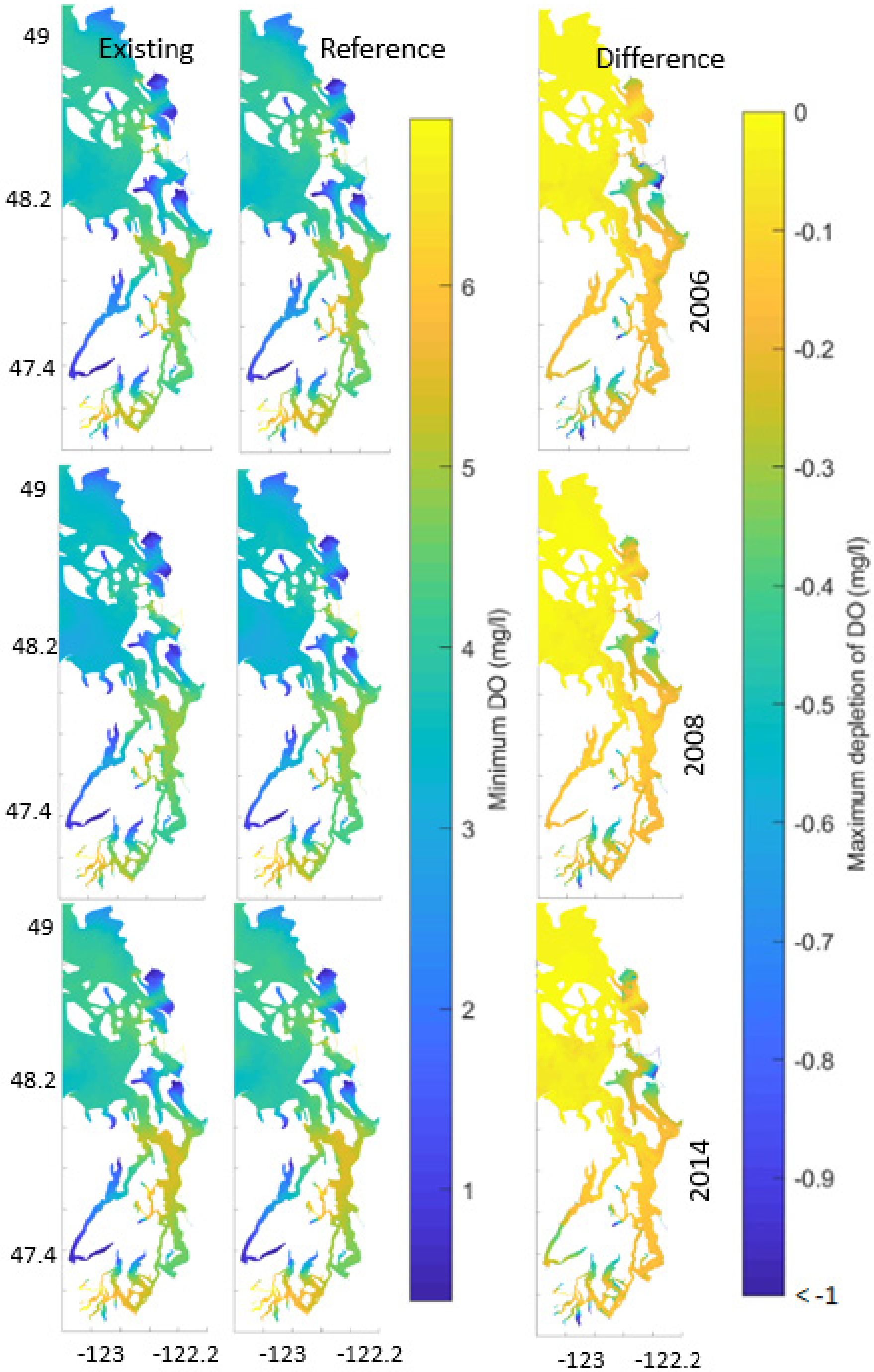
In a legal sense, water quality standards are essential, because they determine how much money is spent by government and industry to clean up our troubled waterways and improve survival for fish, crabs and other animals. According to some estimates, billions of dollars may be needed to bring major sewage-treatment plants into compliance.

> Documentation used to justify dissolved oxygen standards, developed more than 50 years ago, appear to be lost, according to Ecology's Water Quality Program, but agency officials maintain that available studies still support those numeric limits as protective of aquatic creatures.

Developing these new water-quality standards is complicated and intriguing, involving computer models to describe water-quality conditions that existed long before people changed the environment. A typical method of estimating natural conditions is to go out and measure current conditions in specific areas and then subtract all known causes of human degradation, often with the help of computers.

Natural conditions criteria may come into play when a body of water fails to meet established "numeric criteria." Numeric criteria are levels of oxygen and temperature that scientists say will meet the biological needs of aquatic creatures. Exceptions to numeric criteria are allowed for areas that have naturally lower levels of oxygen or naturally higher temperatures than the numeric criteria. For oxygen, the numeric criteria for most of Puget Sound is no less than 6 or 7 milligrams per liter, depending on the location. Based on studies, it appears that most of Puget Sound has never met those standards — not even in prehistoric times. This means that we could eliminate all human causes of low oxygen and still come up short of the approved numeric criteria.

This dilemma raises the stakes for choosing the correct natural conditions criteria. It also raises questions about whether Puget Sound is using the correct numeric standards, originally developed in 1967. Some officials in local government and industry as well as some scientists are calling for Ecology to overhaul the numeric criteria for oxygen throughout Puget Sound. The nonprofit advocacy group Association of Washington Cities, among others, would like the Legislature to fund a study to determine the actual needs of aquatic creatures in Puget Sound. For now, Ecology has placed a higher priority on developing natural conditions criteria.



The minimum dissolved oxygen level for most of Puget Sound is 7 mg/l, and 6 mg/l for areas to the west of Whidbey Island and into Bellingham Bay. The natural or "reference" condition map (center) shows that few areas of Puget Sound meet these minimum numeric standards. Areas in the difference map (right) that are green to blue are most sensitive to depletion of dissolved oxygen from human sources. Map: Ecology

"This matters," states a [news release](#) from the agency, "because Ecology and all organizations working on clean water efforts need to focus the state's pollution-reduction efforts on waterbodies where humans are causing pollution, not on waterbodies that are naturally different."

FITTING NATURE INTO A REGULATORY FRAMEWORK

Arguments over how far to go in cleaning up the streams, bays and open waterways of Puget Sound have their regulatory foundation within the federal Clean Water Act of 1972. The law establishes a national policy to "restore and maintain the chemical, physical and biological integrity of the nation's waters." The law asserts a goal of eliminating all water pollution and directs the Environmental Protection Agency to follow a specific process, in concert with the various states.

The Department of Ecology, authorized by the EPA to administer the Clean Water Act in Washington state, has its hands full in issuing permits for pollutant discharges, developing cleanup plans for polluted waterways, enforcing regulations to protect marine and fresh waters, and safeguarding the health of humans and animals.

Water quality standards have been developed and formally approved to protect aquatic species, human health, human activities and even esthetics, such as odor and appearance. For aquatic species, the numeric limits for physical and chemical conditions are based on the goal of protecting the most sensitive species in designated areas.

Oxygen is considered an essential element for sea life in marine waters. Numeric criteria for oxygen in Puget Sound, ranging from 4 to 7 milligrams per liter, date back to 1967 under the Federal Water Pollution Control Act, the predecessor to the Clean Water Act. Documentation used to justify those standards, developed more than 50 years ago, appear to be lost, according to Ecology's Water Quality Program, but agency officials maintain that available studies still support those numeric limits as protective of aquatic creatures.

Most of Puget Sound is designated for a minimum of 7 mg/l. Areas to the west of Whidbey Island and into Bellingham Bay are designated for no less than 6 mg/l. The innermost portions of Tacoma's Commencement Bay, Olympia's Budd Inlet and Shelton's Oakland Bay are designated for 5 mg/l, down to 4 mg/l in a few relatively tiny areas of those waterways.

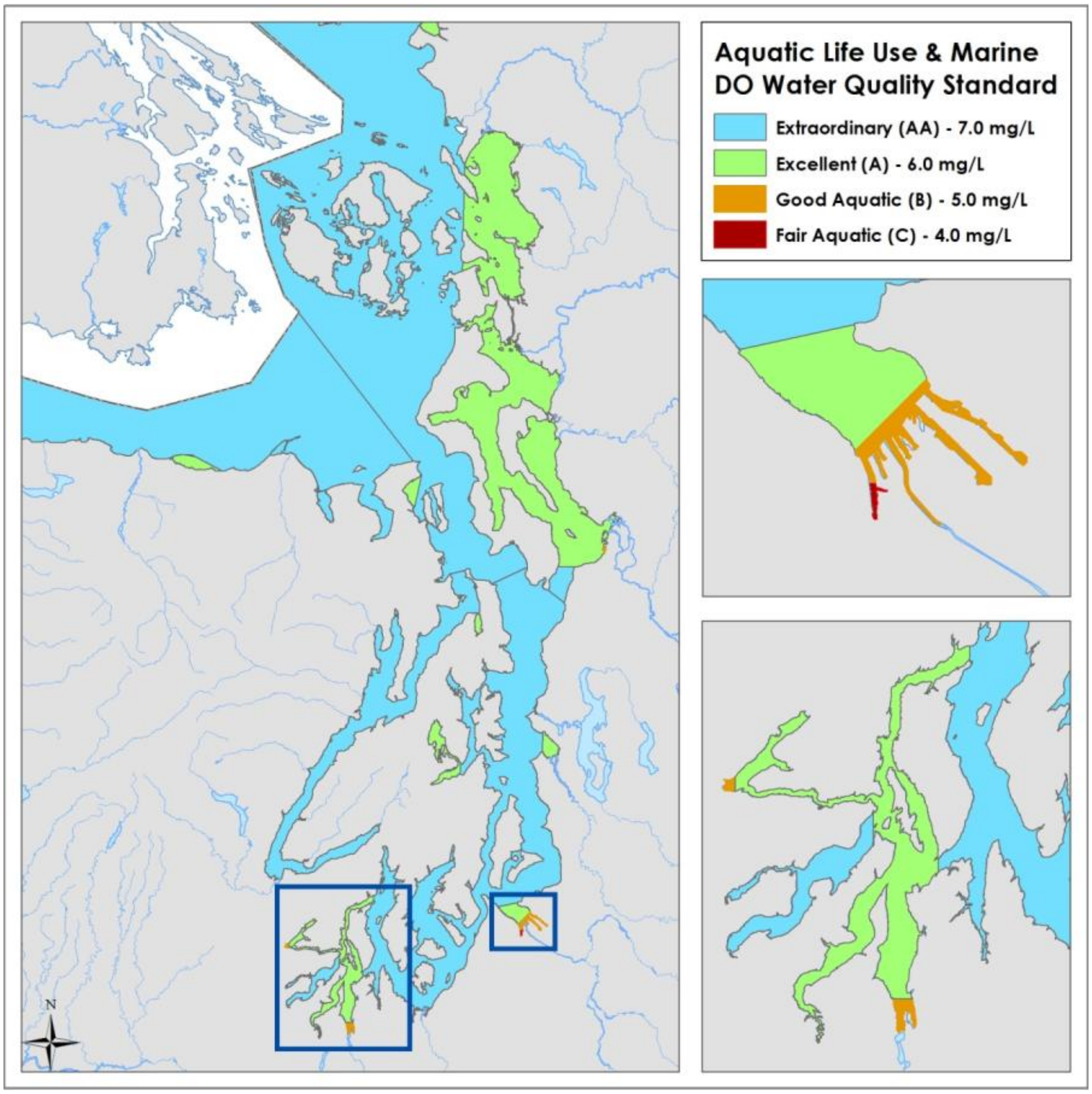
Critics argue that 6 or 7 mg/l is generally overly protective of water quality, since most areas of Puget Sound apparently never met those standards, not even in prehistoric times when marine species were abundant. Some say the criteria should be updated with more recent science, perhaps considering the depth of channels and other factors that affect natural oxygen levels. Chesapeake Bay on the East Coast has taken this approach. As things stand, the numeric criteria for Puget

Sound are destined to be largely displaced by natural conditions criteria based on computer models.

BIOLOGICAL NEEDS OF SPECIES

The concept of using a numeric standard for water quality is rather simple, perhaps too simple, some people say. For example, one can estimate, based on laboratory studies, the biological needs of salmon, including healthy levels of temperature and oxygen. These biological requirements may vary, depending on the activity of the fish, its body condition and other factors.

The biological needs may be complex and dynamic, yet Washington's numeric water quality criteria are reduced to single numbers. Much of Puget Sound has been designated as "extraordinary" water quality, a category that calls for a minimum oxygen level of 7 mg/l and a maximum temperature of 13 degrees C (55.4 F). Other criteria establish limits for turbidity, acidity and bacteria. Besides "extraordinary," various areas of Puget Sound have been designated as "excellent," "good" or "fair," each with their own criteria to protect named species residing there.



According to water quality standards for Puget Sound, as shown on the map, most of the waterway should contain at least 7 milligrams per liter of dissolved oxygen to meet numeric criteria. Where natural levels of oxygen are believed to be lower than these numeric criteria, the Washington Department of Ecology would allow for "natural conditions criteria." The agency is currently revising its process for determining natural conditions. Map: Ecology

Oxygen and temperatures can vary by location and depth in Puget Sound. State regulations call for taking measurements at depths that represent the "dominant aquatic habitat" at each monitoring site. Such monitoring helps to determine whether a water body complies with established criteria or is "impaired" for certain water quality parameters. Because conditions change over time, particularly with seasonal cycles, some areas may comply at one time but not another.

Since few areas of Puget Sound can meet the numeric criteria for dissolved oxygen at all times, even under natural conditions, some individuals and groups are calling for revisions to the criteria. They contend that limits of 6 or 7 mg/l are considerably higher than needed to protect marine life in Puget Sound. Rather than resorting to computer models to determine natural conditions criteria, scientific studies could help establish new numeric criteria based on biological needs.

“Ecology has acknowledged that it has no documentation as to the scientific basis for the marine DO standards that were adopted by a predecessor agency in 1967,” said Carl Schroeder of the Association of Washington Cities, commenting on the proposed natural conditions criteria.

Schroeder noted that cities are responsible for many of the sewage-treatment plants in Puget Sound, including those facing costly upgrades to improve oxygen conditions. Since costs must be passed on to customers via higher sewer rates, local governments must be able to explain the rationale for Ecology’s water quality standards, he said.

After 56 years without a clear scientific foundation, he continued, “it is startling that Ecology continues to move forward without seeking or incorporating information on the dissolved oxygen needs of the organisms present in Puget Sound.”

During last year’s legislative session, Schroeder and others attempted to get Washington lawmakers to appropriate $500,000 for a scientific review of the biological needs of Puget Sound species in connection with the state’s cleanup standards. The proposed study would have involved the Washington Academy of Sciences. Funding for the study was approved by the House but failed to survive final negotiations in the Senate. This year, Schroeder continues to push for legislative funding, despite tight budget conditions.

Lincoln Loehr, a retired oceanographer and environmental consultant, has been on a crusade of sorts to get Ecology to review the numeric criteria for oxygen. He first petitioned the agency to review the oxygen criteria in 1998, before most people were aware that natural conditions criteria would become such a key factor in setting cleanup targets. Loehr shared his views with many technical groups working on the low-oxygen problems of Puget Sound, and in 2017 he petitioned Ecology again to review the numeric criteria.

“Washington’s marine DO water quality criteria, adopted in 1967, have no discoverable scientific basis,” Loehr wrote in a report reviewing the history of numeric criteria and recommending that the EPA step in and develop new criteria. “While the state can identify waters as not meeting these criteria, that determination does not demonstrate that the waters are impaired, as the comparison is made with baseless criteria. Similarly, computer modeling to compare to a 0.2 mg/l decrease in DO from human causes (part of the state's criteria) is not a basis for demonstrating impairment, as it has no biological basis.”

Responses from EPA officials have offered no support for revising the state’s numeric criteria, which federal law says can be more restrictive than federal requirements. Ecology officials defend the existing criteria as being protective of marine species, but critics contend they are overly protective. Loehr argues in favor of changes to the numeric criteria, saying the Clean Water Act calls for standards that accurately reflect the “latest scientific knowledge.”

Sara Thitipraserth, director of natural resources for the Stillaguamish Tribe, expressed similar concerns in letters to Ecology and the EPA.

“It is the view of the Stillaguamish Tribe that the Marine Dissolved Oxygen Water Quality Criteria of Washington state are in need of thoughtful, science-based revision,” she wrote. “They are outdated, simplistic, and fail to consider the geography and hydrology of Puget Sound. Neither are they based on or referenced with scientific research…

“Once appropriate standards are established,” she added, “it is likely that many so-called water quality exceedances will cease to exist. Currently, marine waters with 5 mg/l dissolved oxygen in many deep-water basins are considered noncompliant, when in fact the oxygen level poses no threat to organisms that might be using it. Scientists in the region commonly acknowledge that the harm to a deep-water marine biological community does not occur until the water becomes hypoxic, that is, when oxygen levels drop below 2 mg/l.”

MEASURING THE NEEDS FOR OXYGEN

Tim Essington, a fisheries ecologist at the University of Washington, has studied the effects of oxygen depletion on many species in Puget Sound. Although not directly involved in regulatory issues, Essington’s research involves studying biological thresholds. For example, declining oxygen levels eventually reach a point when fish must respond with physiological or behavioral changes if they are to survive. This level of oxygen is called the "critical threshold" for a given species, and it varies by temperature.

A key issue is whether the laboratory environment accurately represents conditions faced by aquatic animals in the real world. Fish in a lab, for example, are held under precise conditions of oxygen and temperature to see how they respond, whereas fish in the wild are likely to swim away and seek better conditions when faced with low oxygen levels. Activity and stress can affect their metabolism and their need for oxygen. Temperature is another factor.

"In the lab, you are measuring routine behavior; the fish is not trying to chase down food," Essington said. "But in terms of ecological relevance, animals do need to eat. The process of finding food costs oxygen, and there is also the need to avoid predators."

Animals can acclimate to low-oxygen conditions, such as what occurs when a human athlete trains at high altitude, he continued. The oxygen capacity of the blood can change, and fish can even increase the surface area of their gills. Meanwhile, over generations, localized populations within a species may adapt to low-oxygen conditions and pass on those traits to their offspring.

Studying the presence or absence of species under various oxygen conditions can provide clues to their needs in the wild, Essington said, but one needs to understand that the most sensitive species may already be gone. Such observations of wild behavior can be compared to observations in a lab to better understand the oxygen needs of Puget Sound species.

In Chesapeake Bay on the East Coast, the EPA faced the challenge of low-oxygen conditions by dividing the bay into five habitat types, including considerations for the depth of the water. Since deeper water typically contains less oxygen, dominant species are more tolerant of those conditions. The resulting guidelines (PDF) were completed in 2003 with numeric criteria for oxygen, water clarity and chlorophyll. They were subsequently adopted into regulations by the four governmental jurisdictions around the bay: Washington, D.C. and the states of Maryland, Virginia and Delaware.

Proponents of changing Washington state's numeric criteria for oxygen often point to Chesapeake Bay as an example of how to fit biological needs into a regulatory framework.

EPA identified and described five habitats to ensure the protection of the living resources of the Chesapeake Bay and its tidal tributaries. Some say a similar approach would be appropriate for Puget Sound.

An alternative approach

In establishing numeric criteria for Chesapeake Bay, the Environmental Protection Agency divided the bay into five habitat types to protect species in each location. Each has its own standards for dissolved oxygen:

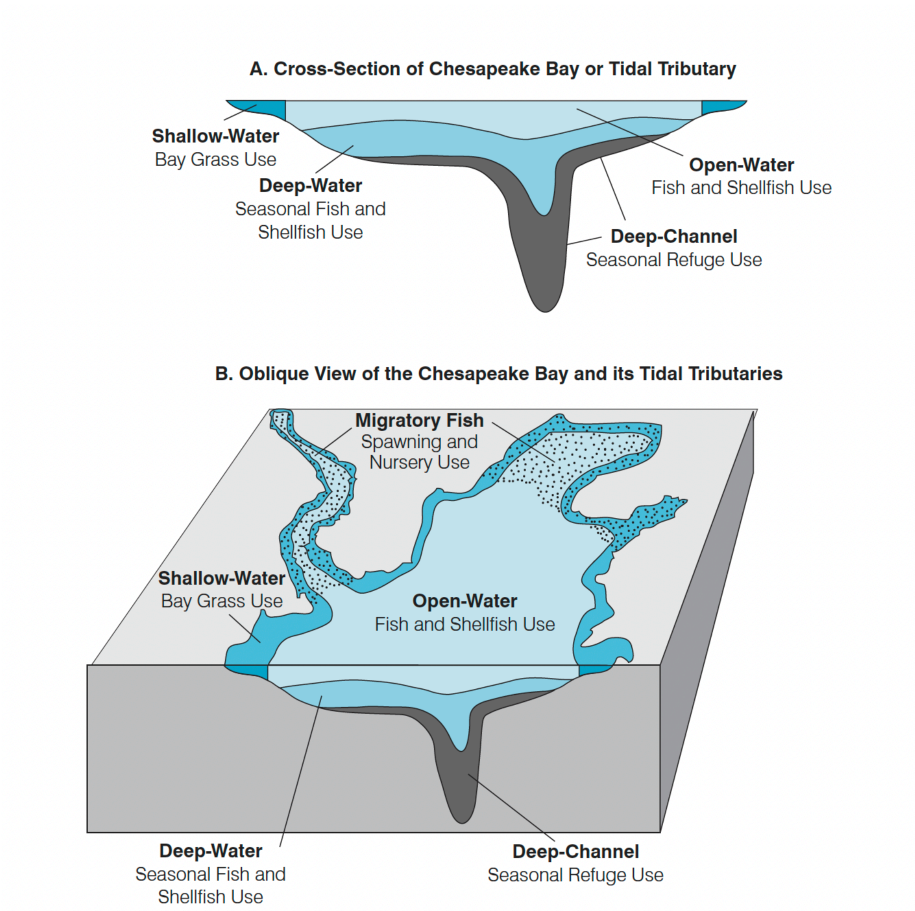
Migratory fish spawning and nursery. Largely freshwater streams and tidally influenced locations where freshwater comes into saltwater. Oxygen levels must generally be above a seven-day average of 6 mg/l from Feb. 1 to May 31, when young fish are migrating. Levels are allowed to drop to 5.0 or 5.5 mg/l, depending on salinity, from June 1 to Jan. 31.

Shallow water bay grass. Mostly underwater areas near the shore where fish and crab find food and protection from predators among the vegetation. Oxygen criteria call for a 30-day average no lower than 5.0 or 5.5 mg/l, depending on salinity, although a seven-day average of at least 4 mg/l also meets the standard.

Open-water fish and shellfish. Includes surface waters in streams, embayments and open waters of the bay where diverse populations of fish spend their time. Oxygen criteria call for a 30-day average no lower than 5.0 or 5.5 mg/l, depending on salinity, although a seven-day average of at least 4 mg/l also meets the standard.

Deep-water seasonal fish and shellfish. Representing transitional waters between the well-mixed surface waters and the deep channels of the bay where bottom-feeding fish, crabs, oysters and other species live. Numeric criteria call a 30-day average oxygen concentration of at least 3 mg/l or a one-day average of 2.3 mg/l, except for Oct. 1 to May 31 when the higher "open-water" criteria apply.

Deep-channel seasonal refuge. The home of sediment-dwelling worms and small clams consumed by bottom-feeding fish and crabs, a habitat known for very-low oxygen levels. To meet the criteria, oxygen levels must never get below 1 mg/l.



Five habitats types designated for Chesapeake Bay. Illustration: EPA

Note: These five habitats also include absolute minimums, separate from averages, which must never be exceeded. For some species, temperature is also considered.

NATURAL CONDITIONS APPROACH

From the beginning, Ecology officials realized that some areas of Puget Sound contained naturally low levels of oxygen that could never meet the numeric criteria, even under the best conditions.

"We have long acknowledged that (portions of) Puget Sound is naturally impaired for DO," said Leanne Weiss, unit supervisor in Ecology's Water Quality Management Division, "and that's why these other processes and options are so important."

In fact, when considering all the nation's waterways, EPA recognized as early as 1997 that natural conditions, absent human impacts, might be lower in oxygen or higher in temperature than numeric criteria in some areas. A 1997 memo (PDF) establishes a policy allowing for numeric limits to be supplanted by natural levels.

Current revisions to Ecology's natural conditions regulations came about from a lawsuit filed by Northwest Environmental Advocates. In response to the lawsuit, the EPA agreed to reconsider its 2008 approval of Ecology's natural conditions rule. After review, the EPA reversed its approval (PDF), leaving Washington without a natural-conditions option for cleanup goals.

One reason for the reversal was the lack of a clear statement that the natural conditions criteria applied only to aquatic life, not to human health standards, according to the EPA. As described in the 1997 EPA memo on natural conditions criteria, aquatic species may adapt over time to waters with naturally low levels of oxygen or high temperature, but that's not the case for humans. People should be protected from harmful natural conditions by changing the "designated use" of a waterway, the memo says. That might mean excluding fishing or other recreational activities or even issuing public-health warnings.

Ecology's revised rule is written to limit its application to aquatic species.

"Having a standard to determine what is normal and natural for a particular waterbody is important information for setting discharge limits and knowing when action is needed to protect or restore water quality," Ecology states on its rule-making webpage. "Nearly every state and many tribal nations have a provision in their EPA-approved water quality standards to protect aquatic life based on natural conditions of the water bodies."

EPA specifically overturned Ecology's natural conditions criteria for both oxygen and temperature in marine waters and freshwater streams. It did not overturn the criteria in lakes, which EPA determined to be adequately protective as written into the rule.

Oxygen is often the driving factor for marine creatures, and it has received much attention from Ecology because low-oxygen conditions are creating serious problems in Puget Sound. While oxygen levels are a concern in some streams, temperature can be a critical factor for fish where logging has removed large trees that help keep the waters cool (Encyclopedia of Puget Sound).

As with oxygen, when studies show that natural conditions are warmer than designated temperatures, streams have been allowed to reach their estimated "natural" temperatures plus 0.3 degrees — the "human use allowance."

EPA did not determine whether the human use allowance of 0.2 mg/l for oxygen and 0.3 degrees C for temperature was or was not close enough to the actual levels expected under natural conditions, but the agency did insist that Ecology provide scientific justification for those allowances. EPA's 1997 memo allowing for natural conditions does not mention any such allowance.

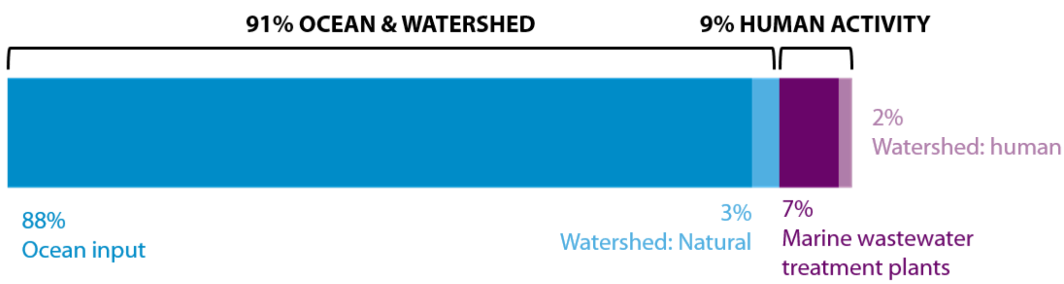
To get natural conditions back into play, Ecology has been working on a performance-based approach — a step-by-step process approved through a formal rule-making procedure. Public comments on the new proposal are being accepted until May 22. Once the process is adopted by Ecology and approved by the EPA, anyone could theoretically follow the process. Ecology would be responsible for establishing allowable limits for temperature or oxygen anywhere in Puget Sound. The resulting natural conditions criteria, based on careful modeling, would be accepted by authorities without further approval.

The first draft maintained 0.2 mg/l and 0.3 degrees C as allowable deviations, consistent with rules adopted years ago and renewed in November. Without these allowances, cleanup standards for oxygen and temperature would need to be set at the natural levels seen in prehistoric times, officials say. Such levels would be unattainable in today's world of human impacts.

Ecology has approved one change to tighten the human use allowance. When natural oxygen conditions are found to be very low — specifically below 2 mg/l — the human use allowance is limited to 10 percent below the natural level. For example, if the natural oxygen level is 1 mg/l, then the allowance can be no more than 0.1 mg/l, setting the cleanup target at 0.9 mg/l.

ENDANGERED SPECIES PROTECTIONS

During the 2008 approval of the natural conditions criteria, federal agencies responsible for protecting listed species under the Endangered Species Act analyzed the effects of Ecology's revised water quality standards for oxygen and temperature, including the relevant human use allowances: 0.2 mg/l for oxygen and 0.3 degrees C for temperature. While the standards may not fully protect listed salmon during all life stages, they are "not likely to jeopardize the continued existence" of the listed species, according to the National Marine Fisheries Service. When the current revisions are complete, the federal agencies are expected to undertake a new analysis of the natural conditions rule, taking into account changing conditions and new research. They must show that the new rule is protective of threatened and endangered species before it can become effective.



Most of the nitrogen in Puget Sound (~91%) comes from natural sources –– mainly the ocean, with a small amount carried in from surrounding watersheds via surface runoff and rivers. Less than 10 percent is attributed to human activity, including wastewater treatment plants (7%) along with agriculture and urban runoff (2%). Levels of dissolved oxygen in Puget Sound are largely determined by how much of this nitrogen reaches the surface layer, where sunlight encourages the rapid growth of plankton. The plankton eventually die and decay, consuming oxygen in the process. Graphic: PSI

Because the performance-based approach relies on computer modeling to identify natural conditions, the process outlined by Ecology prescribes model selection, assumptions, operation and reliability; choice of data; considerations of climate change; interpretation of model outcomes; documentation; peer review; and many other issues. Ecology's proposed revisions have been drafted with guidance from EPA's natural conditions "framework" (PDF).

When the first version of the performance-based approach was released for public comment last May, the document was met with many questions and concerns. Among other things, the EPA called for adding "critical steps" in the process; stronger language to convey that each step is "binding" on the applicant, not voluntary; plus additional detail to "ensure a repeatable and transparent process."

One of the challenges in determining natural conditions is to identify ALL the human sources affecting the waterway. If any human sources are missed, the resulting estimate of natural conditions could lead to cleanup standards that adversely affect species that are still present and preclude the return of missing species.

While an approved performance-based approach would allow Ecology to establish water quality goals without further rulemaking, another approach is to study a particular area and propose water quality criteria that meets the needs of species in that area. Results from this "site-specific approach" would be proposed and adopted as a rule by Ecology with final approval from the EPA.

In the end, whether cleanup goals are based on numeric criteria or on natural conditions, the ultimate goal is to restore water quality for all species in Puget Sound — including, as much as possible, those species that thrived when natural conditions prevailed.

This article was funded in part by King County in conjunction with a series of online workshops exploring Puget Sound water quality. Its content does not necessarily represent the views of King County or its employees.

Related Link

Oxygen for life: The biological impacts of low dissolved oxygen

About the Author

Christopher Dunagan is a senior writer at the Puget Sound Institute.

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Modeling Considerations Checklist

Purpose: To ensure all critical elements necessary to determine natural water quality conditions are examined when using the performance-based approach, to model a natural condition scenario for a TMDL, or to develop site-specific criteria.

Instructions: Elements listed below must be considered when making a natural condition determination. The shaded items are required to be included in the natural condition model or other determination. *If a non-shaded element is deemed not critical, then you must provide scientific rationale why it was not included in the natural conditions analysis.* Other elements included or considered in the analysis must be added to this list, including how the element was applied in the modeling scenario or determination.

Data collection necessary to evaluate the factors in this checklist must be described in the Quality Assurance Project Plan (QAPP) for the study and/or modeling that supports the TMDL or site-specific criteria development. Information from this checklist will be used to document substantiation of a natural condition determination in a TMDL or other supporting report.

Project Name: ____

Form completed by: ____

Date form completed: ____________________________

Supporting QAPP: ____

Minimum Elements	How applied	Sources/References
Boundary conditions		
Channel morphology changes		
Flow reductions or increases		

Hydrologic modifications		
Invasive species		
Microclimate		
Natural nutrient concentrations *(required only for DO and pH natural conditions determinations)*		
Nonpoint sources		
Point source effluent		
System potential shade		
Any biological measures or indices that indicate the water body has high quality biological integrity (or a narrative of how the water body is achieving its use through temporal use, refugia, etc.)		

Discuss how errors and uncertainty in modeling are addressed
Describe the model or other predictive method chosen and why it is the most appropriate method

Definitions:

Boundary conditions – Considers upstream inputs to the water body or segment being evaluated for natural conditions. Also must ensure downstream uses and criteria are not adversely affected.

Channel morphology changes – Considers channel straightening, dredging, levees, aggregation, and incision

Flow reductions or increases - Considers groundwater and surface water changes such as withdrawals and inputs

Hydrologic modifications – Considers hydrologic controls such as dams and weirs

Invasive species – Considers whether other organisms are affecting the biology or chemistry of the water. For example plants influencing DO/pH levels or carp influencing turbidity and sediment oxygen demand

Microclimate – Considers changes in temperature and relative humidity due to increased riparian vegetation to the system potential shade level.

Point source effluent – Removes all effect of permitted discharges.

Natural nutrient concentrations – Considers whether there are natural nutrient sources contributing to the water chemistry and biology or if there is legacy nutrient contamination. This is required only for DO and pH natural conditions determinations.

Nonpoint sources – Factors in land use changes, vegetation removal, and diffuse pollution from human activities.

System potential shade – Ensures full water body shading possible under a natural condition is applied.

Checklist with examples of how and where elements have been applied previously provided as guidance only

Element	How applied	Sources/References
System potential shade		- All temperature TMDLs
Microclimate	- Hourly air temps decreased by 2°C	- Deschutes,Cap Lake, Budd Inlet multi-parameter TMDL (Pub# 12-03-008) and others
Channel morphology changes (e.g. channel straightening, dredging, levees, aggregation, incision)	- Reduced channel width based on increased channel stability expected from mature riparian buffer - Removed levees from natural conditions scenario by digitizing historic disturbance zone and channel from 1907 survey (pre-levees). Re-ran shade analysis using new disturbance zone, widths, and riparian buffers. Also altered channel geometry by applying rating curves from an upstream area of the existing conditions model with no levees.	- Deschutes,Cap Lake, Budd Inlet multi-parameter TMDL (Pub# 12-03-008) and Bear Evans TMDL (Pub# 08-10-058) - White River pH TMDL (unpublished)
Flow reductions or increases (groundwater and surface water)	- Historic 7Q10 base flows (increased) were evaluated - Restored base flows based on estimate of net loss from EIA and water management	- Deschutes,Cap Lake, Budd Inlet multi-parameter TMDL (Pub# 12-03-008) - Bear Evans MP TMDL (Pub #08-10-058) and previous research project
Hydromodifications (hydrologic controls such as dams and weirs)	- Removed Capitol Lake dam and modeled as an estuary (added channel of grid cells).	- Deschutes,Cap Lake, Budd Inlet multi-parameter TMDL (Pub# 12-03-008)
Point source effluent	- Remove effluent in the model - Adjust effluent temperature to stream background condition	

Nonpoint sources **(e.g. Land use changes, vegetation removal, diffuse pollution from human activities)**		
Natural nutrient concentrations; legacy contamination *(required only for DO and pH natural conditions determinations)*	- Inflection point of nutrient concentrations cumulative distribution from sites throughout basin, including reference sites. - 25th percentile of tributary values; 5% less than existing headwater values	- Wenatchee TMDL (Pub# 06-03-018) - White River pH TMDL (unpublished)
Boundary conditions	-	-
Invasive species **(plants influencing DO/pH levels, carp influencing turbidity and SOD)**	- Elodea nuisance growth increased siltation and amplifies impacts of SOD and reduced reareation	- Clarks Creek DO and Sediment TMDL (Pub# 14-10-030)
Any biological measure or indices that indicate water body has high quality biological integrity (or a narrative of how the water body is achieving its use through temporal use, refugia, etc.)	Not likely a modeling input but may be included as evidence a water body is or is not providing its beneficial uses	- Biological Monitoring - Evaluating Physical Habitat and Water Chemistry Data from Statewide Stream Monitoring Programs to Establish Least-Impacted Conditions in Washington State
Discuss how errors and uncertainty in modeling is being addresses		
Model or other predictive method chosen and description of why it is the most appropriate method		

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
PO Box 47600, Olympia, WA 98504-7600 • 360-407-6000

STATE ENVIRONMENTAL POLICY ACT

Determination of Non-Significance

Date of Issuance: May 10, 2024

Lead agency and proponent: Washington Department of Ecology, Water Quality Program

Agency Contact: Marla Koberstein, (360) 628-6376, swqs@ecy.wa.gov

Ecology is proposing to revise chapter 173-201A WAC, Water Quality Standards for Surface Waters of the State of Washington. We are considering the following revisions in this rulemaking:

- WAC 173-201A-020, Definitions: adding a definition for a performance-based approach method and a definition for local and regional sources of human-caused pollution.
- WAC 173-201A-200(1)(c), Aquatic life temperature criteria, subsection (i): updating the allowable insignificant changes to freshwater temperature criteria when natural conditions are the applicable criteria.
- WAC 173-201A-200(1)(d), Aquatic life dissolved oxygen (D.O.) criteria, subsection (i): updating the allowable insignificant changes to freshwater dissolved oxygen criteria when natural conditions are the applicable criteria.
- WAC 173-201A-210(1)(c), Aquatic life temperature criteria, subsection (i) updating the allowable insignificant changes to marine water temperature when natural conditions are the applicable criteria.
- WAC 173-201A-210(1)(d), Aquatic life dissolved oxygen (D.O.), subsection (i): updating the allowable insignificant changes to marine water dissolved oxygen when natural conditions are the applicable criteria.
- WAC 173-201A-260(1), Natural and irreversible human conditions: updating the natural conditions criteria language and describing methods for determining natural conditions criteria values.
- WAC 173-201A-430(2), Site-specific criteria: updating how analyses must be conducted.
- WAC 173-201A-470, Performance-based approach: adding this new section to describe and reference the methodology to determine natural conditions criteria values.

- Ecology publication 24-10-017, A Performance-Based Approach for Developing Site-Specific Natural Conditions Criteria for Aquatic Life in Washington, a separate rule document that provides the methodology to determine natural conditions criteria values.
- Minor, non-substantive edits to rule language in WAC 173-201A-430(2) to reflect the latest version of referenced documents.

We are proposing revisions to natural conditions provisions in our surface water quality standards to provide water quality protection for aquatic life organisms and to establish possible methods for deriving those protective values. We:

- Evaluated the latest scientific data, methods, modeling tools, and approaches to update the natural conditions provisions necessary for refining aquatic life protection.
- Considered the U.S. Environmental Protection Agency's recommend approaches for natural conditions in water quality standards, including a performance-based approach for determining protective natural conditions criteria.
- Considered the U.S. Environmental Protection Agency's draft, deliberative, and Washington-specific recommendations for the performance-based approach methodology.

The Washington State Department of Ecology has determined that this proposal will not have a probable significant adverse impact on the environment. An environmental impact statement (EIS) is not required under RCW 43.21C.030. We have reviewed the attached Environmental Checklist and supporting rulemaking documents. This information is available on our rulemaking webpage.

This determination is based on the following findings and conclusions:

Ecology has determined that the proposed rule amendments will not result in probably significant adverse impacts on the environment. This is a nonproject SEPA that involves a rulemaking for the Washington State Water Quality Standards. The rulemaking, if concluded, will revise natural conditions provisions with the intention of providing protection for aquatic species and their habitats.

An environmental impact statement (EIS) is not required under RCW 43.21C.030(2)(c). This decision was made after review of a completed environmental checklist (attached) and other information provided in the rulemaking documents.

This DNS is issued under WAC 197-11-340(2). The comment period for this DNS runs concurrently with the comment period on the underlying proposal to amend the Water Quality Standards for Surface Waters of the State of Washington (CR-102). Comments will be taken on this DNS and on the underlying rule proposal until July 12, 2024.

Please send written comments to: https://wq.ecology.commentinput.com?id=gHacGx2j4E

Responsible official:

Vincent McGowan, P.E.
Water Quality Program Manager
Department of Ecology
PO Box 47600
Olympia, WA 98504-7600
360-407-6405

Signature

______________________________ Date May 10, 2024

Appeal process:

An appeal of the decision to issue a DNS may be consolidated with the decision on the underlying action (to adopt revisions to chapter 173-201A WAC) and is governed by the Administrative Procedures Act (RCW 34.05).