Puget Sound Nutrient Source Reduction Project

Volume 1: Model Updates and Bounding Scenarios

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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.

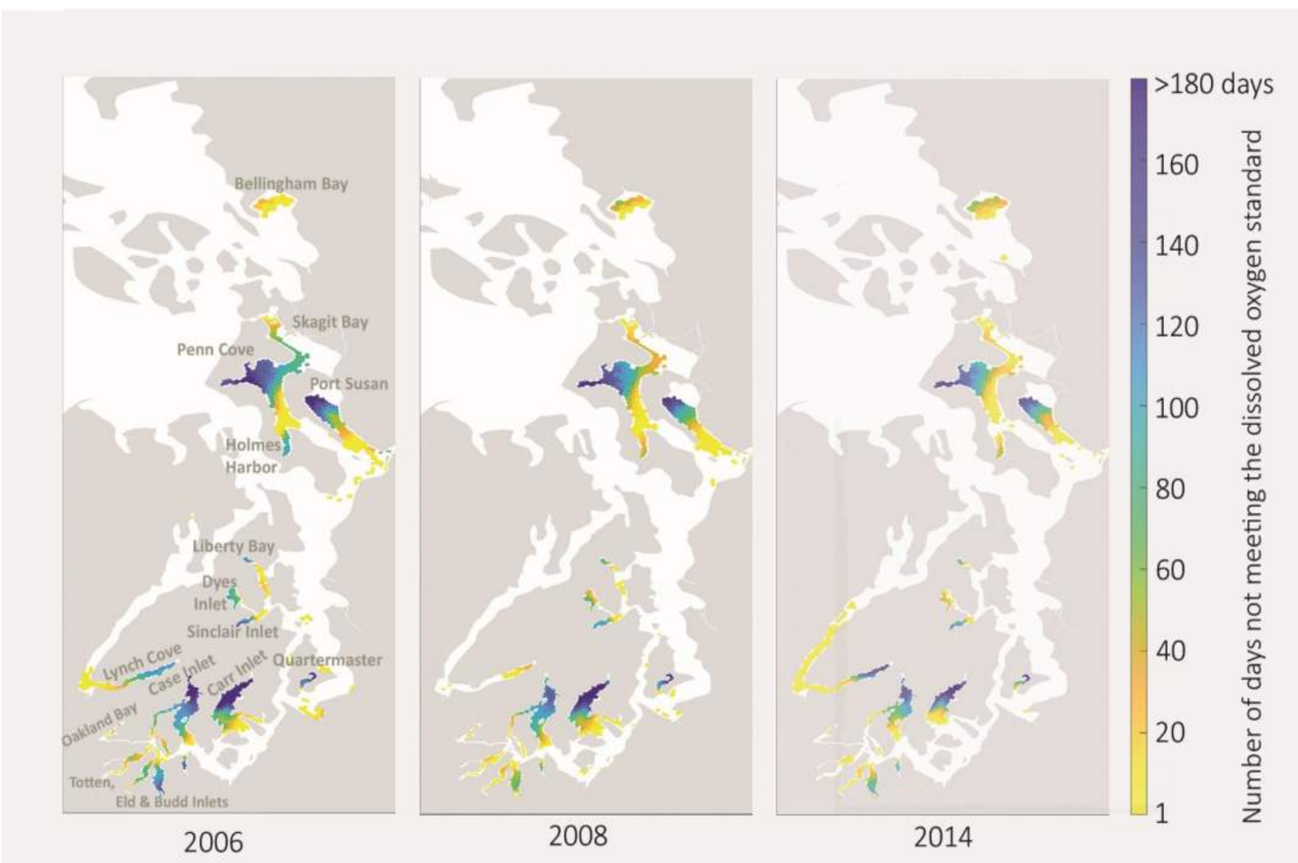


Figure ES2. Number of days not meeting the dissolved oxygen water quality standards for the years 2006, 2008, and 2014.

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).

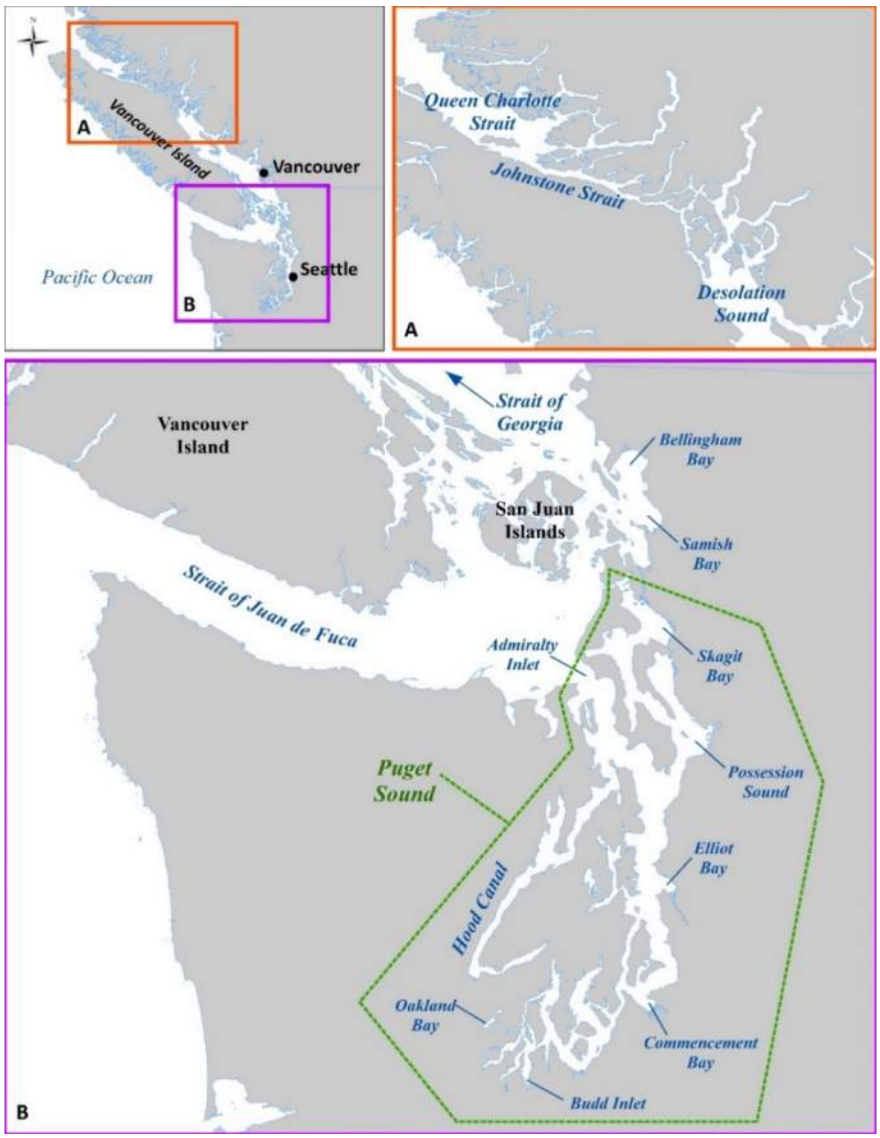


Figure 1. Regions of the Salish Sea (Strait of Juan de Fuca, Strait of Georgia, and Puget Sound), including Johnstone and Queen Charlotte Straits.

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]).

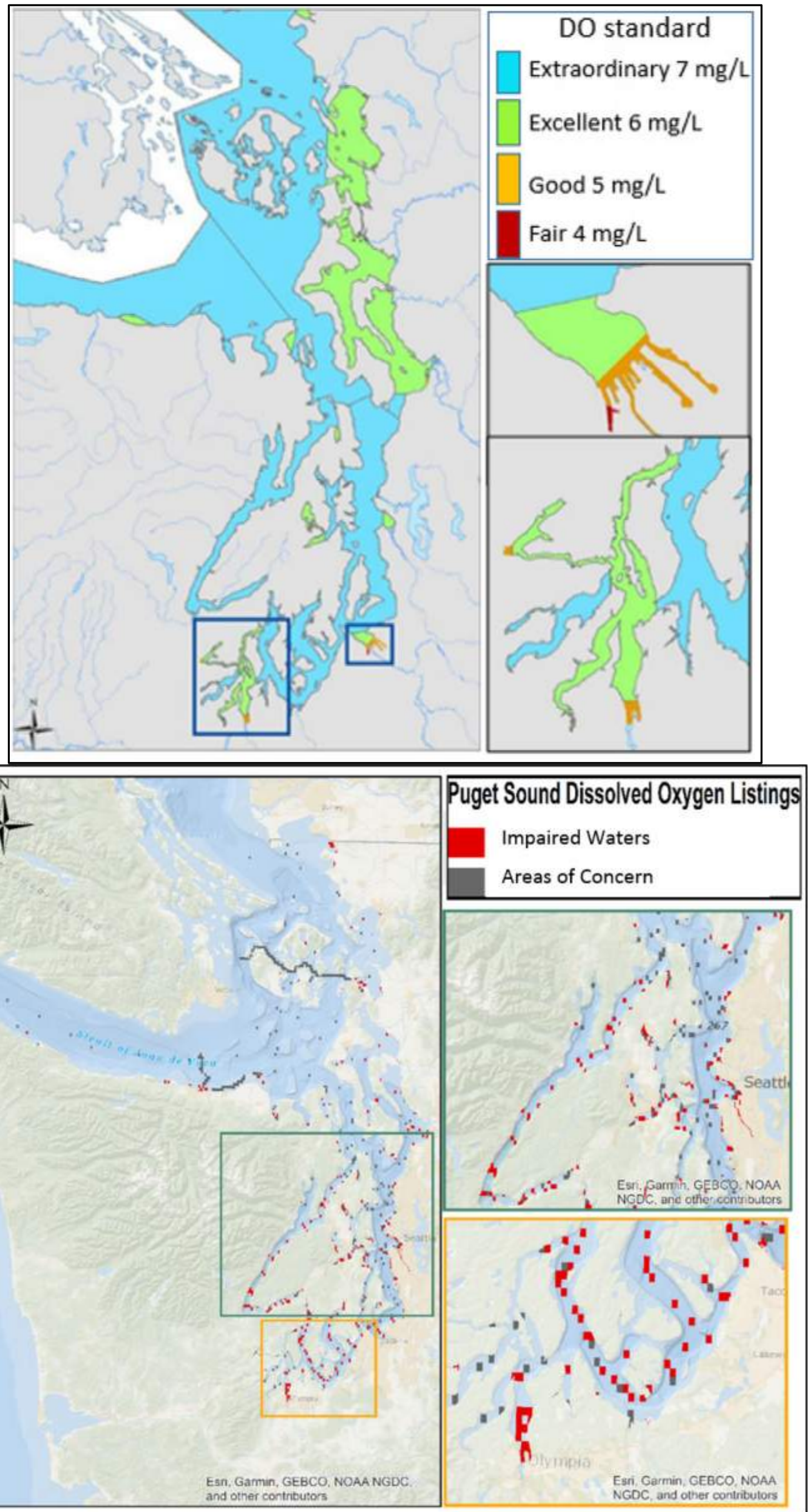


Figure 2. Dissolved oxygen (DO) in Puget Sound.
Above, numeric water quality standards for dissolved oxygen. *Below*, results from Washington's Water Quality Assessment for dissolved oxygen in Puget Sound. Red indicates Category 5 impaired waters, and blue-gray represents Category 2 areas of concern 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

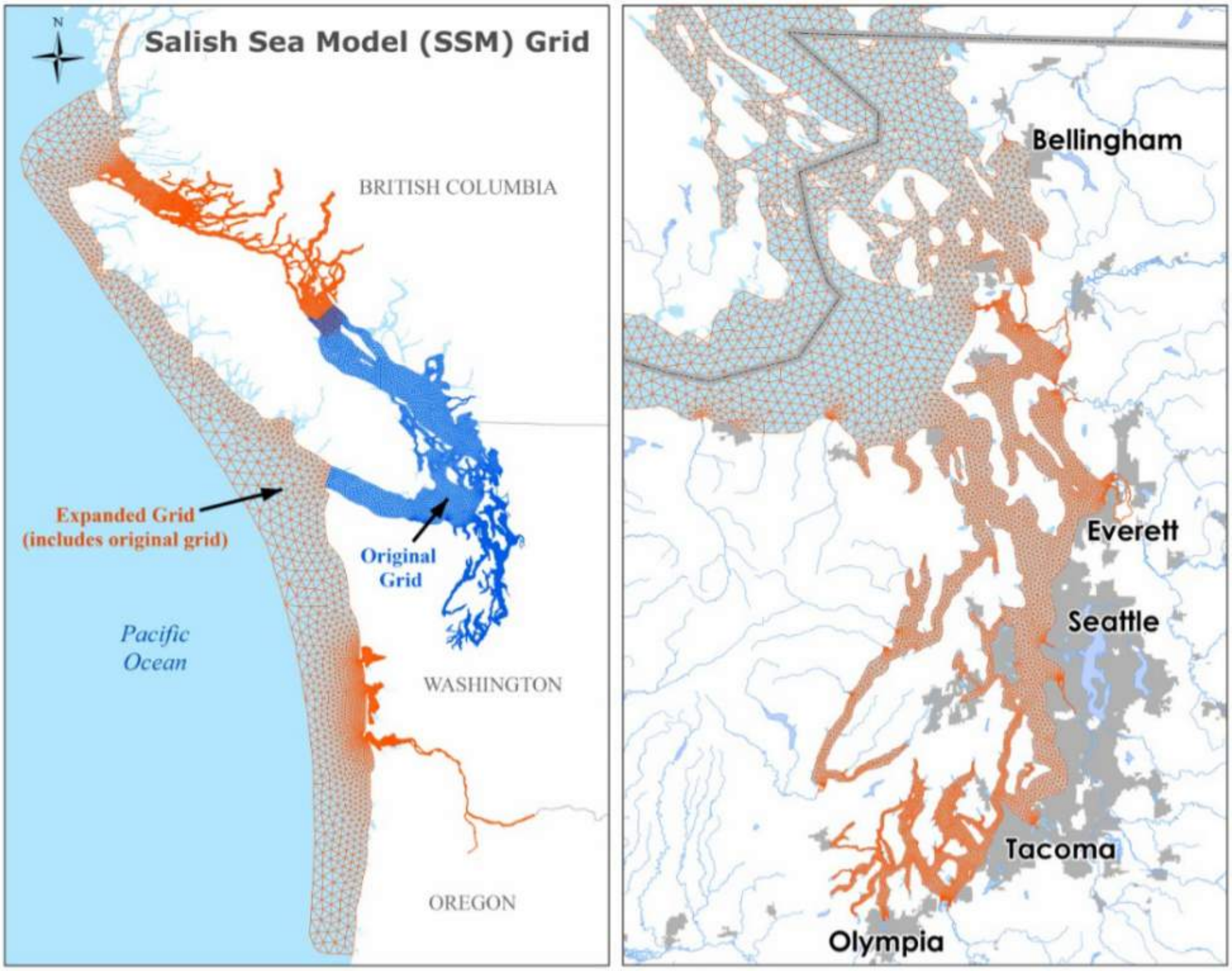


Figure 3. Domain and resolution of both the expanded Salish Sea Model (left) and original Puget Sound Model (right).

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.

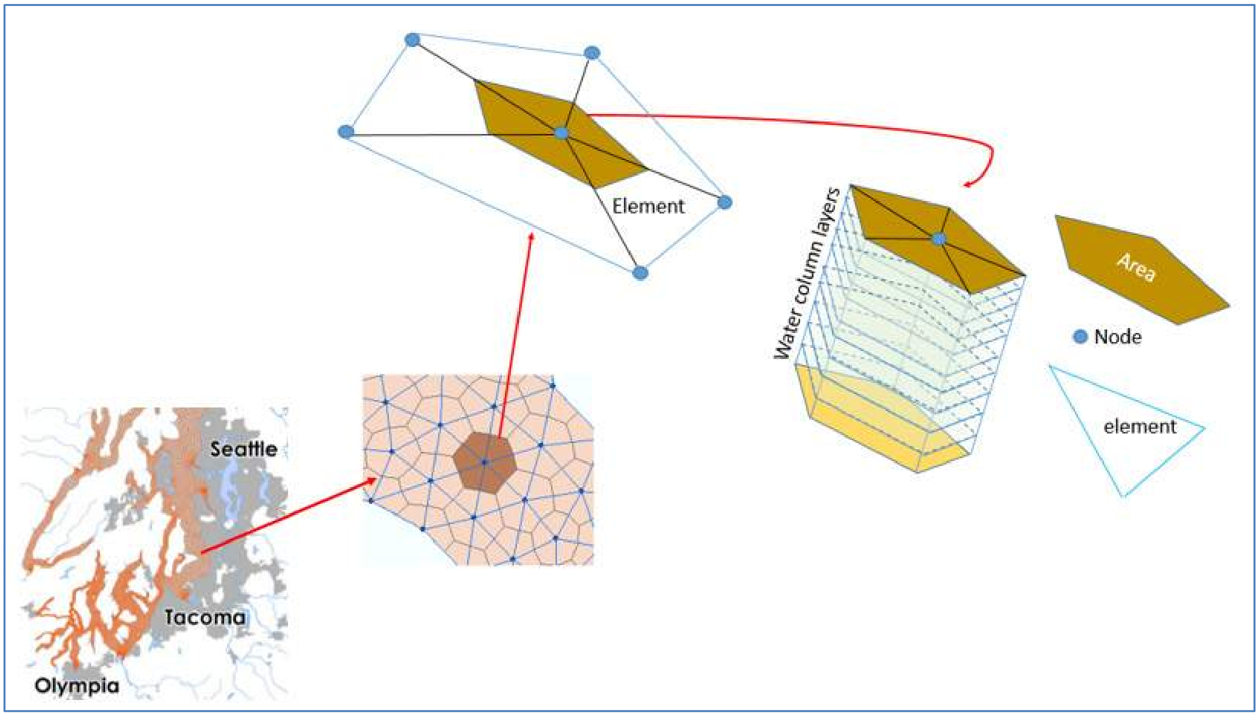


Figure 4. Model nodes, elements, layers, and area of influence of each node.

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.

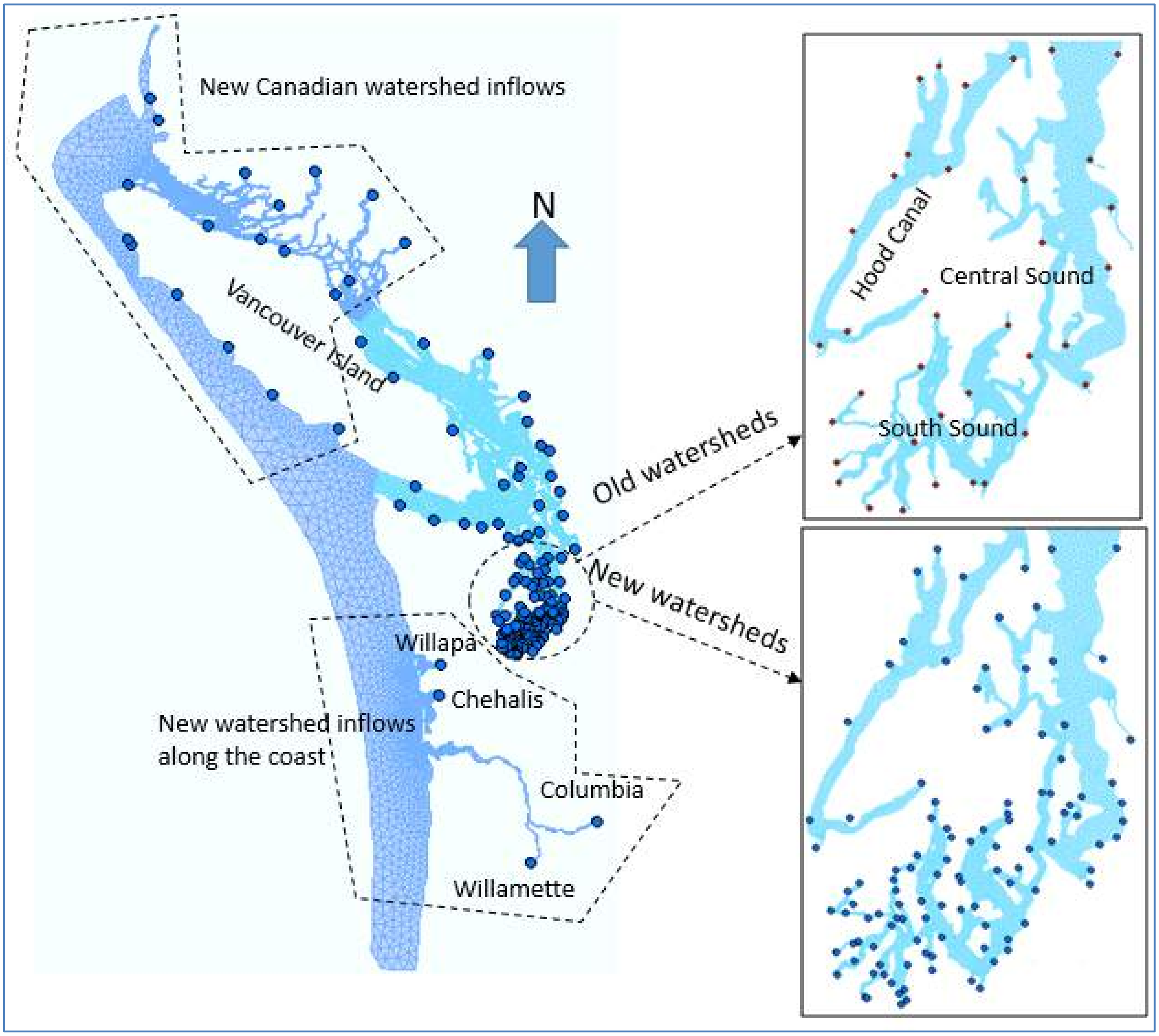


Figure 5. The new Salish Sea Model (SSM), with its refined watershed inflow nodes in South and Central Puget Sound, new Canadian watershed inflow nodes, and new watershed inflows along the Pacific Ocean coastline.

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:

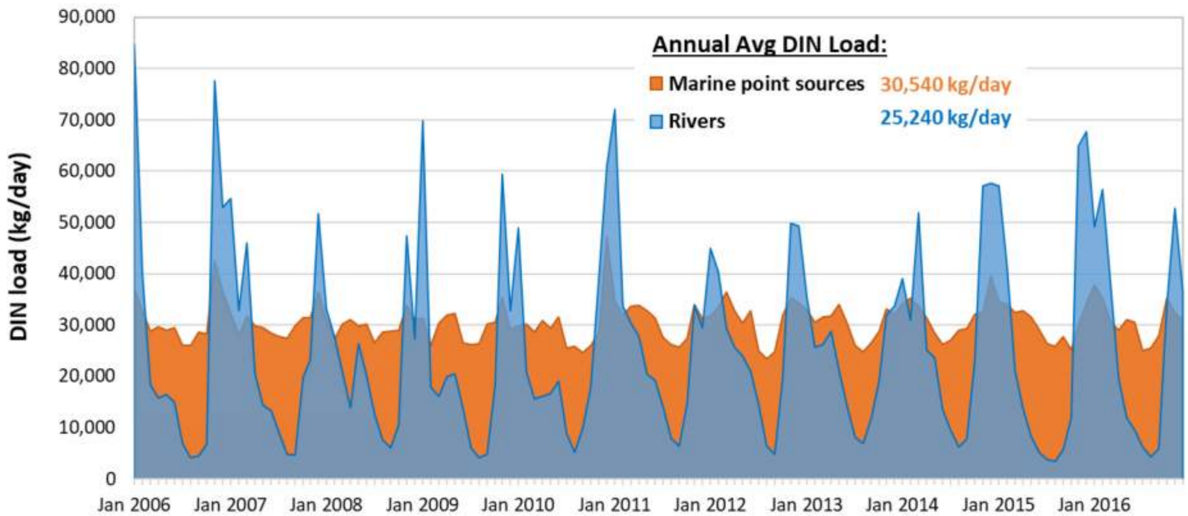
- Marine point sources include all facilities with outfalls in marine waters, such as WWTPs and industrial facilities.
- Watershed sources of nutrients enter the model domain at the point where rivers or streams meet the Salish Sea (i.e., at the mouth or downstream end of each river or stream). Rivers 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.



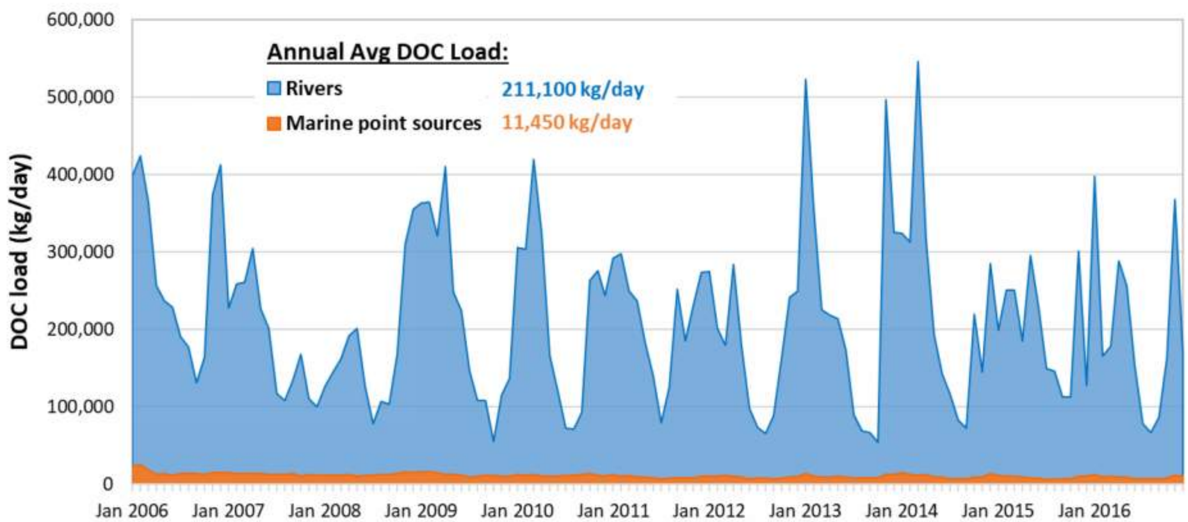


Figure 6. Dissolved inorganic nitrogen (DIN, above) and dissolved organic carbon (DOC, below) loading estimates for Puget Sound land-based sources.

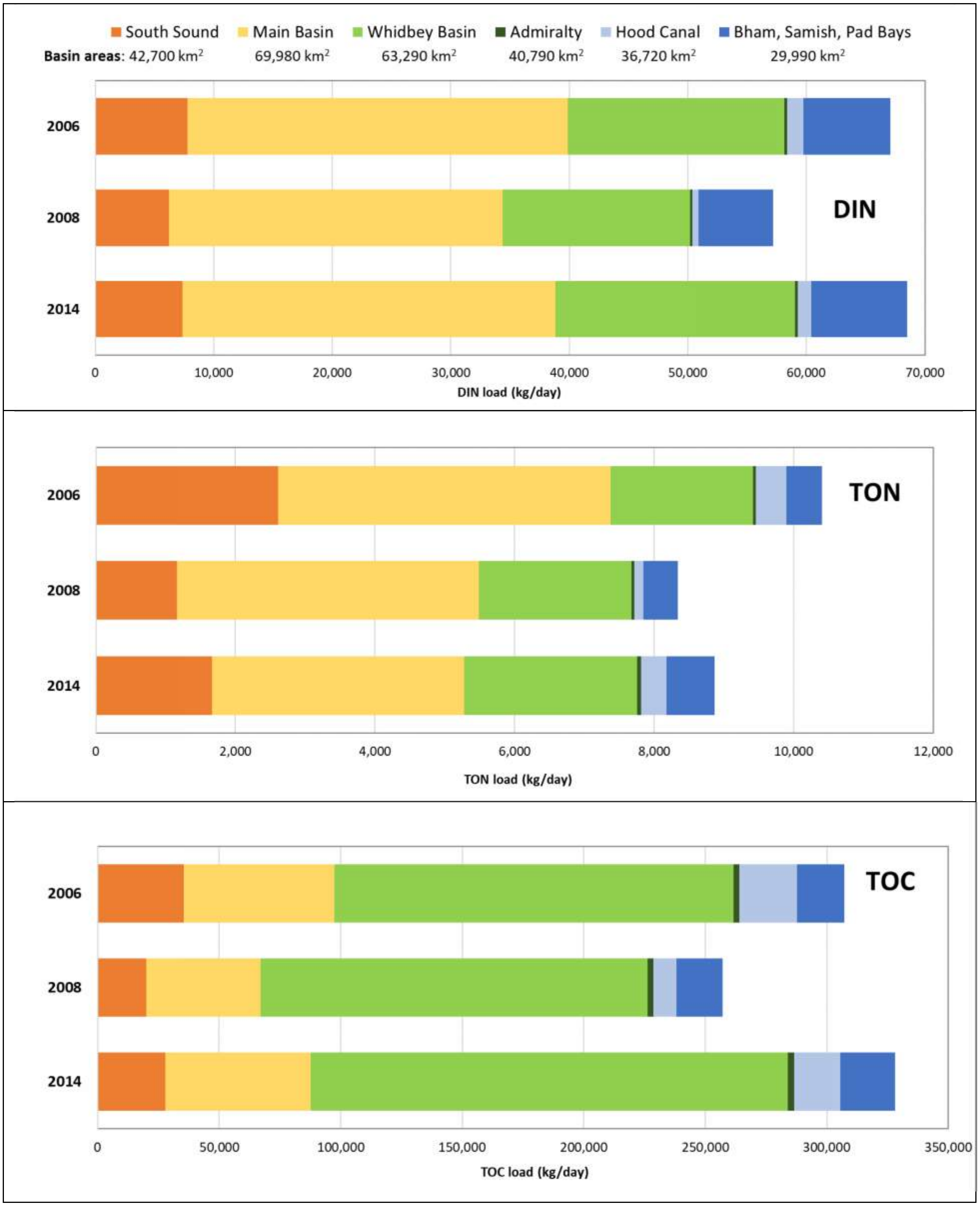


Figure 7. Comparison of dissolved inorganic nitrogen (DIN, above), total organic nitrogen (TON, center), and total organic carbon (TOC, below) loading into different regions of Puget Sound from terrestrial sources (rivers + point sources discharging into marine waters) under 2006, 2008, and 2014 existing 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.

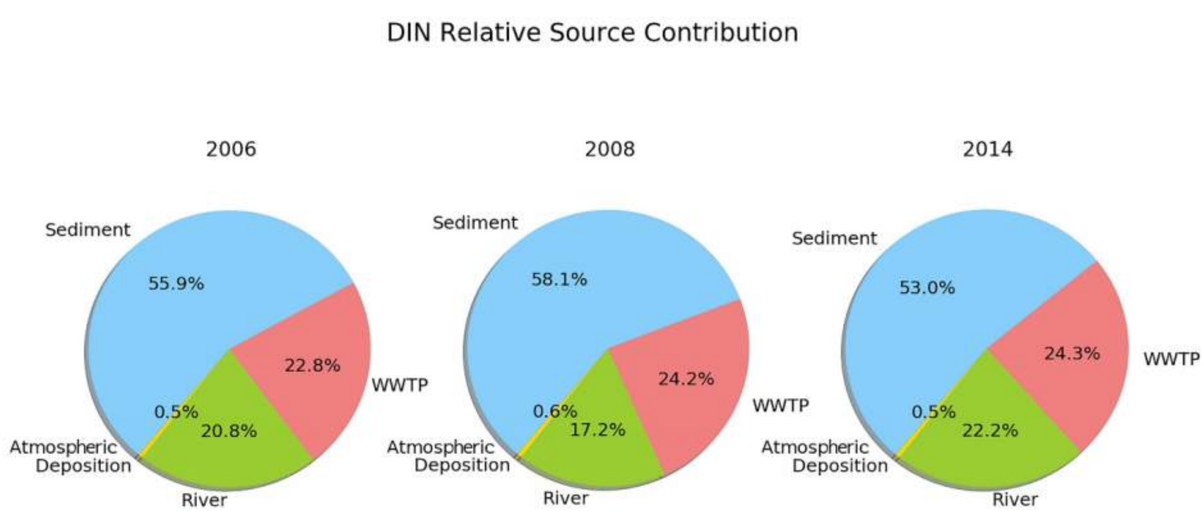


Figure 8. Relative contributions of dissolved inorganic nitrogen (DIN) to Puget Sound from rivers, marine point sources (WWTPs), sediment, and direct atmospheric deposition to marine waters.

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.

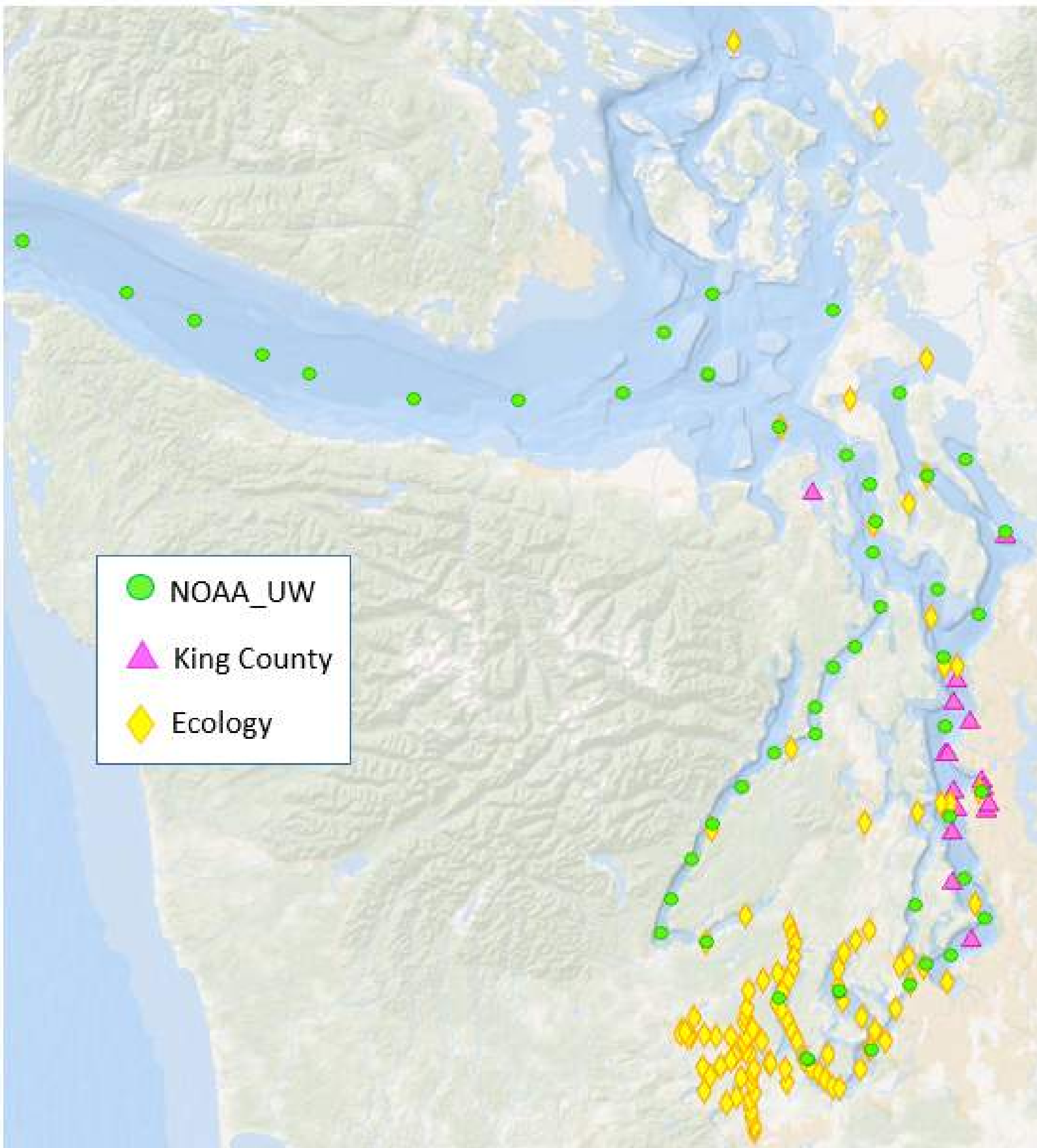


Figure 9. Locations of marine monitoring stations used for water quality calibration checks.

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.

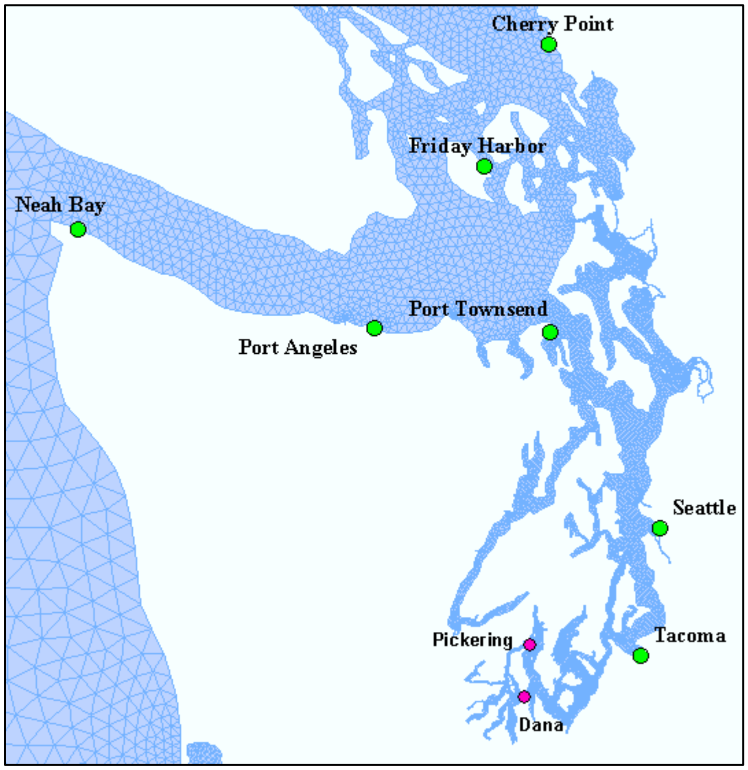


Figure 10. National Oceanic and Atmospheric Administration (NOAA) stations (green dots), where model-predicted water surface elevations were compared with observed data, and Acoustic Doppler Current Profiler (ADCP) stations (red dots), where model-predicted currents were compared with observed data.

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

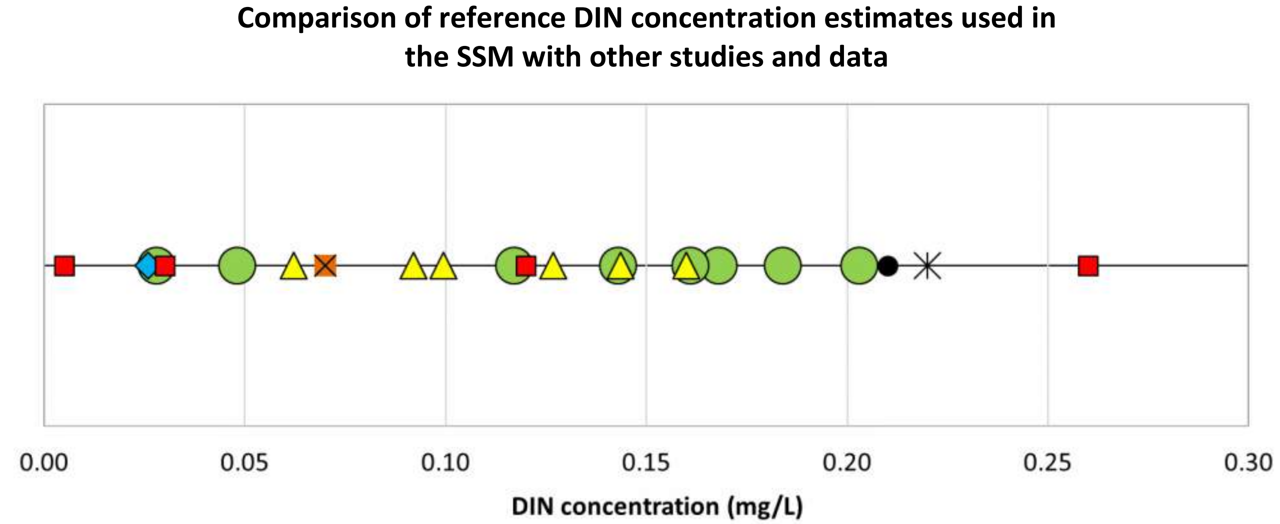
In order to isolate the effect of human sources on marine water quality, we compared the model year existing (hindcast) conditions to a reference condition for the same model year. We created the reference condition scenario by setting watershed inputs and marine source inputs to an estimated natural 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.

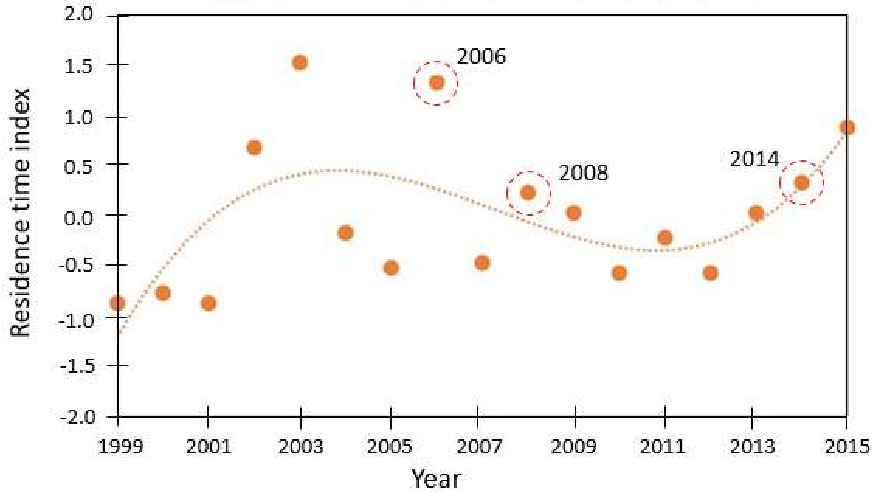


Figure 12. Index of residence time relative to normal in the top 0–30 m in Central Puget Sound, 1999–2015 (PSEMP, 2016).

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.

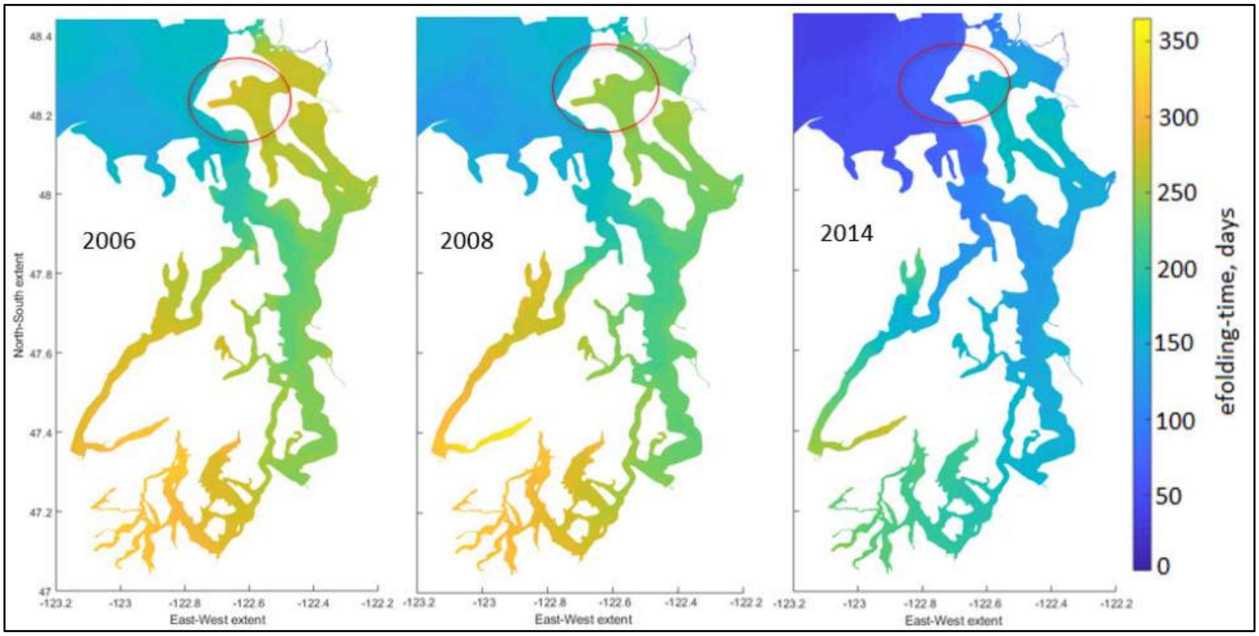


Figure 13. E-folding times (indicative of residence times) in Puget Sound for 2006, 2008, and 2014.

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.

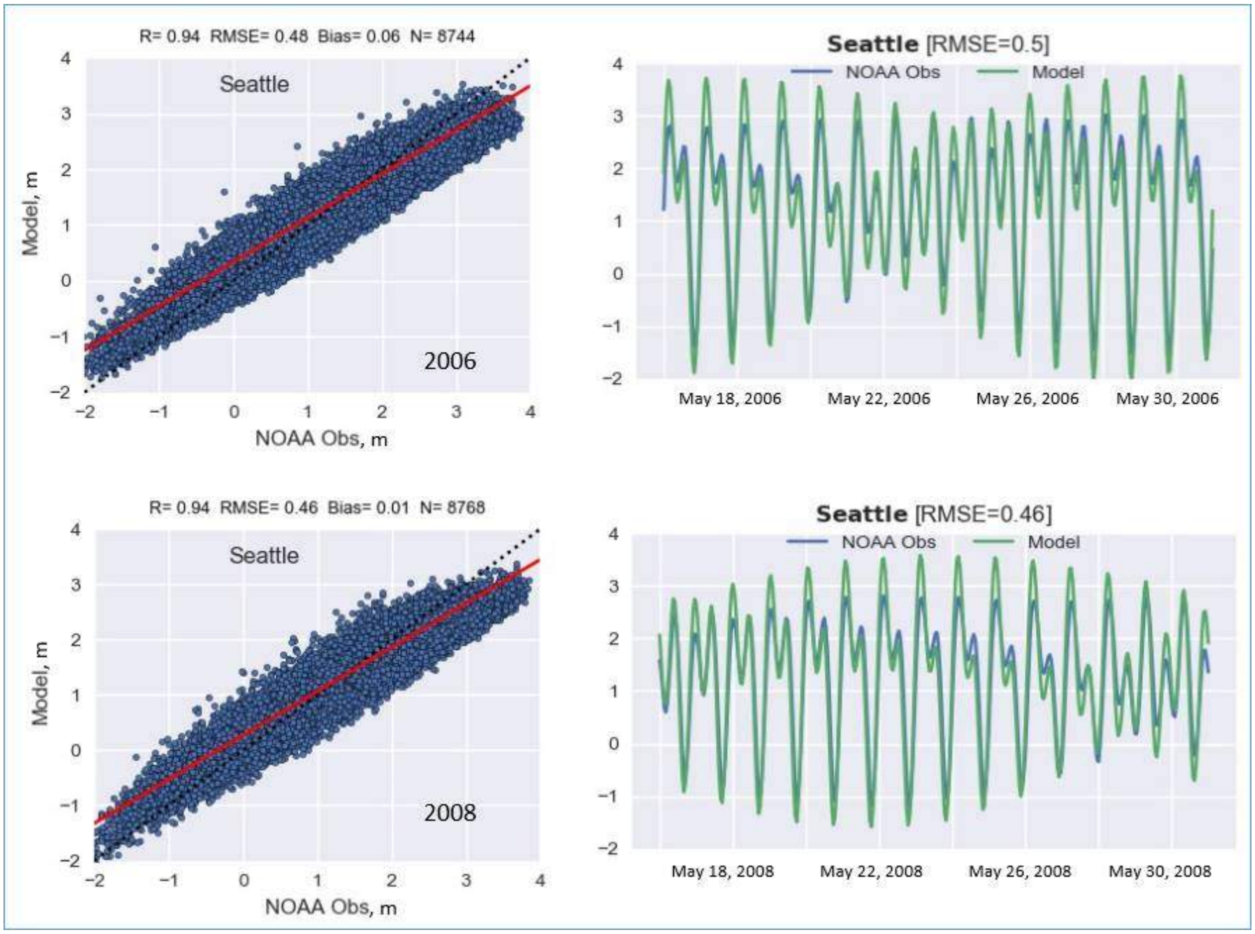


Figure 14. Model predictions and observed data for water surface elevations.
Left panel, typical scatter plots for 2006 (above) and 2008 (below). *Right panel*, time series for the month of May 2006 (above) and May 2008 (below).

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.

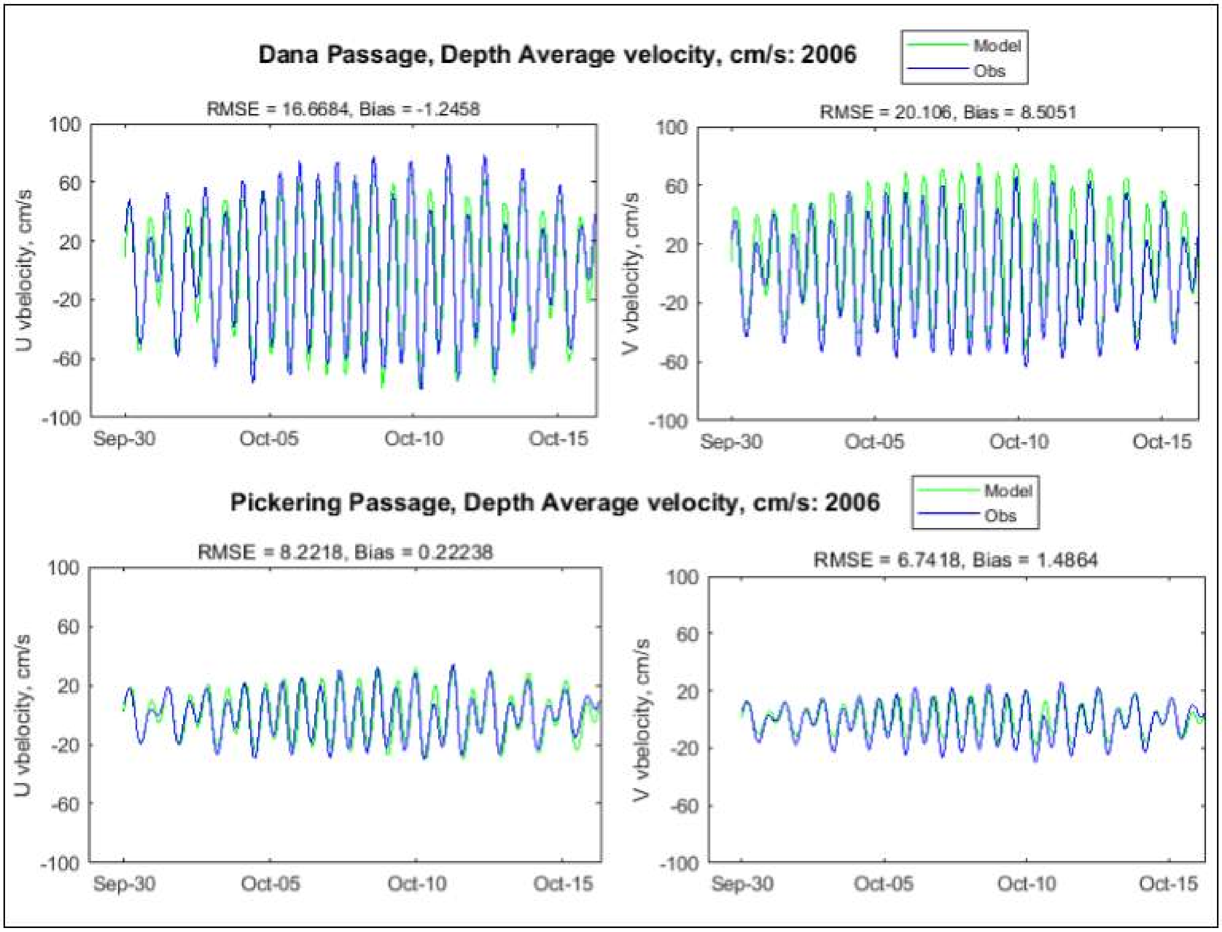


Figure 15. Eastward (left, U velocity) and northward (right, V velocity) depth-averaged current comparison between model prediction and observed data for Dana Passage (above) and Pickering Passage (below).

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.

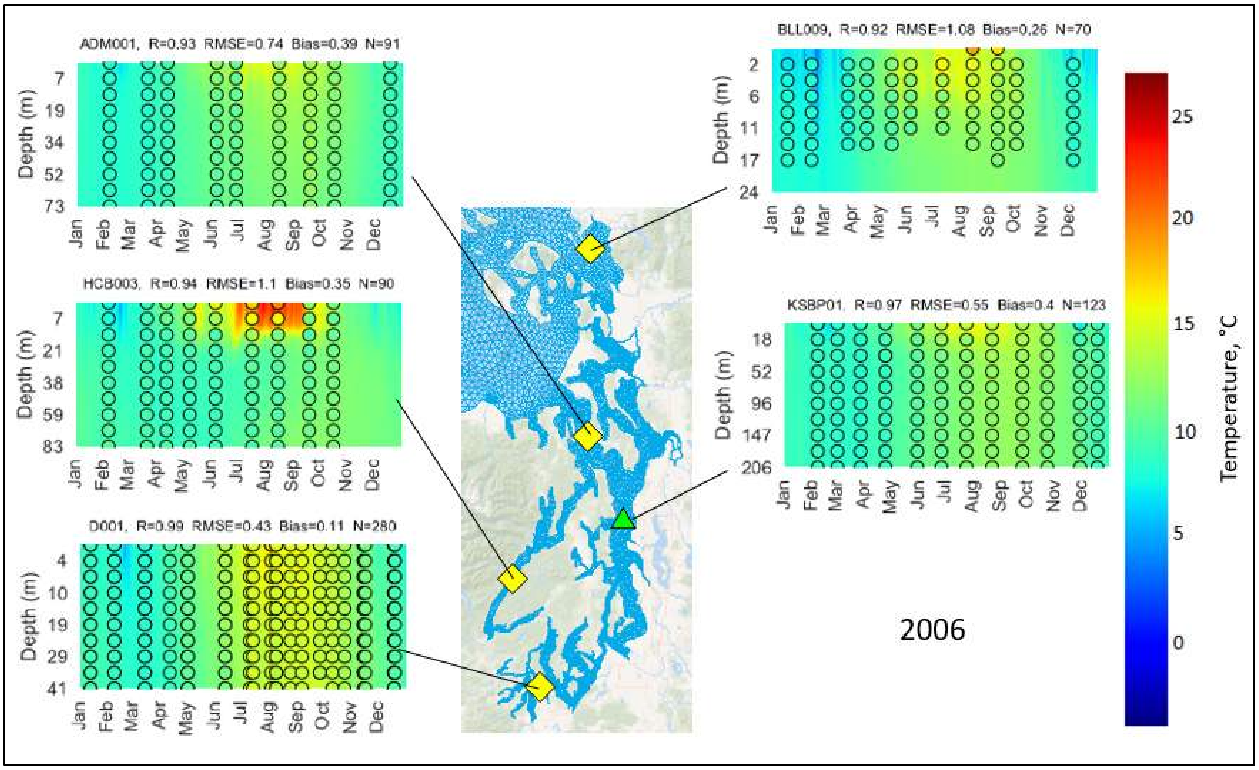


Figure 16. Time-depth plots of observed and predicted temperatures at selected stations for 2006.
The colors inside the circles represent observed measurements taken at a particular depth and time, while the colors in the background represent model-simulated values.

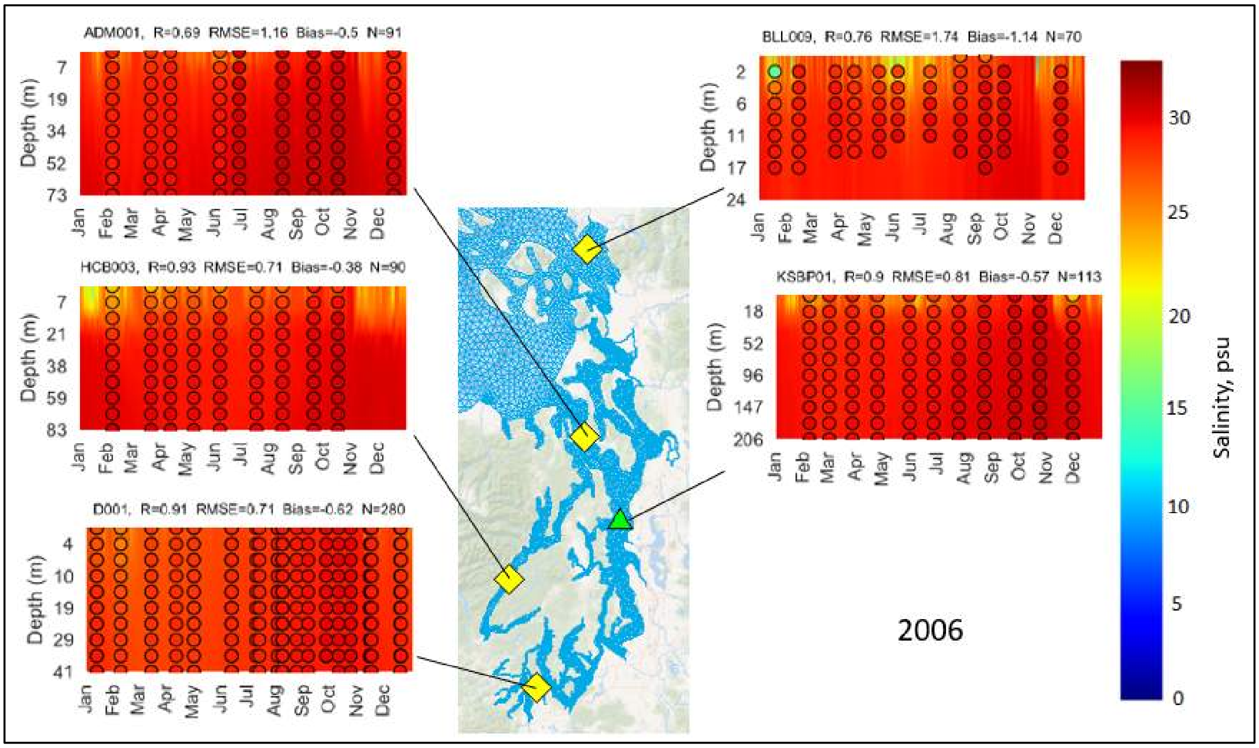


Figure 17. Time-depth plots of observed and predicted salinities at selected stations for 2006.

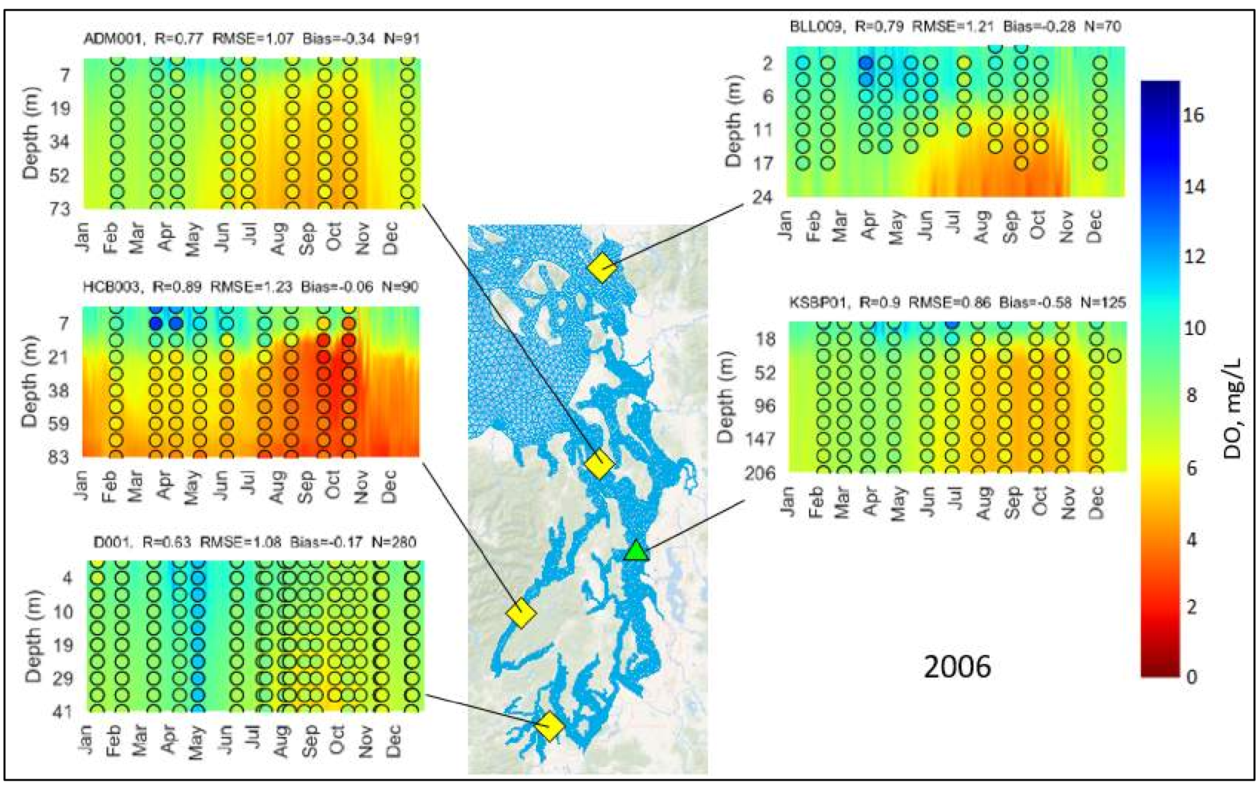


Figure 18. Time-depth plots of observed and predicted dissolved oxygen (DO) at selected stations for 2006.

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.

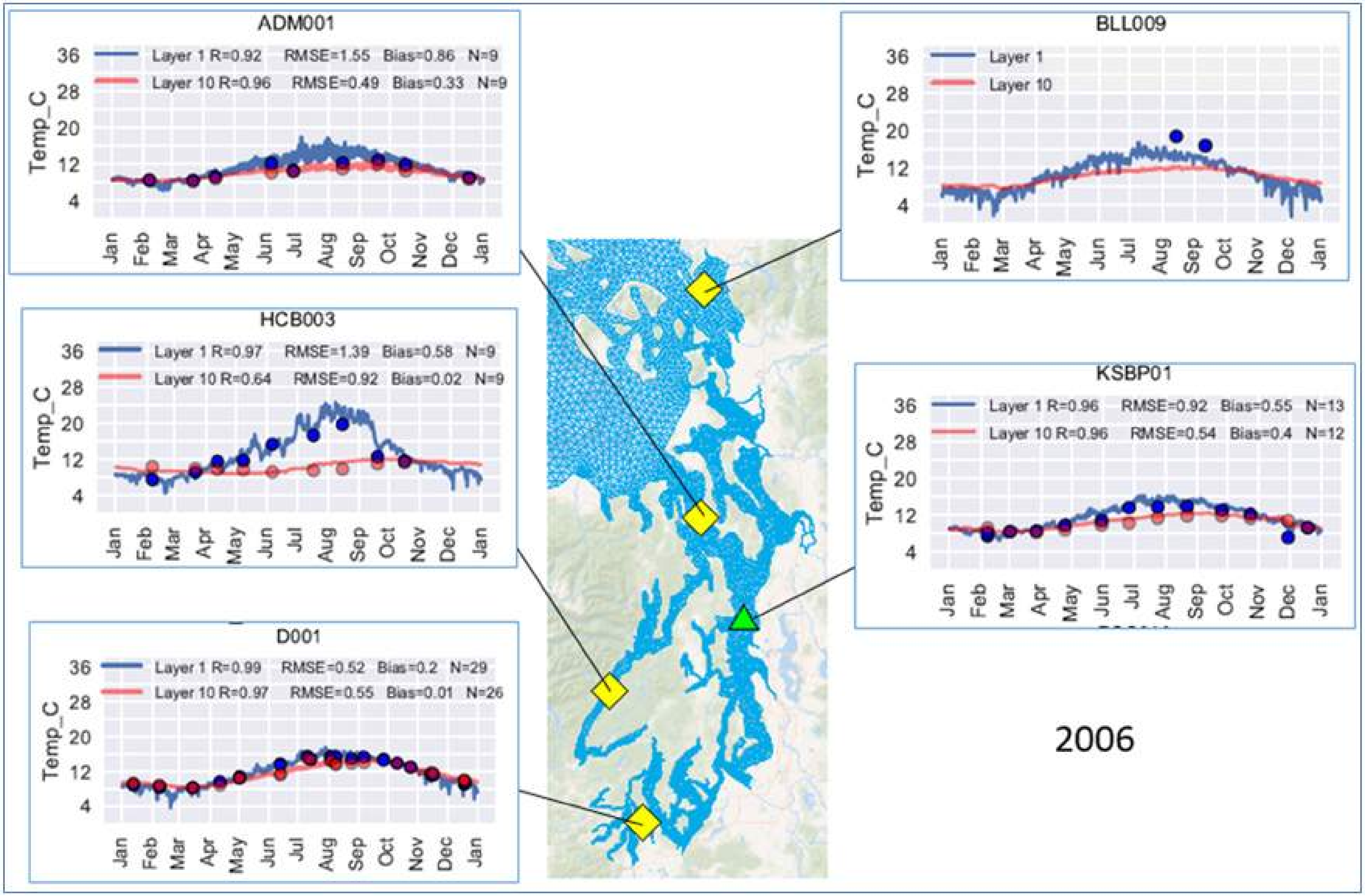


Figure 19. Time series plots for temperature (°C) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

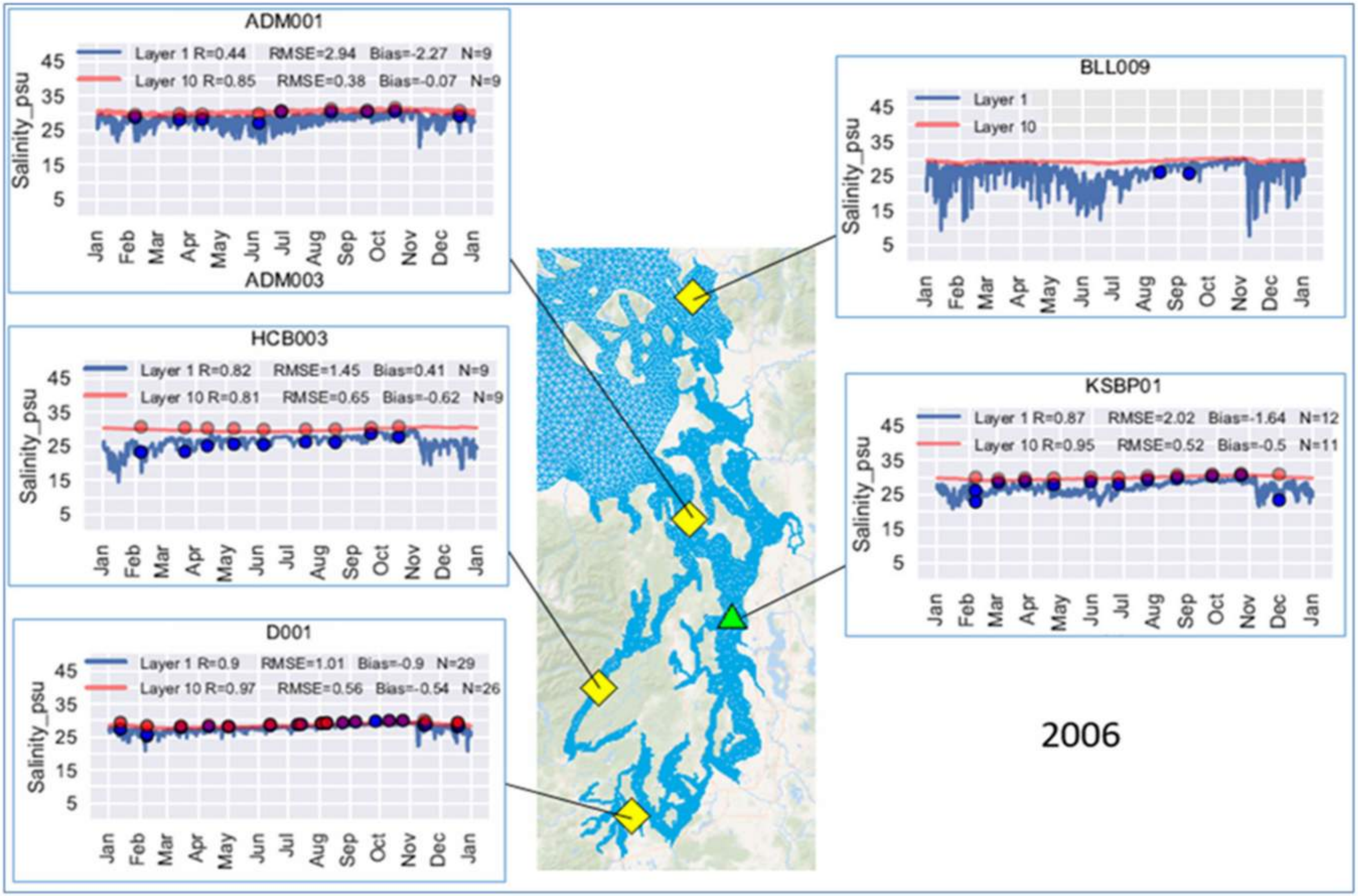


Figure 20. Time series plots for salinity (psu) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

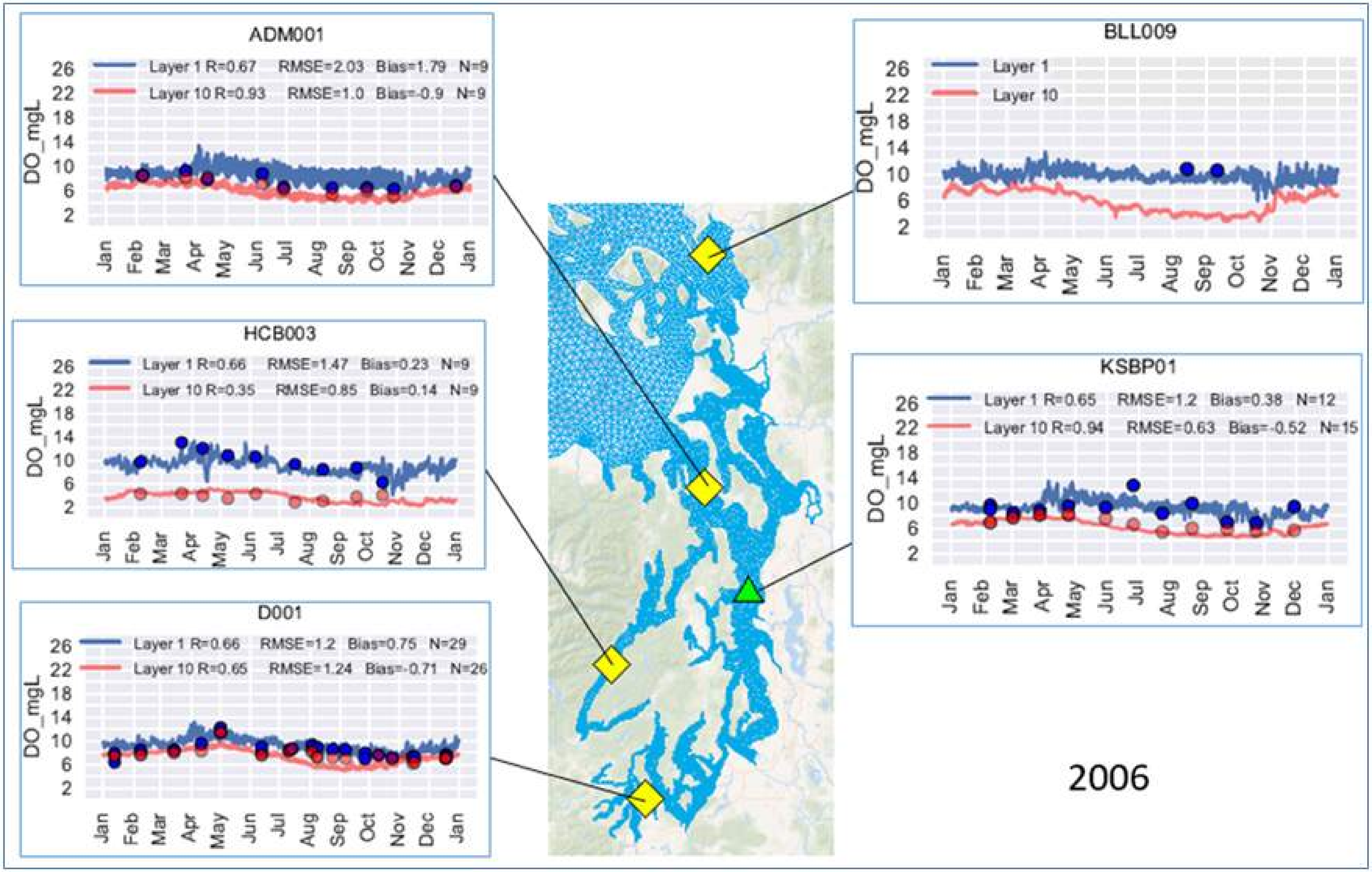


Figure 21. Time series plots for dissolved oxygen (DO, mg/L) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

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.

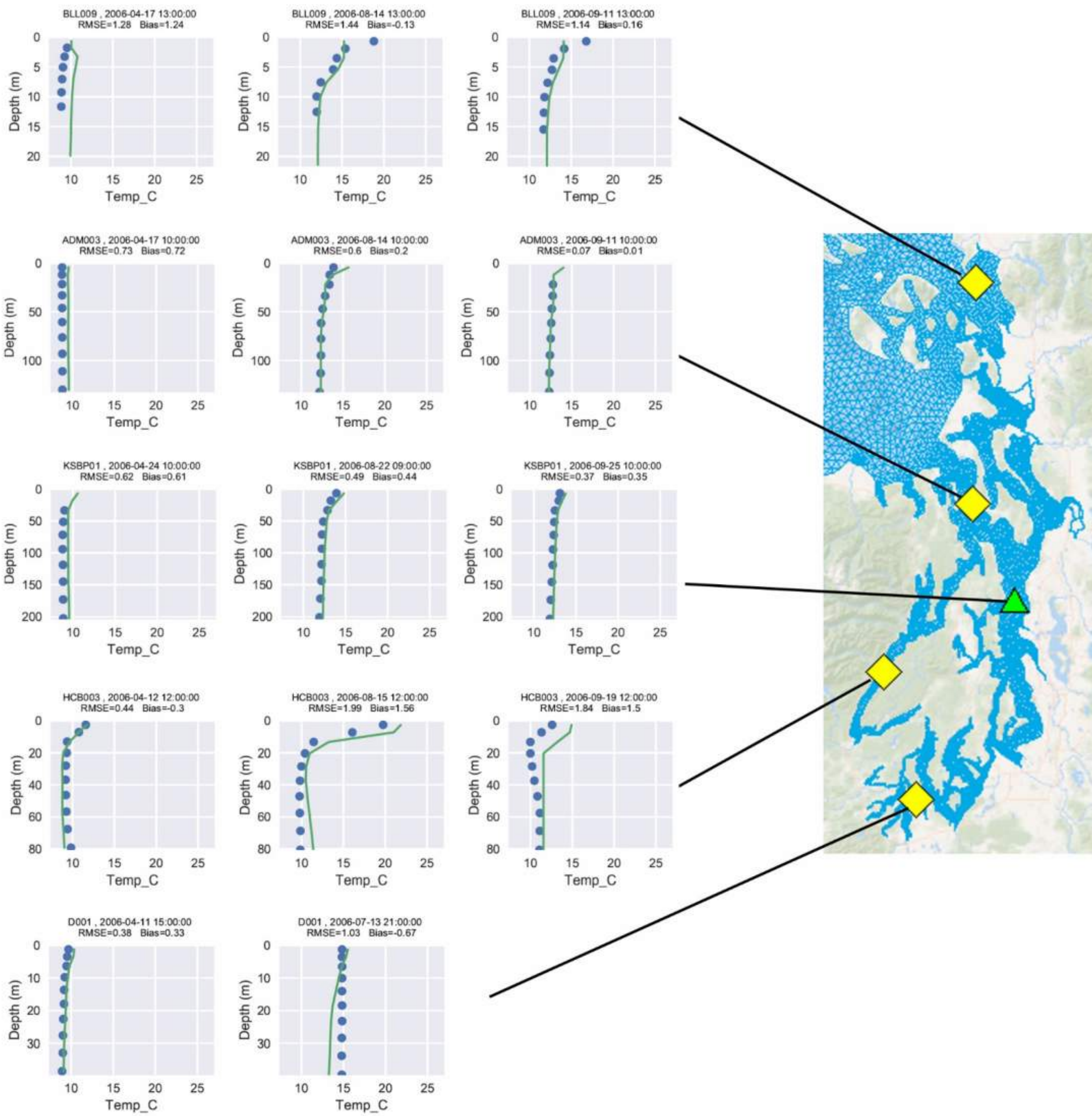


Figure 22. Year 2006 temperature profiles (°C) at selected stations for spring (left column), summer (center column), and fall (right column) conditions.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County Station KSBP01). Fourth row: Hood Canal (Ecology station HCB003). Fifth row: South Puget Sound (Ecology station D001 in Dana Passage).

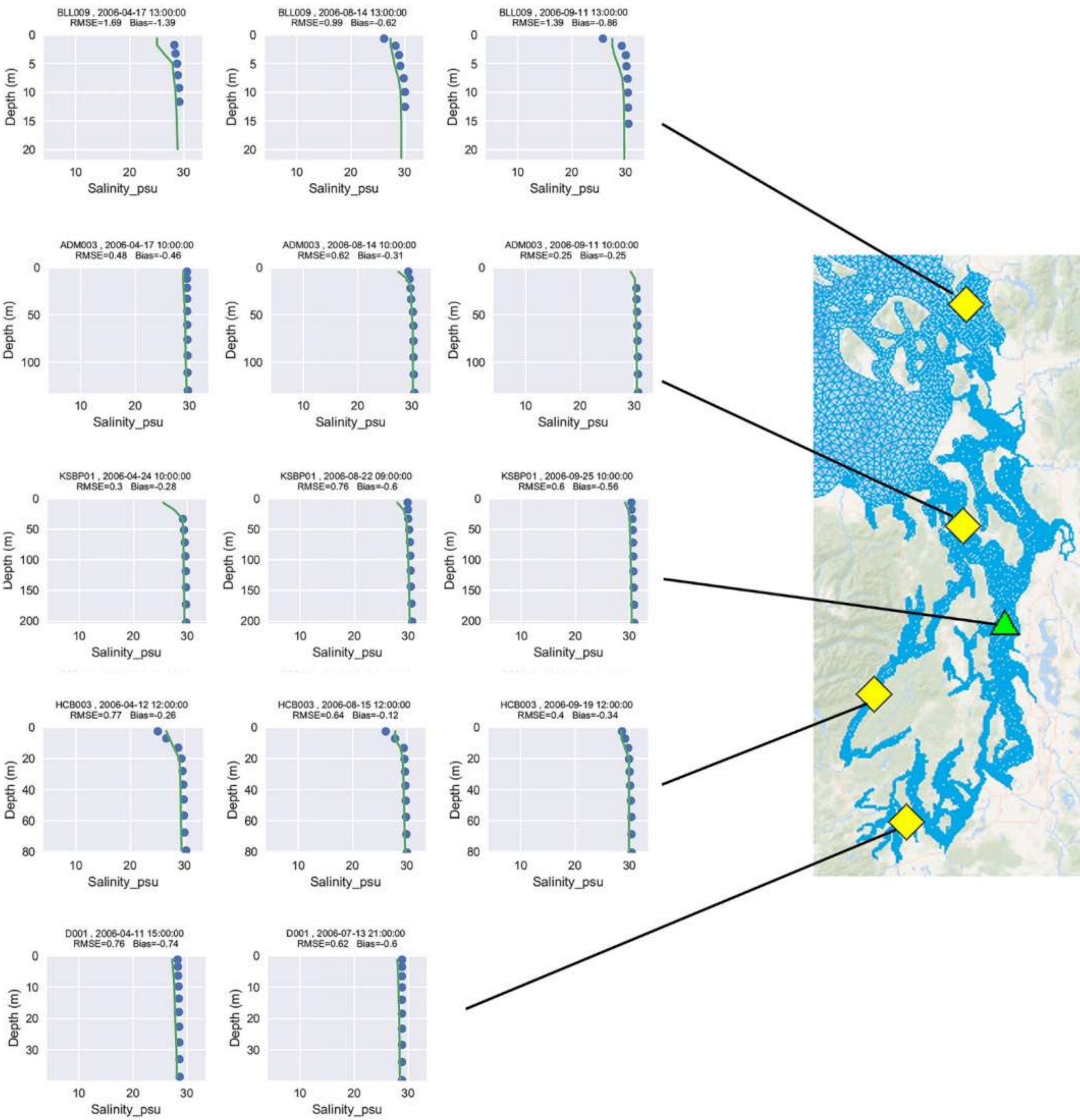


Figure 23. Year 2006 salinity profiles at selected stations for spring (left column), summer (center column), and fall (right column) conditions.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County Station KSBP01). Fourth row: Hood Canal (Ecology station HCB003). Fifth row: South Puget Sound (Ecology station D001 in Dana Passage).

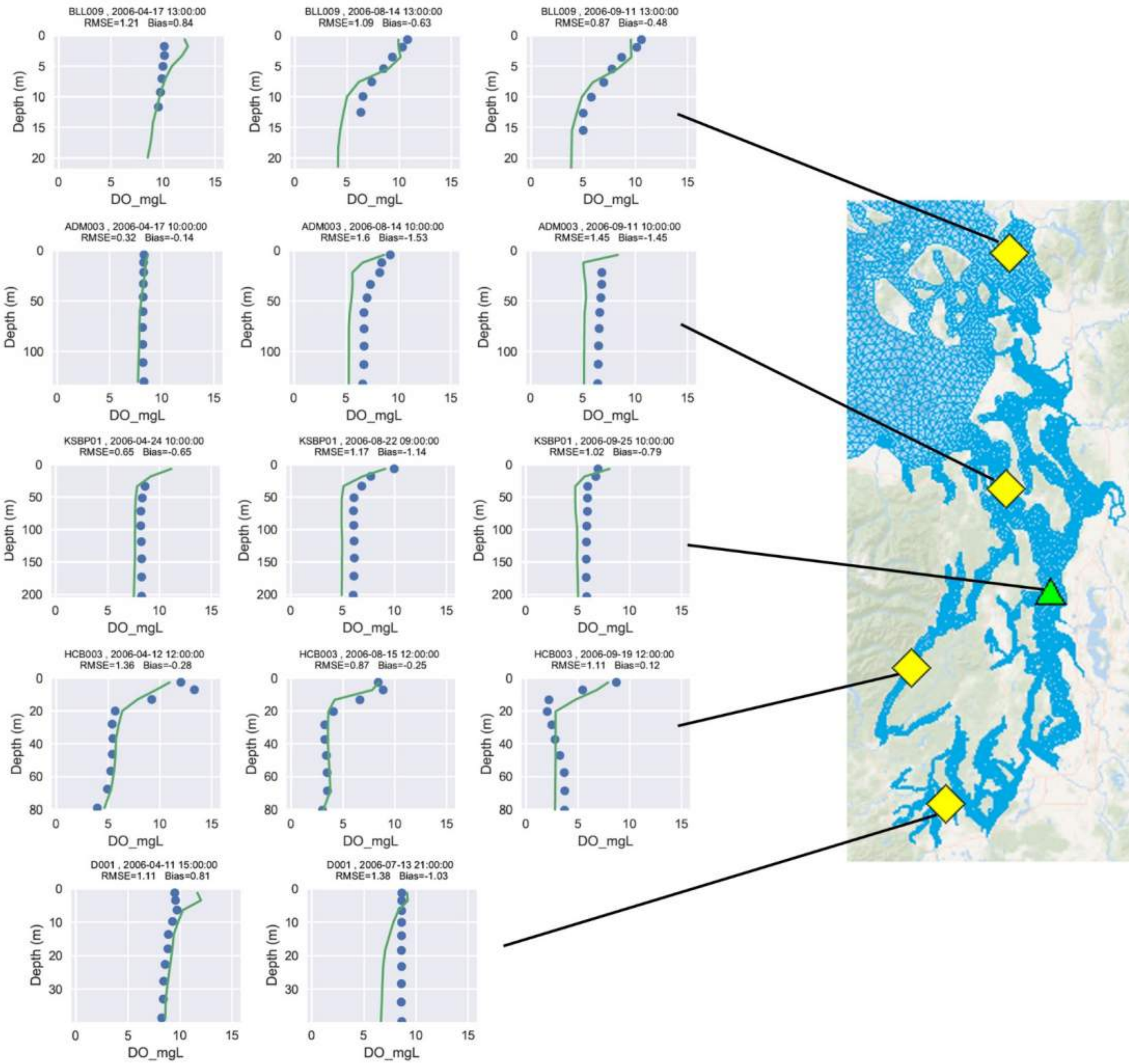


Figure 24. Year 2006 dissolved oxygen (DO, mg/L) profiles at selected stations for spring (left column), summer (center column), and fall (right column) conditions for 2006.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget 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.

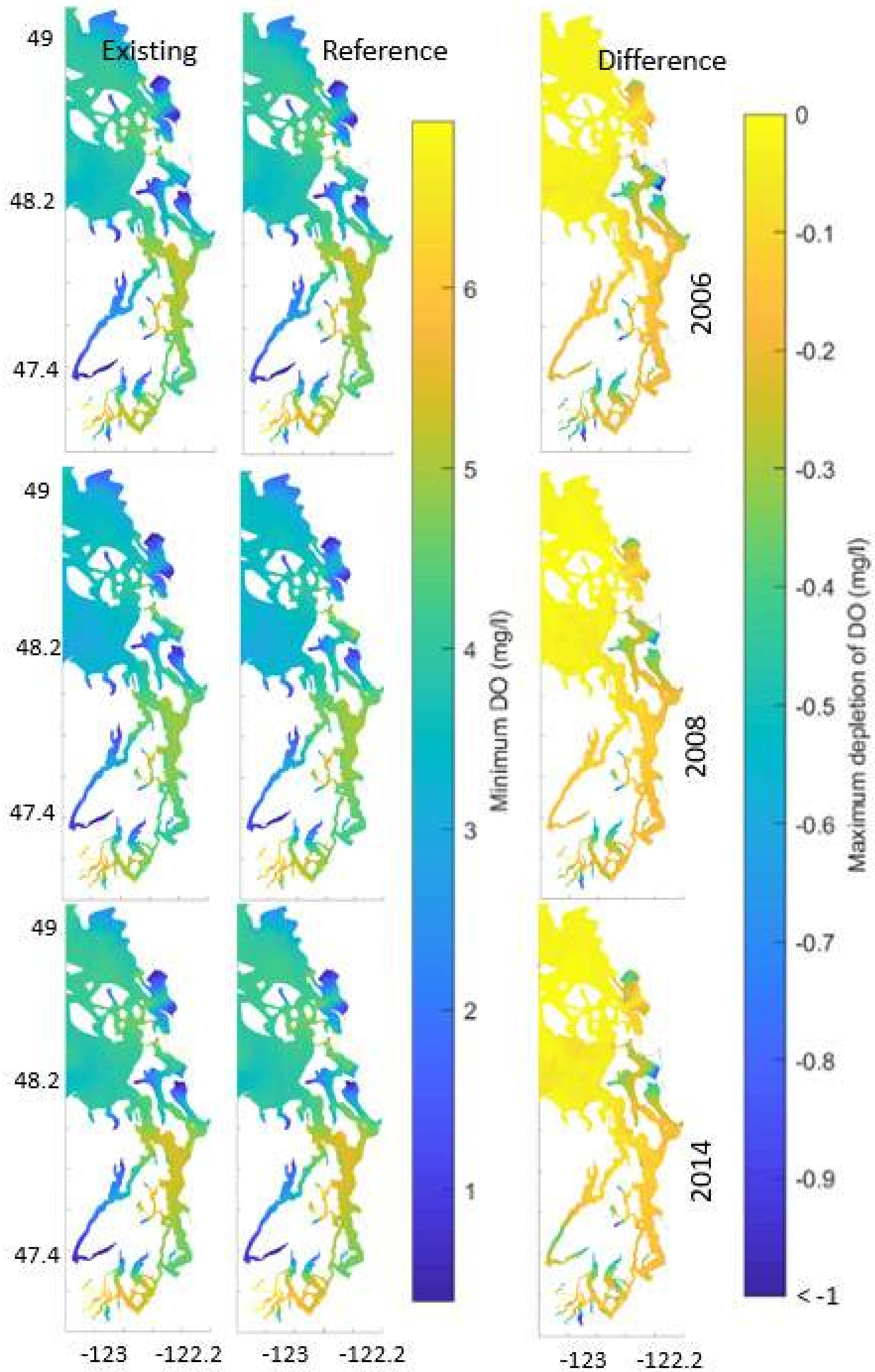


Figure 25. Comparison of the spatial distribution of predicted 2006, 2008, and 2014 minimum dissolved oxygen (DO) concentrations, corresponding reference condition scenarios, and the difference between them.
Areas that are green to blue are most sensitive to DO depletion from all human sources in Washington.

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.

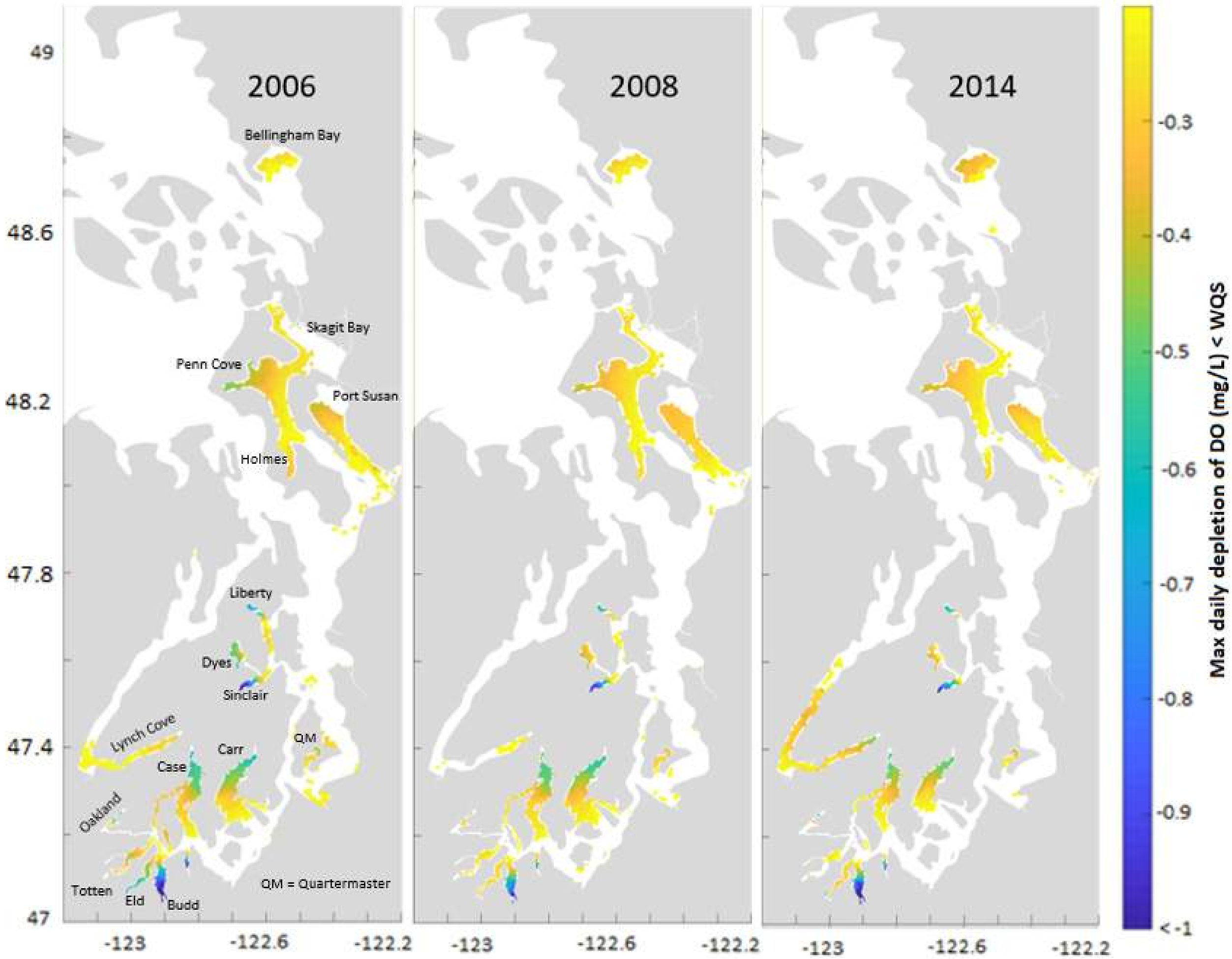


Figure 26. Maximum dissolved oxygen (DO) depletions from anthropogenic sources in 2006, 2008, and 2014, leading to noncompliance with the water quality standards (WQS).

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.

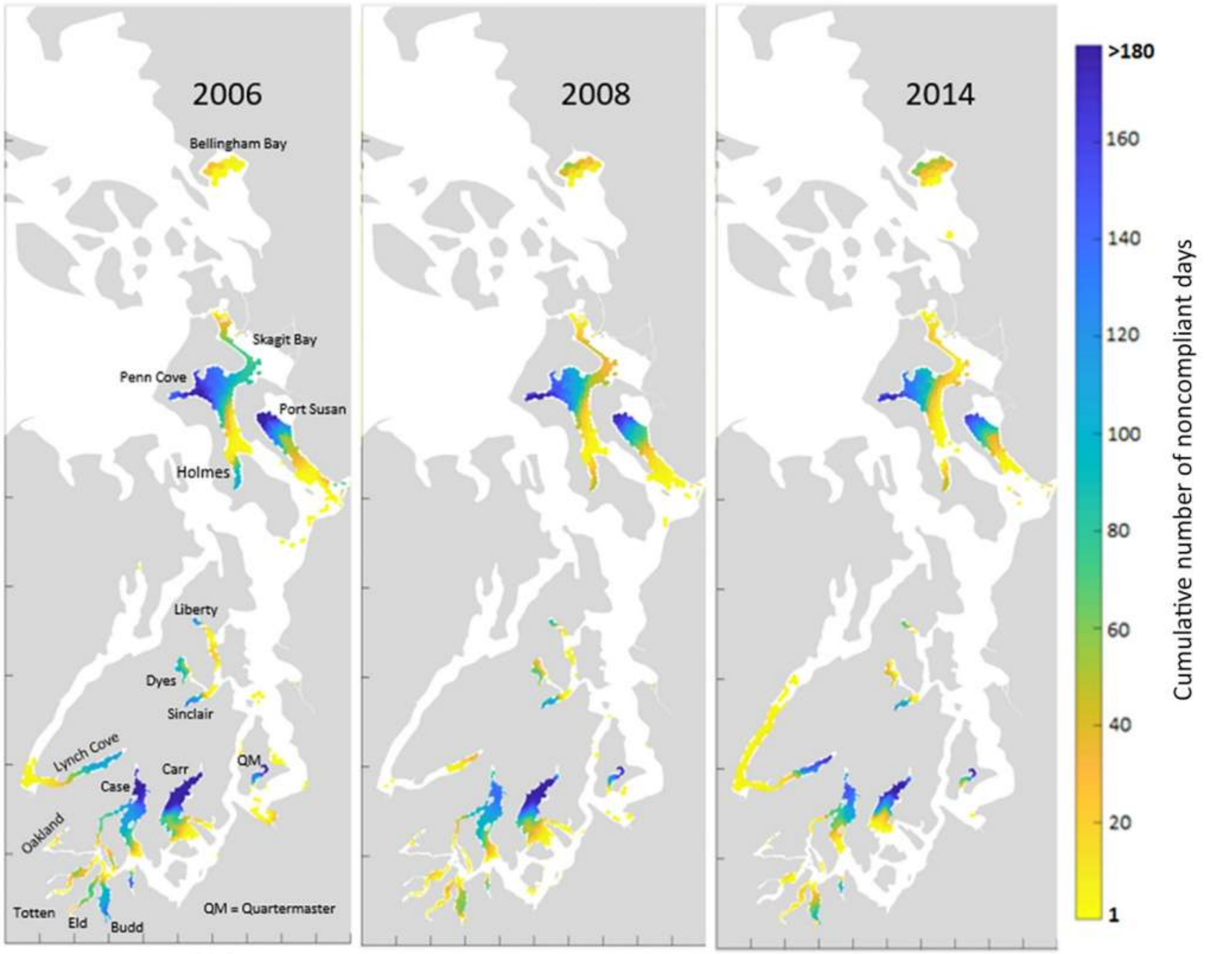


Figure 27. Spatial distribution of cumulative noncompliant days in 2006, 2008, and 2014, showing where depletion of dissolved oxygen (DO) results in noncompliance with water quality standards.

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).

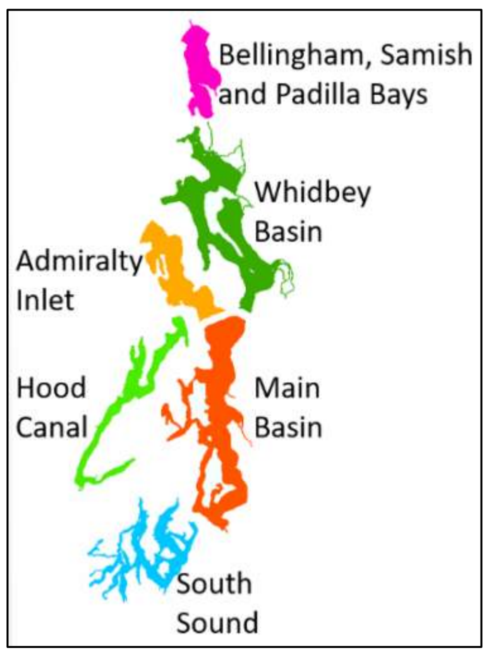


Figure 28. Basins in the greater Puget Sound.

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.

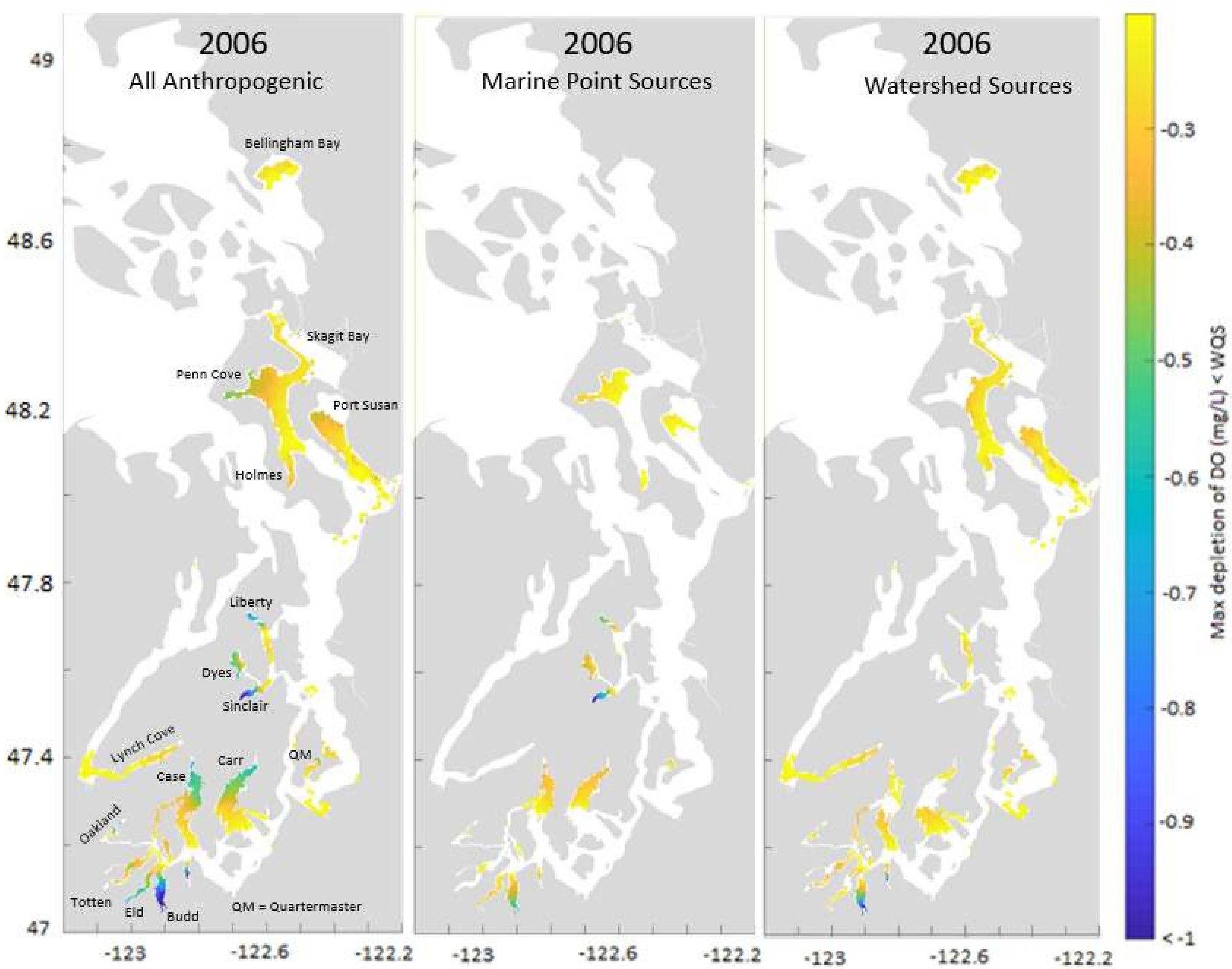


Figure 29. Year 2006 maximum dissolved oxygen (DO) depletions below the water quality standard due to all anthropogenic sources (left), marine point sources (center), and watershed sources (right).

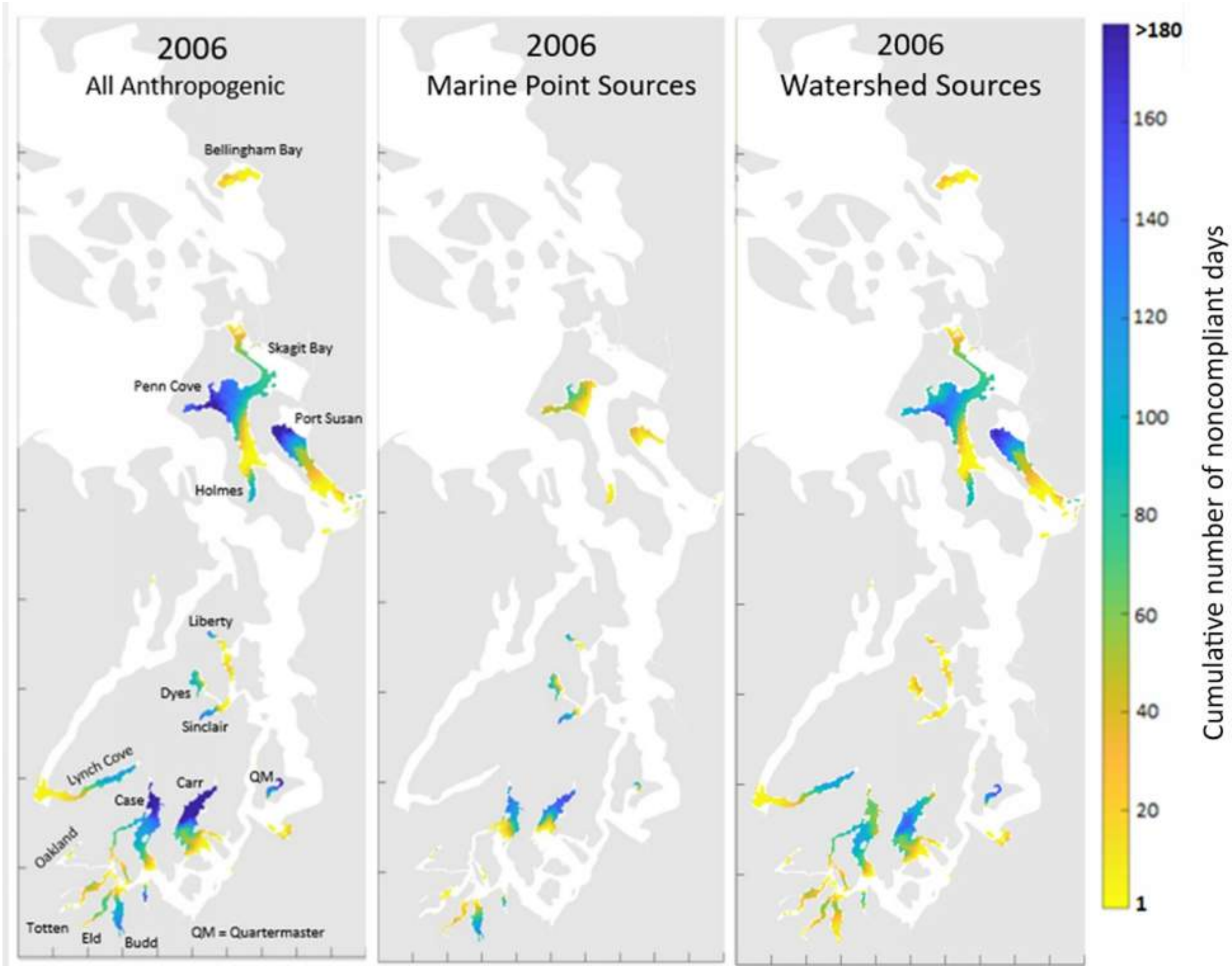


Figure 30. Cumulative number of days in 2006 when dissolved oxygen (DO) did not meet water quality standards due to all anthropogenic sources (left), marine point sources (center), and watershed sources (right).

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.

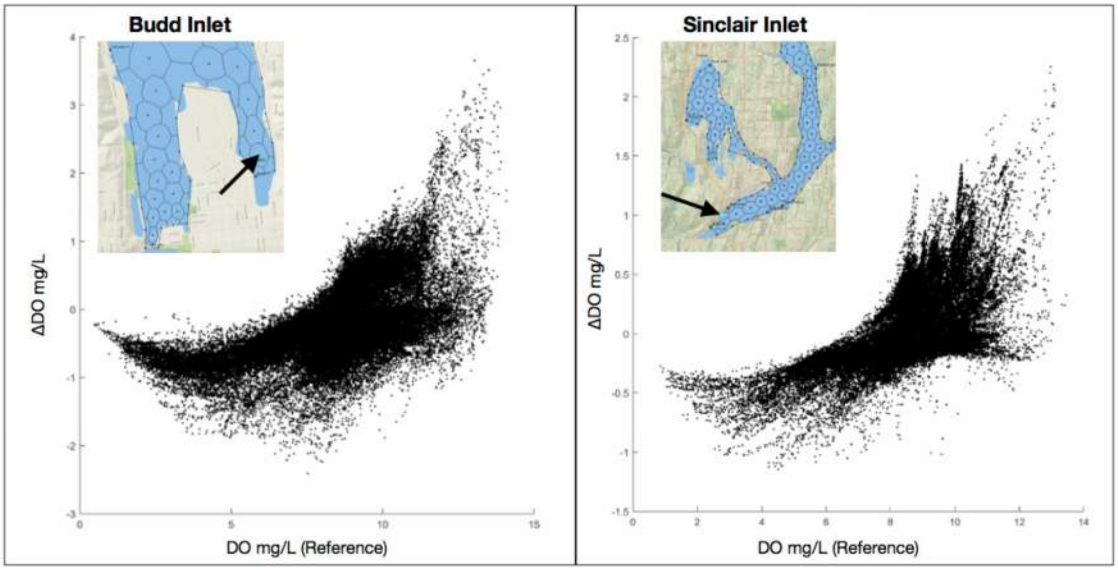


Figure 31. Difference between 2006 existing and reference dissolved oxygen (Δ DO) plotted against the corresponding reference DO concentrations at a model node in Budd Inlet (left) and Sinclair Inlet (right).

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).

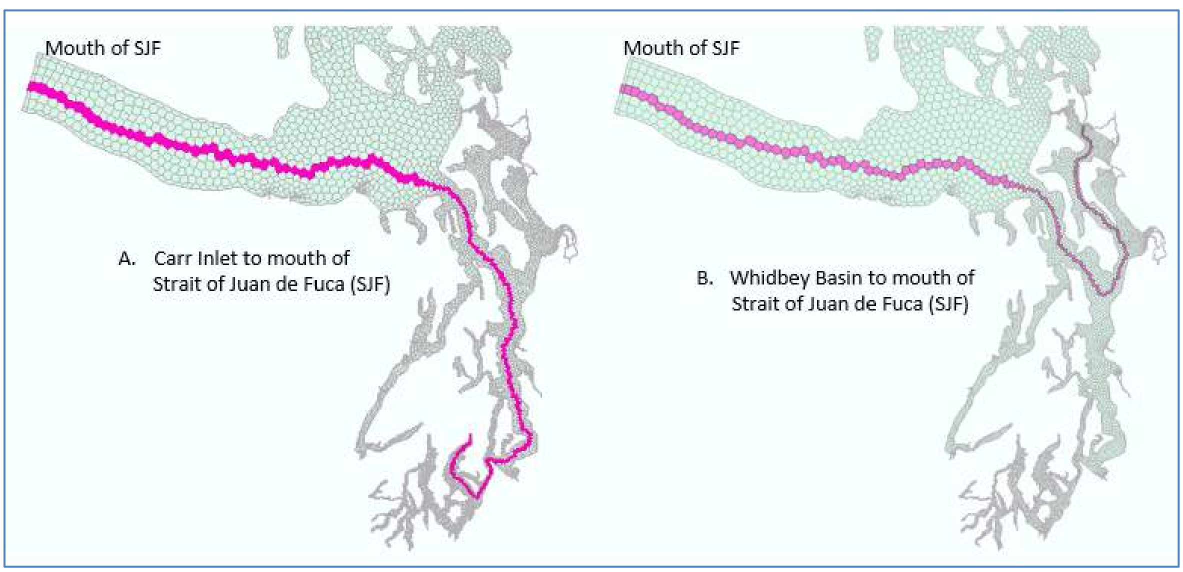


Figure 32. Thalweg transects: (A) mouth of the Strait of Juan de Fuca (SJF) to Carr Inlet, and (B) mouth of the Strait of Juan de Fuca to Whidbey Basin.

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.

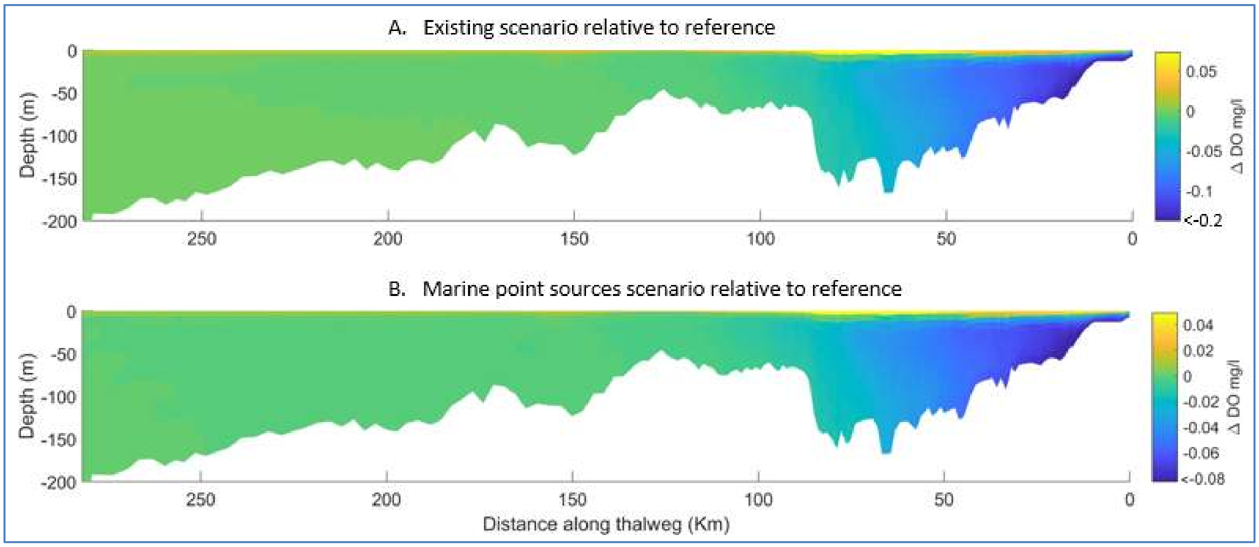


Figure 33. Year 2006 difference in dissolved oxygen (Δ DO, mg/L) between (A) all anthropogenic loading and reference conditions, and (B) marine point source loading and reference conditions computed along a thalweg from the mouth of the Strait of Juan de Fuca (left) to Whidbey Basin (right).

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.

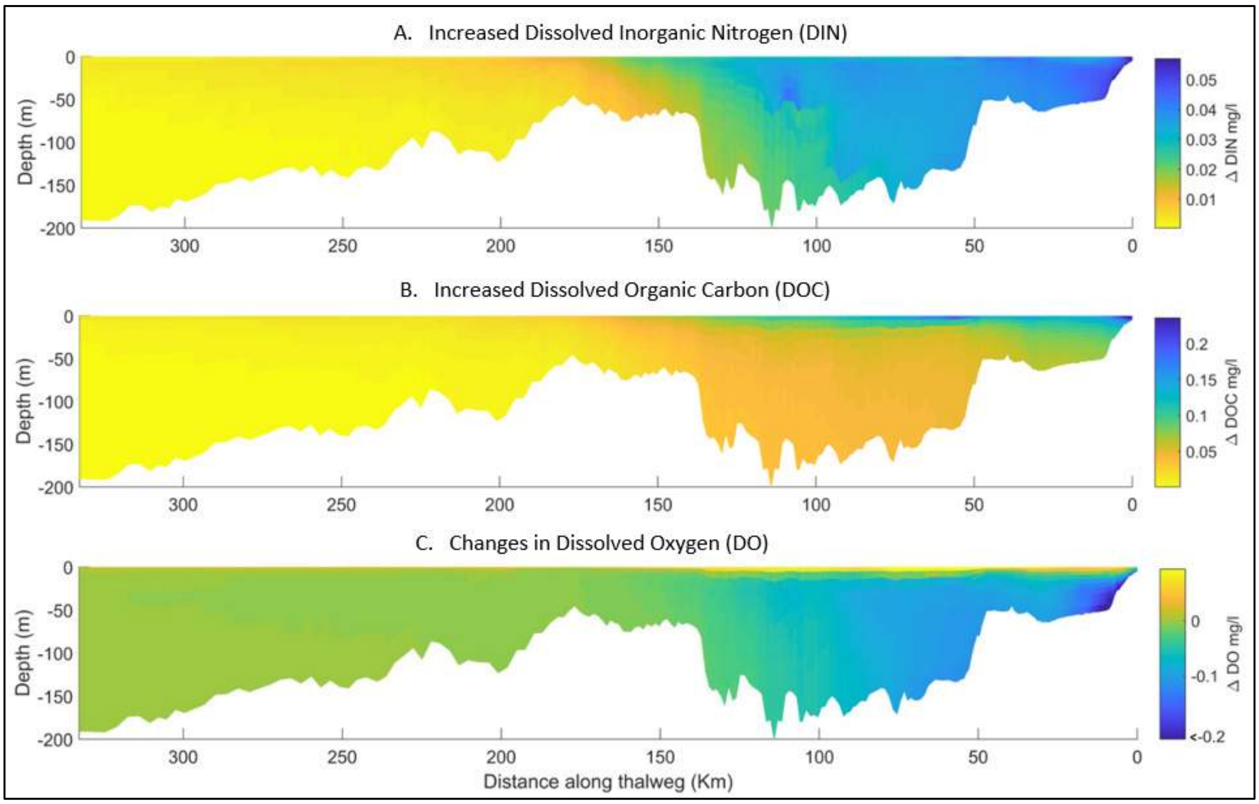


Figure 34. Changes due to anthropogenic loads of dissolved inorganic nitrogen (DIN, above), dissolved organic carbon (DOC, center), and dissolved oxygen (DO, below) along a thalweg from the mouth of Strait of Juan de Fuca (left) to Carr Inlet (right). .

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.

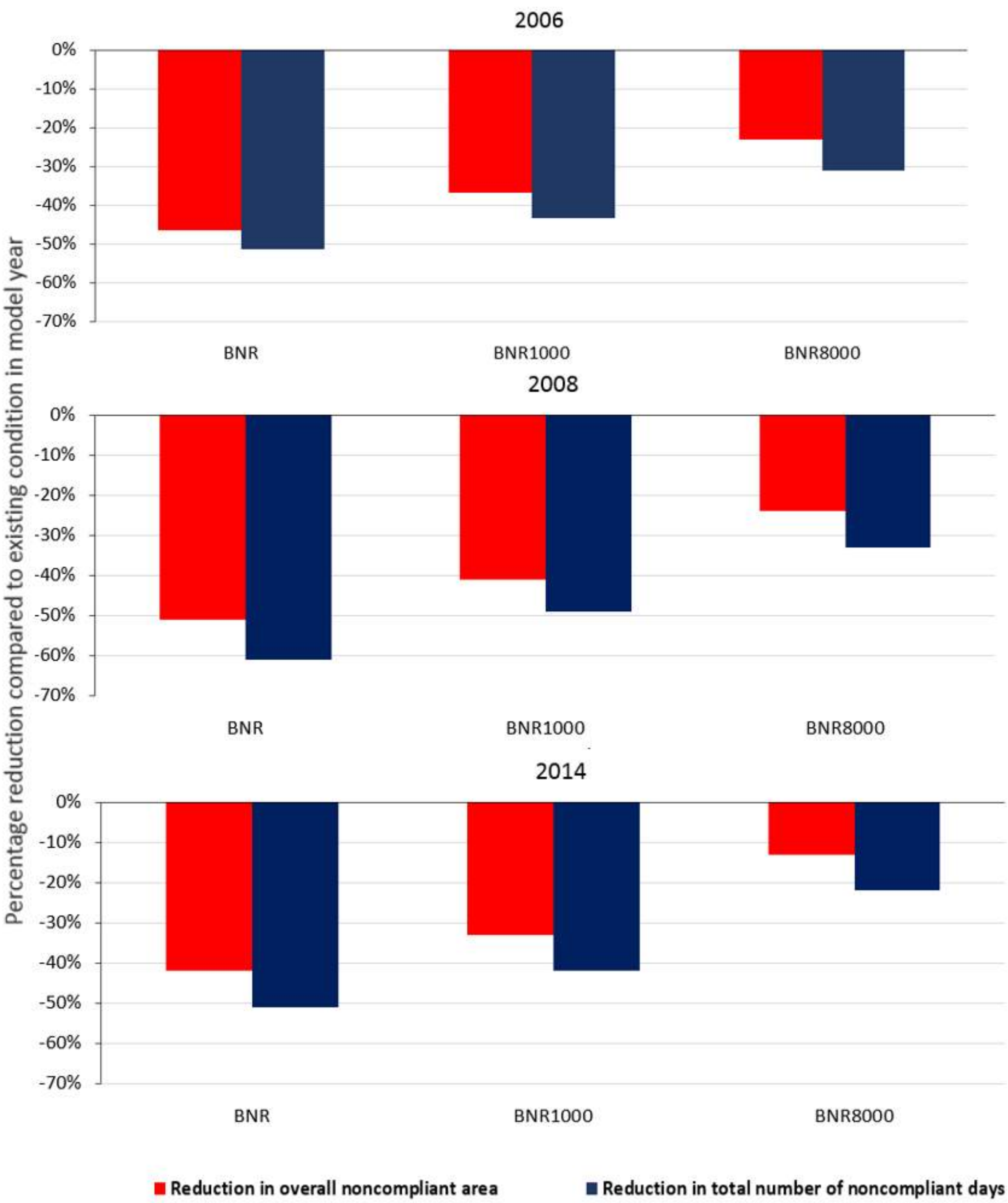


Figure 35. Plots of percent reduction in overall noncompliant area and total noncompliant days for 2006 (above), 2008 (center), and 2014 (below) under different hypothetical biological nitrogen removal (BNR) scenarios.

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%

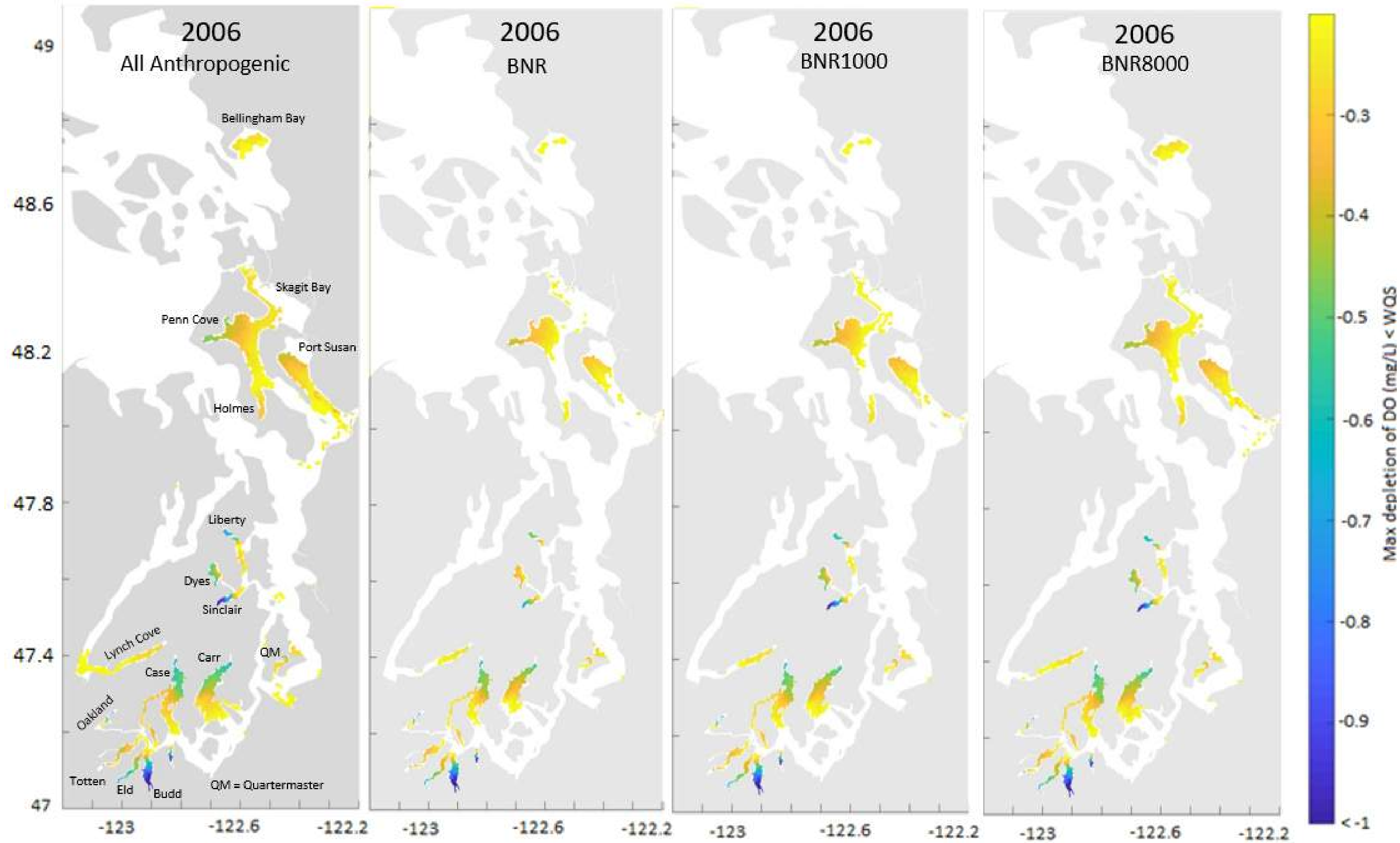


Figure 36. Four scenarios for maximum dissolved oxygen depletions for 2006.
Far left, due to all anthropogenic sources. *Center left*, with biological nitrogen removal (BNR) for all WWTPs discharging into marine waters. *Center right*, with BNR for WWTPs discharging dissolved inorganic nitrogen (DIN) >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.

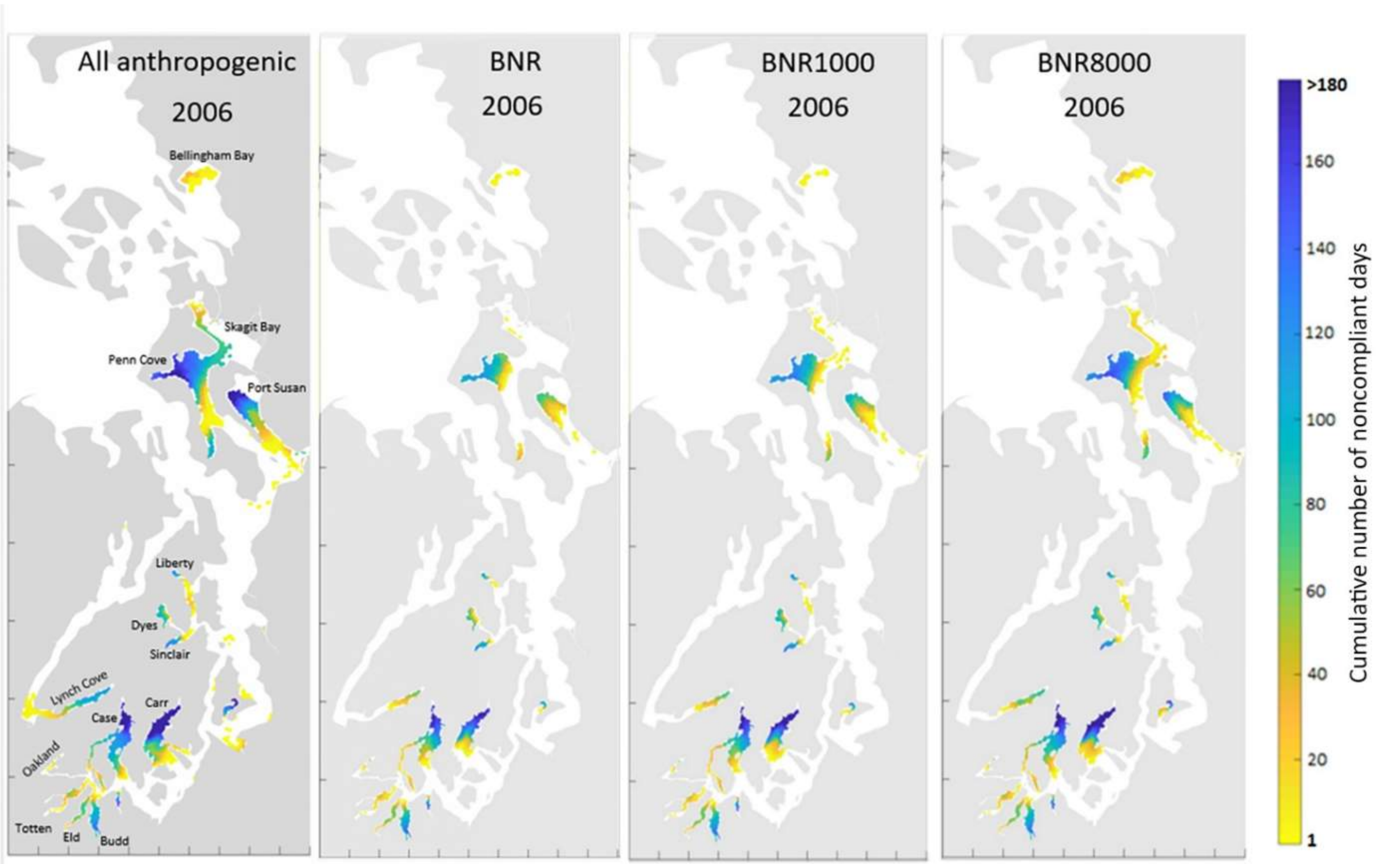


Figure 37. Four scenarios for cumulative number of days with depletions of dissolved oxygen for 2006.
Far left, due to all anthropogenic sources. *Center left*, with biological nitrogen removal (BNR) for all WWTPs discharging into marine waters. *Center right*, with BNR for WWTPs discharging dissolved 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).

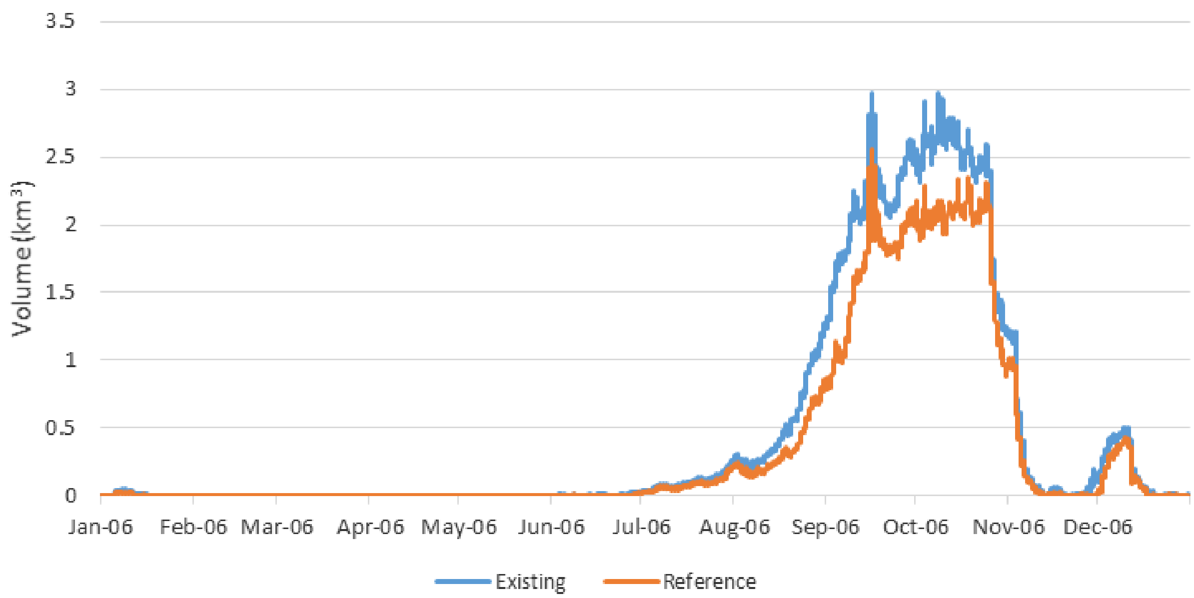


Figure 38. Hypoxic volume in Puget Sound (dissolved oxygen less than 2 mg/L) predicted for existing and reference conditions in 2006.

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, km²)	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

PUGET SOUND INSTITUTE
UNIVERSITY of WASHINGTON

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/m²/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 observations
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.

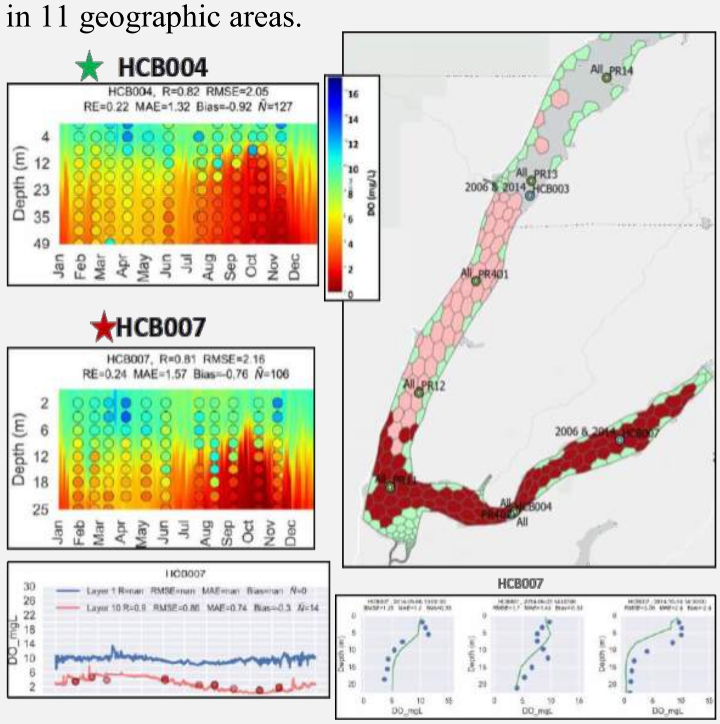

Table 5. Skill metrics on dissolved oxygen results (mg/L) for the state's Applied Model for specific regions, and inlets within them. All sites where results are presented fall within the geographic areas identified by the state as DO non-compliant. Multiple sites and samples are included to represent 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.

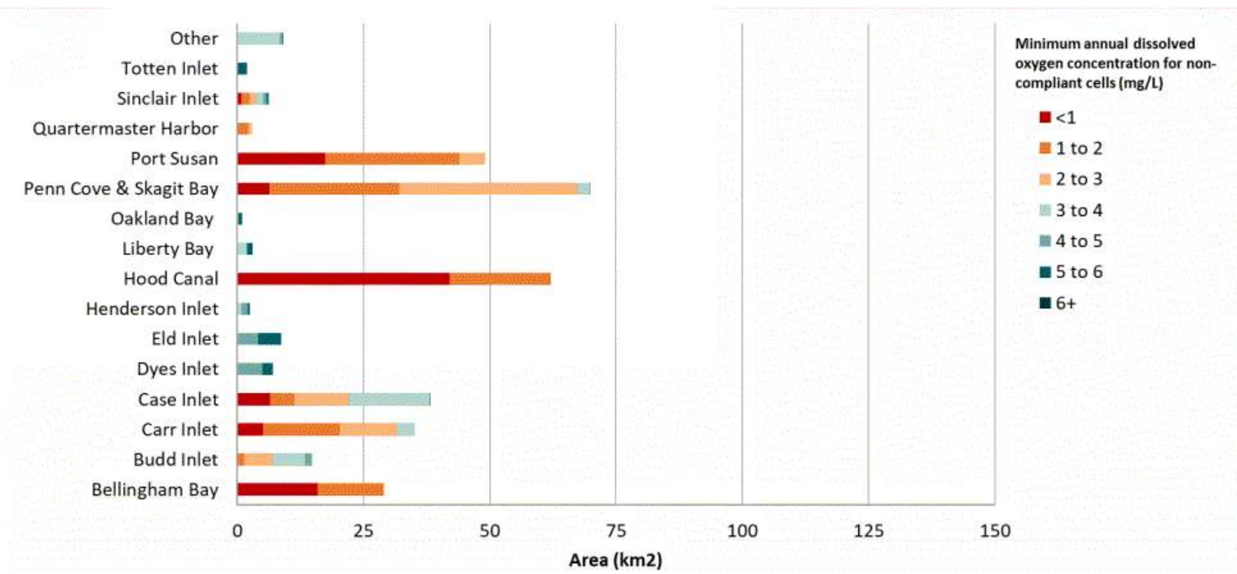

Figure 1. Minimum annual dissolved oxygen concentration for non-compliant areas by embayment for 2014. Sources and details on methodologies are included in Appendix 2. Figures 1 and 2 include all cells in Washington State waters that are calculated to have non-compliance for at least 1 hour for 2014, 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.

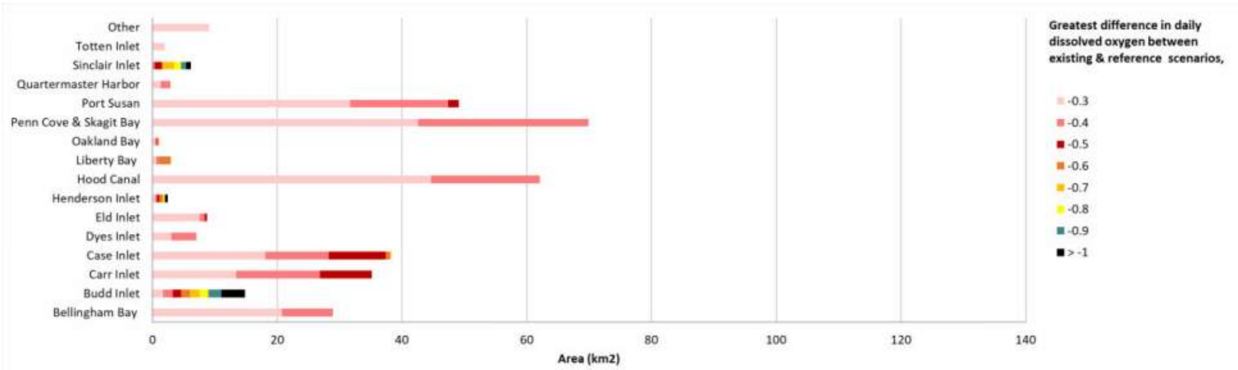

Figure 2. Calculated greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by embayment for 2014. Sources and details on methodologies are included in Appendix 2.

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 ($\gtrapprox$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.

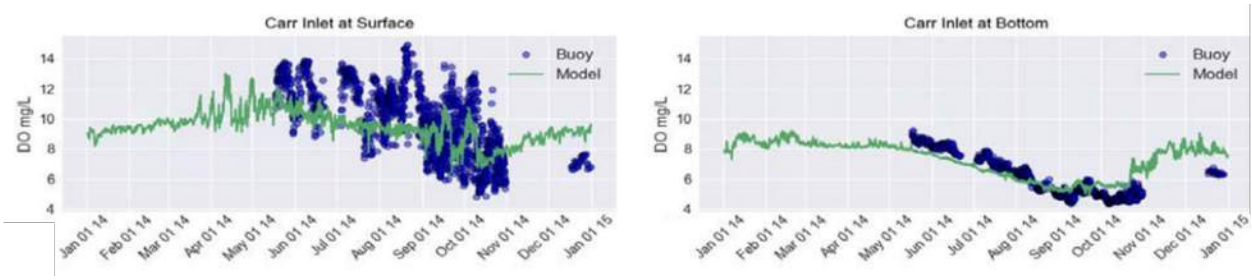

Figure 3. Example from Ahmed et al. (2019) of one of the plots comparing model predictions for 2014 overlaid on continuous monitoring data from the same year.

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

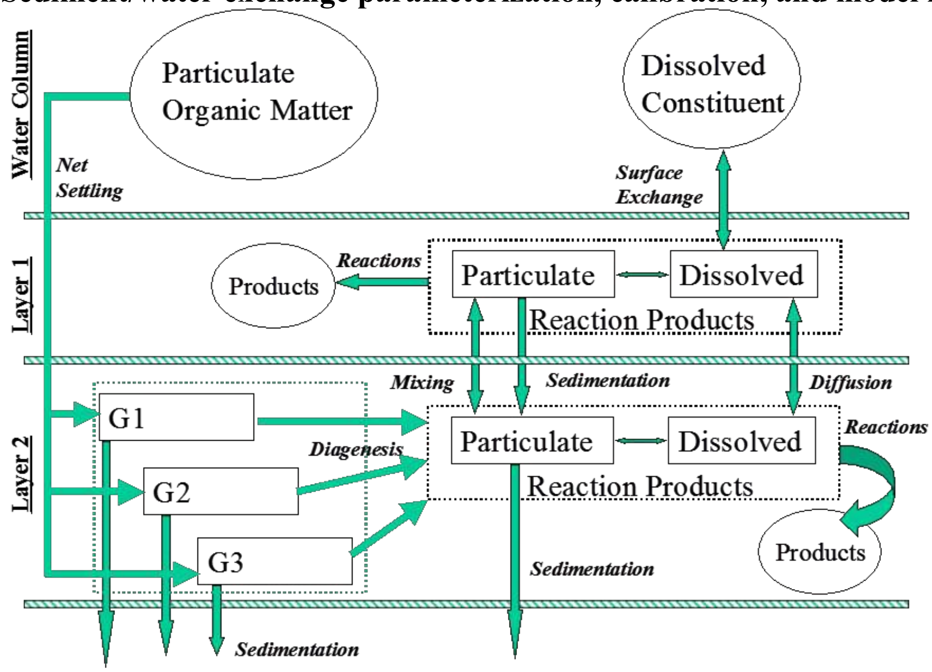

Figure 4. Basic Structure of the Sediment Diagenesis module of the Salish Sea Model (reproduced from Martin and Wool, 2013 and further described in the SSMC website documentation).

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.

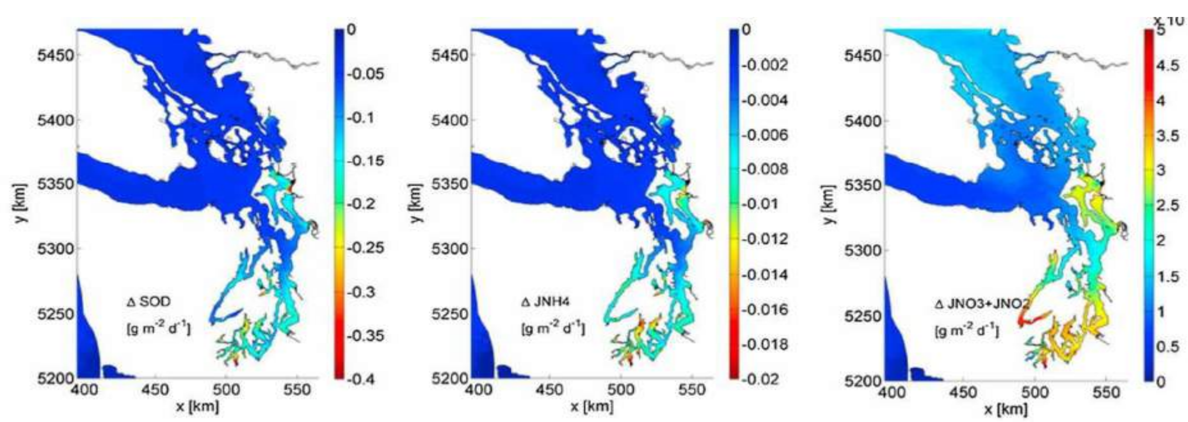

Figure 5. Change in sediment fluxes of DO, ammonium, and nitrate between the baseline 2014 conditions and the hypothetical scenarios without land-based loads (reproduced from Figure 15 of Khangaonkar et al. (2018)).

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):
    - 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.
    - 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.

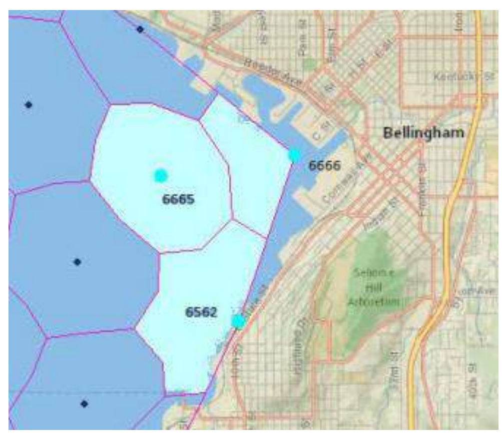

Figure 6. Map of Bellingham Bay showing model grid cells (light blue) that were compared to Merritt (2017) observations (reproduced from Figure I3 of Appendix I of Ahmed et al. (2019)).

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%

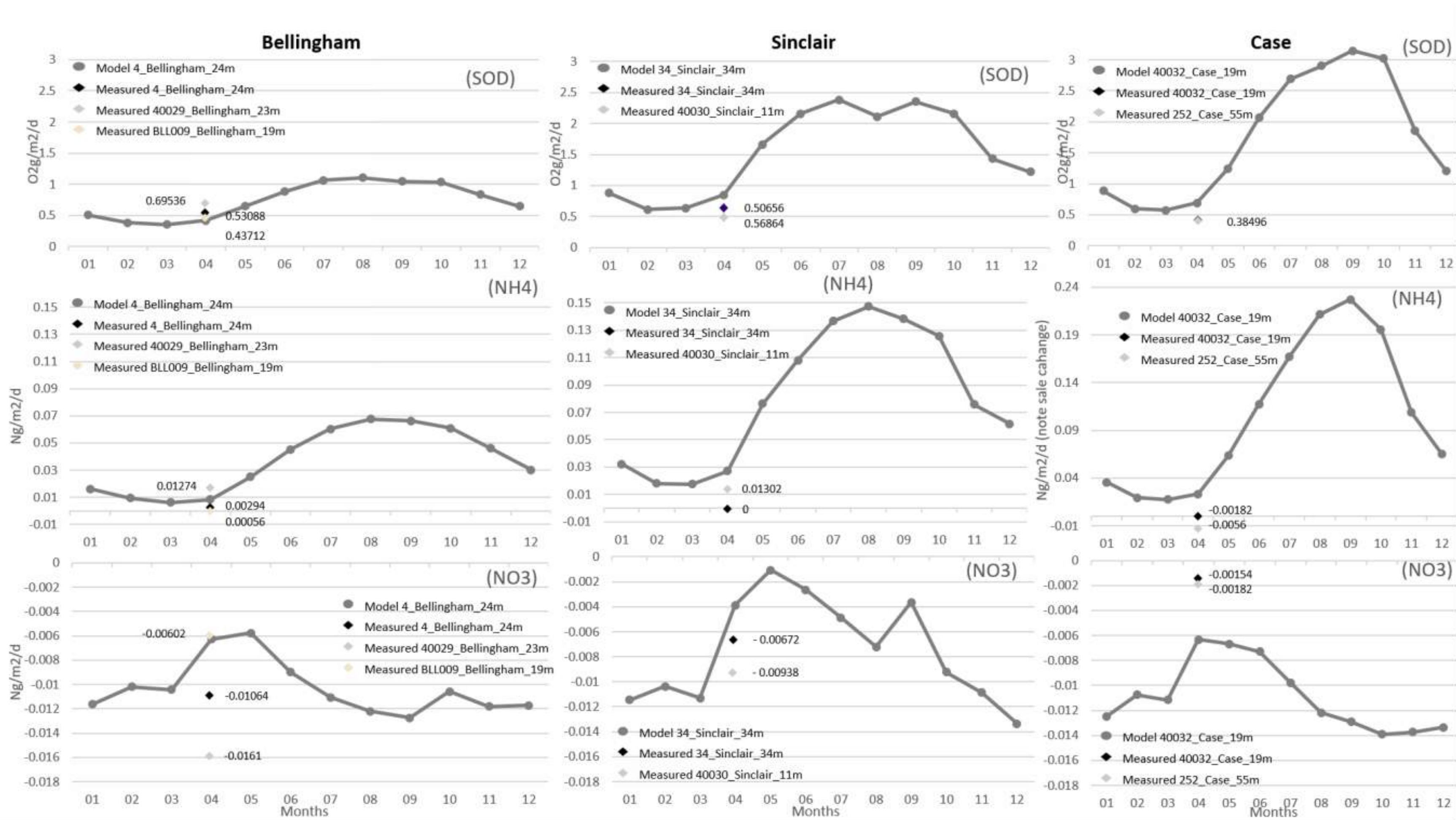

Figure 7. Modeled 2014 sediment/water fluxes at inlets over the year 2014, overlaid with Rigby (2019) site measurements taken for the same time of year in 2018.

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

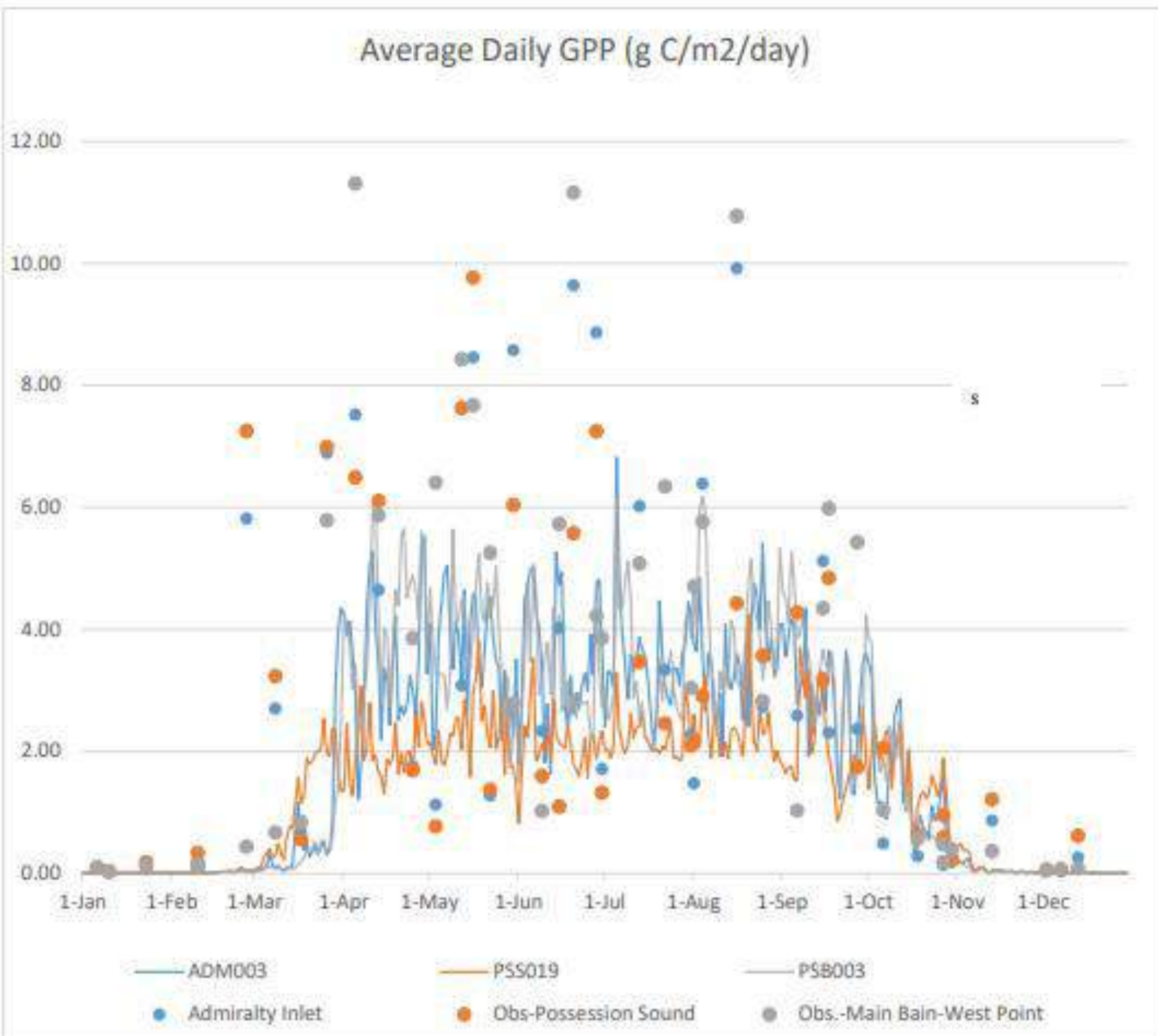

Figure 8. Comparison of 2008 average daily GPP Salish Sea Model output for Admiralty Inlet (blue line), Possession Sound (orange line), and Main Basin-West Point (grey line), with observations from 1999 to 2011 at Admiralty Inlet (blue circle), Possession Sound (orange circle), and Main Basin-West Point) 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).

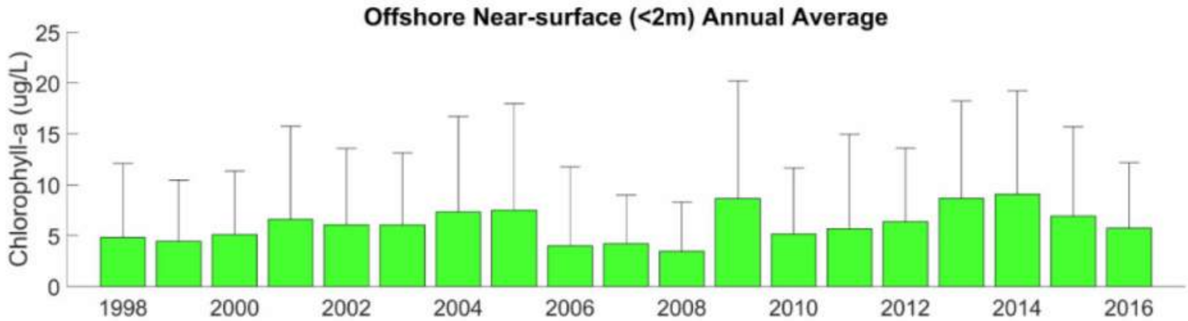

Figure 9. Annual average chlorophyll based on monthly data from Central Puget Sound (Jaeger and Stark, 2017). Reproduced from Figure H1 of Appendix H of Ahmed et al. (2019).

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) Organic Sediment Settling: 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) Sedimentation of POC and PON*:* 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) Sediment-water fluxes 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.

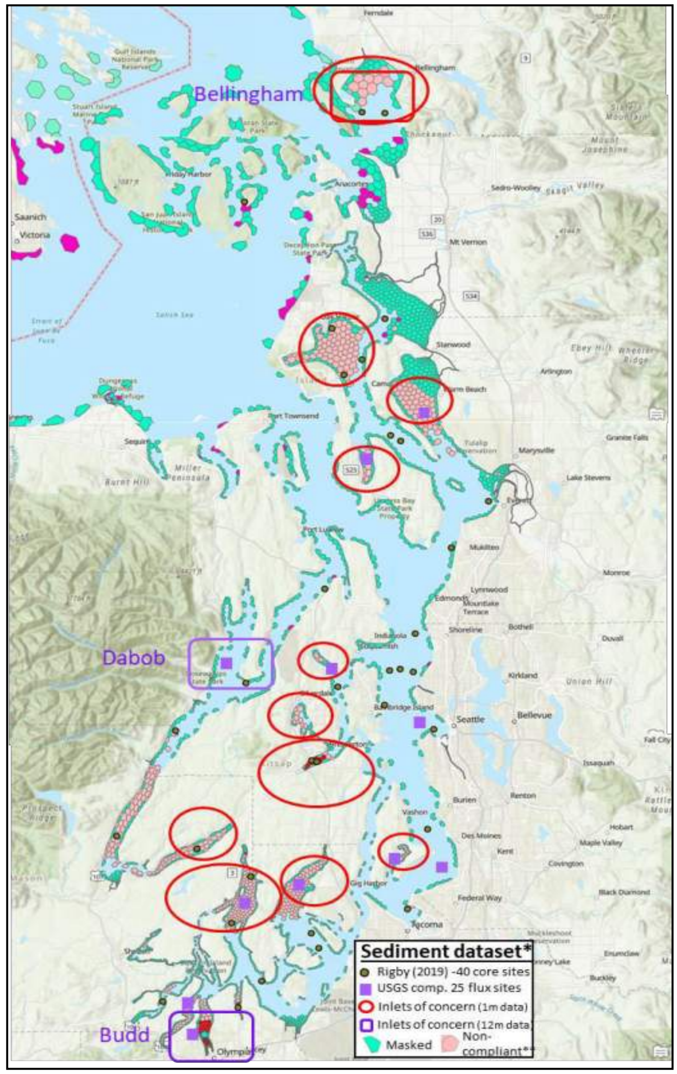

Figure 10. Locations selected for: Rec. 1a, expanded regional flux site validation (purple squares); Rec. 2b further seasonal validation (3 purple boxes); Rec. 2c Spring time comparisons (brown circles), and Rec 2d embayment wide comparisons (3 red ovals, including Bellingham). Reproduced from slides 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.

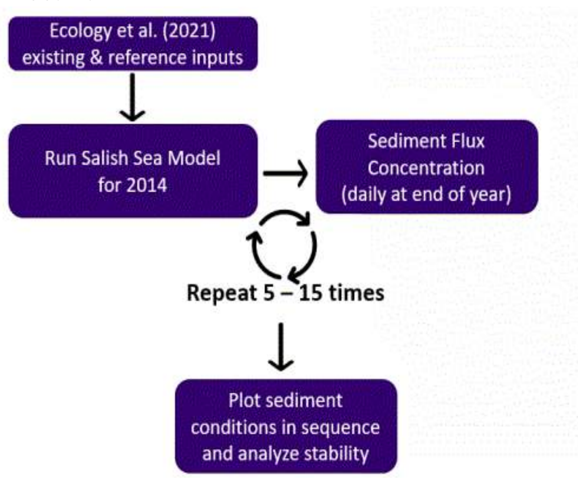

Figure 11. Analysis of Salish Sea Model sediment exchange spin up and stability. Reproduced from slides presented at the Science of Puget Sound Water Quality Sediment Exchange Workshop, October 17, 2022. See the presentation for further details.

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:
    - o 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.
    - o 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

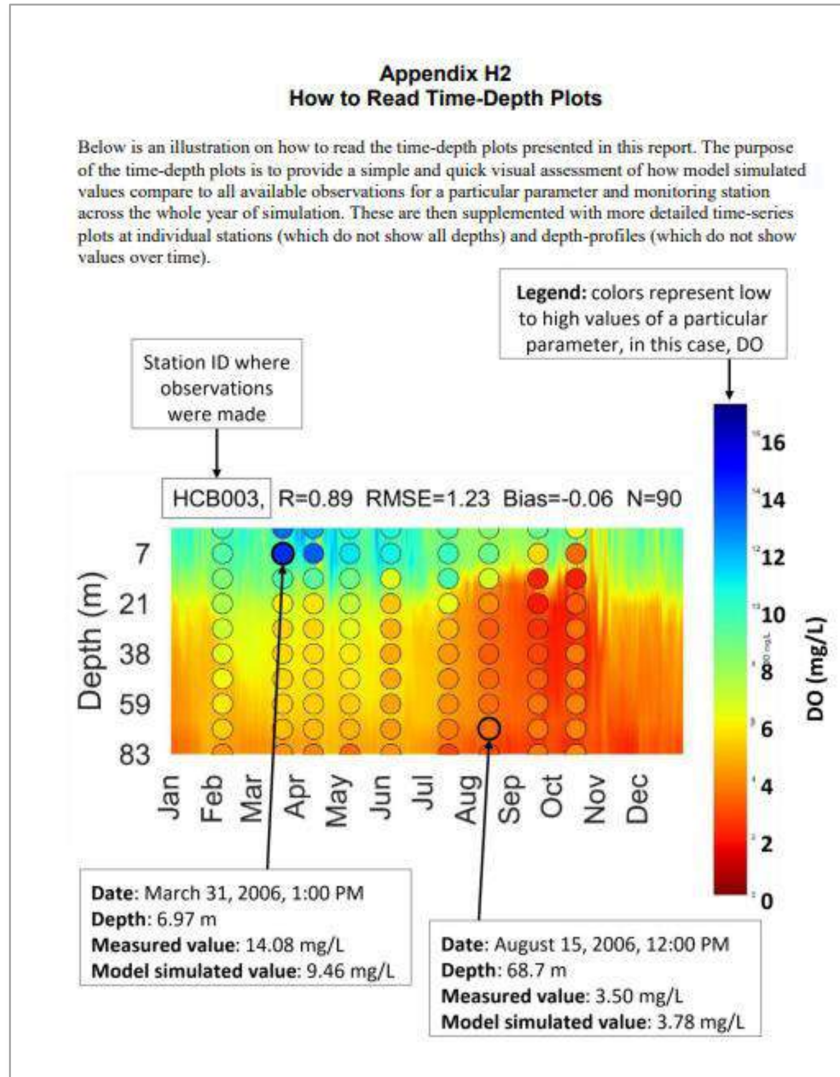
Appendix 1: Inlet-scale review of measured to modeled dissolved oxygen goodness of fit in areas identified as non-compliant in Washington State

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:

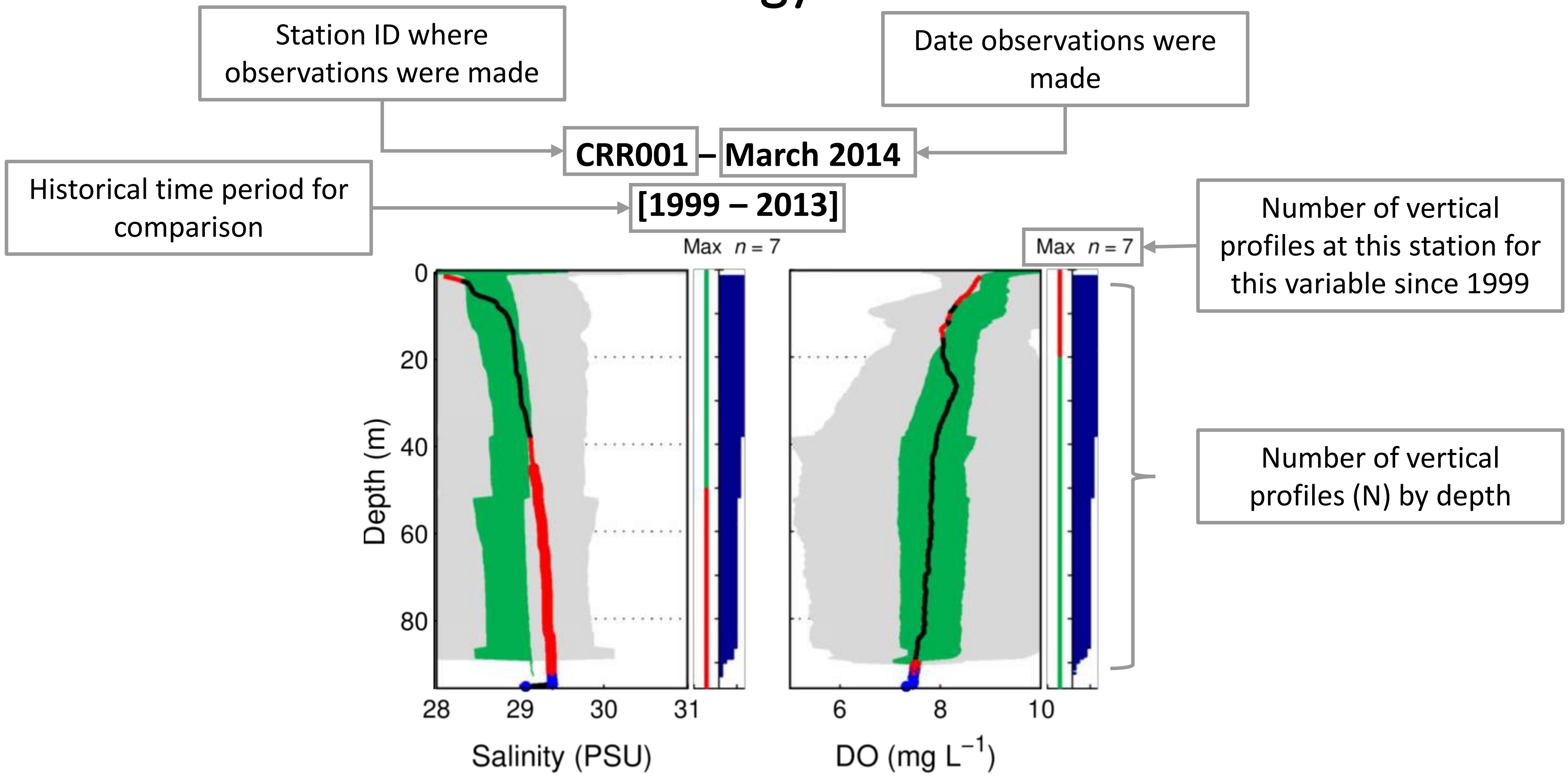
- Including only model to CTD measured validation for sites falling within the contiguous model cells counted as non-compliant within and extending from each embayment/region[2]. Geographic delineation is defined in recent Bounding Scenarios Update report by the State (Ahmed et al., 2021), using the 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 ≥ 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

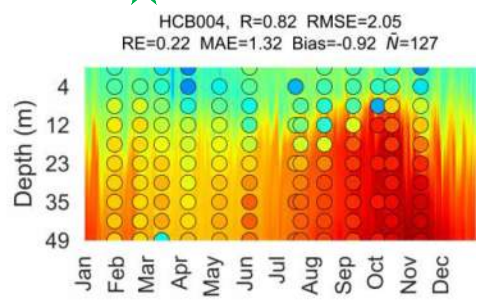
Measured data for 20 year period of CTD casts (not for circulation): results from the year 2014 (overlayed against the range of prior long-term results) are included with each measured/modeled statistical analysis presented following

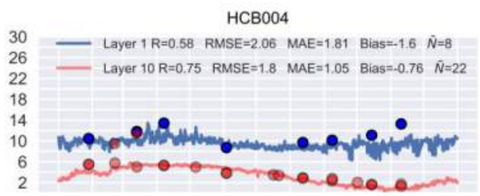
Hood Canal | 2014

Context

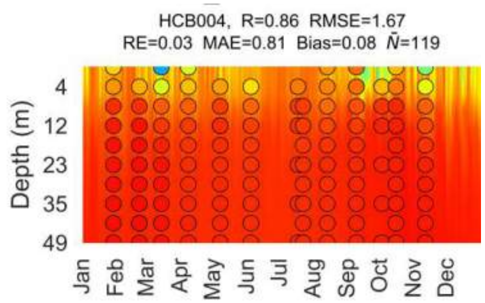
- Salinity plots included for comparison here for HCB004/007

★ HCB004

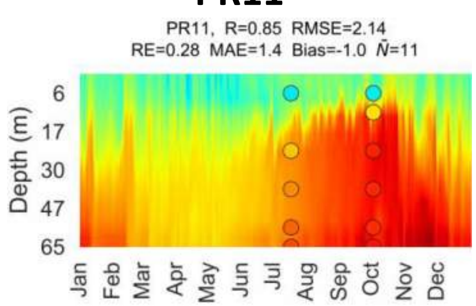


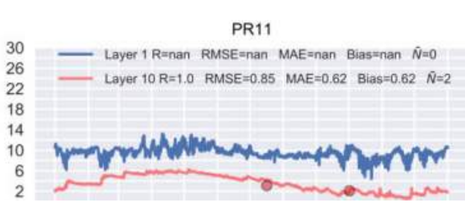


Salinity

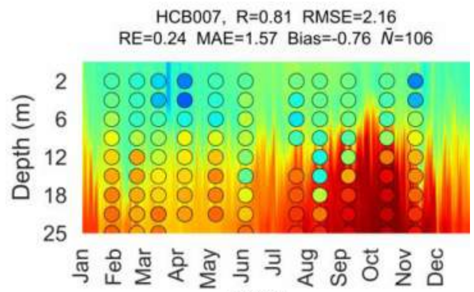


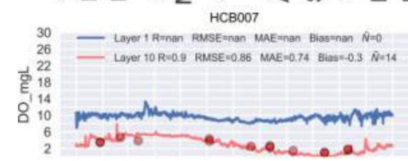
PR11

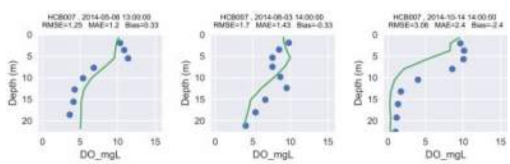




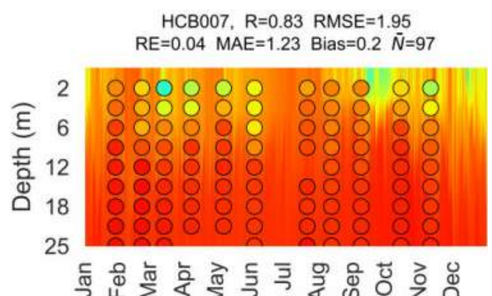
★HCB007



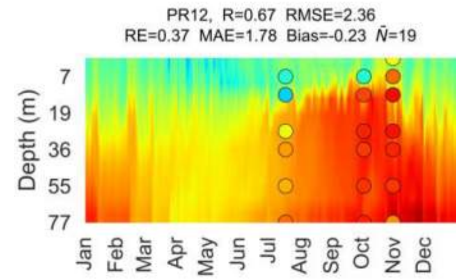


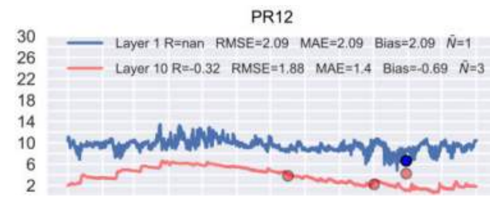


Salinity

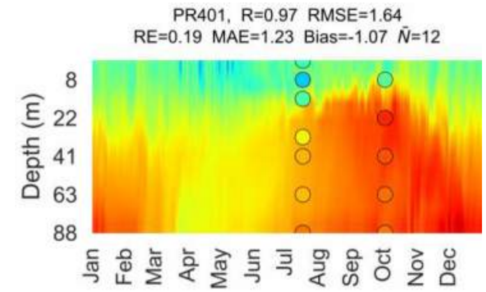


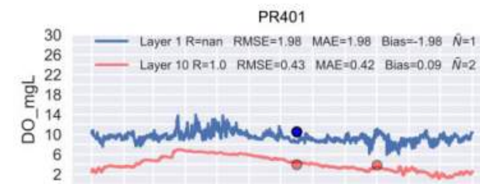
PR12





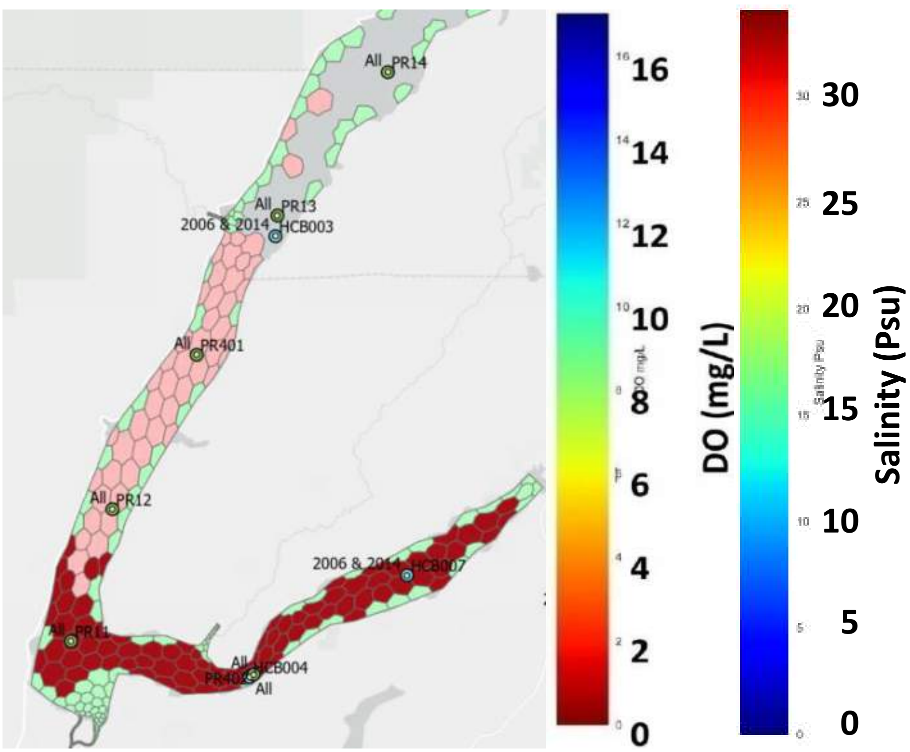
PR401





Context

- PR402 isn't included and is within the same cell as HCB004

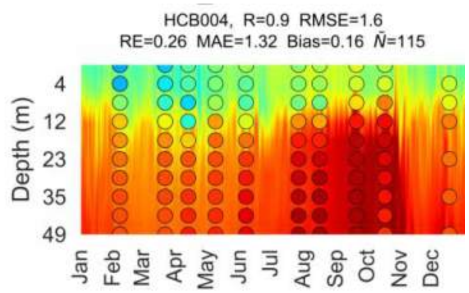


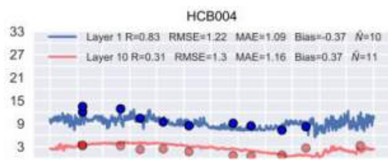
Reflections

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.**

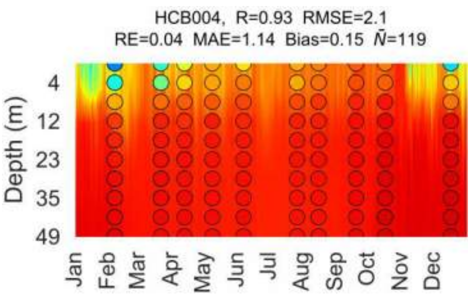
Hood Canal | 2006

HCB004

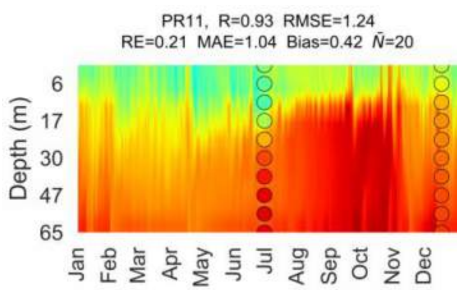


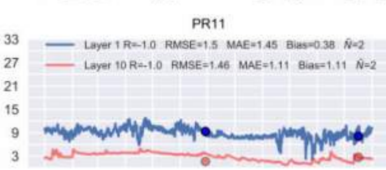


Salinity

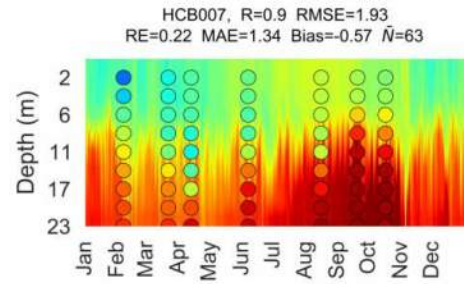


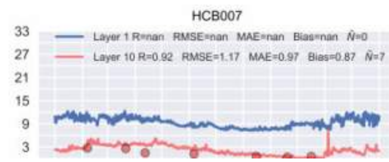
PR11

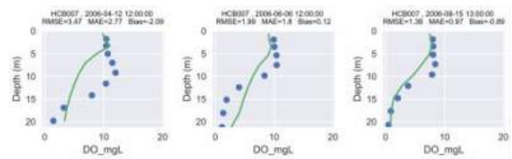




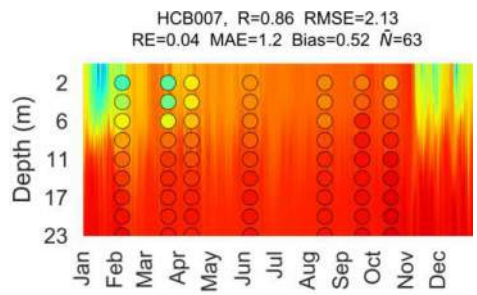
HCB007







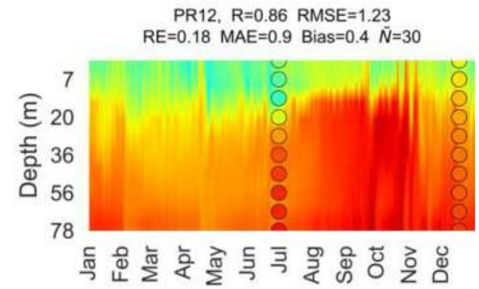
Salinity

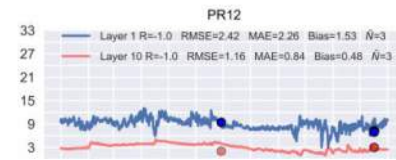


Reflections

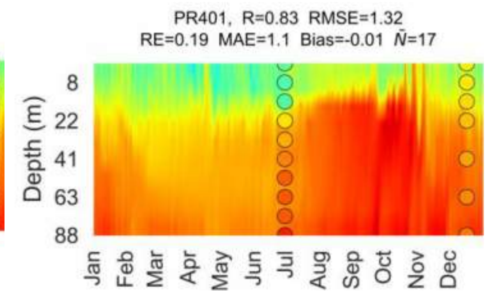
July–Nov: Modeled match measures results in deepest waters, and is better than 2014 in shallow waters. Layer ten shows both higher and lower modeled DO, which is also shown throughout the water-column profile at HCB007 were data are presented (**approximately 3mg/l maximum at 10m at HCB007 in August.**)

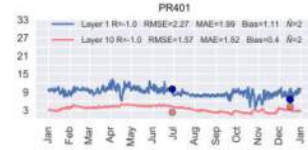
PR12





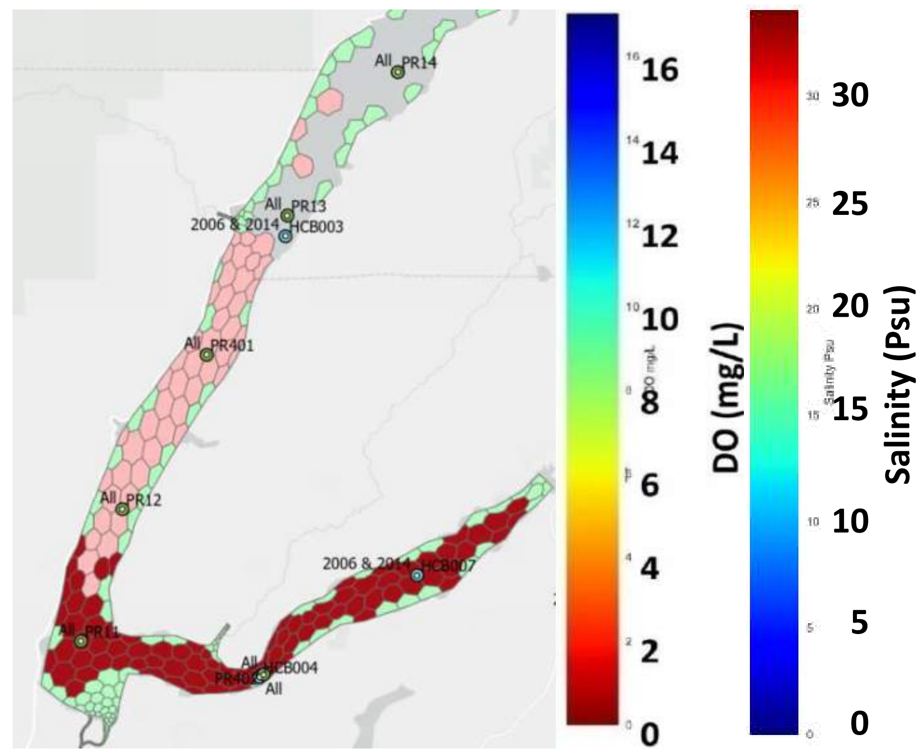
PR401





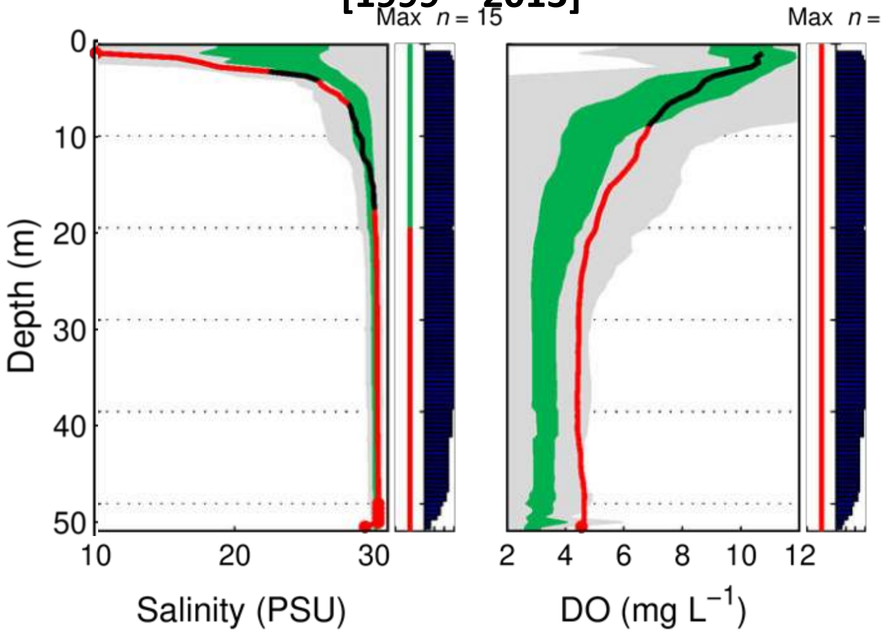
Context

- PR402 isn't included and is within the same cell as HCB004

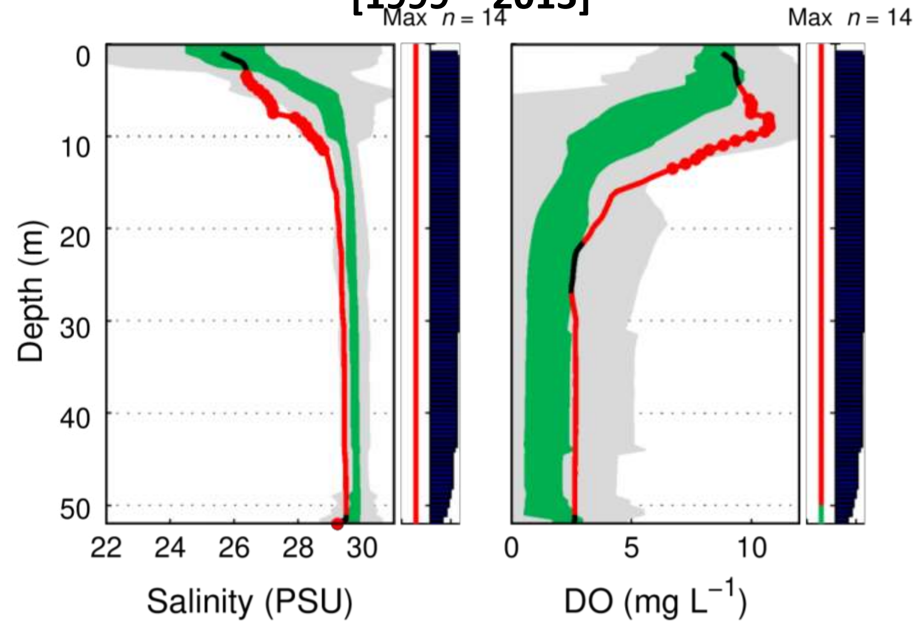


Hood Canal

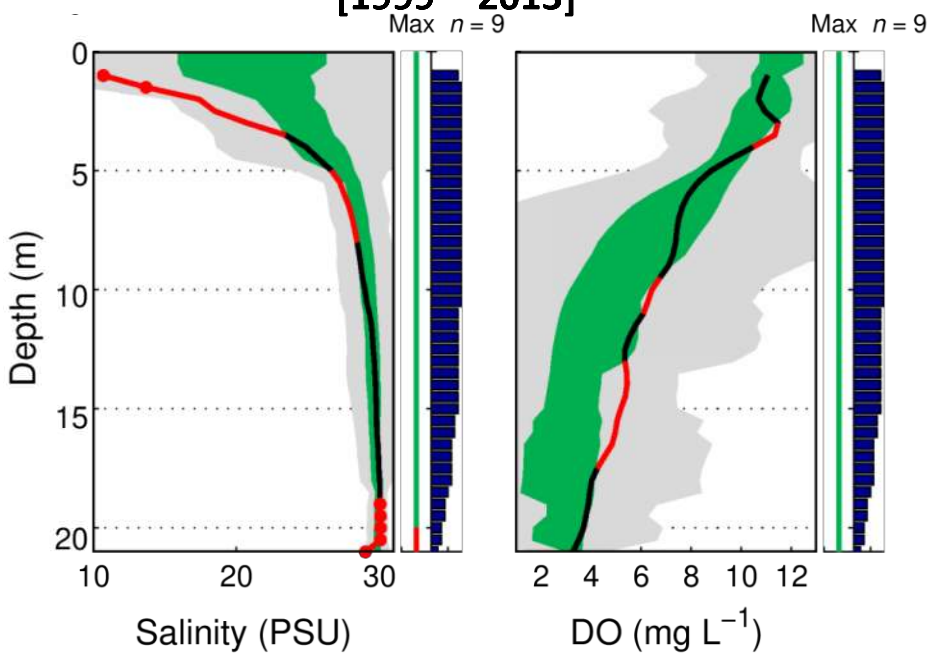
HCB004 – March 2014
[1999 – 2013]



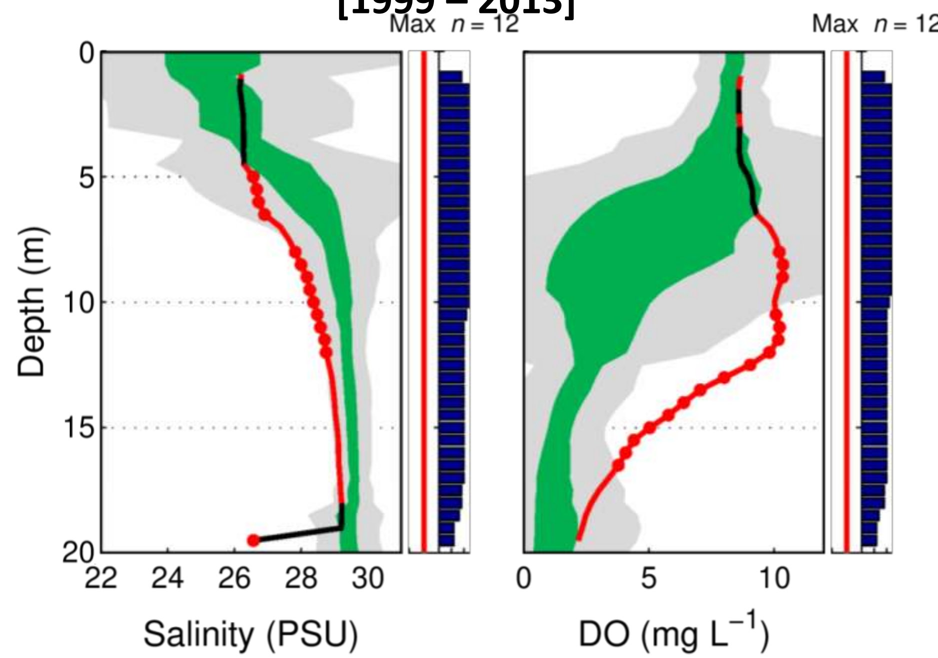
HCB004 – August 2014
[1999 – 2013]



HCB007 – March 2014
[1999 – 2013]

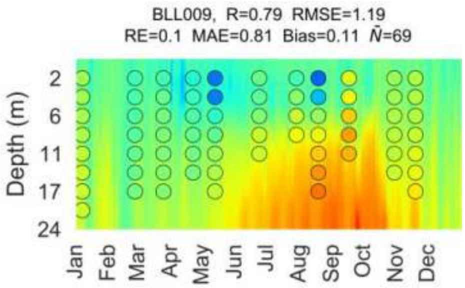


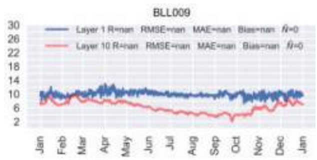
HCB007 – August 2014
[1999 – 2013]

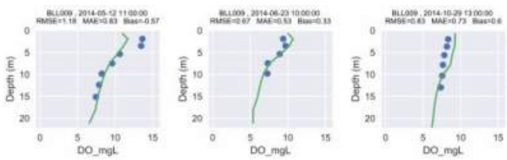


Bellingham Bay | 2006 & 2014

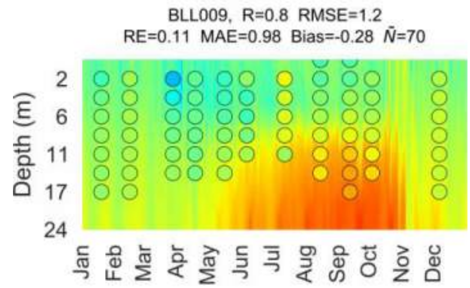
★BLL009 (2014)

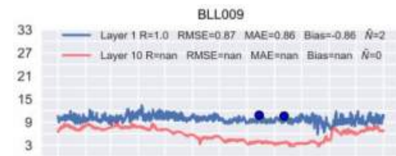


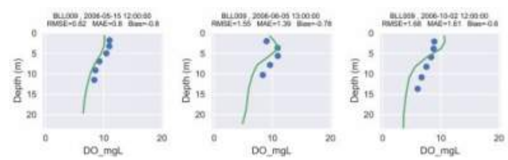


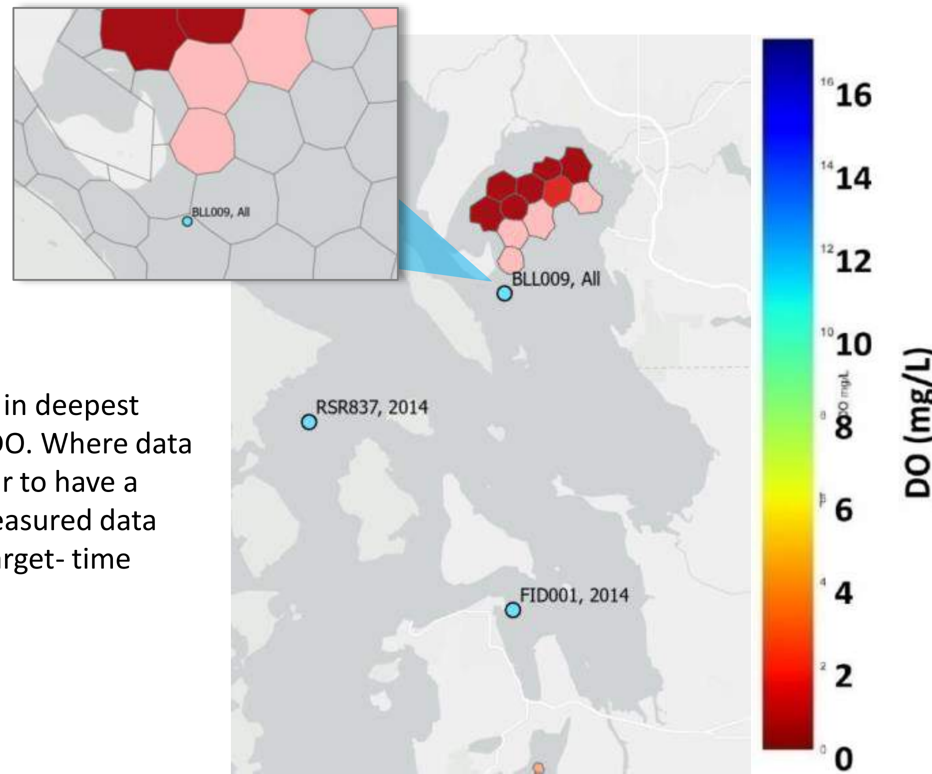


★BLL009 (2006)









Context

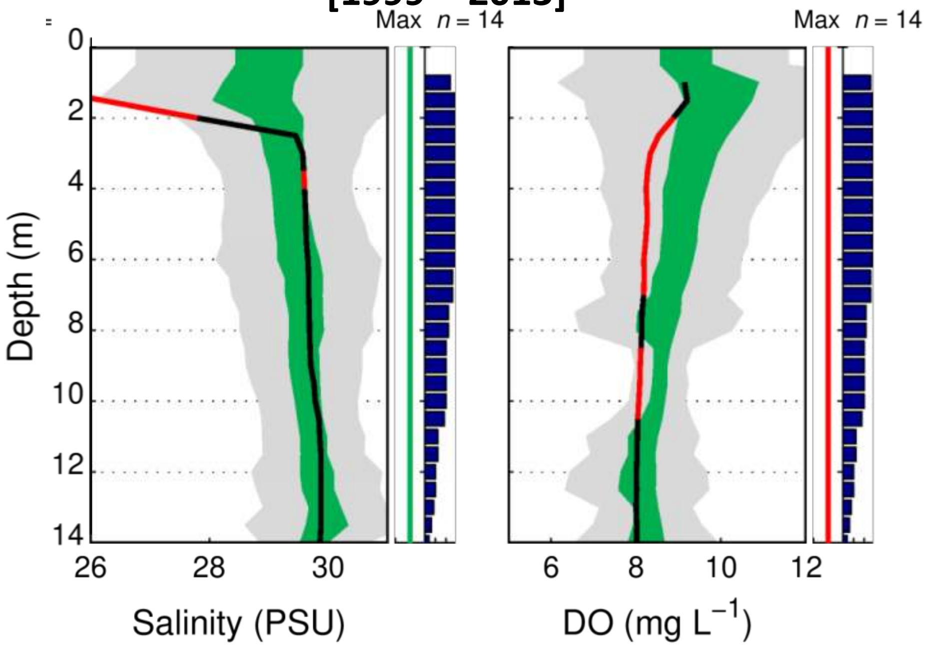
- BLL009 is the closest monitoring station. No other stations are near an area of non-compliance for any years
- BLL009 is located approximately 1km south with one cell of separation from the nearest non-compliant cell
- BLL009 is missing deep water data for comparison during Jul-Nov where DO would be the lowest

Reflections

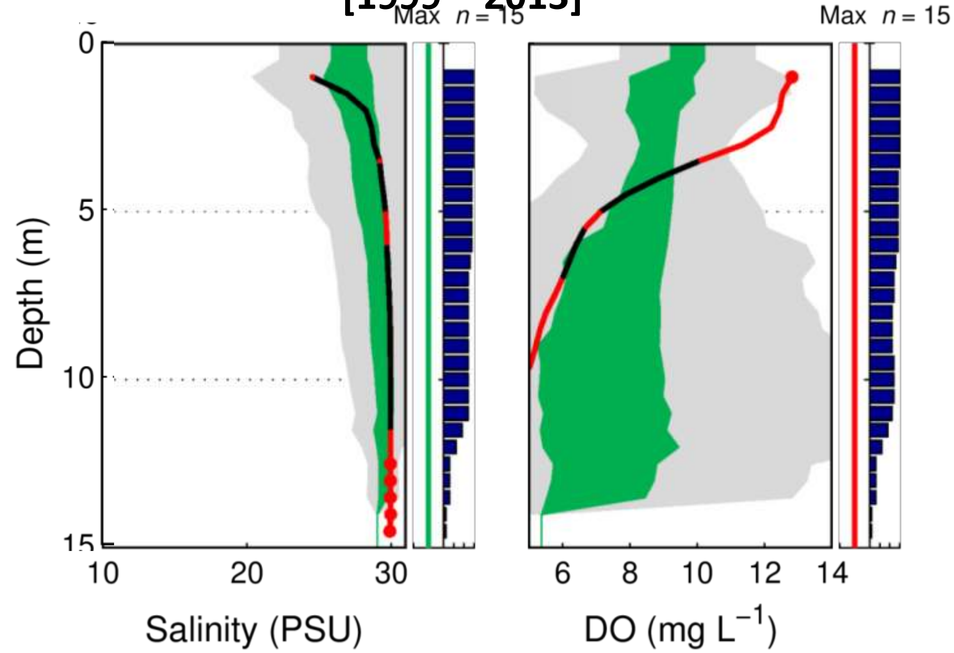
July–Nov: Modeled data not available in deepest waters with greatest presence of low DO. Where data is available, the modeled results appear to have a maximum difference of 2mg/l from measured data within the 0-15m depth range at the target- time period.

Bellingham Bay

BLL009 – March 2014
[1999 – 2013]

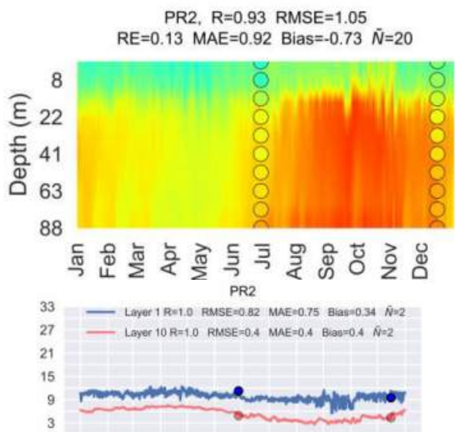


BLL009 – August 2014
[1999 – 2013]

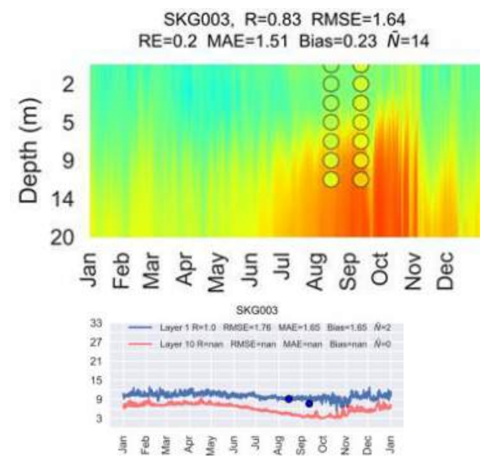


Whidbey Basin| 2006 & 2014

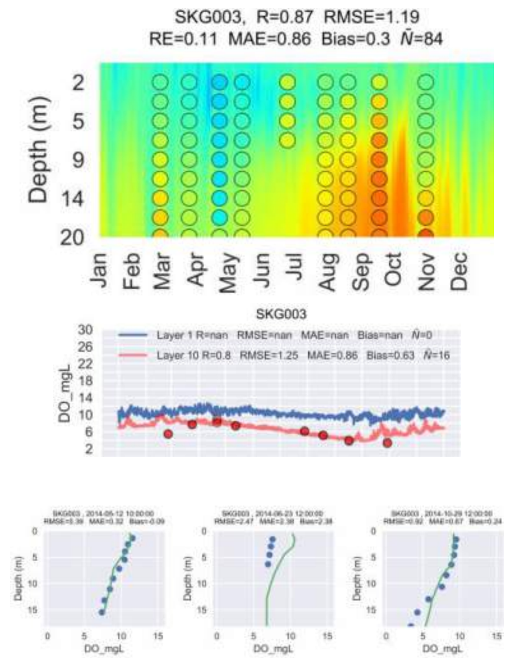
Near Port Susan PR2 (2006)

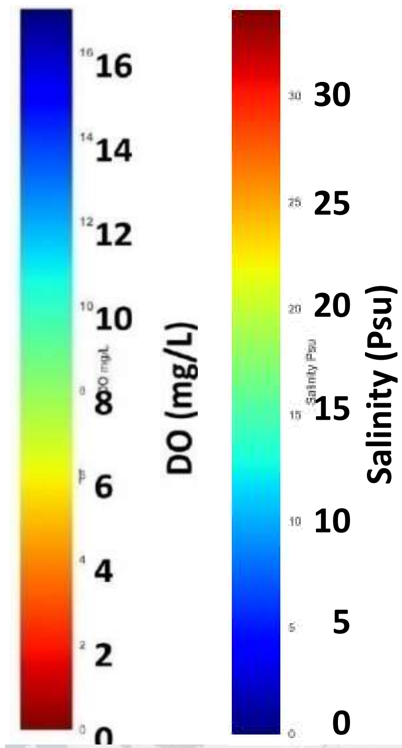


S. Skagit Bay: SKG003 (2006)

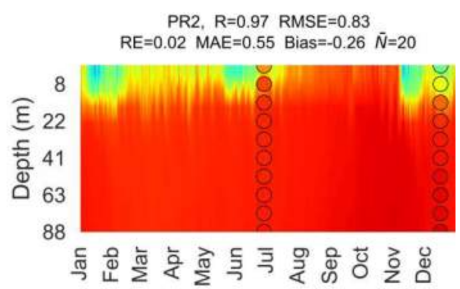


SKG003 (2014)

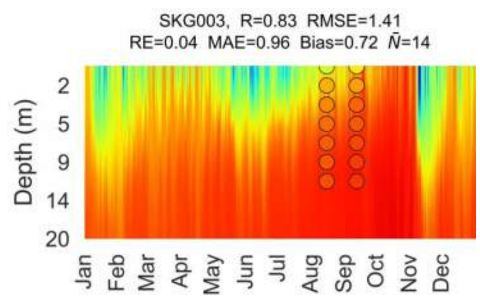




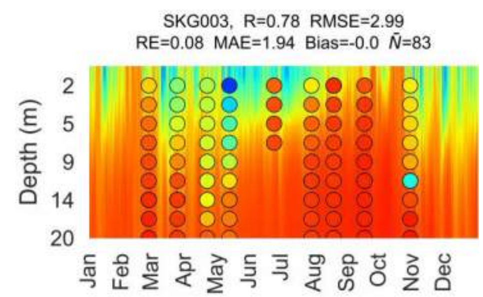
Salinity

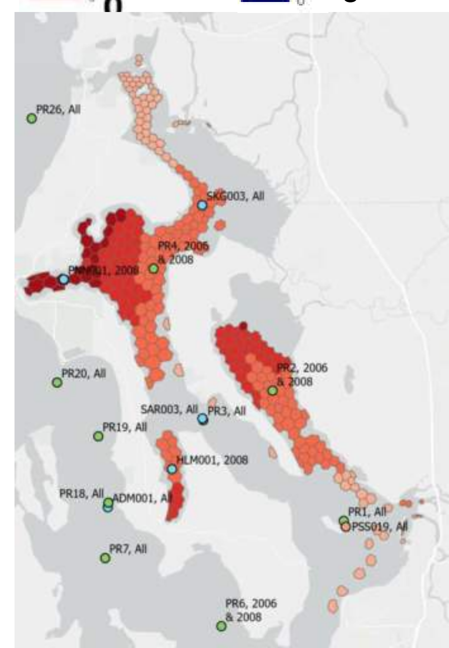


Salinity



Salinity





Context

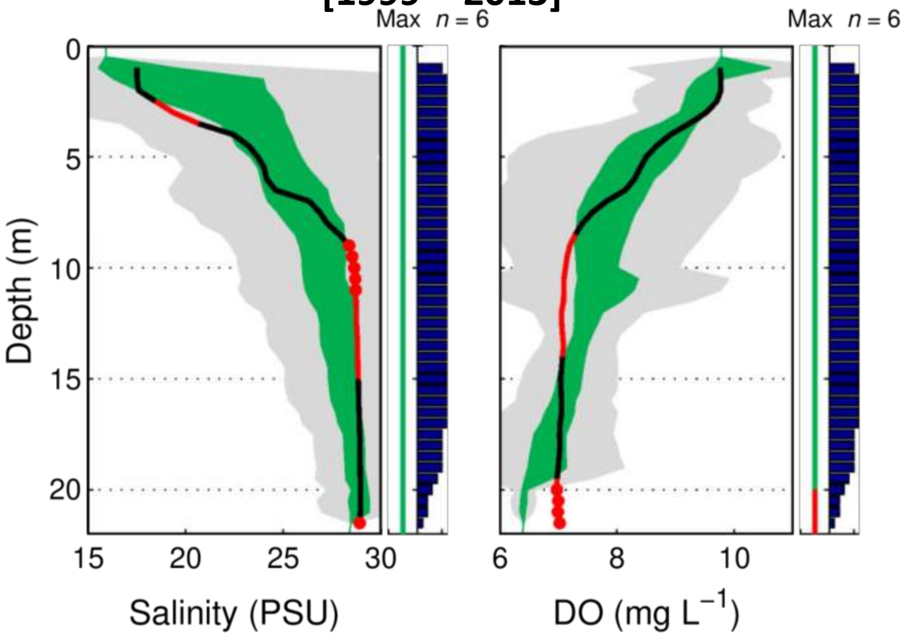
- Measured data not available for Port Susan in 2014
- PR4 isn't plotted in Appendix for 2006

Reflections

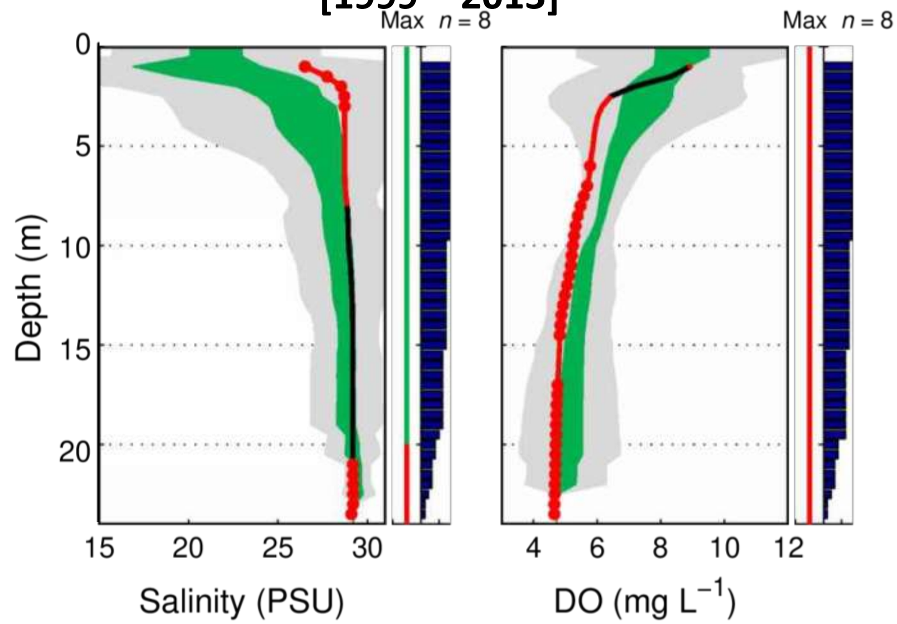
July–Nov: Measured data not available in deepest waters with greatest presence of low DO in Port Susan. Layer ten shows reasonable match of modeled DO for July-Nov, where data is available except Sep-Nov 2014 in Skagit Bay where modeled DO is over estimated for 2 of the 4 months. Similarly, some over 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]

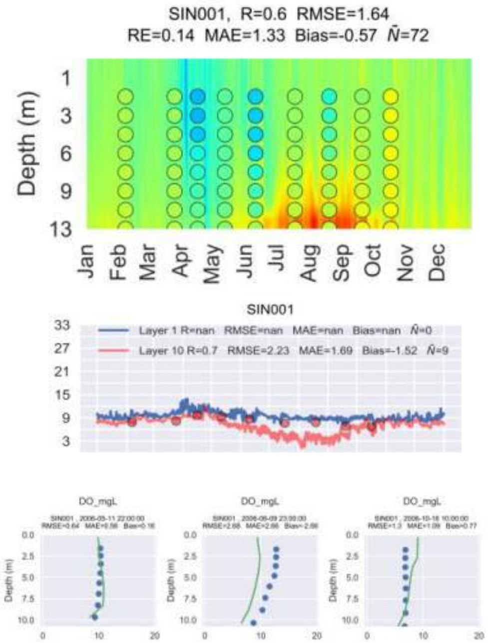


SKG003 – August 2014
[1999 – 2013]

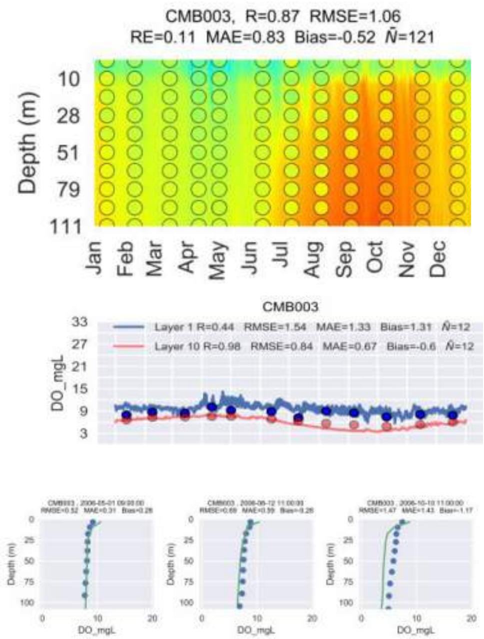


Main Basin | 2006 & 2014

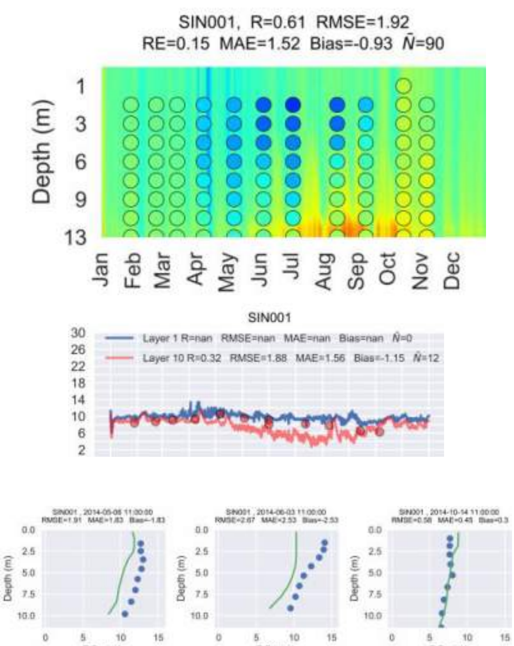
★Sinclair: SIN001 (2006)



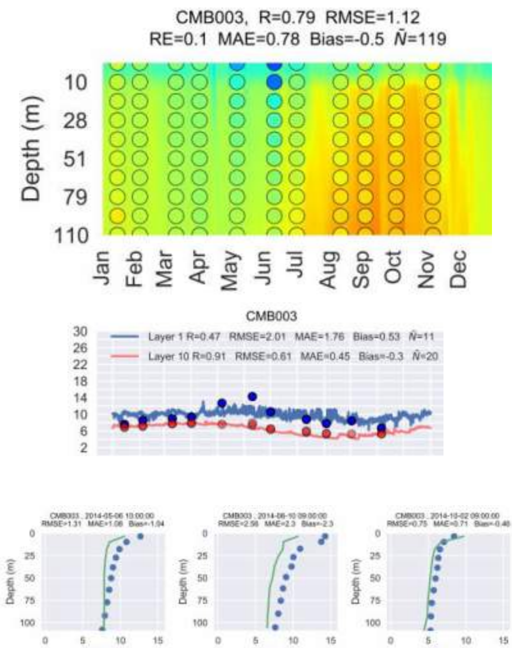
★Commencement: CMB003 (2006)



★SIN001 (2014)

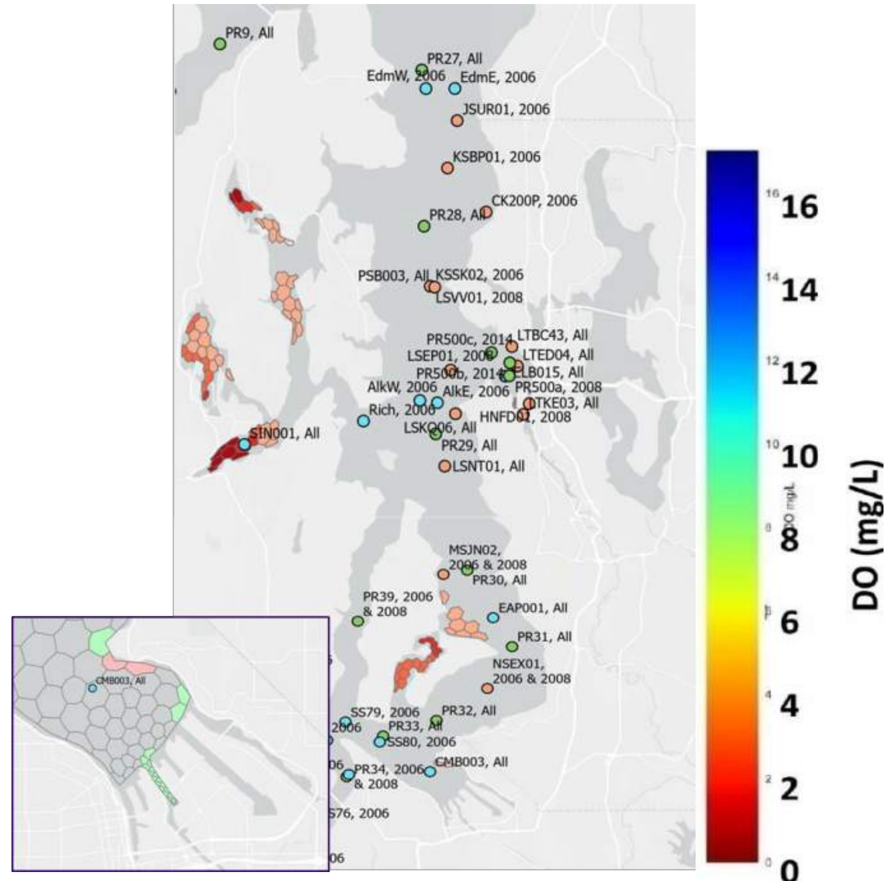


★CMB003 (2014)



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.

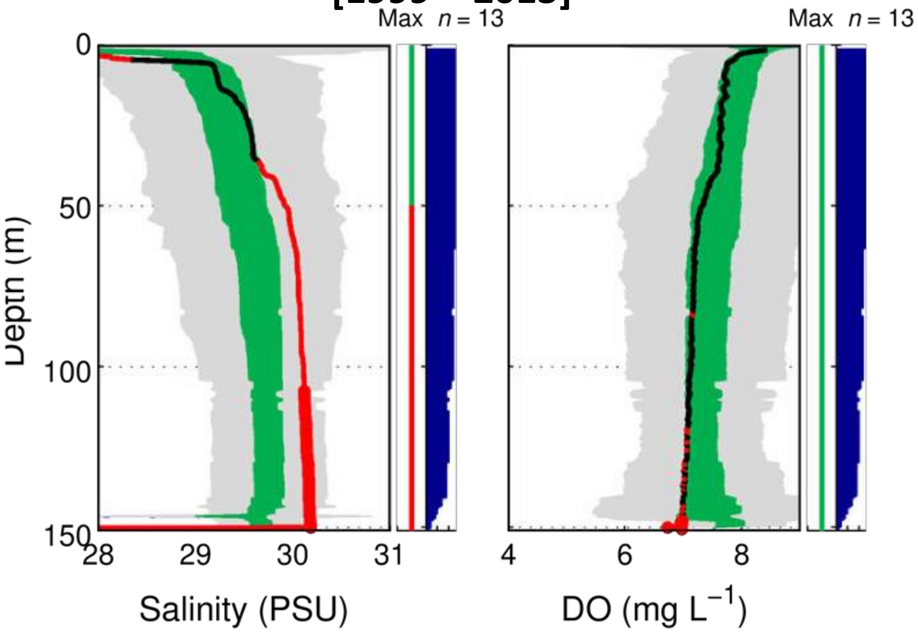


Reflections

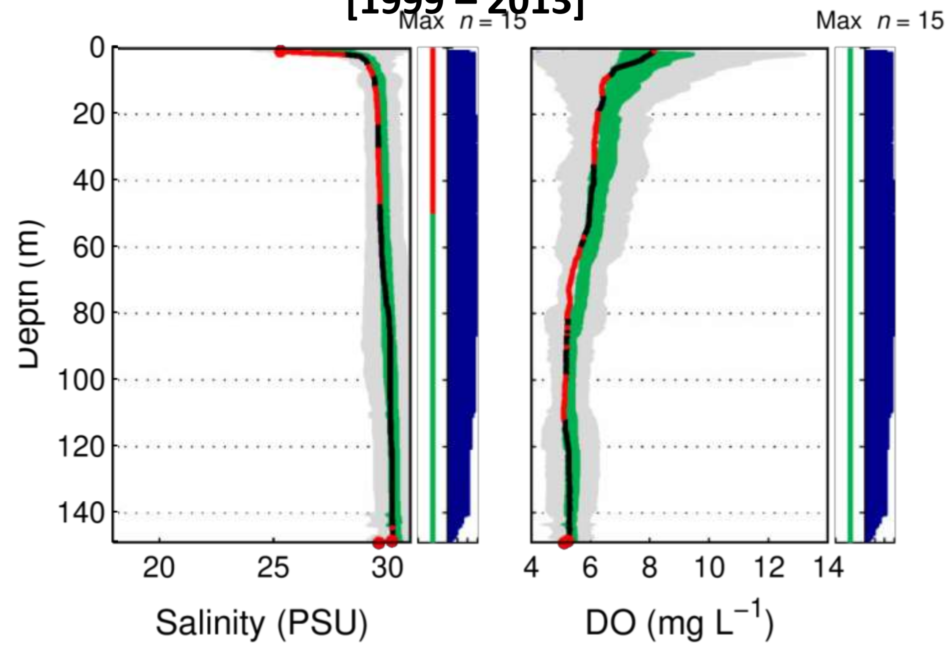
July–Nov: Deeper waters varies in modeled/measured match, however lower modeled than measured DO Jul-Nov is observed throughout most of water column for most months sampled at both stations in the target time-period. For Sinclair, the deepest layer appear 3mg/l lower or more modeled DO for most targeted 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

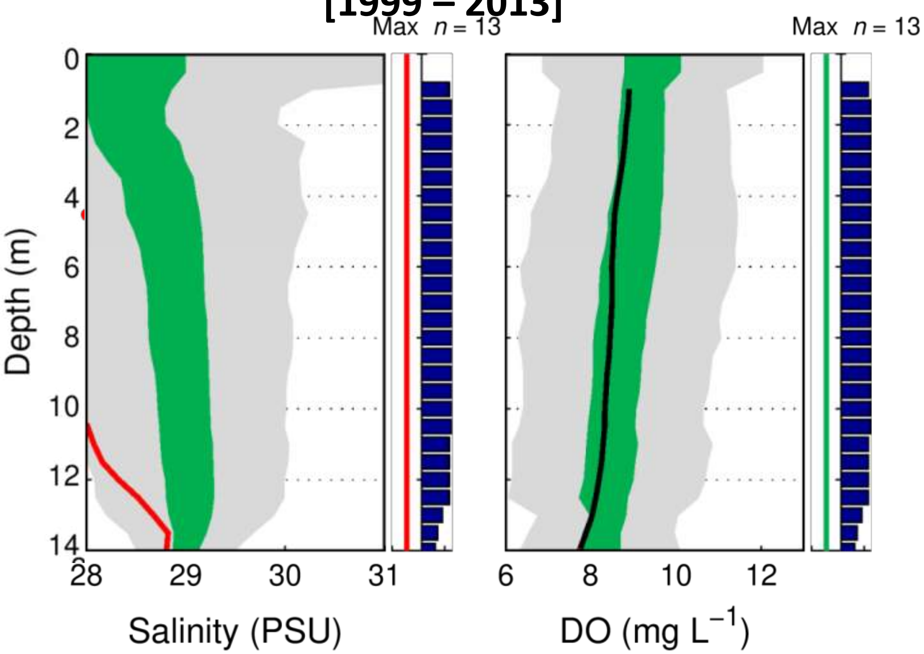
CMB003 – March 2014
[1999 – 2013]



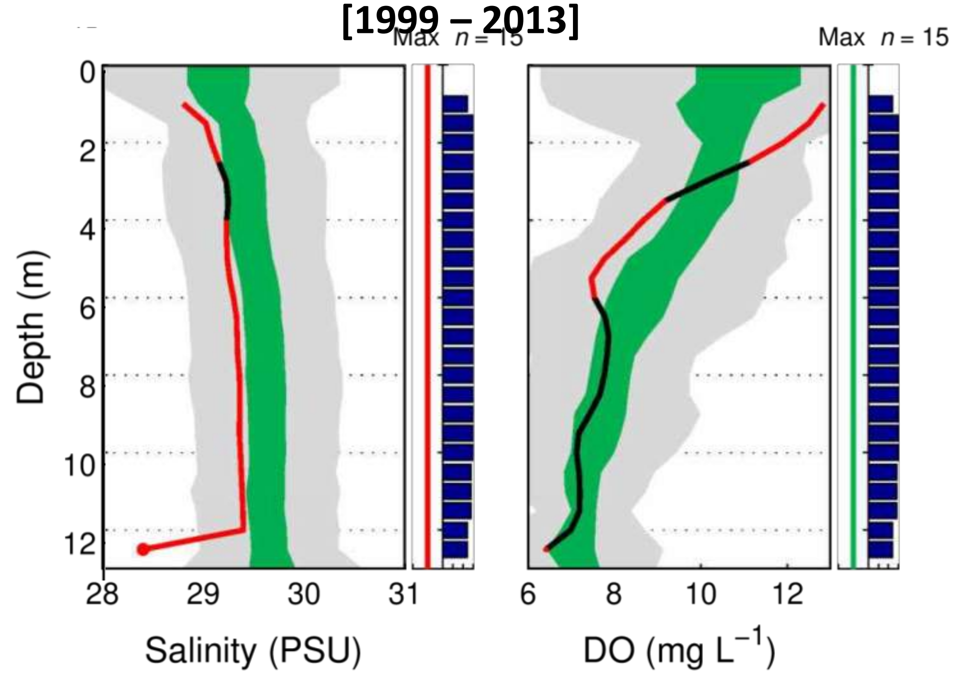
CMB003 – August 2014
[1999 – 2013]



SIN001 – March 2014
[1999 – 2013]

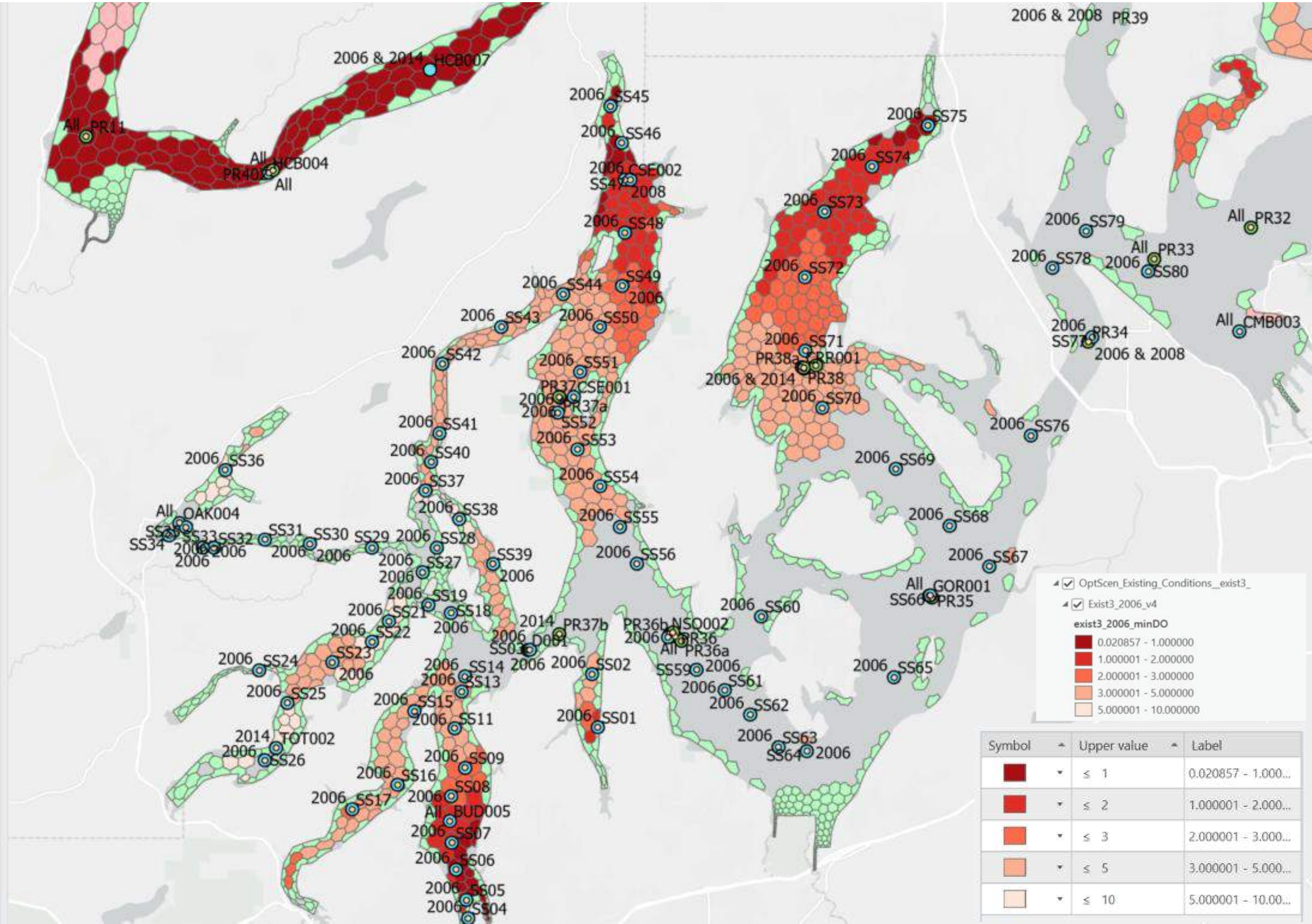


SIN001 – August 2014
[1999 – 2013]



South Sound

- Each inlet is assessed individually following where data are available
- Henderson Inlet: SS02 and SS01 aren't included in the comparison

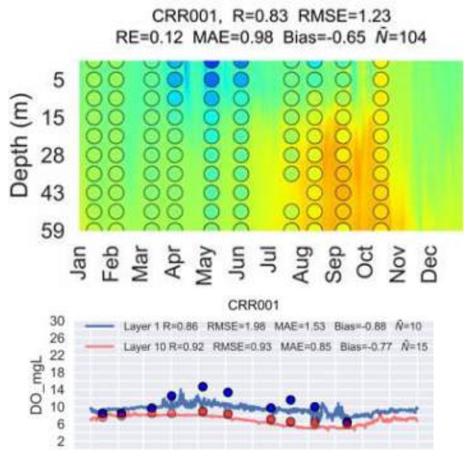


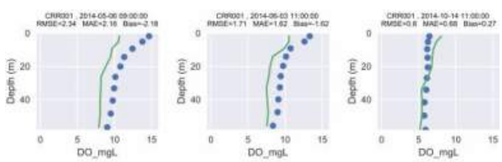
South Sound | 2014

Context

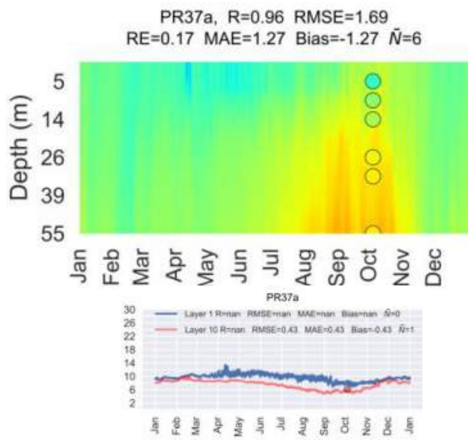
- CSE001 isn't included and is within the same cell as PR37a
- CRR001 and PR38a are in the same cell

★ CRR001 (Carr Inlet)

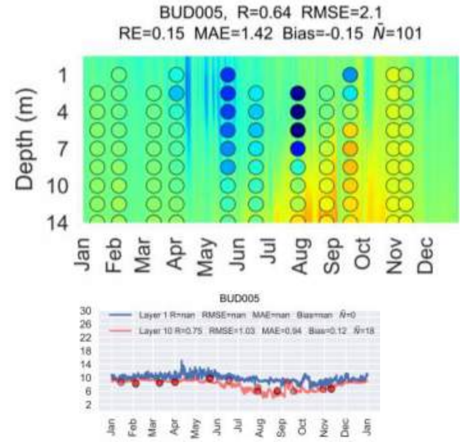




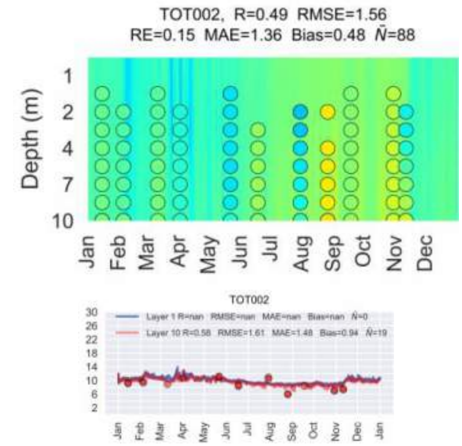
★ PR37a (Case Inlet)

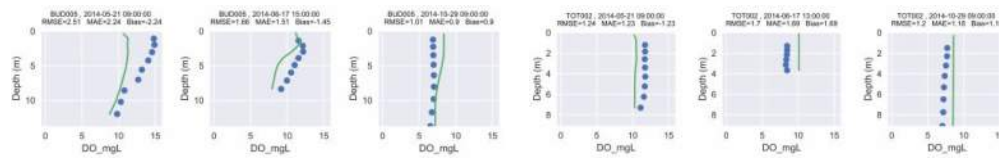


★ BUD005 (Bud Inlet)

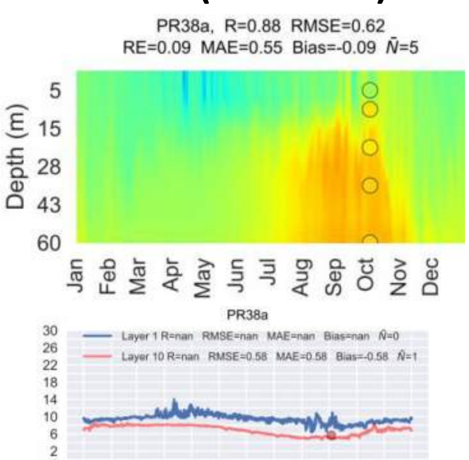


★ TOT002* (Totten Inlet)

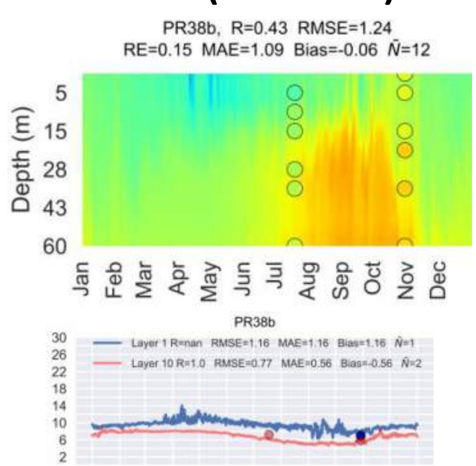




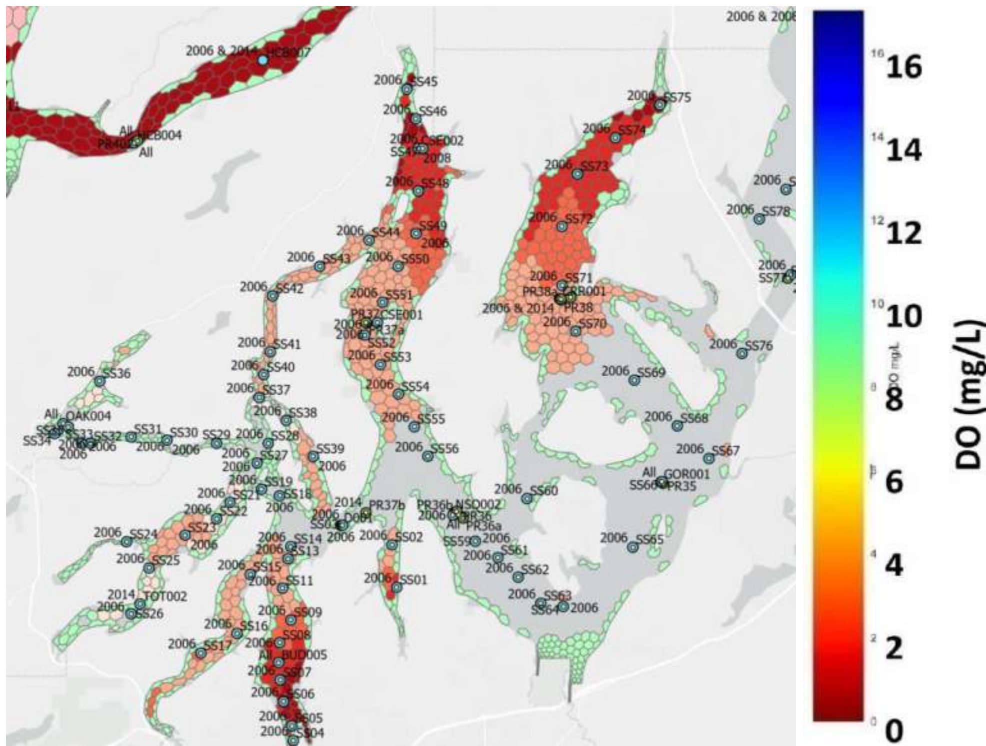
PR38a (Carr Inlet)



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

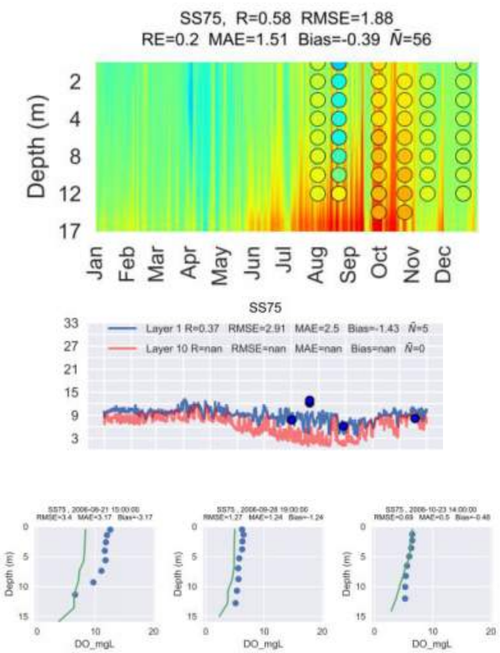


Carr Inlet | 2006

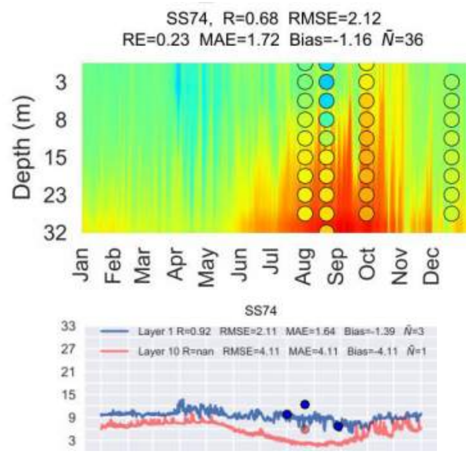
Context

- Located in South Sound
- PR38 isn't included and is within the same cell as CRR001

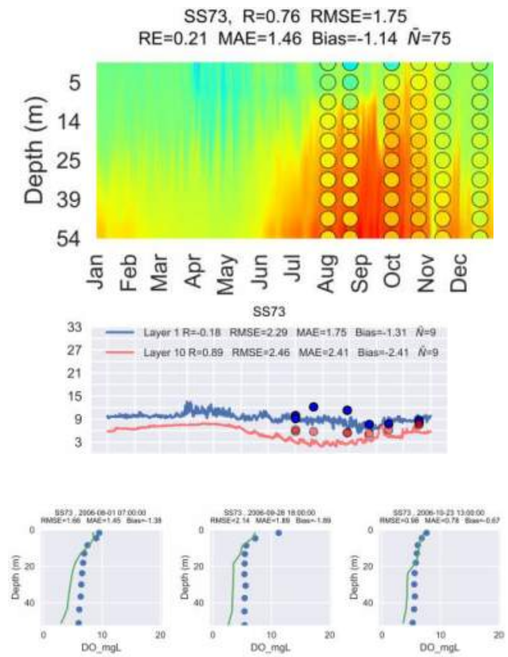
SS75



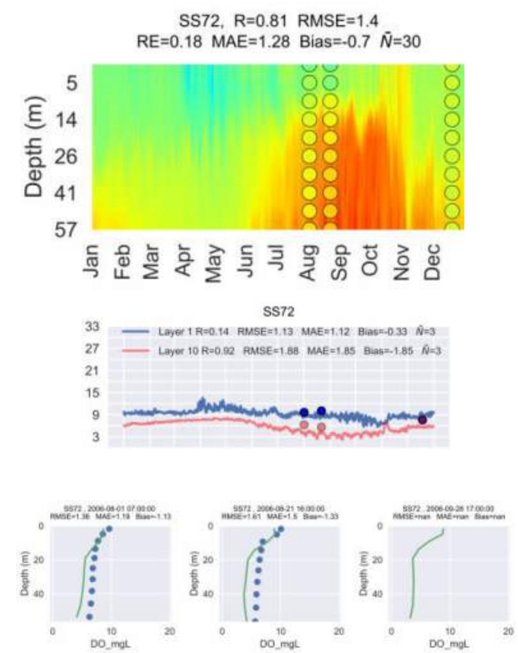
★ SS74



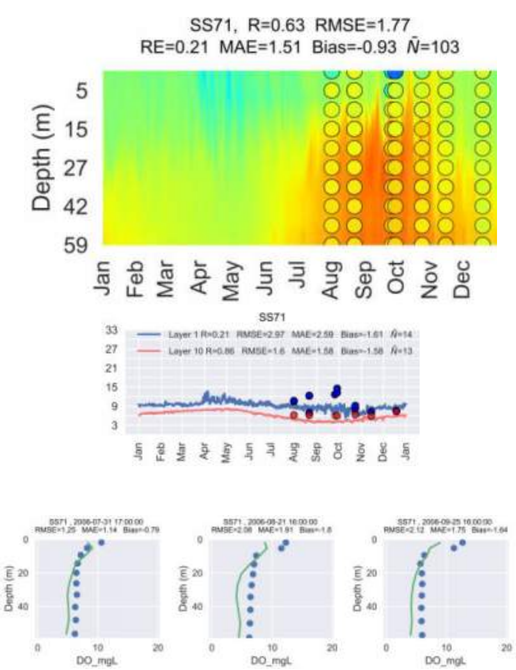
SS73



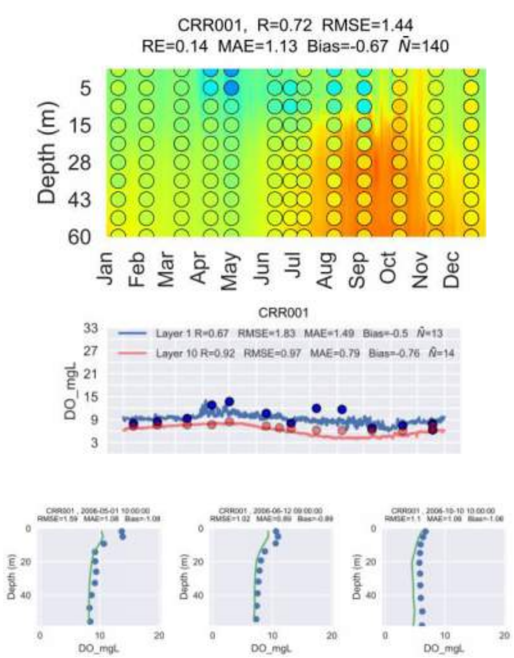
SS72



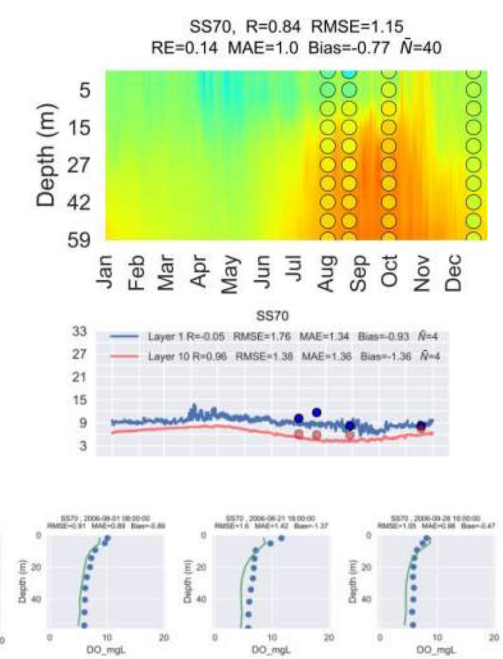
SS71

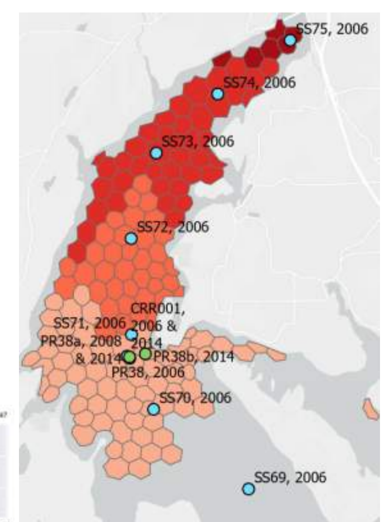


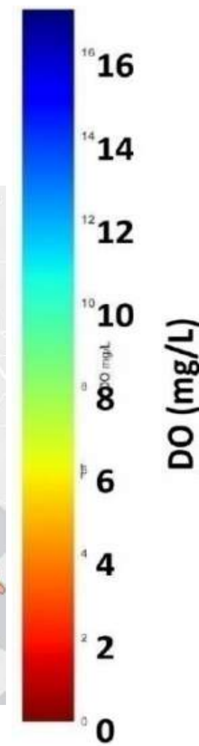
CRR001



★ SS70

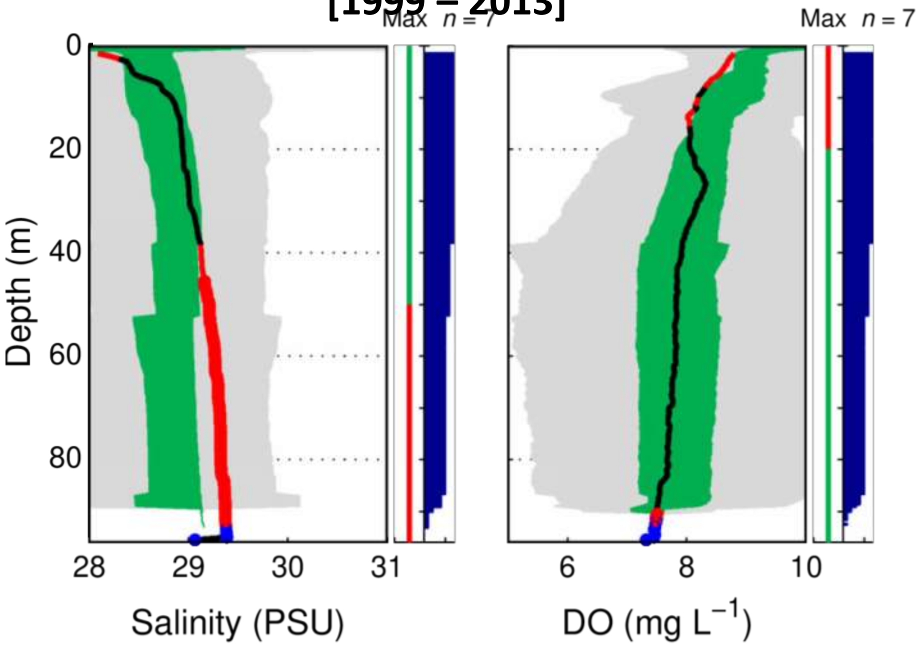




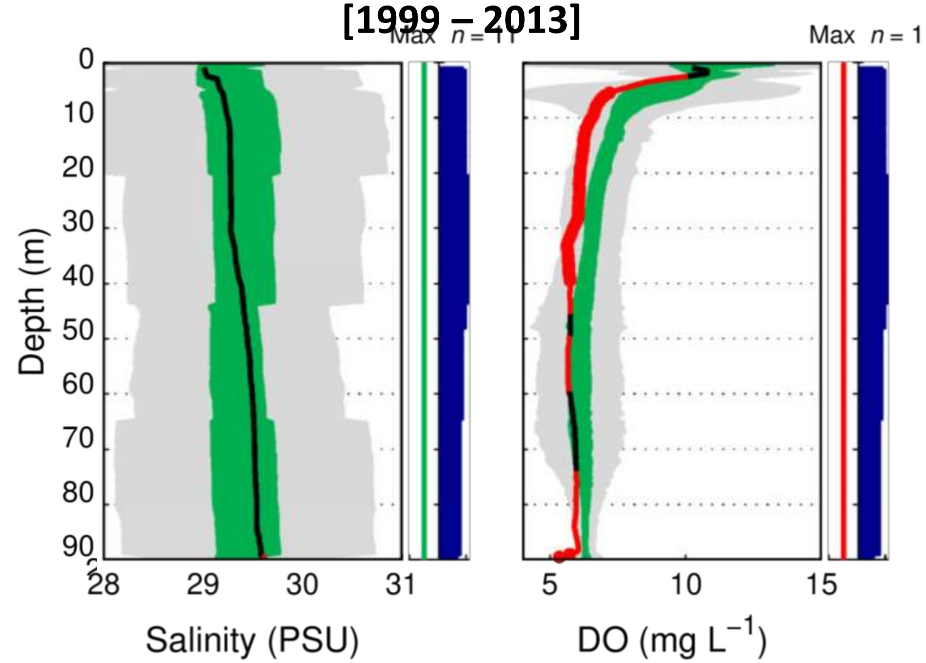


Carr Inlet

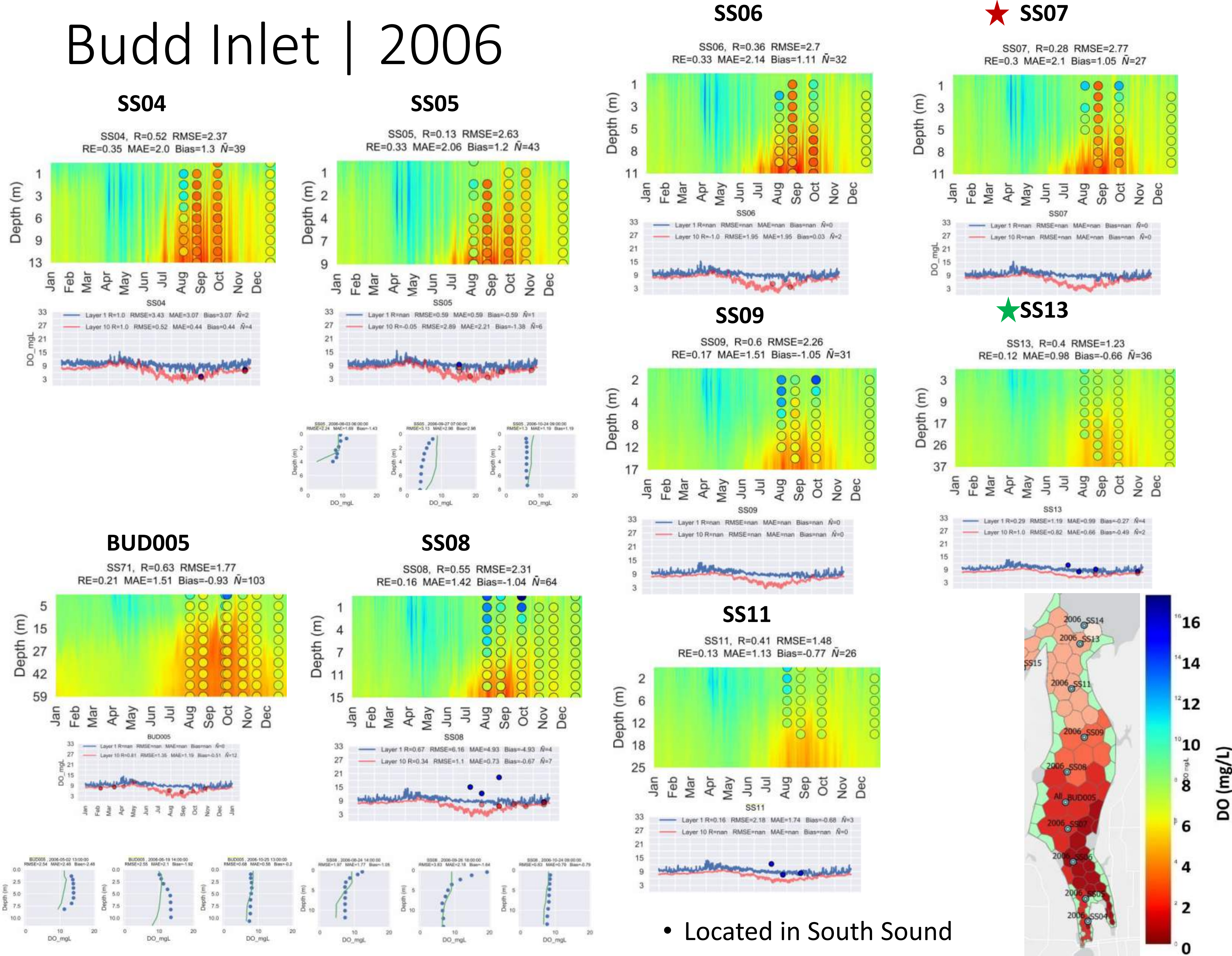
CRR001 – March 2014
[1999 – 2013]



CRR001 – August 2014
[1999 – 2013]



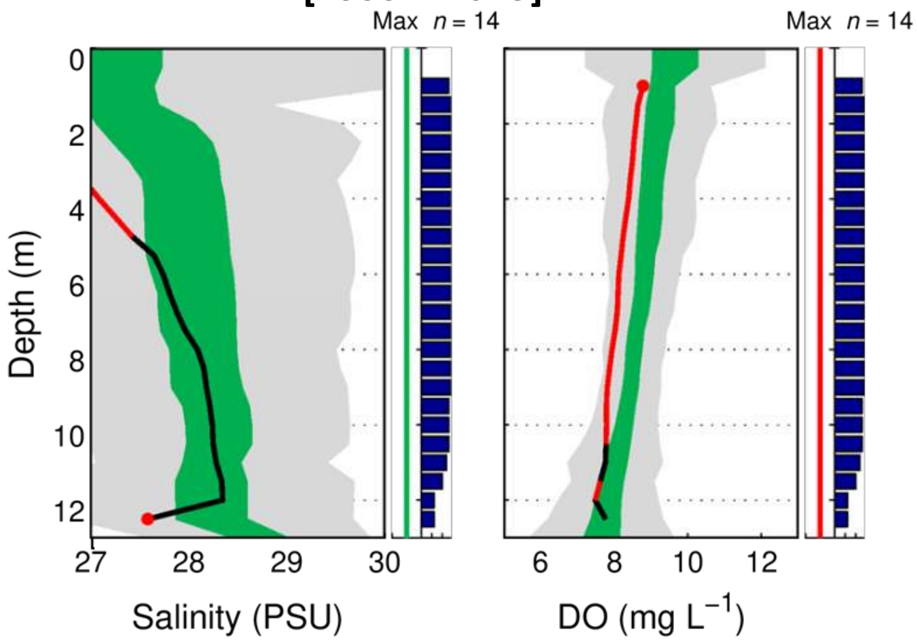
Budd Inlet | 2006



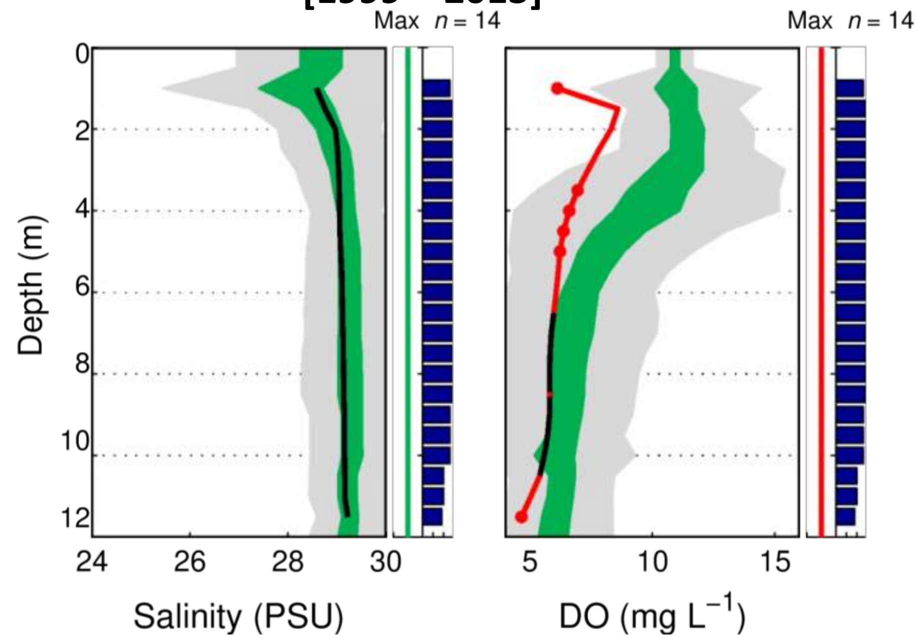
- Located in South Sound

Budd Inlet

BUD005 – March 2014
[1999 – 2013]



BUD005 – August 2014
[1999 – 2013]

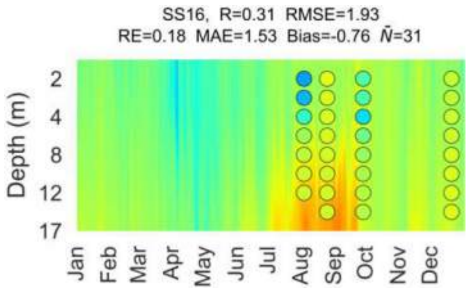


Eld Inlet | 2006

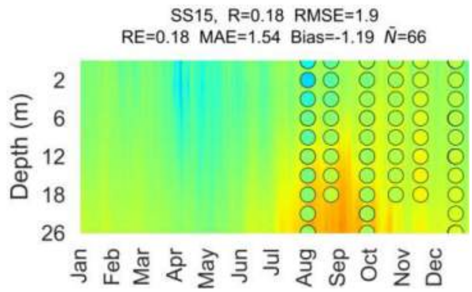
- Located in South Sound
- SS17 isn't included

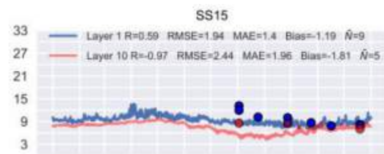
Context

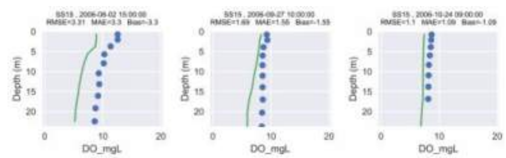
SS16

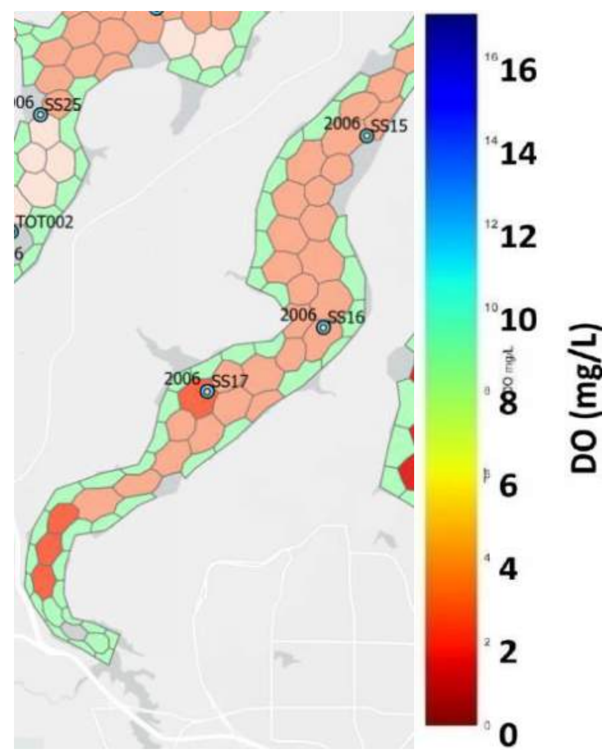


SS15







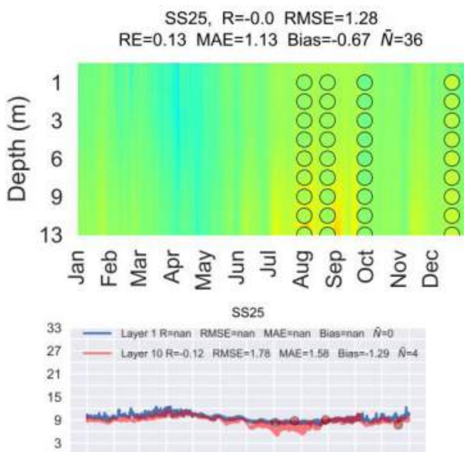


Totten Inlet | 2006

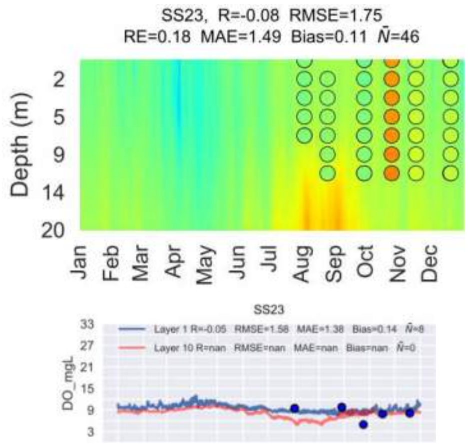
Context

- Located in South Sound
- SS26 is at the farthest end of the inlet, but compliant

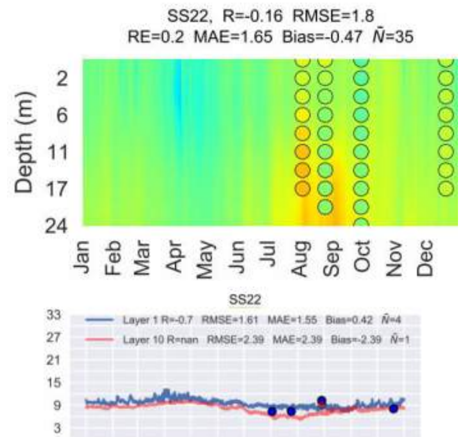
SS25



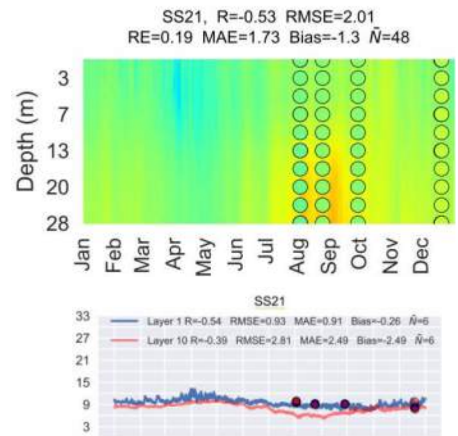
SS23

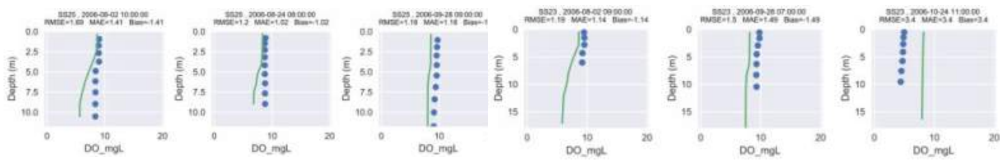


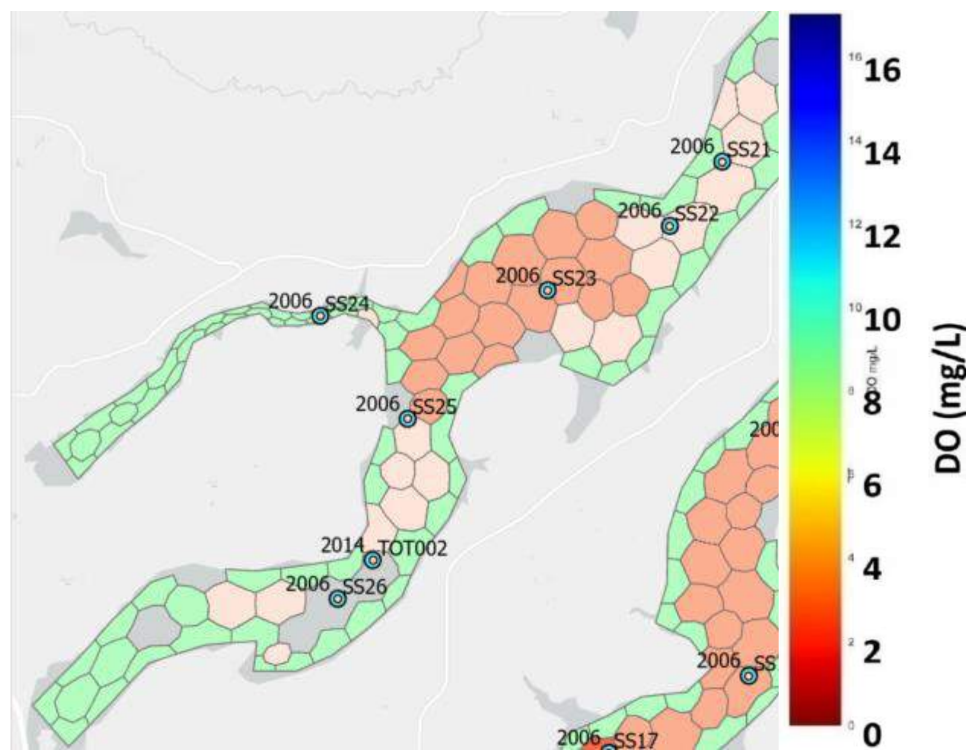
SS22



SS21

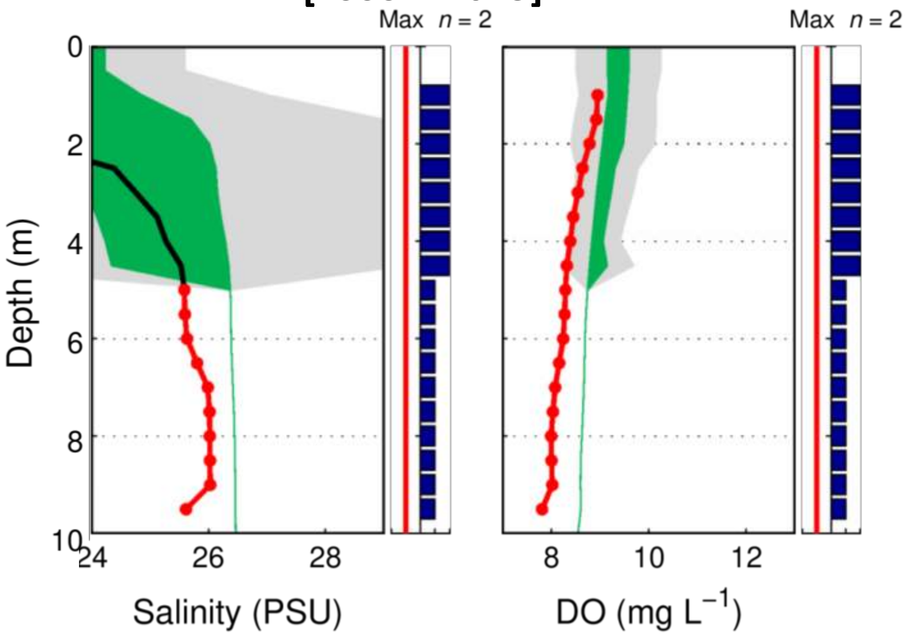




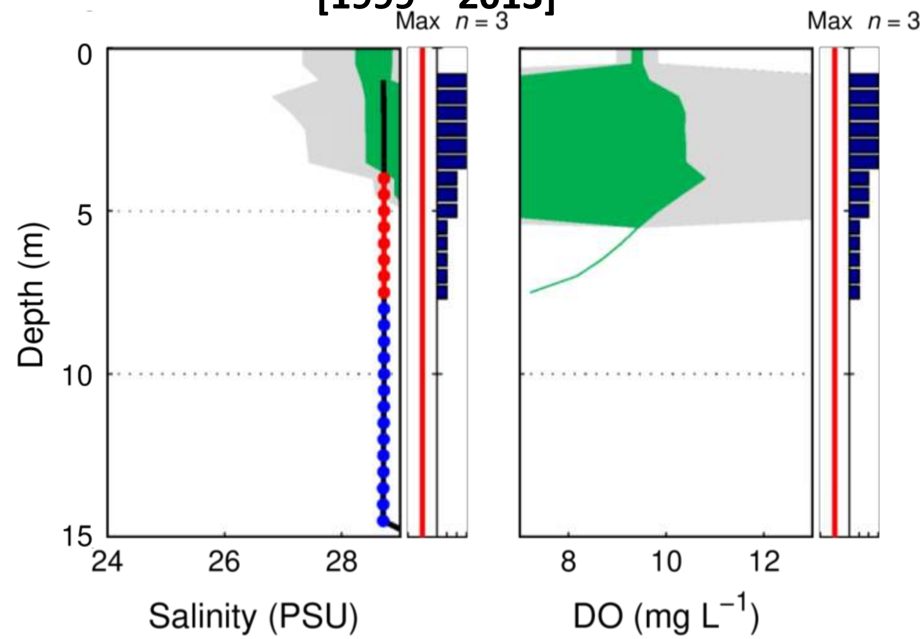


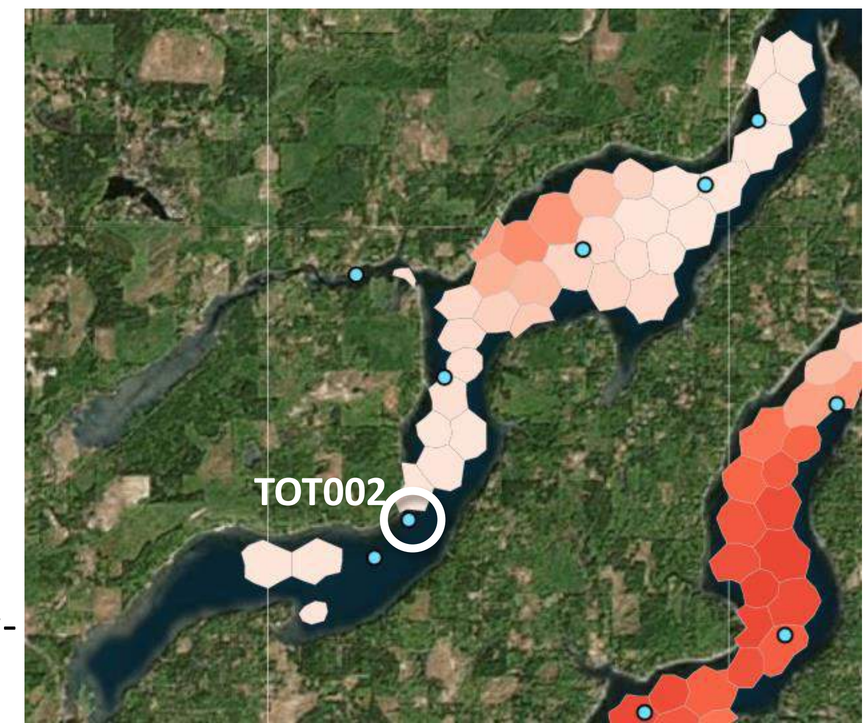
Totten Inlet

TOT002* – March 2014
[1999 – 2013]



TOT002* – August 2014
[1999 – 2013]





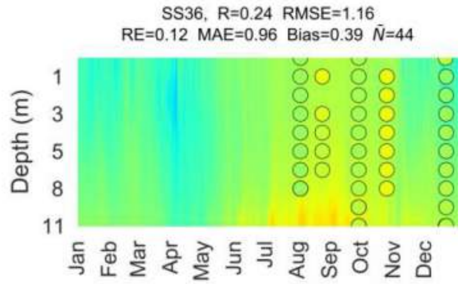
*While the monitoring station is compliant, it's the closest long-term monitoring station to the non-compliant inlet

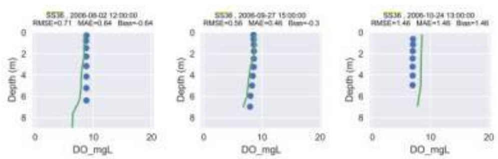
Oakland Bay | 2006

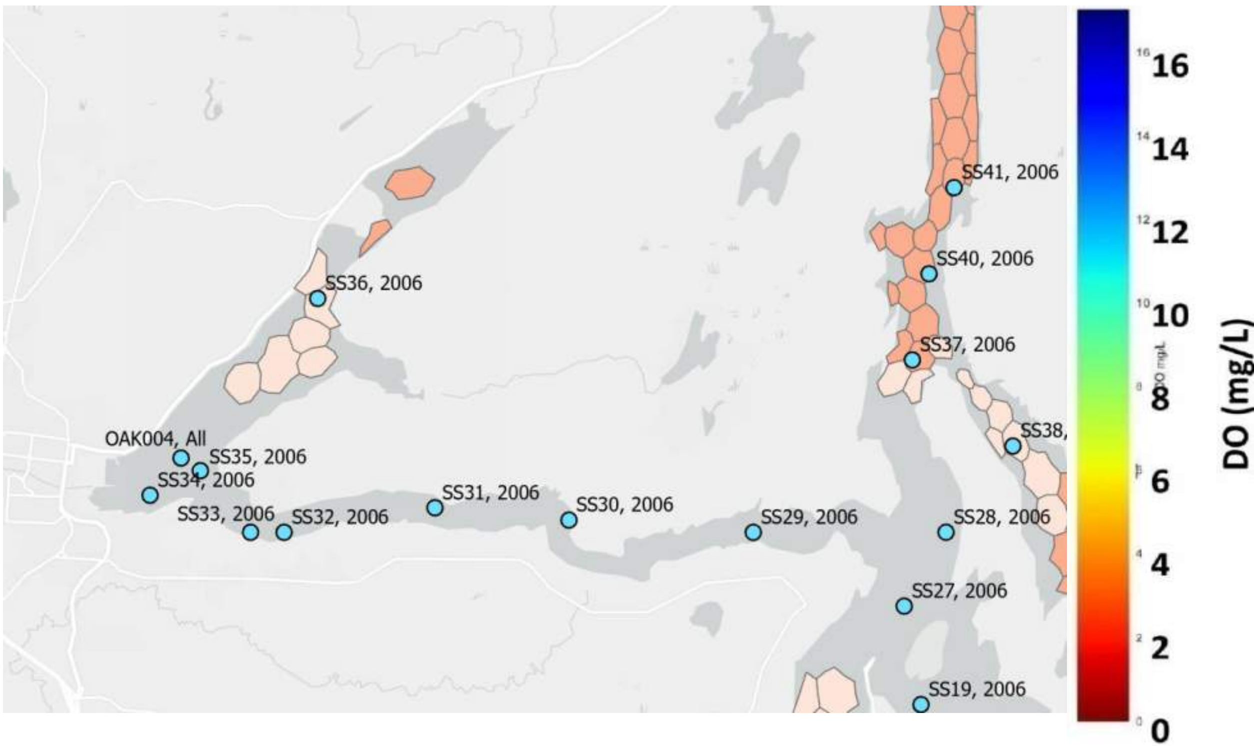
- Located in South Sound

Context

★ **SS36**

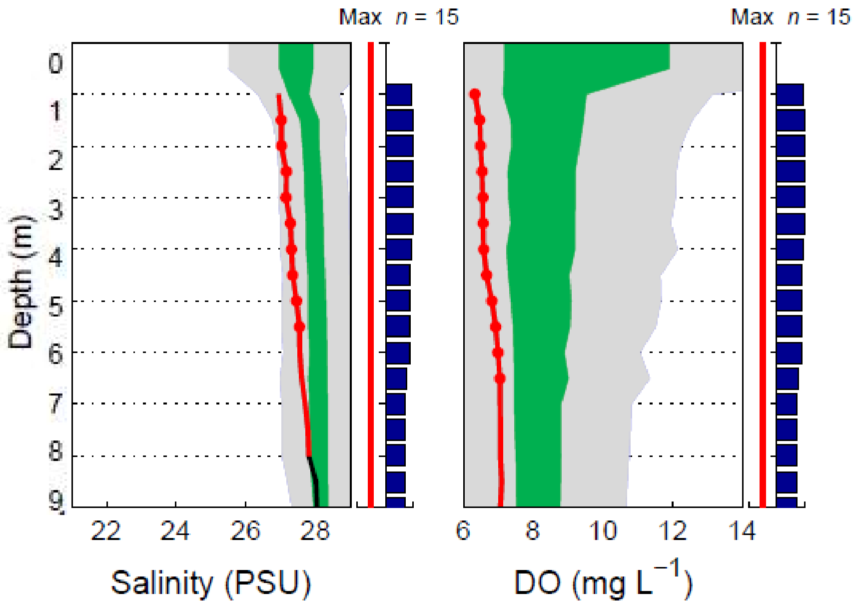






Oakland Bay

OAK004* – August 2014
[1999 – 2013]



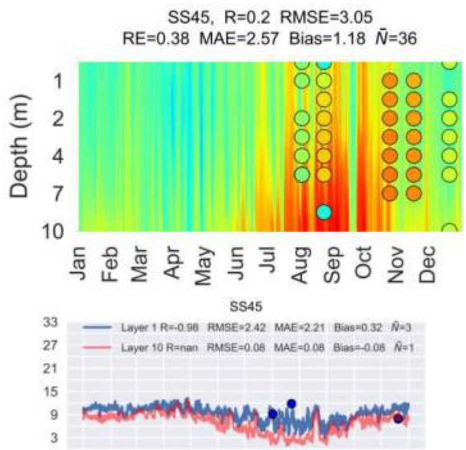
*While the monitoring station is compliant, it's the closest long-term monitoring station to the non-compliant inlet

Case Inlet | 2006

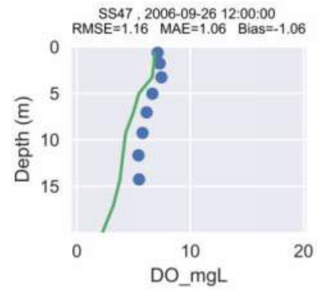
Context

- Located in South Sound
- SS46 is also available, but falls within the masked area
- SS47 only has a partial comparison

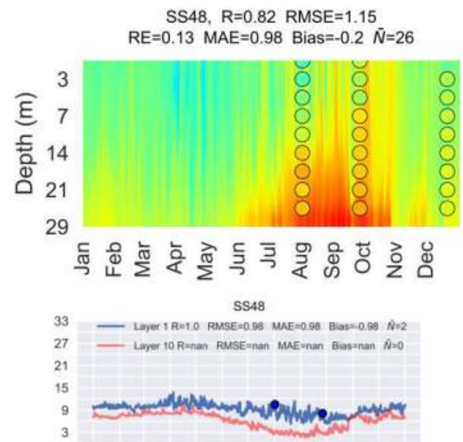
SS45



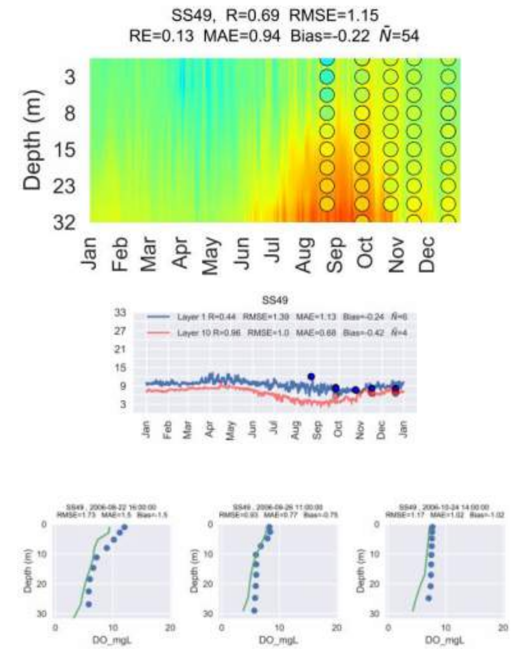
SS47



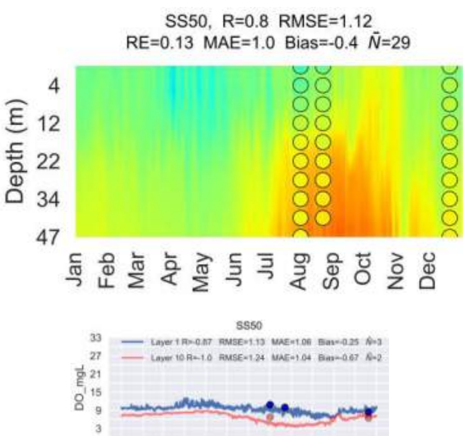
SS48



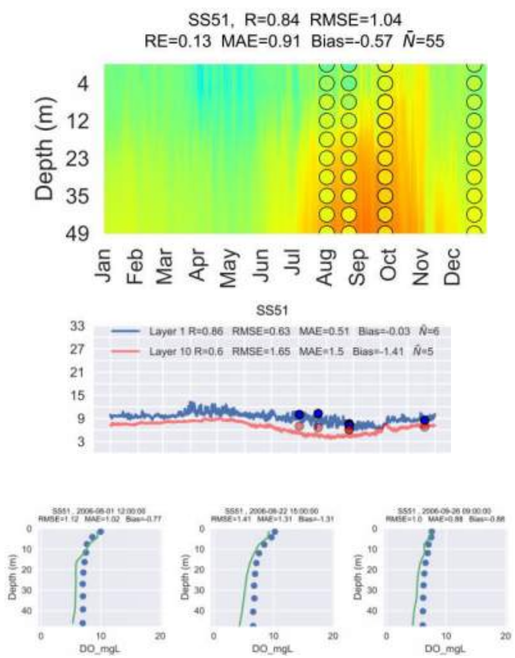
SS49



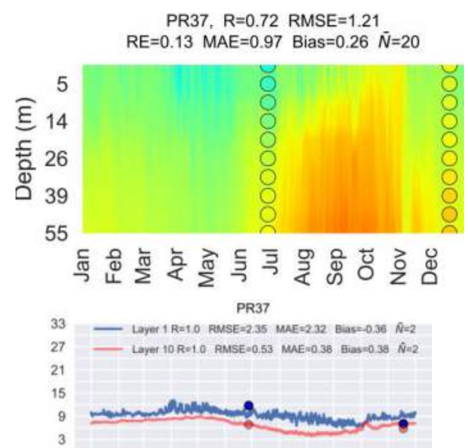
SS50

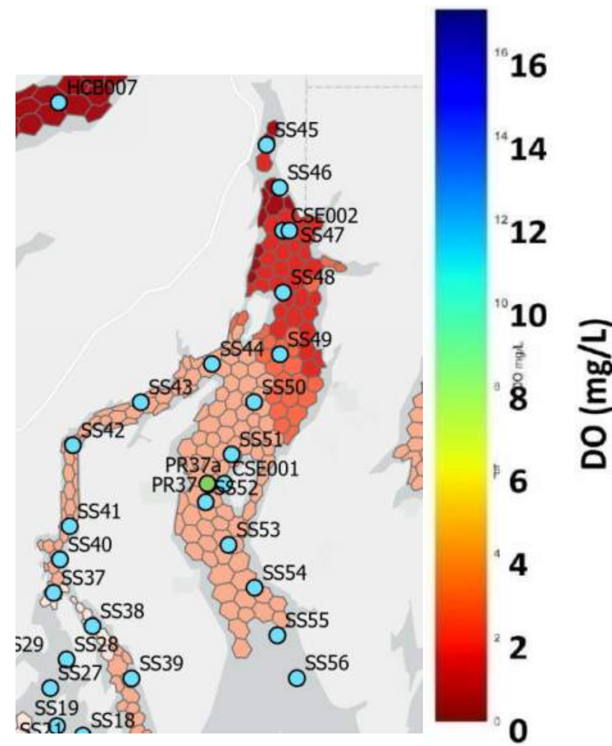


SS51



PR37



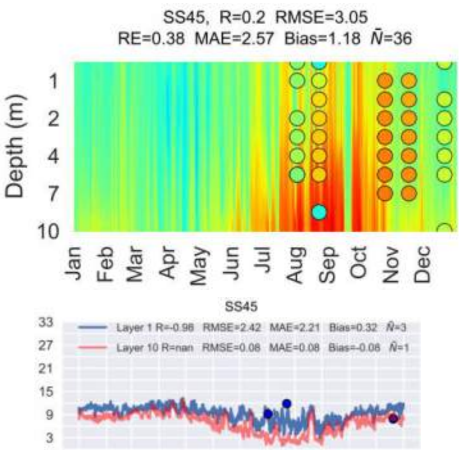


Case Inlet | 2006

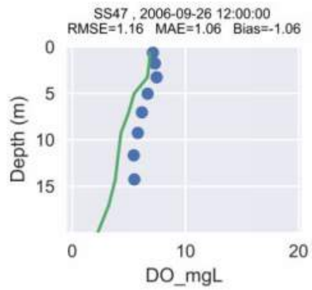
Context

- Located in South Sound
- SS46 is also available, but falls within the masked area
- SS47 only has a partial comparison

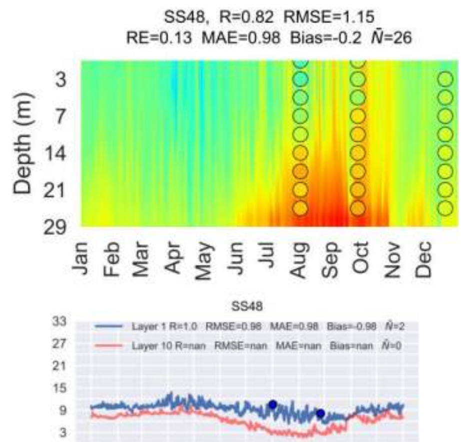
★ SS45



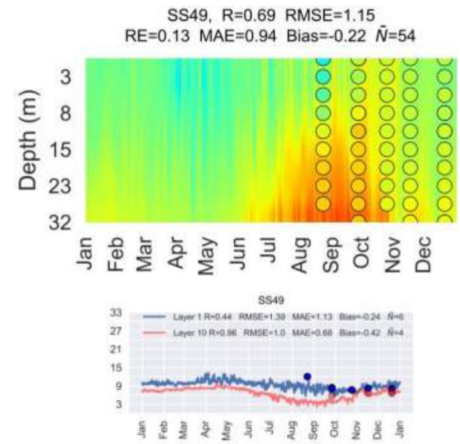
SS47

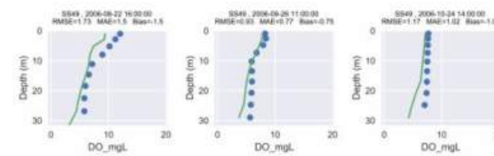


SS48

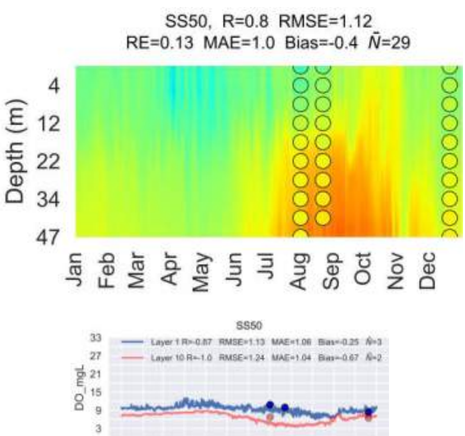


SS49

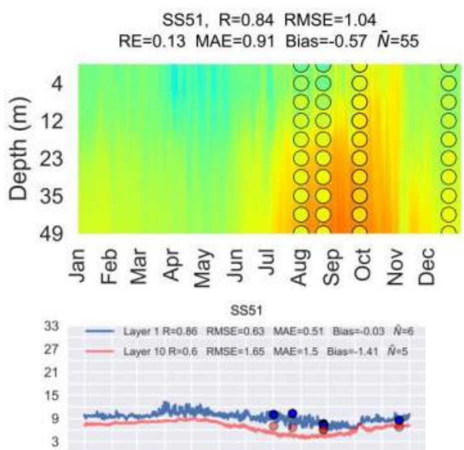


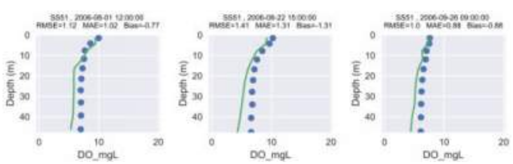


SS50

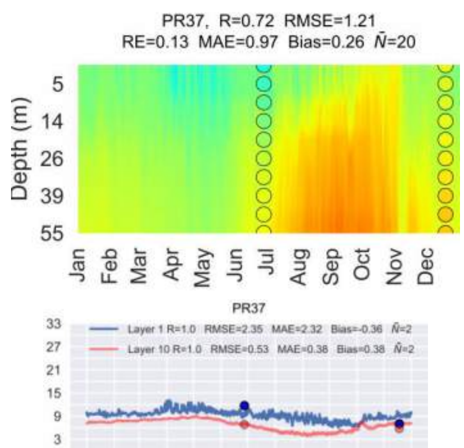


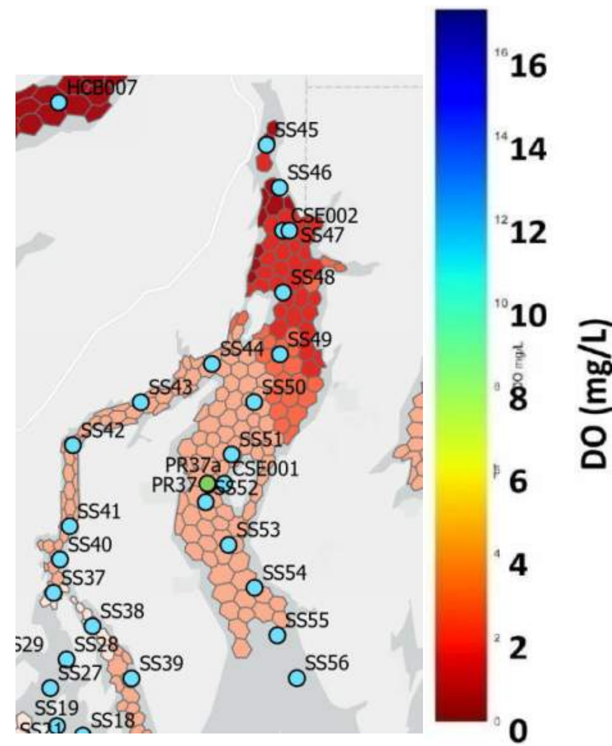
★ SS51





PR37



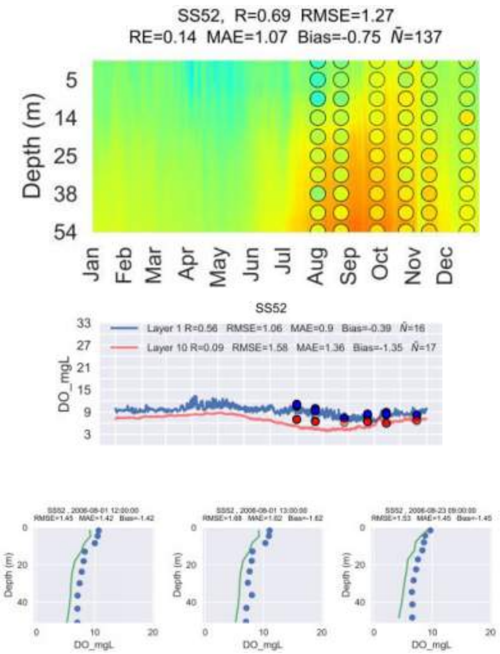


Case Inlet cont. | 2006

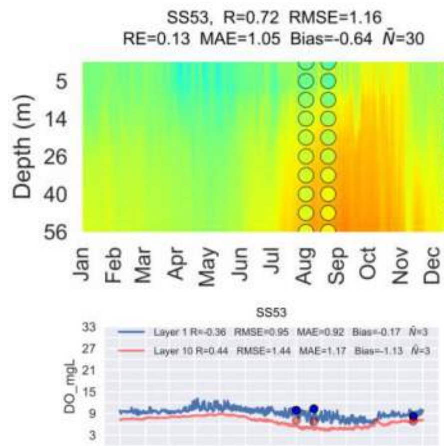
Context

- Located in South Sound
- SS43 is also available, but falls within the masked area

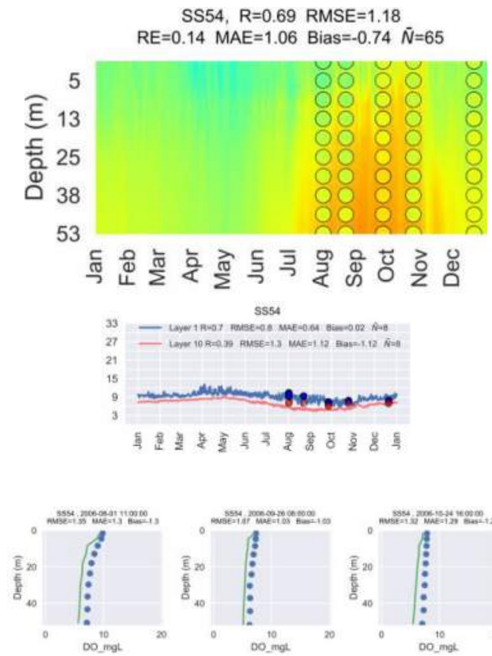
SS52



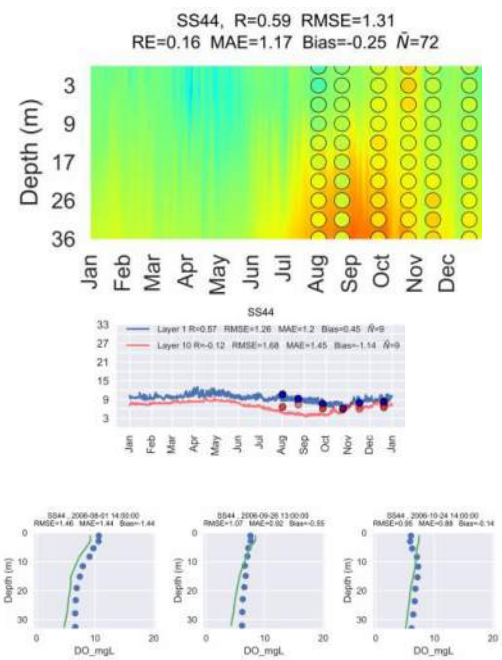
SS53



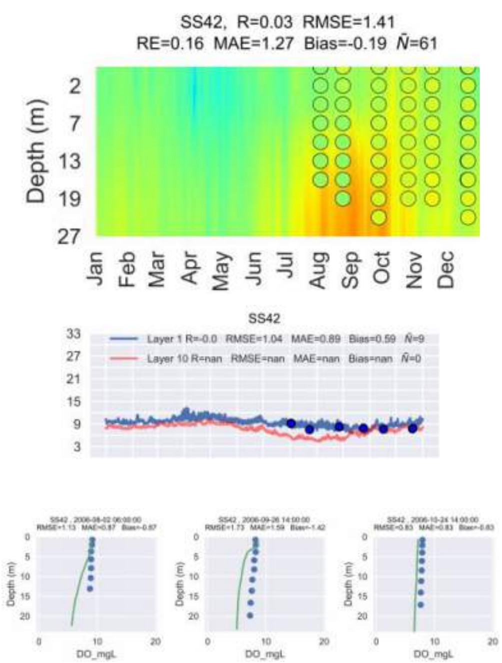
SS54



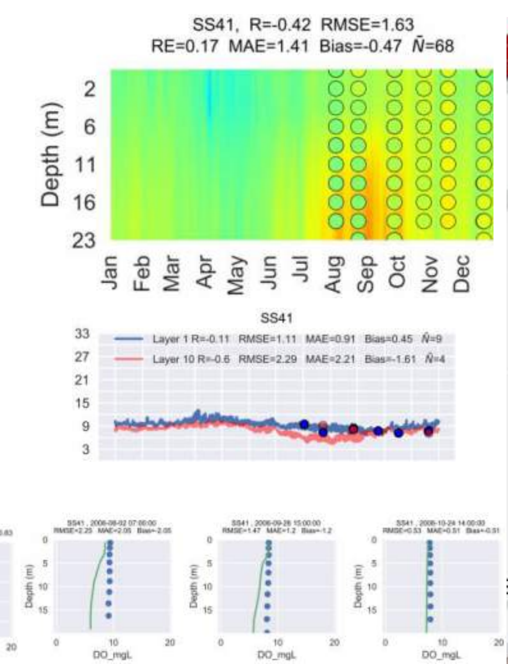
SS44

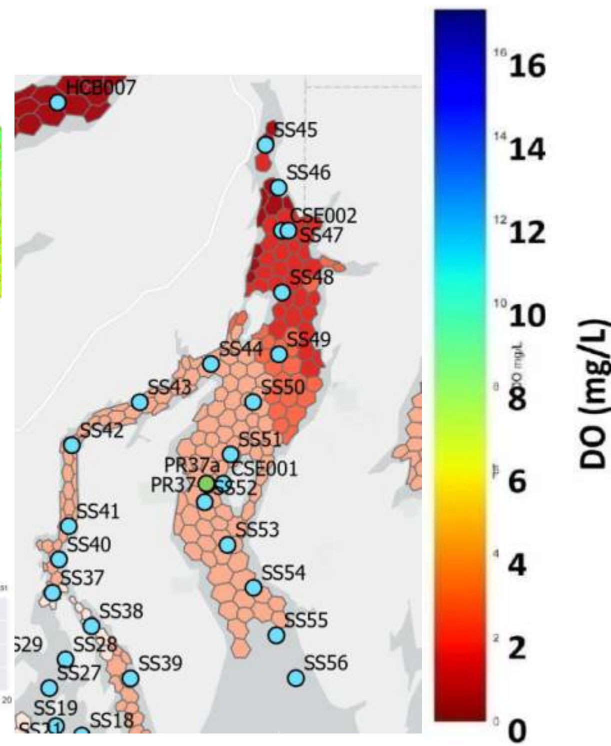


SS42



SS41



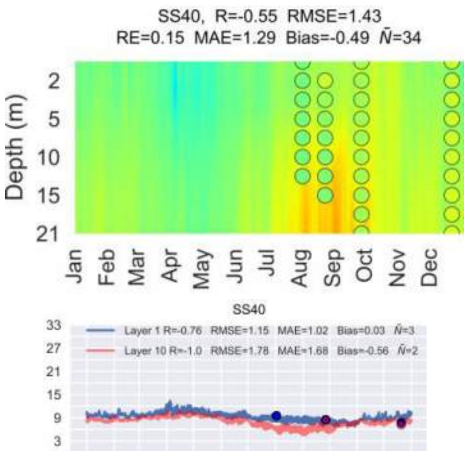


Case Inlet cont.| 2006

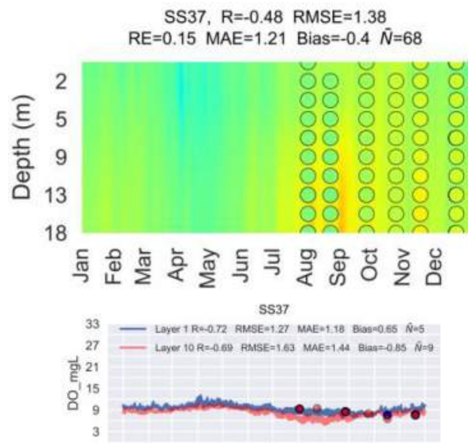
- Located in South Sound

Context

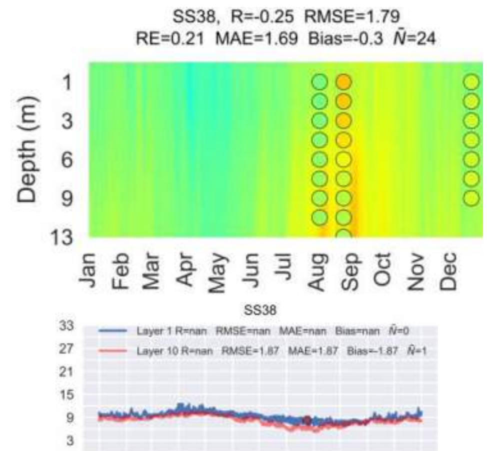
SS40



SS37



SS38



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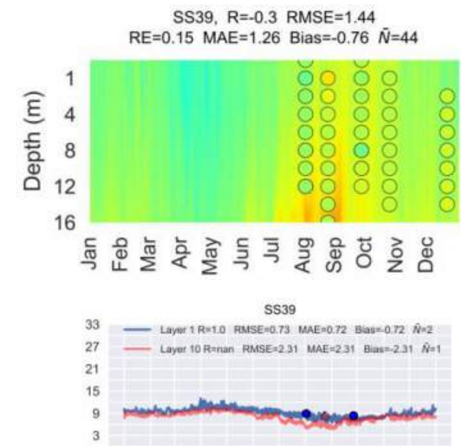
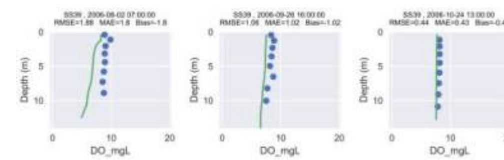
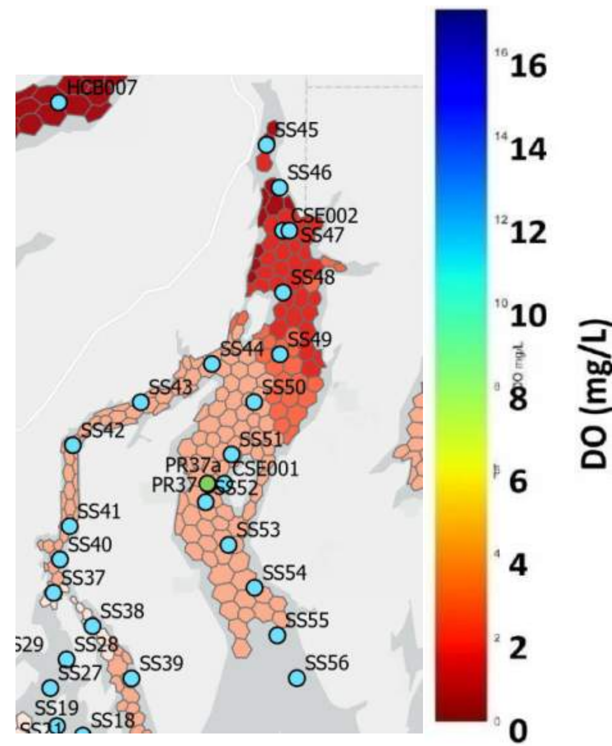
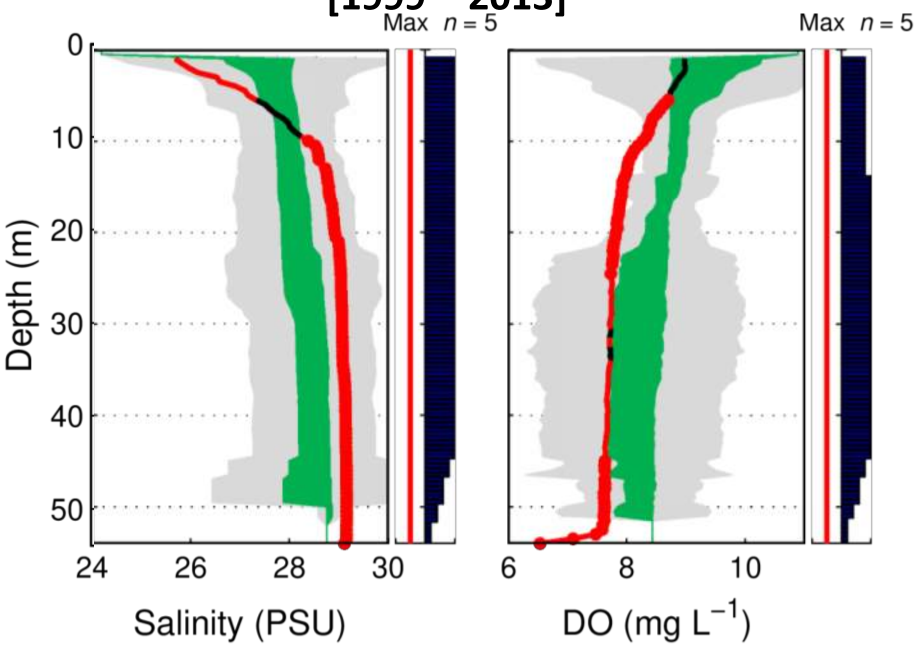




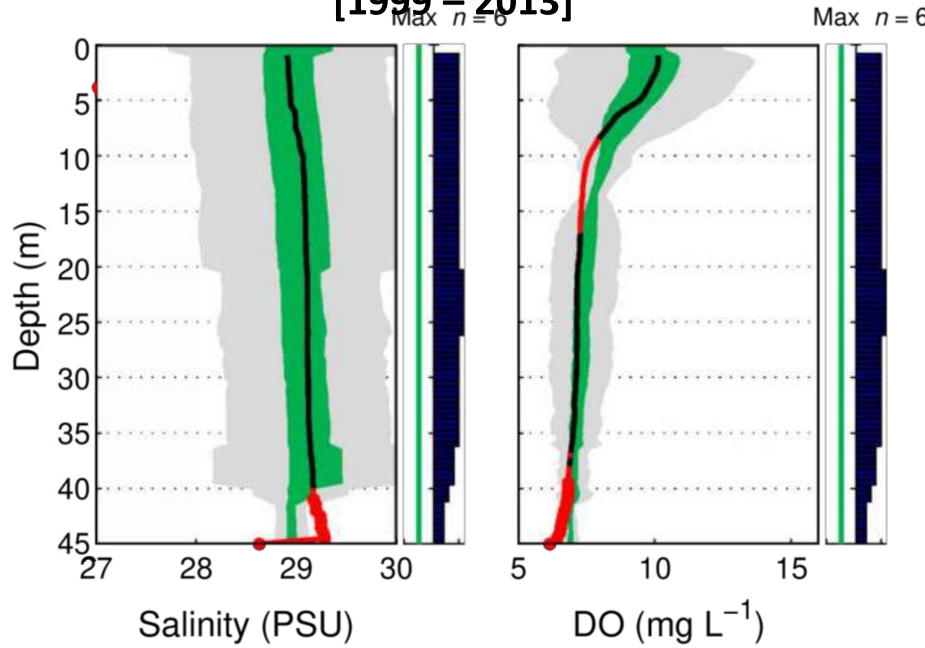


Case Inlet

CSE001* – March 2014
[1999 – 2013]



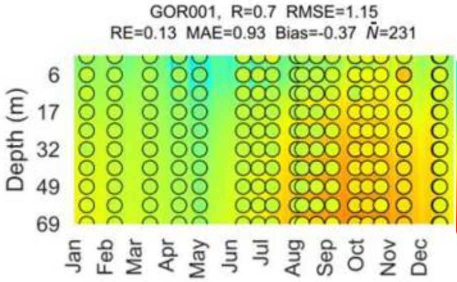
CSE001* – August 2014
[1999 – 2013]

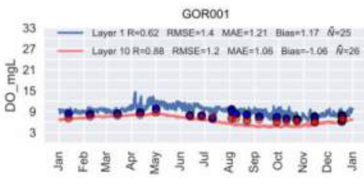


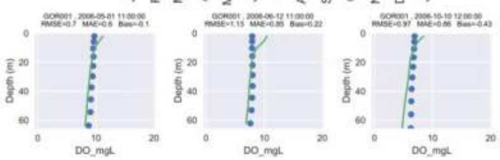
*Ecology et al. 2021 did not compare the model predictions to this monitoring station. However, it falls within the same non-compliant model cell as monitoring station PR37a which was compared.

Deep Location for Comparison | South Sound

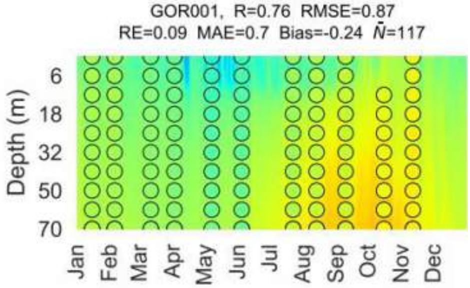
GOR001 - 2006

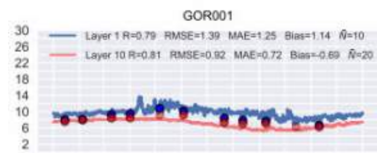


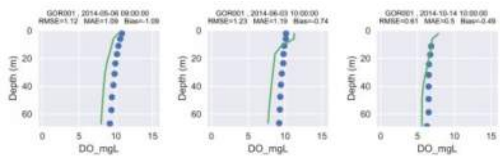




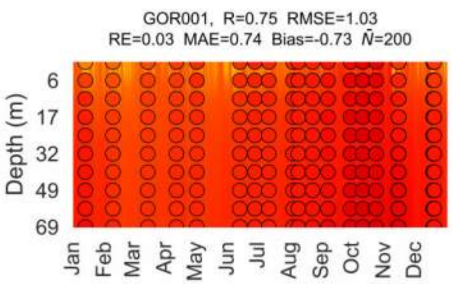
GOR001 - 2014



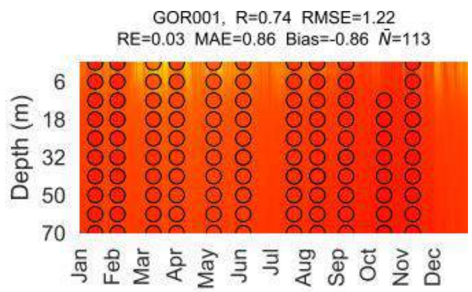




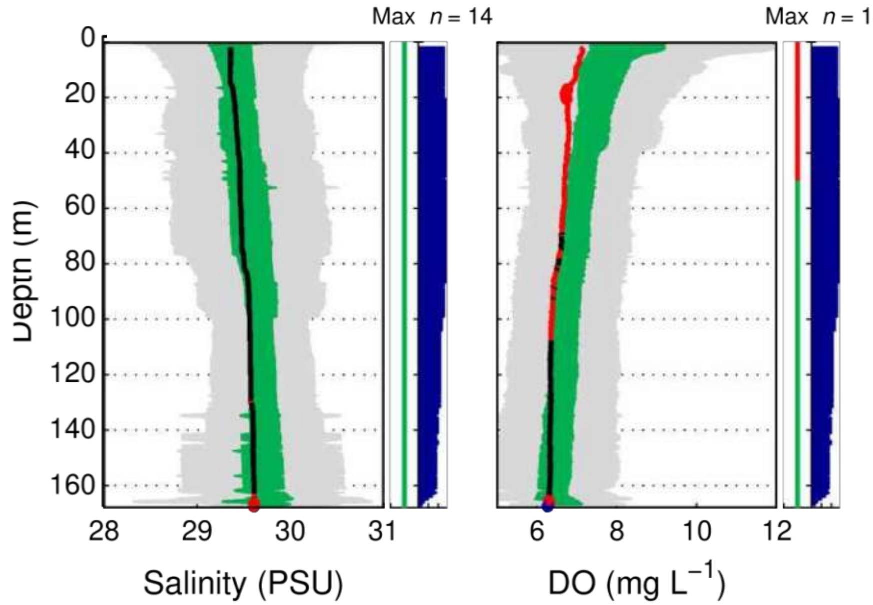
Salinity

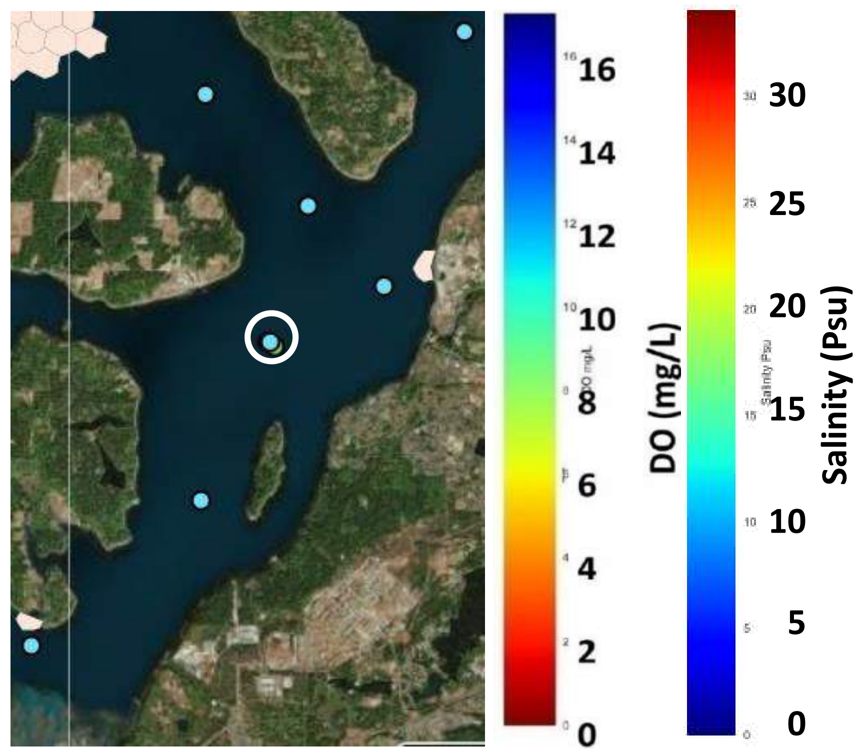


Salinity



GOR001 – August 2014
(1999 – 2013)

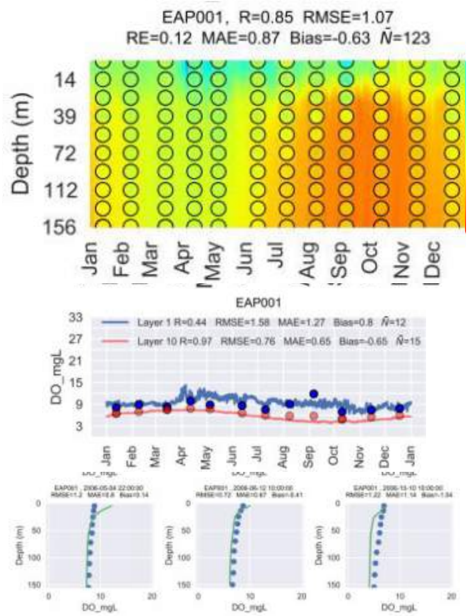




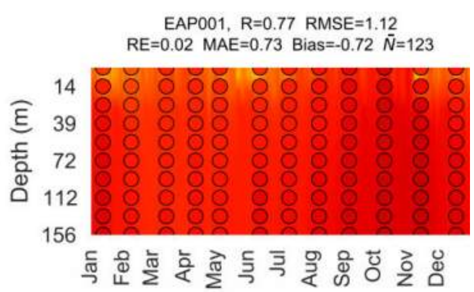
*Note this location has a modeled depth of approximately **65m** and is compliant*

Deep Location for Comparison | Main Basin

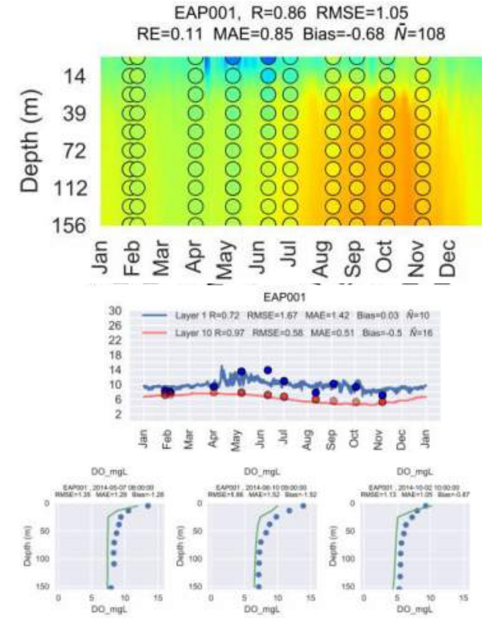
EAP001 - 2006



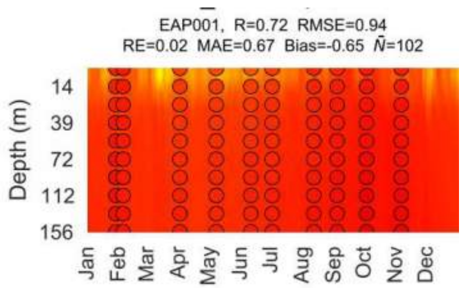
Salinity



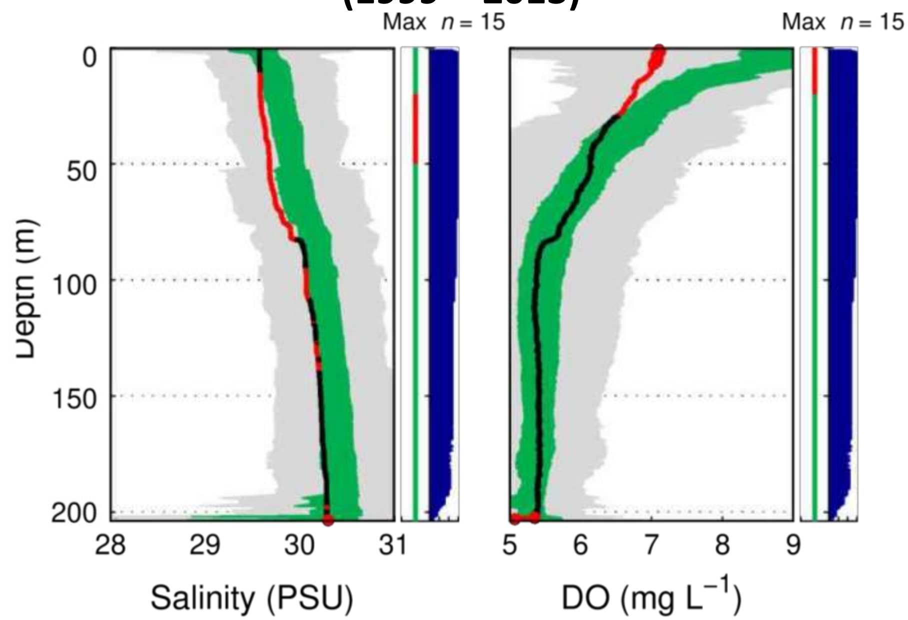
EAP001 - 2014

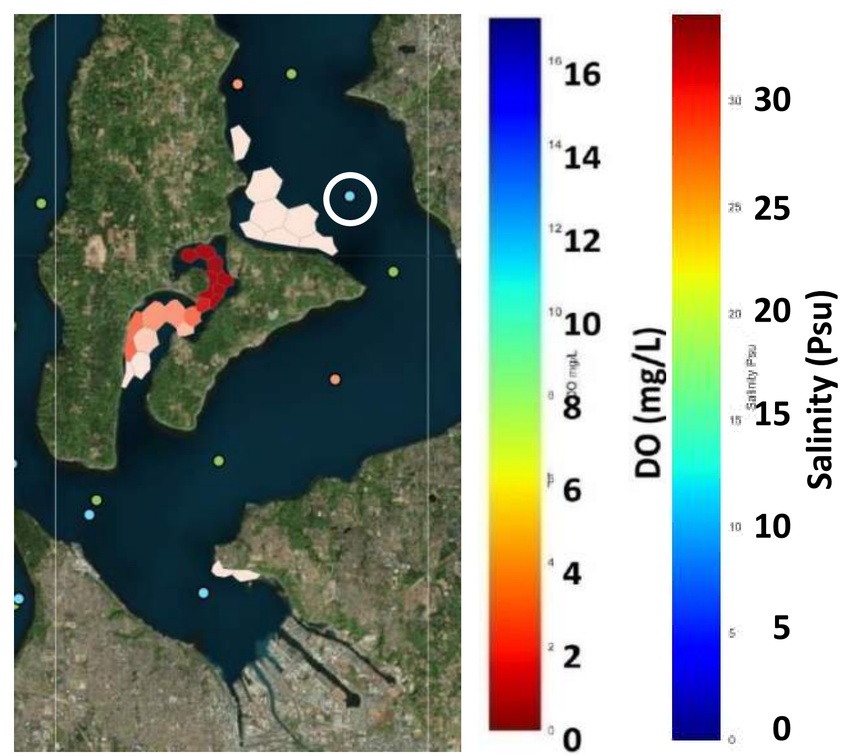


Salinity



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.

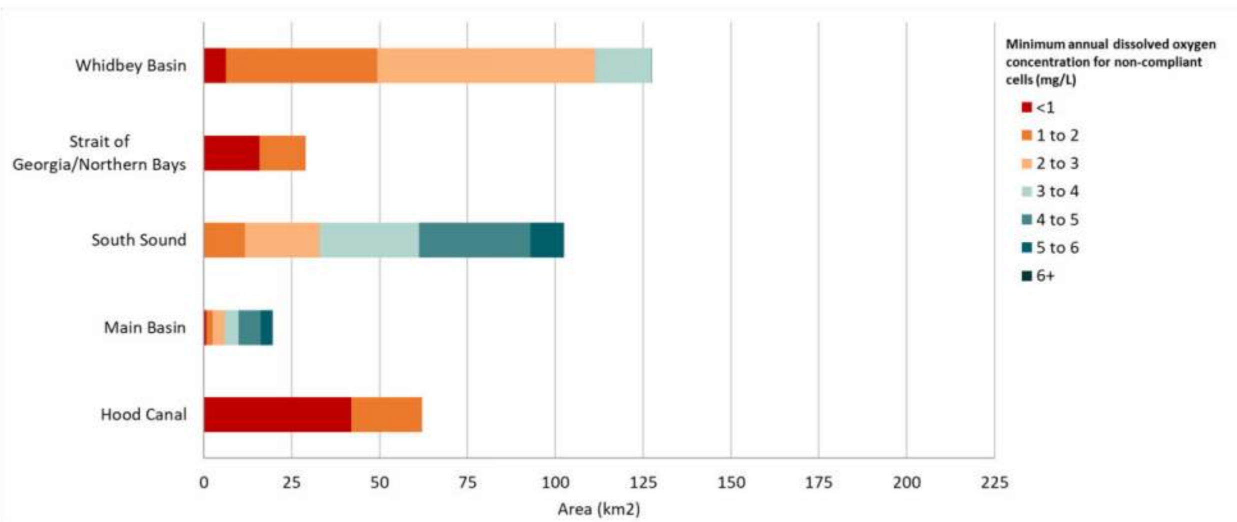


Figure 2.1 2014: Minimum annual dissolved oxygen concentration for non-compliant areas by region
Note that the plot for 2014 minimum annual dissolved oxygen concentration for non-compliant areas by embayment is included in the main body of the report.

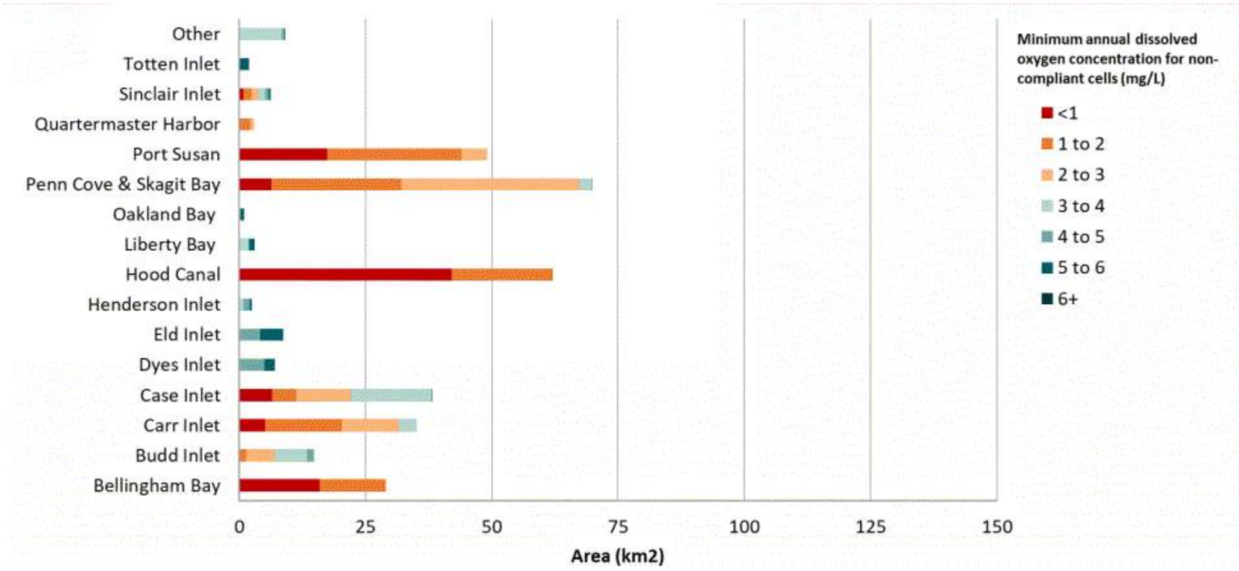


Figure 2.2 2014: Minimum annual dissolved oxygen concentration for non-compliant areas by embayment

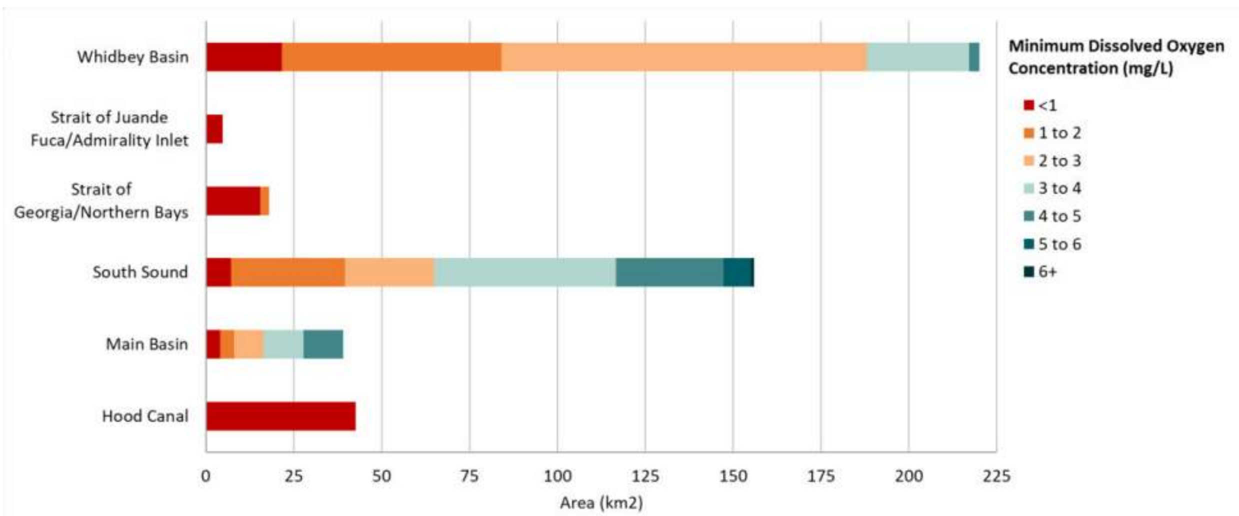


Figure 2.3 2006: Minimum annual dissolved oxygen concentration for non-compliant areas by region

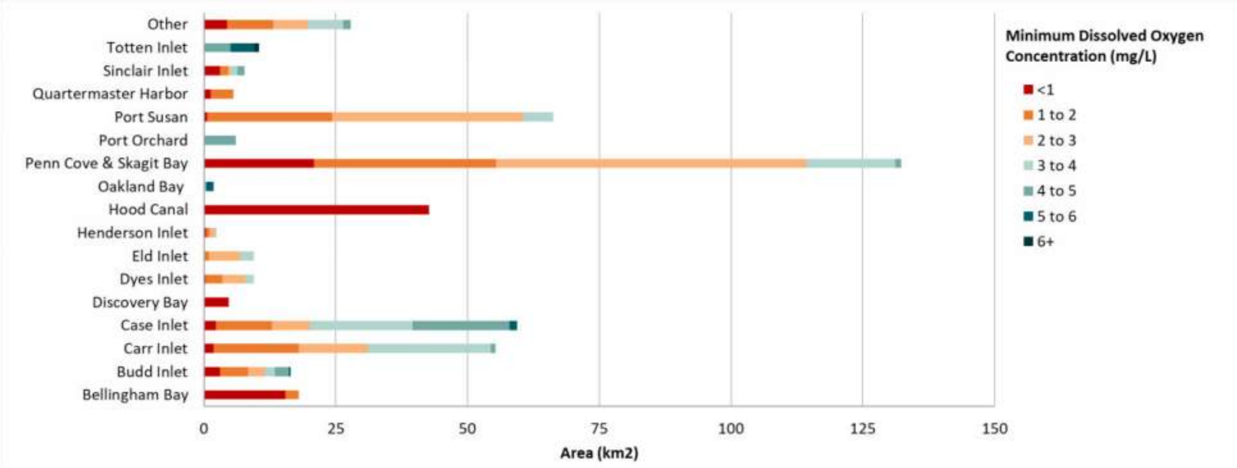


Figure 2.4 2006: Minimum annual dissolved oxygen concentration for non-compliant areas by embayment

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.

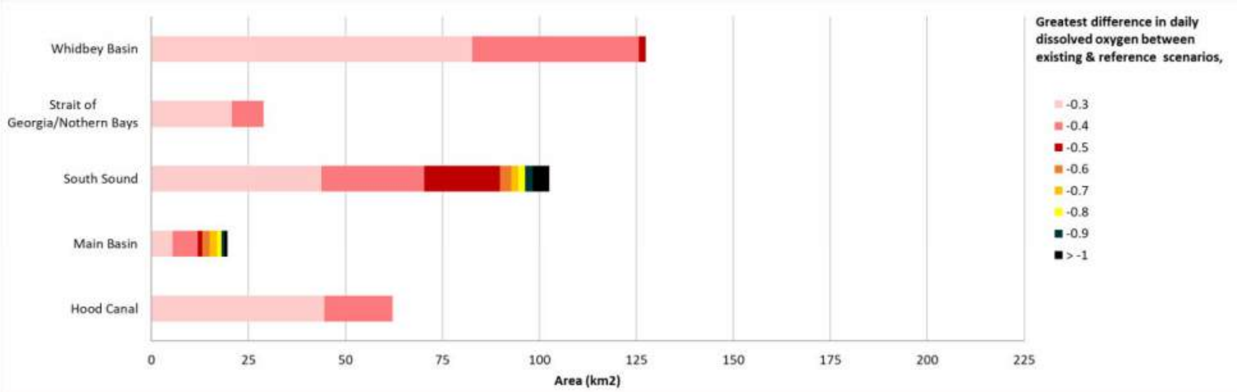


Figure 2.5 2014: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by region

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.

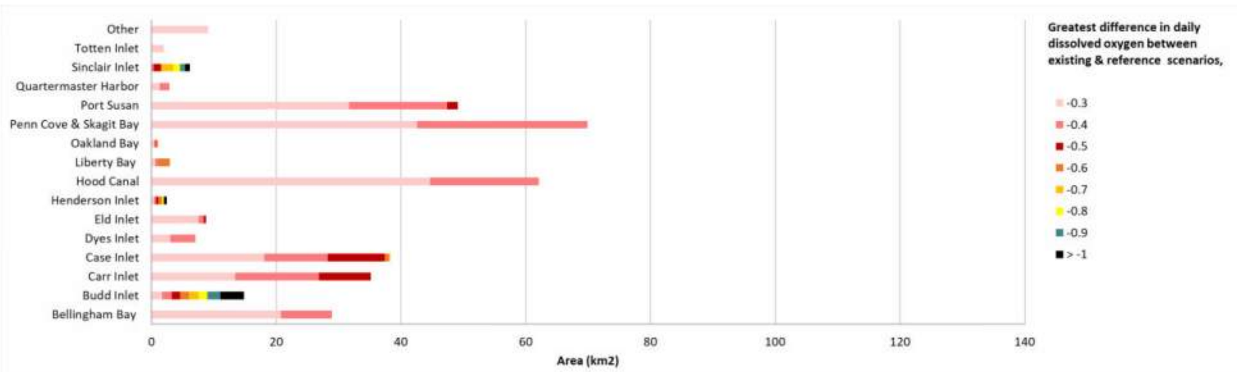


Figure 2.6 2014: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by embayment

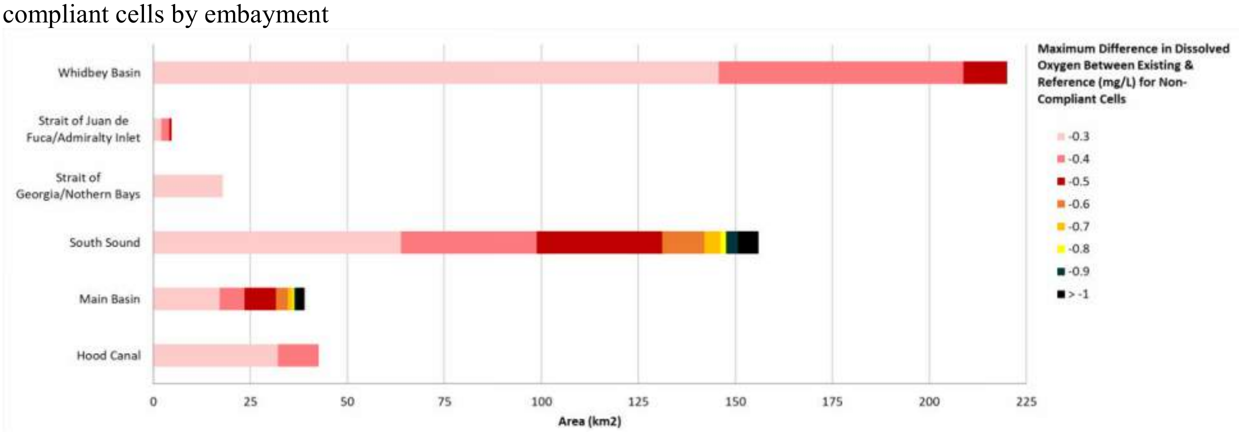


Figure 2.7 2006: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by region

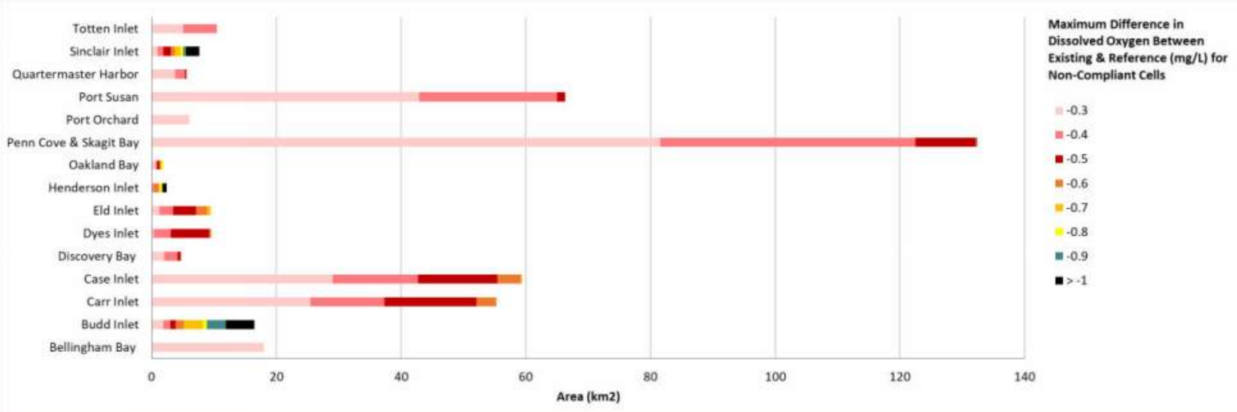


Figure 2.8 2006: Greatest difference in daily dissolved oxygen between existing & reference (mg/L) for non-compliant cells by embayment

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 (%)	TO C: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.

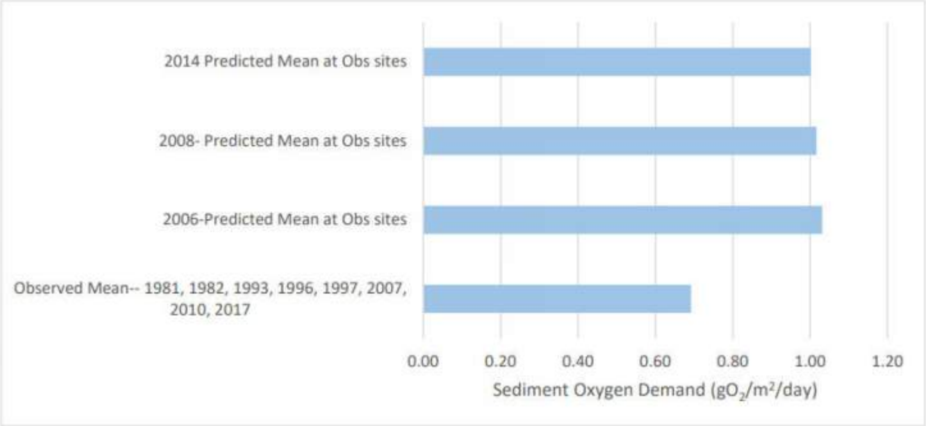


Figure 3.1. Comparison of predicted and observed sediment oxygen demand at multiple locations, but at different times. Reproduced from Figure I2 of Appendix I of Ahmed et al. (2019)

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)]

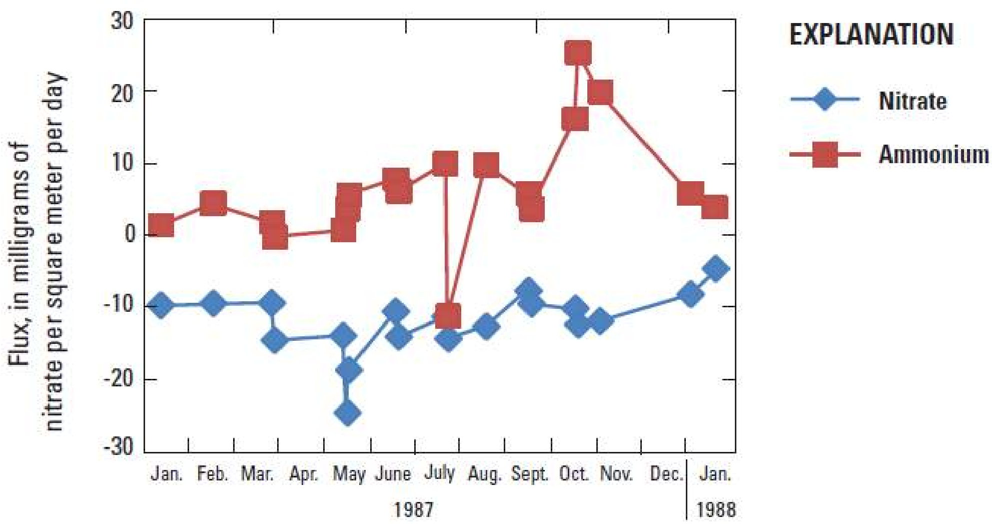


Figure 4. Time-series plot showing nitrate (NO_3^-) and ammonium (NH_4^+) benthic flux in Dabob Bay, Puget Sound, Washington. Negative values indicate flux into the sediment. Data from Colbert and others, University of Washington, unpub. data, 2010.

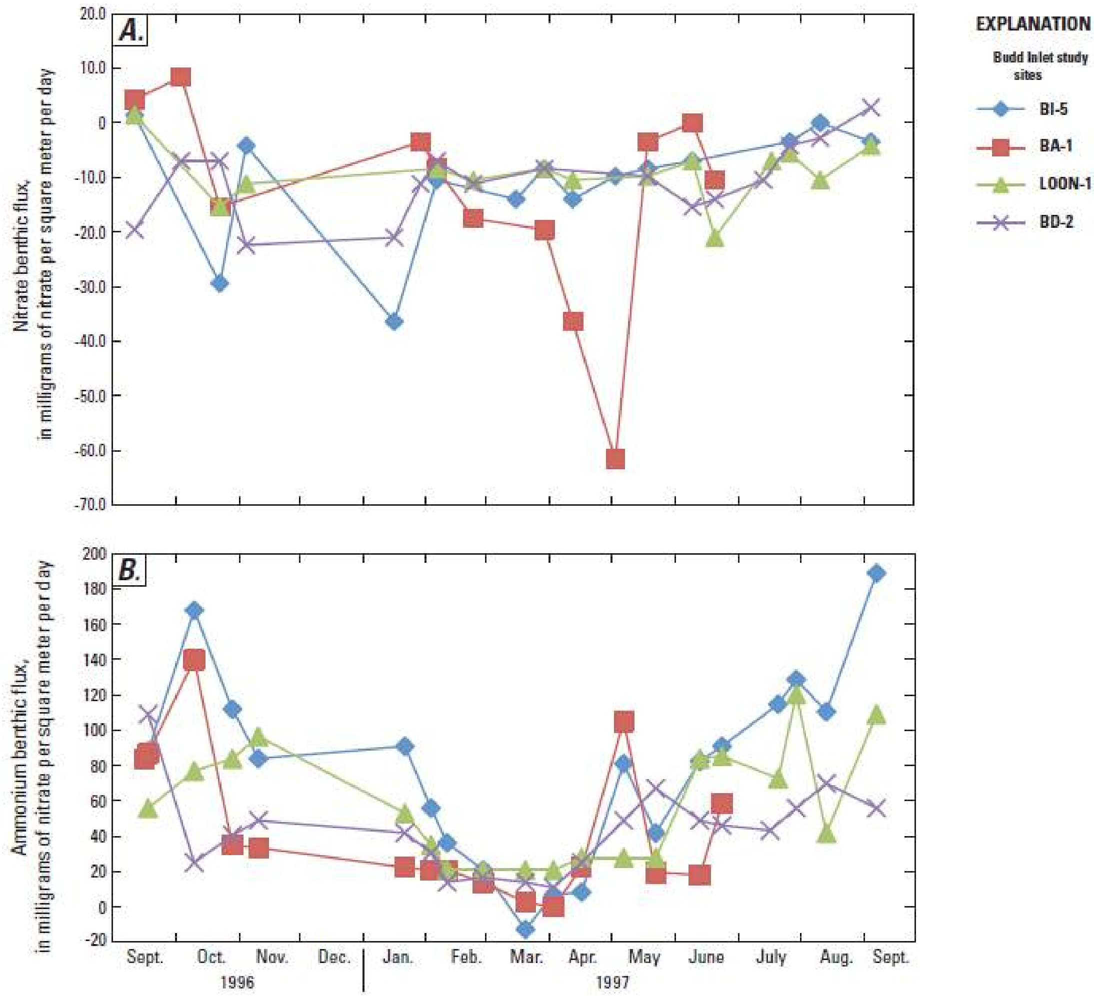


Figure 5. Time-series plot showing (*A*) nitrate and (*B*) ammonium chamber benthic flux from four sites in Budd Inlet, Puget Sound, Washington. Data from Aura Nova Consultants and others, 1998.

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)

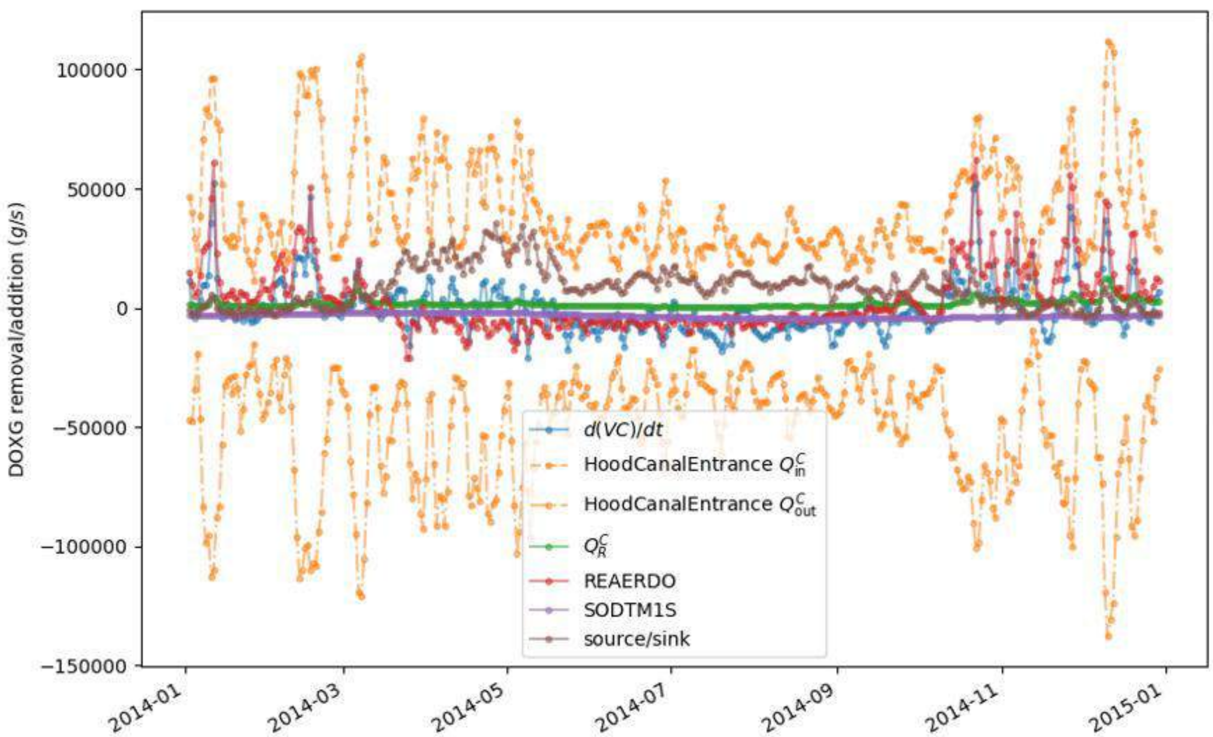
Parameter name and description	Fortran code output No.[1]	Fortran code name and details	Variable list name	Closest matching documentation from Pelletier et al. (2017) etc.
N sedimentation sum layer 2	89	(CPON_GL(I, 1)/1000.0, I=1, MGL)	sed_CPON1: sed particulate organic nitrogen 1 (gN/m3)	PON1 = G1 particulate 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