*Olympia's Budd Inlet Treatment Plant, center, is one of the few nitrogen-removing systems on Puget Sound. Photo: Department of Ecology*

WATER QUALITY

# Low oxygen challenge, part 2: Water-cleanup plans and the search for 'reasonable' actions

**By Christopher Dunagan** Published June 12, 2025 Comments Closed

On a clear autumn day, the blue waters of Budd Inlet reflect the distant snow-capped Olympic Mountains. From the water's surface, nobody can tell if low-oxygen conditions might be lurking below, as they often do, creating a stressful or even deadly environment for sea life.

The fact that beauty can disguise the harsh reality of water quality applies to low-oxygen conditions in numerous bays throughout Puget Sound, from Budd Inlet in South Puget Sound to Penn Cove in

Central Puget Sound to Bellingham Bay in North Puget Sound, along with the southern end of a 68-mile-long fjord we call Hood Canal.

*Olympia's Capitol Lake // Photo: Gärgollaz via Wikimedia Commons*

To address the low-oxygen problems, the Washington Department of Ecology, along with many others, has conducted numerous studies of actual conditions, developed computer models to identify possible solutions, and started the process of regulation. The agency is now nearing completion of an action plan designed to improve the health of Puget Sound. Along the way, we've seen scientific debates and legal battles, as various interests assert wide-ranging opinions about what should be done.

As for Budd Inlet, excess nitrogen, plankton blooms and occasional fish kills are part of the waterway's history. Studies during the 1980s concluded that Budd Inlet's low-oxygen waters were the result of a complex combination of watershed conditions, nitrogen sources and circulation patterns that make Budd Inlet an unusual case study.

Low-oxygen waters were coming into the inlet from freshwater sources — including Olympia's Capitol Lake and nearby streams. Also, before a major system upgrade in 1994, a sewage-treatment plant serving the region was a significant source of nitrogen, known to contribute to oxygen deficits. In addition, according to studies, a significant amount of nitrogen flowed southward into the bay from sewage-treatment plants as far away as Tacoma and Seattle — although the extent of that external nitrogen supply was not known until a modeling effort in 2014. Further complicating the situation throughout Puget Sound is the large, natural supply of nitrogen-rich waters coming in, along the bottom, from the Pacific Ocean.

As described in the previous blog post, federal and state regulations during the 1980s led to upgrades of sewage-treatment plants throughout Puget Sound to meet "secondary treatment" standards for organic wastes. Among them was the regional treatment plant serving Lacey, Olympia, Tumwater and portions of Thurston County, named LOTT. The cooperative venture upgraded the system from primary to secondary in 1982. But even before that, experts realized that much more would be needed to solve the low-oxygen problem.

In 1994, LOTT became the first sewage-treatment system (PDF) on Puget Sound to add nitrogen-removal equipment, known as tertiary treatment, to the treatment process. And, in 2023, LOTT completed construction of a more efficient "second-generation" upgrade to its nitrogen-removal process.

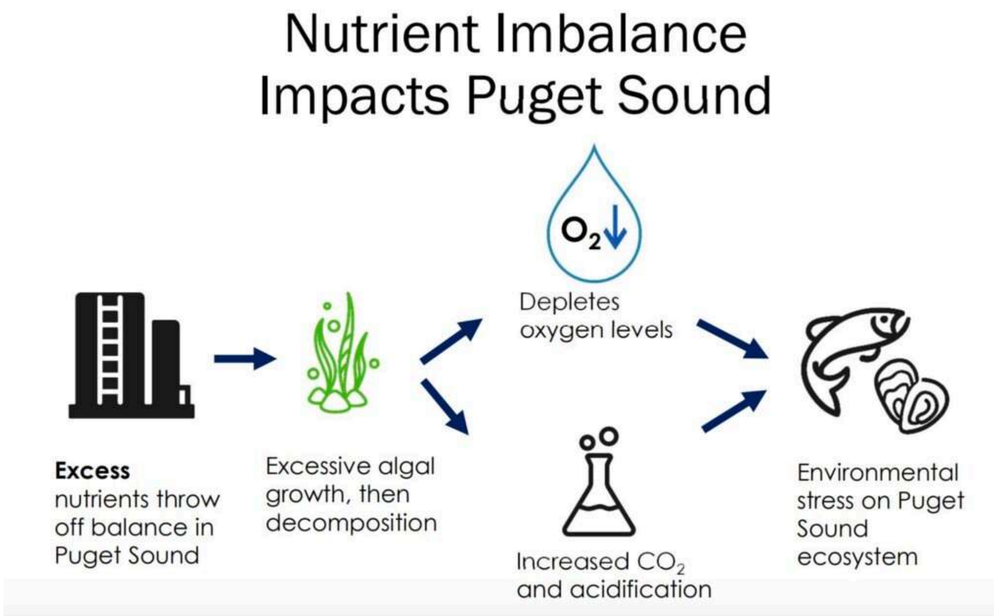
Today, LOTT remains one of the few treatment systems on Puget Sound to institute nitrogen removal, despite ongoing pressure — including lawsuits — from environment groups trying to force upgrades at other treatment plants.

## "Known, available, reasonable"

Since 1945, Washington's water pollution laws seem to be calling for the cleanest water possible, within reason. Through the years, in one form or another, the law has maintained language requiring that wastewater dischargers use "all known, available and reasonable technology" to control pollution — the so-called AKART requirement.

In 2018, Northwest Environmental Advocates, an environmental group, petitioned the Department of Ecology to update its AKART standard to tertiary treatment and require all treatment plants to upgrade their systems to reduce nitrogen levels in effluent to no more than 3 milligrams per liter. After all, said NWEA in the petition, this type of treatment has proven successful in many places across the nation and should be a minimum requirement for keeping up with technology.

"Put simply, it's well past time for Ecology to make Puget Sound sewage treatment plants switch from the 100-year-old treatment technology most of them are using," the group said on its website.




*Graphic: Washington Department of Ecology*

Ecology denied the petition, saying tertiary treatment to remove nitrogen did not meet the definition of "reasonable," as required by law, because such a higher level of treatment is "neither affordable nor necessary for all wastewater treatment plants."

In a 2019 letter of denial (PDF), Ecology Director Maia Bellon acknowledged that nutrient pollution was a significant problem. She said Ecology is committed to limiting nitrogen from sewage treatment plants to current levels and requiring operators to plan for reductions. Ecology's goal, she said, is to develop a plan that limits nitrogen levels in Puget Sound by considering where reductions from various sources would have the greatest effect on improving water quality.

NWEA appealed to Thurston County Superior Court and then to the State Court of Appeals. Both deferred to Ecology's findings that requiring tertiary treatment for all plants in Puget Sound would not be "reasonable." One study cited by Ecology estimated the cost of upgrading all treatment plants at roughly $4.5 billion, or specifically somewhere between $2.24 billion and $8.96 billion.

The appeals court ruled that AKART does not require Ecology to mandate any treatment system across the board or even impose universal water quality standards. "Rather," says the written opinion from June 2021, "the statute mandates that Ecology comply with AKART when issuing permits."

The court concluded that when Ecology applies the required AKART standard to individual permits for each plant, local water conditions — as well as available technology — must be considered.

Another environmental group, Puget Soundkeeper Alliance, brought the AKART issue back to a basic level by appealing a permit issued by Ecology for Seattle's West Point Wastewater Treatment Plant, the largest discharger of sewage effluent in the Puget Sound region. In its appeal to the Pollution Control Hearings Board in May 2024, the group contended that nitrogen and phosphorus are known pollutants and must be controlled with specific effluent limits under both state and federal laws. (Phosphorus is primarily an issue for lakes.)

"State statutes require that permits include and apply 'all known, available, and reasonable technology' or 'AKART' to control pollutants in wastewater or other discharges authorized by … permits," the appeal document (PDF) says.

At the time the appeal was filed, Ecology was working under an approved "nutrient general permit," which prohibited certain treatment plants from increasing current levels of nitrogen in their effluent. Since then, the Pollution Control Hearings Board has invalidated the general permit for facilities that already have an individual permit, such as the West Point plant. Ecology has asked the hearings board to delay proceedings on the West Point appeal until it can issue a new "voluntary" general permit or else place nitrogen restrictions on the facility's individual permit. A decision on the request for delay is expected at any time.

## Impaired waters and cleanup plans

One lawsuit currently moving through the courts could force the state Department of Ecology or the federal Environmental Protection Agency to complete a cleanup plan for nitrogen throughout Puget Sound without further delay. That lawsuit, based on requirements of the 1972 Clean Water Act, was first filed by Northwest Environmental Advocates against the EPA in late 2021. Parties went into negotiations but could not reach agreement on how to proceed, so the case became active again last year.

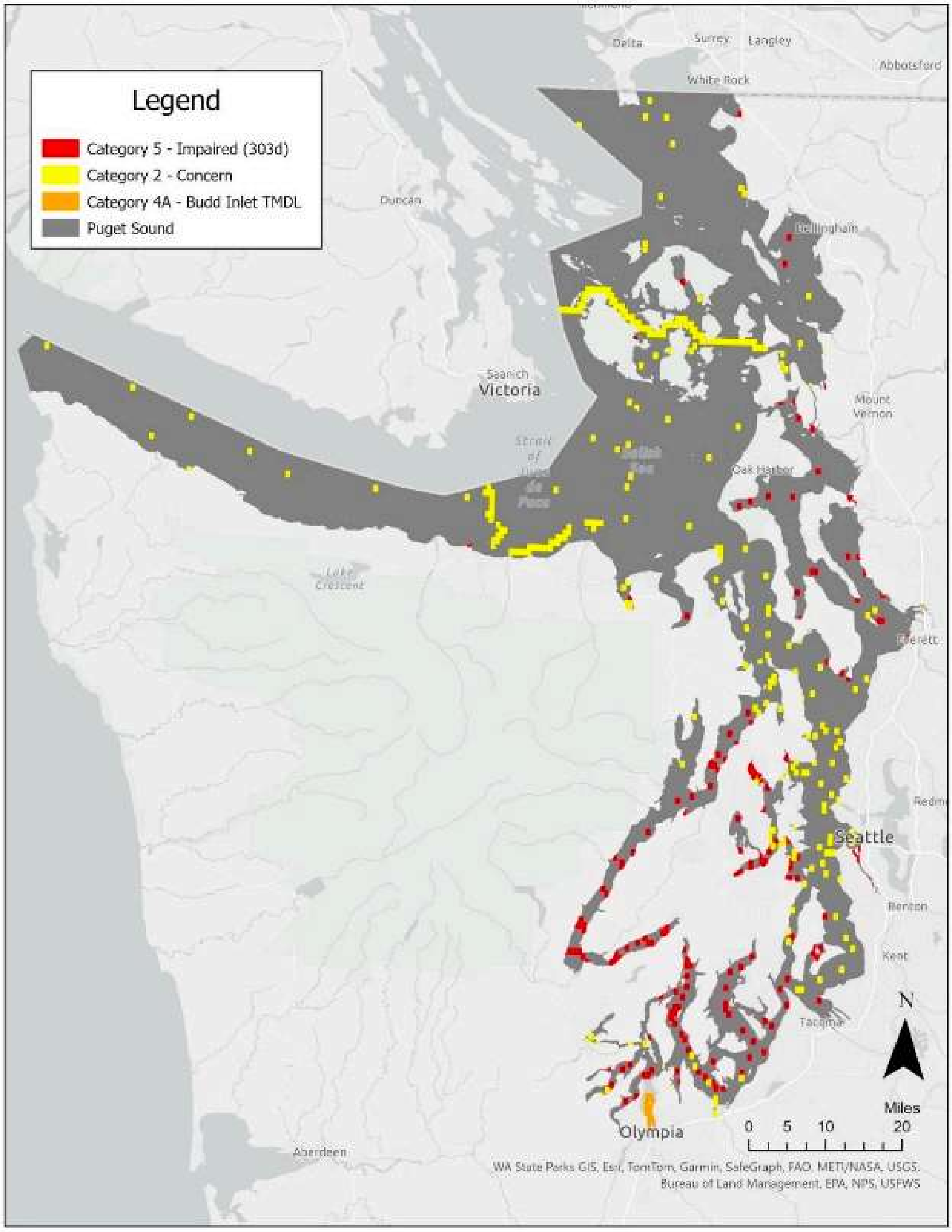
"After years of inaction, it's clear that nothing short of a court order will force EPA and Washington's Department of Ecology to clean up Puget Sound," asserted Nina Bell, NWEA's executive director, in a December 2021 press release about the proposed plan to set nitrogen limits for Puget Sound.

Under the Clean Water Act, states are called on to decide if segments of streams, lakes and marine waters are clean or polluted. The question is: Do the waters meet water-quality standards set by Ecology and approved by the EPA? Standards may include numeric criteria, such as the concentration of dissolved oxygen, or they may be based on natural conditions — theoretical levels that would exist without human influence. (See Encyclopedia of Puget Sound.)

Under the law, water bodies that fail to meet water-quality standards are declared "impaired," and Ecology must undertake a cleanup plan to restore the water body to a healthy condition. The plan involves a determination of the maximum level of pollutants, such as nitrogen, that could be allowed without violating water-quality standards. The document is called a TMDL, for total maximum daily load. The goal of the TMDL process is to reduce various sources of pollution until the total amount is at a safe level, as defined by the calculated TMDL number.

According to Ecology's own estimates at the time, based on modeling, about 20 percent of Puget Sound's marine waters failed to meet water-quality standards for dissolved oxygen, states a legal complaint (PDF) filed by NWEA.

"For over three decades, the marine waters of Puget Sound have been known to be impaired by dangerously low levels of dissolved oxygen, caused by nitrogen pollution…," the document asserts. "Along with oxygen depletion, nitrogen pollution fuels extensive algal




*Impaired waters in Puget Sound, including Category 5 (impaired) in red, Category 2 (waters of concern) in yellow, and Category 4A (TMDL) for Budd Inlet in orange. // Map: Ecology's draft Puget Sound Nutrient Reduction Plan.*

blooms in Puget Sound, some toxic to people, some toxic to shellfish, and some that are upending the food chain that supports imperiled Chinook salmon and orca whales."

Ecology's approach, sanctioned by the EPA, is to develop a "TMDL alternative" — a nutrient-reduction plan. The effect of that approach has been to avoid regulatory actions required by the Clean Water Act, according to the lawsuit. Citing a 1996 case in Idaho, the complaint says that Congress in 1972 intended that TMDLs be developed "in months and a few years, not decades." In 2019, the

EPA approved Ecology's idea of creating a nutrient-reduction plan without a TMDL.

According to the lawsuit, failure by Ecology to submit TMDLs to improve water quality in Puget Sound effectively signals a lack of intent to do so and triggers a requirement that EPA take over development of TMDLs to reduce nitrogen and improve oxygen levels.

In response to NWEA's lawsuit, attorneys for the EPA insist that neither Ecology nor the EPA have abandoned their efforts to clean up Puget Sound, including the need to address sources of nitrogen, so NWEA's demands are not justified.

"When this case reaches the summary judgment stage, EPA will argue that Washington has not abandoned efforts to control dissolved oxygen impairments in the Sound; it has made the Sound the center of a robust, multi-pronged monitoring and regulatory effort," states a response brief (PDF) from EPA filed in February. "And while Washington is currently prioritizing direct controls on nutrient pollution through permitting, its cleanup plans also include developing a TMDL to address any remaining dissolved oxygen impairments in Puget Sound."

U.S. District Judge Barbara Rothstein, who is presiding in the case, has asked that legal motions, briefs and documentation be submitted on a schedule starting July 25 and ending Dec. 5 of this year, with her order to follow.

## Long-term cleanup schedules

Another lawsuit involving pollution-cleanup plans was first filed by NWEA against the EPA in 1991. Even after 34 years, many issues in the stop-and-go case are still quite alive, because Ecology has been unable to keep pace with an agreed schedule for completing TMDLs. EPA needs to step in as a matter of federal law, according to NWEA.

The 1991 lawsuit was filed when Ecology completed about 20 water-quality-improvement plans over 19 years under the 1972 Clean Water Act, a number that NWEA considered grossly inadequate.

The case was settled out of court in 1992 but reactivated in 1994. In 1998, the parties reached an out-of-court settlement with Ecology agreeing to a long-term aggressive schedule. Under the agreement, Ecology would complete 59 TMDLs statewide the first year and the rest — some 1,566 at the time — over 15 years.

In 2019, some 27 years after the agreement was signed, NWEA reactivated the lawsuit again, saying Ecology had completed less than 900 TMDLs — well short of the 1,566 that were scheduled to be done by 2013. Over the 15 years, Ecology completed an average 58 TMDLs per year but added an annual average of 222 additional "impaired-water" segments that require TMDLs.

"In other words," the complaint (PDF) says, "Washington identifies impaired waters for which TMDLs are needed at a rate four times the pace at which it completes TMDLs for impaired waters."

After the 15-year period was up, the pace of TMDL development by Ecology slowed considerably, according to the lawsuit, adding that the agency also failed to submit a prioritized schedule of future TMDL efforts.

Eventually, the lawsuit led to another settlement in 2023. This time, the parties agreed to allow EPA to hire a consultant to carefully examine the TMDL program and make recommendations for improvement. In response to questions, EPA officials said the consultant's report, expected by the end of this year, will describe Ecology's TMDL program, identify challenges to timely completion and offer recommendations on how to complete TMDLs faster.

"This report will be a neutral analysis of Ecology's program so that they can look at the recommendations and decide which options to pursue," according to a statement from the EPA.

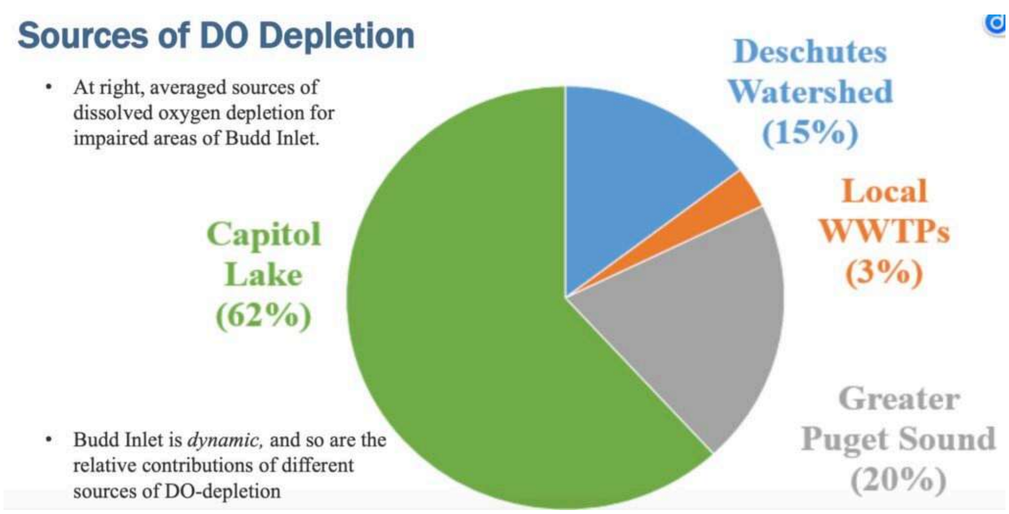
Ecology officials say cleanup plans have become more complex and more comprehensive through the years. Now, a single plan may cover entire watersheds, not just specific segments of streams or marine waters. Newer plans also consider multiple water-quality parameters, not just one, in each TMDL. Officials deny committing any violations of federal law, but say they look forward to the third-party evaluation.

"Though we regularly self-assess to consider opportunities for improvement, this external review is structured to provide new insights and recommendations for ways we can continue to improve while efficiently using our resources for all stages of developing and implementing water quality cleanup plans," Ecology says in a blog post about TMDLs.

"The goal is to reach an agreement on the number of water quality cleanup plans we complete, while ensuring they are effective, support implementation, and clean up Washington's waters."

## Budd Inlet TMDL

Efforts to improve oxygen conditions throughout Puget Sound include a special focus on Budd Inlet, where an approved water-quality cleanup plan, or TMDL, uniquely connects to a larger nitrogen-reduction plan for all of Puget Sound. The plan, completed in 2022, identifies the major sources of low oxygen and spells out actions to bring Budd Inlet back into compliance with water quality standards.

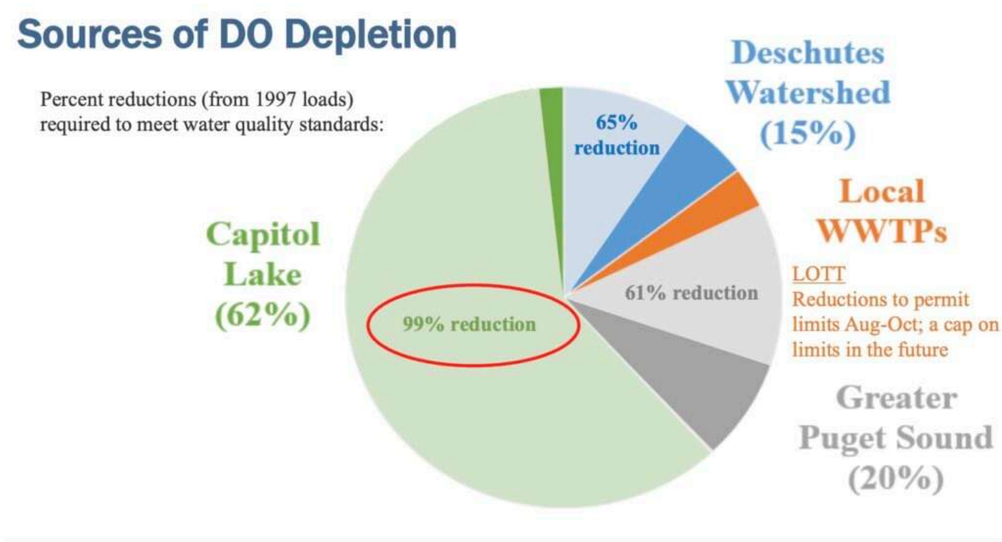



*The causes of low oxygen in Budd Inlet and their proportional effects on water quality // Graphic: Ecology's TMDL for Budd Inlet*

Based on years of study and computer modeling, with a consideration of water conditions in every portion of Budd Inlet, experts learned that the "critical period" for low oxygen typically begins in August and runs through September. This seasonality became a clear factor in deciding how and where restoration efforts should take place.

It turns out that the greatest factor in oxygen depletion is Capitol Lake, a man-made lake created in 1951 by damming the Deschutes River where it flows into the upper end of Budd Inlet. The lake stimulates the growth of freshwater algae and aquatic plants, which die and wash into Budd Inlet, where their decay consumes available oxygen. Scientists estimate that Capitol Lake accounts for 62 percent of Budd Inlet's oxygen depletion.

An environmental impact statement, completed in 2021, provided alternatives for addressing the environmental problems created by the dam, including the effects of dam removal and estuary restoration. In 2023, the Legislature approved funding to move ahead with planning and designs needed to remove the dam and restore 260 acres of estuarine and salt marsh habitat. If things go smoothly, the restoration project could begin within three years.




*The amount of nitrogen reduction from each source required to meet the state's water quality standards // Graphic: Ecology's TMDL for Budd Inlet*

The second-greatest source of oxygen depletion, representing 20 percent of the problem, is a flow of nitrogen into Budd Inlet from the rest of Puget Sound. While waters flow both in and out of inlet — and the net flow is outward — the incoming waters, mostly along the bottom, are much higher in nitrogen.

Unlike most TMDLs, which prescribe actions to reduce various sources of pollution in prescribed amounts, the Budd Inlet cleanup plan calls for a 61 percent reduction in oxygen depletion caused by these incoming waters from Puget Sound. How to accomplish this reduction, known as a "bubble allocation," will be determined by the larger planning effort being conducted throughout Puget Sound, called the Puget Sound Nutrient Source Reduction Project. Meeting water quality standards in Budd Inlet will depend on the success of actions outside as well as inside, the waterway.

Other sources of oxygen depletion in Budd Inlet include upstream areas of the Deschutes River watershed (15 percent of the problem) and sewage treatment plants (3 percent). Various actions are proposed for each of these sources to reduce their contributions to the problem.

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*This article was funded in part by King County in conjunction with a series of online workshops exploring Puget Sound water quality. Its content does not necessarily represent the views of King County or its employees.*

## The series

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Part 2: Water-cleanup plans and the search for 'reasonable' actions

**Part 3:** Computer models spell out the extent of the water-quality problem.

**Part 4:** Many actions may be needed to improve Puget Sound waters

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*Moon jellies seem to do well in warmer, low-oxygen waters, such as those in Sinclair Inlet near Bremerton in August 2022, shown here. Jellyfish may disrupt the food web by consuming large amounts of plankton needed by other species. // Photo by Haila Schultz, University of Washington*

WATER QUALITY

# Low oxygen challenge, part 3: Computer models spell out the extent of the water-quality problem

**By Christopher Dunagan** Published June 12, 2025 Comments Closed

After more than eight years of study amid ongoing discussions, the Washington Department of Ecology has made public a far-reaching plan for reducing human sources of nitrogen that contribute to the destructive low-oxygen conditions in Puget Sound. The plan, called the Puget Sound Nutrient Reduction Plan, calls for reductions in nitrogen from sewage-treatment plants, agricultural operations and a variety of other upstream sources.

The plan is based on decades of monitoring to identify the locations of low-oxygen problems, investigations to quantify sources of nitrogen (both natural and human-derived), and computer modeling to reveal how specific source reductions could affect water quality.


*By the early 2000s, it had become clear that nitrogen from Central Puget Sound was affecting oxygen levels in South Puget Sound, including Budd Inlet, shown here at Capitol Lake. The State Capitol can be seen right of center. // Photo: Washington Department of Ecology*

Nitrogen, an essential ingredient for growth, has been shown to be a problem at times when released into Puget Sound. Excess nitrogen triggers excessive plankton blooms. The plankton eventually die and sink to the bottom, spurring the growth of bacteria, which consume oxygen supplies needed for healthy marine populations.

Besides low-oxygen effects on sea life, some plankton species disrupt the food web, because they cannot be eaten by herring and other small fish that serve as prey for larger fish and marine mammals. Other plankton species excrete dangerous toxins, resulting in “harmful algal blooms” that can kill fish, birds and marine mammals and disrupt commercial shellfish operations. Even beneficial plankton in overabundance can block sunlight and impair eelgrass beds and other essential habitats.

The need for a plan to address the oxygen problems throughout Puget Sound grew out of studies beginning in the 1980s. By the early 2000s, local problems were better understood. It became clear, for example, that low-oxygen levels in Budd Inlet and other South Puget Sound bays were affected by waters coming from the rest of Puget Sound to the north. Since parts of Puget Sound are naturally low in oxygen, an ongoing debate surrounds the extent to which human sources of nitrogen are to blame.

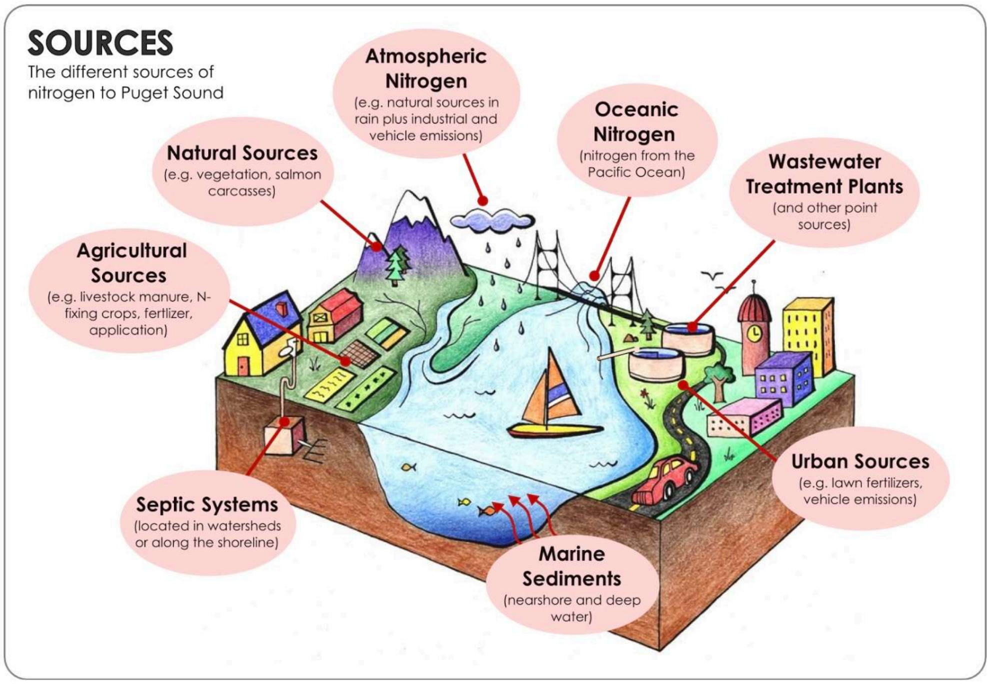
To help pull the information together and develop a plan of action, Ecology launched the Puget Sound Nutrient Source Reduction Project In the spring of 2017. A discussion group, called the Puget Sound Nutrient Forum, started up a year later to hear reports about the latest findings. Participants included researchers, government officials, sewage-treatment plant operators, tribal representatives, environmentalists and others.

## Homing in on nutrient sources

By 2019, Ecology staffers were convinced that human sources of nitrogen, including sewage treatment plants, were playing a key role in pushing oxygen concentrations below state water quality standards in some areas. The Salish Sea Model, designed to simulate actual conditions in Puget Sound, accounts for physical processes — currents, tides and nutrient transport — along with chemical and biological processes that transform chemical compounds, including nitrogen. To the surprise of early researchers studying these dynamic changes, models revealed that nitrogen released at one point could move many miles away and trigger the growth of plankton in remote areas.

Model runs reported in 2019 were based on data from the years 2006, 2008 and 2014 and published in the Ecology report "Model Updates and Bounding Scenarios."

"Modeling results show that portions of Puget Sound, primarily South Sound and Whidbey Basin, experience a large number of days when the marine DO (dissolved oxygen) water quality standard is not met," the report states. "In multiple locations within these two regions, the total number of noncompliant days is over three months."




*The largest source of nitrogen in Puget Sound is water coming from the Pacific Ocean, but many point and nonpoint sourcces influence the levels of oxygen thoughout the Sound. (Click on image to enlarge.) Graphic: Washington Department of Ecology*

Model refinements in 2021 (PDF) began to focus on regions of Puget Sound and to combine scenarios that involved greater or lesser nitrogen discharges from treatment plants versus the upstream watersheds. Further refinements this year provided the foundation for the newly released nutrient reduction plan.

Outcomes of recent model runs have shown that most of the impaired areas are close to meeting the state's natural conditions criteria, which allow dissolved oxygen levels to be as much as 0.2 milligrams per liter above prehistoric levels, as calculated by the model. More than half are within 0.1 mg/l of this standard by some calculations. Nevertheless, significant improvements will be needed to achieve full compliance.

"When it comes to nutrient pollution, there are proven ways to solve the problem, and we will need to use all our tools to get to clean water," said David Giglio, manager of Ecology's Water Quality Program in a news release. "This includes significant investments for wastewater infrastructure. As a region, we need to be as efficient as possible with our resources while we work toward a healthy Puget Sound and restoring salmon runs."

So-called watershed sources include upstream fertilizers used on farms and in urban areas, sewage-treatment plants, septic systems, animal wastes and atmospheric deposition, all washing off the land, eventually entering Puget Sound through 193 rivers and streams in the current model. While nitrogen is a key factor in reducing oxygen levels, the Salish Sea Model also calculates the effects of inflowing organic materials that can reduce oxygen levels through decomposition.

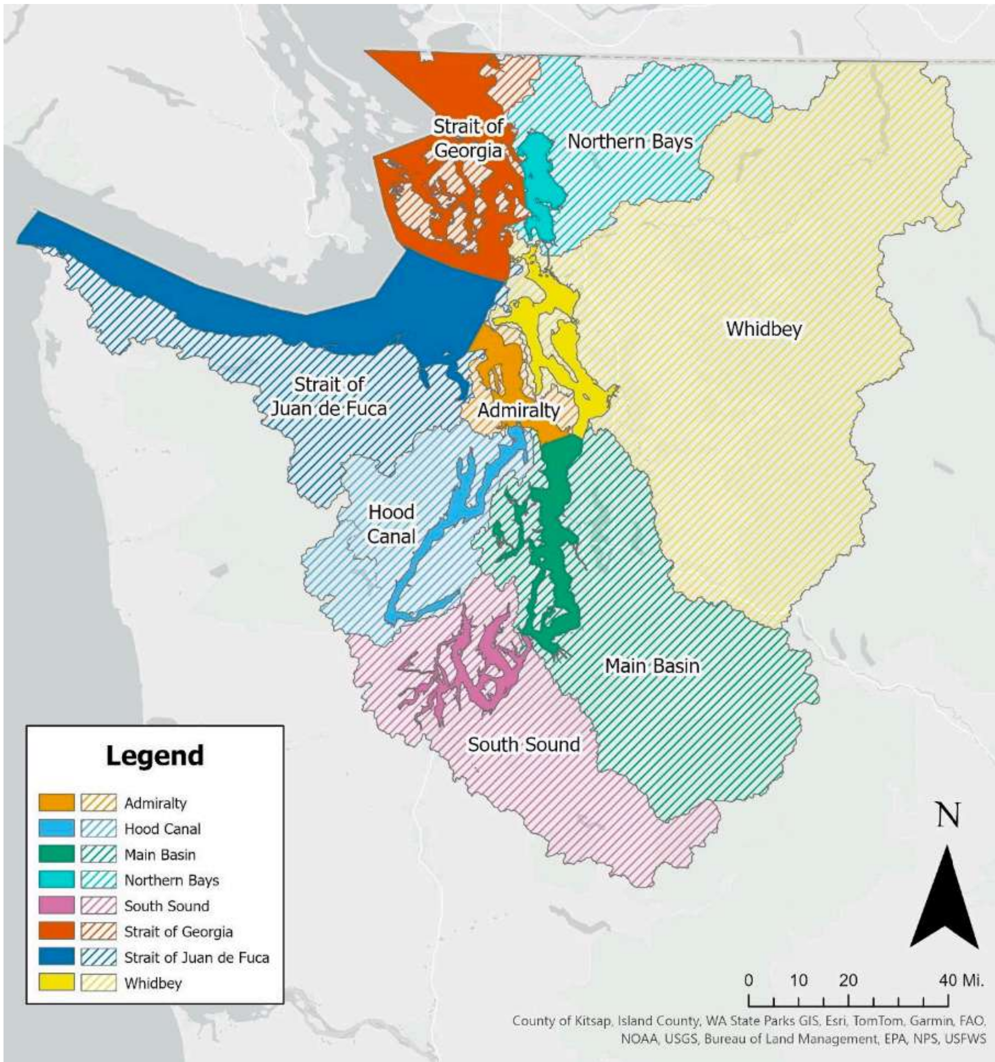
Of all the human sources of nitrogen under consideration, about two-thirds arrives from direct discharges from sewage-treatment plants, with about one-third from upstream sources flowing into rivers and then into the Sound. Natural sources are estimated to contribute about 90 percent of all nitrogen in Puget Sound, but where and when each of these sources arrive in the Sound are key factors in determining oxygen levels at various locations, as accounted for in the model.

Puget Sound currents, driven by tides and incoming freshwater flows, play a major role in oxygen levels at every location in Puget Sound. Most vulnerable to low oxygen levels are small bays as well as the terminal ends of longer inlets, where low circulation and slow flushing rates allow an accumulation of low-oxygen waters on the bottom. Hood Canal, for example, has no major inputs of nitrogen from industry or sewage treatment, yet the southern dead-end portion of the waterway (Lynch Cove) shows persistent low-oxygen conditions, in large part from natural sources of nitrogen.

In some areas, such Central Puget Sound, nitrogen released from treatment plants in Seattle and Tacoma can have far-reaching effects, because the large inputs of nitrogen are carried by strong currents.

## Latest model results

In March, the latest refinements in the Salish Sea Model and fresh findings from model runs were revealed in an online meeting of the Puget Sound Nutrient Forum (PDF). More than a dozen model scenarios looked at combinations of various nitrogen levels coming from treatment plants, paired with various nitrogen reductions from watersheds. Improvements were measured by calculating areas of Puget Sound that could meet water quality standards for each combination. Over a full year, for each combination, the model was able to determine minimum oxygen levels as well as the number of days that water-quality violations would occur anywhere in Puget Sound, as described in the report Model Updates and Optimization Scenarios, Phase 2.




*The eight basins of Puget Sound used in the Puget Sound Nutrient Reduction Plan. (Click to enlarge.) Map: Washington Department of Ecology*

After studying the options based on nutrient reductions at specific locations, Ecology officials selected on option announced today in the draft plan, which establishes regional targets for nitrogen levels in both wastewater and watersheds. Point-source targets will be used to set effluent limits for sewage-treatment plants and industrial facilities.

Watershed targets are aggregated to each of Puget Sound's eight defined basins, including the Strait of Juan de Fuca, Main Basin, South Sound and so on. Watershed targets will be a starting point for a 25-year cleanup effort, including two cleanup plans by 2027.

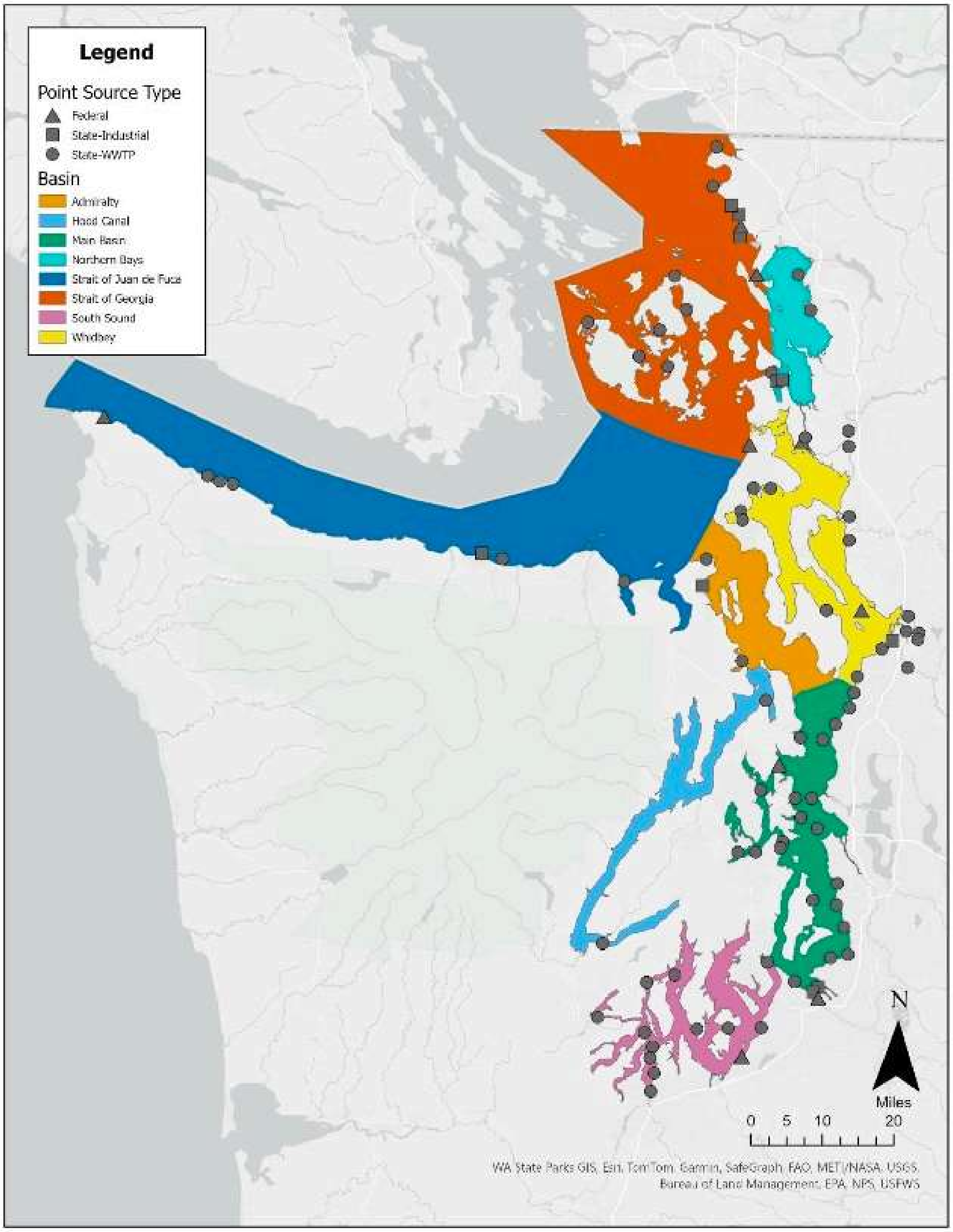
"The watershed targets are represented as a single annual TN (total nitrogen) load for each of the eight Puget Sound basins," the plan says. "Note that these loads represent all upstream nonpoint and point sources of TN in the 163 distinct watersheds draining to Puget Sound."

To meet water-quality standards, the plan calls for a 68 percent reduction in nitrogen coming from human sources in the large watersheds on the east side of Puget Sound, including South Sound. For the small watersheds in that area, the proposed reductions are 61 percent. The reduction goal is 53 percent for Hood Canal and Admiralty Inlet. Watersheds in the Strait of Juan de Fuca and the Strait of Georgia would be capped at existing levels with no further reductions needed.

An important exception is proposed in the "recalcitrant areas" that present major challenges to meeting water quality standards. Specifically, those areas are Lynch Cove in Hood Canal ; Sinclair Inlet and Liberty Bay on the Kitsap Peninsula; and Carr and Henderson inlets in South Sound. To meet water-quality standards, local streams might need to reduce their nutrient loads by 90 percent, according to the plan.

The focus on direct nitrogen inputs to Puget Sound involved 99 "point sources," including 78 sewage treatment plants in Washington, nine sewage treatment plants in British Columbia and 10 industrial facilities.

To gain the best results in water quality with less extensive changes in treatment systems, discharges of nitrogen would be reduced the most during July, August and September — the so-called "hot months" — when sunlight, nutrient buildup and slow mixing triggers plankton blooms, leading to the lowest oxygen levels of the year. The second-highest reductions would be the surrounding months of April, May, June and October, the "warm months" that typically have mixed light levels and water movement. "Cool months," from November through March, are known to have more dynamic changes in weather and mixing and fewer low-oxygen problems.




*Marine point sources identified in the Puget Sound Nutrient Reduction Plan. (Click to enlarge.) Map: Washington Department of Ecology*

Using this strategy, the plan would propose hot, warm and cool periods for treatment plants discharging more than 22 pounds of total nitrogen and more than 13 pounds of dissolved nitrogen per day in these basins: Northern, with one treatment plant; Whidbey, 11 plants; Main, 14 plants; and South Sound, three plants. Specifically, average nitrogen concentrations were set to 3 milligrams per liter in hot months, 5 mg/l in warm months and 8 mg/l in cool months. For plants on Sinclair Inlet, the limit would be 3 mg/l year-round.

Most large treatment plants discharging into the main basin of Puget Sound, such as Seattle and Tacoma, would be limited to 3 mg/l in both hot and warm months, with 8 mg/l in cool months. West Point in Seattle would use the three limits for hot/warm/cool periods mentioned above. Limits would be set to 2014 nitrogen loads for smaller treatment plants and for those discharging into Hood Canal, Admiralty Inlet, Strait of Juan de Fuca and Straight of Georgia.

## Sources of nitrogen in the watersheds

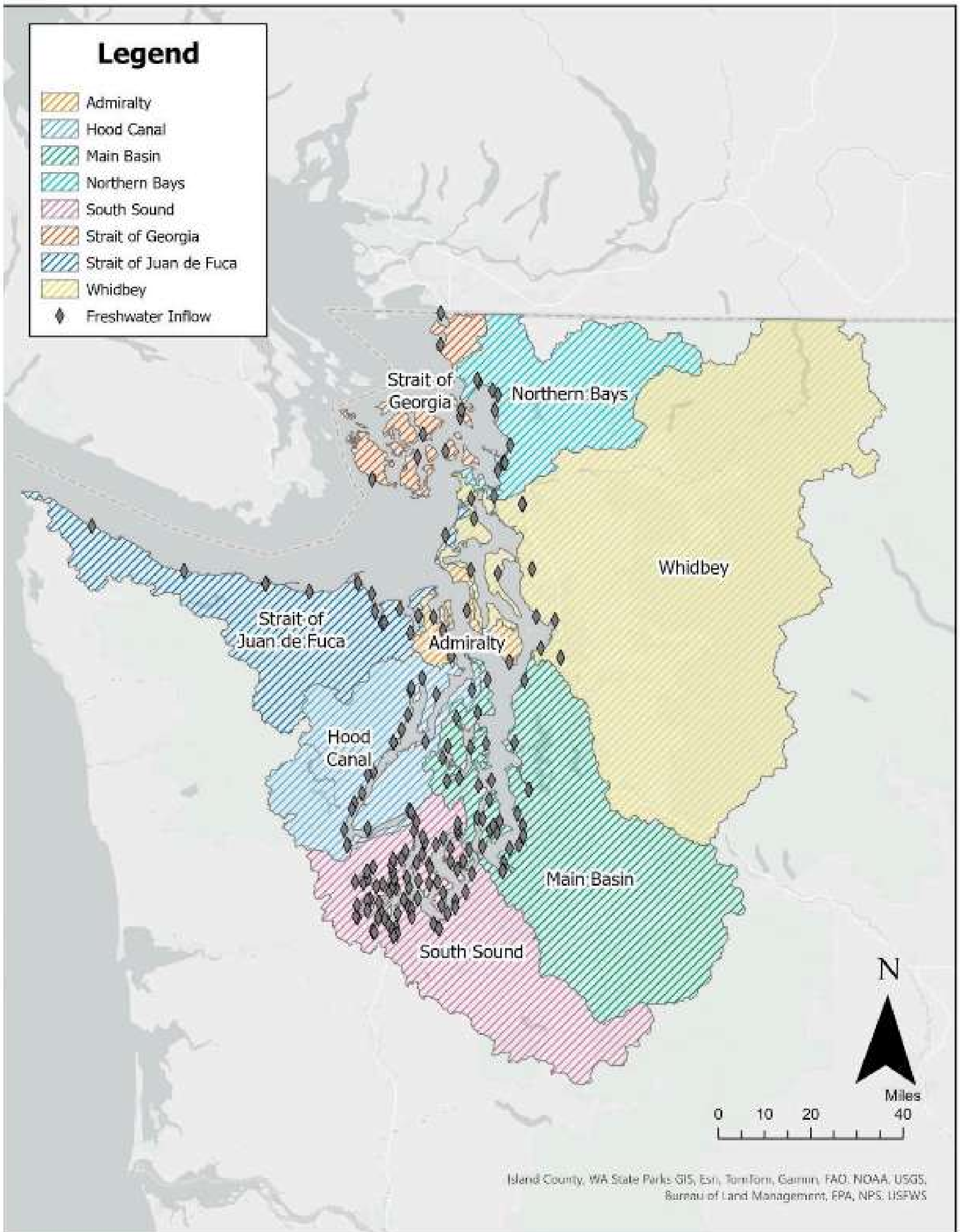
In searching for upstream, land-based sources of nitrogen, scientists have discovered that every river entering Puget Sound contains a unique mix of nitrogen from fertilizers, animal wastes, sewage-treatment plants, alder trees, urban stormwater and septic systems.

The total amount of nitrogen being delivered to Puget Sound varies greatly from river to river and season to season, with the greatest amount of nitrogen arriving during the high river flows of winter, according to a report released this year by the U.S. Geological Survey.

Actual upstream sources of nitrogen in the various rivers are as different as the surrounding land uses — from farm to forest to urban development, according to the study based on a USGS watershed model called SPARROW — SPAtially Referenced Regressions On Watershed attributes. Results of the SPARROW model are under review and yet to be compared with previous models, including Visualizing Ecosystem Land Management Assessments (VELMA) developed by the Environmental Protection Agency and the Hydrological Simulation Program — Fortran (HSPF), a separate USGS model. See also Puget Sound Integrated Modeling Framework.

Of the total nitrogen reaching Puget Sound from 19 major watersheds, more than half came from four river systems: the Nooksack, Snohomish, Cedar-Sammamish and Duwamish-Green. Each of those watersheds contribute about the same amount of nitrogen — around 14 percent of the total — even though the size of the drainage areas is much different. Snohomish is the largest area with 4,836 acres, followed by Nooksack, 3,351; Cedar-Sammamish, 1,688; and Duwamish-Green, 1,361.

Within those four watersheds, the sources of nitrogen are quite different. Nitrogen in the Cedar-Sammamish and Duwamish-Green watersheds, which include urban areas, is dominated by effluent




*Watershed inflows identified in the Puget Sound Nutrient Reduction Plan. (Click to enlarge.) Map: Washington Department of Ecology*

from upstream sewage treatment plants. The Nooksack, a largely rural area including farms, shows heavy inputs from crop fertilizers, livestock and alder trees. The Snohomish, which includes forested areas, gets its nitrogen largely from alder trees and sewage-treatment plants.

The watershed with the greatest drainage area, the Skagit-Samish with 8,861 acres, comes in fifth in the amount of nitrogen released into Puget Sound. Because of large, forested areas, major nitrogen sources include alder trees and the atmospheric deposition of nitrogen-containing particles.

Nitrogen from alder trees was a major source in most of the 19 watersheds, as alder trees have become more common today than in prehistoric times. Such changes were factored into a “reference scenario” to consider changes from prehistoric times.

“A reference scenario was developed to provide an estimate of the pre-industrial local and regional loads, which indicated that the largest increases in (total nitrogen) yield from historical to present were from the Cedar and Green Rivers as well as Chambers Creek,” the report says. Historic modeling could help in developing strategies for reducing nitrogen from various sources.

Septic systems were the largest source of nitrogen coming off the Kitsap Peninsula and the Deschutes and Kennedy-Goldsborough watersheds in South Puget Sound.

The model also calculates phosphorus releases for the various watersheds, because phosphorus tends to stimulate algae growth in freshwater, as nitrogen does in saltwater. Algae coming out of the streams may add to the organic load in the marine waters, contributing to low-oxygen conditions.

Watersheds contributing the greatest phosphorus load to Puget Sound are, in order, the Snohomish, Skagit-Samish, Cedar-Sammamish and Duwamish-Green.

The SPARROW model will be useful in predicting the success of various nitrogen-reduction actions in the watersheds, according to authors of the study. Actions that reduce the amount of nitrogen coming into Puget Sound at certain times of the year, particularly summer and fall, could improve oxygen levels during critical periods.

“The seasonal mass balance representation of streams from headwaters to marine-water discharge points by source is important information to support Ecology’s nutrient reduction plan,” the report states. “Certainly, there are limitations with process representation and simulation accuracy, but the modeling approach directly provided real, interpretable values… Although model uncertainty can be high when zoomed into unique reaches (mean error 50% nitrogen to 72% phosphorus), an ability to quantify uncertainty in space and time is a strength."

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*This article was funded in part by King County in conjunction with a series of online workshops exploring Puget Sound water quality. Its content does not necessarily represent the views of King County or its employees.*

## The Series

**Part 1:** The debate over oxygen in Puget Sound

**Part 2:** Water-cleanup plans and the search for 'reasonable' actions

Part 3: Computer models spell out the extent of the water-quality problem.

**Part 4:** Many actions may be needed to improve Puget Sound waters

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*Previous: Low oxygen challenge, part 2: Water-cleanup plans and the search for 'reasonable' actions*

*Up Next: Low oxygen challenge, part 4: Many actions may be needed to improve Puget Sound waters*

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*To reduce the flow of nitrogen into Puget Sound, action will be needed upstream in the watersheds, experts say. Protecting vegetation along streams is a partial solution. Treatment plants, agriculture, urban stormwater and alder trees contribute to the problem. // Photo: Port of Tacoma*

WATER QUALITY

# Low oxygen challenge, part 4: Many actions may be needed to improve Puget Sound waters

**By Christopher Dunagan** Published June 12, 2025 Comments Closed

A grand plan to reduce human sources of nitrogen in Puget Sound started coming into focus in 2019 when the issue of regulations reached a decisive point.

After years of study and advances in computer modeling, experts at the Washington Department of Ecology were beginning to see what it would take to reduce human sources of nitrogen and improve oxygen conditions harming sea life. But key questions remained:

How would the state agency go about getting sewage-treatment plants to reduce their nitrogen releases, and what could anyone do to address the multitude of upstream sources of nitrogen washing off the land?

The answers have come with some resistance, scientific skirmishes and legal entanglements — and many issues remain unresolved today. For example, uncertainty surrounds new permits for sewage-treatment plants because of recent court rulings. Meanwhile, today, Ecology released its long-awaited plan for reducing nitrogen coming into Puget Sound from both point and nonpoint sources.

## Nutrient general permit

In January 2020, Ecology announced that it would develop a "nutrient general permit" for all sewage systems discharging directly into Puget Sound. The new permit would address nitrogen and would be in addition to existing individual permits that set limits on other forms of pollution. The general permit would require monitoring of nitrogen discharges, planning efforts to reduce nitrogen releases, and eventually numeric limits for nitrogen in effluent.

*The nutrient general permit, now in abeyance, was designed to cover sewage-treatment plants on Puget Sound, including Bremerton's Westside Wastewater Treatment Plant. // Photo: Washington Department of Ecology*

Leading up to the decision, Ecology received mixed support for the idea of a general permit. Treatment plant operators — including cities, counties and sewer districts — were generally skeptical and expressed concerns about complying with two major permits. They wanted to make sure that any decisions would be based on solid science and allow time for implementation. Environmental groups and many individuals strongly supported the general permit — or practically any measures that would bring quick action.

After deciding to create a general permit, Ecology called together experts and formed the Nutrient General Permit Advisory Committee to help draft the parameters of the new permit. Individuals affiliated with wastewater facilities, environmental groups, state and federal agencies and a tribal utility were among the members working together through much of 2020. Their recommendations, issued in October that year, were far from unanimous.

While most everyone agreed that planning should take place at the local level, differences of opinion developed between representatives of the environmental community and officials managing sewer utilities. The greatest divide related to placing numeric limits on nitrogen releases and on a schedule for planning, engineering and equipment upgrades to meet stricter standards, whatever they might be.

There was some agreement that "optimization," — making relatively minor changes to current facilities — could help control nitrogen without the expense of full-blown nitrogen-removal systems. But federal and state officials said optimization alone would not be enough to meet Puget Sound's water-quality standards, based on outputs from computer modeling.

On Dec. 1, 2021, following two public comment periods, Ecology approved the general permit, which divides 58 treatment plants into three categories, dominant, moderate and small nitrogen dischargers. Together, the dominant dischargers release more than 99 percent of the total nitrogen from treatment plants, and they would be asked to do the most.

In the beginning, the general permit allows the plants to maintain their current nitrogen releases with careful monitoring as they optimize their existing facilities. The permit also includes "nutrient action levels" that would trigger further reduction efforts when nitrogen releases exceed their current levels by specific amounts.

## Legal entanglements

Within a month of permit approval, eight sewage-treatment plant owners filed appeals with the state Pollution Control Hearings Board, which consolidated the appeals into one case. Plaintiffs included King and Pierce counties; the cities of Tacoma, Everett, Bremerton and Edmonds; and the Alderwood and Birch Bay sewer districts. These entities argued that the general permit is unlawful because treatment systems already have individual permits to govern their discharges, and the law does not allow a general permit to override an individual permit.

On the opposite side of the issue, Puget Soundkeeper Alliance, Washington Environmental Council (now Washington Conservation Action) and the Suquamish Tribe also filed appeals, saying the general permit did not go far enough or fast enough in reducing nitrogen going into Puget Sound.

If things weren't complicated enough, another lawsuit filed by the city of Tacoma was making its way through the courts. Tacoma officials argued that Ecology had not followed proper procedures in creating a new rule regarding nutrient limits. This took place at an earlier time, before the general permit came into play, and Ecology insisted that it had not created any new rules at that time.

The Tacoma case, joined by other sewer utilities, focused on a letter issued by Ecology when it turned down a petition from Northwest Environmental Advocates asking Ecology to require nitrogen-removing equipment at all treatment plants in Puget Sound. NWEA cited state law that requires the use of "all known, available and reasonable technology (AKART)." The organization said advance treatment capable of removing nitrogen — so-called tertiary treatment — was "known, available and reasonable" and should be used everywhere. Ecology's letter said that AKART does not apply to the current situation, because tertiary treatment is not reasonable, given the high costs and lack of evidence that high-level treatment is needed everywhere throughout Puget Sound. (This issue was covered in part 2 of this series.)

In turning down the AKART petition, the letter noted that Ecology was taking "alternative measures" to address the low-oxygen problem — including setting nutrient limits at existing levels and requiring treatment plants to plan for further decreases in nitrogen. Tacoma's attorneys argued that such commitments without a public process amounted to unlawful rulemaking. As such, Ecology should be prevented from limiting nitrogen levels until going through proper procedures, according to the lawsuit.

The Suquamish and Squaxin Island tribes filed a brief supporting Ecology and stressing that their treaties with the federal government establish legal rights to harvest fish and shellfish. Such rights, they said, are diminished by poor water quality and delays in addressing the problem. Washington Environmental Council took part in that brief.

The case worked its way up to the State Supreme Court, which eventually ruled last year (PDF) that Ecology's letter was not a formal commitment to limiting nitrogen levels, so it did not amount to rulemaking. Although the parties had agreed that monitoring and planning should move forward under the general permit, the Tacoma lawsuit effectively halted the appeals of the general permit for two years.

Last December, the Pollution Control Hearings Board restarted the appeal process for the general permit. Based on an extensive review and citations of state law, the board ruled (PDF) that Ecology cannot require a general permit if a sewage-treatment facility already has an individual permit for controlling pollution. The general permit could go forward as written, however, provided it becomes voluntary on the part of sewer utilities.

Ecology chose not to appeal the matter to the courts. Instead, the agency decided to keep the general permit for facilities voluntarily choosing to take advantage of the permit's special "flexibility" and "regional approach" to addressing the nitrogen problem. For those entities that choose not to opt in to the general permit, Ecology intends to add new nitrogen-related requirements to existing individual permits, including possible administrative orders to require ongoing monitoring and evaluations, such as those under the general permit. See letter to permittees (PDF).

"We don't know how many people will opt in, but we think it is important to keep the regional approach on the table," said Vince McGowan, manager of Ecology's Water Quality Program at the time.

For one thing, flexibility in the general permit could allow "nutrient trading" — the idea that greater nitrogen reduction at one treatment plant could offset less reduction at another plant, while still meeting water-quality goals, he said. This market-based approach offers a strong incentive to shift costs and save money. This could happen if upgrading an old plant is unreasonable or when a new plant could be efficiently expanded beyond its immediate need.

In its ruling, the Pollution Control Hearings Board said if Ecology truly believes that two permits should be mandated, the Legislature could change the state law. Ecology officials say they have not decided whether they will ask the Legislature for such a change.

## Costs and financial challenges

One of the big issues looming over the entire planning effort is the significant costs of adding entirely new treatment processes to already complex facilities designed to remove organic materials from sewage effluent.

Everybody wants to know what nitrogen removal will cost overall and how it will affect sewer bills. Answers about costs vary greatly, depending on the levels of nitrogen removal and the equipment required to meet water-quality goals at a specific location, as predicted by computer models.

In 2023, Susan Burke, an economics professor at Western Washington University, worked with other researchers to examine questions of cost and affordability to Puget Sound sewer customers who will ultimately pay some or all the costs of nitrogen reduction.

"Capital costs associated with adding advanced nutrient removal technologies to all the municipal wastewater treatment plants subject to the Puget Sound Nutrient General Permit are likely to exceed $2 billion, based on a preliminary economic evaluation of potential nutrient limits by Ecology and Tetra Tech (2011) escalated to 2022 dollars," states the "Puget Sound Wastewater Service Affordability Analysis."

The report acknowledges that such estimates are "very low," based on newer information, but they provide a starting point for discussions. In fact, some officials contend the ultimate costs may be many times higher than the range suggested by Tetra Tech in its 2011 report.

The Burke study analyzes the effect of higher sewer rates on 80 utilities around Puget Sound that could be affected by the cost of new nitrogen-removal equipment and ongoing operating costs, including increased electrical consumption.

"Current monthly sewer bills range from $27 to $161," the report states. Changes anticipated under the Puget Sound Nutrient General Permit (PSNGP) could bring monthly sewer bills to between $44 and $196, "depending on the utility and the nutrient-reduction scenario."

Considering a family's ability to pay higher sewer bills, the study concluded that affordability could be an issue for many households in the lowest-income group, which is 20 percent of the population. This is described as the lowest quintile income, or LQI. Future bills could average about 4.4 percent of household income in that group, or just under half of what those families spend on food, based on national statistics.

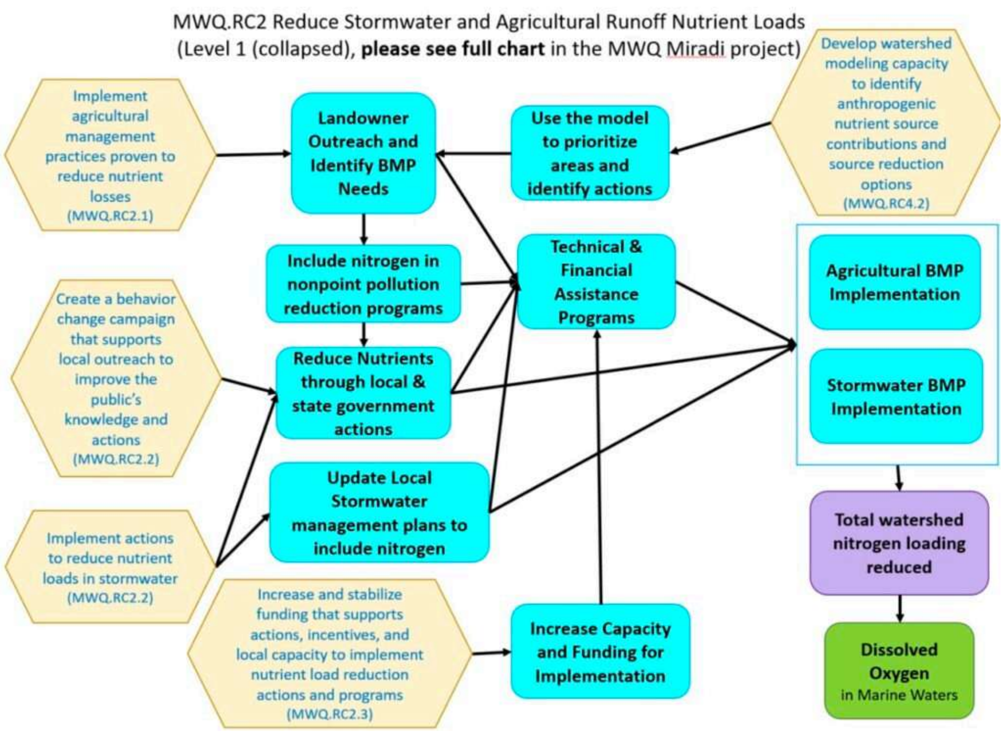
"Our findings suggest that currently only three Puget Sound utilities' sewer rates result in sewer bills less than 2.0 percent of LQI," the report states. "PSNGP-adjusted rates resulted in values ranging between 2.64 percent of LQI and 12.76 percent of LQI. These relatively high values indicate that sewer bills exacerbate the already regressive nature of Washington state's tax structure."

Grants and loans to sewer utilities could help reduce the overall costs borne by ratepayers, the report says, and data about the number of low-income sewer customers in specific areas could help direct those dollars to families with the greatest need. A more-direct effect would be a "low-income assistance program to aid those with the greatest need." Burke is conducting another study looking at a specific type of low-income assistance program, this one under contract with the Washington State Department of Health.

## Reducing nitrogen upstream

Computer modeling and ongoing discussions among experts have concluded that, beyond improvements to sewage-treatment plants, major reductions in nitrogen must also occur upstream across the landscape to improve dissolved oxygen conditions in Puget Sound.

As described in part 3 of this series, nitrogen delivered to Puget Sound in major rivers originate from a variety of sources as unique as the surrounding land uses. While computer models help establish nitrogen-reduction goals, they don't offer prescriptions for accomplishing those goals. Reducing such diverse, nonpoint sources will require a wide-ranging strategy that accounts for the diversity of sources, as described in the "Draft Implementation Strategy to Improve and Protect Puget Sound Marine Water Quality and Dissolved Oxygen."




*"Results chain" showing actions to reduce nitrogen from urban stormwater and agricultural operations. (Click to enlarge.) Source: Puget Sound Marine Water Quality Implementation Strategy*

"Based on the available science and modeling on nitrogen in Puget Sound, human nitrogen source reductions are needed from both point and nonpoint sources in nearly every Puget Sound watershed to improve the DO indicator and meet water quality standards," states the draft implementation strategy released in February under the purview of the Puget Sound Partnership, the state agency leading Puget Sound recovery.

The strategy, developed by specialized teams including more than 40 experts, was designed to help the region reduce nitrogen and thereby improve the health of Puget Sound. The best suggestions to emerge after further planning are expected to be incorporated into the Puget Sound Action Agenda for prioritized funding.

In addition to the implementation strategy, information on reducing upstream sources of nitrogen is provided in Ecology's "Water Quality Management Plan to Control Nonpoint Sources of Pollution." The plan, first adopted in 2015, is currently undergoing revisions, and public comments will be taken until Aug. 29.

Some of the specific ideas for watersheds, covered in these and other documents:

**Pollution Identification and Correction (PIC) programs:** Long used by some jurisdictions to track down sources of bacterial pollution, PIC programs could be employed to locate the most significant sources of nitrogen in a watershed. Water-quality inspectors typically start at one location in a stream and work their way upstream, taking water samples to identify tributaries delivering the most pollution, then moving farther upstream in search of the source or sources.

**Agricultural runoff, primarily crop fertilizers and livestock wastes:** The federal Clean Water Act does not address agricultural pollution, but Washington state law prohibits the discharge of any materials that contribute to pollution. "Best management practices," or BMPs, have been designed to help farmers apply appropriate amounts of fertilizer and to reduce runoff from pastures, livestock-confinement areas and manure storage. Local conservation districts often provide advice to farmers, and grants may be available to help with the expenses of carrying out BMPs and other voluntary actions.

**Urban stormwater runoff:** Nitrogen from lawn fertilizers, pet wastes, wild animals, sewage spills and other sources may wash off the land and into nearby streams, eventually reaching Puget Sound. Methods of containing and infiltrating rainwater into the ground can help keep surface flows from picking up pollution. Commercial stormwater permits may include controls to reduce pollution leaving a property. Municipal stormwater permits, which address runoff from streets and other hard surfaces, may include requirements for source control, water treatment, system maintenance, public education and pollutant limitations. New innovations for onsite nitrogen removal may be required.

**Forestry practices:** Removal of trees and vegetation along streams can lead to increased water temperatures and greater sedimentation. Warmer waters have less oxygen-carrying capacity, and sedimentation can add nitrogen, phosphorus and organic materials that can reduce oxygen levels. Red alder trees, one of the first species to colonize disturbed areas, can contribute to increased nitrogen, because their roots play host to bacteria that fix nitrogen from the air and release it into the soil. Managed forests may include chemical fertilizers or biosolids from sewage-treatment plants. Maintaining and adding trees to stream buffers have been shown to improve temperatures and reduce nitrogen and other pollutants. Specific strategies for reducing nitrogen from alder trees are under discussion.

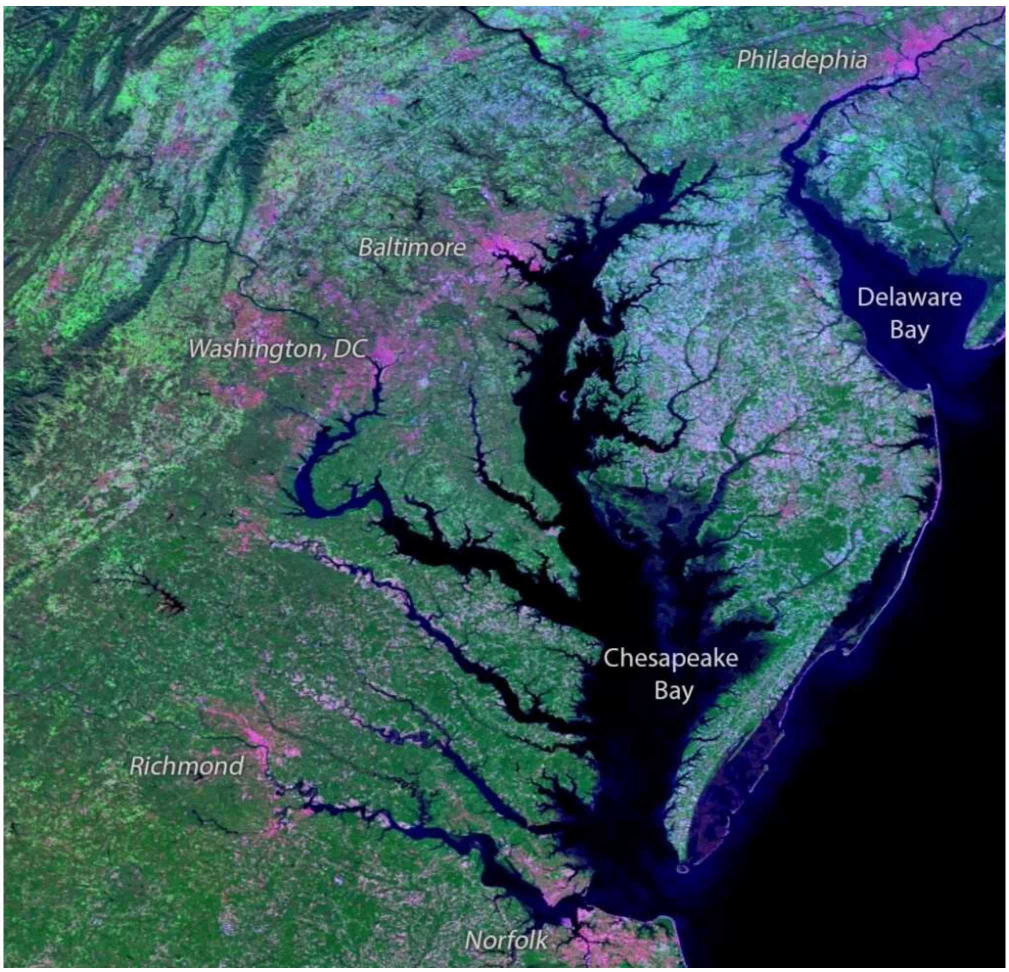
**Natural nitrogen attenuation:** Nitrogen- or phosphate-laden waters that flow through vegetation can reduce their nutrient loads by effectively fertilizing the plants. The vegetation can be part of a natural area or be incorporated into an artificial stormwater system. Maintaining natural vegetation and wetlands can reduce nutrient loads. Artificial systems often require regular maintenance to remove built-up sediment and excessive plant growth.

**Septic systems:** In areas without sewers, septic systems are designed to separate solids from liquids and discharge nitrogen-containing effluent into adjoining drainfields. Malfunctioning systems may release excess nitrogen into surface water or groundwater. Although functioning septic systems can theoretically release nitrogen into local waterways, studies have shown that properly maintained systems are not a significant problem. State regulations require regular septic inspections to ensure proper functioning, although enforcement varies among local health jurisdictions.

## Challenges to restoration

Controlling upstream sources of nitrogen can be challenging, depending on the source, as we know from experiences elsewhere in the country and across the globe. Overall goals for the east side of Puget Sound may include more than a 60 percent reduction in nitrogen loads, according to recent information from Ecology.

Nitrogen coming into Puget Sound with the rivers consists of a large variety of upstream sources with amounts unique to each river: sewage treatment plants, agricultural operations, urban runoff, alder trees and more. Taken together for all of Puget Sound, sewage treatment plants account for more than a third of the total nitrogen coming into Puget Sound from the watersheds, followed by alder trees with about 15 percent. Farm operations, urban runoff, atmospheric deposition and septic systems are each under 10 percent of the total — although, again, sources in one watershed vary significantly from any other watershed. These numbers were calculated using modeling data reported by Noah Schmadel and colleagues at the U.S. Geological Survey.




*While different from Puget Sound in many ways, Chesapeake Bay on the East Coast may offer some lessons in the effort to reduce low-oxygen problems. Satellite photo: NOAA's National Environmental Satellite, Data and Information Service*

While conditions are significantly different in Chesapeake Bay on the East Coast, a 40-year struggle to reduce low-oxygen problems in the bay may offer lessons for Puget Sound. Nitrogen inputs to the bay have been reduced since 1985 in the face of a rapidly growing population, yet the region remains far short of its goals to restore the waterway, according to a 2023 study by the Scientific and Technical Advisory Committee (PDF),, made up of 10 experts from five states, one from the District of Columbia, six from the federal government, and 21 at-large members, mostly from universities and research institutions.

The report says nitrogen from nonpoint sources was reduced by 29 million pounds from 1985 to 2022, yet that is just 36 percent of the long-range goal of 80 million pounds.

"Achieving nonpoint source reductions has proven more challenging than anticipated when the first nutrient reductions targets were established in the early 1990s," the report says. "The challenge is twofold. First, voluntary nonpoint source programs struggle to produce the scale of behavioral change and practice adoption necessary to achieve water quality goals — an implementation gap. Second, the nonpoint source programs and practices implemented may not be as effective as expected at reducing nonpoint source pollution —a response gap."

Despite increases in population, nitrogen discharges from sewage-treatment plants were reduced by about 50 percent from 1985 to 2017, thanks mainly to advances in treatment technology, according to a U.S. Geological Survey report titled "Nitrogen in the Chesapeake Bay Watershed: A Century of Change, 1950–2050." While nitrogen reduction will continue, officials say, dramatic reductions from treatment plants and other point sources are unlikely.

"Although implementation of urban management practices to reduce nonpoint sources of nitrogen (such as stormwater) will continue with new development, the potential nutrient reductions of those practices in the future are uncertain," the report says.

For decades, agriculture has played a prominent role in the low-oxygen problem in the Chesapeake, releasing more nitrogen and phosphorus than any other source. State and local governments have invested heavily in programs to reduce nitrogen from farms, but improvements have been slow, officials say.

Much of the agriculture in the Chesapeake watershed lies on the fertile coastal plain on the eastern shore of the bay and in southeastern Pennsylvania, the report notes. “Unfortunately, many of these regions also tend to have geologic settings (for example, sand/gravel, carbonate aquifers) that facilitate nutrient transport to groundwater and eventually streams.”

Reductions in nitrogen were attributed largely to conservation practices, such farmland retirement, animal waste management systems, and conservation tillage, but also bioretention by ponds and wetlands, the report says.

The ecological response to these efforts, such as water quality in the bay, appear to be delayed, as it takes time for existing nitrogen to work its way through the system, according to the report.

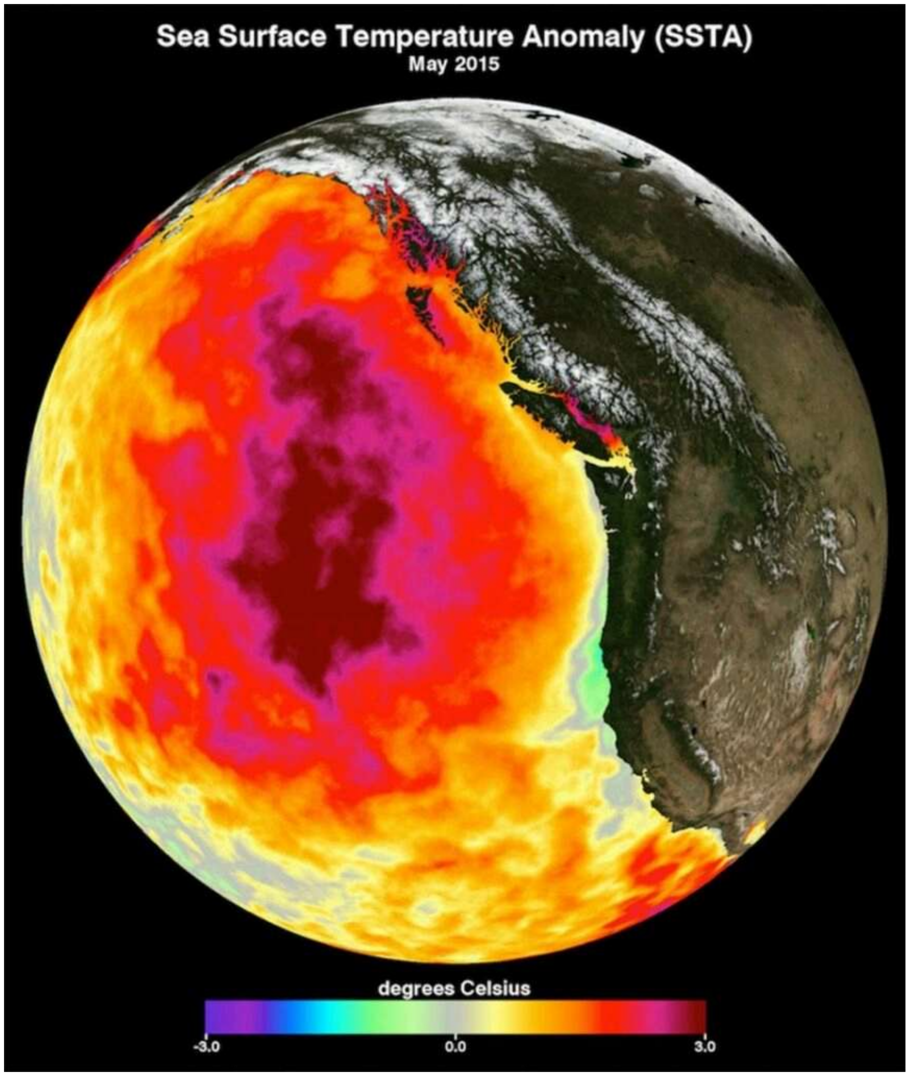
“Can the Chesapeake Bay, and similar estuary communities around the world, find ways to flourish and live sustainably, while at the same time managing nutrients that maintain healthy terrestrial and aquatic ecosystems?” the authors ask. “This” they add, “will be a challenge for the future.”

## Climate change and future conditions

Climate change is expected to reduce dissolved oxygen levels in some parts of Puget Sound as a result of multiple factors, including warming waters, alterations in streamflow and potentially greater amounts of nitrogen coming in from the Pacific Ocean, according to experts.

Depending on the location, Puget Sound waters have increased by 0.8 to 1.6 degrees F between 1950 and 2009, according to localized studies, and this trend is likely to continue or even accelerate as a result of climate change. Warmer water cannot hold as much oxygen as cooler water, so this factor alone could increase stresses on marine life.

Puget Sound also is influenced by incoming flows from the Pacific Ocean, where oxygen levels declined roughly 22 percent from 1956 to 2006 at Ocean Station Papa, a weather buoy about 640 miles off the coast of British Columbia. Similar declines have been measured in the Strait of Georgia north of Puget Sound, primarily from coastal




*By May 2015, a huge mass of warm water had accumulated off the West Coast of North America, with temperatures up to 3 degrees C (5 degrees F) warmer than average. Such events, which can disrupt the food web, are expected to occur more frequently as global warming drives climate change. // Data image: NASA Earth Data*

upwelling of low oxygen water from the deep. Consistent trends have been measured in Washington's Strait of Juan de Fuca, Admiralty Inlet and Hood Canal, suggesting that oceanic conditions could add to future low-oxygen problems in Puget Sound. See "State of Knowledge: Climate Change in Puget Sound."

Climate change is expected to continue an ongoing shift to earlier-in-the-year snowmelt in the mountains, with higher winter streamflows and lower summer streamflows expected over time. These alterations in flow patterns affect both stratification (layering, with freshwater typically on top) and circulation, two major factors that help determine oxygen levels. But neither the precise conditions nor the effects on oxygen levels can be predicted, according to the Climate Impacts Group, a University of Washington program that produced the State of Knowledge report.

"Stratification inhibits mixing of deeper, nutrient-rich water up into the zone where there is enough light for photosynthetic organisms (e.g. algae) to grow and favors the formation of low-oxygen zones at depth," the report states. "In winter, this is not a major limitation, since the main impediment to biological productivity is a lack of sunlight. During the growing season, in contrast, water column stratification can potentially limit the supply of nutrients to phytoplankton and the supply of oxygen to deeper waters."

A 2014 Ecology report, titled "Puget Sound and Straits Dissolved Oxygen Assessment," analyzes impacts of human nitrogen sources along with climate change to the year 2070.

"Stratification overall appears to be strengthening, which could contribute to the downward trend in oxygen," states the report. "The change in stratification from both salinity and temperature changes would also affect circulation. This assessment focuses on changes in DO and nitrogen alone, but additional analyses are needed that also incorporate changes in temperature and salinity at the ocean boundary to assess other potential effects of climate change."

The biggest factors in determining future oxygen levels in Puget Sound are likely to be population growth, land use change and the relative success of strategies to reduce inputs of nitrogen from a variety of human sources, says the report.

"The change in flow regime, coupled with future land-cover-based concentrations, would alter the magnitude and timing of nutrient load delivery from watershed inflows," the report says. "It is possible that future freshwater delivery could partly offset decreases in dissolved oxygen resulting from higher nitrogen loads. Additional investigation is warranted to understand these relationships."

A decade ago, dozens of researchers investigated and reported on an unusual marine heat wave that brought warm waters from the ocean into Puget Sound beginning in 2014 and extending through 2016. The rare water condition nicknamed "the Blob," produced temperatures up to 4 degrees F higher in some places in Puget

Sound. The phenomenon was not good for most sea life, but it offered scientists a fascinating preview of what could happen more frequently in the future, as more heat waves have been reported across the globe.

The warm-water mass, created in the ocean during a period of intense sun and quiet weather conditions, grew large as it moved toward the coast. Scientists reported that plankton blooms started earlier and grew unusually large by the first summer. Plankton were not the typical assortment of species, which helped to distort the food web. Toxic plankton caused the closure of commercial and recreational shellfish beds.

Warm-water fish showed up in large numbers off the coast, and some came into Puget Sound. Anchovy populations seemed to flourish in South Sound. Jellyfish appeared in large numbers and scooped up forage fish, reducing the food supply for other species. Salmon altered their migration patterns. A large number of birds and some marine mammals were sickened or killed by toxic algae.

The warm water decreased oxygen levels in Puget Sound while increasing respiration rates among many species. In Southern Hood Canal, oxygen levels were practically zero in deep water. The Blob began to subside in 2016, and its effects diminished, but repercussions were long-lasting.

Many scientists, caught by surprise by the 2014-16 event, say they are prepared to measure environmental effects from beginning to end when the next big heat wave appears.

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*This article was funded in part by King County in conjunction with a series of online workshops exploring Puget Sound water quality. Its content does not necessarily represent the views of King County or its employees.*

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*Previous: Low oxygen challenge, part 3: Computer models spell out the extent of the water-quality problem*
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*An extensive plankton bloom through Central Puget Sound impressed even longtime researchers with the Washington Department of Ecology. This aerial photo of the Noctiluca bloom was taken in June 2013 between Seattle and Bainbridge Island. The photo was featured in the monthly water-quality report from Ecology's Eyes Over Puget Sound program. // Photo: Washington Department of Ecology*

WATER QUALITY, MODELING

# The quest continues for a nutrient reduction plan

**By Puget Sound Institute** Published December 20, 2022 Comments Closed

*The quest continues for a large-scale plan to reduce human sources of nitrogen and improve the health of Puget Sound. This article is part of the Puget Sound Institute's effort to explore the technical uncertainties related to the science of Puget Sound water quality. The project, jointly funded by King County and PSI, includes online workshops and discussions, along with informational blogs and articles.*

**By Christopher Dunagan**

Human sources of nitrogen in Puget Sound have been blamed for increasing the intensity of algae blooms, lowering oxygen to critical levels, and impairing sea life. In response, officials with the Washington Department of Ecology are developing a Puget Sound Nutrient Reduction Plan to strategically reduce nitrogen in various places.

Ecology experts recognize that the Pacific Ocean is the greatest source of nitrogen to Puget Sound, but how much of that nitrogen contributes to low-oxygen conditions depends on many factors. Because oceanic nitrogen is practically beyond human control, much of the current focus is on the ever-increasing levels of nitrogen from human sources. See Ecology's Oxygen and Nutrients in Puget Sound.

According to Ecology estimates, about two-thirds of the human-induced nitrogen is coming from sewage-treatment plants perched along the shoreline. The rest comes from diverse sources such as septic systems, fertilizers from farms and urban landscapes, animal waste from livestock and pets, and atmospheric deposition from the burning of fossil fuels and organic materials. For planning purposes, these diverse sources of nitrogen are grouped as "watershed" sources, and they enter Puget Sound mostly via streams and stormwater outfalls.

Ecology has begun to address the discharges from sewage-treatment plants with the issuance of a "nutrient general permit" that requires operators to conduct studies, curb nitrogen releases at basically current levels, and eventually cut back on the amount of nitrogen going into Puget Sound.

In response, eight cities, counties, and other sewer operators (listed below) filed appeals to the state's Pollution Control Hearings Board. [Editor's note: King County, which is appealing the permit, is one of the Puget Sound Institute's funders.] A temporary out-of-court agreement has placed some of the permit requirements on hold until the board can decide whether the general permit is legal and necessary.

While stated reasons for the appeals vary among jurisdictions, the sewer operators broadly contend that the new general permit conflicts with federal permits already required of every sewage-treatment plant. Many argue that Ecology has failed to show how their individual operations contribute to the low-oxygen conditions, often mentioning the costs of planning and upgrades to their sewage-treatment plants without clear benefits.

As the eight sewer operators seek to overturn the nutrient general permit, two environmental groups and one tribal government contend that the permit does not go far enough to quickly accomplish corrective actions, considering that many areas of Puget Sound already fail to meet water-quality regulations.

In a joint appeal, the Washington Environmental Council and the Suquamish Tribe argue that loose timelines and other flaws in the permit will allow some treatment plant operators to increase, rather than decrease, nitrogen discharges over the next five years. Similarly, Puget Soundkeeper Alliance is pressing Ecology to establish enforceable limits on nitrogen discharges and to declare that nitrogen reductions can be accomplished with available treatment technology.

Meanwhile, Ecology continues to work on the overall plan to reduce nitrogen loads from all human sources, with a current focus on so-called watershed sources, including stormwater. Solutions involving upland areas may vary for different parts of Puget Sound, according to Dustin Bilhimer, who heads up Ecology's Nutrient Reduction Project. Some areas are more affected by agricultural runoff, while others have extensive discharges of urban stormwater.

Besides improving the ecological health of Puget Sound, the goal is to decrease the number of regulatory water-quality violations, which occur when the level of dissolved oxygen falls below a specific state standard. That standard varies for defined areas of Puget Sound — generally between 4 and 7 milligrams of oxygen per liter in saltwater, depending on the designated use and water-quality classification. Basic concepts are explained further in an Ecology fact sheet (PDF 110 kb) addressing freshwater issues.

Violations of dissolved-oxygen standards have been found so far in 194 designated areas within 46 bays, inlets and open-water sectors in Puget Sound, according to Ecology's Water Quality Assessment, sometimes called the 303(d) list of impaired waters. Another 290 areas in 45 inlets are on the list for low-oxygen problems, but more study is needed to determine regulatory violations.

These lists, prescribed by the Clean Water Act, may include some areas where low-oxygen conditions prevail because of natural conditions — where humans are not primarily to blame for oxygen levels below the numerical standard. Such areas would not be considered a violation and could be removed from the list if they meet so-called natural conditions criteria. At the moment, Ecology is rewriting its natural-conditions criteria for both oxygen and temperature in a formal rule-making process. The rewrite comes at the direction of the Environmental Protection Agency which has temporarily suspended the state's previous natural conditions criteria following a legal challenge.

Excess nitrogen is getting so much attention because nitrogen compounds are a key ingredient — along with sunlight — in the production of excess plankton. Large colonies of plankton eventually die and sink to the bottom, consuming available oxygen as they decay. See related stories: **"**Understanding the causes of low oxygen in Puget Sound" and "Tiny plankton play a mighty role in the health of Puget Sound."

As planning continues, the Puget Sound Nutrient Reduction Project is trying to identify the most significant sources of nitrogen resulting from human activities. The explicit goal is to identify actions that can lead to the highest level of compliance with the state's dissolved-oxygen standards.

Using the Salish Sea Model, experts are studying various scenarios that consider the combined effects of reducing nitrogen from sewage treatment plants and from various watershed sources. Key questions revolve around the locations where nitrogen comes into Puget Sound as well as areas most affected by low-oxygen problems. For example, does it make more sense to reduce smaller inputs of nitrogen close to problem areas or cut back on larger sources farther away?

Considering the multitude of problem areas and nitrogen sources, examining the various options becomes a major challenge, even with the help of computer modeling, according to Ecology's Bilhimer.

From work done so far, it appears that nitrogen-bearing waters readily move from one area of Puget Sound to another, undergoing changes along the way. These enriched waters may contribute to low-oxygen problems a fair distance from the original sources.

Bilhimer says one thing has become abundantly clear from model runs conducted last year: To meet the state's dissolved-oxygen standards in Puget Sound, large reductions of nitrogen are needed from both sewage treatment plants and human watershed sources. Looking to the future, increasing inputs of nitrogen caused by population growth may exacerbate the low-oxygen problems in some areas if actions are not taken, he said.

To improve estimates of nitrogen from watershed sources, new automated monitoring equipment is being installed to gather data on nitrogen levels at 15-minute intervals in eight rivers, rather than the 30-day intervals used for data collected in the past. The result should be better estimates of nitrogen coming from the rivers under various conditions.

This network of monitoring equipment is expected to be in operation by late spring next year. The first device is currently being installed in the Cedar River. Others will go into the Duwamish, Deschutes, Nisqually, Puyallup, Stillaguamish, Nooksack and Skagit rivers.

At the same time, surveys looking upriver in the watersheds will help determine actual sources of nitrogen and their relative contributions to the overall problem, as well as finding ways to address the sources.

To gain a better understanding of upstream sources of nitrogen, Ecology plans to employ a watershed model developed by the U.S. Geological Survey. The model provides a more sophisticated analysis of sources, from urban runoff to agricultural fertilizers to atmospheric deposition. Specifics about the timing and locations of nitrogen flowing into Puget Sound is then incorporated as inputs into the Salish Sea Model. The statistics-based watershed model is called Spatially Referenced Regression On Watershed Attributes, or SPARROW.

An entirely separate modeling project, announced last week, is expected to play a role in the discussion about the effects of nitrogen on the water quality of Puget Sound. In fact, those involved in this new project envision a scope well beyond nitrogen as part of the Puget Sound Integrated Modeling Framework, a new project led by PSI. The work involves coupling together at least five separate models that link data across the watershed. The project will incorporate physical conditions, biological changes and even human interactions within the Puget Sound ecosystem.

In the new project, watershed inputs to Puget Sound will be described using a model developed by the EPA called VELMA, which stands for Visualizing Ecosystem Land Management Assessments. Like SPARROW but with an analytical framework that divides the landscape into discrete segments, VELMA will provide its own estimates of nitrogen going into Puget Sound, estimates that can be used to run the Salish Sea model.

While two or more watershed models might sound like an added complication, being able to compare their outputs will only improve the modeling process and boost confidence in the results, according to Stefano Mazzilli, senior research scientist at PSI. If the separate models produce similar results, it is likely that the modelers are on the right track, he explained. If the results are very different, then modelers will need to figure out what may be wrong with one or more models.

“Having multiple models for estuarine or watershed processes is always beneficial,” Mazzilli said. “Models are built with different purposes, and it is important to recognize that some are better at providing information for particular decisions.”

For example, some models may be better at dealing with rural versus urban areas, or addressing a multitude of environmental stressors, as in studies of toxic chemicals, he noted.

In any case, for a model to be useful to those making decisions about nitrogen, the model must accurately predict the results of actions that could be taken, Mazzilli said. Otherwise, decision-makers won’t know which options will produce the best results. Understanding and reducing uncertainties surrounding the effects of nitrogen and the results of potential actions is the goal a PSI project titled The Science of Puget Sound Water Quality.

As for Ecology's Puget Sound Nutrient Reduction Project, the effort is edging closer to a formal plan after five years of study. The plan will include recommendations for reducing nitrogen to improve the low-oxygen conditions in Puget Sound.

It is worth mentioning, said Bilhimer, that unrelated ecosystem-restoration projects are having their own beneficial effects. For example, efforts to reduce bacterial pollution and reopen shellfish beds — such as in Samish Bay in northern Puget Sound — have also reduced nitrogen levels in the area. Likewise, shoreline restoration projects — such as in Nisqually Estuary in South Puget Sound — have improved natural functions, helping to reduce nitrogen loads, he added.

Further studies of nitrogen sources are planned through next year, according to the latest schedule released Dec. 7 during a meeting of advisers — the so-called Puget Sound Nutrient Forum. Discussions about problem areas and potential solutions will be taken up in 2024, with a special focus on a draft plan to reduce nitrogen from various sources. Formal adoption of the plan could come in 2025.

*Parties filing appeals of the Washington Department of Ecology's new nutrient general permit: Puget Soundkeeper Alliance, King County, City of Tacoma, Washington Environmental Council, Suquamish Tribe, City of Everett, City of Bremerton, Birch Bay Water and Sewer District, Alderwood Water and Wastewater District, Pierce County, and City of Edmonds*.

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# Technical Memorandum

# Review of 2025 Salish Sea Model Updates and Application to Nutrient Management

August 22, 2025

Contributing Authors: Joel Baker, Marielle Kanojia, and Stefano Mazzilli

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# Executive Summary

The Puget Sound water quality management community is navigating complex decisions on how best to manage nitrogen to maintain healthy habitats. Too much nitrogen from human activities can potentially increase algal blooms, decrease dissolved oxygen, add to ocean acidification, and cause other changes that may harm marine life. The cumulative effect of multiple stressors - including those resulting from climate change and the presence of toxic contaminants - make it challenging to find the best solution for the range of water quality problems that affect marine life. Regulation is currently focused on the impacts that nitrogen from human sources has on low dissolved oxygen in Puget Sound. In recent years, Washington State has relied on its version of the Salish Sea Model[1]—a coupled hydrodynamic and biogeochemical model—to evaluate regulatory compliance and assess the effectiveness of various nutrient reduction strategies. Model results released in June 2025, underpin the Draft Puget Sound Nutrient Reduction Plan (Reiman, 2025), an advanced restoration plan that establishes watershed and marine point source nitrogen loading targets designed to meet Washington State's marine dissolved oxygen water quality standards throughout Puget Sound. The State ran several scenarios to explore the potential impact of reducing nutrients from marine point sources and watersheds. The targets were ultimately derived from the Opt2_8 modeling scenario described in Figueroa-Kaminsky et al. (2025), which reflects a modified method for predicting non-compliance, updated nutrient loads, and refinements to the model structure and skill assessment relative to Ahmed et al. (2019) and Ahmed et al. (2021).

For the past several years, the University of Washington Puget Sound Institute has played a central role in advancing the science and modeling that underpin nutrient management decisions in the region. This work has included hosting a series of workshops to build consensus and accelerate scientific progress, running the Salish Sea Model to test additional nutrient reduction scenarios, convening an international Model Evaluation Group to assess model performance, and leading cutting-edge research on species-specific risks that integrates temperature-dependent oxygen supply and demand. In 2023-2024, the Puget Sound Institute convened global experts to advise on how to improve the application of the Salish Sea Model to inform recovery goals and nutrient management decisions in Puget Sound. The Model Evaluation Group included scientists who have led pioneering research and advised regional managers on the application of modeling and monitoring in nutrient management programs in other regions, like the Baltic and Chesapeake Bay. These experts – Bill Dennison, Jacob Carstensen, Jeremy Testa, Kevin Farley, and Peter Vanrolleghem – shared several recommendations to improve confidence in applying the Salish Sea Model to support Puget Sound's recovery goals and regulation (Mazzilli et al., 2024). In Figueroa-Kaminsky et al. (2025), the State made significant advances addressing the prior Model Evaluation Group's recommendations.

In this technical memorandum, Puget Sound Institute reviewed Figueroa-Kaminsky et al. (2025) to evaluate how the model updates and analyses influence the proposed nutrient targets. Key takeaways include:

1. **Shift to total nitrogen targets further tightens limits** | The Draft Puget Sound Nutrient Reduction Plan shifted to using total nitrogen (TN) for targets rather than total inorganic nitrogen or dissolved inorganic nitrogen (TIN/DIN). If the DIN-based scenario reductions are applied directly

[1] There are several versions of the Salish Sea Model; see the Salish Sea Modeling Center for additional context. Throughout this technical memorandum, the Salish Sea Model refers to the version used by the State and reflected in Figueroa-Kaminsky et al. (2025) unless otherwise noted.

as TN in permits, the resulting limits would be stricter than the modeled scenarios by capping all nitrogen forms.

2. Proposed watershed reductions face major feasibility challenges | Reducing nutrients from diffuse sources in watersheds is notoriously challenging because actions are often voluntary, require buy-in from thousands of independent landowners, and are frequently undermined by competing agricultural incentives that encourage fertilizer-intensive cropping practices. The proposed reductions range from 53 – 67% in most basins, which exceeds what has been achieved even in the best cases in Denmark and the Chesapeake Bay (Scientific and Technical Advisory Committee (STAC), 2023). Since 1990, Denmark has cut its nitrogen surplus by ~50%, but only through decades of strong political will and strict regulations on livestock, manure, and fertilizer use (Riemann et al., 2016). Implementing the proposed targets will also require a more sophisticated understanding of the watershed sources. Recent modeling by USGS SPARROW, in collaboration with the State, has taken strong initial steps by estimating seasonal loads from both marine point and watershed sources (Schmadel et al., 2025). A helpful next step would be to show watershed sources separately and aligned to the watershed boundaries in the State's Draft Puget Sound Nutrient Reduction Plan. This would allow managers to see how the nutrient sources line up with the watershed-specific targets set in the plan.

3. Model skill vs. regulatory precision is challenging | The State made thorough and thoughtful refinements to the model and analysis of model skill that advanced several of the Model Evaluation Group's recommendations (Mazzilli et al., 2024). While there are some opportunities for refinement, model skill may be reaching the point of diminishing returns. Although overall model performance improved modestly, errors in embayments remain several times higher than the 0.2 mg/L human use allowance. Additionally, the subtraction of two scenarios does not cancel uncertainty—especially since the reference condition cannot be validated. As a result, when compliance is determined by comparing existing and reference scenarios, the true level of uncertainty in the outcome is larger than the model statistics alone suggest and must be explicitly considered in regulatory applications. It seems unlikely that any model could reduce uncertainty to the point that it is lower than the current human use allowance of 0.2 mg/L.

4. Long-term planning depends on realistic future scenarios | In Ahmed et al. (2021), the State took an important first step by modeling 2040 wastewater loads based on population growth but did not account for climate-driven changes to river flows and ocean conditions, land use shifts, or potential management actions. Since nutrient targets will guide decisions for decades, it would be valuable to run a future scenario that incorporates climate change and land use. This would provide a more complete picture of how future conditions may influence Puget Sound's response to nutrient reductions, particularly given the central role of temperature in shaping oxygen availability for marine life.

# Modeling informs nutrient management

## Modeling informs water quality impairments

Washington uses both Salish Sea Model outputs and measured data to determine 303(d) listings of impaired water bodies. A specific location in Puget Sound is considered non-compliant on a specific date if:

1. **Measured oxygen levels fall below** either the numeric criteria (that ranges from 4 to 7 mg/L) or modeled estimates of natural conditions, whichever is lower

&

2. **Modeling shows that human activities reduce dissolved oxygen** by more than **0.2 mg/L or 10%** below natural conditions, whichever decrease is smaller

Some core model scenarios help assess the effects of human activity and non-compliance:

- **Existing conditions** represent estimated nutrient loads and hydrodynamics in a given year, like 2014.
- **Reference conditions** represent the maximum improvement in dissolved oxygen possible in Puget Sound. In these scenarios, the same hydrodynamics and climate as existing conditions are used, and the river and wastewater treatment plant nutrient loads are replaced with estimated loads before the adoption of modern land-use practices and population growth in Washington State.
- **Natural conditions** aim to reflect what the water quality in Puget Sound was like before substantial human influence, including the global impacts of a changing climate and oceans. Modeling natural conditions would require hindcasting the climate to pre-settlement and removing the influence of all anthropogenic nutrient loads, including those from Canada.

At this time, the Salish Sea Model's *reference condition* scenario only accounts for human impacts from local (i.e., Washington state) sources and does not fully meet the definition for *natural conditions* as outlined in the State's performance-based approach. For example, it does not remove the effects of climate-driven changes in ocean circulation, temperature, or atmospheric conditions. As a result, the model provides a strong foundation for evaluating local nutrient management actions but may not capture the full picture of global or external influences on dissolved oxygen in Puget Sound. Currently, non-local sources like Canada are not assigned targets in the Draft Puget Sound Nutrient Reduction Plan, which focuses specifically on pollution that originates within Washington State.

REFERENCE CONDITIONS

**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 preindustrial 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, ocean, and all other boundary and forcing conditions

A unique reference condition is created for each year the model is run.

## Modeling informs nutrient targets

The State also ran several scenarios to explore the potential impact of reducing nutrients from marine point sources and watersheds on dissolved oxygen levels and non-compliance. The days, area, and magnitude of non-compliance under existing conditions vary across the 2000, 2006, 2008, and

**Explore the Results**
Dig into the detailed results on the State's webmap.

2014 runs (Table 1). Due to computational constraints, though, the scenarios exploring the potential impact of reduced nutrient loads were only run for 2014.

***Table 1.*** *Dissolved oxygen noncompliance under existing conditions for the years 2000, 2006, 2008, and 2014 for Washington waters of the Salish Sea. Table 15 from Figueroa-Kaminsky et al. (2025).*

| Year | Total days of noncompliance | Total area of noncompliance ($km^2$) | Maximum magnitude of DO noncompliance (mg/L) |
|---|---|---|---|
| **2000** | 74,156 | 477 | -1.2 |
| **2006** | 136,367 | 621 | -1.4 |
| **2008** | 70,060 | 465 | -0.9 |
| **2014** | 80,279 | 467 | -1.1 |

[a] Noncompliance excludes masked areas (e.g., Budd Inlet).

## Refining watershed scenarios

In Figueroa-Kaminsky et al. (2025), the State simulated several scenarios that combined marine point source and watershed nutrient load reductions. Building on previous studies like Ahmed et al. (2019) and Ahmed et al. (2021), the State started by running several minor variations on watershed reductions in combination with setting wastewater plants' discharge to 3 mg/L, 5 mg/L, and 8 mg/L DIN in hot, warm, and cool months, respectively. All of the scenarios reduced anthropogenic watershed loads by 58-74% (Washington State Department of Ecology, 2025b, Figueroa-Kaminsky et al. 2025). The State selected H1_C as the optimal watershed scenario because "it resulted in similar levels of noncompliance as other initial scenarios without having to reduce anthropogenic loads in watersheds entering the Straits (i.e., with less effort)." Compared to the other watershed scenarios, H1_C had greater reductions in larger watersheds and those entering the Northern Bays, Main Basin, and South Sound. Non-compliance was persistent in small areas of several embayments, including Lynch Cove, Henderson Inlet, Carr Inlet, Sinclair Inlet, and Liberty Bay. Therefore, the State refined the watershed framework to reduce anthropogenic nutrients by 90% in streams near these embayments with persistent non-compliance. Sound-wide, the refined watershed framework reduces TN anthropogenic watershed loads by 61% (Figueroa-Kaminsky et al. 2025).

## Refining marine point source scenarios

The State then combined the refined watershed framework with 10 additional alternatives for marine point source reductions. Marine point sources refer to the "NPDES permitted domestic wastewater treatment plants and industrial facilities located in Washington and discharging to Puget Sound" (Washington State Department of Ecology, 2025a). These scenarios represented small variations with anthropogenic marine point reductions ranging from 68 – 74% for TN (Washington State Department of Ecology, 2025b). The difference in outcomes between the scenarios was also minimal; the remaining non-compliant areas ranged from 0.8 to 2.5 $km^2$ in Sinclair and Henderson Inlet. Across all of these scenarios, the remaining noncompliant areas showed only minor differences from existing conditions, with maximum dissolved oxygen depletions of 0.3 mg/L relative to reference conditions. This is just above the human use allowance, indicating conditions are nearly compliant. Again, these results reflect the combined impact of both the watershed and marine point source reductions, which, in total, ranged from a 65 – 69% reduction in anthropogenic TN loads across the scenarios. These scenarios also found that the following had a negligible, incremental impact on non-compliance (i.e., $\leq$ 1 day):

- Capping very small wastewater treatment plants at 2014 existing loads

- Capping plants discharging to basins that are either well flushed or have small wastewater treatment plant loads at 2014 existing loads – specifically Admiralty Inlet, Hood Canal, the Strait of Juan de Fuca, and the Strait of Georgia.
- Reducing the discharge for dominant plants in the Main Basin from 5 mg/L to 3 mg/L from April – June and October.

Given where non-compliance persisted, another scenario explored the potential impact of increasing treatment at the three plants discharging to Sinclair Inlet (i.e., Bainbridge Kitsap Co 7, Bremerton, and Port Orchard) to a year-round limit of 3 mg/L, instead of the seasonal limits of 3 mg/L in hot months, 5 mg/L in warm months, and 8 mg/L in cool months. The model predicted that this scenario would further reduce the area not meeting dissolved oxygen standards by 1.57 $km^2$ and decrease the cumulative number of noncompliant cell-days by 22. In other words, every instance where a model grid cell is out of compliance on a given day, which reflects both how many cells and how many days are affected. Breaking down the 22-cell-day reduction: four different cells each improved by 2, 3, 5, and 9 days of compliance, respectively.

## Scenario selected for nutrient reduction targets

The State chose to align the targets in the Draft Nutrient Reduction Strategy with the Opt2_8 modeling scenario (Table 2 and Table 3). The Draft Puget Sound Nutrient Reduction Plan specifically notes, "Scenario Opt2_8 was selected as the basis for the nitrogen targets in this plan because it required a lower amount of nutrient reductions, relative to other scenarios, while achieving DO standards throughout the Sound when the bottom two vertical layers are aggregated. The Phase 2 report did not include results with bottom averaging, but here, we explored that option due to the shallow nature of the assessment units."

*Table 2. Watershed reduction framework applied in the Salish Sea Model scenario Opt2_8. Adapted from Table 4 from the Draft Puget Sound Nutrient Reduction Strategy, Table 2 in Figueroa-Kaminsky et al. (2025), and the June 24, 2025, Nutrient Forum.*

<table>
<tr><th>Basin(s)</th><th>Basin-wide Reduction in Anthropogicn Total Nitrogen Loads</th><th>Detailed Reduction in Anthropogenic Total Nitrogen and Organic Carbon Loads</th></tr>
<tr><td>Northern Bays</td><td>66%</td><td rowspan="2">67.7% in large watersheds*<br>61.2% in all other watersheds</td></tr>
<tr><td>Whidbey</td><td>67%</td></tr>
<tr><td>Main</td><td>68%</td><td>90% in watersheds draining to Sinclair Inlet and Liberty Bay<br>67.7% in large watersheds*<br>61.2% in all other watersheds</td></tr>
<tr><td>South Sound</td><td>63%</td><td>90% in watersheds draining to Carr and Henderson Inlets<br>67.7% in large watersheds*<br>61.2% in all other</td></tr>
<tr><td>Hood Canal</td><td>66%</td><td>90% in watersheds draining to Lynch Cove<br>53.4% in all other watersheds</td></tr>
<tr><td>Admiralty</td><td>53%</td><td>53.4% in all watersheds</td></tr>
<tr><td>Strait of Juan de Fuca</td><td colspan="2" rowspan="2">Capped at 2014 existing levels</td></tr>
<tr><td>Strait of Georgia</td></tr>
</table>

*Defined as average daily anthropogenic TN load greater than 1,000 kg/day

*Table 3. Marine point source reduction framework applied in Salish Sea Model scenario Opt2_8.*

| Loads* | Facilities |
|---|---|
| Capped at 2014 loads | • Industrial facilities<br>• Small wastewater treatment plants discharging less than 22 lbs. TN/day or less than 13 lbs. DIN/day<br>• Wastewater treatment plants discharging to Admiralty Inlet, Hood Canal, the Strait of Juan de Fuca, or the Strait of Georgia |
| 3 mg/L DIN Year-Round | • Three domestic wastewater treatment plants discharging to Sinclair Inlet:<br>▪ Bainbridge Kitsap Co 7<br>▪ Bremerton<br>▪ Port Orchard |
| 8 mg/L DIN – Cool<br>3 mg/L DIN – Warm & Hot | • Dominant wastewater treatment plants dischargers (> 2000 lbs. TN/day) in the Main Basin<br>▪ Except for West Point, which is set at 8 cool, 5 warm, and 3 hot targets because it treats combined sewage |
| 8 mg/L DIN – Cool<br>5 mg/L DIN – Warm<br>3 mg/L DIN – Hot | • Remaining wastewater treatment plants in the Northern Bays, Whidbey, Main, and South Sound Basins |

*The seasons are defined as: cool (November – March), warm (April – June, and October), and hot (July – September). Flows are maintained at 2014 levels.

Table 4 compares the predicted noncompliance in 2014 for existing conditions and the Opt2_8 scenario, which was used to establish the draft nutrient targets. Under existing conditions, 50% of the non-compliant areas in 2014 had changes of 0.3 mg/L, just over the 0.2 mg/L human use allowance. Under Scenario Opt2_8, all the remaining non-compliance is within 0.2 mg/L of the human use allowance.

*Table 4. Dissolved oxygen noncompliance predicted for 2014 existing conditions and the Opt2_8 scenario. Adapted from Table 17 from Figueroa-Kaminsky et al. (2025).*

| Noncompliance Metric | Basin | Total Possible | Existing (2014) | Opt2_8 (2014) |
|---|---|---|---|---|
| Total days of Noncompliance | Northern Bays | 92,345 | 800 | 0 |
| | Whidbey Basin | 190,530 | 18,918 | 0 |
| | Main Basin | 324,850 | 911 | 34 |
| | South Sound | 174,835 | 8,220 | 2 |
| | Hood Canal | 157,680 | 51,340 | 0 |
| | Admiralty | 172,645 | 0 | 0 |
| | US Strait of Georgia | 792,780 | 0 | 0 |
| | US Strait of Juan de Fuca | 1,096,095 | 0 | 0 |
| | Washington waters of the Salish Sea | 3,001,760 | 80,279 | 36 |
| Total area of Noncompliance ($km^2$) | Northern Bays | 188 $km^2$ | 40 | 0 |
| | Whidbey Basin | 371 $km^2$ | 185 | 0 |
| | Main Basin | 617 $km^2$ | 13 | 0.83 |
| | South Sound | 291 $km^2$ | 81 | 0.11 |
| | Hood Canal | 275 $km^2$ | 148 | 0 |
| | Admiralty | 350 $km^2$ | 0 | 0 |

| | | | | |
|---|---|---|---|---|
| | US Strait of Georgia | 1,588 $km^2$ | 0 | 0 |
| | US Strait of Juan de Fuca | 2,319 $km^2$ | 0 | 0 |
| | Washington waters of the Salish Sea | 5,997 $km^2$ | 467 | 0.93 |
| Maximum Magnitude of dissolved oxygen Noncompliance (mg/L) | Northern Bays | n/a | -0.2 | 0 |
| | Whidbey Basin | | -0.5 | 0 |
| | Main Basin | | -1.1 | -0.1 |
| | South Sound | | -0.8 | 0 |
| | Hood Canal | | -0.6 | 0 |
| | Admiralty | | 0 | 0 |
| | US Strait of Georgia | | 0 | 0 |
| | US Strait of Juan de Fuca | | 0 | 0 |
| | Washington waters of the Salish Sea | | -1.1 | -0.1 |

## Puget Sound Nutrient Reduction Plan

The Draft Puget Sound Nutrient Reduction Plan, an advanced restoration plan, establishes watershed and marine point source nitrogen loading targets designed to meet Washington State's marine dissolved oxygen water quality standards throughout Puget Sound. The targets were derived from the Opt2_8 scenario modeled in Figueroa-Kaminsky et al. (2025). The draft plan was released in June 2025 for public comment.

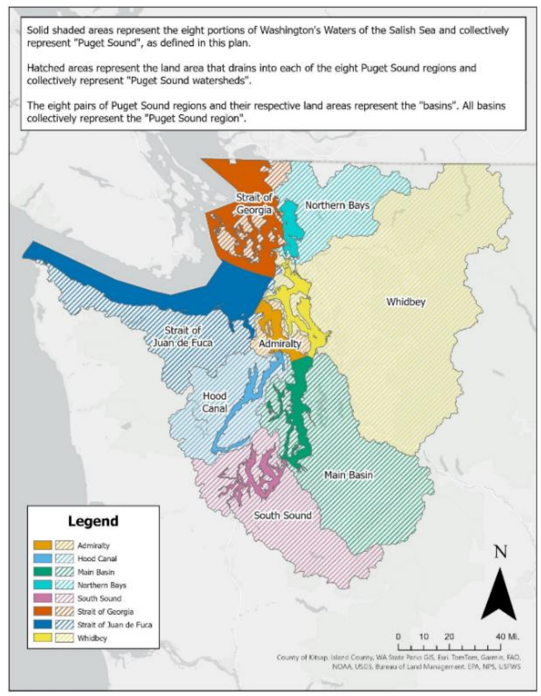

*Figure 1. The eight basins the marine point source and watershed targets apply to. Figure 2 from the Draft Puget Sound Nutrient Reduction Plan.*

### Total nitrogen targets & anthropogenic reductions

The Draft Puget Sound Nutrient Reduction establishes targets for marine point sources and watersheds based on total nitrogen (TN) – the sum of all forms of inorganic and organic nitrogen present in water. The State said its intention in adopting TN was to provide greater implementation flexibility. This represents a notable shift from previous management efforts that primarily focused on total inorganic nitrogen (TIN) or dissolved inorganic nitrogen (DIN), which typically include nitrate, nitrite, and ammonia/um. The inputs to the Salish Sea Model use total nitrogen loads for each river and marine point source, partitioned into DIN and total organic nitrogen (TON). However, within the modeled nutrient scenarios, only the DIN portion of loads is reduced. In addition, the Puget Sound Nutrient General Permit—both the original (2022) and the updated draft (2025) – established action levels using TIN, not TN. Under the General Permit, dominant and moderate dischargers are required to complete a Nutrient Reduction Evaluation that explores treatment options capable of achieving "a final effluent concentration of 3 mg/L TIN (or equivalent load reduction) on a seasonal average (April – October) basis" (Washington State Department of Ecology, 2022 and Washington State Department of Ecology, 2025a). If the State applies the Opt2_8 scenario DIN reduction targets directly as TN when setting Water Quality Based Effluent Limits (WQBELs) for wastewater treatment plants, the resulting permit limits would in effect be more stringent than the scenario itself, since they would cap all forms of nitrogen rather than just dissolved inorganic nitrogen.

The nutrient targets in the plan are aligned with modeled reductions in anthropogenic total nitrogen loads, calculated as the difference between existing and reference loads for the modeled year. These anthropogenic loads reflect only contributions from local and regional U.S. sources, excluding Canadian sources, which remain fixed in both the existing and reference model runs. The State's decision to focus the analysis on U.S. sources is tied to jurisdictional authority, as Canadian discharges fall outside the scope of state regulation. While Canadian point and nonpoint source contributions are represented in the model, they are not targeted for reduction in the draft plan.

## Marine point source targets

The Draft Nutrient Reduction Plan sets the following basin-wide targets for marine point sources – NPDES wastewater treatment plants and industrial facilities in Washington state that discharge to Puget Sound – in each region (Table 5). This mirrors how the Salish Sea Model defines marine point sources. Based on these targets, the State will eventually develop total nitrogen Water Quality Based Effluent Limits for Puget Sound dischargers that will be implemented either through the voluntary Nutrient General Permit or plants' individual NPDES permits. *See Appendix E of the Draft Puget Sound Nutrient Reduction Plan for the facility-specific model input loads used to calculate the basin-wide targets.*

While the Draft Puget Sound Nutrient Reduction Plan does not explicitly assign targets for carbonaceous biochemical oxygen (CBOD), the modeling used to inform the targets assumed an annual average of 8 mg/L year-round at marine point sources. This assumption was converted into facility-specific dissolved organic carbon (DOC) loads (McCarthy et al., 2018). For some plants, concurrently reducing CBOD to 8 mg/L limits the feasibility of potential nutrient reduction treatment options. The scenarios also mirrored the watershed nitrogen reductions by applying the same percentage to total organic carbon reductions.

***Table 5.*** *Marine point source targets. From the June 4, 2025, Nutrient Forum presentation.*

| Basin | Total Annual Target (lbs. Total Nitrogen/year) | Reduction in Anthropogenic Total Nitrogen* |
|---|---:|---:|
| Northern Bays | 449,000 | 58% |
| Whidbey | 1,130,000 | 63% |
| Main | 6,300,000 | 72% |
| South Sound | 898,000 | 66% |
| Hood Canal | 823 | 0% |
| Admiralty | 54,400 | 0% |
| Strait of Juan de Fuca | 233,000 | 0% |
| Strait of Georgia | 563,000 | 0% |

*Relative to 2014 loads.

## Watershed targets

The Draft Puget Sound Nutrient Reduction Plan sets the following watershed targets for point sources and nonpoint sources entering tributaries of Puget Sound (Table 6). These proposed watershed targets will be managed through as yet undeveloped individualized water clean-up plans. The proposed nutrient reduction targets do not consider freshwater dissolved oxygen impairments within the watersheds, so additional load reductions may be necessary in the future. *See Appendix F of the Puget Sound Nutrient Reduction Plan for the detailed watershed load inputs to the model used to collectively determine the basin-wide targets.*

*Table 6. Watershed targets. From the June 24, 2025, Nutrient Forum presentation.*

| Basin | Total Annual Target (lbs. Total Nitrogen/year) | Reduction in Anthropogenic Total Nitrogen* |
|---|---|---|
| Northern Bays | 3,390,000 | 66% |
| Whidbey | 11,900,000 | 67% |
| Main | 4,330,000 | 68% |
| South Sound | 2,940,000 | 63% |
| Hood Canal | 1,030,000 | 66% |
| Admiralty | 50,100 | 53% |
| Strait of Juan de Fuca | 929,000 | 0% |
| Strait of Georgia | 1,070,000 | 0% |

*Relative to 2014 loads

### *Watershed nutrient sources*

Recent modeling by USGS SPARROW, in collaboration with the State, has made important progress in understanding nutrient sources and their seasonal patterns. The current pre-print results (Schmadel et al., 2025) report combines contributions from marine point sources and watershed sources as defined in the Draft Puget Sound Nutrient Reduction Plan. A helpful next step would be to segment watershed sources and align them to the watershed boundaries in the State's Draft Nutrient Reduction Plan. Doing so would help managers see how nutrient sources align with watershed-specific targets and support the development of required water clean-up plans.

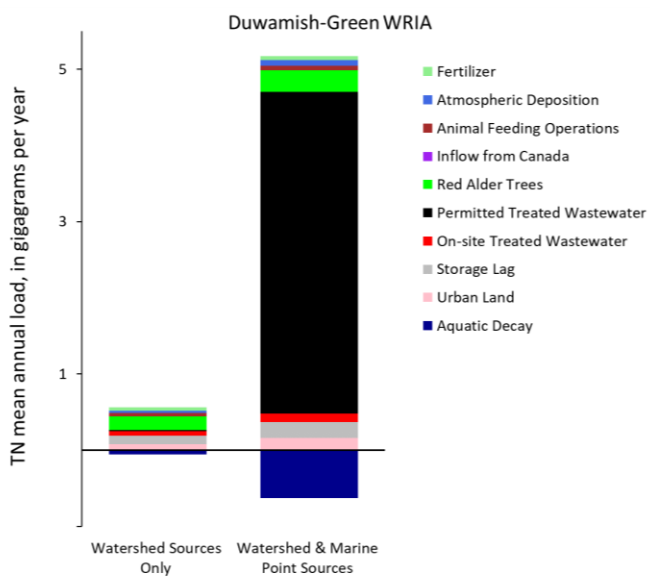


*Figure 2. Nutrient sources in the Duwamish-Green WRIA. Watershed sources are based on the accumulated loads at COMID 23977634. The marine point & watershed sources are determined by aggregating the incremental loads within the WRIA.*

To assess the feasibility of segmenting SPARROW outputs, we extracted the a) watershed sources and b) marine point & watershed sources for the Duwamish-Green WRIA (Figure 2). Because SPARROW has made its full model outputs publicly available, this type of analysis is relatively straightforward—provided the State identifies the terminal COMIDs that represent watershed inflows to the Salish Sea Model, upstream of marine point sources.

## What has changed: methods for predicting non-compliance

In Figueroa-Kaminsky et al., (2025) the State updated its method for assessing dissolved oxygen non-compliance by translating predictions from the Salish Sea Model grid to the 303(d) assessment unit grid. The Salish Sea Model predicts water quality conditions for over 16,000 nodes and associated grid cells. However, Washington's water quality standards are applied to the regulatory 303(d) grid, which does not align with the model grid. To bridge this difference, Ecology developed a translation process that projects

Salish Sea Model outputs onto the 303(d) assessment units. The method calculates an hourly, volume-weighted dissolved oxygen concentration for each of the ten vertical layers within a 303(d) assessment unit. These hourly results are then aggregated into a daily minimum value for each layer, which is evaluated against the water quality standard. If dissolved oxygen in any layer falls below the standard for even a single hour, the entire cell is considered non-compliant for the day. In cases where a 303(d) unit spans multiple polygons with different numeric dissolved oxygen criteria, the more conservative standard is applied. We anticipate that this revised spatial aggregation has a negligible effect on overall estimates of non-compliance.

Additionally, the analysis uses a new metric – **total days of DO noncompliance** – which combines both how widespread the problem is and how long it lasts. It represents the sum of all days across all 303(d) grid cells where dissolved oxygen falls below the standard. In other words, each cell is checked every day of the year; if it is out of compliance on a given day, that counts as one cell-day of noncompliance. Adding these up across all cells gives the total. The maximum possible value in a year is over 3 million.

**Updated mask:** Previous modeling masked the nearshore because of limitations with the Salish Sea Model. Figueroa-Kaminsky et al., (2025) expanded this to mask:

- Budd Inlet because it is addressed in a separate EPA-approved TMDL and the Salish Sea Model does not currently account for the influence of the Capitol Lake Dam on its hydrodynamics.
- Nodes that represent depths of 4 m or less during ebb tides because the temperature predictions were unreasonably low in the winter during low tides.
- Selected hours in the winter where predicted temperatures at other very shallow subtidal locations were negative in the surface layers.
- 303(d) grid cells where more than 50% of their area is masked.

*See Appendix D of Figueroa-Kaminsky et al., (2025) for the step-by-step process for how Salish Sea Model results are masked and re-projected onto the 303(d) grid. See Appendix F of Ahmed et al., (2021) for a detailed description of how non-compliance is evaluated.*

## What has changed: updated marine point source & watershed loads

In Figueroa-Kaminsky et al., 2025), Appendix C1 and Appendix B1 summarize how the State updated the point source and watershed TN & TOC loads. Appendix C2 and Appendix B3 also plot the flow and water quality for each source.

### Marine point sources

As part of the modeling updates that informed the nutrient reduction targets, the State discovered additional data and used monthly averages to fill in gaps and revise nutrient load estimates for seven wastewater treatment plants—Brightwater, Carolyn, Hartstene, McNeil, Tulalip, Sequim, and Rustlewood. While industrial facilities accounted for only 1.7% of the total nitrogen (TN) load from U.S. marine dischargers in 2014, they contributed approximately 25% of the total organic carbon (TOC) load. Updated load estimates for several industrial sources—including aluminum producers, pulp and paper mills, and petroleum refineries—were based on newer permit data and input from The State permit managers.

The State also corrected the location of one Canadian facility, Port Renfrew. This adjustment had a negligible effect on overall Canadian WWTP load estimates, changing the total by less than 0.03% relative to previous assessments in Ahmed et al., (2019).

Overall, updates to existing and anthropogenic TN loads resulted in less than a 5% increase across all U.S. marine point sources. However, certain basins showed more pronounced changes due to improvements in data sources and estimation methods:

- **Strait of Georgia (SOG):** Anthropogenic TN loads increased by 60% in 2014primarily due to revised estimates at oil refineries, which now incorporate plant-specific nitrate/nitrite data – rather than relying on the earlier assumption that all inorganic nitrogen was ammonium.
- **Strait of Juan de Fuca (SJF):** TN loads rose by 16.5% in 2014, largely driven by updated data for McKinley Paper. The State replaced prior surrogate data (from WestRock) with post-2017 plant-specific measurements for nitrogen and carbon species, using these to construct regressions that filled historical gaps.
- **Northern Bays:** TN load estimates increased by 12% in 2014, primarily due to the inclusion of new facility-specific data for the Sequim WWTP.

For other basins, the differences were minimal, generally below 1%.

Table 7 summarizes the differences between the marine point source loads in the Optimization Phase 1 (Ahmed et al., 2021) and Optimization Phase 2 (Figueroa-Kaminsky et al., 2025) reports.

*Table 7. Comparison of annual daily average existing, reference, and anthropogenic total nitrogen (TN) point source loads entering different basin in the Salish Sea in Optimization Phase 1 (Ahmed et al. 2021) and Optimization Phase 2 (Figueroa-Kaminsky et al., (2025) during 2006 and 2014. Table C1-1 from Figueroa-Kaminsky et al. (2025).*

| Total Nitrogen: Existing Loads by Basin | 2006 Opt1 load (kg/day) | 2006 Opt2 load (kg/day) | 2006 Diff. in load (kg/day) | 2006 Diff. in load (%) | 2014 Opt1 load (kg/day) | 2014 Opt2 (kg/day) | 2014 Diff. in load (kg/day) | 2014 Diff. in load (%) |
|---|---|---|---|---|---|---|---|---|
| South Sound | 3,510 | 3,510 | 0.00 | 0.0% | 3,260 | 3,270 | 10.00 | 0.3% |
| Main Basin | 29,100 | 29,100 | 0.00 | 0.0% | 27,500 | 27,500 | 0.00 | 0.0% |
| Hood Canal | 1.22 | 1.21 | -0.01 | -0.8% | 1.02 | 1.02 | 0.00 | 0.0% |
| Whidbey Basin | 3,360 | 3,370 | 10.00 | 0.3% | 3,810 | 3,810 | 0.00 | 0.0% |
| Admiralty | 75.1 | 75.1 | 0.00 | 0.0% | 67.4 | 67.4 | 0.00 | 0.0% |
| Northern Bays | 1,120 | 1,250 | 130 | 11.6% | 1,170 | 1,310 | 140 | 12.0% |
| SOG—US | 496 | 758 | 262 | 52.8% | 434 | 697 | 263 | 60.6% |
| SJF—US | 278 | 316 | 38.0 | 13.7% | 250 | 290 | 40.0 | 16.0% |
| **Salish Sea US Total** | **37,940** | **38,380** | **440** | **1.2%** | **36,492** | **36,945** | **453** | **1.2%** |

| Total Nitrogen: Reference loads by Basin | 2006 Opt1 load (kg/day) | 2006 Opt2 load (kg/day) | 2006 Diff. in load (kg/day) | 2006 Diff. in load (%) | 2014 Opt1 load (kg/day) | 2014 Opt2 (kg/day) | 2014 Diff. in load (kg/day) | 2014 Diff. in load (%) |
|---|---|---|---|---|---|---|---|---|
| South Sound | 29.1 | 29.1 | 0.00 | 0.0% | 22.6 | 22.6 | 0.00 | 0.0% |
| Main Basin | 197 | 197 | 0.00 | 0.0% | 186 | 187 | 1.00 | 0.5% |
| Hood Canal | 0.006 | 0.006 | 0.00 | 0.0% | 0.006 | 0.006 | 0.00 | 0.0% |
| Whidbey Basin | 31.3 | 31.3 | 0.00 | 0.0% | 16.9 | 16.9 | 0.00 | 0.0% |
| Admiralty | 1.84 | 1.84 | 0.00 | 0.0% | 1.76 | 1.75 | -0.01 | -0.6% |
| Northern Bays | 8.04 | 13.30 | 5.26 | 65.4% | 8.32 | 13.7 | 5.38 | 64.7% |
| SOG—US | 6.74 | 11.60 | 4.86 | 72.1% | 5.79 | 10.7 | 4.91 | 84.8% |
| SJF—US | 1.67 | 1.54 | -0.13 | -7.8% | 1.64 | 1.50 | -0.14 | -8.5% |
| **Salish Sea US Total** | **276** | **286** | **10.0** | **3.6%** | **243** | **254** | **11.1** | **4.6%** |

| Total Nitrogen: Anthropogenic loads by Basin | 2006 Opt1 load (kg/day) | 2006 Opt2 load (kg/day) | 2006 Diff. in load (kg/day) | 2006 Diff. in load (%) | 2014 Opt1 load (kg/day) | 2014 Opt2 (kg/day) | 2014 Diff. in load (kg/day) | 2014 Diff. in load (%) |
|---|---|---|---|---|---|---|---|---|
| South Sound | 3,480 | 3,480 | 0.00 | 0.0% | 3,240 | 3,250 | 10.00 | 0.3% |
| Main Basin | 28,900 | 28,900 | 0.00 | 0.0% | 27,300 | 27,300 | 0.00 | 0.0% |
| Hood Canal | 1.21 | 1.20 | -0.01 | -0.8% | 1.01 | 1.01 | 0.00 | 0.0% |
| Whidbey Basin | 3,330 | 3,340 | 10.00 | 0.3% | 3,790 | 3,790 | 0.00 | 0.0% |
| Admiralty | 73.3 | 73.3 | 0.00 | 0.0% | 65.6 | 65.7 | 0.10 | 0.2% |
| Northern Bays | 1,120 | 1,240 | 120 | 10.7% | 1,160 | 1,300 | 140 | 12.1% |
| SOG—US | 489 | 746 | 257 | 52.6% | 428 | 686 | 258 | 60.3% |
| SJF—US | 277 | 314 | 37.0 | 13.4% | 248 | 289 | 41.0 | 16.5% |
| **Salish Sea US Total** | **37,671** | **38,095** | **424** | **1.1%** | **36,233** | **36,682** | **449** | **1.2%** |

## Watershed loads

As part of the Optimization Phase 2 (Opt2) updates to the Salish Sea Model, the State refined watershed delineations, flow estimates, and nutrient load regressions to improve spatial accuracy and data quality.

### Flow inputs

The number of freshwater quality sites used by the State to inform watershed regressions expanded significantly. The State incorporated additional data from its Environmental Information Management system, local governments, Tribes, and federal sources (e.g., USGS, EPA WQX), allowing for site-specific regressions in more basins and reducing reliance on neighboring watershed surrogates. As a result, "the percentage of total watershed area borrowing flow data from neighboring watersheds has dropped from 22% to 8%." (Figueroa-Kaminsky et al., 2025). Ultimately, these had a minimal impact on freshwater flows. The total modeled flow across Washington watersheds decreased by approximately 3% compared to Ahmed et al. (2021). Notably:

- **Strait of Georgia:** Had the largest relative change, dropping by 38% (equivalent to 6 cubic meters per second (cms), annual daily average) in 2014, due to more realistic WRF-Hydro-based estimates for the San Juan Islands rather than relying on downscaled estimates from the Samish River.
- **Whidbey:** Had the largest absolute decrease in flow, 78 cms annual daily average (7%) in 2014, largely due to corrected Skagit River data.

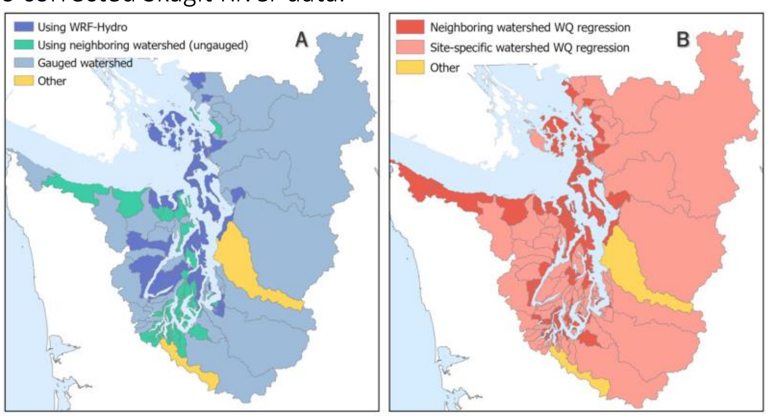


*Figure 3. Figure B1-5 from Figueroa-Kaminsky et al. (2025). (A) Current status of flow data availability for Opt2 watersheds. Additional flow data has been acquired since (Ahmed et al. 2021), which includes more gauged watersheds and the use of National Oceanic and Atmospheric Administration (NOAA) Weather Research Forecast (WRF) Hydro data (green). (B) Current status of water quality availability for Opt2 watersheds. The "Other" category refers to flow-controlled watersheds such as Lake Washington and Deschutes/Capitol Lake.*

### Nitrogen Loads

Additional freshwater nitrogen data allowed the State to develop and refine site-specific regressions between river flow rates and TN concentrations for more watersheds. Estimated existing TN loads from all sources increased modestly by less than 5% overall. However, anthropogenic TN loads increased more significantly—by 20% in 2014— due to expanded spatial and temporal data coverage and improved site-specific regression models. The largest increase in anthropogenic loads occurred in:

- **Main Basin**: Increased by 1,710 kg/day or 59% in 2014, driven by the incorporation of direct field observations for Dyes Inlet and expanded temporal coverage for the Green River.
- **Hood Canal**: Increased by 670 kg/day or 152% in 2014; reflecting a shift from surrogate regressions to more site-specific data. The percentage of watersheds with native nitrogen data increased from 25% to 60%, correcting earlier underestimates. Hood Canal's TN load is still about

a third that of South Sound, despite slightly higher annual flows due to much lower development and TN concentrations in the Hood Canal tributaries.

Table 8 summarizes the differences between the watershed loads in the Optimization Phase 1 (Ahmed et al., 2021) and Optimization Phase 2 (Figueroa-Kaminsky et al., 2025) reports.

***Table 8.*** *Comparison of annual daily average existing, reference, and anthropogenic total nitrogen (TN) watershed loads entering different basins in the Salish Sea in Optimization Phase 1 (Ahmed et al., 2021) and Optimization Phase 2 (Figueroa-Kaminsky et al., 2025). Table B2-2 from Figueroa-Kaminsky et al (2025).*

| **Total Nitrogen: Existing loads by Basin** | **2006 Opt1 load (kg/day)** | **2006 Opt2 load (kg/day)** | **2006 Diff. in load (kg/day)** | **2006 Diff. in load (%)** | **2014 Opt1 load (kg/day)** | **2014 Opt2 load (kg/day)** | **2014 Diff. in load (kg/day)** | **2014 Diff. in load (%)** |
|---|---|---|---|---|---|---|---|---|
| South Sound | 6,800 | 6,950 | 150 | 2.2% | 5,710 | 5,800 | 90.0 | 1.6% |
| Main Basin | 7,840 | 8,970 | 1,130 | 14.4% | 7,440 | 8,510 | 1,070 | 14.4% |
| Hood Canal | 1,700 | 2,470 | 770 | 45.3% | 1,260 | 2,020 | 760 | 60.3% |
| Whidbey Basin | 16,990 | 16,760 | -230 | -1.4% | 19,690 | 19,220 | -470 | -2.4% |
| Admiralty | 169 | 124 | -45.0 | -26.6% | 216 | 116 | -100 | -46.3% |
| Northern Bays1 | 6,750 | 6,020 | -730 | -10.8% | 6,720 | 6,600 | -120 | -1.8% |
| SOG – US | 669 | 1,110 | 441 | 65.9% | 777 | 1,320 | 543 | 69.9% |
| SJF – US | 774 | 1,230 | 456 | 58.9% | 955 | 1,150 | 195 | 20.4% |
| **Salish Sea US Total** | **41,692** | **43,634** | **1,942** | **4.7%** | **42,758** | **44,736** | **1,968** | **4.6%** |
| **Total Nitrogen: Reference loads by Basin** | **2006 Opt1 load (kg/day)** | **2006 Opt2 load (kg/day)** | **2006 Diff. in load (kg/day)** | **2006 Diff. in load (%)** | **2014 Opt1 load (kg/day)** | **2014 Opt2 load (kg/day)** | **2014 Diff. in load (kg/day)** | **2014 Diff. in load (%)** |
| South Sound | 2,770 | 2,880 | 110 | 3.9% | 2,310 | 2,360 | 50.0 | 2.2% |
| Main Basin | 4,440 | 3,820 | -620 | -13.9% | 4,550 | 3,910 | -640 | -14.1% |
| Hood Canal | 1,070 | 1,070 | 0.0 | 0.2% | 818 | 907 | 89.0 | 10.9% |
| Whidbey Basin | 11,410 | 11,000 | -410 | -3.6% | 13,330 | 12,500 | -830 | -6.2% |
| Admiralty | 16.3 | 15.4 | -0.90 | -5.7% | 16.3 | 14.6 | -2.20 | -13.1% |
| Northern Bays1 | 2,560 | 2,540 | -20.0 | -0.8% | 3,060 | 2,960 | -100.0 | -3.3% |
| SOG – US | 232 | 136 | -96.0 | -41.3% | 287 | 178 | -109 | -38.0% |
| SJF – US | 521 | 557 | 36.0 | 6.9% | 491 | 501 | 10.0 | 2.0% |
| **Salish Sea US Total** | **23,019** | **22,018** | **-1,001** | **-4.3%** | **24,853** | **23,331** | **-1,532** | **-6.2%** |
| **Total Nitrogen: Anthropogenic loads by Basin** | **2006 Opt1 load (kg/day)** | **2006 Opt2 load (kg/day)** | **2006 Diff. in load (kg/day)** | **2006 Diff. in load (%)** | **2014 Opt1 load (kg/day)** | **2014 Opt2 load (kg/day)** | **2014 Diff. in load (kg/day)** | **2014 Diff. in load (%)** |
| South Sound | 4,030 | 4,070 | 40.0 | 1.0% | 3,410 | 3,440 | 30.0 | 0.9% |
| Main Basin | 3,400 | 5,150 | 1,750 | 51.4% | 2,890 | 4,600 | 1,710 | 59.2% |
| Hood Canal | 628 | 1,400 | 772 | 123% | 440 | 1,110 | 670 | 152% |
| Whidbey Basin | 5,580 | 5,760 | 180 | 3.2% | 6,360 | 6,720 | 360 | 5.7% |
| Admiralty | 152 | 108 | -44.0 | -28.8% | 199 | 102 | -97.0 | -48.7% |
| Northern Bays1 | 4,190 | 3,480 | -710 | -16.9% | 3,660 | 3,640 | -20.0 | -0.5% |
| SOG – US | 438 | 978 | 540 | 123% | 490 | 1,140 | 650 | 133% |
| SJF – US | 254 | 673 | 419 | 165% | 464 | 650 | 186 | 40.1% |
| **Salish Sea US Total** | **18,672** | **21,619** | **2,947** | **15.8%** | **17,913** | **21,402** | **3,489** | **19.5%** |

## Existing & reference loads

Table 9 summarizes the existing and reference loads following the updates.

***Table 9.*** *Average annual daily flows and average annual daily total nitrogen (TN) and total organic carbon (TOC) marine point source and watershed loads entering Washington waters of Salish Sea for each of the four modeled years. Table 1 from Figueroa-Kaminsky et al. (2025).*

| Average annual flow or load | Source | 2000 | 2006 | 2008 | 2014 |
|---|---|---|---|---|---|
| **Flows (cms)** | Marine point sources | 19.1 | 20.1 | 17.7 | 18.1 |
| | Watersheds | 1,370 | 1,810 | 1,560 | 1,950 |
| | **Total** | **1,390** | **1,830** | **1,580** | **1,970** |
| **TN loads (kg/day)** | Marine point sources — existing | 37,400 | 38,400 | 36,200 | 36,900 |
| | Marine point sources — reference | 256 | 286 | 244 | 254 |
| | Marine point — anthro. | 37,100 | 38,100 | 36,000 | 36,600 |
| | Watersheds — existing | 28,800 | 43,600 | 32,400 | 44,700 |
| | Watersheds — reference | 15,000 | 22,000 | 16,900 | 23,300 |
| | Watersheds — anthro. | 13,800 | 21,600 | 15,500 | 21,400 |
| | **Total — existing** | **66,200** | **82,000** | **68,600** | **81,600** |
| | **Total — reference** | **15,300** | **22,300** | **17,100** | **23,600** |
| | **Total — anthro.** | **50,900** | **59,700** | **51,500** | **58,000** |
| **Anthro. TN load (%)** | Marine point sources | 73% | 64% | 70% | 63% |
| | Watersheds | 27% | 36% | 30% | 37% |
| **TOC loads (kg/day)** | Marine point sources — existing | 21,900 | 17,200 | 17,200 | 14,700 |
| | Marine point sources — reference | 3,330 | 3,690 | 3,020 | 3,170 |
| | Marine point sources — anthro. | 18,600 | 13,500 | 14,200 | 11,500 |
| | Watersheds — existing | 174,000 | 316,000 | 223,000 | 322,000 |
| | Watersheds — reference | 134,000 | 198,000 | 150,000 | 198,000 |
| | Watersheds — anthro. | 40,000 | 118,000 | 73,000 | 124,000 |
| | **Total — existing** | **196,000** | **333,000** | **240,000** | **337,000** |
| | **Total — reference** | **137,000** | **202,000** | **153,000** | **201,000** |
| | **Total — anthro.** | **59,000** | **131,000** | **87,000** | **136,000** |
| **Anthro. TOC load (%)** | Marine point sources | 32% | 10% | 16% | 8.5% |
| | Watersheds | 68% | 90% | 84% | 91% |

[a] All values are rounded to three significant figures
cms = cubic meters per second
anthro. = anthropogenic

# What has changed: Model structure and skill assessment

The State implemented a series of targeted refinements to the Salish Sea Model to improve dissolved oxygen and nutrient predictions, including:

1. **Updated FVCOM-ICM4 & open boundary tidal constituents:** The model updated the biogeochemical code version, which includes more detailed formulations of both light penetration and hydrodynamic processes. A key enhancement is the corrected photosynthetically active radiation (PAR) scheme, which handles sunlight more realistically. It simulates the lack of sunlight at night and higher, more accurate sunlight levels (i.e., PAR and solar radiation) during daylight hours, instead of spreading light evenly throughout the day. This change helps the model better reflect when and how much sunlight is available for algae to grow. The State also updated the open boundary tidal constituents using the 2015 Eastern North Pacific database (Szpilka et al., 2018), rather than the 2003 version. Additionally, ICM4 supports spatially variable bottom friction, which resulted in similar surface elevation accuracy (average annual RMSE throughout Puget Sound went from 0.43 to 0.41). Variable bottom friction had a larger effect on average water surface elevation in the research version of the model because of its finer-resolution grid (Premathilake & Khangaonkar, 2022).

2. **Refined the reaeration scheme:** The model now uses seasonal formulas to simulate how oxygen from the atmosphere mixes into the water; this modestly improved the annual RMSE for dissolved oxygen from 1.09 to 0.91 Sound-wide.

3. **Recalibrated biogeochemical parameters through sensitivity testing:** A series of parameter adjustments were made based on test runs aimed at improving agreement with observed data:
   - **Water column settling rate parameters** were adjusted and net settling rate parameters were maintained to better match observed sediment oxygen demand. The State found that, "Reducing water column settling velocities WSLAB and WSREF to 2.5 m/d (by a factor of 2) while keeping net sediment velocity in sediments (WSLNET, WSRNET to 1.0 m/d results in SOD fluxes that generally match observations."
   - **Nitrogen mineralization rates** were revised to better simulate ammonium ($NH_4^+$) dynamics, which are important for oxygen demand and nutrient cycling (Table 10).

*Table 10. Updates to kinetic mineralization rates. Table A-6 from Figueroa-Kaminsky et al. (2025).*

| Mineralization Parameter | Definition | Used by Ahmed et al. (2019) | Used in Current Work |
|---|---|---|---|
| KLDN | Minimum mineralization rate of labile dissolved organic nitrogen (1/day) | 0.05 | 0.075 |
| KLPN | Minimum hydrolysis rate of labile particulate organic nitrogen ( 1/day) | 0.01 | 0.05 |
| KHNNT | Half saturation concentration of $NH_4^+$ required for nitrification (g $N/m^3$ ) | 0.5 | 0.75 |

   - **Updated algal rates** to better capture observed chlorophyll concentration — particularly in embayments – the State increased algal growth by updating the maximum photosynthetic rate for the second algal group from 350 to 450 g C/g Chl/day (Cerco & Noel, 2019), while maintaining the original rate for the first group at 350. Additionally, the initial slope of the photosynthesis–irradiance curve (α) was adjusted to reflect longer and earlier seasonal blooms. This change allows algal group 1 to bloom earlier in spring ($\alpha = 8$) and group 2 to sustain growth later into fall ($\alpha = 12$), consistent with observations.

4. **Stabilized initial sediment conditions:** To ensure more consistent sediment oxygen demand estimates, the State modified the model's initialization by running a ten-year simulation that loops the same year. Organic material that settles on the seafloor breaks down in different ways over time. This approach allows organic material in sediments to reach a steady state. In particular, it improved the partitioning of particulate organic matter into more reactive (G1) and less reactive (G2) fractions, helping to avoid under- or overestimating long-term oxygen demand near the seafloor. Cumulatively, model refinements have also reduced predicted peak sediment oxygen demand values compared to earlier versions. For example, the highest average sediment oxygen demand predicted across the domain for 2006 is now 0.86 g $O_2/m^2$/day, down from 1.4 g $O_2/m^2$/day reported in earlier modeling (Ahmed et al., 2019).

## Model skill analysis

Following the model refinements, the State conducted both its standard skill assessments and several targeted evaluations to test model performance across key processes and variables.

The model predicts that embayments – where most non-compliance occurs – are strongly influenced by sediment oxygen demand, microbial respiration, and algal respiration. Sediment oxygen demand accounts for the largest share of dissolved oxygen loss in bottom waters, while microbial respiration is consistently elevated in embayments, especially near their tips. A notable exception is Lynch Cove in Hood Canal, where chronically low oxygen likely constrains respiration year-round. Algal respiration also dominates total microbial oxygen demand in most locations, especially in shallow embayments. For example, at Oakland Bay (OAK004), one of the shallowest sites at 12 meters, it accounts for ~57% of total bottom-water respiration. In deeper locations, such as SAR003 (140.5 m), contributions shift, with algal respiration reduced (~22%) and heterotrophic respiration and nitrification playing larger roles (~38% and 41%, respectively). Given their dominant role in driving oxygen dynamics in embayments, these processes were prioritized in the State's targeted model skill evaluations.

1. **Parameter sensitivity testing**: A modified Monte Carlo analysis was performed using 60 model runs for 2014, varying five biologically important parameters within literature-supported ranges. The sensitivity tests varied the nitrogen uptake, algal settling velocities, maximum photosynthetic rate, minimum respiration rate of labile dissolved organic carbon, and dissolution rate of labile particulate organic carbon. This analysis supported retaining the base calibration established with the model refinements.

2. **Freshwater nitrate-nitrite validation**: Ecology compared its riverine nitrate–nitrite regression models to new high-frequency, continuous monitoring data collected since 2023 at the mouths of four major rivers: the Nooksack, Skagit, Snohomish, and Puyallup. *See Appendix B4 of Figueroa-Kaminsky et al. (2025).*

3. **Sediment oxygen demand and nutrient fluxes**: Model predictions of sediment oxygen demand and nitrogen fluxes were compared to observations at 31 locations, using recent measurements from Shull (2018) and Merritt (2017), and a broader historical dataset compiled by Sheibley and Paulson (2014). *These comparisons are detailed in Appendix I of Figueroa-Kaminsky et al. (2025).*

4. **Microbial respiration in bottom waters**: Total microbial respiration was evaluated at 15 sites against the first region-wide assessment of microbial respiration in the near-bottom waters of the U.S. Salish Sea (Apple and Bjornson, 2019). *Results are presented in Appendix K of Figueroa-Kaminsky et al. (2025).*

5. **Primary productivity and phytoplankton biomass**: To improve alignment with available $^{14}C$-based measurements of primary productivity, an additional model run for the year 2000 was completed and compared. Phytoplankton biomass was also evaluated using long-term and seasonal chlorophyll-a monitoring data from the Washington State Department of Ecology, King County, NANOOS, and Western Washington University. *Additional detail in Appendix J of Figueroa-Kaminsky et al. (2025).*

Table 11 summarizes the model skill for the State's different versions of the. Generally, the model improvements from previous versions were modest.

*Table 11. Comparison of 2014 model performance for Bounding Scenarios (Ahmed et al. 2019), Optimization Phase 1 (Ahmed et al. 2021), and Optimization Phase 2 (Figueroa-Kaminsky et al. 2025) reports. Table 8 from Figueroa-Kaminsky et al. (2025).*

| Report | Variable | R | WSS | RMSE | $RMSE_C$ | RE | MAE | Bias | $Sd_{\_obs}$ | N |
|---|---|---|---|---|---|---|---|---|---|---|
| BSR | Temperature (°C) | 0.95 | -- | 0.87 | -- | -- | -- | -0.41 | -- | 88,781 |
| Opt1 | Temperature (°C) | 0.95 | 0.94 | 0.78 | 0.74 | 0.06 | 0.62 | -0.23 | -- | 97,687 |
| Opt2 | Temperature (°C) | 0.95 | 0.95 | 0.71 | 0.71 | 0.06 | 0.58 | 0.04 | 1.87 | 99,074 |
| BSR | Salinity (psu) | 0.75 | -- | 0.88 | -- | -- | -- | -0.37 | -- | 88,585 |
| Opt1 | Salinity (psu) | 0.82 | 0.87 | 0.84 | 0.71 | 0.02 | 0.51 | -0.44 | -- | 97,487 |
| Opt2 | Salinity (psu) | 0.83 | 0.90 | 0.72 | 0.72 | 0.01 | 0.39 | -0.07 | 1.13 | 98,884 |
| BSR | DO (mg/L) | 0.81 | -- | 0.96 | -- | -- | -- | -0.34 | -- | 87,284 |
| Opt1 | DO (mg/L) | 0.83 | 0.89 | 0.98 | 0.89 | 0.11 | 0.74 | -0.43 | -- | 96,152 |
| Opt2 | DO (mg/L) | 0.86 | 0.93 | 0.82 | 0.81 | 0.08 | 0.57 | -0.08 | 1.54 | 97,566 |
| BSR | Chl-a (μg/L) | 0.52 | -- | 3.48 | -- | -- | -- | -0.13 | -- | 88,895 |
| Opt1 | Chl-a (μg/L) | 0.52 | 0.67 | 3.42 | 3.42 | 0.71 | 1.41 | -0.11 | -- | 87,671 |
| Opt2 | Chl-a (μg/L) | 0.52 | 0.68 | 3.27 | 3.27 | 0.71 | 1.35 | 0.03 | 3.71 | 98,932 |
| BSR | $NO_3$-$NO_3$ (N-mg/L) | 0.84 | -- | 0.07 | -- | -- | -- | 0 | -- | 1,848 |
| Opt1 | $NO_3$-$NO_2$ (N-mg/L) | 0.84 | 0.90 | 0.07 | 0.07 | 0.15 | 0.05 | 0 | -- | 1,934 |
| Opt2 | $NO_3$-$NO_2$ (N-mg/L) | 0.83 | 0.9 | 0.07 | 0.07 | 0.15 | 0.05 | -0.01 | 0.10 | 1,916 |
| BSR | $NH_4^+$ (N-mg/L) | 0.32 | -- | 0.02 | -- | -- | -- | 0 | -- | 1,510 |
| Opt1 | $NH_4^+$ (N-mg/L) | 0.35 | 0.56 | 0.02 | 0.02 | 0.58 | 0.01 | 0 | -- | 1,595 |
| Opt2 | $NH_4^+$ (N-mg/L) | 0.43 | 0.60 | 0.02 | 0.02 | 0.70 | 0.02 | 0.01 | 0.02 | 1,572 |
| BSR | PAR (E-m²/day) | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Opt1 | PAR (E-m²/day) | 0.61 | 0.66 | 6.00 | 5.94 | 0.78 | 1.08 | -0.81 | -- | 82,178 |
| Opt2 | PAR (E-m²/day) | 0.68 | 0.79 | 6.36 | 6.33 | 0.76 | 1.39 | -0.60 | 8.50 | 63,813 |

"--" means not calculated or reported.

## Model skill in embayments

Model performance was further segmented by depth and sub-region, including embayments, to assess spatial variation in model accuracy. The State's analysis effectively advances the Model Evaluation Group's recommendation to assess model skill at different depths in the water column and in embayments, which are more susceptible to dissolved oxygen non-compliance. Overall, the model performs better in the open estuary than in embayments across all depth layers. It is generally more accurate in predicting dissolved oxygen concentrations in the middle and bottom layers—where oxygen levels are typically lowest.

In embayments, model error (measured as root mean square error, or RMSE) ranges from 0.94 to 1.57 mg/L of dissolved oxygen (Figure 4). Additionally, the model generally underestimates dissolved oxygen in embayments, especially in the bottom layer, where the average bias in 2014 was –0.31 mg/L.

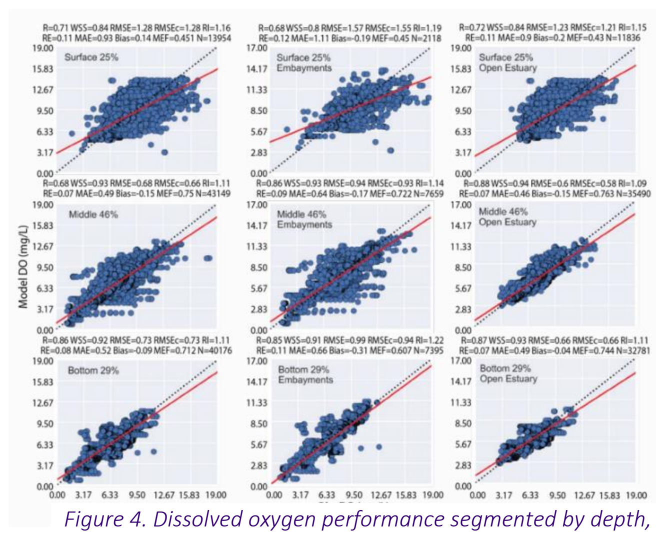


*Figure 4. Dissolved oxygen performance segmented by depth, embayments, and open channel. Figure from March 2025 Nutrient Forum.*

*Table 12. Model skill for different depths in the open estuary vs. embayments.*

| | RMSE | | |
|---|---|---|---|
| | Surface | Middle | Bottom |
| Open estuary | 1.23 | 0.6 | 0.66 |
| Embayments* | 1.57 | 0.94 | 0.99 |

**Figures D-1, D-2, and D-3 in Figueroa-Kaminsky et al. (2025) show which monitoring locations were classified as embayments or open estuary for the model skill comparison.*

## Implications of model updates

In Figueroa-Kaminsky et al. (2025), the State describes updates to the point source and watershed loads used as inputs to the Salish Sea Model, as well as other targeted refinements and model evaluation made. Key refinements included adopting a more advanced version of the core model (FVCOM-ICM4) that provides improved light and hydrodynamic process simulation. In addition, refinements addressed: the reaeration scheme, stabilizing sediment oxygen demand through steady-state initialization, recalibrating particulate settling, nutrient cycling, algal growth parameters, and updating open boundary tidal constituents to the 2015 Eastern North Pacific database (Szpilka et al., 2018).

Following the model refinements, the State conducted model skill evaluation and targeted analyses. These included: parameter sensitivity testing, depth- and embayment-specific skill assessment, comparison of freshwater regressions to new continuous data, and evaluations against observations for sediment oxygen demand, microbial respiration, and primary productivity. Prior to these refinements, the University of Washington Puget Sound Institute convened a Model Evaluation Group of experts (Mazzilli et al., 2024) who recommend ways to improve the application of the Salish Sea Model for recovery goals and regulatory decisions. Figueroa-Kaminsky et al. (2025) have made significant advances to address these recommendations with the current model refinements and analysis.

While several opportunities remain to refine model skill, further refinements are unlikely to fully resolve the challenges associated with its regulatory application and associated uncertainties (discussed following). Key opportunities for refinement include, to:

1. **Conduct multi-year runs and validation** | The current range of single-year runs offers initial insight into interannual variability, and repeating a year during spin-up helps stabilized the model. However, neither simulates results across a “water cycle” year (and range of interannual variability) or captures the value of validation for a year that was not used in calibration. Nutrients, algae, and oxygen levels depend on prior seasons and years, as well as the natural sequence of wet and dry years, warm and cool conditions. Multi-year runs provide a more realistic picture of system response inter-annually and greater confidence that management strategies will remain effective under the full range of conditions Puget Sound experiences. Additionally, they offer an opportunity to conduct independent validation runs for time periods beyond those used in calibration.

2. **Expand monitoring in embayments with predicted non-compliance** | Consistent with the Model Evaluation Group’s recommendations and subsequent State analysis, additional monitoring should be prioritized in embayments where the model predicts dissolved oxygen non-compliance. The State’s recommended locations include Holmes Harbor, Dabob Bay/Quilcene Bay, Liberty Bay, Dyes Inlet, Sinclair Inlet, Case Inlet, Carr Inlet, Henderson Inlet, and Oakland Bay.

3. **Target sediment oxygen demand monitoring in areas with model-observation mismatches** | Additional data collection should be directed to areas where model skill is weaker for sediment oxygen demand and nutrient fluxes. This could be used to further improve sediment/water column parameterization, addressing spatial variability between regions of Puget Sound (Mazzilli et al., 2024). Priority sites include Skagit Bay, Sinclair Inlet, Saratoga Passage, Port Gardner, Commencement Bay, Case Inlet west of Devil’s Head (Nisqually Reach), North Central Basin, Bellingham Bay (multiple stations), Central Basin North (Shilshole), Inner Budd Inlet, Central Puget Sound, West Sound San Juan, and Hood Canal at Hoodsport.

4. **Expand parameter evaluation for silicate and pH** | Future model refinements should also consider the Model Evaluation Group's recommendation to evaluate processes related to silicate and pH in greater detail, to improve representation of biogeochemical dynamics and their interactions with nutrient cycling and dissolved oxygen.

5. **Address the role of suspended sediments in light limitation** | The most recent updates to the Salish Sea Model includes sediment transport, influencing turbidity and light penetration and photosynthesis. This is especially critical near river mouths with high nutrient concentrations. Future validation (and potential refinement) should explicitly represent suspended sediment dynamics so that primary production calibration is not confounded with growth, decay, and settling parameters.

6. **Evaluate the need for refining nearshore modeling** | Nearshore areas are notoriously difficult to model due to high variability and limited monitoring data. At present, the model appropriately masks these zones where confidence is lower, which makes sense for regulatory purposes. However, as many areas that are identified as non-compliant have adjoining masked cells (and because water quality standards are designed to protect marine life in these near shores), it will be important to determine whether critical habitats exist within these masked nearshore areas. Identifying such habitats would help prioritize if targeted monitoring and model refinement are necessary to ensure vulnerable species and ecosystems receive adequate protection.

Despite the State's comprehensive and systematic refinements (and while additional improvements remain possible), the model may be approaching the limits of what can be achieved given the specific precision demands of regulatory applications in Washington State. The model's overall performance has improved modestly reflected in a decrease in annual, domain-wide RMSE from 0.78 in Ahmed et al. (2021) to 0.71 in Figueroa-Kaminsky et al. (2025). However, the magnitude of error in embayments (averaged across all locations and the entire year) remains at 0.94 and 0.99 annual RMSE in the mid- and bottom-waters, respectively. Model error in embayments is still several times greater than the 0.2 mg/L human use allowance used to assess regulatory compliance. Although the region-wide skill of the Salish Sea Model is on par with other regulatory water quality models used nationally, Washington's unique 0.2 mg/L threshold demands a higher level of precision than the model may currently provide in these embayments of concern.

Improvements between model versions have been relatively modest, suggesting the model may be approaching diminishing returns in terms of refining model skill further. Additionally, the State has suggested that subtracting two model scenarios will cancel out the error. In practice, the uncertainties in each scenario can combine in unpredictable ways, and there is no guarantee that positive and negative errors offset one another. This is especially important because the reference condition scenario cannot be validated against observations; by definition, its accuracy is unknowable (Mazzilli et al., 2024). As a result, when compliance is determined by comparing existing and reference scenarios, the true level of uncertainty in the outcome is likely larger than the model performance statistics alone suggest, and must be explicitly considered in regulatory applications. Taken together, the mismatch between achievable model precision and regulatory requirements suggests that the model may not be able to reduce uncertainty to the point that it is lower than the current human use allowance of 0.2 mg/L. However, the available model results could be used to more directly understand risk to marine life, which may increase confidence in the efficacy of management actions.

These findings highlight both the progress and the limitations of the Salish Sea Model as it is applied to nutrient management in Puget Sound.

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# Biological sensitivity of Salish Sea taxa to low oxygen levels: determining observed metabolic demand thresholds of key taxa based on concomitantly measuring abundance, oxygen, and temperature

**Critical Analysis Report, February 2025**

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**Summary:**
The primary questions that this analysis proposed to address was: what are the critical oxygen thresholds of key taxa (across life stages), and when and where in Puget Sound do oxygen levels fall below these thresholds? In order to better understand dissolved oxygen (DO) thresholds for Salish sea species, we first processed and collated available Salish sea fish surveys that had concurrent oxygen and temperature information into an initial database repository (Table 1). This data is collated in a Github repository for future research use, and Tim Essington (essing@uw.edu) is the primary contact. Second, we conducted preliminary analysis of all suitable data both qualitatively and quantitatively, using a probabilistic generalized linear model. This was done to identify if critical oxygen and temperature ranges existed among species based on available survey data.

Based on the statistical analysis using all suitable data, we did not find evidence of a strong DO threshold for herring and Chinook salmon (data was collected by Fisheries & Oceans Canada and the University of Washington in the broader Puget Sound). However, exploration of the available presence and absence data provided qualitative information on thresholds for the taxa examined. Interestingly, we found that fish were present at depths with low DO levels even when there was more oxygen available higher in the water column. Specifically, fish are found at lower DO levels, as low as 1.3 mg/L for herring and 2.06 mg/L for Chinook salmon, even when DO levels higher in the water column were >6 mg/L (Figures 3 and 4). Overall, we suggest that the current data does not provide a clear threshold for herring or Chinook salmon. Qualitative analysis of presence and absence data does suggest that any thresholds are likely below 1.3 mg/L and 2.06 mg/L, respectively. Future survey efforts can provide better insight if CTD sampling is conducted immediately preceding or following trawl surveys and key metadata like tow time, distance, and depth are recorded. Additionally, conducting more surveys overall, and specifically targeting these surveys for the fall when lower and wider ranges of DO are typical will likely improve the model inference in future analyses.

**Background and research objectives:**
Maintaining adequate levels of DO is critical for the survival and well-being of benthic and pelagic marine organisms (Davis, 1975; Vaquer-Sunyer and Duarte, 2008). However, accurately predicting responses and impacts on aquatic species can be difficult (Moriarty et al., 2020; Sato et al., 2016). Currently, our scientific understanding and ability to forecast habitat and species shifts due to changes in oxygen demand and supply are limited by a lack of knowledge on Salish

Sea species' vulnerability to the synergistic impacts of low DO and warming waters. Synergistic impacts are due to the joint effects of oxygen and temperature and emerge from differences in temperature-dependent rates of oxygen intake vs. oxygen expenditure (Deutsch et al. 2015). As a result, the consequences of oxygen changes cannot be considered without also knowing the temperature that an organism will experience (Essington et al., forthcoming). Several topics associated with DO threshold values for Salish Sea species were identified as research needs and critical uncertainties by the Interdisciplinary Team during the Marine Water Quality Implementation Strategy development process. The research undertaken in this project is a first step towards addressing these critical uncertainties. The primary questions that this analysis will answer are: What are the critical oxygen thresholds of key taxa (across life stages), and when and where in Puget Sound do oxygen levels fall below these thresholds?

**Methods:**
Three steps, and associated methodologies, were applied in this project:

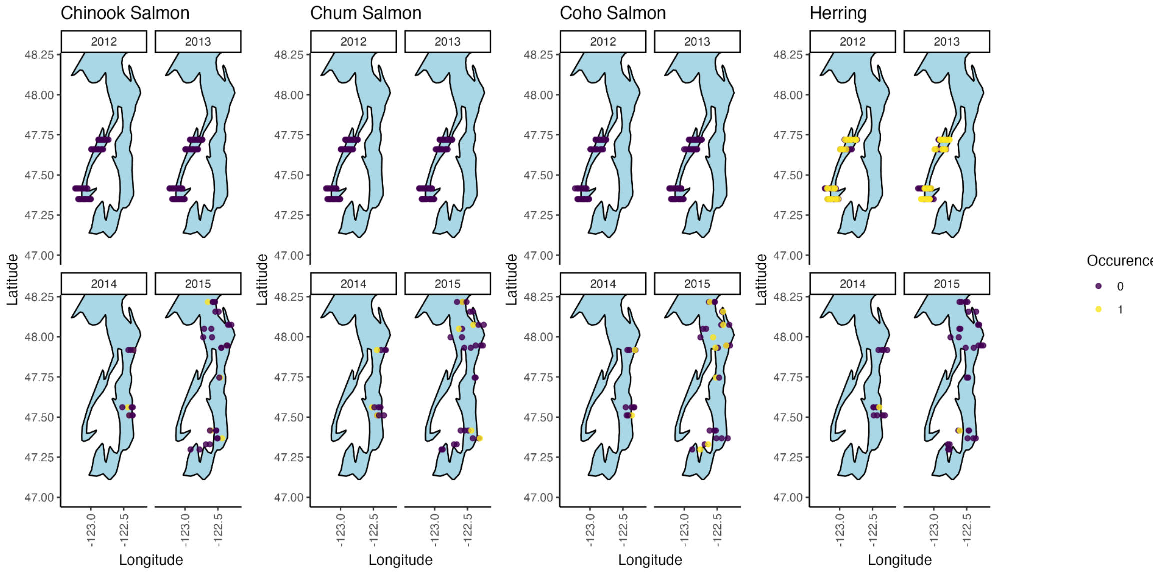
1) Collation and processing of available Salish Sea survey data where there were concurrent oxygen and temperature and fish surveys conducted. Tim Essington will serve as the primary contact for the compiled database for future research.
2) Preliminary data exploration and qualitative analysis of critical oxygen and temperature ranges were conducted for species with sufficient data.
3) Hypothesis testing and model selection to understand if temperature and oxygen levels predicted fish presence.

<u>Collation and Processing of Salish Sea Survey Data</u>
Multiple Salish Sea datasets that included fish abundance with concurrent CTD (a conductivity, temperature, and depth instrument) casts were collated and reviewed, including:

- Department of Fisheries and Oceans, Canada pelagic species surveys: RV Ricker mid-water trawl surveys (2014 and 2015 available) (hereafter, DFO).
- Long Live the Kings continuation of RV Ricker sampling sites in the Salish Sea - 2021 and 2022 available, but lacking tow depth and time information needed to calculate CPUE and match with CTD data (hereafter, LLTK).
- Washington Department of Fish and Wildlife bottom trawl surveys – biological data collated (1989-2007), but the availability and extent of associated DO and other physical datasets were unknown (hereafter, WDFW).
- University of Washington Hood Canal dataset, curated by Tim Essington and colleagues combining survey data from Hood Canal with CTD data (hereafter, UW).

After considering all four datasets, only the DFO and UW datasets were found to have the required physical (i.e., DO, temperature) and fish abundance (Catch Per Unit Effort- CPUE) information suitable for this current analysis. Additional information on future survey needs is provided in the discussion.

**Figure 1.** Map of fish occurrence and survey stations from both UW and DFO surveys in the Southern Salish Sea. Plots are grouped by species and years. Here, purple indicates that fish did not occur in a survey, and yellow indicates at least one fish was caught in that survey. Overlapping points were slightly "nudged' so that multiple surveys were visible in one region.




We received datasets in varied formats and processing levels, thus much of the effort in this project was dedicated to quality control and data processing. For each dataset (DFO and UW), we calculated the Catch Per Unit Effort, based on the net opening for each survey and the length of the tow. CTD data, which surveys the environment along the water column, was matched to the fish survey data to the closest survey depth.

The solubility of oxygen in water is affected by temperature, thus we calculated temperature-adjusted DO values for the analysis. The temperature adjusted DO equation took the following form,

Adjusted DO = DO * exp(KB * (1 / Temperature - Temperature/Temperature Reference))

The key components of the formula are:

- DO: The original dissolved oxygen concentration measurement.
- KB: A constant that represents the temperature coefficient for the solubility of oxygen in water. This value typically ranges from 0.0241 to 0.0272, depending on the specific water conditions.
- Temperature: The water temperature in Kelvin units.
- Temperature Reference: A reference temperature in Kelvin units, often 293.15 K (20°C), used as the baseline for the temperature adjustment.

By using this formula, we can reliably adjust DO measurements to a common temperature, facilitating meaningful comparisons and analysis of the data across different sampling points or time periods. All measurements presented below as DO mg/L, are temperature-adjusted DO values. We included covariates from the CTD in the analysis, with the main focus on DO. We included minimum water column DO, DO at the depth the fish were surveyed, and temperature at the depth the fish were surveyed. Datasets were evaluated for completeness and accuracy, coded based on the data source (i.e., source = “DFO” or “UW”), and assimilated into one dataset.

Exploration and Qualitative Analysis of Oxygen, Temperature and Taxa Data

To understand the range of DO and temperature values across available data we plotted the range of DO and temperature where fish were present and absent for herring and Chinook, chum, and coho salmon (Figure 2). To understand the entire DO profile that might be available to a fish relative to the DO at the depth they were found in surveys, we further analyzed the more detailed UW dataset. This included plotting Chinook salmon and herring CPUE data verses DO depth profiles (Figure 3 and 4).

Statistical Hypothesis Testing

We used generalized linear models to estimate the probability of Chinook salmon and herring occurrence with varying temperature and DO. The model was developed and applied using the Ime4 package in R (Bates et al., 2014). Due to a limitation of statistical power and limited overlap between surveys, we ran these models for just two species: Chinook salmon (*Oncorhynchus tshawytscha*) and Pacific herring (*Clupea pallasii*). We ran separate models for each species and used a binomial distribution to estimate the probability of fish occurrence across temperatures and DO levels. We expected that fish (Chinook salmon or herring) presence may be impacted by DO levels throughout the water column, in addition to the temperature and DO at the depth at which they are surveyed. Specifically, if fish presence was impacted by DO, we expected fish might be present in regions of the water column that had greater DO than other regions.

DO and temperature covariates were obtained from CTD data collected during the fish surveys in similar locations to the trawls. We included CTD temperature and DO at the mean net tow depth as a predictor. Additionally, we hypothesized that minimum DO present throughout the complete water column would have an effect on the presence of fish in the net surveys and thus included minimum DO as a covariate as well.

To control for differences in observed fish occurrence among data sources within the model framework, we included a data source factor (either DFO or UW). We also accounted for survey depth, location, day of year, and time of day (applying a diel factor for day or night survey). Specifically, we incorporated a linear predictor for latitude, to account for changes in fish occurrence based on latitudinal variation in survey locations (there was not enough variation in survey longitudes to necessitate incorporating a full spatial field). Further, we incorporated a linear predictor for depth and day of year to account for changes in fish occurrence based on sample depth and seasonality. We mean-scaled all environmental covariates to allow for meaningful comparison across conditions but present the actual covariate values in the following plots.

First, we constructed a null model that estimated fish occurrence while controlling for survey design (Table 1) and sequentially added covariate complexity to address hypotheses regarding temperature and oxygen impacts on fish occurrence (Table 1). The full model took the form:

$$logit(\gamma_i) = \alpha + S_l + V_m + \beta x_i + \beta y_i + \beta z_i + \beta m_i + \beta d_i + \beta t_i$$

where Yi is the expected occurrence, for the *i*-th observation in space and time with a logit-link function, α is the intercept, $S_l$ is the factor for data source which controls for differences in observed fish occurrence among each data source (DFO or UW), $V_m$ is a factor for diel survey time which controls for differences in observed fish occurrence among night and day surveys. $\beta x_i$ represents the linear effect of latitude, where $x_i$ the latitude for each observation, which is included to control for differences in fish presence that occurred across survey latitudes and β describes the slope of the relationship. $\beta y_i$ represents the linear effect of depth, where $y_i$ the depth for each observation, which is included to control for differences in fish presence that occurred across survey depth and β describes the slope of the relationship. $\beta z_i$ represents the linear effect of DOY, where $z_i$ the DOY for each observation, which is included to control for differences in fish presence that occurred across survey DOY and β describes the slope of the relationship. Finally, $\beta m_i$, $\beta d_i$ and $\beta t_i$ account for linear effects of minimum water column DO, DO at the depth fish were surveyed, and temperature at the depth fish were surveyed, respectively. The complete set of models tested, nested within this full model are presented in Table 1.

**Table 1**. Datasets considered for this analysis.

| **Dataset** | **Years** | **Further notes and additional data required for analysis** |
|---|---|---|
| Department of Fisheries and Oceans Canada (DFO)<br><br>Main contact: Chrys Neville (Chrys.Neville@dfo-mpo.gc.ca) | 2014, 2015; Surveys conducted in July, October and November via mid-water pelagic trawl; sampled day only, 40 tows conducted in total. | NA, used in analysis |
| University of Washington (UW)<br><br>Main contact: Tim Essington (essing@uw.edu) | 2012 - 2013; approximately 80 tows per year at 4 stations in the Hood Canal, sampled day and night via midwater trawl, June - October. | NA, used in analysis |
| Long Live the Kings (LLTK)<br><br>Main contact: Liz Duffy (eduffy@lltk.org) | 2021-2023; approximately 47 total tows at stations across the Salish Sea, sampled day only via Purse Seine, July. | Collect gear depth and total tow effort (linear distance or tow time). |
| Washington Department of Fish and Wildlife (WDFW) | Did not receive data because of lacking CTD | No available CTD data, see accompanying |

| | | |
|---|---|---|
| Main contact: Jennifer Blaine (Jennifer.Blaine@dfw.wa.gov) | information. | recommendations in text for all related CTD recommendations. |

To test hypotheses regarding the importance of temperature and DO in predicting fish occurrence, we compared multiple models against a base model (Table 1) and judged the degree of support for each model using corrected Akaike information criterion (AICc) (Akaike 1973, Hurvich and Tsai 1989, Burnham and Anderson 2002). AICc was used to account for small sample sizes (Table 1). We present models in the results ranked by delta AICc (ΔAICc) which represents the difference between each model's AICc value and the lowest AICc value in your set of candidate models (Table 2). A ΔAICc greater than 2 is considered meaningful.

**Table 2.** Model structure and model selection criteria ($\Delta AIC_c$) applied to the presence and absence of Chinook salmon and herring in the Salish Sea. We evaluated 7 candidate models per species. Overall differences in $AIC_c$ values between the null model and B-D alternative models are small (<= 2) so the null model cannot be dismissed for either species. Covariates not included in the base model are highlighted in bold to demonstrate changes in model complexity.

| **Model Name** | **Model** | **delta AICc** |
|---|---|---|
| Chinook Mod Null | Latitude + source + diel + depth + DOY | 0 |
| Chinook Mod B | Latitude + source + diel + depth + DOY + **min_DO** | 0.9 |
| Chinook Mod C | Latitude + source + diel + depth + DOY + **DO** | 1.7 |
| Chinook Mod D | Latitude + source + diel + depth + DOY + **temperature** | 1.9 |
| Chinook Mod E | Latitude + source + diel + depth + DOY + **DO + temperature** | 2.8 |
| Chinook Mod F | Latitude + source + diel + depth + DOY + **min_DO + temperature** | 3 |
| Chinook Mod Full | Latitude + source + diel + depth + DOY + **min_DO + DO + temperature** | 4.5 |
| Herring Mod Null | Latitude + source + diel + depth + DOY | 0 |
| Herring Mod B | Latitude + source + diel + depth + DOY + **min_DO** | 1.4 |
| Herring Mod C | Latitude + source + diel + depth + DOY + **DO** | 1.9 |
| Herring Mod D | Latitude + source + diel + depth + DOY + **temperature** | 1.9 |
| Herring Mod E | Latitude + source + diel + depth + DOY + **DO + temperature** | 3.2 |
| Herring Mod F | Latitude + source + diel + depth + DOY + **min_DO + temperature** | 3.4 |

| | | |
|---|---|---|
| Herring Mod Full | Latitude + source + diel + depth + DOY + **min_DO + DO + temperature** | 5.3 |

**Results and Discussion:**

Collation and Processing of Salish Sea Survey Data
We found that two of the available data sources could be applied in this analysis, DFO and UW. Unfortunately, WDFW was not able to access CTD data files that coincided with these fish surveys. The LLTK data will be viable for this type of analysis in future years, however, in previous years there was no record of trawl depth or trawl time (i.e. minutes), which is needed to calculate CPUE and to match the CPUE data with the DO data. For future integration of LLTK survey data into subsequent analyses we have two recommendations. First, we recommend that the linear distance traveled for each tow be recorded, or as a minimum, the tow start and end time (as was available with the DFO data). This allows standardization of catch data by sampling effort and across datasets. Second, we recommend that the depth(s) of the survey net is recorded (i.e. start and end net depth). Depth information allows the matching of depth specific CTD data and provides context to understand the conditions where fish were caught versus conditions throughout the water column.

The following is recommended for any future survey efforts aiming to collect data that can improve understanding of fish DO thresholds in the Salish Sea:

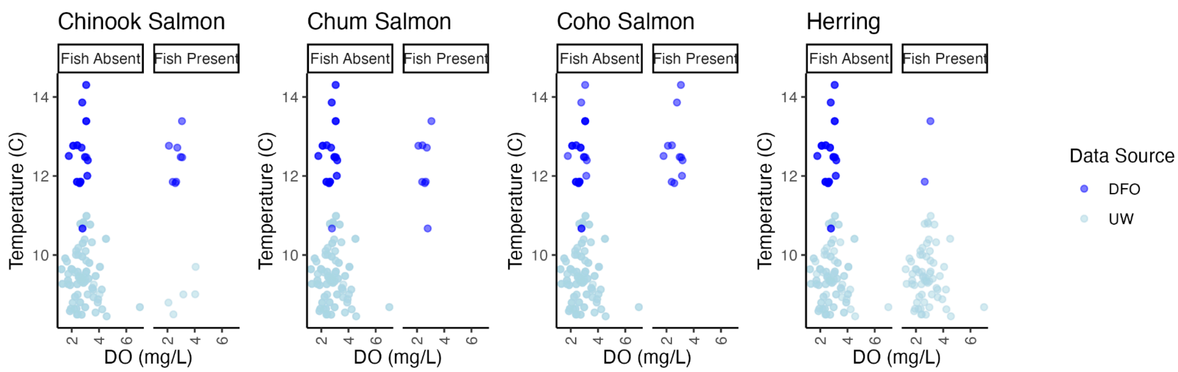
- Conduct CTD sampling (DO and temperature) immediately preceding or following trawl surveys for fish abundances, recording the tow effort (i.e. tow time or distance traveled), gear type, gear depth, location of trawl start and end (latitude and longitude). This is likely more accurate with two boats; however we acknowledge the added survey costs associated with a multi-boat approach likely make it not feasible.
- Ensure the instruments, for example a CTD, have been calibrated and tested, and data processed on a regular cadence.
- Focus surveys seasonally in the Fall to cover the widest range of water column DO concentrations. We suggest the Fall because this is when lower DO values are generally most likely to occur widely. Increased spatial effort across a range of DO values, and low DO values, will allow for increased inference related to DO and temperature thresholds.
- Provide consistent metadata for data-users to provide the necessary context to ensure that data is applied correctly.

Exploration and Qualitative Analysis of Oxygen, Temperature and Taxa Data

We qualitatively explored the oxygen threshold limits of herring and multiple salmon species by plotting fish presence and absence across temperature and DO values to demonstrate the range of conditions that these fish occurred in (Figure 2). Together, these datasets provide insight into the range of temperatures and DO conditions in which Chinook salmon and herring occur. That is that any threshold values must be beyond the range of the environmental conditions represented within the currently available data. We found that the DFO data captured a smaller range of DO values and overall warmer temperatures than the UW surveys (Figure 2). The UW CTD captured DO levels from 1.22 to 6.9 mg DO/L, while the DFO CTD dataset surveyed had a lower and narrower DO range, 1.78 to 3.17 mg/L (Figure 2). The UW CTD captured temperatures from 8.4 -10.9 ℃, while the DFO CTD dataset captured temperatures from 10.6 - 14.3 ℃ (Figure 2).

While chum and coho were not caught frequently enough to incorporate in a statistical model, plots of presents and absence (Figure 2) offer insight into the oxygen conditions that these fish experienced. Qualitatively, there did not appear to be a threshold where fish no longer occurred, fish were caught at very low DO levels (herring: 1.2 - 6.99 mg /L, Chinook salmon: 2.06 - 4.06 mg/L, chum: 2.1 - 3.1 mg/L, coho: 1.79 - 3.17 mg/L).

**Figure 2.** Fish occurrence by the range of temperature (C) and dissolved oxygen (DO mg/L, adjusted for temperature) values at the same depth where fish were caught. Plots are grouped by species, and colors indicate the data source.




Further examination of the more detailed UW data indicates that herring and Chinook salmon do not appear to “prefer” higher DO regions in the water column (Figures 3 and 4). We found that fish were present at depths with low DO levels even when there was more oxygen available higher in the water column. Specifically, fish were found at lower DO levels (as low as 1.3 mg/L for herring and 2.06 mg/L for Chinook), even when DO levels at other places in the water column were >6 mg/L (Figures 3 and 4). Overall, this qualitative review of the UW data do not indicate a specific threshold for herring or Chinook salmon, but the data do indicate that thresholds are likely below 1.3 mg/L and 2.06 mg/L, respectively, at least for the temperatures experienced in these sampling events.

**Figure 3.** Depth (ft) and water column DO for UW surveys that caught adult Chinook salmon. The catch per unit effort (CPUE) is represented by the size of the red dot, and the horizontal dashed line indicates the depth where the fish was caught. Plots are grouped by survey month and year (month.year) and the survey location. These surveys took place in Hood Canal, and Da = Dabob Bay, Hp = Hoodsport, and Un = Union.

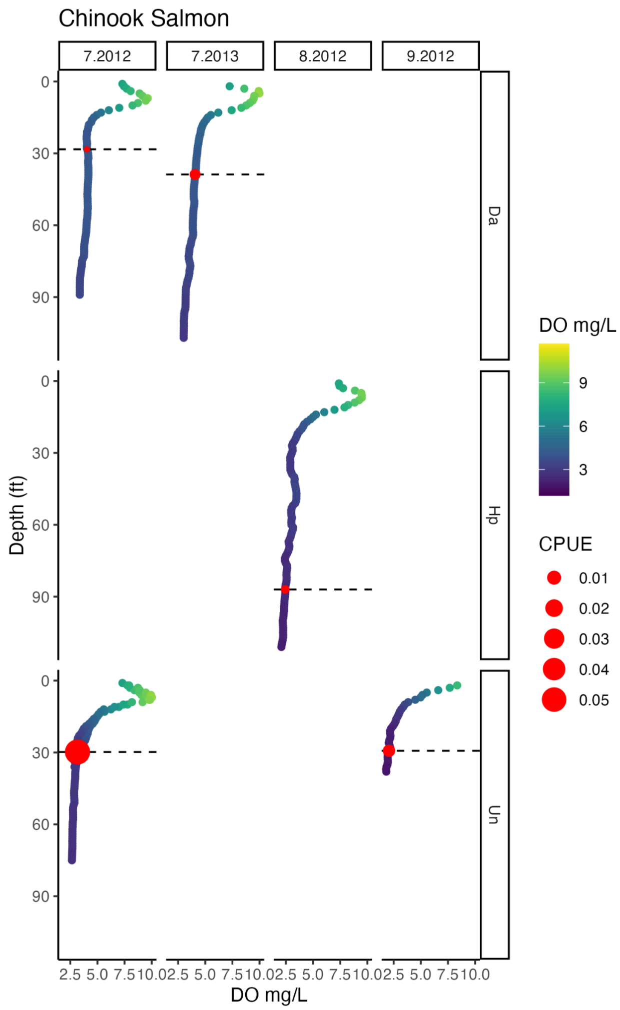
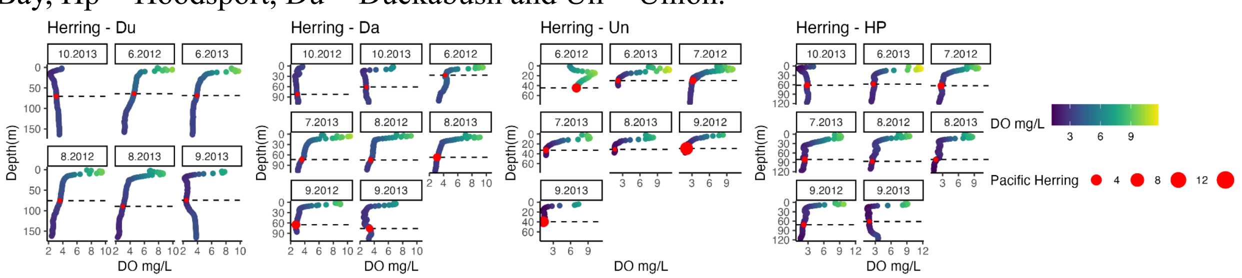



**Figure 4.** Depth (ft) and water column DO for UW surveys that caught adult Herring. The catch per unit effort (CPUE) is represented by the size of the red dot, and the horizontal dashed line indicates the depth where the fish was caught. Plots are grouped by survey month and year (month.year) and the survey location. These surveys took place in Hood Canal, and Da = Dabob Bay, Hp = Hoodsport, Du = Duckabush and Un = Union.




<u>Hypothesis Testing and Modeling of Environmental Drivers</u>

We used a generalized linear model to estimate the effects of DO on the probability of capturing a herring or a Chinook salmon. For both species, there was no support for models that contained any combination of DO or temperature covariates over a simpler (null) model that only considered location, depth, and day of year without environmental covariates (Table 2). We used $AIC_c$ to identify the most appropriate model among the seven candidate models (Table 2). $AIC_c$ balances model complexity against how well the model fits the data, with a specific correction for small sample sizes. We calculated $\Delta AIC_c$ by subtracting the lowest $AIC_c$ from the remaining models. A $\Delta$ $AIC_c$ greater than 2 is considered meaningful because it represents a substantial difference in model support based on statistical theory. We found that overall differences in $AIC_c$ values between the null model and B-D alternative models were small (<= 2) so the null model cannot be dismissed for either species. This means that there was no support for the proposed hypotheses using the data collated for this project. We found that DO does not statistically predict the probability of observing a Chinook salmon or herring.

Given the lack of statistical support for including DO or temperature relationships in models estimating fish presence, we suggest that the best way to gain insight into DO and temperature limits from the current dataset is to evaluate the plots of the data qualitatively, as presented prior. This also provides insight into why the available data presents limitations in drawing inferences about DO thresholds. In particular, there was minimal overlap in survey location and timing between both data sets which resulted in fish species being caught in variable environmental conditions from each other (Figure 1 and Figure 2). Conducting more surveys overall, and specifically targeting these surveys for the fall when lower and wider ranges of DO are typical will likely improve the model inference in future analyses.

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