# 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

Funding: This Technical Memorandum 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.

# 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.

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.

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.

## 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 km² 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.*

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

*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.

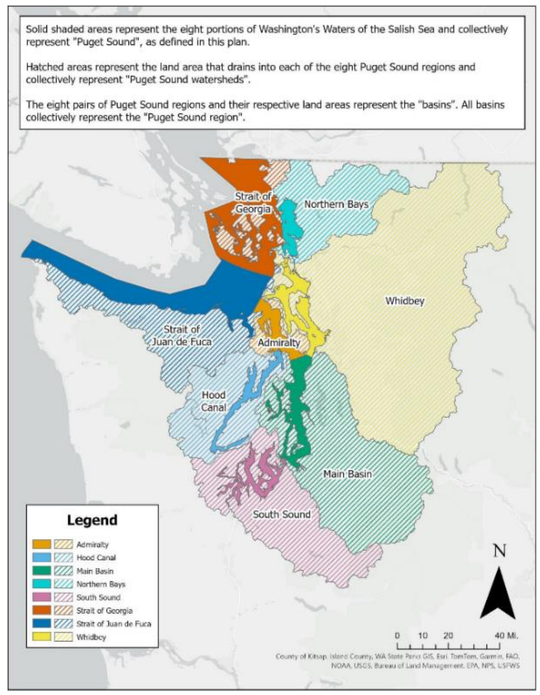


*Figure 1. The eight basins the marine point source and watershed targets apply to. Figure 2 from the Draft Puget Sound Nutrient Reduction Plan.*

### 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.

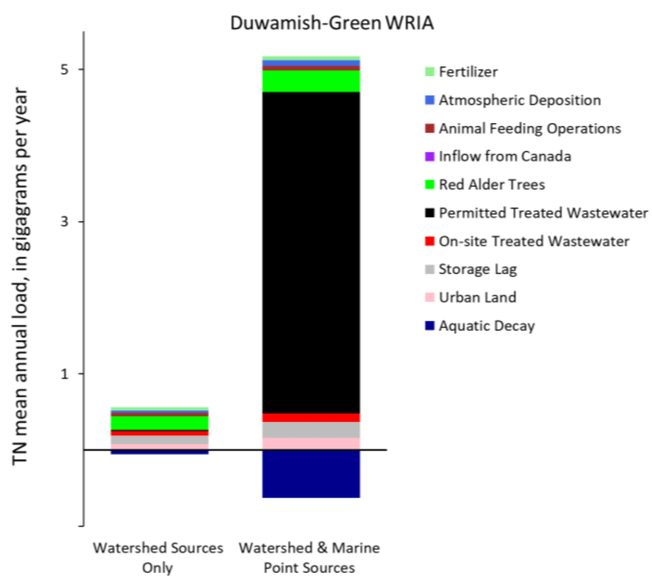


*Figure 2. Nutrient sources in the Duwamish-Green WRIA. Watershed sources are based on the accumulated loads at COMID 23977634. The marine point & watershed sources are determined by aggregating the incremental loads within the WRIA.*

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.

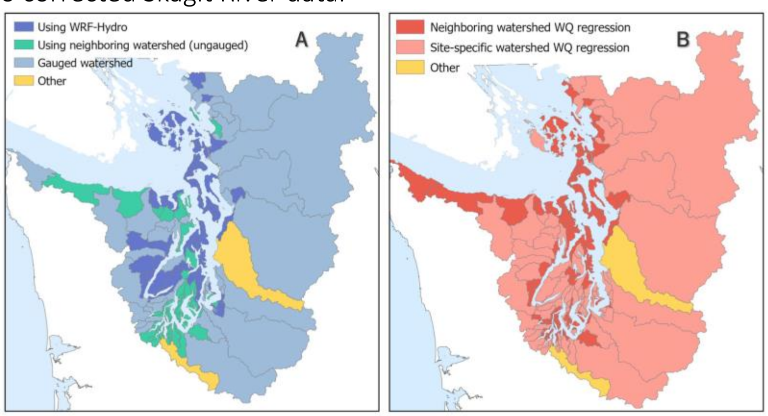


*Figure 3. Figure B1-5 from Figueroa-Kaminsky et al. (2025). (A) Current status of flow data availability for Opt2 watersheds. Additional flow data has been acquired since (Ahmed et al. 2021), which includes more gauged watersheds and the use of National Oceanic and Atmospheric Administration (NOAA) 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%** | **42,768** | **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 (α = 8) and group 2 to sustain growth later into fall (α = 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.

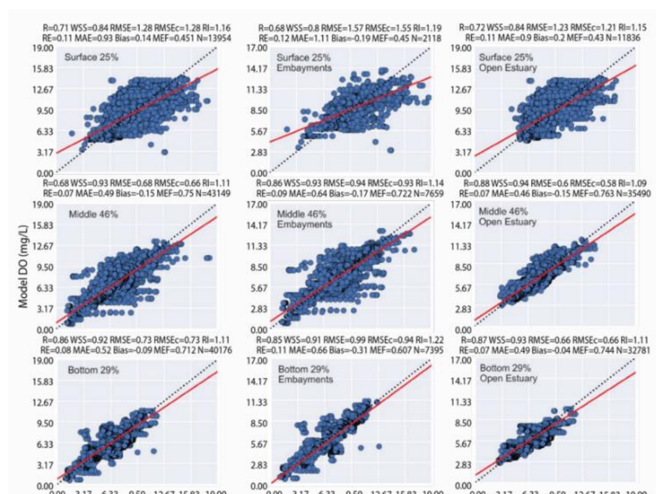


*Figure 4. Dissolved oxygen performance segmented by depth, embayments, and open channel. Figure from March 2025 Nutrient Forum.*

*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.

# References


Ahmed, A., Figueroa-Kaminsky, C., Gala, J., Mohamedali, T., Pelletier, G., & Sheelagh, M. (2019). *Puget Sound Nutrient Source Reduction Project. Volume 1: Model Updates and Bounding Scenarios* (19-03–001; p. 102). Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1903001.html

Ahmed, A., Gala, J., Mohamedali, T., Figueroa-Kaminsky, C., & McCarthy, S. (2021). *Technical Memorandum: Puget Sound Nutrient Source Reduction Project Phase II - Optimization Scenarios (Year 1)* (Technical Memo 06–509). Department of Ecology. https://www.ezview.wa.gov/Portals/_1962/Documents/PSNSRP/OptimizationScenarioTechMemo_9_13_2021.pdf

Cerco, C. F., & Noel, M. R. (2019). Twenty-year simulation of Chesapeake Bay water quality using the CE-QUAL-ICM eutrophication model. *Journal of the American Water Resources Association*, *55*(2), 411–431. https://doi.org/10.1111/1752-1688.12723

Figueroa-Kaminsky, A., Ahmed, A., & Khangaonkar, T. (2025a). *Optimization Phase 2: Refinements to the Salish Sea Model and nutrient reduction scenarios* [Ecology Publication No. 25-03-004]. Washington State Department of Ecology.

Figueroa-Kaminsky, A., Ahmed, A., & Khangaonkar, T. (2025b). *Optimization Phase 2: Refinements to the Salish Sea Model and nutrient reduction scenarios* [Ecology Publication No. 25-03-004]. Washington State Department of Ecology.

Mazzilli, S., Baker, J. E., & Larson, M. (2024). *Salish Sea Model evaluation and proposed actions to improve confidence in model application*. Report on input and review from the Puget Sound Institute Modeling Evaluation Group members: Bill Dennison, Jacob Carstensen, Jeremy Testa, Kevin Farley, and Peter Vanrolleghem. University of Washington Puget Sound Institute.

https://www.pugetsoundinstitute.org/wp-content/uploads/2024/06/2024.06.26_Salish-Sea-Model-Evaluation-and-Proposed-Actions-to-Improve-Confidence-in-Model-Application.pdf

Premathilake, L., & Khangaonkar, T. (2022). Explicit quantification of residence and flushing times in the Salish Sea using a sub-basin scale shoreline resolving model. *Estuarine, Coastal and Shelf Science*, *276*, 108022. https://doi.org/10.1016/j.ecss.2022.108022

Reiman, J. (2025). *Draft Puget Sound nutrient reduction plan* [Ecology Publication No. 25-10-038]. Washington State Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/2510038.html

Riemann, B., Carstensen, J., Dahl, K., Fossing, H., Hansen, J. W., Jakobsen, H. H., Josefson, A. B., Krause-Jensen, D., Markager, S., & Stæhr, P. A. (2016). Recovery of Danish coastal ecosystems after reductions in nutrient loading: A holistic ecosystem approach. *Estuaries and Coasts*, *39*, 82–97.

Schmadel, N. M., Figueroa-Kaminsky, C., Wise, D., & Wasielewski, J. (2025). *Simulated seasonal loads of total nitrogen and total phosphorus by major source from watersheds draining to Washington waters of the Salish Sea, 2005 through 2020*.

Scientific and Technical Advisory Committee (STAC). (2023). *Achieving water quality goals in the Chesapeake Bay: A comprehensive evaluation of system response (Executive summary)*. Chesapeake Bay Program.

Szpilka, C. M., Cerco, C. F., & Kim, S.-C. (2018). Application of a sediment diagenesis model in support of Chesapeake Bay water quality modeling. *Journal of Environmental Engineering*, *144*(7), 04018048. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001386

Washington State Department of Ecology. (2022). *Puget Sound nutrient general permit: For discharges of wastewater effluent to Puget Sound and the Strait of Juan de Fuca from domestic wastewater treatment plants with flows over 1 million gallons per day* [Permit No. WA0990001]. Washington

State Department of Ecology. https://apps.ecology.wa.gov/paris/DownloadDocument.aspx?Id=390719

Washington State Department of Ecology. (2025a). *Draft Puget Sound nutrient general permit: For discharges of wastewater effluent to Puget Sound and the Strait of Juan de Fuca from domestic wastewater treatment plants with flows over 1 million gallons per day* [Permit No. WA0990001]. Washington State Department of Ecology. https://fortress.wa.gov/ecy/ezshare/wq/permits/PSNGP-2025-DraftPermit.pdf

Washington State Department of Ecology. (2025b, March 27). *Nutrient Forum: Opt2 scenarios* [PowerPoint presentation slides]. Nutrient Forum. https://www.ezview.wa.gov/Portals/_1962/Documents/PSNSRP/NutrientForum_Opt2Scenarios_March_2025.pdf

Washington State Department of Ecology. (2025c, June 24). *Puget Sound Nutrient Reduction Plan* [PowerPoint presentation slides]. Nutrient Forum. https://www.ezview.wa.gov/Portals/_1962/Documents/PSNSRP/Puget%20Sound%20Nutrient%20Reduction%20Plan.pdf