Puget Sound
Nutrient Source Reduction Project

Volume 1: Model Updates and Bounding Scenarios

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Cover image: Salish Sea Model grid and domain.

Puget Sound
Nutrient Source Reduction Project

Volume 1:
Model Updates and Bounding Scenarios

by

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Executive Summary

Low levels of dissolved oxygen have been measured throughout Puget Sound and the Salish Sea. In numerous places, seasonal oxygen levels are below those needed for fish and other marine life to thrive, and water quality standards are not being met. Nutrient pollution from human activities is worsening the region's naturally low oxygen levels. Areas most affected are poorly flushed inlets, including Penn Cove, Quartermaster Harbor, and Case, Carr, Budd, Sinclair, and Dyes Inlets.

Many Puget Sound locations are listed on the U.S. Environmental Protection Agency's Clean Water Act Section 303(d) list as "impaired." Federal law requires states to identify sources of pollution and develop water quality improvement plans for waters listed as impaired.

Excessive nutrients flowing into marine waters can lead to profound consequences for the ecosystem. In addition to low levels of oxygen, some effects include:

- Acidification, which can prevent shellfish and other marine organisms from forming shells.
- Shifts in the number and types of bottom-dwelling invertebrates.
- Increases in abundance of macroalgae, which can impair the health of eelgrass beds.
- Seasonal reductions in fish habitat and intensification of fish kill events.
- Potential disruption of the food web.

Figure ES1. Salish Sea Model area (orange grid).

Washington State Department of Ecology (Ecology) recognizes the need to manage human sources of nutrients in the Puget Sound region. To understand the significance of these sources and identify potential solutions, Ecology used a peer-reviewed, state-of-the-science computer modeling tool called the Salish Sea Model. It models conditions in the Salish Sea, extending into the coastal waters of southwest British Columbia, Washington, and northwest Oregon (Figure ES1). This report shares the findings of the first set of modeled scenarios; it will inform discussions and guide the next round of modeling, to begin in 2019.

Excessive nutrients in rivers and from point sources flowing into the Sound, such as municipal wastewater treatment plants, deplete dissolved oxygen below the water quality standards.

In this report, Ecology evaluated changes in marine dissolved oxygen due to reducing nitrogen and carbon at municipal wastewater plants.

The years 2006, 2008, and 2014 were modeled to represent a range of climate and ocean conditions affecting Puget Sound. Model scenarios tested the impacts of:

- Current levels of nutrient pollution from rivers and wastewater treatment plants discharging directly to marine waters.
- Reduced nitrogen and carbon at all municipal wastewater treatment plants discharging to marine waters.
- Reduced nitrogen and carbon at only midsize and large municipal wastewater treatment plants discharging to marine waters.
- Reduced nitrogen and carbon at only large municipal wastewater treatment plants discharging to marine waters.

Only the 79 municipal wastewater treatment plants that discharge directly into the United States portion of the Salish Sea were simulated with lower nutrient levels. Canadian and industrial treatment plants remained at current loadings in all the scenarios tested. Plants were grouped into three categories: all plants, midsize, and large. Midsize plants include Chambers Creek, Tacoma Central, Brightwater, Everett outfall in the Snohomish River, Everett-Marysville, and Bellingham. Large plants are South King County and West Point.

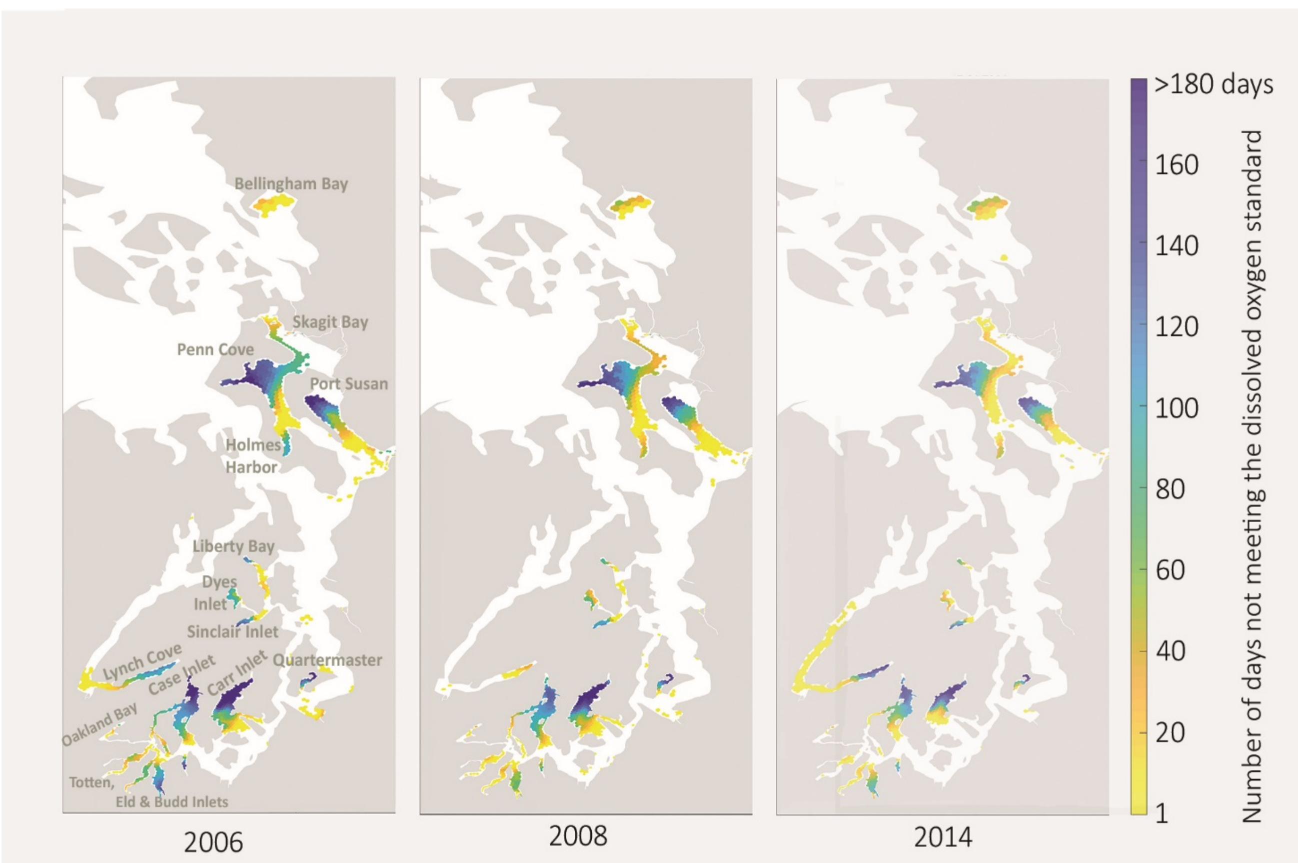

Figure ES2. Number of days not meeting the dissolved oxygen water quality standards for the years 2006, 2008, and 2014.

During all three years under the current nutrient loads, dissolved oxygen standards were not met. For example, Figure ES2 shows the number of days per year that water quality standards were not met, and where the noncompliance occurred. Complete details and results of the scenarios are complex and begin on page 72 of this report.

Ecology found that implementing nutrient reduction at wastewater treatment plants would achieve significant improvements toward meeting the dissolved oxygen water quality standards. The model estimates improvements in the number of days (Table ES1) and area (Table ES2) not meeting the standards.

Table ES1. Improvement in the number of noncompliant days due to nutrient reduction at wastewater treatment plants.

Year	Improvement in dissolved oxygen (% reduction in noncompliant days)		
	All plants	**Mid & large plants**	**Large plants**
2006	51%	43%	31%
2008	61%	49%	33%
2014	51%	42%	22%

Table ES2. Improvement in noncompliant area due to nutrient reduction at wastewater treatment plants.

Year	Improvement in dissolved oxygen (% reduction in noncompliant area)		
	All plants	**Mid & large plants**	**Large plants**
2006	47%	37%	23%
2008	51%	41%	24%
2014	42%	33%	13%

Under existing conditions, approximately 20% of the area in the greater Puget Sound does not meet the dissolved oxygen standards. If reductions are made at all municipal wastewater treatment plants as modeled, approximately 10% of the greater Puget Sound would not meet the standards. This represents roughly a 50% improvement in compliance area for the dissolved oxygen standards.

The results of the first phase of modeling conducted in 2018 confirm that human sources of nutrients are having a significant impact on dissolved oxygen in multiple Puget Sound embayments. It is clear from the modeling study that it will take a combination of nutrient reductions from wastewater treatment plants and other sources of nutrient pollution in watersheds to meet marine water quality standards.

Therefore, future evaluations of nutrient reduction strategies will need to include a comprehensive suite of measures. These measures should include nutrient load reductions from both wastewater treatment plants and watersheds to comply fully with Washington's marine water quality standards for dissolved oxygen.

To address this complex issue, evaluations of different combinations of marine and watershed source reductions are planned for the next phase of modeling, beginning in early 2019.

Abstract

Low dissolved oxygen (DO) levels have been observed throughout the Salish Sea,[1] and recent studies[2] have shown that nutrient inputs from anthropogenic sources influence these low DO events in Puget Sound. This work is the first in a series of technical studies to inform the Puget Sound Nutrient Source Reduction Project (PSNSRP). The PSNSRP is an effort to guide regional investments in nutrient reductions with the goal of meeting Washington State marine water quality standards for DO in Puget Sound.

The Washington State Department of Ecology (Ecology) conducted hydrodynamic and water quality simulations using a peer-reviewed, state-of-the-science regional biogeochemical model. We applied the model to a set of hypothetical (or bounding) scenarios to test the effects of major changes in nutrient loadings to the system. In addition, we implemented model enhancements to watershed hydrology and anthropogenic loading inputs, checked model calibration, explored alternative parametrizations, assessed model performance, evaluated the existing water quality conditions throughout Puget Sound for multiple years to better understand interannual variability, and determined human contributions to low DO concentrations.

Results from this project confirm that regional nutrient contributions from humans exacerbate low DO, especially in poorly flushed areas, such as inlets. *Hypoxic events*, when DO levels dip to between 2 and 3 mg/L or lower, can have severe ecosystem consequences. Hypoxic area varies temporally, and during 2006 it was estimated to peak around 52,500 acres (212 km^2) within the greater Puget Sound, out of which approximately 19% (around 10,000 acres) are attributable to human nutrient loadings. Furthermore, model results show that Puget Sound's cumulative annual hypoxic volumes for 2006, 2008, and 2014 were between 28% and 35% higher than under reference (pre-industrial) conditions.

Washington State's DO water quality standards are set at levels above hypoxic to protect healthy, robust aquatic communities, including the most sensitive species. We found the following when applying the standards to the model results:

- The total area of greater Puget Sound waters not meeting the marine DO standard was estimated to be around 151,000 acres (612 km^2) in 2006, 132,000 acres (536 km^2) in 2008, and 126,000 acres (511 km^2) in 2014. These areas correspond roughly to about 23%, 20%, and 19% of greater Puget Sound in each year, respectively, excluding the intertidal zone.
- Noncompliant areas are located within all Puget Sound basins except Admiralty Inlet. All areas not meeting the water quality standard have depleted levels of DO in the water column as a result of human loadings from Washington State. Model computations take into account multiple oceanographic, hydrographic, and climatological drivers, so that depletions due to human activity alone can be computed by excluding other influences, such as that of the Pacific Ocean.

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[1] The Salish Sea includes the Strait of Juan de Fuca, the Strait of Georgia, Puget Sound, and all of their connecting channels and adjoining waters, such as Haro Strait, Rosario Strait, Bellingham Bay, Hood Canal, and the waters around and between the San Juan Islands in Washington State and the Gulf Islands in British Columbia, Canada.
[2] Ahmed et al. (2014); Albertson et al. (2002); Roberts et al. (2014).

- Extreme DO depletions of almost 2 mg/L below the water quality standard are predicted to occur at specific poorly flushed locations, with an overall mean around 0.3 mg/L below the standard.
- Portions of Puget Sound, primarily in South Sound and Whidbey Basin, experience a large number of days per year when the marine DO standards are not met. The number of noncompliant days varies by year and location. For instance, the maximum number of noncompliant days occurred in 2006 (Carr Inlet, 250 days), followed by 2008 (Carr Inlet, 216 days), and 2014 (Quartermaster Harbor, 198 days). The average cumulative number of noncompliant days computed over all areas not meeting the standard was 63, 50, and 46 in each of those years, respectively.

We modeled three scenarios consisting of hypothetical reductions in both dissolved inorganic nitrogen and organic carbon loadings from Washington State municipal wastewater treatment plants (WWTPs) discharging into the Salish Sea. These bounding scenarios were based on load reductions that could occur if seasonal biological nitrogen removal (BNR) technology were applied, as follows:

- At all municipal WWTPs.
- Only at WWTPs with dissolved inorganic nitrogen loading of 1000 kg/day or higher.
- Only at WWTPs with dissolved inorganic nitrogen loading of 8000 kg/day or higher.

This modeling study confirmed that the inner basins of Puget Sound share a portion of their waters, so that discharges in one basin can affect the water quality in other basins. Model simulations for 2006 show that the selected hypothetical nutrient reductions diminish the impacted areas by 47%, 37%, and 23% for each of the scenarios listed above, respectively. Similar reductions were observed for 2008 and 2014. The nutrient load reductions also resulted in significant improvements in the total number of noncompliant days (up to 61% reduction when applying seasonal BNR to all WWTPs).

These hypothetical wastewater treatment reductions could return marine water quality to a level that complies with the DO standard at many locations and considerably reduce the number of noncompliant days. However, full compliance with the standards at all locations cannot be achieved through these actions alone. This analysis compares the relative influence of all marine point sources to human activities in watersheds. When all anthropogenic watershed sources were set to reference conditions and marine point source discharges remained as they are, the water quality noncompliant area was about 31% of the actual noncompliant area computed for 2006.

It is clear that a comprehensive suite of measures, including watershed load reductions, is needed to fully comply with water quality standards in Puget Sound. Evaluation of different combinations of marine and watershed nutrient source reductions will begin in the next phase of modeling in 2019.

Introduction

Background

The Salish Sea is a network of coastal waterways spanning southwest British Columbia (Canada) and northwest Washington State (United States). It includes three major waterbodies: Strait of Juan de Fuca, Strait of Georgia, and Puget Sound (Figure 1). It also includes their connecting channels and adjoining waters, such as Haro Strait, Rosario Strait, Bellingham Bay, Hood Canal, and the waters surrounding the San Juan Islands in Washington State and the Gulf Islands in British Columbia (Figure 1).

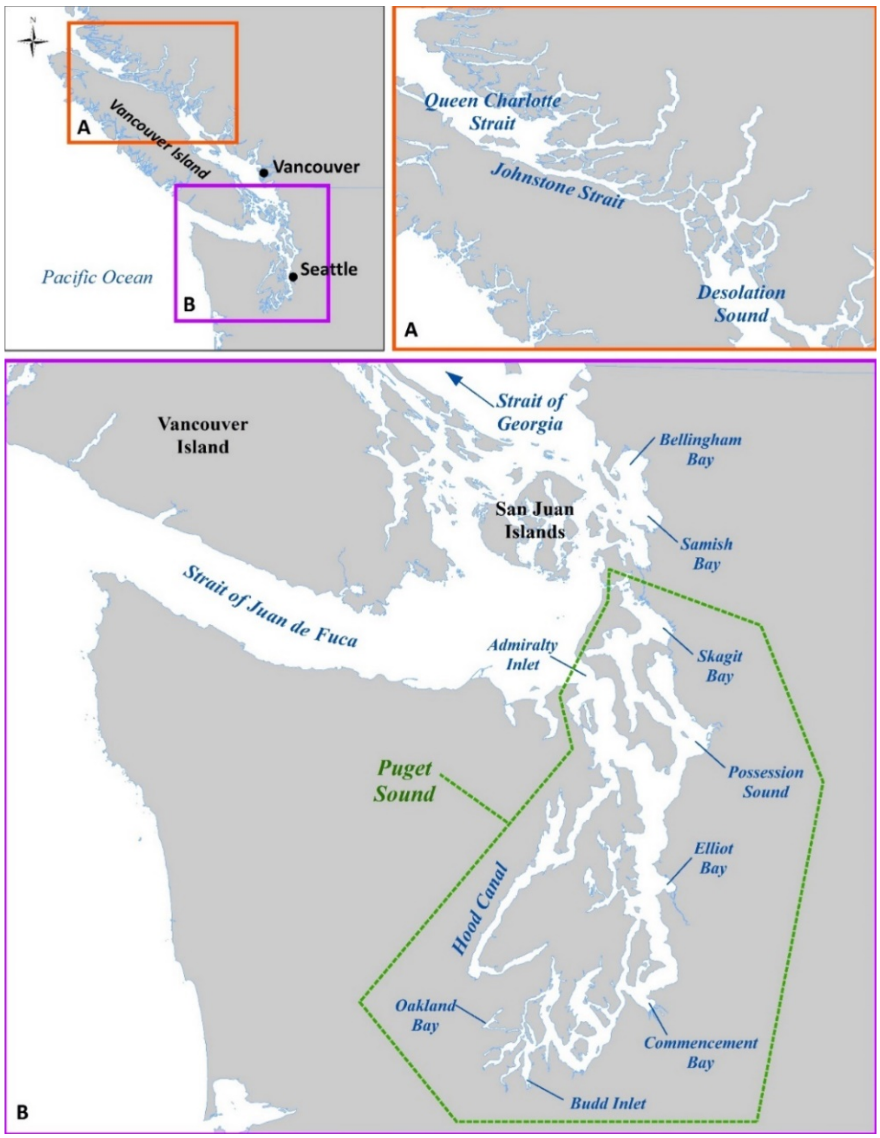


Figure 1. Regions of the Salish Sea (Strait of Juan de Fuca, Strait of Georgia, and Puget Sound), including Johnstone and Queen Charlotte Straits.

Low dissolved oxygen (DO) levels have been observed throughout the Salish Sea, and recent studies have shown that nutrient inputs from anthropogenic sources have influenced low DO in

Puget Sound (Ahmed et al., 2014; Albertson et al., 2002; Roberts et al., 2014). Recent sensitivity assessments of nutrient pollution in the Salish Sea have also shown that land-based nutrient sources may be responsible for most of the exposure to bottom-layer hypoxic waters (Khangaonkar et al., 2018).

Nitrogen acts like a fertilizer, causing algae to grow, and it is a limiting nutrient in Puget Sound (Newton and Van Voorhis, 2002). Nitrogen is a naturally occurring nutrient. However, too much nitrogen results in excessive algal growth. Algal growth generates organic carbon. Organic carbon may also be present in the form of detritus from terrestrial loads. Organic carbon decomposes and consumes oxygen. In some cases, due to excessive nutrient inflows, oxygen is depleted to low levels, which prompts shifts in the form and function of the ecosystem and its ability to support aquatic life (Diaz and Rosenberg, 2008; Glibert et al., 2005). This process is referred to as *eutrophication*.

Nutrient over-enrichment can result in additional eutrophication indicators, beyond increases in phytoplankton and biomass. This report does not include an assessment of other potential impacts from nutrient over-enrichment, but it is important to recognize the connection to other chemical and biological responses. These include:

- Production of carbon dioxide from remineralization of organic carbon, which lowers the pH, contributing to acidification of the water column (Wallace et al., 2014; Feely et al., 2010; Pelletier et al., 2017b). As water becomes acidic, less calcium carbonate is available for marine organisms to form shells (Bednarsek et al., 2017, and references therein).
- Changes to the benthic (bottom-dwelling) macroinvertebrate community structure and species diversity, habitat compression, and shifts to microbial-dominated energy flow, resulting in changes to the food chain (Diaz and Rosenberg, 2008, and references therein).
- Changes to micronutrient availability that can lead to increased incidence and duration of harmful algal blooms (Howarth et al., 2011, and references therein).
- Increased growth and abundance of opportunistic and ephemeral macroalgae, in particular, species of *Ulva* (Teichberg et al., 2010, and references therein).
- Deleterious effects to eelgrass meadows (Burkholder et al., 2007; Hessing-Lewis et al., 2011). Declines in eelgrass shoot density with increasing macroalgal abundance have been demonstrated (Bittick et al., 2018; Nelson and Lee, 2001).

Specific parts of the Salish Sea, such as the shallow inlets and bays in southern Puget Sound, are more sensitive to eutrophication, due to reduced flushing compared to the Main Basin and more open marine waters (Ahmed et al., 2017; Khangaonkar et al., 2012; Sutherland et al., 2011). In addition, future population growth in the Salish Sea region will likely increase human nutrient loads, including excess nitrogen and carbon from wastewater, stormwater, agricultural runoff, and other land-use activities. Regional population growth will contribute to further DO concentration reductions if no actions are taken to reduce human nutrient sources (Roberts et al., 2014). Figure 2 shows the DO numeric criteria that apply in the marine waters of the United States and Puget Sound, where water quality data indicates that waterbody segments are not meeting the numeric part of the standards (based on Washington's Water Quality Assessment that was approved by EPA in 2016 [Ecology, 2018]).

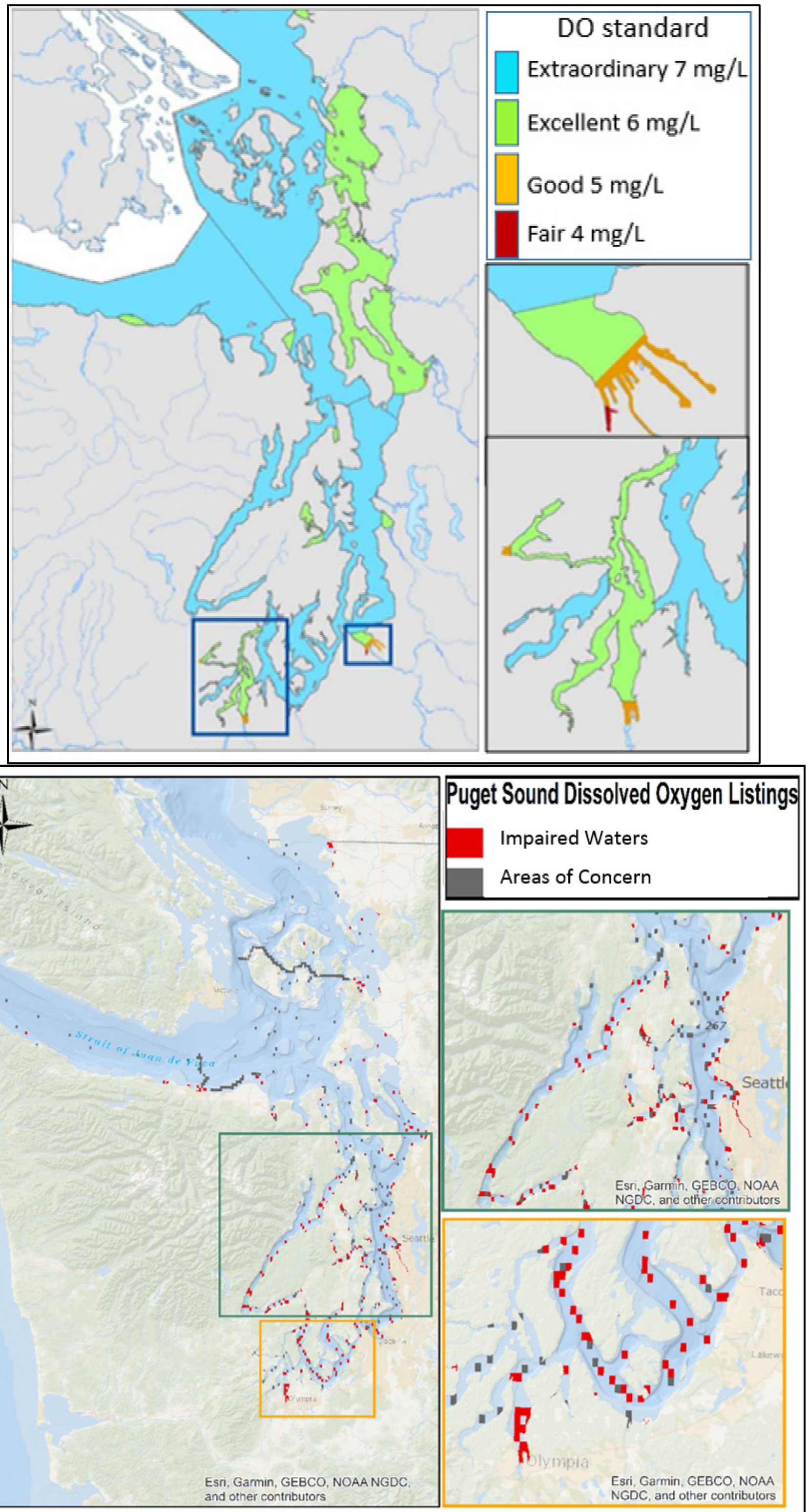


Figure 2. Dissolved oxygen (DO) in Puget Sound.
Above, numeric water quality standards for dissolved oxygen. *Below*, results from Washington's Water Quality Assessment for dissolved oxygen in Puget Sound. Red indicates Category 5 impaired waters, and blue-gray represents Category 2 areas of concern for 2016.

The Water Quality Assessment for DO is based only on the numeric part of the standard. Although a waterbody segment may be included in Category 5 as impaired or Category 2 as an area of concern, that listing process does not consider the 0.2 mg/L human allowance from natural conditions that is part of the DO standards. We use an estimated reference condition computed for each model year to measure anthropogenic change.

Areas vulnerable to eutrophication in Puget Sound are thought to share three key characteristics: poor vertical mixing of the water column that may lead to stratification, dissolved inorganic nitrogen (DIN) limitations on phytoplankton growth, and long residence times (Encyclopedia of Puget Sound, 2018a). Yet, the complexity of the system is remarkable, necessitating the aid of mechanistic models to reveal causes and effects, and sources and sinks. For instance, using a circulation model, Banas et al. (2015) showed that local salinity is not a reliable indicator of the influence of the nearest rivers on Puget Sound water quality. Khangaonkar et al. (2018), using a biogeochemical model, showed that land-based sources of nutrients have a significant impact on water quality.

Although large-scale climatological, meteorological, and hydrological drivers produce large variabilities in Puget Sound water quality (PSEMP, 2012–2017), sensitivity to anthropogenic nutrient additions within the Salish Sea is heightened in locations that have low flushing rates and adjoin urbanized shorelines (Mackas and Harrison, 1997). Albertson et al. (2007) qualified South Puget Sound as relatively more "sluggish and stratified" and highlighted the importance of wind patterns and magnitude to water circulation in the region. EPA (1992) also identified several restricted bays, inlets, and passages in Puget Sound as potentially sensitive to eutrophication based on their frequency of DIN depletion in surface waters and low DO.

Thom et al. (1988) demonstrated that Fauntleroy Cove, in southwest Seattle, has experienced localized eutrophication. They recommended studies on the freshwater nutrient contributions to Puget Sound and the degree of "nutrient trapping" in embayments. Other observational studies have identified various Puget Sound inlets that experience persistent or seasonal stratification, depletion of nitrogen at the surface, and substantial enhancement of primary production due to nutrient addition, consequently making these locations vulnerable to eutrophication (Newton and Reynolds, 2002; Eisner and Newton, 1997; Newton et al., 1998). Mechanistic modeling studies associated those same locations that experience poor flushing, such as South Puget Sound inlets, with human-influenced low DO conditions (Ahmed et al., 2014, 2017; Roberts et al., 2014).

The deteriorating quality of Puget Sound benthic assemblages, as shown via a decline in the overall area of unaffected benthos, along with observations of adversely affected communities in terminal inlets, are suggestive of biogeochemical ecosystem changes potentially related to low oxygen episodes (Weakland et al., 2018). Such changes in the benthic community composition can occur in estuaries at varying low DO levels (Howarth et al., 2011, and references therein), and can be synergistically confounded by the presence of sulfide in the sediments, which can occur under low-oxygen conditions (Vaquer-Sunyer and Duarte, 2010). While implications of benthic community changes to Puget Sound food webs have not yet been studied, Macdonald et al. (2012) discuss the profound effect of the makeup of benthic communities in the Salish Sea's ecosystem function.

In recent years, late summer aerial observations and photography reveal intense algal blooms, copious jellyfish patches, and remnants of floating macroalgal mats in terminal inlets of Puget Sound (Krembs et al., 2012; Krembs, 2014–2018). The significance of the latter observations and their potential linkages to eutrophic processes and food web changes are yet to be elucidated. Nelson et al. (2003) found that macroalgal blooms peaked in summer and autumn at various Puget Sound sites, and biomass was greatest at sites with the highest water column nitrogen concentrations, suggesting that additional anthropogenic nitrogen can increase macroalgal biomass in the region. Van Alstyne (2016) conducted research in Penn Cove and showed, via isotopic analyses, that nitrogen from oceanic origin is the primary nitrogen source for macroalgal (genus *Ulva*) biomass, but anthropogenic sources also contribute. The most likely sources of additional nitrogen for *Ulva* samples collected in September were wastewater treatment plants.

The Washington State Department of Ecology (Ecology) has undertaken a Puget Sound Nutrient Source Reduction Project (PSNSRP) to address these water quality concerns in Puget Sound. This is a collaborative process aimed at reducing nutrients from point and nonpoint sources. The PSNSRP will guide regional investments in point and nonpoint source nutrient controls so that Puget Sound will meet DO water quality criteria and aquatic life designated uses by 2040.

To commence the PSNSRP, Ecology aims to establish an initial framework for improvements in water quality that can be achieved through reductions in current source conditions. These are referred to as “bounding scenarios.” One scenario is designed to assess the overall impact of watershed loads and marine point sources. A subset of the bounding scenarios are based on achievable technological upgrades, where seasonal biological nitrogen removal (BNR) is added to secondary treatment at municipal wastewater treatment plants (WWTPs). BNR effluent limits are set to be 8 mg/L for both dissolved inorganic nitrogen (DIN) and carbonaceous biological oxygen demand ($CBOD_5$), based on a study (Tetra Tech, 2011) that consisted of a technical and economic evaluation of nutrient removal at WWTPs. These effluent limits were applied on a seasonal basis, from April through October.

A mechanistic model is essential to cover complex interactions that affect marine water quality. Processes that contribute nutrients include atmospheric deposition, river and stream inflows, point source discharges, nonpoint source inputs, nutrient fluxes into and out of the oceanic boundary, and sediment–water exchanges. Hydrodynamic characteristics such as tides, stratification, mixing, and freshwater inflows govern transport of nutrients and other variables. Photosynthesis and respiration rates govern biological nutrient transformations and DO dynamics. Light, nutrient availability, temperature, and phytoplankton influence photosynthesis rates as well as algal growth, respiration, death, and settling. The Salish Sea Model simulates all of these processes, and it was identified as the tool that will help in developing the Puget Sound Nutrient Management Strategy. As results from other biogeochemical models for the Puget Sound become available, comparison of output from diverse models may further our understanding of system dynamics.

The Salish Sea Model

The Salish Sea Model[3] (SSM) was developed by Pacific Northwest National Laboratory in collaboration with Ecology, with funding from the United States Environmental Protection Agency (EPA). The SSM is a state-of-the-science computer modeling tool used to simulate the complex physical, chemical, and biological patterns inherent in this system. It has been developed over the past decade to analyze regional hypoxia, with continuous improvements over that time period. It has been the basis for over 20 peer-reviewed publications. This tool will be used to assess marine water quality standards and evaluate nutrient reduction options for improving and restoring Puget Sound (the Sound) to meet our water quality goals.

A first generation of the SSM was named "Puget Sound Model" (PSM), with ocean boundaries established near the mouths of the Strait of Juan de Fuca and Georgia Strait, while inner boundaries extended to all estuarine waters south and east of these open boundaries, culminating in Oakland Bay in the southernmost inner region of the model domain (see Figure 1). The model is based on the coupled hydrodynamic (Finite Volume Coastal Ocean Model, FVCOM) and water quality (CE-QUAL-ICM) models as implemented by Kim and Khangaonkar (2012). The hydrodynamics and water quality calibration of the first-generation PSM has been documented previously in Khangaonkar et al. (2011, 2012).

A second generation of the model included the addition of sediment diagenesis and carbonate systems as reported by Pelletier et al. (2017a, 2017b) and Bianucci et al. (2018). These first- and second-generation PSMs required open boundary adjustments for model calibration to accurately simulate estuarine exchange, due to the fact that the open boundary was close to entrances to the Strait of Juan de Fuca and the north boundary of Georgia Strait (Khangaonkar et al., 2018). Also, the secondary pathway for estuarine exchange through Johnstone Strait at the north end of Georgia Strait was found to be significant (Khangaonkar et al., 2017). Therefore, the model domain was expanded westward to the continental shelf in the Pacific Ocean, northward to include Johnstone Strait, and southward to Oregon's Waldport (south of Yaquina Bay), while retaining the previously developed sediment diagenesis and ocean acidification modules as described by Khangaonkar et al. (2018). This is the third-generation model, named simply the Salish Sea Model or SSM. The PSM and the SSM domains are shown in Figure 3.

In building the SSM, the grid of the older PSM was expanded out to the new model domain extent, primarily to improve handling of boundary conditions. The bathymetry of the additional area through Discovery Islands and Johnstone Strait were based on the Cascadia grid employed by the Department of Fisheries and Oceans, Canada (DFO) tsunami propagation research. The continental shelf expansion was based on bathymetry of the Advanced Circulation (ADCIRC) model of the Eastern North Pacific (ENPAC) (Spargo et al., 2003), as reported by Khangaonkar et al. (2018). The model grid also includes ten vertical layers, distributed with greater layer density near the surface (Khangaonkar et al., 2017).

[3] https://ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Salish-Sea-modeling

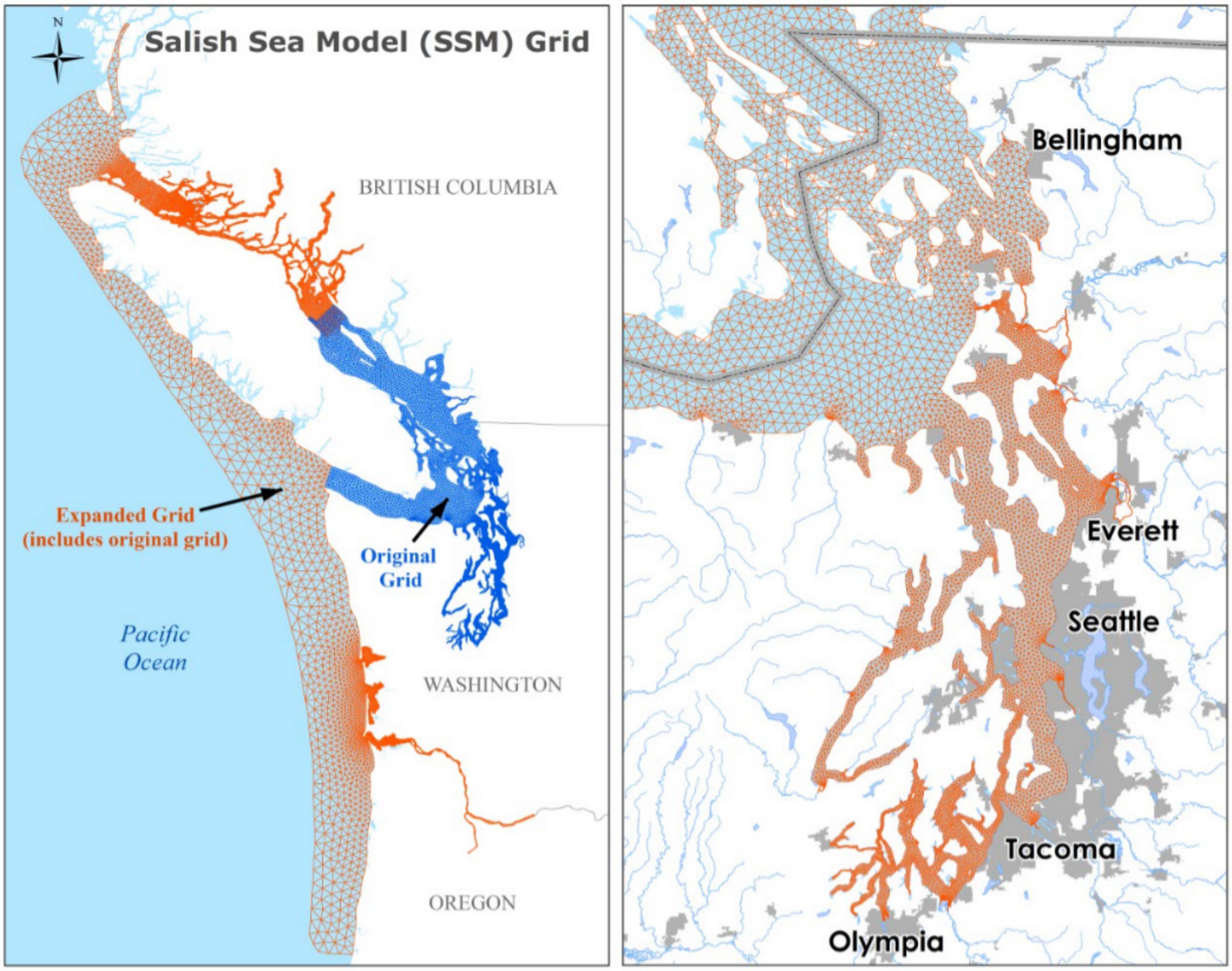


Figure 3. Domain and resolution of both the expanded Salish Sea Model (left) and original Puget Sound Model (right).

Bathymetry smoothing procedures and hydrodynamic formulations such as horizontal and vertical mixing schemes and bottom friction are discussed in Khangaonkar et al. (2018). The SSM grid consists of 16,012 nodes and 25,019 triangular elements. Grid resolution in the expanded grid (but within the old model domain) remains the same as before, while the grid resolution becomes coarser towards the continental shelf. The SSM hydrodynamics and water quality calibration is described for 2014 conditions by Khangaonkar et al. (2018). Figure 4 depicts the three-dimensional model with its nodes and elements, as well as vertical layers. Also shown in Figure 4 is the area of influence (grid cell) surrounding each node. The model predicts average water quality concentrations for each grid cell and layer for each time step.

Regions of Puget Sound that do not meet the DO standard are expressed in terms of area (e.g., acres or km^2). Since the model is three dimensional, each vertical column of water is represented by ten layered grid cells. Area, in this context, refers to the surface area of the vertical column (which is equivalent to the area represented by the grid cell in Figure 4). If DO levels in one or more layers in the water column does not meet the DO standard, the surface area of that water column is counted towards the total noncompliant area.

This report describes improved estimates of current watershed and marine point source inputs to the SSM. A finer resolution was used to delineate watersheds, which allowed for distributed flows from sub-watersheds into multiple model nodes instead of large watersheds discharging to a single model node. This refinement was limited to freshwater inflows entering South and Central Puget Sound. An additional freshwater flow input was also included to represent flow from the North Fork Skokomish River via Lake Cushman, which is used for generating electricity by Tacoma Public Utility, and which enters Hood Canal at the "great bend." This was previously missing.

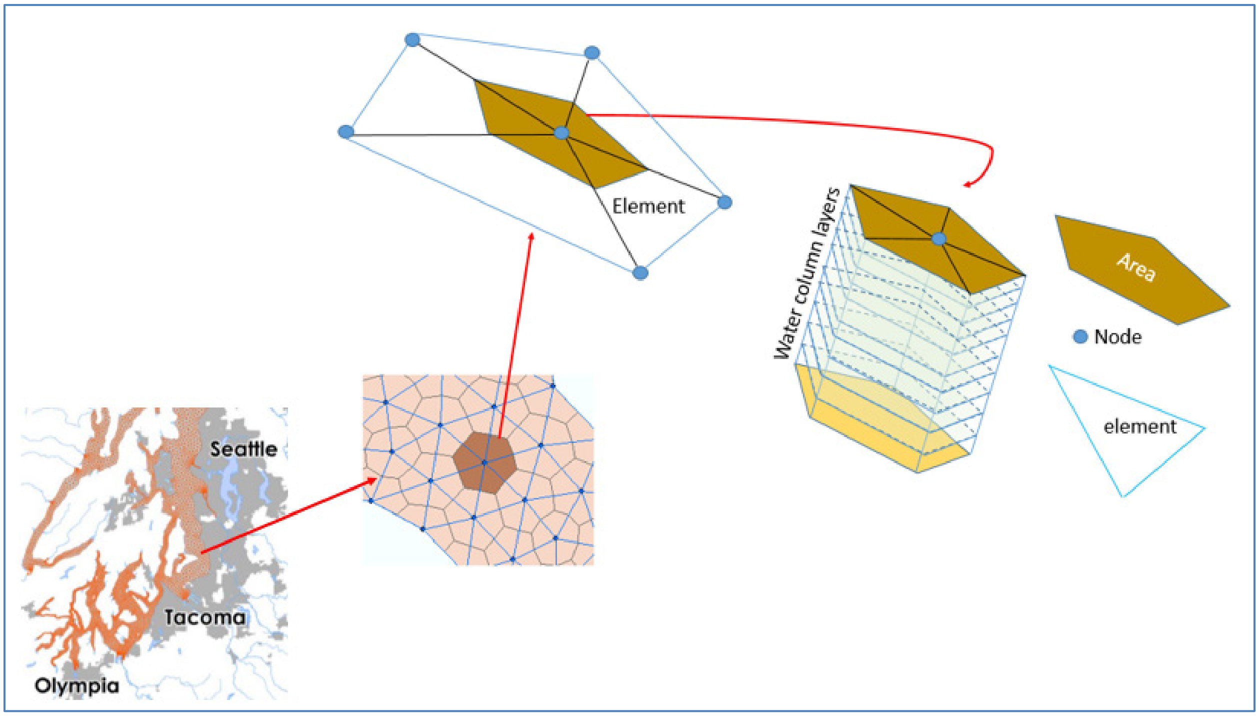


Figure 4. Model nodes, elements, layers, and area of influence of each node.

Also, flow and water quality to represent the Lake Washington inflow into Puget Sound was updated with data obtained from the Corps of Engineers and King County. In addition, new watersheds were added in northern Vancouver Island and mainland British Columbia to represent freshwater inflows to the SSM in this region. Four major watershed inflows along the Washington–Oregon Coast — Willapa, Chehalis, Columbia, and Willamette — were previously added as part of the grid expansion (Khangaonkar et al., 2018).

Water quality inputs into the model from point sources were also improved through new regressions using a larger set of data, available since 2006. Model simulations will be presented for 2006, 2008, and 2014, and calibrations checked to observed data for these years. This report will supply information for Ecology's PSNSRP, which will design management strategies for anthropogenic nutrient inputs affecting DO.

Project Description

Project goal

The project goals are to (1) run the SSM with improvements and updates to model inputs and check calibration of the model, and (2) use the calibrated model to run and evaluate bounding scenarios, which will be used to inform and develop the nutrient management strategy for Puget Sound. This report is the first in a series of modeling reports that will aid in development of a nutrient management strategy. Volume 1 provides information that will be used to guide further optimization modeling runs.

Project objectives

The project objectives include the following:

- Update the database (river and marine point source flows and water quality, and marine observations).
- Refine existing river and stream inputs and incorporate additional surface flow for the expanded grid.
- Check calibration of the expanded model to observed data for the years 2006, 2008, and 2014.
- Evaluate the relative impacts of regional anthropogenic nutrient sources on DO both spatially and temporally for 2006, 2008, and 2014 through broad perturbations in the SSM (bounding scenarios).

Methods

Boundary Conditions

Tidal forcings for the years 2006, 2008, and 2014 for the open boundary along the continental shelf were based on tidal constituents derived from the ENPAC model (Spargo et al., 2003). These include S2 (principal solar semidiurnal), M2 (principal lunar semidiurnal), N2 (larger lunar elliptic semidiurnal), K2 (lunisolar semidiurnal), K1 (lunisolar declinational diurnal), P1 (solar diurnal), O1 (lunar declinational diurnal), Q1 (larger lunar elliptic diurnal), M4 (shallow water over tides of principal lunar), and M6 (shallow water sixth diurnal constituent). Each of these tidal components has an amplitude and phase angle for each of the 87 nodes at the model open boundary at the continental shelf. An input file with these components for the open boundary model nodes was generated and included in Appendix A1.

Water quality at the open boundary for 2006, 2008, and 2014 was established using data from the Department of Fisheries and Oceans, Canada (DFO) and interpolated and extrapolated to the model ocean boundary over space and time using the procedure developed by Pacific Northwest National Laboratory (Khangaonkar et al., 2018). Appendix A2 contains the model open boundary water quality generated with this procedure.

The model is also forced with wind and heat flux at the water surface. These meteorological forcings are based on Weather Research and Forecasting model reanalysis data generated by the University of Washington Mesoscale Analysis and Forecasting Group.

The atmospheric carbon dioxide mixing ratio (xCO_2, or mole fraction of CO_2) was measured at the National Oceanic and Atmospheric Administration (NOAA) buoy at Cape Elizabeth, Washington (Table 1), and reported in NOAA's Puget Sound Ecosystem Monitoring Program (PSEMP) report for the year 2016 (PSEMP, 2017). Khangaonkar et al. (2018) used a pCO_2 value of 400 µatm for the 2014 SSM run. Since the partial pressure of carbon dioxide (pCO_2) input is currently spatially and temporally uniform in the Salish Sea Model (SSM), an annual average value reflective of measurements at Cape Elizabeth was used for model input. These values are 386 µatm and 390 µatm for 2006 and 2008, respectively.

Table 1. Atmospheric carbon dioxide mixing ratio (xCO_2) annual average concentrations (ppm) (± SD) at Cape Elizabeth, Washington (PSEMP, 2017).

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
xCO_2 (ppm)	386 ± 8	390 ± 7	390 ± 6	389 ± 7	393 ± 6	394 ± 8	397 ± 8	402 ± 7	403 ± 8	402 ± 8	406 ± 6

The model is driven with freshwater inflows from 161 watersheds and 99 municipal and industrial point sources. Appendix A3 contains a list of the watersheds, and Appendix A4 contains plots of inflows for these watersheds for the years 2006, 2008, and 2014. Appendix A5 identifies all of the marine point sources included in the model, and Appendix A6 contains plots of inflows for these marine point sources for the years 2006, 2008, and 2014. Concentrations of water quality parameters for the years 2006, 2008, and 2014 for watershed and marine point source inflows are presented in Appendices A7 and A8.

Watershed Updates

The updated SSM version used for this project included:

- Refinement of watershed inflows into South and Central Puget Sound.
- Addition of watershed inflows in coastal areas, northwest British Columbia, and Lake Cushman.
- Other watershed flows and water quality updates.

There are now a total of 161 freshwater inputs entering the model with the refined watershed delineation and addition of new watersheds, while the previous models had fewer freshwater inputs with 64 and 69 for the Puget Sound Model (PSM) (Bianucci et al., 2018) and SSM (Khangaonkar et al., 2018), respectively. These inputs represent the loading of nutrients entering marine waters in the SSM domain at the mouth of each of these rivers. In this context, river inflows into SSM are integrated and do not distinguish between all upstream watershed sources.

River inflows into South and Central Puget Sound were refined relative to the previous representation in the first-generation PSM. Previous studies identified embayments in South and Central Puget Sound as vulnerable to eutrophication and low DO conditions, so we focused on freshwater refinements in these regions. Higher resolution of watershed inflow data is now available. The refinement involved subdividing the original watersheds into smaller hydrologic units. This resulted in more freshwater inflows entering South and Central Puget Sound, but did not change the total amount of freshwater being added. Figure 5 illustrates some of these updates.

Flow and water quality estimates for the refined watersheds were originally developed for a different model of South and Central Puget Sound as part of the South and Central Puget Sound Dissolved Oxygen (SPSDO) study. These methods are described in more detail by Mohamedali et al. (2011a, 2011b). The process involved a multiple linear regression technique to create a daily time series of water quality constituents using daily USGS flows and monthly water quality data collected between 2006 and 2007 as part of the SPSDO study (Roberts et al., 2008).

The refined watershed delineations for the SSM remained consistent with the ones developed for the SPSDO study, except that a few watersheds (e.g., Sinclair/Dyes Inlet) were refined further. This refinement was done by superimposing 12-digit USGS Hydrologic Unit Code (HUC12) watershed delineations over the original PSM watersheds and using that as a basis of subdividing larger watersheds into smaller catchments.

Freshwater inflows entering the expanded model domain were also added, as described in Appendix B. These included inflows in coastal areas, northwest British Columbia, Vancouver Island, and from Lake Cushman.

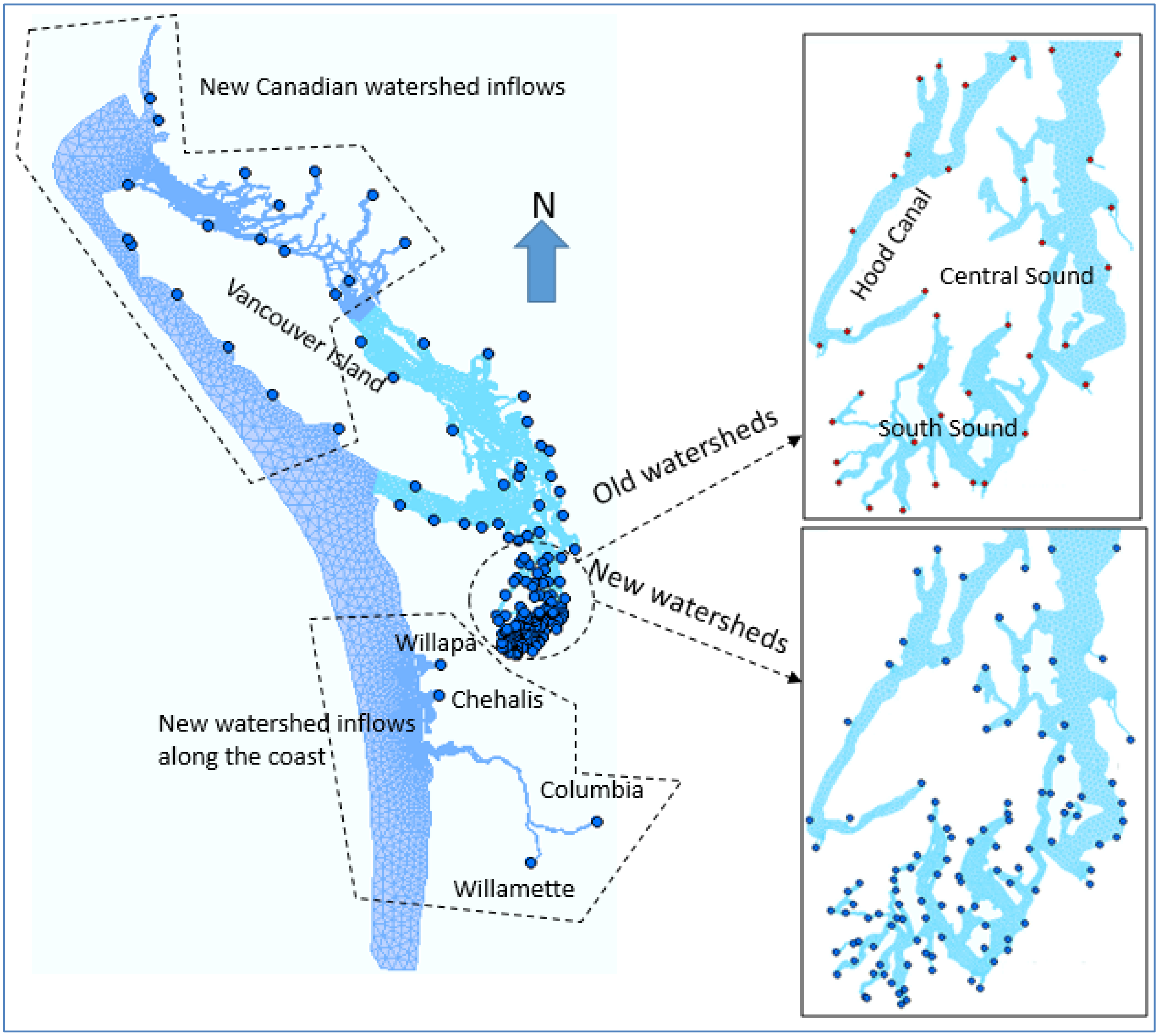


Figure 5. The new Salish Sea Model (SSM), with its refined watershed inflow nodes in South and Central Puget Sound, new Canadian watershed inflow nodes, and new watershed inflows along the Pacific Ocean coastline.

Marine Point Source Flows and Water Quality

A total of 99 marine point source inputs are included in the SSM. These include both municipal wastewater treatment plants (WWTPs) and industrial discharges that are under Washington State jurisdiction, as well as WWTPs under U.S. federal government and Canadian jurisdiction. The original marine point source flow and water quality time series described in Mohamedali at al. (2011a) were developed for the years 1999 through 2008. These time series were created using a multiple linear regression approach analogous to that used for the watershed inflows, thus creating a continuous time series for each year of input for the SSM using mostly monthly water quality data. We have now extended these time series to more recent years, through June 2017. The updated time series also include new WWTPs that have come online since 2008. Data for this recent time period were obtained from a combination of sources. Quality control procedures, data quality, and representativeness objectives are found in the Quality Assurance Project Plan or quality assurance/quality control document of each organization from which we used data, as cited in McCarthy et al. (2018).

Data for marine point sources under Washington State jurisdiction were obtained primarily from Ecology's Water Quality Permitting and Reporting Information System (PARIS), which houses monthly discharge monitoring reports for all point sources under the National Pollutant Discharge Elimination System (NPDES) program. Data for WWTPs under federal jurisdiction were obtained through the EPA Region 10 NPDES Program (R. Grandinetti, EPA Region 10, pers. comm., 2018).

Annual reports for all WWTPs in Canada for the period 1999 to 2016 were obtained from Capitol Regional District (2018) and Metro Vancouver (2018). Raw data for the WWTPs were also obtained for 2017 to complete the long-term database.

Marine point sources were reviewed for any process or outfall location changes. If there was a change in the treatment process, a new regression was developed and applied to the time period following the treatment change. Previous regressions were used where no new data were available. New regressions were also developed if a particular facility started monitoring for parameter(s) not previously monitored. Any changes in outfall locations were noted and a new model grid node closest to the new outfall was selected. Also, treatment plant shutdowns and new sources coming online were noted.

Summary of Nutrient Influx

Oceanic

Mackas and Harrison (1997) estimated the ocean input of nitrogen to Puget Sound to be around 408,000 kg/day, or about 88% of the total nitrogen entering Puget Sound. This oceanic influx of nitrogen enters as the inflowing branch of the estuarine exchange flow. However, the rate of algal inorganic nitrogen consumption in the euphotic zone (between the surface and about 30 m depth) is much greater than the advective flux of inorganic nitrogen to the surface from the lower layers (Khangaonkar et al., 2018). So, a significant portion of the oceanic nitrogen input is not expected to penetrate the euphotic zone, but instead flows back out to the outer coast. Davis et al. (2014) estimated that about 98% of the water exiting the Strait of Juan the Fuca is of oceanic origin.

Understanding the impact of oceanic nitrogen within Puget Sound is further complicated by the large estimated percentage (60%–66%) of the water at Admiralty Inlet that is refluxed back into Puget Sound (Ebbesmeyer and Barnes, 1980; Khangaonkar et al., 2017). The magnitude of the average oceanic flux of nutrients at Admiralty Inlet does not fully characterize the dynamics of nutrient movements *within* the entire Puget Sound, as the relative contribution from terrestrial sources varies between basins, and it appears to be much higher in poorly flushed inlets. The model's hydrodynamic solution accounts for the spatial and temporal variations of this oceanic input as described in Khangaonkar et al. (2018).

Land-based inflows

Land-based or terrestrial inputs of nutrients include both marine point sources and watershed sources:

- Marine point sources include all facilities with outfalls in marine waters, such as WWTPs and industrial facilities.
- Watershed sources of nutrients enter the model domain at the point where rivers or streams meet the Salish Sea (i.e., at the mouth or downstream end of each river or stream). Rivers are pathways for both point and nonpoint sources upstream. The model includes loads from rivers, streams, and their watersheds, as well as flows from shoreline fringes. Watershed loads include base flow (which is predominantly fed by groundwater). Groundwater contributions are discussed in Mohamedali et al. (2011a, 2011b).

On an annual basis, rivers account for approximately 45% and 95% of the incoming terrestrial organic nitrogen and carbon load, respectively. Figure 6 shows the seasonal variation of the dissolved inorganic nitrogen (DIN) and dissolved organic carbon (DOC) loadings from point sources and rivers into Puget Sound. While rivers dominate the seasonal DOC loads, marine point sources are the dominant land-based DIN source during the summer. Figure 7 shows the breakdown of terrestrial loads of DIN, total organic nitrogen (TON), and total organic carbon (TOC) flowing into different Puget Sound basins. Appendix A9 contains tables with annual average DIN load for 2006, 2008, and 2014. The largest proportion of nitrogen inflows are discharged into the Main Basin, whereas the largest proportion of carbon is discharged into Whidbey Basin.

Other sources

The biochemical processes occurring in the sediments constitute a significant source of DIN to the water column. Sinking particles remove organic nitrogen from the water column. As accumulated organic matter in the sediment is remineralized, decomposition of proteins in organic detritus produces a flux of DIN (primarily in the form of ammonium) to the bottom layer of the water column. A relatively small portion of DIN (as nitrate) is removed from the water column at the water–sediment boundary, but a much larger fraction of DIN returns to the water column from the sediments in the form of ammonium ions. Appendix C contains a map of the modeled ammonium sediment flux delivered to the water column for 2006, 2008, and 2014.

Direct atmospheric deposition into the Salish Sea is estimated to be a minor contributor of nitrogen to the system, at a flux of approximately 1 kg/ha/yr (based on AIRPACT, a regional atmospheric modeling system). This estimate does not include the atmospheric deposition into watersheds, which is already indirectly accounted for in the inflows from rivers. Appendix C contains further information about atmospheric deposition estimates.

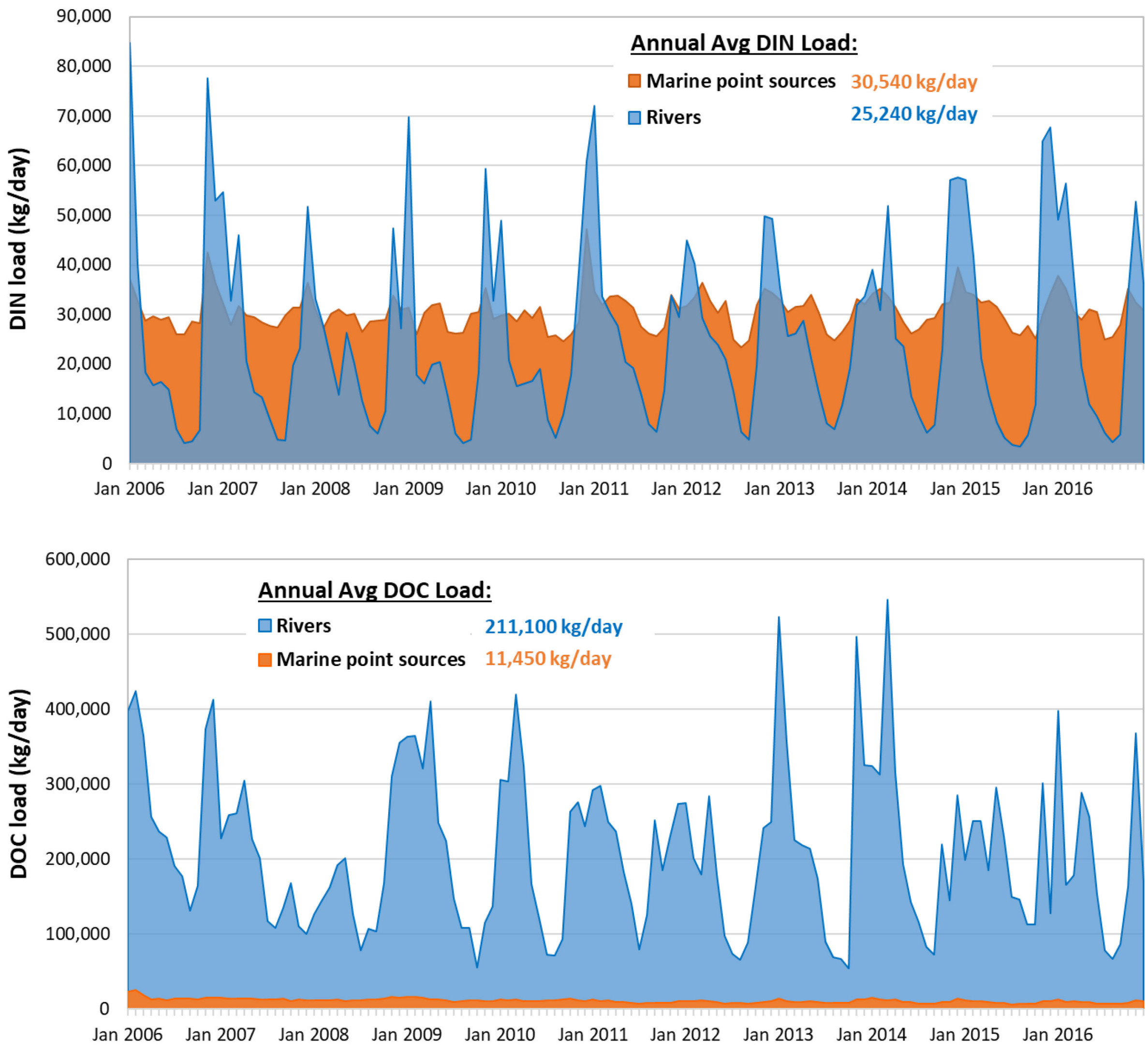


Figure 6. Dissolved inorganic nitrogen (DIN, above) and dissolved organic carbon (DOC, below) loading estimates for Puget Sound land-based sources.

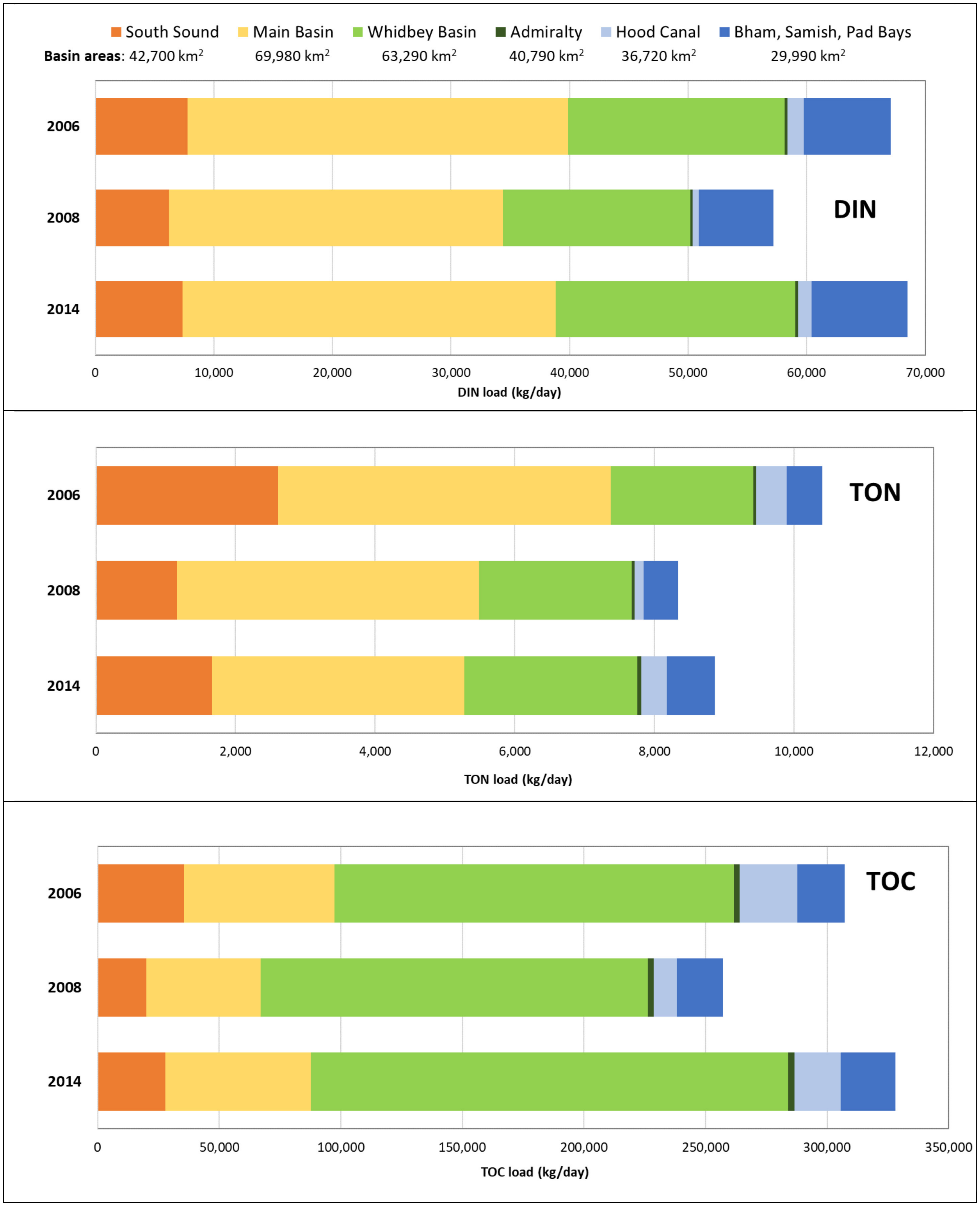


Figure 7. Comparison of dissolved inorganic nitrogen (DIN, above), total organic nitrogen (TON, center), and total organic carbon (TOC, below) loading into different regions of Puget Sound from terrestrial sources (rivers + point sources discharging into marine waters) under 2006, 2008, and 2014 existing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

Figure 8 shows the estimated relative contributions of the non-oceanic DIN loads into Puget Sound.[4] Table 2 shows the average estimated daily loads from non-oceanic sources. It is important to note that each of these loads enters the system at different points in space and time. Therefore, the impact that each load has on localized biogeochemical processes is markedly different, non-linear, and cannot be gauged by this overall comparison. Rather, it is through the model computations at each time step, grid node, and vertical layer that we understand the complex interrelationship of these loadings.

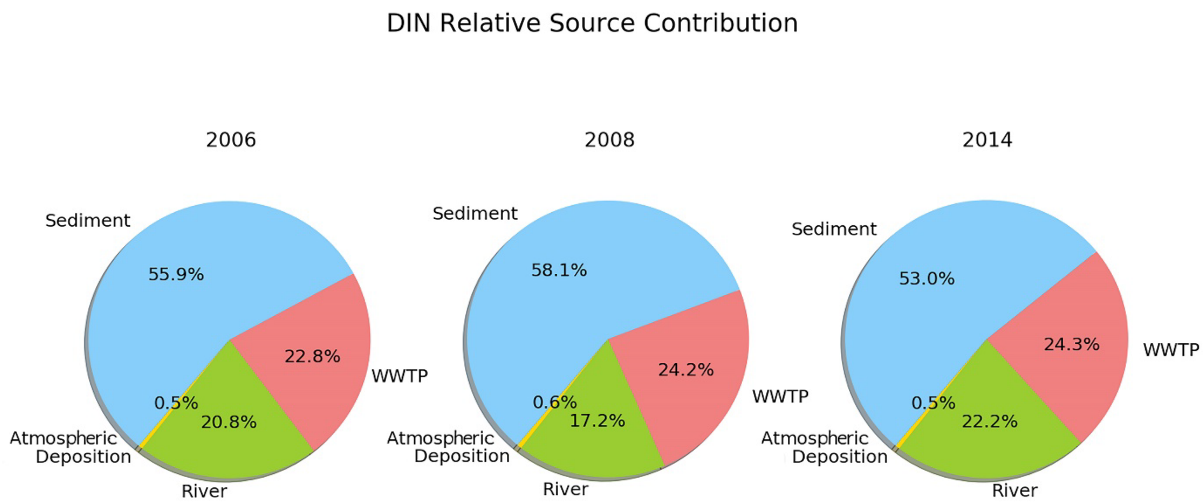


Figure 8. Relative contributions of dissolved inorganic nitrogen (DIN) to Puget Sound from rivers, marine point sources (WWTPs), sediment, and direct atmospheric deposition to marine waters.

Table 2. Average annual non-oceanic inorganic nitrogen loads (kg/day) entering Puget Sound's water column.

Source	2006 (kg/day)	2008 (kg/day)	2014 (kg/day)
Sediment	77,000	72,000	70,000
Direct atmospheric deposition to marine waters	700	700	700
Rivers	28,500	21,100	29,000
Marine point sources (wastewater treatment plants)	31,200	30,000	32,000

[4] Puget Sound refers to only South Sound, Main Basin, Whidbey Basin, Admiralty Inlet, and Hood Canal.

Water Quality Observations Database

Marine water quality monitoring data were obtained from Ecology's Marine Monitoring Unit, King County, NOAA, and the University of Washington (UW). Figure 9 shows the locations of these stations. These data were primarily used to check the calibration (i.e., to compare simulated values with observed data for the years 2006, 2008, and 2014). Appendix D contains details on how the observed database was developed. Since the model grid has ten layers and CTD (conductivity, temperature, and depth instrument) casts result in more than one data point corresponding to each layer, error statistics were based on comparing model-predicted concentration to individual observed data in a given layer for a particular time window.

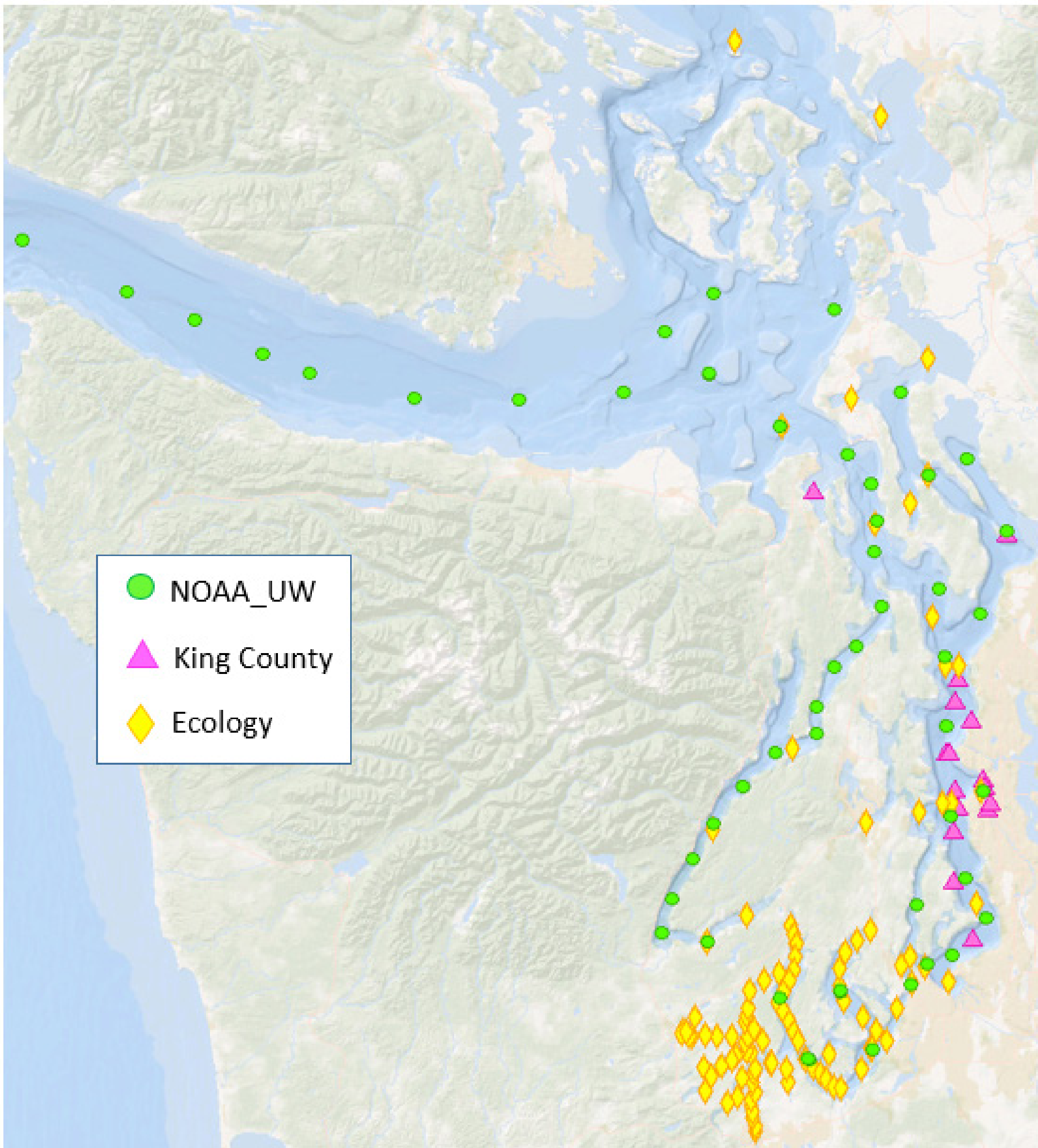


Figure 9. Locations of marine monitoring stations used for water quality calibration checks.

After checking data qualifiers, we discarded data that did not meet quality objectives. In the case of moorings or buoy data, if quality control procedures were not complete (as is often the case with this type of data), we used them only in a qualitative sense to examine overall patterns and trends.

Model Parameters

The SSM contains model parameters, including rates and constants, used to govern hydrodynamic and biogeochemical processes. The majority of parameter values for the SSM are commonly accepted to be the same constant values across a large number of studies (e.g., Martin and Wool, 2013; Di Toro, 2001; and Testa et al., 2013).

We reviewed two model calibration sets for DO and pH: Khangaonkar et al. (2018) and Bianucci et al. (2018). Khangaonkar et al. (2018) improved the DO calibration compared to that of Bianucci et al. (2018). However, as noted by Khangaonkar et al. (2018), further improvement to pH calibration was necessary. In the current project, year 2008 was selected to see if pH calibration could be improved while maintaining the DO calibration. We started with the rates and constants used in Khangaonkar et al. (2018), along with the updates in watershed and marine point source inputs as discussed in this report, and performed a calibration check. Alternative rates and constants were explored through sensitivity analyses and are further discussed in Appendix E, but the final set of parameters used for the bounding scenarios remained consistent with those published in Khangaonkar et al. (2018).

The SSM is continually undergoing evaluation and refinement, and there may be future refinements that improve performance. At this time, the SSM is at a state of maturity where we believe that differences in estimated impacts due to model refinements will be small moving forward.

Model Calibration Check

Model calibration was checked to confirm adequacy of model performance for two reasons: (1) modifications were made to watershed inflows, as well as other changes as described earlier, and (2) Khangaonkar et al. (2018) used the year 2014 for calibration, rather than 2006 and 2008, which are additional years included in this report.

The hydrodynamic calibration check included a comparison of model predictions to observed data at NOAA stations for water surface elevations. Model-predicted currents were compared with observed Acoustic Doppler Current Profiler (ADCP) data for the year 2006 at Pickering and Dana Passages in South Puget Sound. Figure 10 illustrates the locations of both NOAA and ADCP stations.

Temperature, salinity, and other water quality variables predicted by the model were also compared with observed data at marine stations discussed above and shown in Figure 9. Both time series plots as well as scatter plots were used to establish model skill. Model skill statistics were compared with values presented by Khangaonkar et al. (2018) for year 2014 and with those presented for year 2008 by Bianucci et al. (2018). In addition, predicted primary production and sediment oxygen demand (SOD) were compared with observed data, where available.

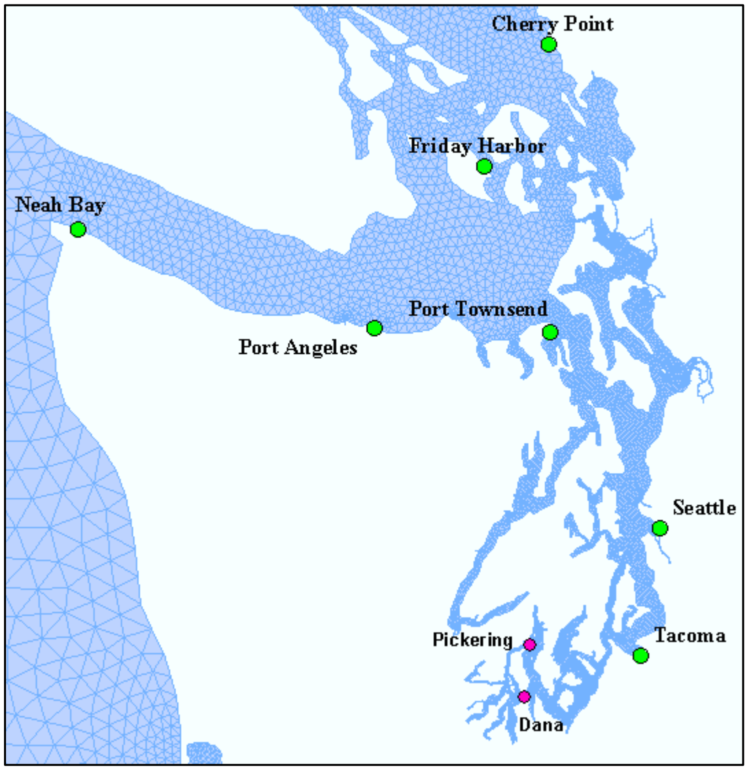


Figure 10. National Oceanic and Atmospheric Administration (NOAA) stations (green dots), where model-predicted water surface elevations were compared with observed data, and Acoustic Doppler Current Profiler (ADCP) stations (red dots), where model-predicted currents were compared with observed data.

Sensitivity runs

Sensitivity runs involved varying key water quality parameters and rates to understand their impact on model predictions, with the goal of optimizing model performance. A different set of rates and constants was evaluated that resulted in similar performance. Output from an alternative parametrization was used to compare the root mean square error (RMSE) of DO depletions between existing and reference conditions with output from the optimized and selected parametrization from Khangaonkar et al. (2018).

Reference Conditions

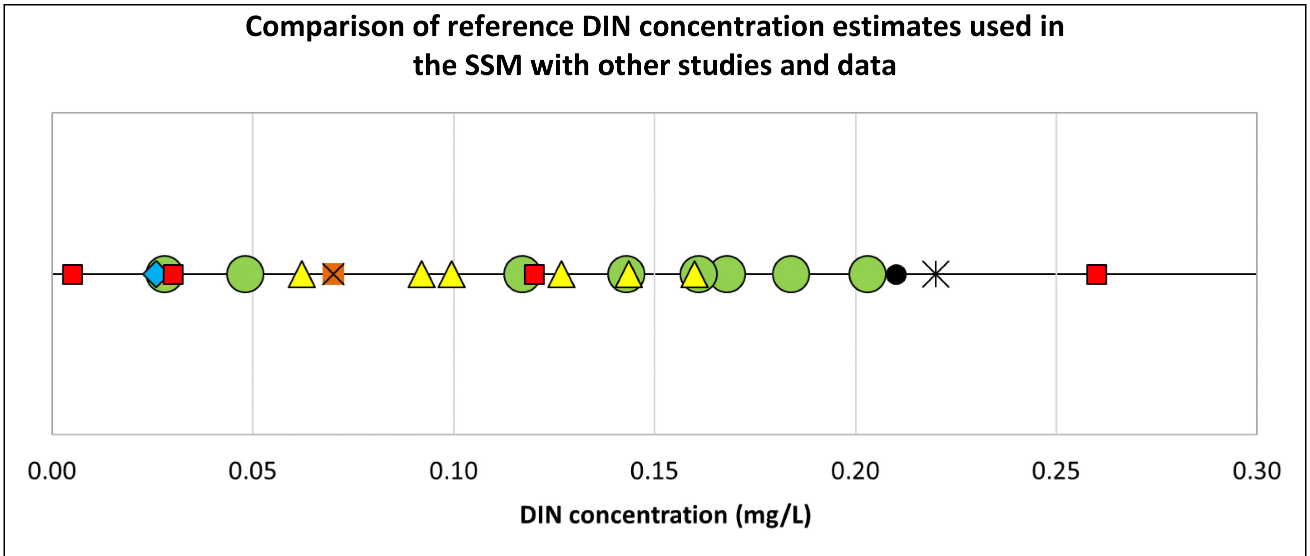
In order to isolate the effect of human sources on marine water quality, we compared the model year existing (hindcast) conditions to a reference condition for the same model year. We created the reference condition scenario by setting watershed inputs and marine source inputs to an estimated natural load of nitrogen and carbon while keeping the model year climate, hydrology, and ocean boundary conditions the same as the existing conditions scenario. The reference condition is our best estimate of natural conditions and is specific to each model year. Reference conditions were used to calculate DO depletion due to human influence, and they were derived by excluding estimated anthropogenic inputs of nutrients from contemporary loadings used in hindcast model runs.

A key aspect of the reference conditions used in this report is that all of Washington's WWTP effluent and river concentrations are set to reference river concentrations. However, there is no change in ocean boundary conditions, Canadian point sources, or Canadian river inputs in the reference condition scenario. Thus, in the reference condition, significant loadings from external sources such as the Fraser River (which is the largest freshwater flow into the Salish Sea) and from the Pacific Ocean remain unchanged. As a result, differences between the existing model year condition and its reference condition reflect changes due only to estimated anthropogenic nutrient inputs in the Washington portion of the Salish Sea.

Methods used to calculate reference conditions using the SSM are described in previous reports (Mohamedali et al., 2011a, 2011b; Pelletier et al., 2017b). Monthly reference condition loads for rivers were estimated by taking the 10th percentile of measured monthly nutrient concentrations at monitored locations, and in some cases, using atmospheric concentrations during the wetter months (if these were lower). The 50th percentile was used for rivers in the Olympic Peninsula that do not have significant human nutrient sources in their watersheds. This approach follows one of the three options in EPA's nutrient criteria guidance manual (EPA, 2000). For the SSM, reference concentration estimates vary seasonally by month, and regionally to account for spatial variation. The reason we aggregated reference concentrations regionally was to have a larger dataset from which to calculate the 10th percentiles. Also, there are a lot of smaller rivers and streams that are unmonitored, so having a regional approach enabled the establishment of reference conditions for unmonitored freshwater inputs that enter the SSM. This regional approach has the following limitations:

- Reference condition estimates still contain an anthropogenic signal because they are based on contemporary data, and watersheds with more development have higher reference concentrations. Also, atmospheric data used to develop the reference condition include the influence of anthropogenic regional and global nitrogen emissions.
- The regional aggregation of rivers averages natural spatial differences between rivers grouped in the same region. For example, Skagit River's reference concentrations are likely overestimated, since the 10th percentile reference concentrations for other rivers entering the Whidbey Basin region turn out to be close in value to current Skagit River concentrations.

Because of these limitations and uncertainties around what the "true" natural or reference conditions are, we performed a meta-analysis to corroborate and compare our reference condition estimates with other studies and data. This comparison is presented in Figure 11 and illustrates that our estimates are within the same range as other estimates developed using different methods and analyses.



● 1. Our estimates (Mohamedali et al., 2011; Pelletier et al., 2017b)	Reference DIN concentration estimates used in the SSM. Each green circle represents the annual average DIN concentrations for rivers and streams entering the following regions in Puget Sound (from left to right on the plot: Strait of Juan de Fuca, Hood Canal, Whidbey Basin, Commencement Bay, Puget Main, South Puget Sound, Strait of Georgia, and Elliott Bay).
⚹ 2. Toxics study -forested basins (Herrera Environmental Consultants, 2011)	DIN concentrations in surface runoff (base flow and stormwater events) measured as part of the Puget Sound Toxics Loading study. The value here is the median of data collected from predominantly forested subbasins in the Puyallup and Snohomish watersheds.
☒ 3. Hood -forested basins (Steinberg et al., 2010)	The Hood Canal Dissolved Oxygen Program estimated natural background concentrations for streams entering Hood Canal based on the annual average DIN concentrations for the least impacted rivers in the Olympic Peninsula.
● 4. USGS background (Smith et al., 2003)	The estimate on the plot is the 75th percentile of background concentrations predicted from an empirical model developed by the USGS. This particular estimate is for the "Western Forested Mountains," which includes the Puget Sound area.
◆ 5. EMAP Cascades Data available at: www.epa.gov/emap	EPA's Environmental Monitoring & Assessment Program (EMAP) data are available online. This estimate is the 50th percentile of DIN data measured in streams in the Cascades region for the period 1999 to 2000.
△ 6. Upstream data	Annual means of monthly 10th percentiles of ambient data (WY 2002–2009) collected at Ecology's long-term ambient monitoring stations located in the upper reaches of Puget Sound watershed (from left to right on the plot: Skagit, Green, Stillaguamish, Nooksack, Cedar, and Snoqualmie).
■ 7. EPA ecoregional criteria (EPA, 2001, Appendix B)	EPA developed nutrient criteria based on various data sources collected between 1990 and 1999. The red squares represent the 25th percentile of the criteria for each ecoregion (from left to right on the plot: Cascades, N. Cascades, and Puget Lowlands).

Figure 11. Reference dissolved inorganic nitrogen (DIN) concentration estimates used in the Salish Sea Model compared with other studies and data.

We also reviewed our original reference condition methodology described in Mohamedali et al. (2011a, 2011b) based on EPA's nutrient criteria guidance manual (EPA, 2000). First, we expanded the current data set used to estimate reference condition percentiles (2001–2009) to include newer ambient water quality data (2010–2015). The expanded data set resulted in similar reference condition estimates, and in most regions, the current reference concentration estimates were lower. We also compared our reference conditions using data from reference streams, which are sampling sites located in areas of minimal human impact (EPA, 2000; Von Prause, 2014). Data from reference sites are spatially and temporally limited. Thus, while this approach helped to provide a comparison for select rivers, our current approach uses more data available at a higher spatial and temporal resolution throughout all regions. This review supports our continued use of the current methods for estimating reference conditions. However, we plan to continue to review our methodology as new data become available.

Another limitation of the current reference condition is a consequence of sparse organic carbon observations. This results in the use of regressions primarily based on data sets collected in smaller rivers and streams in South Puget Sound from 2006 to 2007. To remedy this data paucity, Ecology began monitoring organic carbon at freshwater monitoring stations in October 2017. We also have compiled recent USGS data, and we are pursuing other event-based measurements that could be conducted if funding becomes available. These data sets will improve our freshwater organic carbon loadings estimates, and they will also expand the data set from which improved reference condition estimates can be derived.

Bounding Scenarios

Among other benefits, Ecology's Puget Sound Nutrient Source Reduction Project (PSNSRP) aims to achieve DO and carbonate system improvements from optimum reductions in anthropogenic nutrient and carbon loads in marine point source and watershed discharges. The bounding scenarios represent the range of the response of water quality in Puget Sound to major hypothetical loading changes focused on reductions to marine point source inputs from municipal WWTPs.

To choose model years that represent the range of interannual variability, we considered the residence time index for Central Puget Sound as presented in the Puget Sound Ecosystem Monitoring Program report for the year 2015 (PSEMP, 2016) and reproduced in Figure 12. The residence time index was estimated by a Knudsen relationship using river flow and observational marine data for the upper 30 meters (Albertson et al., 2016; Knudsen, 1900). Residence time is displayed as an index relative to a 16-year baseline (the dotted line in Figure 12). The residence time index for 2014 appears to be at the baseline, while 2008 is slightly higher and 2006 is much higher than the baseline value. Years with a positive index reflect higher residence times than the baseline.

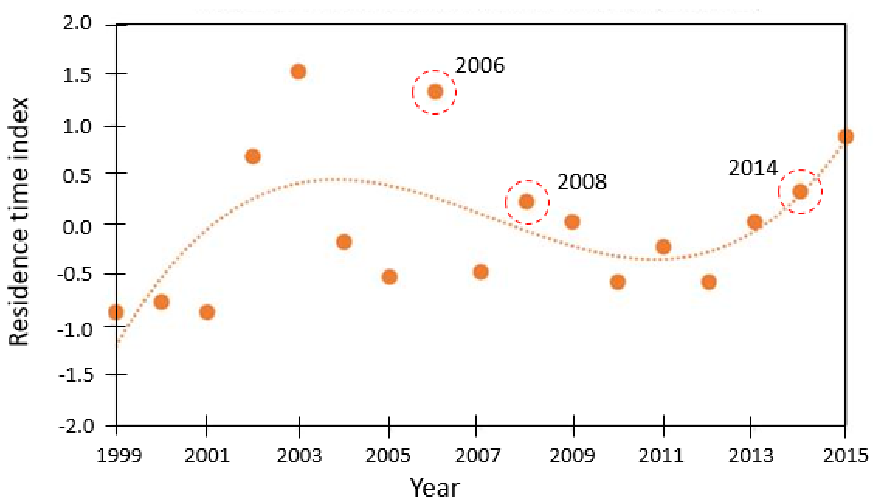


Figure 12. Index of residence time relative to normal in the top 0–30 m in Central Puget Sound, 1999–2015 (PSEMP, 2016).

The residence time index reflects different hydrodynamic characteristics in each of these years. These characteristics are also reflected in the differences in annual average flows, as shown in Table 3.

Table 3. Annual average flows (m^3/s).

River	2006	2008	2014
Fraser	2364	2750	3185
Skagit	548	515	669
Stillaguamish	135	122	149
Nisqually	62	59	61
Skokomish	57	30	39

A virtual dye study was conducted previously, using the PSM model for the years 2006, 2008, and 2014. An initial dye concentration was input to the model at the start of the model run. The dye concentration at each model grid cell was tracked with time. The time it took for the concentration to reach 37% of the initial concentration (also known as *e-folding time*) was noted for each grid cell.

These e-folding times are relative to the open boundary at the mouths of the Straits of Juan de Fuca and Georgia. E-folding times are plotted in Figure 13 for 2006, 2008, and 2014. The e-folding times (considered as indicative of residence times) varied between the years. For example, e-folding times in Penn Cove (red circles in Figure 13) varied between approximately 270 days in 2006, 250 days in 2008, and 170 days in 2014.

Longer residence times promote stagnation and buildup of pollutant concentrations, increase primary productivity and depletion of nutrients, increase nitrification (oxidation of ammonia to nitrate, which depletes oxygen), increase settling of particulate organic matter (e.g., dead algae), and increase decomposition of organic carbon (which depletes oxygen). Higher residence times are indicative of where the potential hot spots are for biogeochemical stressors. Thus, consideration of interannual variability is important when evaluating anthropogenic nutrient reductions on DO concentrations.

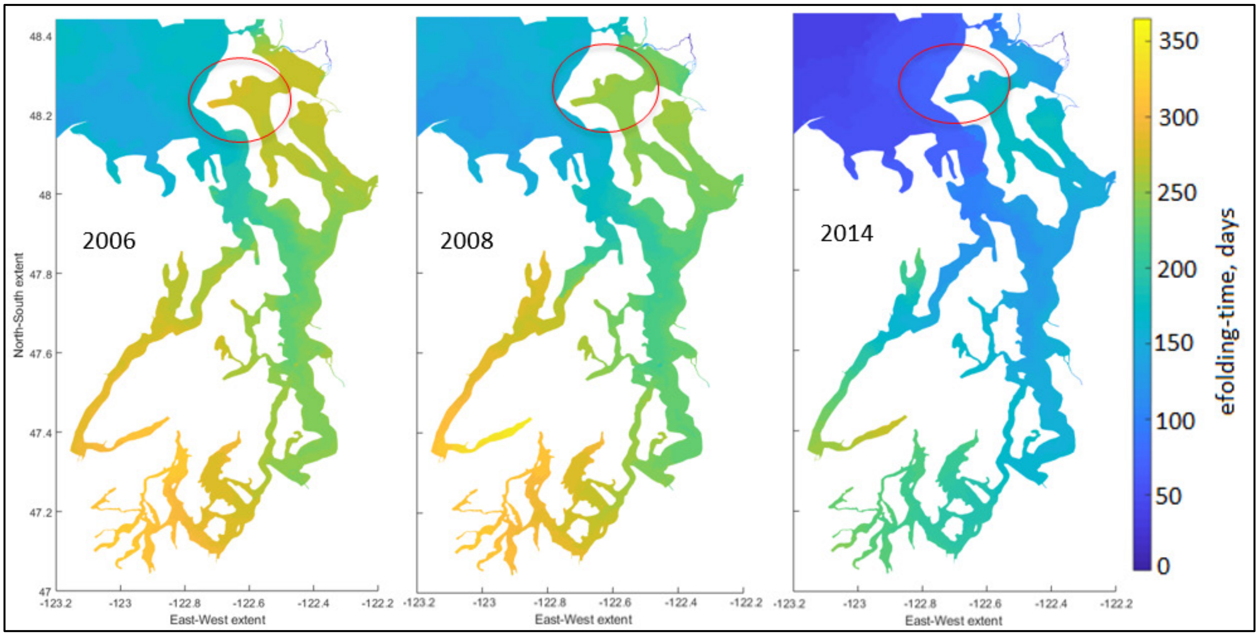


Figure 13. E-folding times (indicative of residence times) in Puget Sound for 2006, 2008, and 2014.

Hindcast model runs for the years 2006, 2008, and 2014 were conducted. Throughout this report, the term "existing condition" refers to the model output derived for each year from those hindcast runs. Table 4 shows the various bounding scenarios considered in this report. Seasonal biological nitrogen removal (BNR) indicated in the table refers to wastewater treatment technology that achieves dissolved inorganic nitrogen (DIN = NH^{4+} + NO^{3-}/NO^{2-}) and carbonaceous biological oxygen demand ($CBOD_5$) at levels equal to or less than 8 mg/L from April through October, per Tetra Tech (2011). The impact of each of the scenarios listed in Table 4 was obtained from computing the difference between each scenario and reference conditions.

Table 4. List of bounding scenarios.

Scenarios for 2006, 2008, and 2014	
1	Impact of all anthropogenic sources
2	Impact of marine point sources only (watershed sources set at reference conditions)
3	Improvement with BNR at all Washington municipal WWTPs discharging into Salish Sea waters
4	Improvement with BNR at Washington municipal WWTPs that discharge DIN >1000 kg/day into Salish Sea waters
5	Improvement with BNR at Washington municipal WWTPs that discharge DIN >8000 kg/day into Salish Sea waters

BNR: Biological nitrogen removal

Marine point sources with DIN loads greater than 1000 kg/day include the municipal WWTPs Chambers Creek, Tacoma Central, Brightwater, South King County, West Point, Everett outfall in the Snohomish River, Everett-Marysville combined outfall in Port Gardner, and Bellingham. Brightwater WWTP was not included in the 2006 or 2008 loading scenarios, because it came online in 2012. Brightwater WWTP is included in the 2014 runs. Marine point sources with DIN loads of 8000 kg/day or greater include the South King County and West Point municipal WWTPs.

Each scenario was compared to the reference condition. For instance, the impact of the total anthropogenic sources (item 1 in Table 4) during the years studied was assessed by subtracting the modeled reference condition from the existing condition for each years' result. Likewise, the impact of marine point sources (item 2 in Table 4) was assessed by comparing the effect of the discharges from all marine point sources alone to the effect of the reference loads. Note that this scenario involves the removal of the anthropogenic river loads.

Results and Discussion

Model Performance: Hydrodynamics

Hydrodynamic model evaluation included comparing model predictions with observed data for salinity, temperature, water surface elevations, tidal harmonics, and currents. Salinity and temperature statistics are presented under the section “Model Performance: Water Quality.”

Water surface elevations

Model-predicted water surface elevations were compared with those observed at seven National Oceanic and Atmospheric Administration (NOAA) stations. Relative error in water surface elevation predictions (as a percentage of the tidal range) were compared for 2006 and 2014 with those previously published by Khangaonkar et al. (2017 and 2018, respectively) and are presented in Table 5. The relative errors in predictions are comparable to the published values within Puget Sound, but they are slightly higher at Cherry Point and Friday Harbor. Khangaonkar et al. (2017) used a Salish Sea model expanded farther than the one we are employing in this report, with grids extending beyond the continental shelf. In addition, changes and updates to the model described in Khangaonkar et al. (2018) were made, as explained in this report.

Table 5. Relative error in predictions of water surface elevations (% of tidal range) at National Oceanic and Atmospheric Administration monitoring stations.

Station	2014	2008	2006	2006 Extended SSM, Khangaonkar et al. (2017)	2014 SSM, Khangaonkar et al. (2018)
Cherry Point	11.6	12.4	12.0	9.8	≤10
Friday Harbor	10.9	11.4	11.4	7.7	≤10
Port Angeles	6.8	7.5	7.3	7.7	≤10
Port Townsend	8.2	8.7	8.6	7.9	≤10
Seattle	8.0	8.5	8.5	8.6	≤10
Tacoma	8.6	8.8	8.9	8.7	≤10
Neah Bay	10.6	10.7	10.7	NA	NA

Appendix F includes scatter plots of water surface elevation for the seven NOAA stations, showing overall statistics for paired 2006, 2008, and 2014 predicted and observed data sets, as well as time series plots of water surface elevations for the last two weeks of May.

Figure 14 shows a typical scatter plot and time series plot at NOAA’s Seattle station. The model does well at predicting the different phases of the tidal cycle.

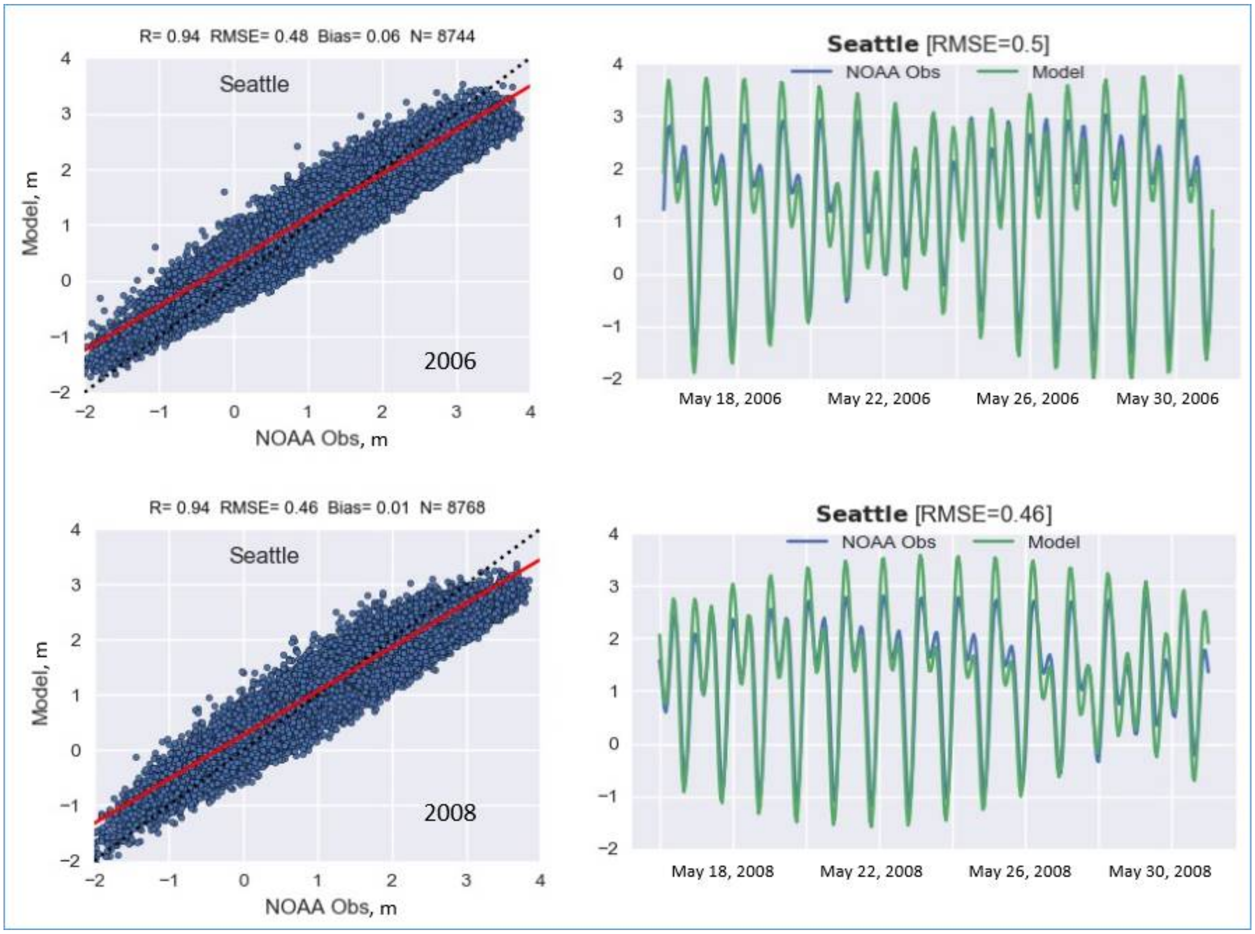


Figure 14. Model predictions and observed data for water surface elevations.
Left panel, typical scatter plots for 2006 (above) and 2008 (below). *Right panel*, time series for the month of May 2006 (above) and May 2008 (below).

Currents

Observed current data are available at two stations (Pickering and Dana Passages) for 2006 only. Table 6 shows the average root mean square error (RMSE) statistic at these stations. The RMSE compares well with those presented by Khangaonkar et al. (2011).

Table 6. Root mean square error (RMSE) (m/s) of predicted and observed currents for October 2006.

Source	**Location**	**Pickering Passage**	**Dana Passage**
Khangaonkar et al., 2011	Surface	0.20	0.34
	Bottom	0.12	0.28
Salish Sea Model predictions	Surface	0.11	0.21
	Bottom	0.06	0.20

Appendix F contains a detailed analysis of the eastward and northward current components for all layers, as well as depth-averaged currents at the Pickering and Dana Passages stations. Figure 15 shows the depth-averaged time series plot of predicted and observed eastward (U, cm/s) and northward (V, cm/s) currents at Dana and Pickering Passages.

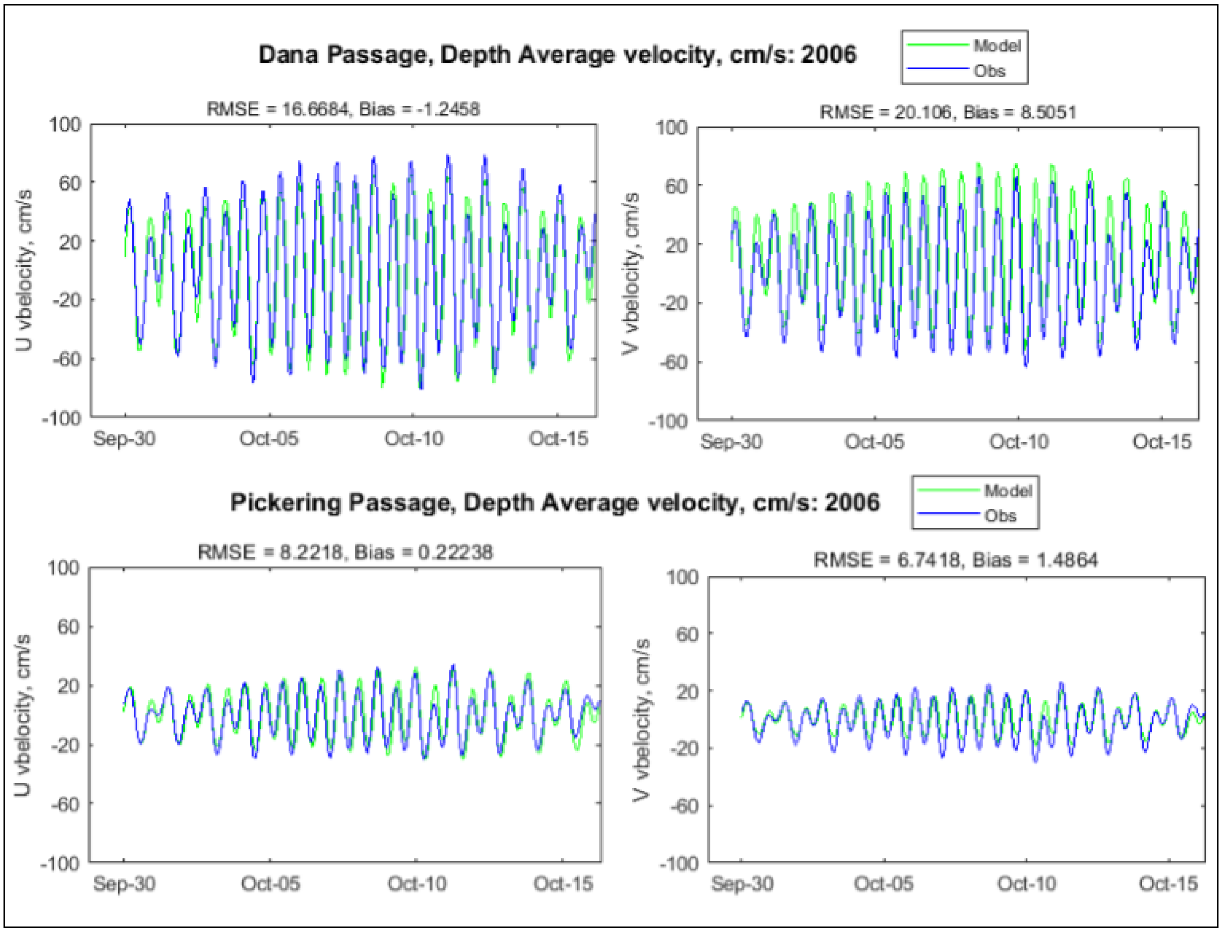


Figure 15. Eastward (left, U velocity) and northward (right, V velocity) depth-averaged current comparison between model prediction and observed data for Dana Passage (above) and Pickering Passage (below).

Model Performance: Water Quality

Model performance quality objectives described in McCarthy et al. (2018) were met. We used the root mean square error (RMSE), correlation coefficient (R), and bias as indicators of goodness of fit. These measures of goodness of fit to observed data reveal the model's overall high level of skill for predicting DO and its capability to accurately predict DO response to nutrient reduction scenarios. Model performance statistics, as shown below, are about the same or better than previous SSM studies. Additionally, the performance statistics presented here are similar to those reported for other biogeochemical modeling efforts focused on hypoxia (Cerco and Noel, 2013; Irby et al., 2016).

The overall statistics for 2008 and 2006 for the SSM are shown in Table 7 with a comparison of statistics for the intermediate-scale Puget Sound Model (PSM) as per Bianucci et al. (2018). Statistics for 2014 for the SSM are also included to compare with the statistics presented by Khangaonkar et al. (2018).

The current model setup improves the overall temperature and salinity predictions for 2006, 2008, and 2014. This is demonstrated by the relative increase in correlation coefficient (R), relative reduction in RMSE compared to those presented by Bianucci et al. (2018) for the intermediate-scale PSM for 2008, and compared to those presented by Khangaonkar et al. (2018) for the expanded SSM for 2014 (Table 7). With respect to DO predictions, RMSE values are much improved compared to those reported by Bianucci et al. (2018) and are similar to those reported by Khangaonkar et al. (2018).

Table 7 also shows that the statistics for pH have not generally improved compared to Bianucci et al. (2018). Improvement to the pH calibration for the SSM is underway at Pacific Northwest National Laboratory .

Appendix G presents model performance for overall water quality and for each station, for the years 2006, 2008, and 2014. Appendix G1 contains a map of all the station locations where model performance was evaluated for water quality. Appendix G2 contains an explanation of how to read time-depth plots. Appendices G3, G4, and G5 contain model performance plots for 2006, 2008, and 2014, respectively.

Table 7. Overall performance statistics for 2006, 2008, and 2014 for the updated SSM and two previous versions.
R = correlation coefficient; RMSE = root mean square error; n = number of observations.

Temperature (°C)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.90	1.48	1.28	67858
2008 SSM	0.95	0.56	-0.05	67857
2006 SSM	0.95	0.69	0.39	140080
2014 SSM	0.95	0.87	-0.41	89222
2014 SSM (Khangaonkar et al. 2018)	0.93	0.76	-0.28	38218

Salinity (psu)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.61	1.33	-0.68	66934
2008 SSM	0.76	0.81	0.03	66958
2006 SSM	0.84	0.77	-0.47	138845
2014 SSM	0.75	0.88	-0.37	89025
2014 SSM (Khangaonkar et al. 2018)	0.75	0.97	-0.12	38043

Dissolved oxygen (mg/L)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.80	1.8	-1.56	66538
2008 SSM	0.85	0.98	-0.53	66931
2006 SSM	0.80	1.09	-0.57	135115
2014 SSM	0.81	0.96	-0.34	87725
2014 SSM (Khangaonkar et al. 2018)	0.83	0.99	-0.24	26082

NO_3 (mg/L)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.80	0.08	-0.001	1902
2008 SSM	0.78	0.09	-0.04	1381
2006 SSM	0.81	0.07	-0.02	678
2014 SSM	0.84	0.07	0.00	1849
2014 SSM (Khangaonkar et al. 2018)	0.82	0.09	0.013	1187

Chlorophyll (µg/L)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.50	2.78	-0.3	66041
2008 SSM	0.49	3.10	0.33	66941
2006 SSM	0.52	4.48	0.19	112567
2014 SSM	0.52	3.48	-0.13	89338
2014 SSM (Khangaonkar et al. 2018)	0.54	4.37	0.83	26940

pH (total scale)				
model runs	R	RMSE	Bias	n
2008 PSM (Bianucci et al. 2018)	0.64	0.14	-0.07	584
2008 SSM	0.74	0.18	0.15	589
2006 SSM	NA	NA	NA	NA
2014 SSM	0.60	0.28	0.14	622

Time-depth plots

Figures 16, 17, and 18 show typical time-depth plots for temperature, salinity, and DO for observed and predicted data for year 2006 at selected stations in South Puget Sound (Ecology station D001 in Dana Passage), Central Puget Sound (King County Station KSBP01), Hood Canal (Ecology station HCB003), Admiralty Inlet (Ecology station ADM001), and Bellingham Bay (Ecology station BLL009). Specific error statistics for each station are included.

The background color in Figures 16–18 is indicative of the model prediction for each parameter at each station, while the circles indicate multiple observations at depth at the same location. The color within the circles has the same scale as that for model predictions (see Appendix G2 for an explanation on how to read the time-depth plots). Time-depth plots for all stations and for years 2006, 2008, and 2014 are presented in Appendix G3 through G5, respectively.

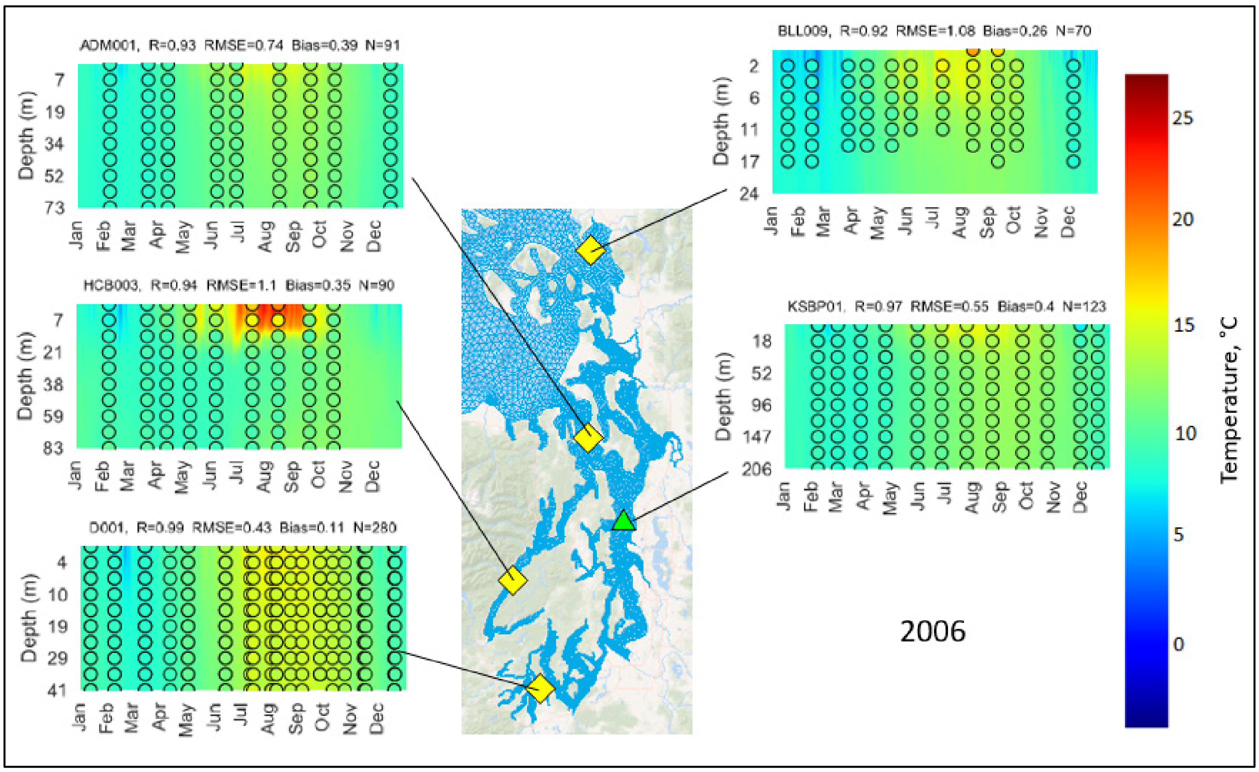


Figure 16. Time-depth plots of observed and predicted temperatures at selected stations for 2006. The colors inside the circles represent observed measurements taken at a particular depth and time, while the colors in the background represent model-simulated values.

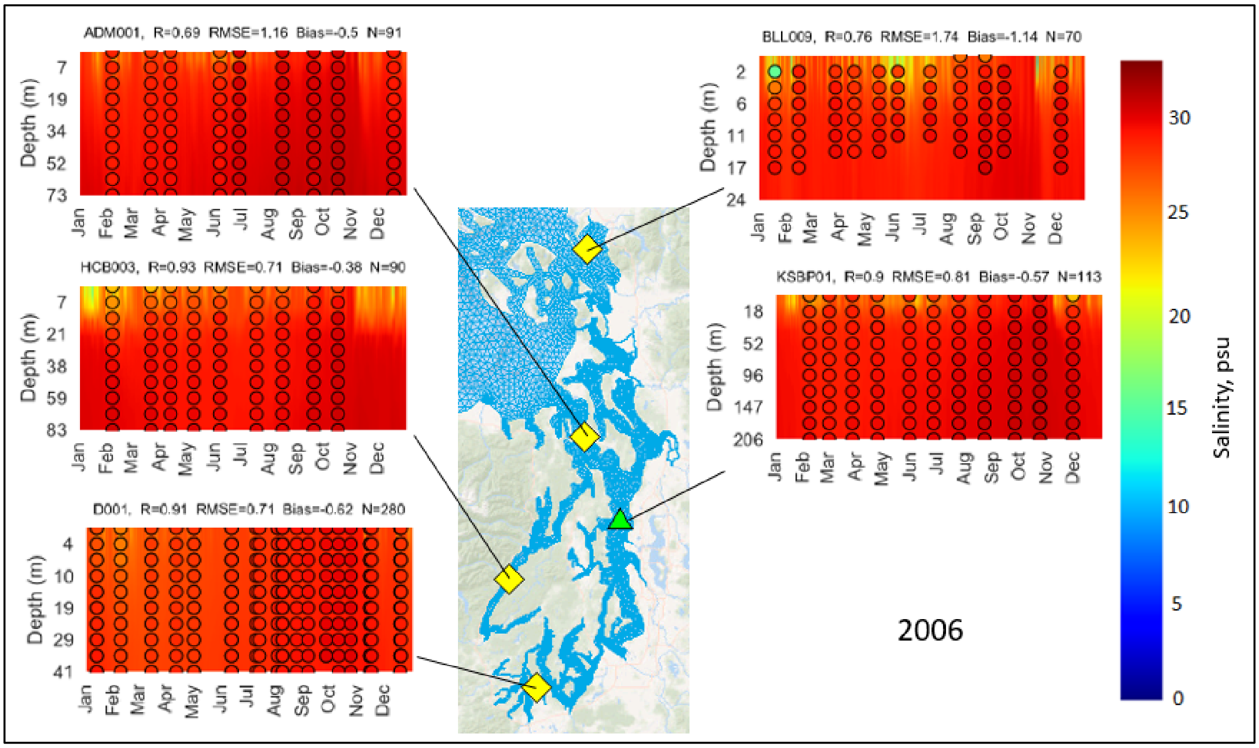


Figure 17. Time-depth plots of observed and predicted salinities at selected stations for 2006.

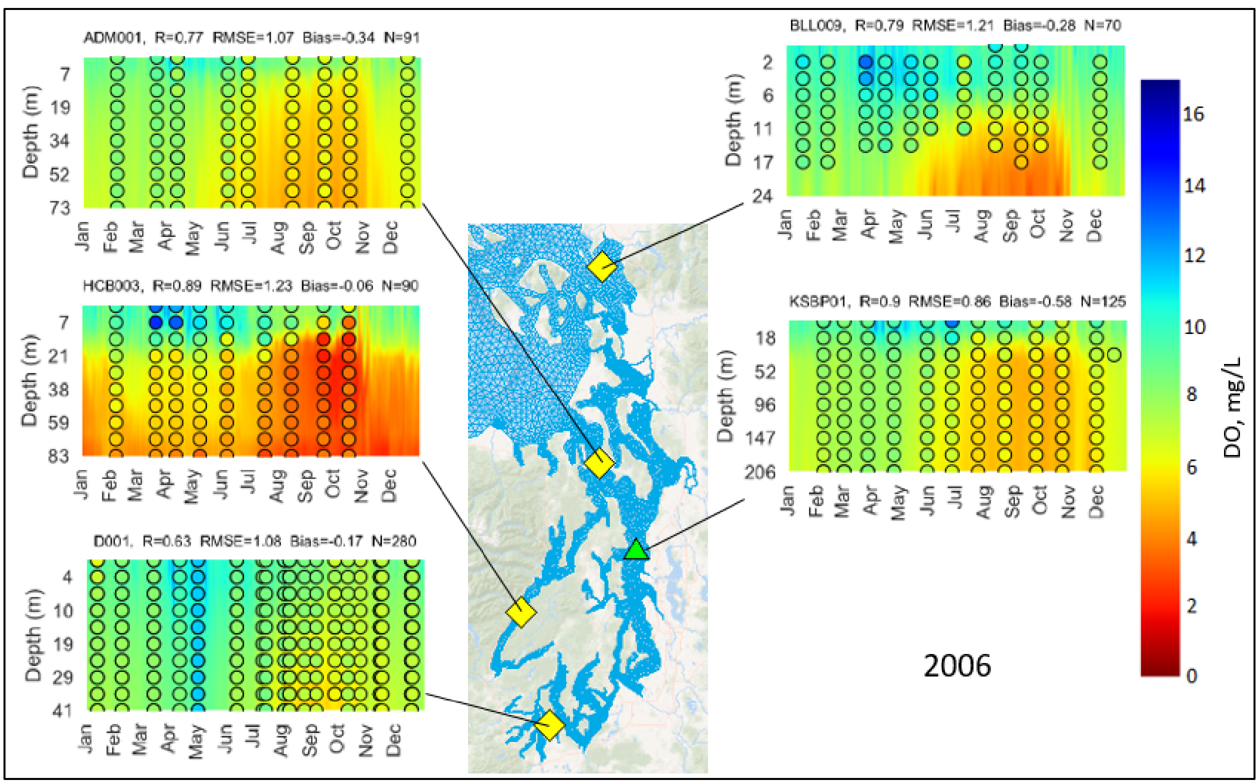


Figure 18. Time-depth plots of observed and predicted dissolved oxygen (DO) at selected stations for 2006.

Time series plots

Figures 19, 20, and 21 show the time series plots for temperature, salinity, and DO for observed and predicted data for 2006 at selected stations in South Puget Sound (Ecology station D001 in Dana Passage), Central Puget Sound (King County station KSBP01), Hood Canal (Ecology station HCB003), Admiralty Inlet (Ecology station ADM001), and Bellingham Bay (Ecology station BLL009) at the surface and bottom layers. Specific error statistics for each station are also included for the surface and bottom layers. Time series plots for all stations for 2006, 2008, and 2014 are presented in Appendices G3 through G5.

In general, model performance as measured by root mean square error (RMSE) is better for the bottom layer relative to the surface layer. Observed data at the Bellingham station for surface and bottom layers is scant, so error statistics for this station cannot be adequately estimated.

The model performs well in predicting the warming of the surface layer in Hood Canal, as seen in observed data. The distinct salinity difference between surface and bottom layer is also well predicted by the model at the Hood Canal Station. Observed data at other stations for surface and bottom layers show little stratification. The model also performs well in predicting the observed hypoxia in Hood Canal.

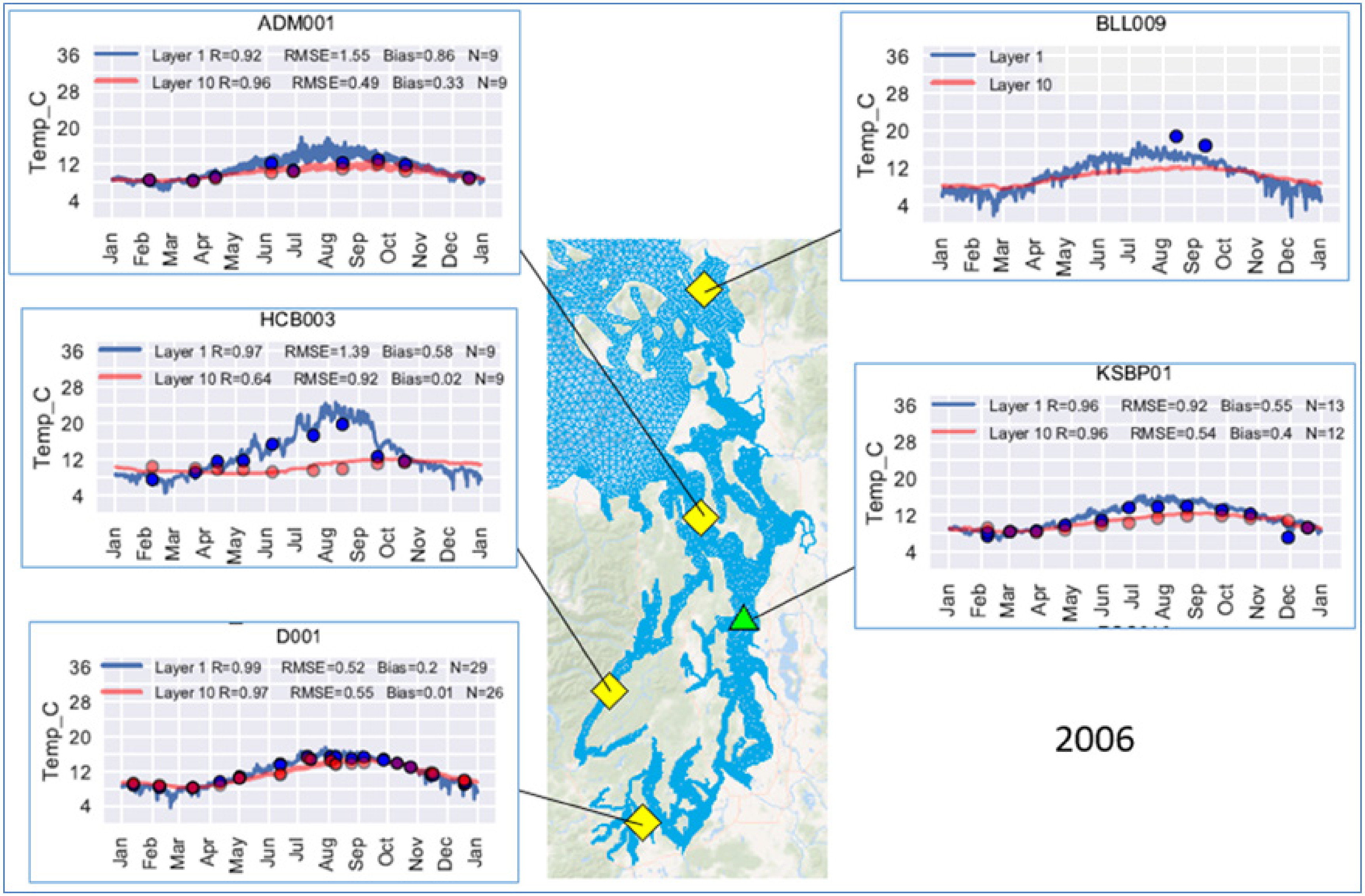


Figure 19. Time series plots for temperature (°C) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

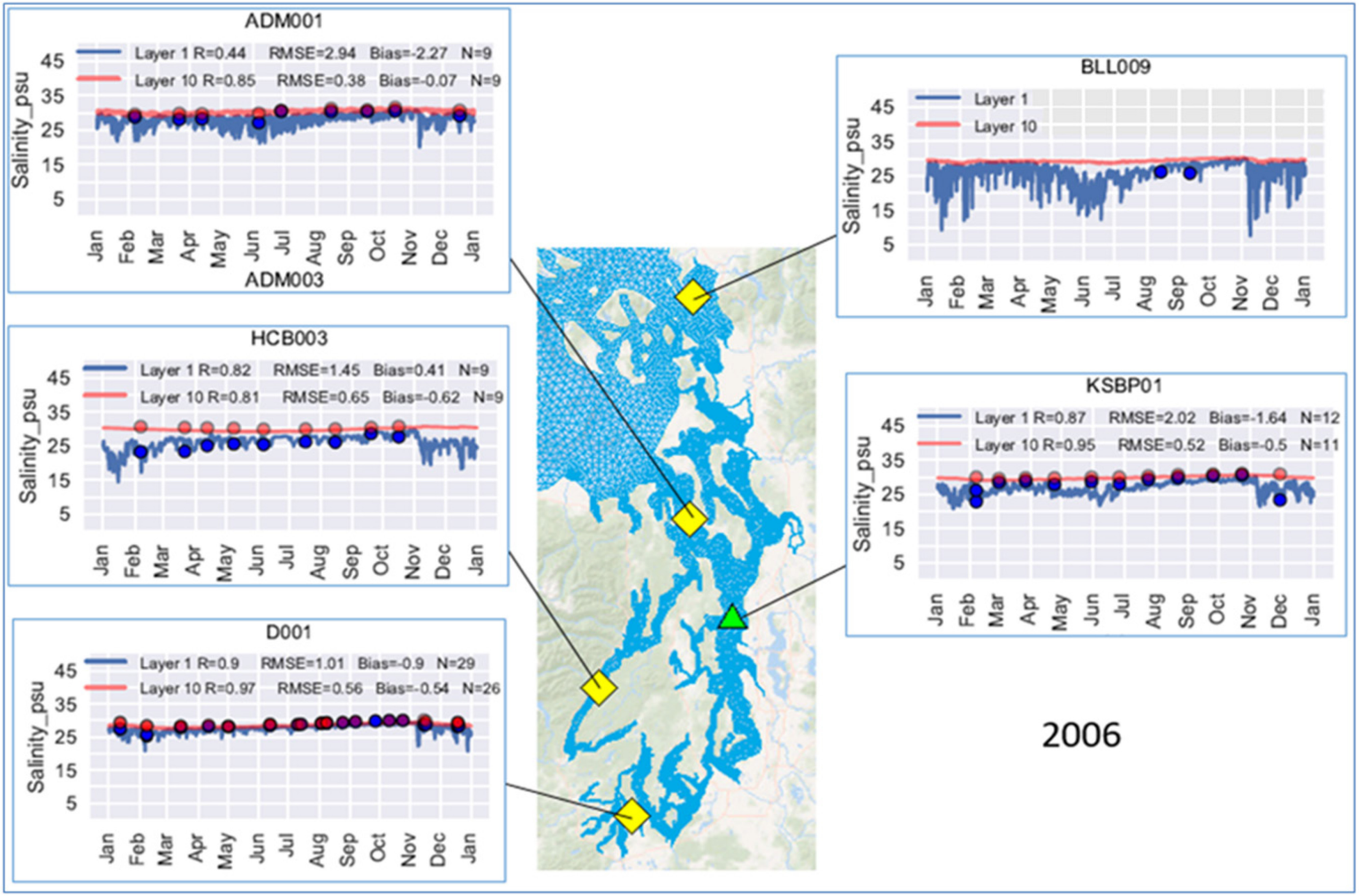


Figure 20. Time series plots for salinity (psu) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

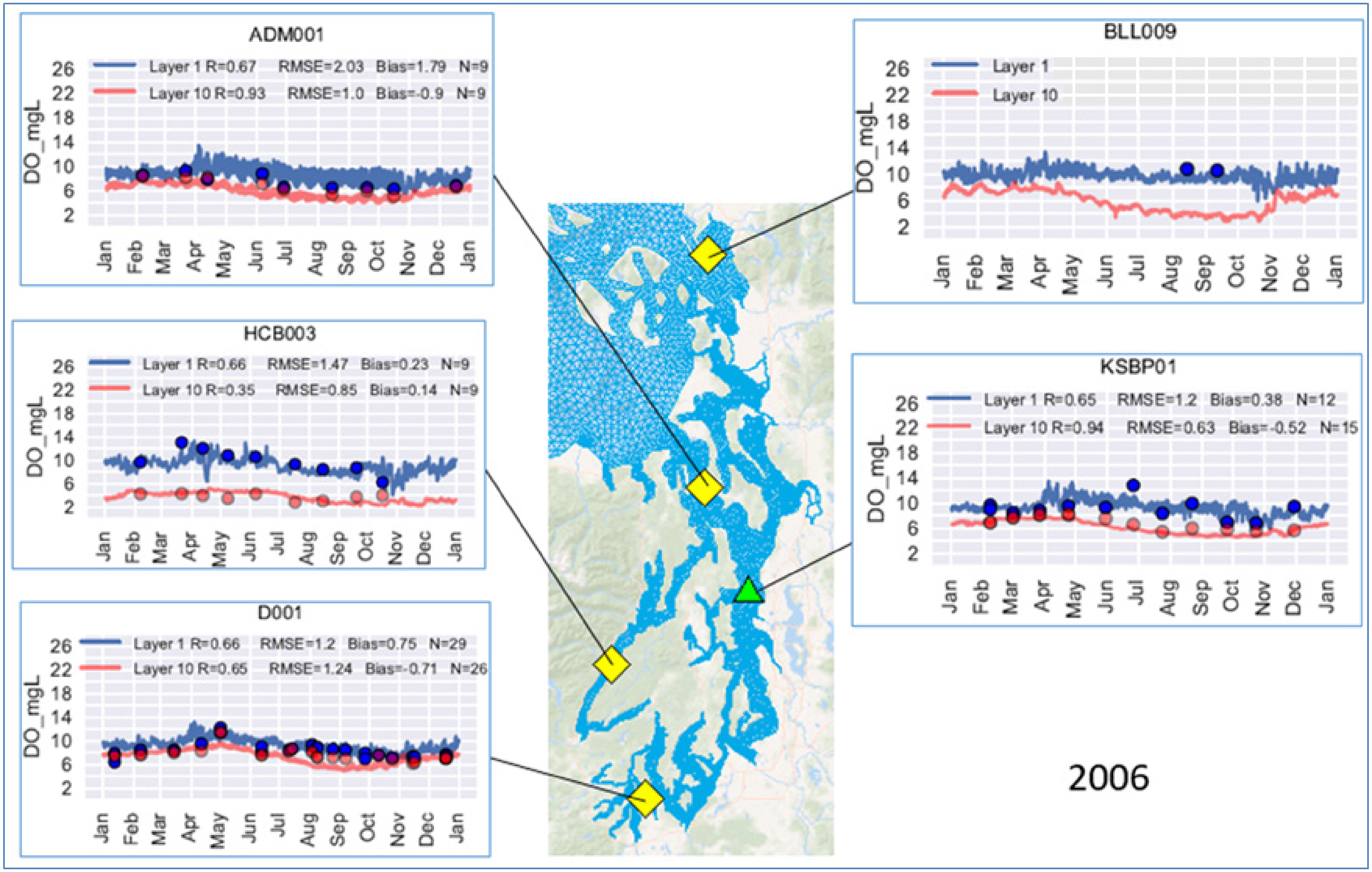


Figure 21. Time series plots for dissolved oxygen (DO, mg/L) at the surface (blue) and bottom (red) at selected stations for 2006. Circles show observations.

Profile plots

Figures 22, 23, and 24 show profile plots for temperature, salinity, and oxygen for observed and predicted data for 2006 at selected stations in South Puget Sound (Ecology station D001 in Dana Passage), Central Puget Sound (King County Station KSBP01), Hood Canal (Ecology station HCB003), Admiralty Inlet (Ecology station ADM003), and Bellingham Bay (Ecology station BLL009). Specific error statistics for each station are included for each of the profile plots. Profile plots for all stations and for 2006, 2008, and 2014 are presented in Appendices G3 through G5, respectively.

In addition to model performance in predicting observed data, the profile plots also show how well the model predicts the stratification in the water column. Figures 22, 23, and 24 reveal stations where thermal, salinity, and oxygen stratification is relatively more pronounced, such as Hood Canal. These figures also show that the model does a good job in simulating the stratification and the shallow thermocline, halocline, and oxycline, respectively.

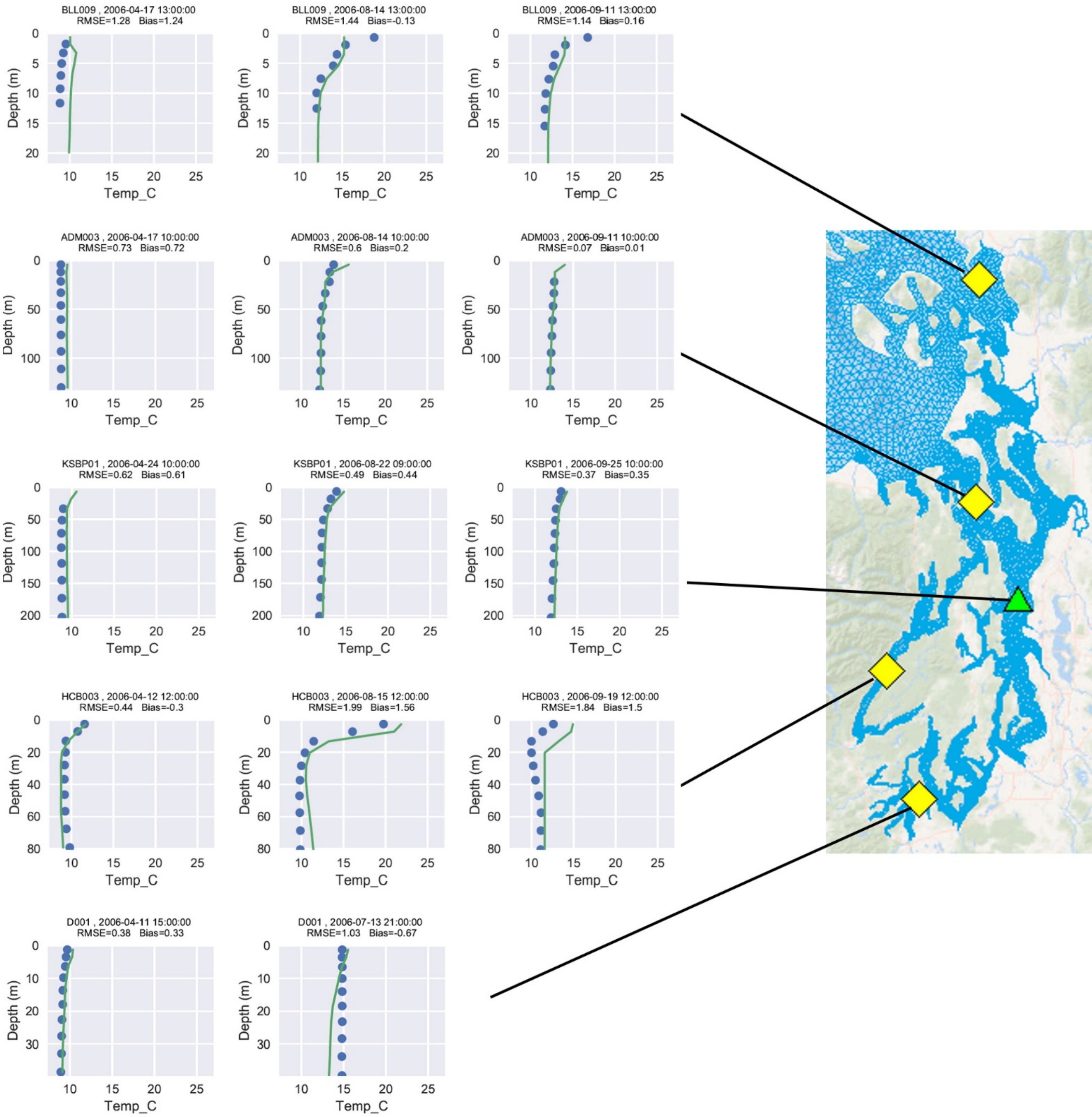


Figure 22. Year 2006 temperature profiles (°C) at selected stations for spring (left column), summer (center column), and fall (right column) conditions.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County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

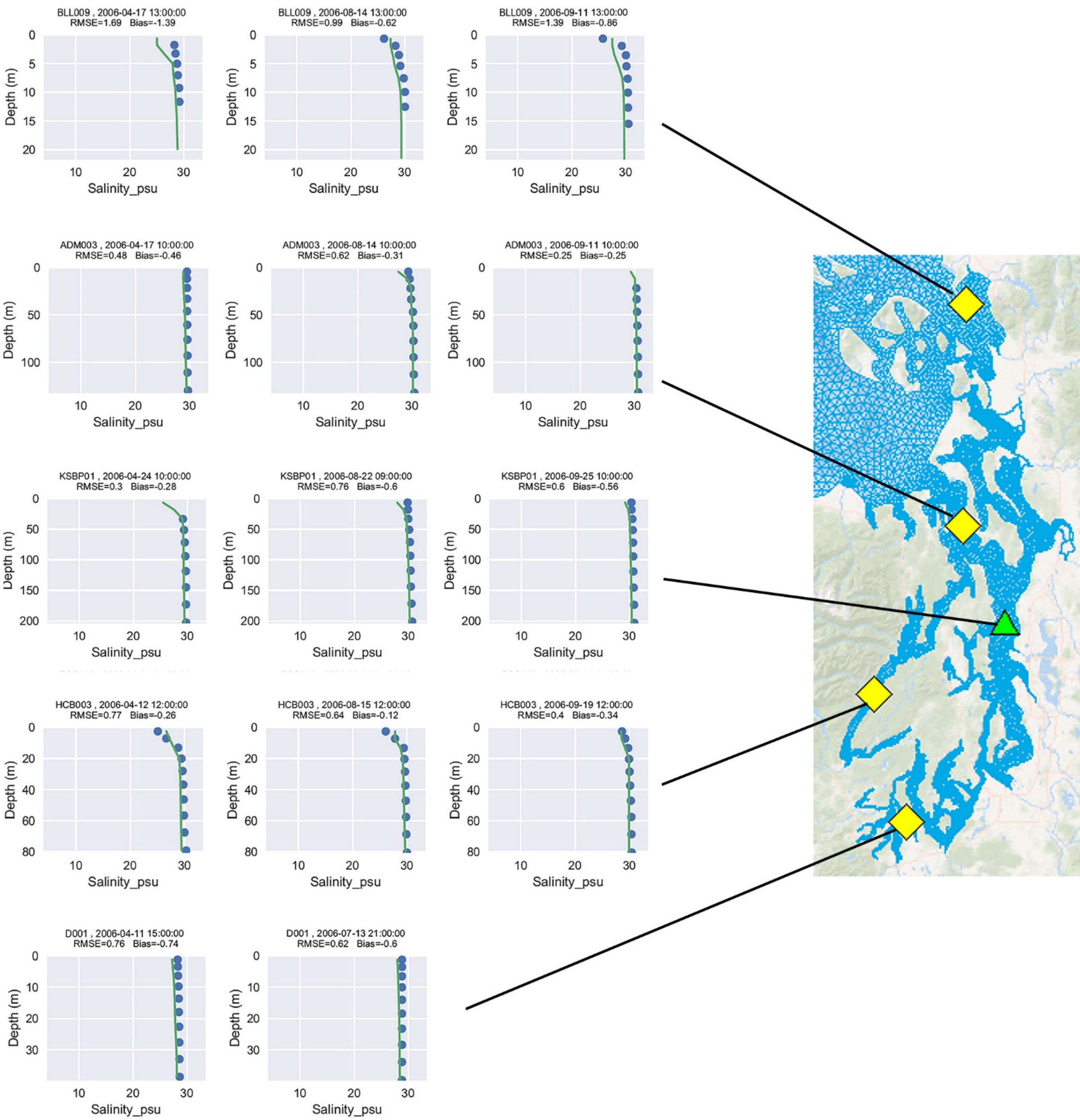


Figure 23. Year 2006 salinity profiles at selected stations for spring (left column), summer (center column), and fall (right column) conditions.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County Station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

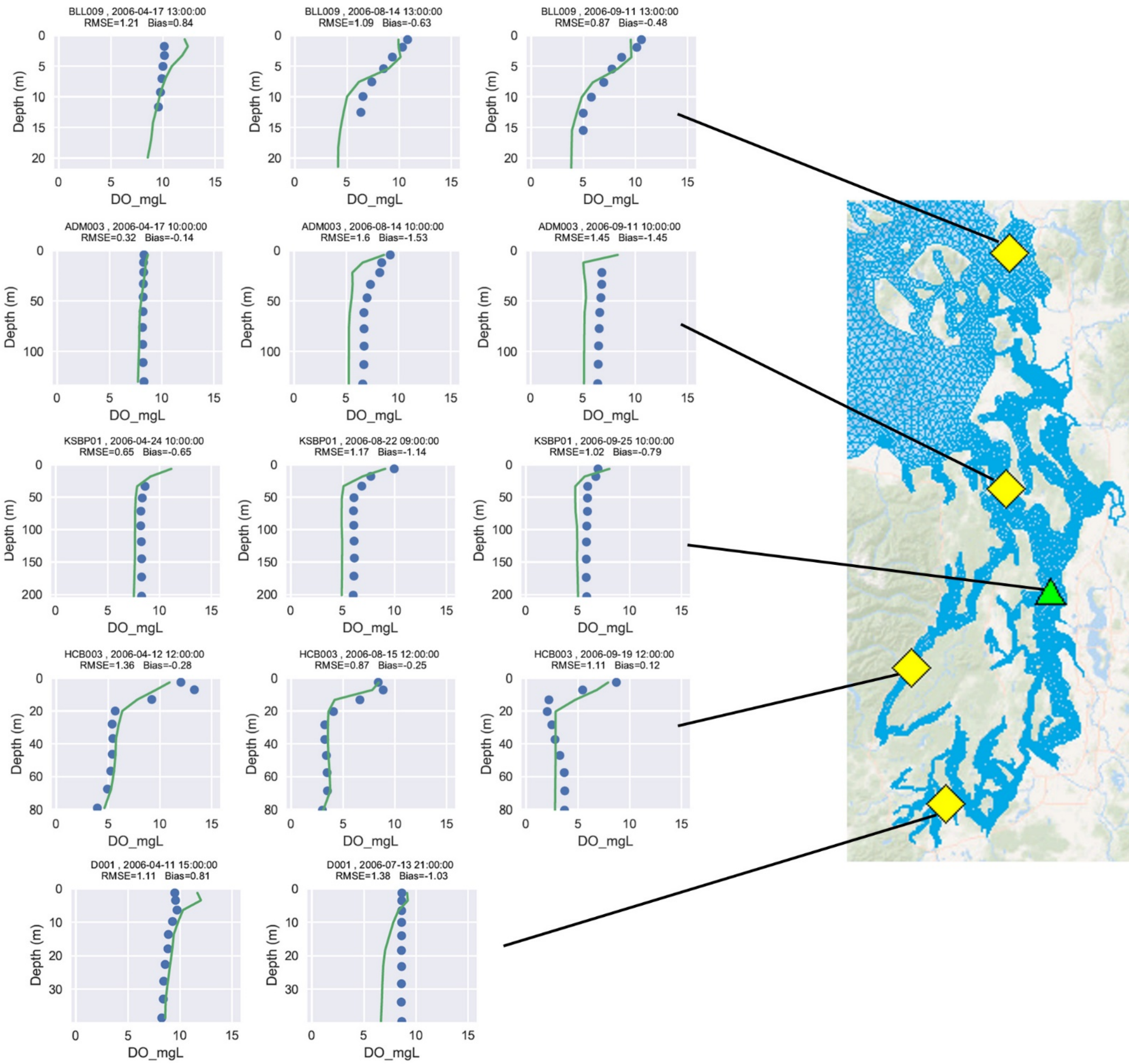


Figure 24. Year 2006 dissolved oxygen (DO, mg/L) profiles at selected stations for spring (left column), summer (center column), and fall (right column) conditions for 2006.
Top row: Bellingham Bay (Ecology station BLL009). Second row: Admiralty Inlet (Ecology station ADM003). Third row: Central Puget Sound (King County Station KSBP01). Fourth row: Hood Canal (Ecology station HCB003). Fifth row: South Puget Sound (Ecology station D001 in Dana Passage).

Phytoplankton productivity

Overall model performance can also be gauged when comparing model predictions with observed phytoplankton productivity. However, since productivity observations are not available for the modeled years, only a qualitative comparison with available observations from different time periods is possible. Appendix H contains a comparison of available gross primary productivity between observed and modeled data. Predicted values for 2008, both average and peak, are significantly lower than measured values in the Main Basin from 1999 to 2001. Nonetheless, available chlorophyll data (Jaeger and Stark, 2017) imply that lower productivity was prevalent in 2008 when compared to the years 1999 to 2001, suggesting that predicted values may reflect the expected lower productivity for that model year. Since phytoplankton productivity is a key ecosystem function, it is necessary to conduct more model runs for different years to assess whether the model predicts peak and average daily gross primary productivity reflective of years in which observations are available.

Sediment oxygen demand

Sediment oxygen demand (SOD) is another parameter we used to qualitatively assess model performance. The range of predicted SOD is very similar between 2006 and 2008: from 0.2 to 1.4 and 1.3 g/m^2/day of O_2, respectively. The peak difference in O_2 between the existing and reference scenarios in both years is about 0.4 g/m^2/day. The difference between annual mean SOD among model years is relatively small (within 1%), and the spatial pattern of the SOD distribution in the model domain is almost identical from one year to the next. Appendix I contains 2006 and 2008 SOD maps for the existing and reference scenarios and their difference.

Pelletier et al. (2017a) compared predicted annual SOD means with observed means available at various locations in Puget Sound in 2006, albeit collected at different times and durations. Upon conducting a similar comparison, including predictions for 2006, 2008, and 2014 and using a new observational data set (Merritt, 2017), we obtained analogous statistics. The large difference (about 51%) between predictions and observations is expected and generally considered reasonable (Brady et al., 2013). These differences may be due to a combination of the following factors: model bias, incongruent temporal or spatial scales, or potential biases associated with measuring sediment fluxes (Engel and Macko, 1993).

Most of the SOD observations in our region prior to 2017 were conducted with flux chambers. A new data set is available using sediment core incubation methods (Merritt, 2017). The average difference between the predicted and observed means of the older data sets (Pelletier et al., 2017a) used for comparison remains virtually unchanged (about 87%), but with a slight improvement — the predicted mean is about 3% lower at the observed locations with the latest model updates. However, the average difference between the predicted and observed means using the Merritt data set alone is significantly lower (23%), suggesting that the sediment core incubation method more closely matches model output. This highlights the challenges associated with field measurements of sediment fluxes and the resulting variability in observed data.

Furthermore, the Merritt (2017) data provide higher spatial resolution. This data set consists of sediment flux measurements at locations within Bellingham Bay, with observational clusters in which samples collected were close enough to each other that, in some instances, they fall within the same model grid cell. While the data demonstrate large SOD spatial variability (with a coefficient of variation up to 30% within the same grid cell), the data are not temporally rich. Three grid cells with more than one observation were selected for a closer comparison with model output. Predicted June means for two boundary grid cells during each of the three years modeled (2006, 2008, and 2014) were slightly statistically significantly higher than the observational mean for June 2017. On the other hand, the predicted means and observational mean for June 2017 for a grid cell away from the shoreline are statistically the same, with overlapping 95th percentile confidence intervals. Table I2 in Appendix I contains the results of a nonparametric analysis comparing these means.

Merritt (2017) suggests that a high organic carbon depositional environment may be changing the remineralization dynamics at some locations, lowering the sediment oxygen uptake, and leading to formation of sulfides. This possibility merits investigation, because Bellingham Bay is cataloged as having adversely affected benthic communities (Weakland et al., 2018). Higher temporal resolution of river load observations may lead to improvements in SOD predictions, particularly in areas near river mouths or at sheltered embayments. Appendix I contains further details about comparisons conducted, as well as potential future directions in terms of model and sediment flux comparisons and improvements.

Comparison of model predictions with high-resolution temporal data

Another qualitative measure of model performance is comparison of predictions to high-resolution temporal data available for the time periods that were modeled. Often, data from moorings or buoys have only partially undergone quality assurance and quality control procedures, and so quantitative comparisons are not possible. Another shortcoming is that available mooring data were collected at intertidal locations, which this version of the SSM is not designed to adequately address. Nonetheless, these qualitative comparisons do provide insights into potential model limitations and biases.

A qualitative comparison of predictions and observations at buoy locations revealed congruence in patterns and overall magnitudes in temperature, salinity, and DO. In the bottom layer, plots of model predictions and observations show an almost perfect visual fit. Appendix J contains these plots, as well as a discussion regarding data and model limitations and insights from the comparisons.

A comparison with model nodes next to, but not co-located with, data from moorings show that the model missed the chlorophyll peaks at these nearshore locations, and thus missed both the DO extremes (peaks and minima), but predicted levels in the mean value range. Appendix J contains plots showing model predictions compared to data collected from moorings. As discussed in McCarthy et al. (2018), one of the limitations of the current version of the SSM is that it does not adequately resolve tidally influenced areas. Improving nearshore predictions involves higher grid resolution, with more accurate bathymetry and simulation of key location-specific biogeochemical forcings. For example, incorporation of eelgrass meadows, in locations where they exist, is a step towards adequately modeling the water quality in the nearshore.

Model performance statistics are not computed including areas that consist of intertidal or very shallow subtidal areas, such as Padilla Bay, as discussed in McCarthy et al. (2018). In addition, model results in tidally influenced areas were not used in the water quality noncompliance computations.

Model performance improvements

Overall, while the differences between model and observations suggest that there is room for model improvements (e.g., increase resolution in narrow inlets, very shallow subtidal/intertidal regions, and around islands), the statistical metrics are definitely within reasonable ranges. At the model's intermediate scale, improvements in terrestrial nutrient loadings can also make a difference. The question of variability of DIN and DOC loads from rivers is an important one, because the monthly data (used to develop daily time series river inputs into the model using a regression approach) may not adequately reflect peak loads or loading during specific rainfall events. Thus, a more frequent or continuous temporal record could improve inputs and model quality to address that question. Biogeochemistry at inlets and bays could be somewhat modulated by influx of overland allochthonous carbon loadings, which are not well resolved in the model. More marine and freshwater organic carbon observational data are needed to improve our understanding. In addition, the effect of settling rates on both dissolved and particulate organic carbon, and subsequent remineralization dynamics through respiration, is a topic that deserves more focus, as discussed in Appendix E.

Sensitivity Tests

Sensitivity runs were made for 2008 with changes to rates and constants as shown in Table 8. This table also shows the associated RMSE, correlation coefficient (R), and bias. These tests were conducted to examine the model's response to changes in potentially key parameters, but this work did not result in modifications to the baseline parameter set. We continue to use the Khangaonkar et al. (2018) parameter set for all bounding scenario runs.

Table 8. Variables used in sensitivity test runs for 2008 and resulting skill metrics.

Item	Variable	Description	Current value	Sensitivity test	DO RMSE	R	Bias
1	Existing	Using rates and constants from Khangaonkar et al. (2018)			0.98	0.85	-0.53
2	ALPHMN1, ALPHMN2	Initial slope of photosynthetic production vs. irradiance (alpha) for algal group 1 and 2	12, 12	8, 10	0.99	0.84	-0.51
3	KHN1	Half-saturation concentration for nitrogen uptake for algal group 1	0.06 g/m^3	0.02 g/m^3	0.98	0.85	-0.55
4	KHNNT	Half-saturation concentration of NH_4 required for nitrification	0.5 g/m^3	1 g/m^3	0.95	0.85	-0.5
5	OBC150	Open boundary depth truncation	200 m	150 m	0.79	0.86	-0.16
6	Item 2 through 4 combined	ALPHA1, ALPHA2, KHN1, KHNNT	12, 12, 0.06, 0.5	8,10, 0.02, 1	1.1	0.83	-0.67

ALPHMN is the initial slope of the primary production versus irradiance relationship, and it impacts the light limitation for algal growth. A large value of ALPHMN increases the algal growth rate under lower irradiance conditions. We conducted a sensitivity run to quantify DO response to changes in ALPHMN and ensuing variations in phytoplankton growth. The ALPHMN was changed from 12 for both algal groups to 8 for algal group 1 and 10 for algal group 2. The resultant DO predictions had a slightly higher RMSE and a lower R, even though there was a slight improvement in the bias. This sensitivity test showed no significant change in DO predictions from current values of ALPHMN.

KHN1 is the half-saturation constant for nitrogen uptake for algal group 1. Smaller values of KHN1 reduce the nitrogen limitation on algal growth. We conducted a sensitivity run to test if the half-saturation for nitrogen uptake value at a lower concentration would improve performance. In the sensitivity test, KHN1 was reduced from 0.06 g/m^3 to 0.02 g/m^3. The resulting DO predictions with the lower KHN1 had similar statistics compared to the higher KHN1, but the bias increased with the lower KHN1 value. Appendix E contains a detailed analysis regarding KHN parametrization.

The process of nitrification involves the conversion of ammonia to nitrate. DO is consumed during nitrification. KHNNT is the half-saturation constant for ammonia uptake for nitrification. A higher value would be more limiting. We conducted a sensitivity run to test whether model performance would improve with a higher KHNNT value. KHNNT was increased from 0.5 g/m^3 to 1 g/m^3, which resulted in a slight improvement in RMSE and bias, while the R remained the same.

OBC150 refers to the truncation of the depth at 150 meters at the coastal open boundary, below which water quality remains constant. A depth of 200 m was used by Khangaonkar et al. (2018). The truncation depth was used as a calibration switch pertaining to the homogeneity of deeper waters off the continental shelf. These deeper waters were represented using the Canadian Department of Fisheries and Oceans (DFO) data to generate open boundary water quality. However, this data set is also sparse, with quarterly profiles and stations limited to the northern portion of the model. The DFO data was both temporally and spatially interpolated to generate the open boundary water quality. This test examines how sensitive the open boundary water quality is in DO predictions. The results show sensitivity to the OBC change, with RMSE, R, and bias significantly improving. One recommendation resulting from this test is to use the water quality predictions from larger ocean models, for example, the U.S. Navy's Hybrid Coordinate Ocean Model (HYCOM).

The last sensitivity test was done with a combination of lower ALPHMN, KHN1, and higher KHNNT, plus other variations detailed in Appendix E. This run showed a slight worsening of RMSE, R, and bias for DO predictions compared to the run using the rates and constants from Khangaonkar et al. (2018), and slight improvements to carbonate system parameter statistics.

Uncertainty in Dissolved Oxygen Depletion Estimates

The RMSE of differences is calculated to understand the uncertainty associated with the result of subtracting one model scenario from another model scenario (i.e., the difference between two model scenarios). In this case, we calculated the error associated with the DO depletions computed from the difference between the existing and reference model scenarios.

The following equations (Snedecor and Cochran, 1989) were used to estimate the RMSE of differences, and are based on first calculating the variance of the difference between existing and reference conditions. We are using the variance of the existing condition as an estimate of the variance of the reference condition.

VAR_{exist} = variance of predictions under existing conditions = $(RMSE_{exist})^2$

VAR_{ref} = variance of predictions under reference conditions, assumed equal to VAR_{exist}

R = Pearson's correlation coefficient between existing and reference conditions

VAR_{diff} = variance of the difference between existing and reference predictions

$= VAR_{exist} + VAR_{ref} - 2 \times R \times RMSE_{exist} \times RMSE_{ref}$

$$RMSE_{diff} = \sqrt{VAR_{diff}}$$

Using the Khangaonkar et al. (2018) parametrization, the resulting $RMSE_{diff}$ for the difference of existing and reference conditions for 2006, 2008, and 2014 is 0.049, 0.030, and 0.041 mg/L of DO, respectively. This is much smaller than the RMSE of 1.1, 0.98, and 0.96 mg/L of DO for existing conditions in 2006, 2008, and 2014, respectively. For the alternate parametrization described in this report in row 6 of Table 8, which was used for model year 2008 (but not used for bounding scenarios), the $RMSE_{diff}$ was found to be 0.030 mg/L of DO. This suggests that the $RMSE_{diff}$ is small when reasonable sets of parametrizations are used for calibration.

Dissolved Oxygen Depletions Due to Anthropogenic Loading

The applicable water quality standard requires that when a waterbody's DO concentration is lower than the established numeric criteria and the condition is due to natural conditions, then human actions considered cumulatively may not cause the DO of that waterbody to decrease more than 0.2 mg/L below natural conditions. This is referred to as the human allowance. On the other hand, if the natural condition (in this case our estimated reference scenario) is above the water quality criteria, then human actions considered cumulatively may not cause the DO of that waterbody to decrease below the numeric criteria.

The cumulative impact of all human activities causes DO concentrations to decrease by more than 0.2 mg/L at multiple locations in Puget Sound. Figure 25 shows the spatial distribution of minimum water column DO for both existing and reference conditions, along with the difference between the two, for 2006, 2008, and 2014. Spatial patterns in minimum DO under the reference scenario closely resemble the existing condition patterns. The difference plot shows that maximum DO depletions (depletions below the reference condition DO levels) are predicted to occur in inlets where flushing is relatively poor compared to the main channel, such as Case, Carr, Dyes, Sinclair, Budd, and Henderson Inlets. Well-mixed basins, on the other hand, are predicted to experience smaller DO depletions relative to the reference scenario. Most of the central Main Basin, for instance, is predicted to experience close to, but less than, a 0.2 mg/L reduction in DO.

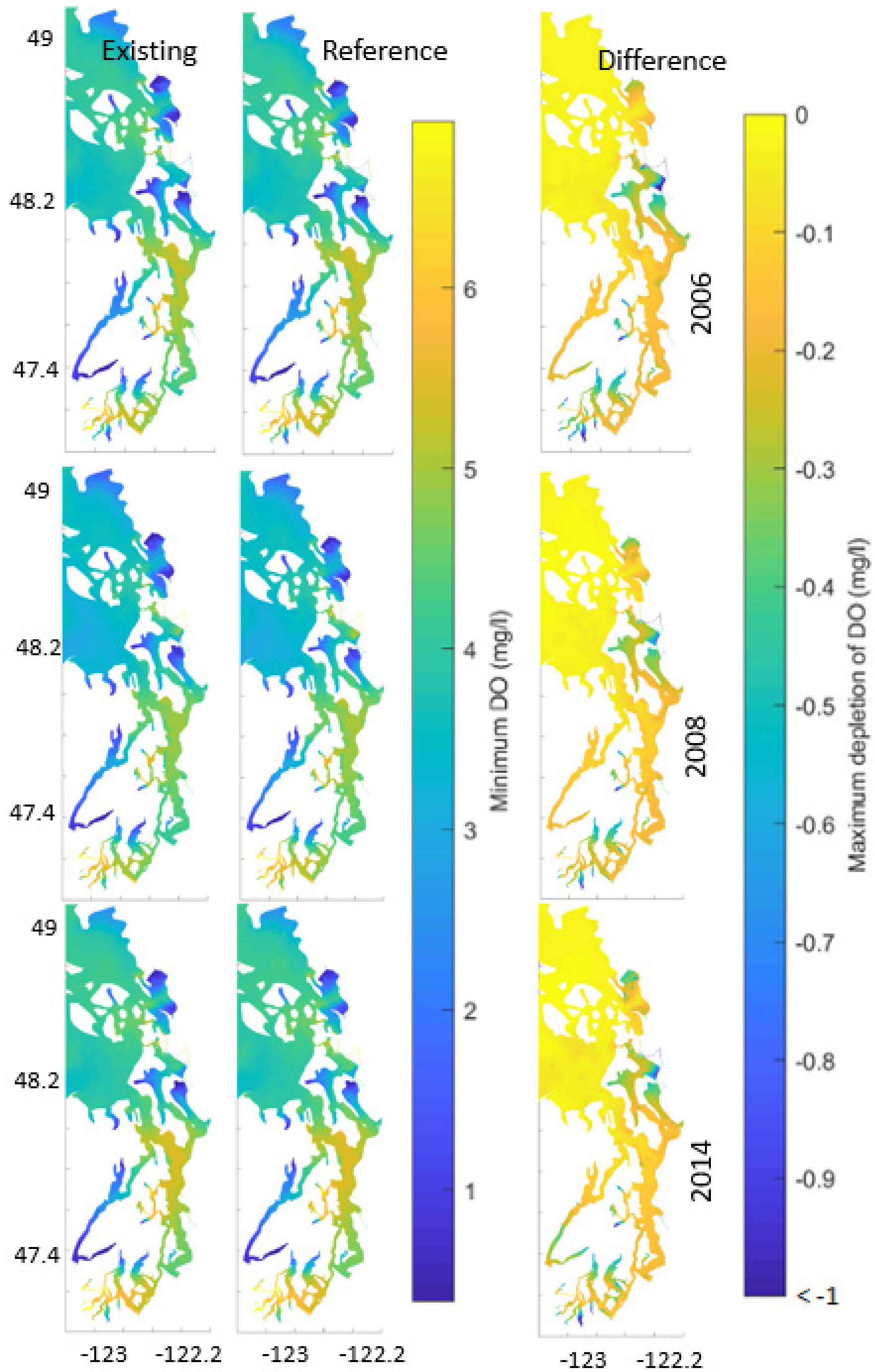


Figure 25. Comparison of the spatial distribution of predicted 2006, 2008, and 2014 minimum dissolved oxygen (DO) concentrations, corresponding reference condition scenarios, and the difference between them.
Areas that are green to blue are most sensitive to DO depletion from all human sources in Washington.

Since the DO standard incorporates a human allowance, depletions equal to or less than the allowance are not shown in subsequent maps. In addition, subsequent maps also do not show tidally influenced regions not appropriately resolved in this model version, as discussed in McCarthy et al. (2018).

The range of magnitude of anthropogenic DO depletions that cause water quality standard noncompliance varies for each model grid layer in each cell. Both Tier 1 (when the natural condition is above the numeric standard) as well as Tier 2 (when the natural/reference condition is below the numeric standard, and the human allowance must be met) were evaluated for each grid layer of each model cell. The maximum temporal depletions (either Tier 1 or Tier 2) were computed for each layer of each model cell. Finally, the maximum depletion among vertical layers for each cell was computed. We also computed the depths below modeled water surface elevations where DO depletions do not meet the water quality standards. The median depths (and maximum depths in parentheses) where the standard was not met were: 19.7 m (92.8 m) in 2006, 22 m (87.5 m) in 2008, and 17 m (88 m) in 2014.

The total area of greater Puget Sound waters not meeting the marine DO standard was estimated to be 151,000 acres (612 km^2), 132,000 acres (536 km^2), and 126,000 acres (511 km^2) in 2006, 2008, and 2014, respectively. These areas correspond roughly to about 23%, 20%, and 19% of greater Puget Sound, excluding the intertidal zone. Tables 9 and 10 contain the breakdown of the above noncompliant areas with respect to their corresponding levels of human-induced DO depletions, as well as summary statistics for minimum DO levels and cumulative number of noncompliant days for each depletion bracket. The median minimum DO levels in noncompliant areas are less than 4 mg/L, indicating that anthropogenic depletions often exacerbate already low oxygen events that result as a consequence of physical basin configuration and oceanographic, climatological, hydrologic, and meteorological drivers.

Table 9. Anthropogenic maximum dissolved oxygen (DO) depletions causing standard noncompliance, total area of noncompliance, minimum DO, and number of cumulative noncompliant days in greater Puget Sound for 2006.

Maximum DO depletions (mg/L)		Noncompliant area		Minimum DO in noncompliant area (mg/L)		Cumulative noncompliance (days)	
from	to	acres	km^2	median	95th percentile	median	95th percentile
-0.2	-0.4	124,900	505.5	3.42	5.13	39	146
-0.4	-0.6	20,400	82.5	2.02	4.2	169	243
-0.6	-0.8	2,900	11.8	2.03	3.4	107	182
-0.8	-1	1,400	5.7	1.53	2.68	118	139
-1	-1.2	670	2.7	1.3	2.62	126	161
-1.2	-1.4	440	1.8	1.34	1.75	102	147
-1.4	-1.6	360	1.5	1.29	1.93	108	162
-1.6	-1.8	150	0.6	0.54	0.69	152	160
-1.8	-2	50	0.2	0.39	0.5	157	163

Table 10. Anthropogenic maximum dissolved oxygen (DO) depletions causing standard noncompliance, total area of noncompliance, minimum DO, and number of cumulative noncompliant days in greater Puget Sound for 2008.

Maximum DO depletions (mg/L)		Noncompliant area		Minimum DO in noncompliant area (mg/L)		Cumulative noncompliance (days)	
from	to	acres	km^2	median	95th percentile	median	95th percentile
-0.2	-0.4	116,400	471.1	3.96	5.58	29	151
-0.4	-0.6	12,800	51.7	2.23	4.7	136	210
-0.6	-0.8	1,800	7.4	3.88	4.58	59	91
-0.8	-1	1,100	4.6	3.79	4.37	54	111
-1	-1.2	140	0.6	3.93	3.93	7	67
-1.2	-1.4	30	0.1	3.35	3.95	15	29
-1.4	-1.6	30	0.1	1.91	2.05	44	61
-1.6	-1.8	0	0	NA	NA	0	0
-1.8	-2	0	0	NA	NA	0	0

Figure 26 shows the spatial distribution of maximum DO depletions that cause water quality standard noncompliance. These DO depletions may occur in any vertical layer. Locations with larger DO depletions are reflective of longer residence times in these areas. For example, in the Penn Cove area, the e-folding times were longest in 2006 and shortest in 2014 (see Figure 13), thus depletions are largest in 2006 and smallest in 2014. For Lynch Cove, the e-folding times are longest in 2014 and shortest in 2008, thus the depletions are largest in 2014 and smallest in 2008. The maximum DO depletions below the water quality standards for the years 2006, 2008, and 2014 were –1.9 mg/L, –1.5 mg/L, and –2 mg/L, respectively, all occurring in the East Bay of Budd Inlet. The overall median DO depletions for 2006, 2008, and 2014 were –0.29 mg/L, –0.27 mg/L, and –0.28 mg/L, respectively.

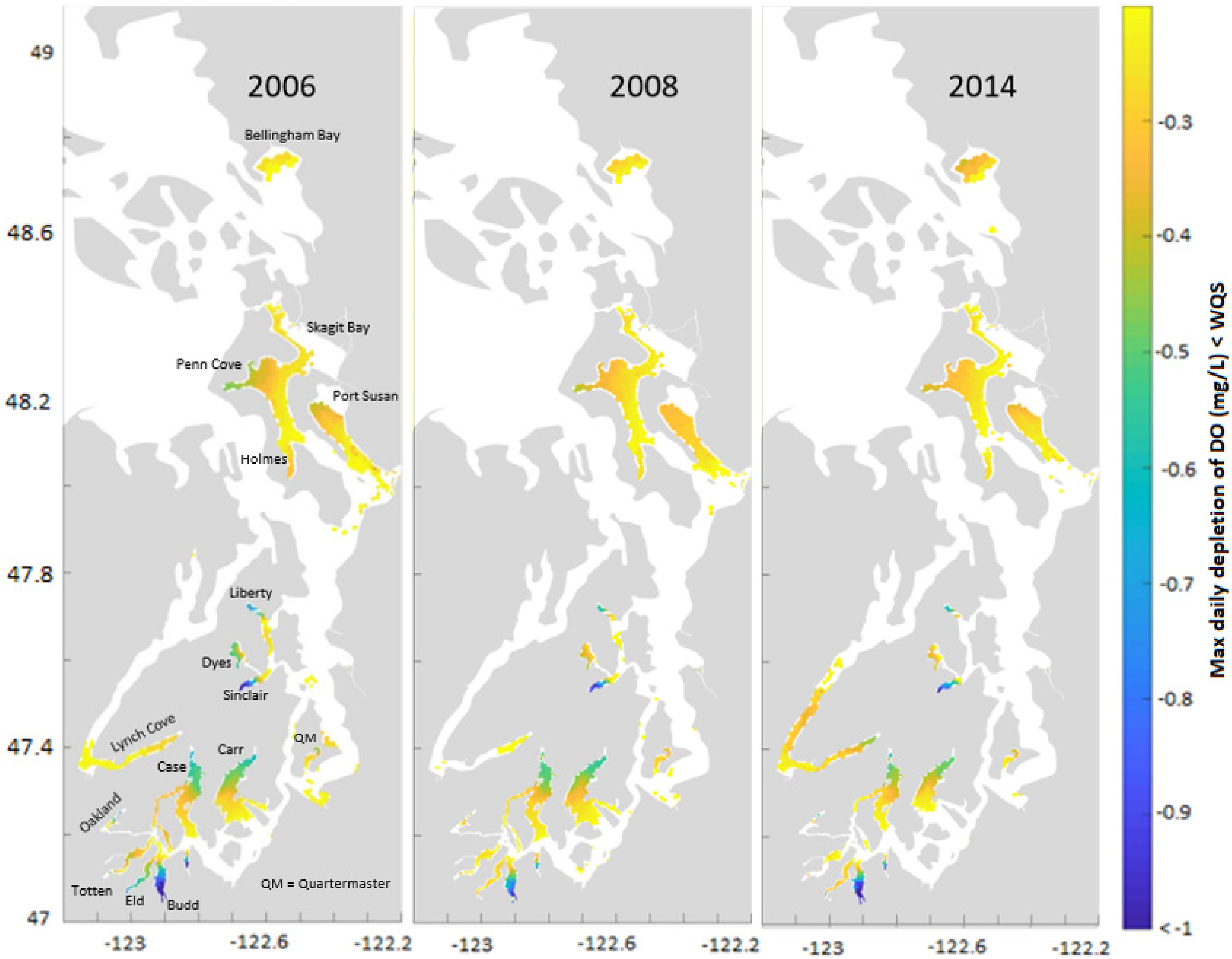


Figure 26. Maximum dissolved oxygen (DO) depletions from anthropogenic sources in 2006, 2008, and 2014, leading to noncompliance with the water quality standards (WQS).

Figure 27 shows the spatial distribution of the cumulative number of days that the DO concentrations were below the water quality standards for 2006, 2008, and 2014. Various locations during 2006, such as Lynch Cove, Holmes Harbor, and parts of Skagit Bay, are predicted to have experienced a significantly higher number of days below the standard compared to 2008 or 2014. Other locations such as Penn Cove, portions of Port Susan, Quartermaster Harbor, Case, Carr, Sinclair and Dyes Inlets, and Liberty Bay are predicted to have experienced a cumulative three months or more of noncompliance with the water quality standard during each of the three years. The maximum number of cumulative noncompliant days occurred in Carr Inlet in 2006 and 2008, where for 250 and 216 days, respectively, water quality standards were not met. In 2014, however, the maximum number of cumulative noncompliant days (198) occurred in Quartermaster Harbor.

The locations with the maximum number of cumulative noncompliant days does not coincide with the locations where the largest DO depletions occurred. The maximum DO depletions in Carr Inlet and Quartermaster Harbor were between –0.4 and –0.5 mg/L. At Budd Inlet, the location of maximum DO depletions in 2006, 2008, and 2014, the cumulative number of noncompliant days were 142, 33, and 95 days for each of those years, respectively.

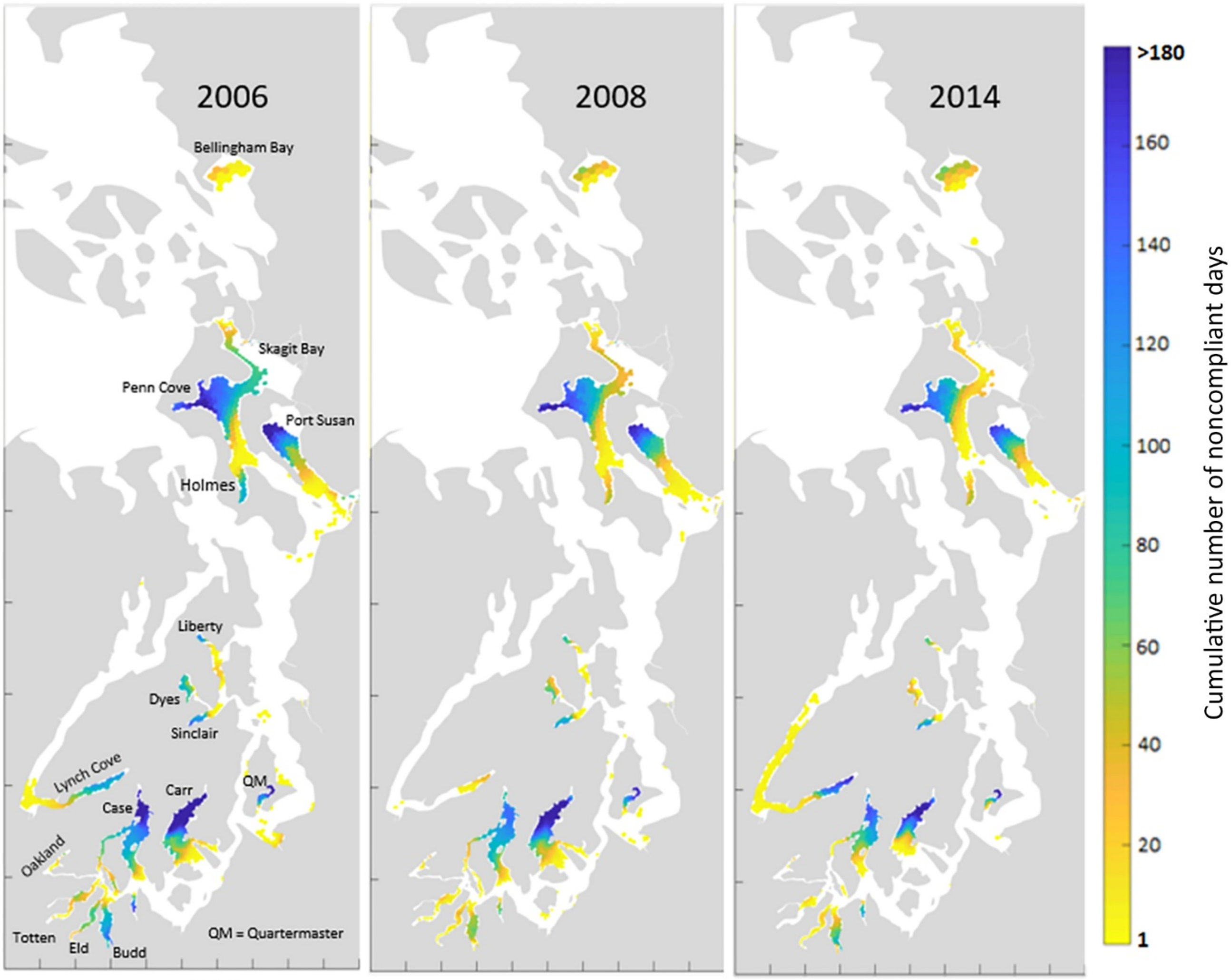


Figure 27. Spatial distribution of cumulative noncompliant days in 2006, 2008, and 2014, showing where depletion of dissolved oxygen (DO) results in noncompliance with water quality standards.

The differences in water quality in the three study years are likely due to multiple factors. Key factors that influence those differences include (1) hydrodynamics that affect residence times, (2) nitrogen loading that affects nutrient availability, and (3) organic carbon loading that depletes DO through heterotrophic bacterial decomposition of organic matter.

Regional factors may also play a role in differences between years. For example, the average e-folding times (as defined and discussed earlier, see Figure 13) for South Sound (which includes Budd Inlet, where maximum DO depletions occurred) were 289 days, 289 days, and 222 days, respectively, for 2006, 2008 and 2014. Annual average DIN loadings for South Sound were 7,800 kg/day, 6,200 kg/day, and 7,400 kg/day for the three years, respectively, and total organic carbon (TOC) loadings were 35,300 kg/day, 20,000 kg/day, and 27,900 kg/day, respectively. So, while residence times for South Sound in 2006 and 2008 were the same, both DIN and TOC loadings in South Sound were significantly higher in 2006 compared to 2008. Also, the Salish Sea as a whole had longer residence times in 2006 compared to 2008, even though regional differences were present. As a result, we see significantly larger maximum DO depletions, as well as a greater number of days with DO depletions, in Budd Inlet and overall in 2006 compared to 2008.

On the other hand, residence times throughout Puget Sound were shorter in 2014 compared to 2006. Thus, even though overall loadings in 2014 were higher, the cumulative number of noncompliant days was much higher in 2006 compared to 2014, while maximum depletions were similar.

Figure 28 shows the outline of the various basins in the greater Puget Sound, separated by shallow sills. These regions will be referenced in the following discussion.

Figure 29 shows the spatial distribution of the maximum DO depletions below the water quality standard in 2006 from (1) all anthropogenic sources, (2) only marine point sources, and (3) only anthropogenic watershed sources. Other years are not shown here because the distributions are similar. Maximum depletions refer to the largest predicted magnitude of DO water column reductions experienced during the year within any vertical layer in each model grid cell. At every impacted location, the effect of all anthropogenic loads results in larger DO depletions than those due to either marine point sources or anthropogenic watershed sources alone (Figure 29).

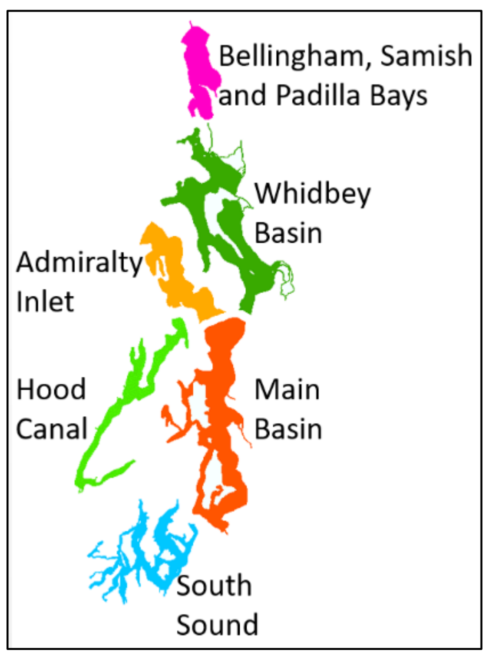


Figure 28. Basins in the greater Puget Sound.

It is noteworthy that the regions with the greatest impact from marine and anthropogenic watershed sources vary. Anthropogenic watershed sources alone produce DO depletions in Bellingham Bay, Whidbey Basin, South Sound, Hood Canal, and Main Basin, with a median of –0.22 mg/L and a peak depletion of –1.2

mg/L in East Bay of Budd Inlet. On the other hand, marine point sources alone produce some DO depletions in Whidbey Basin, and multiple depletions in South Sound and Main Basin, with a median of –0.28 mg/L and peak depletion of –1.4 mg/L in Sinclair Inlet. The combined effect of marine point and watershed sources can exacerbate DO depletions much more than either of the sources alone. Note this phenomenon in Penn Cove, Liberty Bay, Sinclair and Dyes Inlets, and Budd Inlet (e.g., with a median depletion of –0.29 mg/L and a peak depletion of –1.9 mg/L in East Bay of Budd Inlet).

Figure 30 shows the cumulative number of noncompliant days attributable to marine point sources if anthropogenic watershed sources were turned off, and the corresponding magnitude of noncompliant days for anthropogenic watershed sources only. There are significant differences between the two, with anthropogenic watershed sources creating a much larger number of noncompliant days in the domain, spread over a larger area. In terms of noncompliant area, if all anthropogenic watershed sources were turned off and marine point source emissions remained as they are, the water quality noncompliant area would be about 31% of the actual noncompliant area computed for 2006.

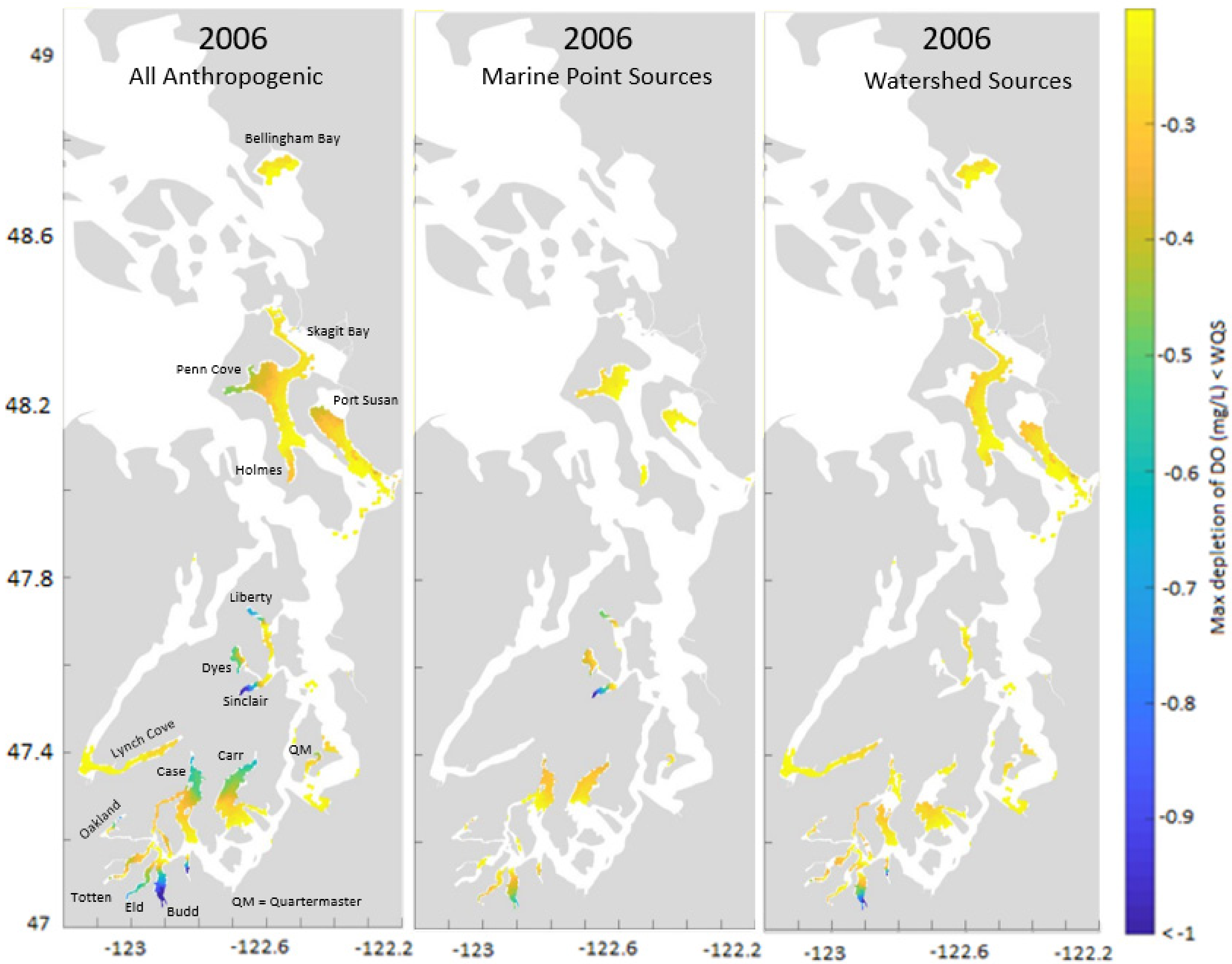


Figure 29. Year 2006 maximum dissolved oxygen (DO) depletions below the water quality standard due to all anthropogenic sources (left), marine point sources (center), and watershed sources (right).

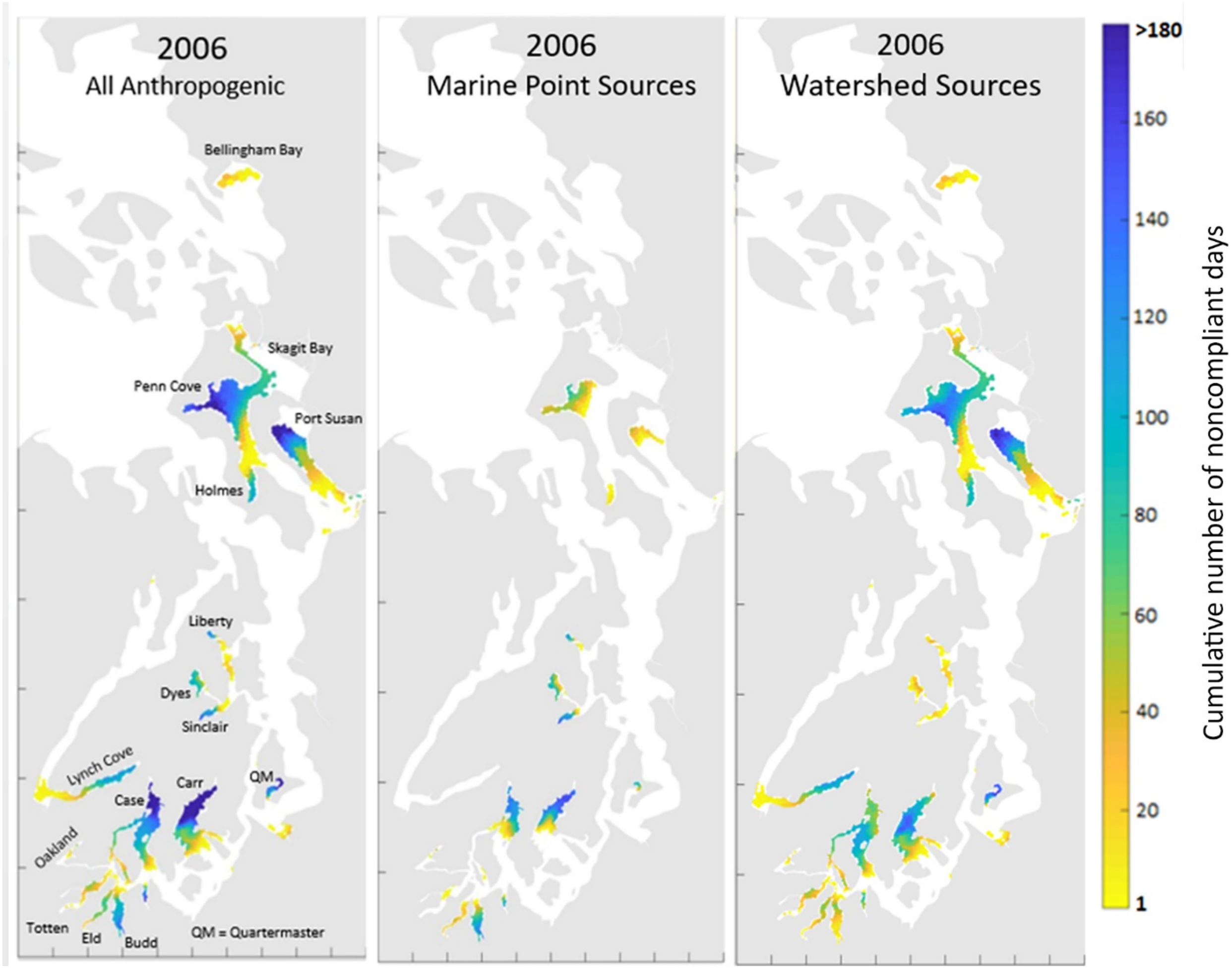


Figure 30. Cumulative number of days in 2006 when dissolved oxygen (DO) did not meet water quality standards due to all anthropogenic sources (left), marine point sources (center), and watershed sources (right).

At embayments where large depletions occur, the DO levels in the reference condition can dip significantly below the standard, which is 5 or 6 mg/L at several inlets and bays within Puget Sound. The large predicted depletions in these areas further exacerbate, in some cases down to anoxic conditions, already low DO reference levels. To illustrate this point, Figure 31 plots changes in DO concentrations (ΔDO) and the corresponding reference DO concentrations at which they occur in model nodes within two inlets that are strongly affected by low DO: Budd and Sinclair Inlets. Positive values for ΔDO, which indicate an increase in DO due to added nutrients, tend to occur mainly at high concentrations of DO, because added nutrients increase photosynthesis in the euphotic zone when DO is already high due to increased photosynthetic rates. On the other hand, negative values for ΔDO tend to occur mainly at low concentrations of DO, because added nutrients will also increase respiration in portions of the water column during times when DO is lowest due to increased respiration rates. Appendix K contains more plots at different locations that show the relationships between the DO depletions and the corresponding reference scenarios.

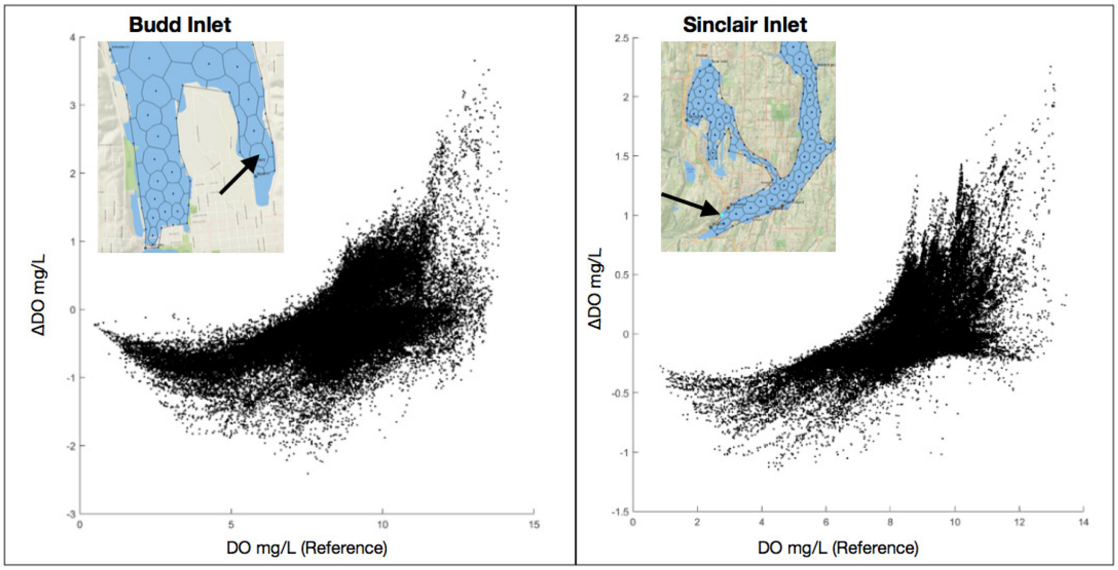


Figure 31. Difference between 2006 existing and reference dissolved oxygen (Δ DO) plotted against the corresponding reference DO concentrations at a model node in Budd Inlet (left) and Sinclair Inlet (right).

In order to assess water quality spatial trends from the open ocean to inner inlets in Puget Sound, two transects were selected. The first transect is along the thalweg from the mouth of the Strait of Juan de Fuca to Carr Inlet, and the other extends from the mouth of the Strait of Juan de Fuca to Whidbey Basin (Figure 32).

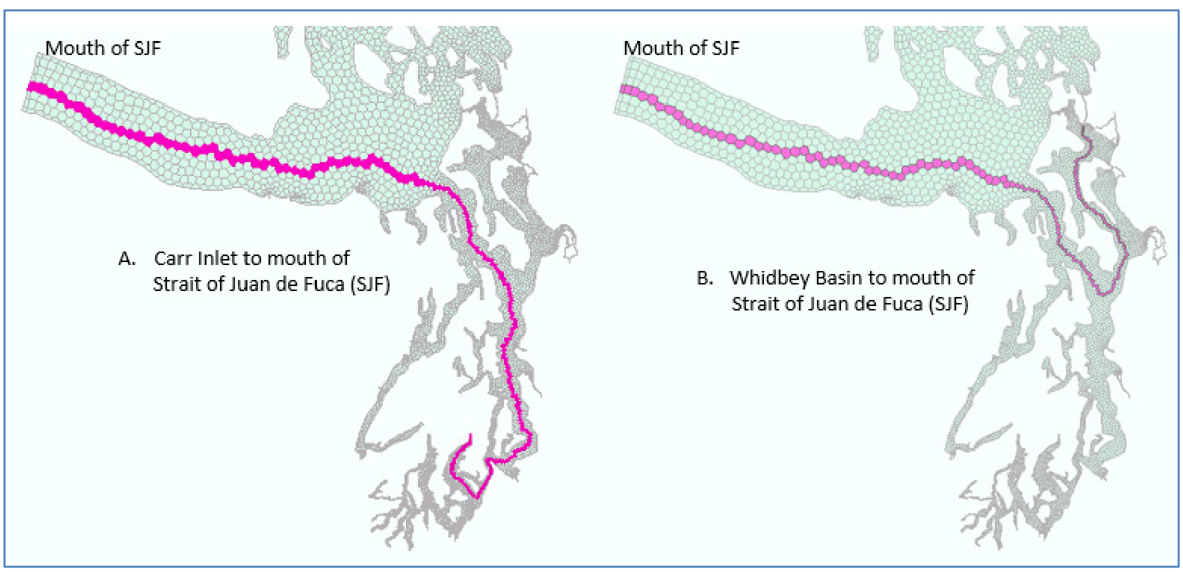


Figure 32. Thalweg transects: (A) mouth of the Strait of Juan de Fuca (SJF) to Carr Inlet, and (B) mouth of the Strait of Juan de Fuca to Whidbey Basin.

Thalwegs of annually averaged DO depletions along the transect from the Strait of Juan de Fuca to Whidbey Basin are shown in Figure 33. Depletions are generally vertically uniform within well-mixed areas below approximately 30 m, and depletions diminish in magnitude longitudinally away from inlets and bays until they become imperceptible. The overall magnitude of average annual depletion varies more noticeably in the innermost portions of the basins.

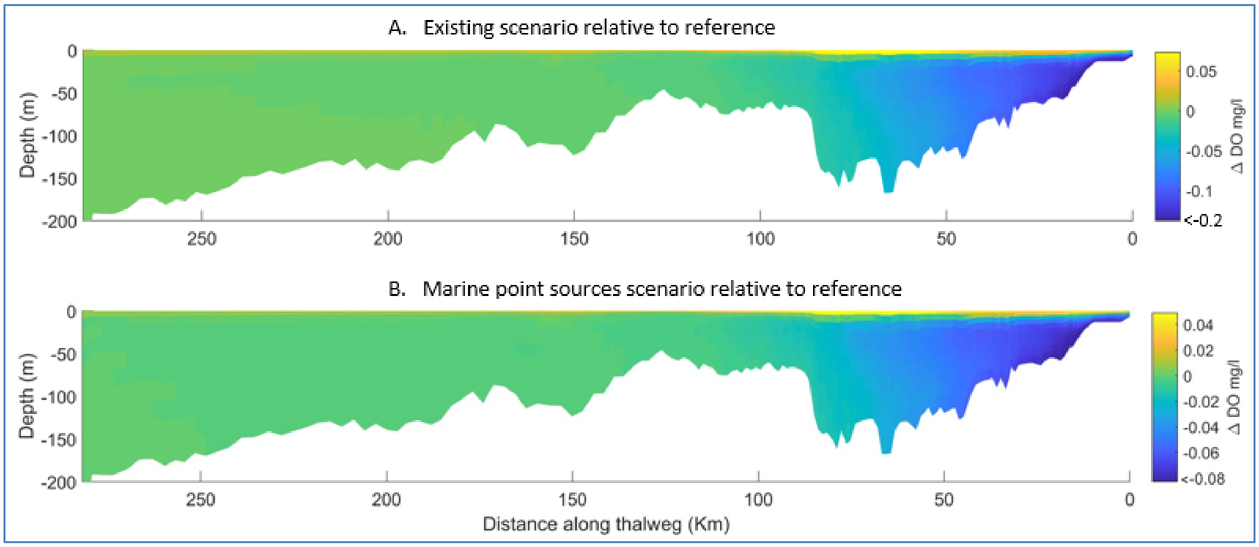


Figure 33. Year 2006 difference in dissolved oxygen (Δ DO, mg/L) between (A) all anthropogenic loading and reference conditions, and (B) marine point source loading and reference conditions computed along a thalweg from the mouth of the Strait of Juan de Fuca (left) to Whidbey Basin (right).

Figure 34 shows the relative increases between reference and existing conditions in average annual DIN and DOC, as well as changes in DO, along a transect from the Strait of Juan de Fuca to Carr Inlet. Near the ocean boundary, on the left side of Figure 34, there is very little increase in DIN or DOC due to anthropogenic sources. Larger increases are apparent in the portion of the transect corresponding to the Main Basin and South Puget Sound. For example, at around 90 km horizontal distance and a depth of about 50 m, there is a noticeable increase in DIN. This increase is probably due to a point source outfall near that location.

Greater DOC increases in the surface layer are likely tied to the "leakage" of DOC from increased algal growth and metabolism in the euphotic zone (above approximately 30 m). Below the euphotic zone, increases in DOC are uniform in the Main Basin, and within Carr Inlet increases in DOC are also more pronounced at the surface and closest to the terminus of the inlet. Dissolved oxygen depletions appear well mixed below the euphotic zone in most of the Main Basin and increase in magnitude closest to the terminus of the inlet.

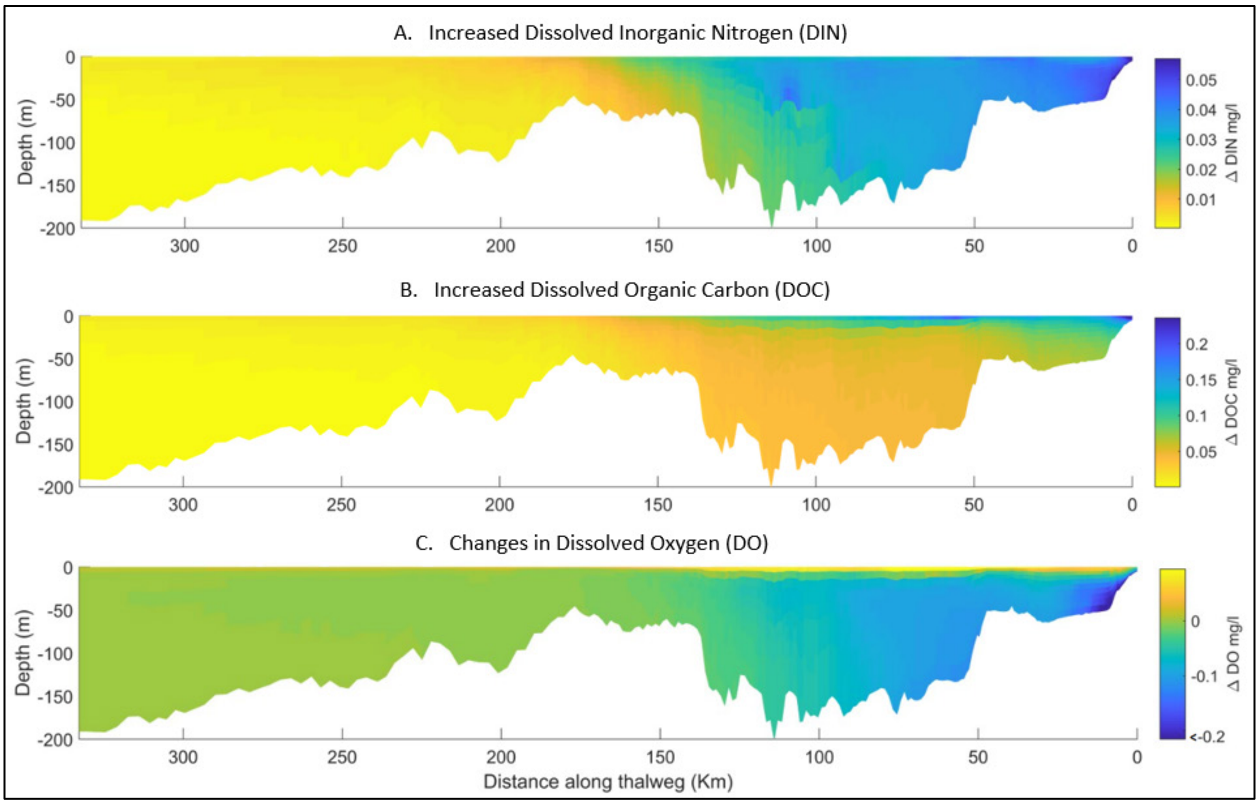


Figure 34. Changes due to anthropogenic loads of dissolved inorganic nitrogen (DIN, above), dissolved organic carbon (DOC, center), and dissolved oxygen (DO, below) along a thalweg from the mouth of Strait of Juan de Fuca (left) to Carr Inlet (right). .

Bounding Scenario Results

This section portrays the improvements and impacts associated with each of the last three scenarios listed in Table 4, considered bounding scenarios. These improvements are calculated using the hindcast model runs for the years 2006, 2008, and 2014 as baselines.

When conducting DO modeling scenarios, the relative proportion of estimated source contributions will be different depending on the order in which each source is added to or subtracted from the whole load. This nonlinearity occurs because reducing from the high end of the total nutrient loads does not reduce the availability of nutrients as much as when nutrient levels are lower. Therefore, the first sources removed can have less of an effect on phytoplankton growth because nutrient limitation is less when the loading is higher. However, reducing nutrients when loading is just above reference conditions would have a stronger influence on phytoplankton growth, because nutrient limitation is greater when loading is less. Thus, the improvements described below may vary upon the order of implementation of source reductions, and in this case, the improvements represent the result of a single category of the source reductions provided in Table 4. Evaluating individual scenarios is an important step in understanding the relative impacts of different existing nutrient sources. As further hypothetical management scenarios to achieve the water quality standards are tested, these scenarios should consider the full oxygen benefit of combined reductions from multiple sources, including the nonlinear relationship between nutrient load reduction and oxygen benefit.

Significant temporal and spatial improvements towards meeting the DO standard were realized with all three hypothetical treatment scenarios:

- BNR: Seasonal biological nitrogen removal at all municipal WWTPs discharging effluent to marine waters.
- BNR1000: Seasonal biological nitrogen removal at municipal WWTPs discharging effluent to marine waters with DIN loads of 1000 kg/day or greater.
- BNR8000: Seasonal biological nitrogen removal at municipal WWTPs discharging effluent to marine waters with DIN loads of 8000 kg/day or greater.

For each of these three scenarios, all river loads were kept at existing conditions. These scenarios result in improvements via reductions of the noncompliant area and the cumulative number of noncompliant days, as shown in Figure 35 and further described below.

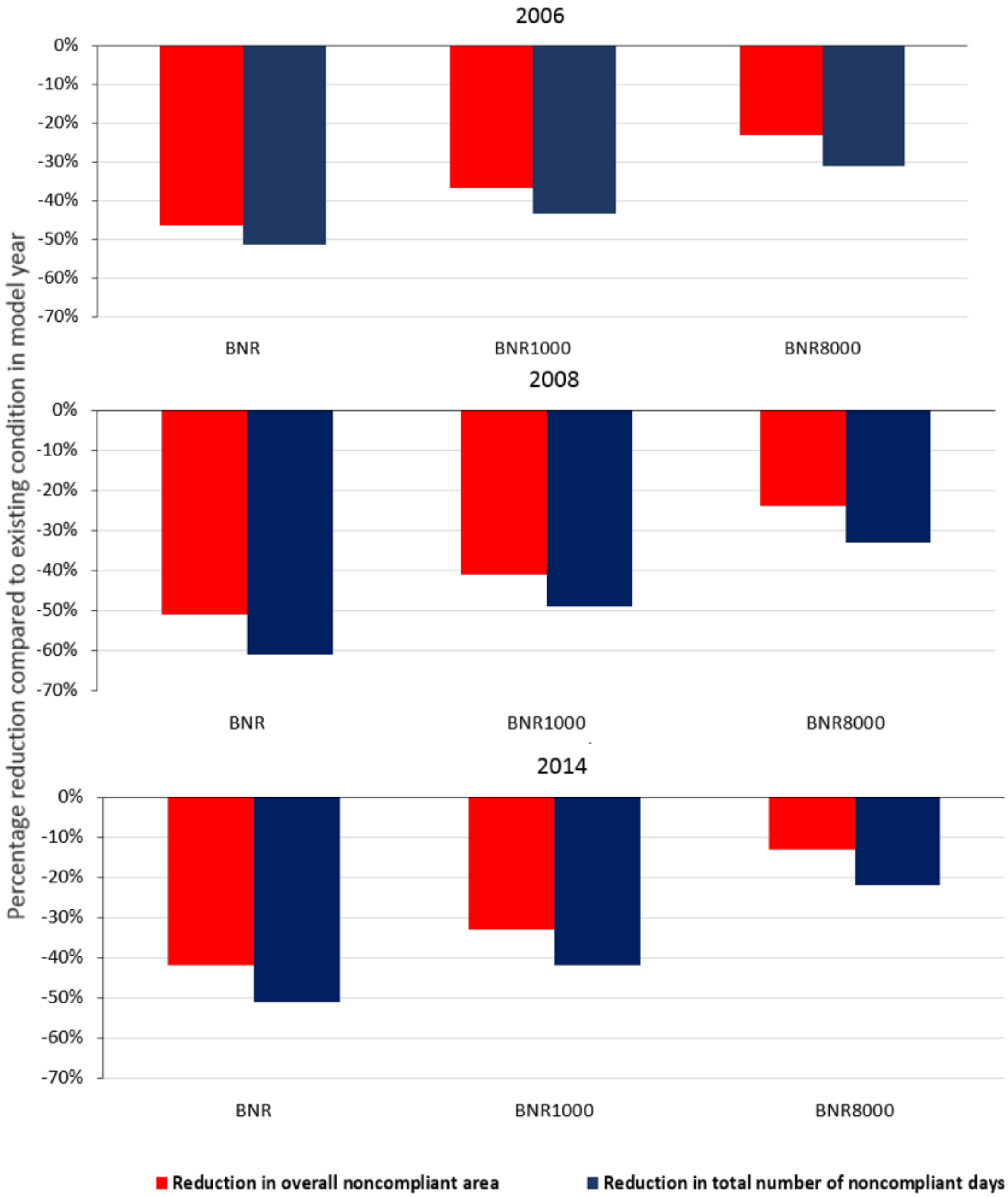


Figure 35. Plots of percent reduction in overall noncompliant area and total noncompliant days for 2006 (above), 2008 (center), and 2014 (below) under different hypothetical biological nitrogen removal (BNR) scenarios.

Improvements in maximum dissolved oxygen depletions and noncompliant area

Maximum DO depletions not meeting the standard when all anthropogenic sources are present were compared with those occurring in the same model grid cells under each of the BNR scenarios. The difference is the improvement in maximum DO depletions from reduced loadings.

Figure 36 shows the maximum depletions (calculated over the entire year for each model grid cell area) below water quality standards for 2006 when all anthropogenic sources are present, and when each of the three scenarios outlined above (BNR, BNR1000, and BNR8000) were applied. Appendix G contains similar maps for years 2008 and 2014.

All three scenarios show improvements, and standards are met at many locations, particularly where a relatively small magnitude of enhancement is needed to meet the standards. However, large DO deficits remain at several locations, including Budd and Sinclair Inlets (Figure 36).

Large improvements in maximum DO depletions in some areas are due to nutrient reductions from local, nearby point sources. For example, depletions in Sinclair Inlet are reduced the most when local WWTPs (Bremerton and Port Orchard WWTPs) apply BNR. Nutrient removal under BNR1000 and BNR8000 scenarios include the nearby King County WWTPs; however, their impact in Sinclair Inlet appears to be lower compared to those of the local WWTPs discharging to Sinclair Inlet. Another example of the influence of local point sources is in Budd Inlet, where improvement in DO depletions under the BNR scenario is low compared to the other two scenarios. That is because the largest local WWTP in Budd Inlet, LOTT, is currently already removing nitrogen from its effluent through nitrification and denitrification processes. So, in contrast to Sinclair Inlet, the BNR scenario does not change nutrient loadings *within* Budd Inlet significantly.

Table 11 shows the percent reduction in impacted area for 2006, 2008, and 2014 from the three nutrient removal scenarios. Across all years, BNR gives the best overall improvement, followed by BNR1000 and then BNR8000. However, relatively lower improvements were observed in the year 2014 for all treatment scenarios.

Table 11. Model scenario improvements, measured as percent reduction of noncompliant area where maximum dissolved oxygen depletions did not meet the water quality standard.

Scenario	**Improvement (% reduction in noncompliant area)**		
	2006	**2008**	**2014**
BNR	47%	51%	42%
BNR1000	37%	41%	33%
BNR8000	23%	24%	13%

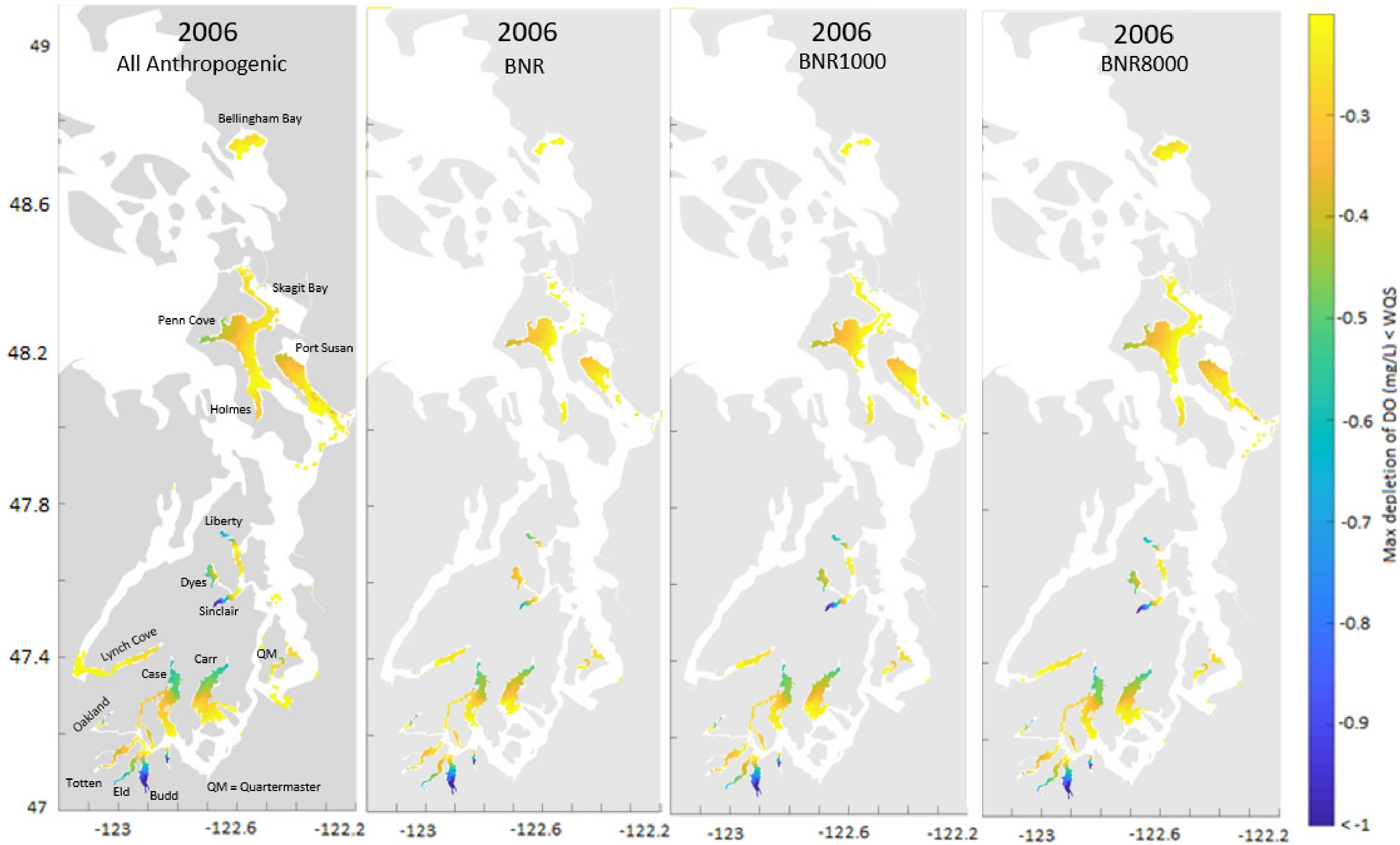


Figure 36. Four scenarios for maximum dissolved oxygen depletions for 2006.
Far left, due to all anthropogenic sources. *Center left*, with biological nitrogen removal (BNR) for all WWTPs discharging into marine waters. *Center right*, with BNR for WWTPs discharging dissolved inorganic nitrogen (DIN) >1000 kg/day (BNR1000). *Far right*, with BNR for WWTPs discharging DIN >8000 kg/day (BNR8000).

Improvements in cumulative number of days of DO depletions

To assess improvements in number of cumulative days in which DO depletions do not meet the standard, the total number of noncompliant days computed for each model grid cell were summed up for each scenario and compared to the sum of noncompliant days predicted in all cells for existing conditions in 2006, 2008, and 2014. The sum of the cumulative number of noncompliant days in all grid cells turns out to be large in 2014 (51,367 days), larger in 2008 (65,025), and even larger in 2006 (93,955). Percent improvements were computed relative to these numbers for each of the scenarios (shown in Table 12). The BNR scenario (all municipal WWTPs discharging into marine waters implementing biological nitrogen removal) consistently shows the greatest improvement in the number of days when DO depletions cause noncompliance with water quality standards.

Table 12. Three model scenario improvements (% reduction) in the number of days dissolved oxygen is below water quality standards.

Scenario	Improvement (% reduction) in total number of noncompliant days		
	2006	2008	2014
BNR	51%	61%	51%
BNR1000	43%	49%	42%
BNR8000	31%	33%	22%

Figure 37 shows the spatial distribution of the cumulative number of noncompliant days not meeting the water quality standards for 2006 under each BNR scenario. Maps for 2008 and 2014 are similar to those shown in Figure 36 and are included in Appendix G6.

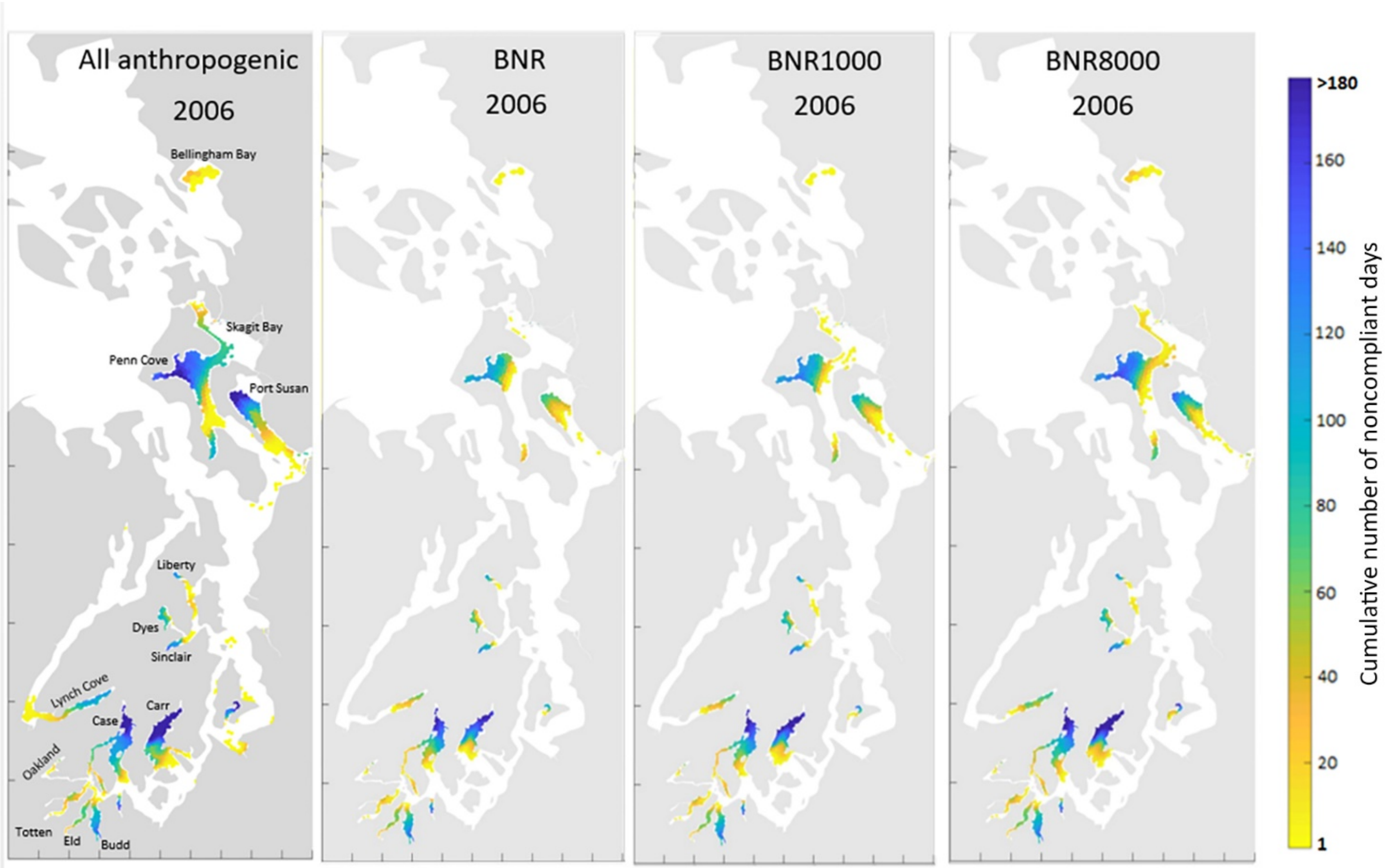


Figure 37. Four scenarios for cumulative number of days with depletions of dissolved oxygen for 2006.
Far left, due to all anthropogenic sources. *Center left*, with biological nitrogen removal (BNR) for all WWTPs discharging into marine waters. *Center right*, with BNR for WWTPs discharging dissolved inorganic nitrogen (DIN) >1000 kg/day (BNR1000). *Far right*, with BNR for WWTPs discharging DIN >8000 kg/day (BNR8000).

Hypoxic volume

The Ecological Society of America defines hypoxia as falling within the range of 2 to 3 mg/L of DO (ESA, 2018). When hypoxic levels in the Salish Sea occur, these very low oxygen regions consist of a relatively small but significant volume of water, with well-documented consequences for aquatic life. Hypoxia can change the biotic structure of bottom habitats, because the benthic communities living in them are generally immobile (Diaz and Rosenberg, 2008). A more noticeable impact of hypoxia occurs when there are fish kills, which happened in 2006. In that year, a severe fish kill event was documented in southern Hood Canal (Encyclopedia of Puget Sound, 2018b), corresponding with a rapid vertical displacement of hypoxic water, such that even mobile organisms such as fish were unable to avoid exposure. Hypoxic area varies temporally, and during 2006 it was estimated to peak around 52,500 acres (212 km^2) within greater Puget Sound, out of which approximately 19% (around 10,000 acres) was attributable to human nutrient loadings.

Figure 38 shows a comparison of existing and reference hypoxic volumes for 2006, when the SSM predicts the peak hypoxic volume occurred in September (at less than 2 mg/L of DO). Peak volume at less than 3 mg/L occurred in October that year. The volume less than 2 mg/L was much smaller (2.97 km^3) than the volume less than 3 mg/L (126 km^3). These comprised about 0.2% and 7.6%, respectively, of the entire Puget Sound Model domain volume, which includes the Strait of Juan de Fuca and a portion of the Strait of Georgia (see Figure 3).

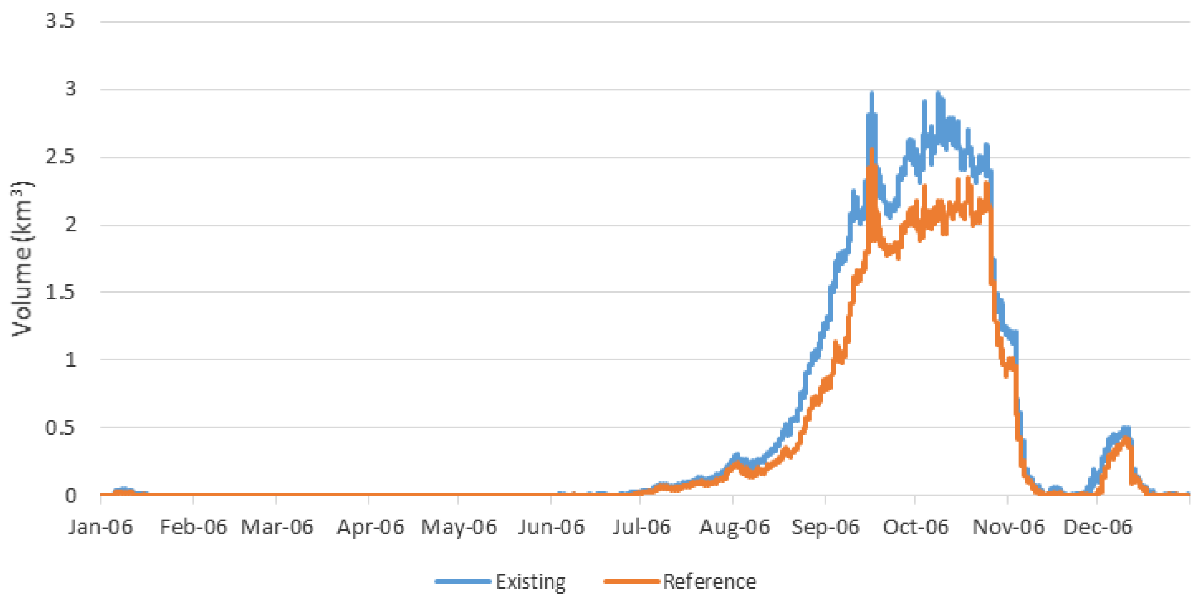


Figure 38. Hypoxic volume in Puget Sound (dissolved oxygen less than 2 mg/L) predicted for existing and reference conditions in 2006.

Annual cumulative hypoxic volume was calculated as the sum of volumes under the hypoxic threshold during each hour over the year. Model simulations for 2006, 2008, and 2014 show that for these years the annual cumulative hypoxic volume under existing loadings was 28%, 35%, and 28% higher, respectively, than the cumulative hypoxic volume Puget Sound would have experienced under reference conditions. During those years, reference conditions ranged from

1640 km^3-hrs to 3120 km^3-hrs. Table 13 shows the percent increase in annual cumulative hypoxic volume for each of the scenarios conducted relative to reference conditions. Note that under all scenarios there is a significantly higher cumulative hypoxic volume relative to reference conditions, which indicates that a comprehensive suite of measures, including watershed load reduction, is needed to fully address human-caused hypoxia in Puget Sound.

Table 13. Percent increase in annual cumulative hypoxic volume associated with each model scenario relative to the reference condition.

Scenario	2006	2008	2014
Total existing load (all sources)	28%	35%	28%
Watershed existing anthropogenic loads only	12%	14%	14%
Marine existing anthropogenic point sources only	16%	21%	14%
BNR8000	25%	30%	26%
BNR1000	23%	28%	23%
BNR	22%	27%	22%

Regional improvements in dissolved oxygen with seasonal biological nutrient reduction

For each of the bounding scenarios (BNR, BNR1000, and BNR8000), and for each of the three years (2006, 2008, and 2014), improvements in DO depletions were estimated using:

- percent reduction in the area experiencing DO standard noncompliance.
- percent reduction in the number of days of noncompliance.
- percent reduction in the maximum regional DO depletion.
- percent reduction in the mean regional DO depletion.

Reduction in noncompliant area

The percent reduction in area where the DO standard was not met for each of the six basins is presented in Table 14. As shown previously, BNR resulted in the largest reduction in area where noncompliances with the water quality standards were originally computed, followed by BNR1000, and then BNR8000. Other observations are as follows:

- Since *Admiralty Inlet* met the DO standard under anthropogenic nutrient loads for all three years, the improvement from the three treatment levels were labeled “not applicable.”
- In *Bellingham Bay*, two treatment levels (BNR and BNR1000) resulted in similar percent reduction in area of DO standard noncompliance and almost no improvement for the BNR8000 scenario. This is because BNR was applied to the Bellingham WWTP under both BNR and BNR1000 scenarios, but not for the BNR8000 scenario. On an interannual basis, 2006 shows a larger reduction in affected area compared with 2008 or 2014.
- In *Hood Canal*, improvements were observed under all treatment levels and in all years. However, the largest improvements were in year 2008, followed by 2006, and then 2014. The

average DO depletions below the water quality standard in Hood Canal for these three years from all anthropogenic sources were low and close to the 0.2 mg/L human allowance (–0.23 mg/L in 2006, –0.21 mg/L in 2008, and –0.28 mg/L in 2014). Thus, it takes slight improvements in DO to bring this area to within DO standards. Nutrient reductions outside Hood Canal have an impact on DO depletions within Hood Canal. This is consistent with the work of Banas et al. (2015), who found 1%–3% of the volume of the Main Basin transported to Hood Canal in a 20-day period.

- In the *Main Basin*, *South Sound*, and *Whidbey Basin*, reductions in the DO noncompliant area were observed for all treatment levels and years. Banas et al. (2015) found that 6%–8% of the volume of Main Basin is transported to South Sound and 15%–31% is transported to Whidbey Basin, while 45%–54% is retained in the Main Basin during a 20-day period. Biological nitrogen removal was applied in the Main Basin under all treatment levels, though there was a variation in the number of facilities implementing it within the hypothetical scenarios.

Table 14. Percent reduction in area where the water quality standards were not met.

Region	Year	Noncompliant area (existing conditions, km^2)	Reduction in noncompliant area (%)		
			BNR	BNR1000	BNR8000
Admiralty Inlet	2006	NA	NA	NA	NA
	2008	NA	NA	NA	NA
	2014	NA	NA	NA	NA
Bellingham Bay	2006	31.4	66	66	7
	2008	31.4	51	51	0
	2014	42.4	26	26	0
Hood Canal	2006	44.7	70	67	57
	2008	11.8	86	86	75
	2014	83.5	14	12	7
Main Basin	2006	71.7	57	44	39
	2008	44.4	54	39	38
	2014	26.3	38	29	12
South Sound	2006	193	25	20	13
	2008	119	36	29	18
	2014	137	34	28	12
Whidbey Basin	2006	272	53	38	22
	2008	260	60	46	27
	2014	222	60	46	18

Reduction in number of noncompliant days

The percent reduction in the number of noncompliant days for each of the six basins is presented in Table 15. Again, as expected, BNR resulted in the highest reduction in the number of noncompliant days. This was followed by BNR1000 and then BNR8000. Other observations are as follows:

- *Admiralty Inlet* met the DO standards.
- *Bellingham Bay* showed similar reductions in the number of noncompliant days from BNR and BNR1000 treatment level for reasons discussed earlier, with little improvement from the BNR8000 treatment scenario.
- *Hood Canal* showed some of the largest reductions in noncompliant days, primarily because in this basin, slight improvements cause noncompliances to disappear.
- *Main Basin*, *South Sound*, and *Whidbey Basin* showed some of the same characteristics in percent reduction of the number of noncompliant days as percent reduction in impacted area discussed earlier.

Table 15. Percent reductions in total number of days not meeting the dissolved oxygen water quality standards.

Region	year	Total number of noncompliant days (existing condition)	Reduction in noncompliant days (%)		
			BNR	BNR1000	BNR8000
Admiralty	2006	NA	NA	NA	NA
	2008	NA	NA	NA	NA
	2014	NA	NA	NA	NA
Bellingham Bay	2006	98	87	87	6
	2008	292	77	77	5
	2014	464	59	59	2
Hood Canal	2006	3620	83	77	62
	2008	245	99	97	88
	2014	3469	36	32	20
Main Basin	2006	7572	57	43	33
	2008	5482	71	49	30
	2014	4237	62	47	24
South Sound	2006	57861	39	33	23
	2008	40767	49	42	27
	2014	28850	38	33	15
Whidbey Basin	2006	24804	73	63	46
	2008	18239	82	66	47
	2014	14347	77	63	36

Reduction in the maximum and mean DO depletion

Percent reduction in the maximum and mean regional DO depletion for each of the six basins is presented in Table 16. Biological nitrogen removal at all WWTPs (BNR) resulted in the largest improvement in DO depletion. The conclusions are similar to those discussed for the two previous tables. However, for the Main Basin, BNR shows a relatively higher reduction in maximum DO depletion in 2006 (56%) compared to that for BNR1000 and BNR8000 (3% and 2%, respectively). The maximum depletion in Main Basin occurs in Sinclair Inlet; the highest reduction in DO depletion from BNR reflects the impact of BNR at local municipal WWTPs discharging there.

Table 16. Regional percent reduction in the maximum and mean daily dissolved oxygen depletion.

Region	year	Maximum depletion (existing condition, mg/L)	Mean depletion (existing condition, mg/L)	Reduction in maximum depletion (%)			Reduction in mean depletion (%)		
				BNR	BNR1000	BNR8000	BNR	BNR1000	BNR8000
Admiralty	2006	NA	NA	NA	NA	NA	NA	NA	NA
	2008	NA	NA	NA	NA	NA	NA	NA	NA
	2014	NA	NA	NA	NA	NA	NA	NA	NA
Bellingham Bay	2006	-0.27	-0.23	19	18	1	70	69	8
	2008	-0.31	-0.25	19	18	0.8	54	54	0.9
	2014	-0.40	-0.30	16	16	0.4	33	33	0.5
Hood Canal	2006	-0.29	-0.23	11	9	7	74	70	58
	2008	-0.24	-0.21	13	12	8	85	85	74
	2014	-0.46	-0.28	8	7	3	16	14	8
Main Basin	2006	-1.49	-0.34	56	3	2	57	36	31
	2008	-1.07	-0.34	51	5	4	59	34	29
	2014	-1.30	-0.41	52	3	2	48	25	11
South Sound	2006	-1.90	-0.44	3	2	1.6	24	20	13
	2008	-1.50	-0.36	4.6	3.7	2	36	30	19
	2014	-2.11	-0.42	4	3	1	29	24	12
Whidbey Basin	2006	-1.16	-0.28	3	2.6	1.8	57	42	26
	2008	-0.52	-0.27	10	7	4	66	52	32
	2014	-0.40	-0.26	21	14	7	66	52	24

Conclusions

Improvements to the Salish Sea Model's (SSM's) performance were achieved via refinements to river and stream loadings and hydrology, as well as updates to point source flows and nutrient loadings. To consider interannual variability, three years (2006, 2008, and 2014) with distinct hydrodynamic conditions were chosen based on the residence time index for Central Puget Sound. A robust field database was compiled to assess model performance for these years, including monthly casts, seasonal cruises, and moorings of multiple water quality parameters. The model (1) demonstrated high skill in reproducing dissolved oxygen (DO) concentrations in space and time, and (2) met model quality expectations. The uncertainty of model predictions for DO depletions (from 0.03 to 0.05 mg/L) is well below the anthropogenic allowance in the Washington State water quality standard (0.2 mg/L). Further enhancements will be needed to improve DO predictions in nearshore (intertidal and very shallow subtidal) areas.

An alternative parametrization was developed after dozens of sensitivity tests were performed to assess parameters and rates. The SSM was most sensitive to changes in reaeration coefficients and the truncation depth at which the incoming ocean water quality is held constant. We showed that increased model performance is feasible via improvements to oceanic boundary conditions, and we plan to pursue the use of a global ocean model (the U.S. Navy's Hybrid Coordinate Ocean Model, or HYCOM) to improve these boundary conditions. The model is moderately sensitive to settling rates, organic carbon dissolution and respiration rates, and nitrification rates. Model output using the alternative parametrization reveals similar spatial and temporal patterns as the baseline parametrization from Khangaonkar et al. (2018), which was used for all model scenarios.

Modeling scenarios compared DO levels under existing nutrient loadings in 2006, 2008, and 2014 to estimated reference conditions for these years. The results of these scenarios confirmed that the cumulative impact of all human activities causes DO concentrations to decrease by more than the 0.2 mg/L human allowance established in the DO water quality standards. This decrease in DO concentration occurs at multiple locations in greater Puget Sound. Maximum DO depletions of 1.9 mg/L (mean of 0.36 mg/L), 1.5 mg/L (mean of 0.32 mg/L), and 2 mg/L (mean of 0.35 mg/L) were predicted for 2006, 2008, and 2014, respectively. These depletions are highly variable throughout Puget Sound.

The total area of greater Puget Sound waters not meeting the marine DO standard was estimated to be around 151,000 acres (612 km^2), 132,000 acres (536 km^2), and 126,000 acres (511 km^2) in 2006, 2008, and 2014, respectively. The locations most impacted consist of poorly flushed inlets and bays, such as Penn Cove; Quartermaster Harbor; Case, Carr, Budd, Sinclair, and Dyes Inlets; and Liberty Bay.

The cumulative annual hypoxic (DO less than 2 mg/L) volume in Puget Sound was 28%, 35%, and 28% higher than under reference conditions for 2006, 2008, and 2014, respectively. Anthropogenic depletions often exacerbate already low oxygen events that result as a consequence of physical basin configuration and oceanographic, climatological, hydrologic, and meteorological drivers.

Modeling results show that portions of Puget Sound, primarily South Sound and Whidbey Basin, experience a large number of days when the marine DO water quality standard is not met. In multiple locations within these two regions, the total number of noncompliant days is over three months. This number varies by year and location. For instance, the largest total number of noncompliant days (250) occurred in 2006, followed by 2008 (216 days) and 2014 (198 days). The average cumulative number of noncompliant days computed over all areas not meeting the water quality standard was 63, 50, and 46 days in each of those years, respectively.

We examined hypothetical modifications representing major (or "bounding") changes to Washington's marine point sources of nutrients by comparing various point source reduction scenarios with estimated reference conditions. Spatial analysis of the regional impact of each scenario confirmed that the inner basins of Puget Sound do share a certain portion of their waters, so that discharges in one basin can affect the water quality in others. Significant reduction of the total number of days of noncompliance with the DO water quality standard can be achieved with each of the three seasonal BNR scenarios. For example, BNR at all wastewater treatment plants (WWTPs), BNR1000, and BNR8000 result in a 61%, 49%, and 33% reduction in the total number of noncompliant days for 2008, with slightly lower improvements in 2006 and 2014. Approximately 47%, 51%, and 42% of the impacted area came into compliance with water quality standards with seasonal BNR at all WWTPs in 2006, 2008, and 2014, respectively. Additionally, modeling results indicated that each of the three scenarios led to improvements in DO at most or all locations where water quality noncompliance was identified in the existing condition.

The largest estimated improvements occurred with implementation of seasonal BNR at all WWTPs. Some embayments (e.g., Sinclair Inlet and Bellingham Bay) showed improvements in DO depletions most likely due to enhanced treatment at local WWTPs that discharge to that embayment, rather than because of enhanced treatment at WWTPs in different basins. However, basin-wide or interbasin improvements also add to such local improvements in DO. It is important to note that due to nonlinearities of the biogeochemical system, the estimated magnitude of improvements may vary depending on the order of potential nutrient source reductions evaluated, so these results cannot be construed as definitive, but rather as a first estimate based on the hypothetical scenarios posed.

In summary, under existing conditions, approximately 20% of the area in the greater Puget Sound, excluding intertidal areas, does not meet the dissolved oxygen standards. If reductions are made at all municipal wastewater treatment plants discharging into marine waters, approximately 10% of the greater Puget Sound would not meet the standards. This represents roughly a 50% improvement in compliance area for the dissolved oxygen standards.

It is clear from these scenario tests that anthropogenic watershed loads also contributed significantly to DO depletions in 2006, 2008, and 2014. Thus, a successful nutrient reduction strategy will need to include reductions to loads and sources within the watersheds to achieve full compliance with Washington's marine water quality standards.

Next Steps

Future modeling work will respond to the policy questions posed within the context of the Puget Sound Nutrient Source Reduction Project (PSNSRP). The next phase of the project is the *optimization phase*, which involves extensive input from stakeholders to help determine the different modeling scenarios needed to address the costs and benefits of different combinations of nutrient source reductions. Ecology plans to conduct model runs for hypothetical scenarios derived from those stakeholder consultations. In addition, we plan to conduct the following next steps:

- Review and improve river loadings as new data become available. This will include (1) reviewing the multiple linear regression equations developed primarily on data collected during 2006 and 2007, and (2) analyzing how well these equations represent conditions during more recent years.
- Conduct modeling to incorporate new marine and freshwater observations, as they become available, including freshwater nitrogen and carbon data, marine organic carbon concentrations, sediment flux data, and respiration rates. Consider modeling a year for which productivity data are available.
- Collaborate in the development of hypothetical scenarios that represent future conditions in the Salish Sea, including new and future projected discharges; projected future meteorological, hydrological, and oceanographic inputs; and regional population growth.
- Incorporate output from the U.S. Navy's Hybrid Coordinate Ocean Model into the Salish Sea Model to improve the oceanic boundary condition where limited or no observations are available.
- Review reference conditions as new data sets become available, and update or improve these estimates, as appropriate.
- Incorporate updates, when available, to SSM parametrization that result in improvements to model performance.

References

Ahmed, A., G. Pelletier, M. Roberts, and A. Kolosseus. 2014. South Puget Sound Dissolved Oxygen Study, Water Quality Model Calibration and Scenarios. Publication 14-03-004. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1403004.html.

Ahmed, A., G. Pelletier, and M. Roberts. 2017. South Puget Sound flushing times and residual flows. Estuarine, Coastal and Shelf Science 187: 9–21. https://doi.org/10.1016/j.ecss.2016.12.027.

Albertson, S.L., K. Erickson, J.A. Newton, G. Pelletier, R.A. Reynolds, and M.L. Roberts. 2002. South Puget Sound Water Quality Study, Phase 1. Publication 02-03-021. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/0203021.html.

Albertson, S., J. Bos, G. Pelletier, and M. Roberts. 2007. Estuarine Flow in the South Basin of Puget Sound and its Effects on Near-Bottom Dissolved Oxygen. Publication 07-03-033. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/0703033.html.

Albertson, S., C. Krembs, M. Keyzers, L. Hermanson, J. Bos, and C. Maloy. 2016. Water mass characterization. Pp. 17–18 *in* S.K. Moore, R. Wold, K. Stark, J. Bos, P. Williams, K. Dzinbal, C. Krembs, and J. Newton (Eds.), *Puget Sound Marine Waters: 2015 Overview*. Puget Sound Ecosystem Monitoring Program Marine Waters Workgroup and NOAA Northwest Fisheries Science.

Banas, N.S., L. Conway-Cranos, and D.A. Sutherland. 2015. Patterns of river influence and connectivity among subbasins of Puget Sound, with application to bacterial and nutrient loading. Estuaries and Coasts 38: 735–753.

Bednarsek, N.,T. Klinger, C.J. Harvey, S. Weisberg, R.M. McCabe, R.A. Feely, J. Newton, and N. Tolimieri. 2017. New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. Ecological Indicators 76: 240–244.

Bianucci L., W. Long, T. Khangaonkar, G. Pelletier, A. Ahmed, T. Mohamedali, M. Roberts, and C. Figueroa-Kaminsky. 2018. Sensitivity of the regional ocean acidification and the carbonate system in Puget Sound to ocean and freshwater inputs. Elementa Science of the Anthropocene*,* 6(1): 22.

Bittick, S., M. Sutula, and P. Fong. 2018. A tale of two algal blooms: Negative and predictable effects of two common bloom-forming macroalgae on seagrass and epiphytes. Marine Environmental Research 140: 1–9.

Brady, D.C., J.M. Testa, D.M. Di Toro, W.R. Boynton, and W.M. Kemp. 2013. Sediment flux modeling: Calibration and application for coastal systems. Estuarine, Coastal and Shelf Science 117: 107–124. http://dx.doi.org/10.1016/j.ecss.2012.11.003.

Burkholder, J., D. Tomasko, and B. Touchette, 2007. Seagrasses and eutrophication. Journal of Experimental Marine Biology and Ecology 350: 46–72.

Capitol Regional District. 2018. Document library. https://www.crd.bc.ca/about/document-library/Documents/annual-reports/environmental-protection/wastewater-marine-environment.

Cerco, C., and R. Noel. 2013. Twenty-one-year simulation of Chesapeake Bay water quality using the CE-QUAL-ICM eutrophication model. JAWRA 49(5): 1119–1133.

Davis, K.A., N.S. Banas, S.N. Giddings, S.A. Siedlecki, P. MacCready, E.J. Lessard, R.M. Kudela, and B.M. Hickey. 2014. Estuary-enhanced upwelling of marine nutrients fuels coastal productivity in the U.S. Pacific Northwest. Journal of Geophysical Research-Oceans 119: 8778–8799. http://doi.org/10.1002/2014JC010248.

Diaz, R., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. Science 321: 926–929.

Di Toro, D.M. 2001. Sediment Flux Modeling. Wiley Interscience, John Wiley & Sons, Inc., New York.

Ebbesmeyer, C.C., and C.A. Barnes. 1980. Control of a fjord basin's dynamics by tidal mixing in embracing sill zones. Estuarine and Coastal Marine Sciences 11: 311–330.

Ecology [Washington State Department of Ecology]. 2018. EPA-approved water quality assessment. Washington State Department of Ecology. Accessed December 28, 2018. https://ecology.wa.gov/Water-Shorelines/Water-quality/Water-improvement/Assessment-of-state-waters-303d/EPA-approved-assessment.

Eisner, L., and J. Newton. 1997. Budd Inlet Focused Monitoring Report for 1992, 1993, and 1994. Publication 97-327. Washington State Department of Ecology. https://test-fortress.wa.gov/ecy/publications/SummaryPages/97327.html.

Encyclopedia of Puget Sound. 2018a. Dissolved oxygen and hypoxia in Puget Sound. Puget Sound Institute, University of Washington, Tacoma Center for Urban Waters. https://www.eopugetsound.org/articles/dissolved-oxygen-and-hypoxia-puget-sound.

Encyclopedia of Puget Sound. 2018b. Puget Sound science review: Eutrophication of marine waters. Puget Sound Institute, University of Washington, Tacoma Center for Urban Waters. https://www.eopugetsound.org/science-review/section-5-eutrophication-marine-waters.

Engel, M., and S. Macko (editors). 1993. Organic Geochemistry: Principles and Applications. Plenum Press, New York.

EPA. 1992. Nutrients and Phytoplankton in Puget Sound, contract with Rensel and Associates and PTI Environmental Services, 68-D8-0085. Publication 910/9-91-002. U.S. Environmental Protection Agency. https://ntrl.ntis.gov/NTRL.

EPA. 2000. Nutrient Criteria Technical Guidance Manual: Rivers and Streams. EPA-822-B-00-002. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. https://www.epa.gov/nutrient-policy-data/criteria-development-guidance-rivers-and-streams.

EPA. 2001. Ambient Water Quality Criteria Recommendations: Rivers and Streams in Nutrient Ecoregion II. EPA-822-B-00-015. Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, D.C. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20003FVH.txt.

ESA [Ecological Society of America]. n.d. Hypoxia. Ecological Society of America, Washington, D.C. http://www.esa.org/esa/wp-content/uploads/2012/12/hypoxia.pdf.

Glibert, P.M., S. Seitzinger, C.A. Heil, J.M. Burkholder, M.W. Parrow, L.A. Codispoti, V. Kelly. 2005. The role of eutrophication in the global proliferation of harmful algal blooms. Oceanography 18 (2): 198–209.

Herrera Environmental Consultants, Inc. 2011. Toxics in Surface Runoff to Puget Sound: Phase 3 Data and Load Estimates. Publication 11-03-010. Prepared for Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/summarypages/1103010.html.

Hessing-Lewis, M., S. Hacker, B. Menge, S. Rumrill. 2011. Context-dependent eelgrass–macroalgae interactions along an estuarine gradient in the Pacific Northwest, USA. Estuaries and Coasts 34: 1169–1181.

Howarth, R., and R. Marino. 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnology and Oceanography 51(1, part 2): 364–376.

Howarth, R., F. Chan, D. Conley, J. Garnier, S. Doney, R. Marino, and G. Billen. 2011. Coupled biogeochemical cycles: Eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. Frontiers in Ecology and the Environment 9(1): 18–26. https://doi.org/10.1890/100008.

Irby, I., M. Friedrichs, C. Friedrichs, A. Bever, R. Hood, L. Lanerolle, et al. 2016. Challenges associated with modeling low-oxygen waters in Chesapeake Bay: A multiple model comparison. Biogeosciences 13: 2011–2028.

Jaeger, S., and K. Stark. 2017. Nutrient and Phytoplankton Trends and Dynamics in Central Puget Sound. King County Department of Natural Resources & Parks, Water and Land Resources Division. Presentation on July 19, 2017, at Washington State Department of Ecology's Nutrient Dialogue. http://your.kingcounty.gov/dnrp/library/water-and-land/science/presentations/2017-07-19-Jaeger-Stark-re-Nutrient-and-Phytoplankton-Trends-and-Dynamics-in-CPS.pdf.

Khangaonkar, T., Z. Yang, T. Kim, and M. Roberts. 2011. Tidally averaged circulation in Puget Sound sub-basins: Comparison of historical data, analytical model, and numerical model. Journal of Estuarine Coastal and Shelf Science 93(4): 305–319.

Khangaonkar, T., B. Sackmann, W. Long, T. Mohamedali, and M. Roberts. 2012. Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and DO in Puget Sound using an unstructured grid model. Ocean Dynamics 62(9): 1353–1379.

Khangaonkar, T., W. Long, and W. Xu. 2017. Assessment of circulation and inter-basin transport in the Salish Sea including Johnstone Strait and Discovery Islands pathways. Ocean Modelling 109: 11–32.

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

Kim, T., and T. Khangaonkar. 2012. An offline unstructured biogeochemical model (UBM) for complex estuarine and coastal environments. Environmental Modelling & Software 31: 47–63.

Knudsen, M. 1900. Ein hydrographischer Lehratsz. Ann. Hydrologr. Maritimen Meteor. 28: 316–320.

Krembs, C. (editor). 2014. Eyes Over Puget Sound: Surface Conditions Report, September 9, 2014. Publication 14-03-077. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/1403077.pdf.

Krembs, C. (editor). 2015. Eyes Over Puget Sound: Surface Conditions Report, September 21, 2015. Publication 15-03-077. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/1503077.pdf.

Krembs, C. (editor). 2016. Eyes Over Puget Sound: Surface Conditions Report, September 26, 2016. Publication 16-03-077. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/1603077.pdf.

Krembs, C. (editor). 2017. Eyes Over Puget Sound: Surface Conditions Report, August 28, 2017. Publication 17-03-072. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/1703072.pdf.

Krembs, C. (editor). 2018. Eyes Over Puget Sound: Surface Conditions Report, September 17, 2018. Publication 18-03-074. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/1803074.pdf.

Krembs, C., J. Bos, S. Albertson, M. Keyzers, L. Friedenberg, J. Ruffner, B. Sackmann, and C. Maloy. 2012. POSTER: South Puget Sound 2011 and 2012 in review: Aerial and water column observations from Ecology's long-term monitoring program. Publication 12-03-052. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1203052.html.

Macdonald, T.A., B.J. Burd, and A. van Roodselaar. 2012. Size structure of marine soft-bottom macrobenthic communities across natural habitat gradients: Implications for productivity and ecosystem function. PLoS One 7(7): e40071. doi: 10.1371/journal.pone.0040071.

Mackas, D., and Harrison, P. 1997. Nitrogenous nutrient sources and sinks in the Juan de Fuca Strait/Strait of Georgia/Puget Sound estuarine system: Assessing the potential for eutrophication. Estuarine, Coastal and Shelf Science 44: 1–21.

Martin, J.L., and T.A. Wool. 2013. Supplement to Water Analysis Simulation Program User Documentation. WASP Sediment diagenesis Routines: Model Theory and Users Guide. U.S. Environmental Protection Agency, Region 4, Atlanta, Georgia.

McCarthy, S., C. Figueroa-Kaminsky, A. Ahmed, T. Mohamedali, and G. Pelletier. 2018. Quality Assurance Project Plan: Salish Sea Model Applications. Publication 18-03-111. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1803111.html.

Merritt, E. 2017. The influence of sedimentary biogeochemistry on oxygen consumption and nutrient cycling in Bellingham Bay, Washington. Thesis, Western Washington University, NSF REU at Shannon Point Marine Center. Anacortes, Washington.

Metro Vancouver. 2018. Annual Reports. http://www.metrovancouver.org/services/liquid-waste/treatment/environmental-monitoring/annual-reports/Pages/default.aspx.

Mohamedali, T., M. Roberts, B. Sackmann, and A. Kolosseus. 2011a. Puget Sound dissolved oxygen model nutrient load summary for 1999–2008. Publication 11-03-057. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1103057.html.

Mohamedali, T., M. Roberts, B. Sackmann, A. Whiley, and A. Kolosseus. 2011b. South Puget Sound dissolved oxygen study: Interim nutrient load summary for 2006–2007. Publication 11-03-001. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1103001.html.

Nelson, T., and A. Lee. 2001. A manipulative experiment demonstrates that blooms of the macroalga *Ulvaria obscura* can reduce eelgrass shoot density. Aquatic Botany 71: 149–154.

Nelson, T., A. Nelson., and M. Tjoelker. 2003. Seasonal and spatial patterns of "green tides" (Ulvoid algal blooms) and related water quality parameters in the coastal waters of Washington State, USA. Botanica Marina 46: 263–275.

Newton, J.A., M. Edie, and J. Summers. 1998. Primary productivity in Budd Inlet: Seasonal patterns of variation and controlling factors. Pp. 132–151 *in* Puget Sound Research '98 Proceedings. Puget Sound Action Team, Olympia, Washington.

Newton, J., and R.A. Reynolds. 2002. Oceanographic Field Studies in South Puget Sound, Chapter 2 of South Puget Sound Water Quality Study, Phase 1. Publication 02-03-021. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/0203021.pdf.

Newton, J., and K. Van Voorhis. 2002. Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound. Publication 02-03-059.

Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/0203059.pdf.

Pelletier, G., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky. 2017a. Salish Sea Model Sediment Diagenesis Module. Publication 17-03-010. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1703010.html.

Pelletier, G., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky. 2017b. Salish Sea Model Ocean Acidification Module and the Response to Regional Anthropogenic Nutrient Sources. Publication 17-03-009. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1703009.html.

PSEMP [PSEMP Marine Waters Workgroup]. 2012. Puget Sound Marine Waters: 2011 Overview. Edited by S.K. Moore, R. Runcie, K. Stark, J. Newton, and K. Dzinbal. Produced by NOAA's Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workshop. www.psp.wa.gov/downloads/psemp/PSmarinewaters_2011_overview.pdf.

PSEMP [PSEMP Marine Waters Workgroup]. 2013. Puget Sound Marine Waters: 2012 Overview. Edited by S.K. Moore, K. Stark, J. Bos, P. Williams, J. Newton, and K. Dzinbal. Produced by NOAA's Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workshop. http://www.psp.wa.gov/downloads/psemp/PSmarinewaters_2012_overview.pdf.

PSEMP [PSEMP Marine Waters Workgroup]. 2014. Puget Sound Marine Waters: 2013 Overview. Edited by S.K. Moore, K. Stark, J. Bos, P. Williams, J. Newton, and K. Dzinbal. Produced by NOAA's Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workshop. http://www.psp.wa.gov/downloads/psemp/PSmarinewaters_2013_overview.pdf.

PSEMP [PSEMP Marine Waters Workgroup]. 2015. Puget Sound Marine Waters: 2014 Overview. Edited by S.K. Moore, R. Wold, K. Stark, J. Bos, P. Williams, K. Dzinbal, C. Krembs, and J. Newton. http://www.psp.wa.gov/PSEMP/PSmarinewatersoverview.php.

PSEMP [PSEMP Marine Waters Workgroup]. 2016. Puget Sound Marine Waters: 2015 Overview. Edited by S.K. Moore, R. Wold, K. Stark, J. Bos, P. Williams, K. Dzinbal, C. Krembs, and J. Newton. Produced by NOAA's Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workshop. www.psp.wa.gov/PSEMP/PSmarinewatersoverview.php.

PSEMP [PSEMP Marine Waters Workgroup]. 2017. Puget Sound Marine Waters: 2016 Overview. Edited by S.K. Moore, R. Wold, K. Stark, J. Bos, P. Williams, N. Hamel, A. Edwards, C. Krembs, and J. Newton. Produced by NOAA's Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workshop. http://www.psp.wa.gov/PSmarinewatersoverview.php.

Roberts, M., J. Bos, and S. Albertson. 2008. South Sound Dissolved Oxygen Study: Interim Data Report. Publication 08-03-037. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/0803037.html.

Roberts, M., T. Mohamedali, B. Sackmann, T. Khangaonkar, and W. Long. 2014. Puget Sound and the Straits Dissolved Oxygen Assessment Impacts of Current and Future Human Nitrogen Sources and Climate Change through 2070. Publication 14-03-007. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1403007.html.

Smith, R.A., R.B. Alexander, and G.E. Schwarz. 2003. Natural background concentrations of nutrients in streams and rivers of the conterminous United States. Environmental Science & Technology 37(14): 3039–3047. https://water.usgs.gov/nawqa/sparrow/intro/es&t.pdf.

Snedecor, G., and Cochran, W. 1989. Statistical Methods, 8th edition. Iowa State University Press, Ames.

Spargo, E., J. Westerink, R. Luettich, and D. Mark. 2003. Developing a tidal constituent database for the eastern North Pacific Ocean. Eighth International Conference on Estuarine and Coastal Modeling: pp. 217–235. https://doi.org/10.1061/40734(145)15.

Steinberg, P.D., M.T. Brett, J.S. Bechtold, J.E. Richey, L.M. Porensky, and S.N. Smith. 2010. The influence of watershed characteristics on nitrogen export to and marine fate in Hood Canal, Washington, USA. Biogeochemistry 106(3): 415–433. www.springerlink.com/content/4737t5245l234715.

Sutherland, D.A., P. MacCready, N. Banas, and L. Smedstad. 2011. A model study of the Salish Sea estuarine circulation. Journal of Physical Oceanography 41: 1125–1143.

Testa, J.M., D.C. Brady, D.M Di Toro, W.R. Boynton, J.C. Cornwell, and W.M. Kemp. 2013. Sediment flux modeling: Simulating nitrogen, phosphorus, and silica cycles. Estuarine, Coastal, and Shelf Science 131: 245–263.

Tetra Tech. 2011. Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities. Publication 11-10-060. Prepared for Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/documents/1110060.pdf.

Teichberg, M., S.E. Fox, Y.S. Olsen, I. Valiela, P. Martinetto, O. Iribarne, et al. 2010. Eutrophication and macroalgal blooms in temperate and tropical coastal waters: Nutrient enrichment experiments with *Ulva* spp.. Global Change Biology 16: 2624–2637.

Thom, R., A. Copping, and R. Albright. 1988. Nearshore Primary Productivity in Central Puget Sound: A Case for Nutrient Limitation in the Nearshore Systems of Puget Sound. *In* Proceedings, First Annual Meeting on Puget Sound Research, Vol 2, March 18–19, 1988.

Van Alstyne, K. 2016. Seasonal changes in nutrient limitation and nitrate sources in the green macroalga *Ulva lactuca* at sites with and without green tides in a northeastern Pacific embayment. Marine Pollution Bulletin 103: 186–194.

Vaquer-Sunyer, R., and C. Duarte. 2010. Sulfide exposure accelerates hypoxia-driven mortality. Limnol. Oceanogr. 55(3): 1075–1082.

Von Prause, M. 2014. River and Stream Water Quality Monitoring Report: Water Year 2013. Publication 14-03-047. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1403047.html.

Weakland, S., V. Partridge, M. Dutch. 2018. Sediment Quality in Puget Sound: Changes in Chemistry, Toxicity and Benthic Invertebrates at Multiple Geographic Scales, 1989–2015. Publication 18-03-004. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1803004.html.

Glossary, Acronyms, and Abbreviations

Glossary

Advective flux: Transport with bulk fluid flow.

Allochthonous carbon: Organic compounds originating from terrestrial sources, in this case, outside of the Salish Sea aquatic system.

Anoxic: Dissolved oxygen in the water column is at 0 mg/L.

Anthropogenic: Human-caused.

Biological Nitrogen Removal (BNR): General term for a wastewater treatment process that removes nitrogen through the manipulation of oxygen within the treatment train to drive nitrification and denitrification. Nitrogen removal efficiency depends on site-specific conditions, such as treatment processes, climate, and the overall strength of the raw wastewater.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Euphotic zone: Vertical layer in the water column where light is available and photosynthesis takes place.

Greater Puget Sound: Includes Samish, Padilla, and Bellingham Bays, as well as South Sound, Main Basin, Whidbey Basin, Admiralty Inlet, and Hood Canal (see also Puget Sound).

Hindcast: Historical model run.

Hypoxic: Dissolved oxygen in the water column is lower than 2 to 3 mg/L.

Marine point source: Point sources (see "point source" definition below) that discharge specifically to, or in close proximity to, marine waters. In this report, marine point sources are included as inputs into the Salish Sea Model.

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Point source: Pollution from a single, identifiable discharge at a specific location into the natural environment. This includes water discharged from pipes, outfalls, or any other discrete discharge with a direct conveyance to surface water. It also includes a discharge to ground where pollutants reach a surface water where there is direct hydraulic pollutant conveyance. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, and industrial waste treatment facilities.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Primary production: Biomass production due to photosynthesis by phytoplankton.

Puget Sound: Includes South Sound, Main Basin, Whidbey Basin, Admiralty Inlet, and Hood Canal (see also greater Puget Sound).

Rivers/streams: A freshwater pathway that delivers nutrients and drains watershed areas. In the context of this report, "rivers inputs" and "river inflows" are used interchangeably with "watersheds," "watershed inputs," and "watershed inflows" to represent the delivery of flow and nutrient inputs into the Salish Sea Model. In the model, these estimates are for the mouth of each river, stream, or watershed and represent loading at the point at which the freshwater inflow enters the Salish Sea. These estimates include but do not distinguish between various upstream point and nonpoint sources in the watersheds that contribute to the loading at the mouth.

Salish Sea: Puget Sound, Strait of Georgia, and Strait of Juan de Fuca, including their connecting channels and adjoining waters (Figure 1).

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Thalweg: The deepest portion of a stream or navigable channel.

Tidal forcing: Tidal elevation time series at open boundary.

Tidal range: The difference between NOAA's minimum and maximum water surface elevations for a given year.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting water quality standards. A TMDL is equal to the sum of all of the following: (1) individual waste load allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a margin of safety to allow for uncertainty in the waste load determination. A reserve for future growth is also generally provided.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

Watershed inflows: See definition of "rivers" above.

Watershed load: Nutrient inputs originating in a watershed and primarily discharged into the Salish Sea via rivers and streams. Watershed loads can be composed of both point and nonpoint sources.

303(d) list: Section 303(d) of the federal Clean Water Act requires Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water — such as for drinking, recreation, aquatic habitat, and industrial use — are impaired by pollutants. These are water quality–limited estuaries, lakes, and streams that fall short of state surface water quality standards and are not expected to improve within the next two years.

Acronyms and Abbreviations

Ω_{arag}	Aragonite saturation state
ADCP	Acoustic Doppler Current Profiler
BC	British Columbia
BNR	biological nitrogen removal
C	carbon
$CBOD_5$	five-day carbonaceous biological oxygen demand
Chl-a	chlorophyll-a
CO_2	carbon dioxide
CTD	conductivity, temperature, and depth
DFO	Department of Fisheries and Oceans, Canada
DIC	dissolved inorganic carbon
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
DOC	dissolved organic carbon
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
et al.	and others
Lat	latitude
Lon	longitude
NH_4	ammonium
NO_3	nitrate
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
O_2	molecular oxygen composed of two atoms of oxygen
PARIS	Ecology's Water Quality Permitting and Reporting Information System
pCO_2	partial pressure of carbon dioxide
PNNL	Pacific Northwest National Laboratory
PO_4	phosphate
PRISM	Puget Sound Regional Synthesis Model
PSM	Puget Sound Model
PSNSRP	Puget Sound Nutrient Source Reduction Project
RMSE	root mean square error
S	salinity
SJF	Strait of Juan de Fuca
SOD	sediment oxygen demand
SOG	Strait of Georgia
SPSDO	South and Central Puget Sound Dissolved Oxygen
SSM	Salish Sea Model
T	temperature
TA	total alkalinity
TOC	total organic carbon

TON	total organic nitrogen
UW	University of Washington
WA	Washington State
WAC	Washington Administrative Code
WQS	water quality standard
WWTP	wastewater treatment plant
xCO_2	mixing ratio of carbon dioxide (mole fraction), expressed in ppm

Units of Measurement

ft	feet
g	gram, a unit of mass
$g/m^2/day$	gram per meter squared per day
kg	kilograms, a unit of mass equal to 1,000 grams
kg/day	kilograms per day
kg/ha/yr	kilograms per hectare per year
km	kilometer, a unit of length equal to 1,000 meters
km^3-hrs	cubic kilometer-hours
m	meter
mg	milligram
ppm	parts per million
psu	practical salinity units
s.u.	standard units
µatm	microatmospheres
yr	year

Appendices

Appendices A through K are available only on the internet, linked to this report at https://fortress.wa.gov/ecy/publications/SummaryPages/1903001.html.

Appendix A. Boundary Conditions

Appendix A1. Tidal Components at Open Boundary for 2006, 2008, and 2014

Appendix A2. Open Boundary Water Quality for 2006, 2008, and 2014

Appendix A3. List of Rivers Entering the Salish Sea

Appendix A4. Watershed Inflows for 2006, 2008, and 2014

Appendix A5. List of Marine Point Sources Entering the Salish Sea

Appendix A6. Marine Point Source Inflows for 2006, 2008, and 2014

Appendix A7. Watershed Inflow Water Quality for 2006, 2008, and 2014

Appendix A8. Marine Point Source Inflow Water Quality for 2006, 2008, and 2014

Appendix A9. Annual Average Dissolved Inorganic Nitrogen Loads for 2006, 2008, and 2014

Appendix B. Updated Watershed Flows and Water Quality

Appendix C. Other Sources of Nitrogen Influx to the Salish Sea

Appendix D. Observed Water Quality Databases

Appendix E. Parameters and Rates

Appendix E1. Parameters and Rates

Appendix E2. Parameters and Rates for Sensitivity Analyses

Appendix F. Comparison of Observed and Predicted Water Surface Elevations and Currents

Appendix G. Water Quality Binder for 2006, 2008, 2014, and Bounding Scenario Plots

Appendix G1. Marine Station Locations

Appendix G2. How to Read Time-Depth Plots

Appendix G3. Water Quality Binder for 2006

Appendix G4. Water Quality Binder for 2008

Appendix G5. Water Quality Binder for 2014

Appendix G6. Bounding Scenario Planview Maps

Appendix H. Comparison of Observed and Predicted Phytoplankton Primary Productivity

Appendix I. Sediment Oxygen Demand

Appendix J. ORCA Buoys and Moorings

Appendix K. Change in Dissolved Oxygen versus Reference Dissolved Oxygen