South Puget Sound Dissolved Oxygen Study

Water Quality Model Calibration and Scenarios

External Review DRAFT - 10/10/13

DEPARTMENT OF
ECOLOGY
State of Washington

October 2013 - DRAFT

Publication No. xx-xx-xxx

Publication and Contact Information

This report is available on the Department of Ecology's web site at
https://fortress.wa.gov/ecy/publications/SummaryPages/xxxxxxx.html

Data for this project are available at Ecology's South Puget Sound Dissolved Oxygen Study website at http://www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html.

The Activity Tracker Code for this study is 06-509.

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South Puget Sound Dissolved Oxygen Study

Water Quality Model Calibration and Scenarios

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October 11, 2013

Dear Interested Parties:

As a part of multi-year Puget Sound dissolved oxygen studies, the Department of Ecology (Ecology) is issuing two draft reports for review and comment. These draft documents are the fourth installment in a series of dissolved oxygen reports that Ecology began in 2006. The purpose of these studies is to assess how dissolved oxygen levels in Puget Sound respond to human and natural nitrogen loads.

These two reports are:

- *Draft: South Puget Sound Dissolved Oxygen Study: Water Quality Model Calibration and Scenarios.* This report focuses on areas of Puget Sound from South Puget Sound northward to Edmonds. This draft report is available at http://www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html.
- *Draft: Dissolved Oxygen Assessment for Puget Sound and the Straits: Impacts of Current and Future Human Nitrogen Sources and Climate Change through 2070*. This report focuses on a larger geographic area known as the Salish Sea (which encompasses Puget Sound, the Strait of Juan de Fuca, the Strait of Georgia, and Canadian waters northward to Johnstone Strait). This draft report is available at http://www.ecy.wa.gov/programs/wq/PugetSound/DOModel.html.

We are releasing these draft reports together since they both examine dissolved oxygen in Puget Sound. Dissolved oxygen is critical to the health of fish and other aquatic life. When excess nitrogen enters marine waters, it causes excess algae growth. As algae die and decay, they use up and deplete dissolved oxygen.

Dissolved oxygen levels are affected by many things – some are natural and some are human made. The most detrimental human-caused factor is release of excess nitrogen. Sources of nitrogen from people include discharges from wastewater treatment plants and septic systems, and runoff from fertilizers and domestic animals.

Both studies use computerized prediction tools – often called “models” – to evaluate nitrogen coming from natural conditions (such as incoming waters of the Pacific Ocean) and contributions from people. The reports also provide the first assessment of how predicted changes in the Pacific Ocean and climate change may affect Puget Sound in the future.

While the dissolved oxygen studies with their previous reports provide a great deal of information, more research and certainty is needed before effective actions can be identified to improve dissolved oxygen levels.

According to the South Puget Sound modeling results, most of South and Central Puget Sound are meeting water quality standards for dissolved oxygen. However, some portions of South Puget Sound inlets and Central Puget Sound's East Passage do not.

Next steps in the Puget Sound dissolved oxygen studies include improving and refining the models which are expected to be available in 2015. As Ecology moves forward with these Puget Sound water quality studies, coordination will continue with stakeholder advisory groups, cities, counties, tribes, academia, and other organizations on study findings and next steps.

If you have any questions about the Puget Sound dissolved oxygen studies, please contact me at 360-407-7543 or andrew.kolosseus@ecy.wa.gov.

Sincerely,

Andrew Kolosseus
Washington State Department of Ecology
Water Quality Program

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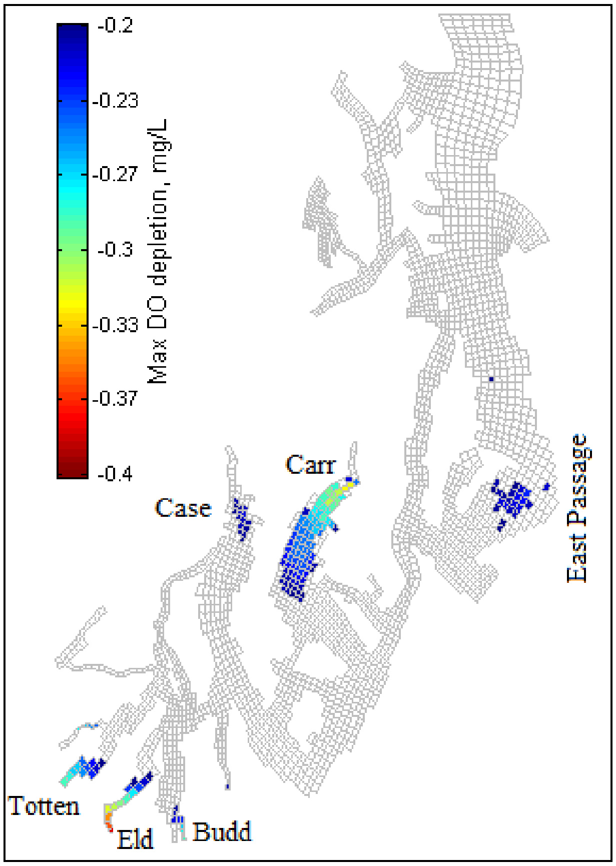
Abstract

Portions of South and Central Puget Sound are on the Clean Water Act Section 303(d) list of impaired waters because observed dissolved oxygen measurements do not meet the numeric criteria of the Washington State water quality standards. Human sources of nutrients can increase algae growth, which can decrease oxygen as the additional organic matter decays. Low oxygen can impair fish and other marine life. Computer modeling tools are needed to isolate the impacts of human contributions.

The purpose of this study is to identify how much human contributions are contributing to low dissolved oxygen (DO) concentrations in South Puget Sound. Previous reports summarize data collection, nutrient load estimates for marine point sources and watershed inflows that include point and nonpoint sources, and the circulation model calibration. This report summarizes the calibration and application of the water quality model to isolate the impacts from groups of sources.

The calibrated model appropriately predicts the regional and seasonal patterns of chlorophyll, DO, and nitrogen throughout South and Central Puget Sound. The model predicts that internal (inside the model domain) current human nutrient loads from marine point sources and watersheds as well as external (north of model domain) current anthropogenic loads are causing DO to decline by as much as 0.4 mg/L in portions of Totten, Eld, Budd, Carr, and Case inlets, and East Passage, which violates the standards (see Figure_ABS 1).



Figure_ABS 1. Predicted dissolved oxygen standard violations under current conditions

There are not violations across the entire South or Central Puget Sound. While keeping the external anthropogenic load constant, internal marine point sources exert a greater impact than human sources within watershed inflows. Reducing the internal human nutrient load would decrease the magnitude and extent of DO depletion. Additional scenarios are needed to isolate the effects of individual sources.

This is the first study to evaluate the impact of humans on DO concentrations within South and Central Puget Sound, which fall below the numeric criteria in the water quality standards.

For more information, see http://www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html.

Acknowledgements

The authors of this report wish to thank the following people for their contribution to this report:

- The South Puget Sound Dissolved Oxygen Study Advisory Committee has met at key project milestones to review and discuss interim findings. The Advisory Committee also provided comments on this report and related documents:

Dave Adams	Citizens for a Healthy Bay
John Bolender	Mason Conservation District
Seth Book	Mason County Department of Health Services
Kevin Buckley	Snoqualmie Tribe
Roma Call	Puget Sound Partnership
Ben Cope	EPA Region 10
Joe Gibbens	Fort Lewis Public Works
Bill Dewey	Taylor Shellfish Co.
Larry Ekstrom	Pierce County Public Works and Utilities
John Eliasson	Washington State Dept. of Health
Duane Fagergren	Puget Sound Partnership
Bill Fox	Cosmopolitan Engineering Group
Cheryl Greengrove	University of Washington - Tacoma
Keith Grellener	Kitsap
Mitsuhiro Kawase	University of Washington
Bill Kingman	City of DuPont
Andrew Kolosseus	Department of Ecology
Scott Steltzner	Squaxin Island Tribe
Dave Lenning	Washington State Dept. of Health
Lincoln Loehr	Stoel Rives
Tom Moore	Mason County Department of Utilities and Waste Management
Bruce Nairn	King County WTD
Greg Narum	Simpson Tacoma Kraft
Anthony Paulson, Ph. D.	U.S. Geological Survey
Dave Ragsdale	EPA Region 10
Debbie Riley	Mason County Environmental Health
Wayne Robinson	LOTT Alliance
Lynn Schneider	WA State Dept of Health
Dan Thompson	Tacoma Wastewater Treatment Plant
Dave Peeler	People for Puget Sound
Bruce Wishart	People for Puget Sound
Dan Wrye	Pierce County Public Works and Utilities
Tyle Zuchowski	LOTT Alliance
Char Naylor	Puyallup Tribe
Dave Clark	HDR

- Venkat Kolluru and Shwet Prakash (ERM) provided technical support for model development, application, and calibration.

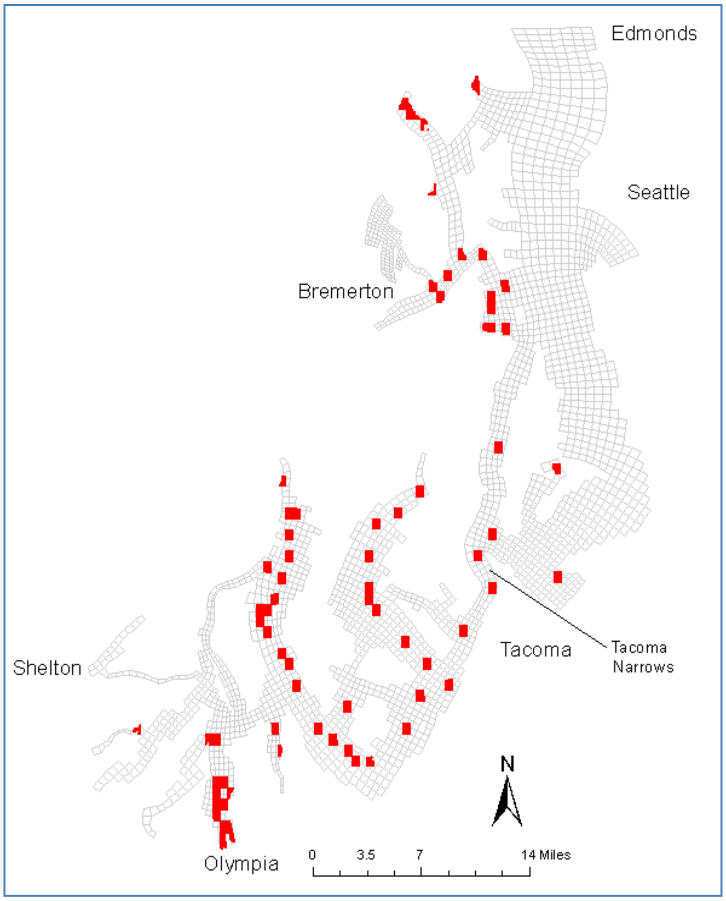
- Bob Ambrose provided consultation to guide the process of model development and calibration.
- Brandon Sackmann created the tools for pre- and post-processing of model inputs and outputs. Brandon also contributed valuable insight and ideas that significantly improved the process of model calibration and scenario evaluation.
- Skip Albertson was instrumental in the original hydrodynamic model setup which was the starting point for the present work.
- Chuck Hoffman provided the mixing zone modeling analysis that guided the setup of model inputs for wastewater treatment plants.
- Teizeen Mohamedali helped with estimation of total anthropogenic nitrogen loadings in different areas of Salish Sea including South and Central Puget Sound.
- In addition, several Washington State Department of Ecology staff reviewed and commented on initial results:
    - Kim McKee, Bob Bergquist, Greg Zentner, Chuck Hoffman, Dave Garland, Mark Henley, Kevin Fitzpatrick, Melissa Gildersleeve, and Kelly Susewind (Water Quality Program)
    - Karol Erickson, Will Kendra, Bob Cusimano, and Rob Duff (Environmental Assessment Program)

Executive Summary

Introduction

Portions of South and Central Puget Sound are on the Clean Water Act Section 303(d) list of impaired waters because observed dissolved oxygen (DO) measurements do not meet the numeric criteria of the Washington State water quality standards for DO (Figure ES-1). Under the federal Clean Water Act, the Department of Ecology establishes water quality standards to protect the physical, chemical, and biological integrity of Washington's waters. Minimum levels of DO are established to protect fish and other aquatic life. Low levels of DO can cause fish and other marine life to become stressed and die or flee their habitat.

Figure ES-1. 2012 Clean Water Act Section 303(d) Category 5 (impaired waters) listings for marine DO in South and Central Puget Sound with the model grid.



Low concentrations of DO result from the complex interactions of physical, chemical, and biological processes that vary by season and location. Sunlight and nutrients spur algae growth. As the algae die, bacteria consume oxygen as they decompose the organic matter. Excess nutrients from humans can cause additional algae growth beyond natural conditions and decrease near-bottom DO concentrations.

Nitrogen is typically the nutrient that limits algae growth in marine ecosystems. Circulation patterns affect the amount of nitrogen available for algae growth. Stratification can limit the replenishment of nitrogen from waters near the bottom to near the surface where it can be used by algae. Stratification can also limit the replenishment of higher DO near surface to lower DO near bottom. DO saturation also varies with water temperature, which varies seasonally.

Nitrogen enters South and Central Puget Sound waters from multiple human and natural sources. The largest overall source of nitrogen is the exchange of marine water that enters and leaves Central Puget Sound at Edmonds through both tidal flows and estuarine circulation. The dominant human sources are through marine point source discharges of treated municipal wastewater. Watershed inflows, which include both natural and human components, deliver nitrogen to the surface waters of South and Central Puget Sound.

Watershed inflows include the effects of septic systems, stormwater, wastewater treatment plants discharging to rivers, upland atmospheric deposition, and other sources associated with developed land in addition to natural contributions. Atmospheric deposition adds nitrogen directly to the marine water surface. Finally, nitrogen in particles that settle to the sediments are transformed to bioavailable nitrogen and released to the water column where they can fuel additional algae blooms. Sediment processes also exert an oxygen demand on bottom waters.

Because measurements reflect the effects of both natural and human sources of nitrogen, we develop computer modeling tools to distinguish how much DO depletion results from human nitrogen inputs. The South and Central Puget Sound DO model includes all of South Puget Sound, the primary area of interest, as well as Central Puget Sound south of Edmonds. We included Central Puget Sound because the human nitrogen loads from marine point source discharges deliver far more nitrogen than those in the South Puget Sound.

Natural processes can cause DO concentrations to fall below the numeric thresholds established in the water quality standards (WAC 173-201A). These thresholds vary by location from 4.0 to 7.0 mg/L. If natural conditions are below the thresholds, then the combined effect of all human sources cannot cause DO levels to decrease by more than 0.2 mg/L at any place or any time [(WAC 173-201A-210(1)(d)(i)]. Ecology determines whether a violation occurs by using computer modeling tools to compare DO concentrations under current conditions to those predicted to occur without human sources of nitrogen.

Water Quality Model Description and Setup

Ecology applied the Generalized Environmental Modeling System for Surface Waters (GEMSS) to simulate circulation and water quality in South and Central Puget Sound. GEMSS is an integrated system of three-dimensional hydrodynamic and transport models embedded in a geographic information and environmental data system (GIS) and set of pre- and post-processing tools. Additional information on GEMSS is provided in the main body of the report. GEMSS has previously been applied in Budd Inlet (Roberts et al., 2012) and many other waterbodies (e.g., Fischera et al., 2005).

The circulation model simulates water surface elevations, velocity, temperature, and salinity throughout the model domain (Roberts et al., 2013, in press). The model uses grid cells with a typical resolution of 600 meters that varies from 300 to 1300 meters by location. Each grid cell has up to 17 layers that are 4 m thick in the intertidal zone and increase in thickness with water depth up to 29 meters in the deepest locations. Shallow inlets have fewer layers than deeper inlets.

Mohamedali et al. (2011) developed load estimates for 31 municipal wastewater treatment plants, two industrial treatment plants, and 45 watershed inflows representing all freshwater flowing into South and Central Puget Sound.

Wastewater treatment plants deliver 3,250 kilograms/day (kg/d) of total nitrogen (TN) to South Puget Sound and 24,740 kg TN /d to Central Puget Sound. Watersheds deliver 2,410 kg TN/d to South Puget Sound and 2,910 kg TN/d to Central Puget Sound. Natural sources within the watersheds deliver 1,510 kg TN/d to South Puget Sound and 2,530 kg TN/d to Central Puget Sound. Atmospheric deposition to the marine water surface discharges an additional 360 kg TN/d. Comparing the natural and anthropogenic loads from sources within the South and Central Puget Sound, anthropogenic sources contribute about 6 times the nutrient loading compared to natural loads. External anthropogenic load entering the Edmonds open boundary from north is relatively high at approximately 40,000 kg TN /d.

Water quality data collected near Edmonds were used to establish profiles of DO, nutrients, and chlorophyll at the open boundary for the model (Roberts et al., 2008). Nitrogen and oxygen sediment fluxes were based in part on limited data collected in South Puget Sound shallow inlets (Roberts et al., 2008). Regional values for sediment oxygen demand were increased from measurements during model calibration but kept within literature values. The model ran from January through October 2007, which required approximately 10 days of computational time. Initial conditions for January 2007 were developed from marine monitoring data described in Roberts et al. (2008). Figure ES-2 presents the model domain and place names used in this study.

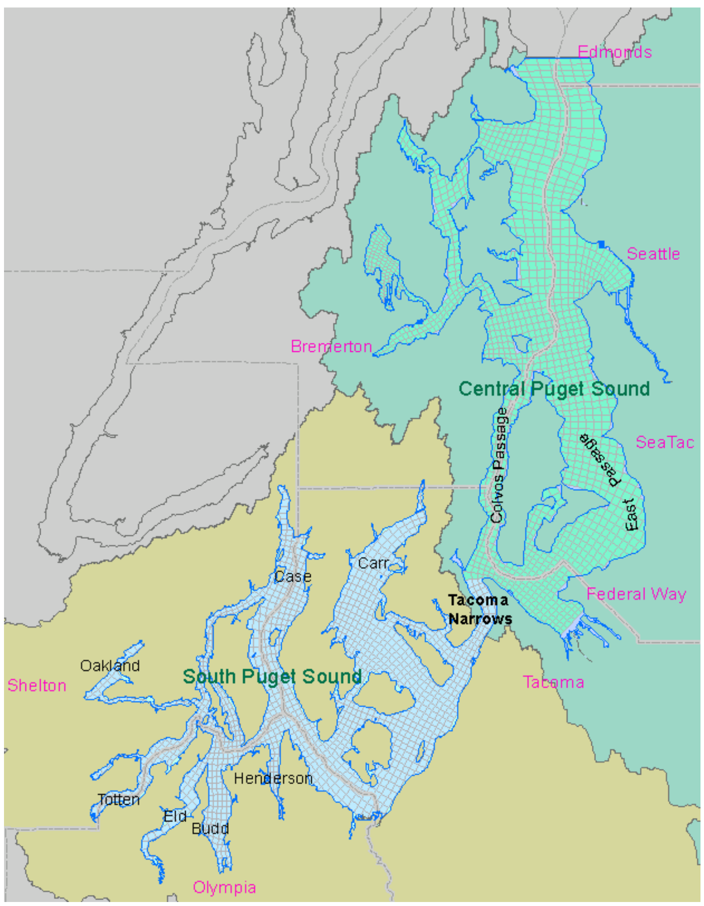


Figure ES-2. South and Central Puget Sound study area.

Water Quality Model Calibration to Current Conditions

Following calibration of the circulation model described in Roberts et al. (2013, in press), Ecology calibrated the water quality model to marine data collected in 2007. The model was run a total of 1190 times in batches of 50 to 70 runs at a time. We began with rates calibrated to Budd Inlet (Roberts et al., 2012) but modified them to optimize the fit to the entire South and Central Puget Sound region. Predicted results were compared with measurements as both time series at the surface and bottom and as profiles at key stations. Root mean square error (RMSE) and mean bias were used to provide objective measures of model skill to supplement visual observation of model results. Model runs with the highest skill during each batch of runs were evaluated to identify parameters to vary in subsequent batches. The calibration process focused on algal kinetics such as growth, respiration, and decay rates, as well as sediment fluxes.

The calibrated model predicts the seasonal and regional patterns in DO, nitrogen, and chlorophyll a concentrations throughout the model domain. Overall the model optimizes predictions of deeper DO concentrations. In the shallower inlets of South Puget Sound, the model tends to overpredict bottom-layer DO. However, the potential bias of predicted results is not statistically significant. While calibration focused on the RMSE for time series and profiles at key locations, we also compared detailed depth-time plots to monitoring data at 106 stations and evaluated surface and bottom DO, dissolved inorganic nitrogen (DIN), and chlorophyll throughout the model domain. The uncertainty of model predictions was comparable to previous modeling studies of Budd Inlet (Roberts et al., 2012).

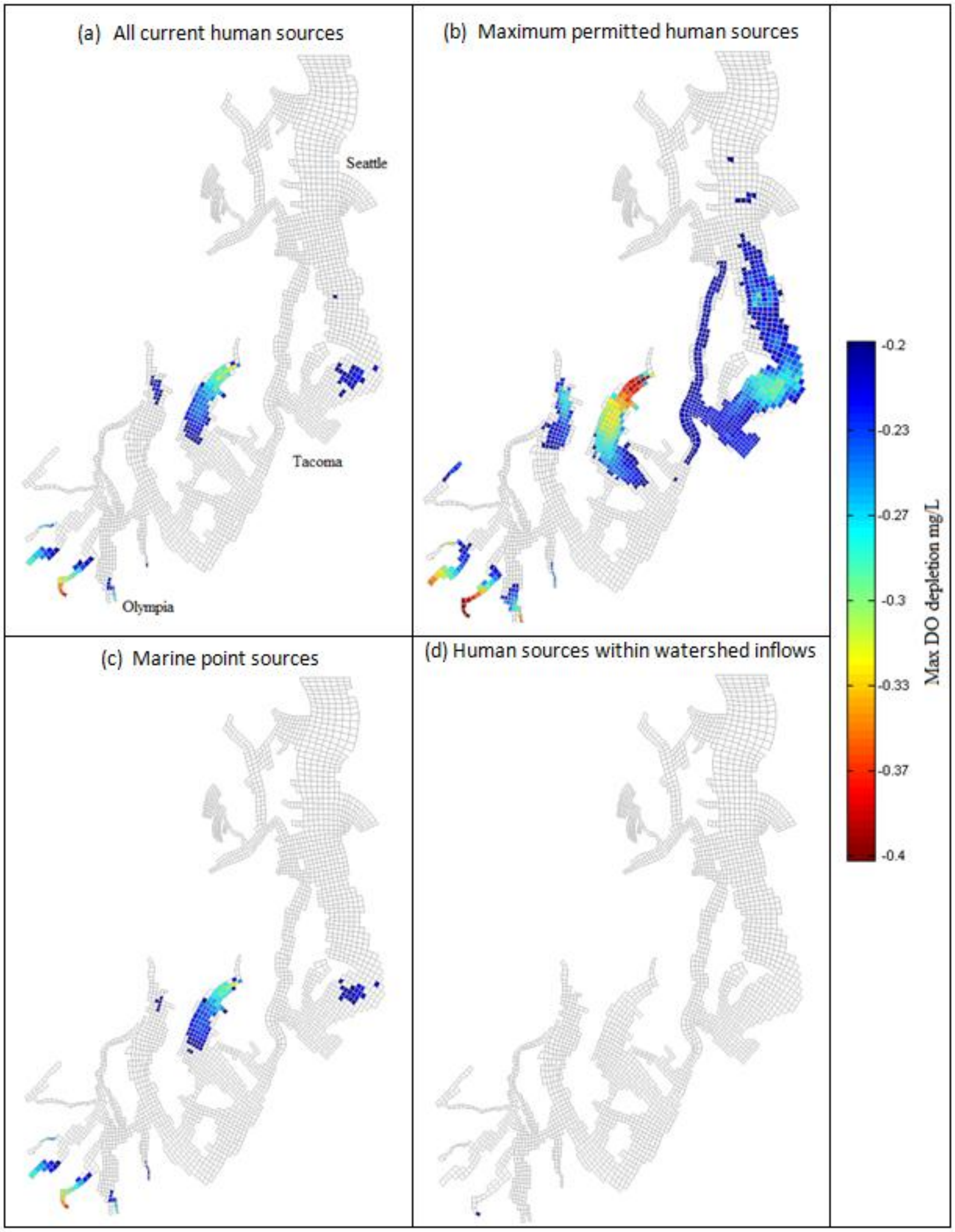
Scenario Results

The calibrated model was applied to a series of scenarios to isolate the influence of different sources and to provide initial results for potential management strategies. We applied the calibrated model to natural conditions, where watershed inflow concentrations were set to natural levels and nonpoint sources do not contribute nitrogen loads. To ensure hydrodynamic conditions remained the same, we used the same flow for marine point sources and assumed they would discharge at the same natural concentrations established for watershed inflows. This avoids the discharge of zero concentrations that could complicate scenario comparisons.

Natural concentrations of nitrogen and DO at the Edmonds open boundary were obtained using ratios of natural to current concentrations estimated from the Puget Sound / Salish Sea DO model (Khangaonkar et al., 2012) and current concentrations at Edmonds. In addition, we adjusted the sediment fluxes of nitrogen and oxygen under natural conditions to reflect the lower loading. For the various scenarios, the Edmonds open boundary concentrations and sediment fluxes were prorated between the current and natural conditions based on incoming load of total nitrogen to the model domain.

Compared with natural conditions, current human nutrient loads to South and Central Puget Sound (both internal and external to model domain) cause >0.2 mg/L decreases in daily minimum oxygen concentrations in portions of Totten, Eld, Budd, Carr, and Case inlets of South Puget Sound (Figure ES-3a). We also found violations in East Passage in Central Puget Sound.

It should be noted that the DO concentrations under natural conditions in these areas are predicted to be below the numeric criteria of DO standard.



Figures ES-3. Regions where current nutrient loads cause > 0.2 mg/L DO depletion for 2007 conditions.

If marine point sources (internal to model domain) discharged at their maximum permitted loads every day of the year, maximum loads would cause >0.2 mg/L depletions in more regions of the South Sound inlets, as well as a large portion of Central Puget Sound (Figure ES-3b).

In addition, we compared minimum DO concentrations with only human sources within watershed inflows (no marine point sources) and only marine point sources (watershed inflows at natural conditions) within the model domain. We found that marine point sources alone cause >0.2 mg/L depletion in more regions (Figure ES-3c) than human sources in watershed inflows alone (Figure ES-3d).

If all model domain human sources were reduced by 25, 50, or 75%, fewer areas would have >0.2 mg/L depletion, and the maximum depletion would decrease (Figure ES-4). A 25% reduction would eliminate nearly all of the violations in East Passage and Case Inlet, and would reduce the magnitude and extent of violations in the other South Puget Sound inlets. A 50% reduction would further decrease the maximum depletion, and a 75% reduction would eliminate all violations except in Eld Inlet, where the maximum violation would be 0.24 mg/L.

We also explored the relative influence of South and Central Puget Sound sources. We reduced Central Puget Sound sources to natural inputs only, kept South Puget Sound sources at current conditions, and adjusted the sediment flux scalars using two methods:

1. Reduce the sediment fluxes proportional to decreases in sources throughout South and Central Puget Sound. This first method assumes that a high proportion of current Central Puget Sound human sources reaches South Puget Sound. In this method, model results indicate that Central Puget Sound sources have a significant impact in all areas where the maximum depletion was >0.2 mg/L. The remaining South Puget Sound sources still would cause depletions in DO, but by themselves would not cause violations >0.2 mg/L except in Eld Inlet.

2. Reduce the sediment scalars only in Central Puget Sound. This second method assumes that a low proportion of Central Puget Sound human sources reaches South Puget Sound. In this second method, model results indicate that Central Puget Sound sources impact Case Inlet, Carr Inlet, and East Passage but not the western inlets.

The two methods bracket the potential response. The actual response would most likely lie somewhere in-between. Central Puget Sound sources influence at least East Passage, Carr, and Case Inlets. Additional modeling is needed to reduce this source of uncertainty.

The modeling objectives were to evaluate the relative contributions of different sources and to identify sources that may be contributing to water quality standards violations. These scenario results indicate that the current sources violate the standards, marine point sources have a greater impact than human sources within watersheds, and Central Puget Sound sources influence at least East Passage, Carr Inlet, and Case Inlet. South Puget Sound sources have the largest impact on finger inlets. Domain-wide nutrient reductions up to 75% would eliminate violations in all but one cell in Eld Inlet.

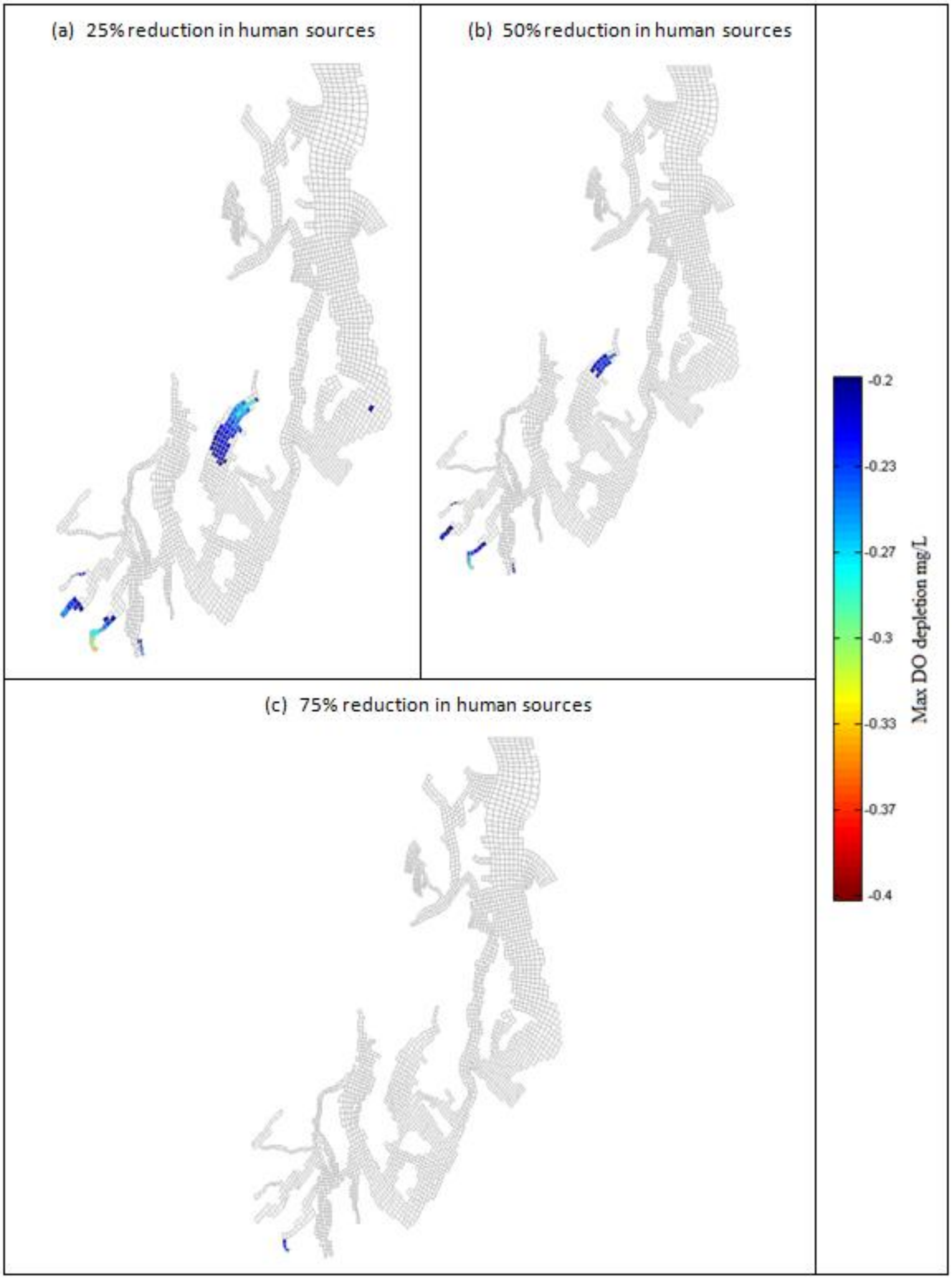


Figure ES-4. Regions where loads reduced by (a) 25%, (b) 50%, or (c) 75% would cause >0.2 mg/L DO depletion for 2007 conditions.

Sources of uncertainty in decreasing order of likely influence on results of scenarios are as follows:

- Relationship between changes in nutrient loading and corresponding changes in sediment flux. This is more significant for scenarios involving reduction of loading from selected sources or within partial regions. This uncertainty is likely less influential for scenarios involving reductions from all sources in all regions.
- Possible under-estimation of violations due to possible over-prediction of DO (though not statistically significant) in the bottom layers of shallow inlets.
- Changes in open boundary loading of nutrients from sources external to the model domain
- Changes in open boundary loading from reflux of loads within the model domain

Discussion and Conclusions

The circulation and water quality models were calibrated to 2007 conditions. Overall the model reproduces the complicated seasonal and regional patterns in DO, chlorophyll a, and nitrogen. No model application perfectly reproduces monitoring data. Differences between predicted and measured values are reasonable and appropriate for the modeling objectives.

The modeling objective was to evaluate the relative contributions of different sources and to identify sources that may be contributing to water quality standards violations. These scenario results indicate:

- Current human sources are causing DO standard violations in the landward end of several South Puget Sound inlets and East Passage in Central Puget Sound. There are not violations across the entire South or Central Puget Sound. The spatial extent of violations is smaller than the current 303(d) listings indicate.
- Human sources decrease DO by up to 0.38 mg/L below natural conditions. Violations occur for up to 13 weeks. Violations are in the bottom part of the water column.
- Within model domain, marine point sources exert a greater impact than human sources within watershed inflows.
- Decreasing human nutrient loading reduces the magnitude and extent of violations.
- A 75% reduction in human nutrient loading (inside the model domain) would eliminate violations in all but one cell in Eld Inlet, where the maximum depletion would remain at 0.24 mg/L compared with natural conditions.
- South Puget Sound sources decrease oxygen in Carr, Case, Totten, Eld, and Budd Inlets.
- Central Puget Sound sources decrease oxygen in East Passage, Carr Inlet, and Case Inlet.

- Central Puget Sound sources may decrease oxygen in Totten, Eld, and Budd inlets if a high proportion of these sources reach South Puget Sound.

- The proportion of Central Puget Sound sources reaching South Puget Sound has not yet been determined.

Observed DO concentrations display enormous variability, both seasonally and regionally. The water quality model predicts complex responses to algae growth, nitrogen levels, and circulation characteristics (Figure ES-5). These include intrusion of marine waters through the Edmonds boundary and formation of low DO water through algal growth and decomposition in South and Central Puget Sound. The addition of human nutrients beyond natural sources affects DO concentrations, and the impacts also vary seasonally and regionally.

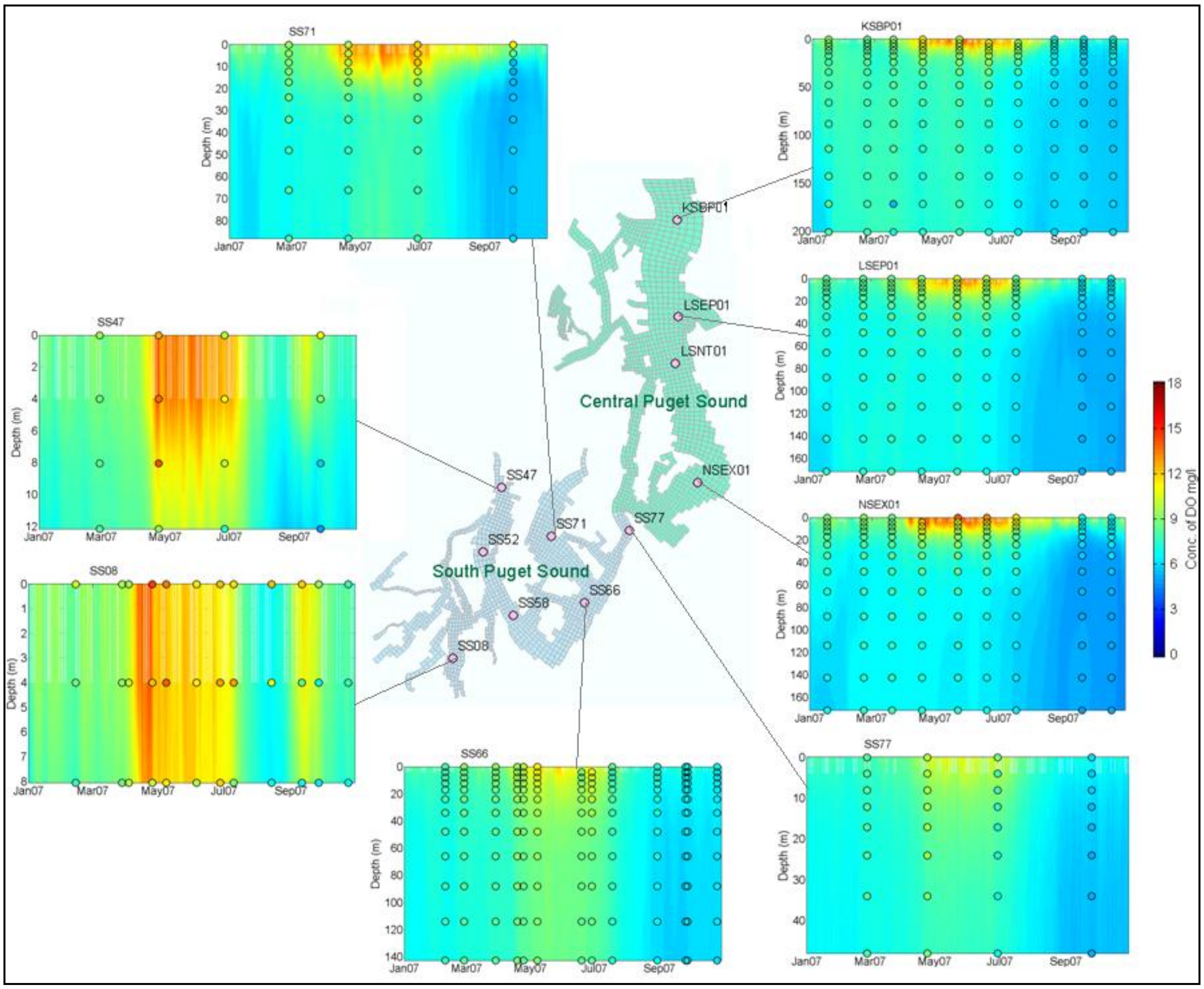


Figure ES-5. Predicted and observed DO at key locations in (a) Central and (b) South Puget Sound.

In the spring, chlorophyll a levels reflect strong algae growth, particularly in the shallow regions of South and Central Puget Sound. East Passage also exhibits strong algae growth, potentially spurred by vertical mixing near the Tacoma Narrows sill. Surface DO levels increase while DIN decreases during high algae growth. In the fall, DO reflects both marine water inflows and seasonal declines from biogeochemical processes. Productivity extends to the sediments in the shallow inlets, but human contributions still contribute to drawdown in some of these areas.

The Tacoma Narrows strongly influences circulation and water quality in both South and Central Puget Sound. The shallow water depth at the sill coupled with large tidal exchanges leads to very strong vertical mixing. Surface chlorophyll is lower and bottom DO higher than the adjacent deeper water in Central and South Puget Sound.

This is the first study to evaluate the impact of humans on DO concentrations within South and Central Puget Sound, which fall below the numeric criteria in the water quality standards. .

We recommend that the calibrated model be applied to additional scenarios to refine the understanding of particular sources. We recommend using both the circulation and the water quality model to evaluate the proportion of Central Puget Sound human nutrient sources that enter South Puget Sound. We also recommend evaluating specific sources within South Puget Sound.

Additional scenarios should be combined into potential sets of management actions to support the future development of load and wasteload allocations if a TMDL is pursued. Ecology may not conduct a TMDL if alternative management approaches are used to address violations.

We recommend continued coordination with the larger Puget Sound / Salish Sea model efforts. The Puget Sound / Salish Sea model has additional layers in shallow inlets that could be used to refine predictions in both models. An upcoming effort will also add the capability to simulate sediment-water exchanges interactively.

Summary of Public Involvement

Ecology has convened stakeholders in meetings since 2006. These individuals and organizations provided feedback on the overall project approach as well as on interim results.

Introduction

What is the South Puget Sound Dissolved Oxygen Study?

The objectives of the South Puget Sound Dissolved Oxygen Study are to evaluate the relative contributions of different nutrient sources and to identify sources that may be contributing to low dissolved oxygen (DO) in South Puget Sound. The study includes data collection and modeling to determine whether human nitrogen loads are contributing to low levels of DO in South Puget Sound.

Portions of South and Central Puget Sound are on the Clean Water Act Section 303(d) list of impaired waters because they do not meet the numeric criteria of the Washington State water quality standards for DO. Under the Clean Water Act, the Department of Ecology establishes water quality standards to protect the physical, chemical, and biological integrity of Washington's waters. Standards include minimum levels of DO to protect fish and other aquatic life. Low levels of DO can cause fish and other marine life to become stressed and die or flee their habitat. Modeling tools are needed to distinguish how much depletion results from human nitrogen inputs.

Multiple physical, chemical, and biological processes contribute to seasonally low DO levels in late summer. Sunlight and nutrients lead to algae growth. Excessive algae growth, or a bloom, produces high organic matter levels. When the algae die and sink to the bottom, bacteria decompose the organic matter and consume oxygen in the process. Lower DO levels can occur where water stagnates, when water columns stratify, and where ample nutrients and warm temperatures occur. Nitrogen is typically the nutrient that limits algae growth in marine ecosystems. Discharges from wastewater treatment plants, septic systems, and other sources add nitrogen to Puget Sound. Different sources of nitrogen are discussed later in this section.

The South Puget Sound Dissolved Oxygen Study includes three components:

1. **Data Collection**: Roberts et al. (2008) summarizes data collected from 90 marine stations within South and Central Puget Sound, 29 point sources, and 39 rivers and streams in 2006 and 2007.

   Mohamedali et al. (2011) developed load estimates for municipal wastewater treatment plants (WWTPs) discharging to marine waters (marine point sources) as well as from watersheds, which include natural, nonpoint sources such as septic systems, and point source contributions.

2. **Model Development**: Roberts et al. (2013, in press) describes the circulation model calibrated to 2006 and 2007 conditions. This report presents the water quality model calibration to 2006 and 2007.

3. **Scenarios**: Ecology applied the model to alternative loading scenarios to evaluate the effects of human contributions relative to natural nitrogen sources. Scenarios also evaluated impacts

from groups of sources. This report summarizes the results of the initial what-if scenarios. A future report will evaluate impacts from individual sources of nitrogen.

Geographic Setting

This effort focuses on South Puget Sound, south of the Tacoma Narrows (Figure 1) However, Central Puget Sound sources contribute more human nitrogen loads than South Puget Sound because of the higher population (Mohamedali et al., 2011). The estuarine circulation patterns result in a net landward motion in the lower water column where the large wastewater outfalls discharge. Because of the potential influence on South Puget Sound water quality, Ecology included the entire South and Central Puget Sound area in the study.

South and Central Puget Sound (Figure 1) include a complex and interconnected system of straits and open waters in Washington State. South Puget Sound is defined traditionally by the Tacoma Narrows and an entrance sill located just to the south of the Tacoma Narrows. The sill is a shallow reach formed during the glacial epochs tens of thousands of years ago, with typical depths around 50 meters. Deeper regions both seaward and landward of the sill are greater than 150 meters.

Central Puget Sound, also called the main basin, extends from the Tacoma Narrows to the north or seaward. Commencement Bay, Colvos Passage, Quartermaster Harbor, Sinclair and Dyes Inlets, Elliott Bay and Liberty Bay are all distinct areas within Central Puget Sound. Due to the complex circulation patterns further north, Ecology located the northern model boundary near Edmonds. This location balances the need to include Central Puget Sound water quality contributions against the circulation complexities further north.

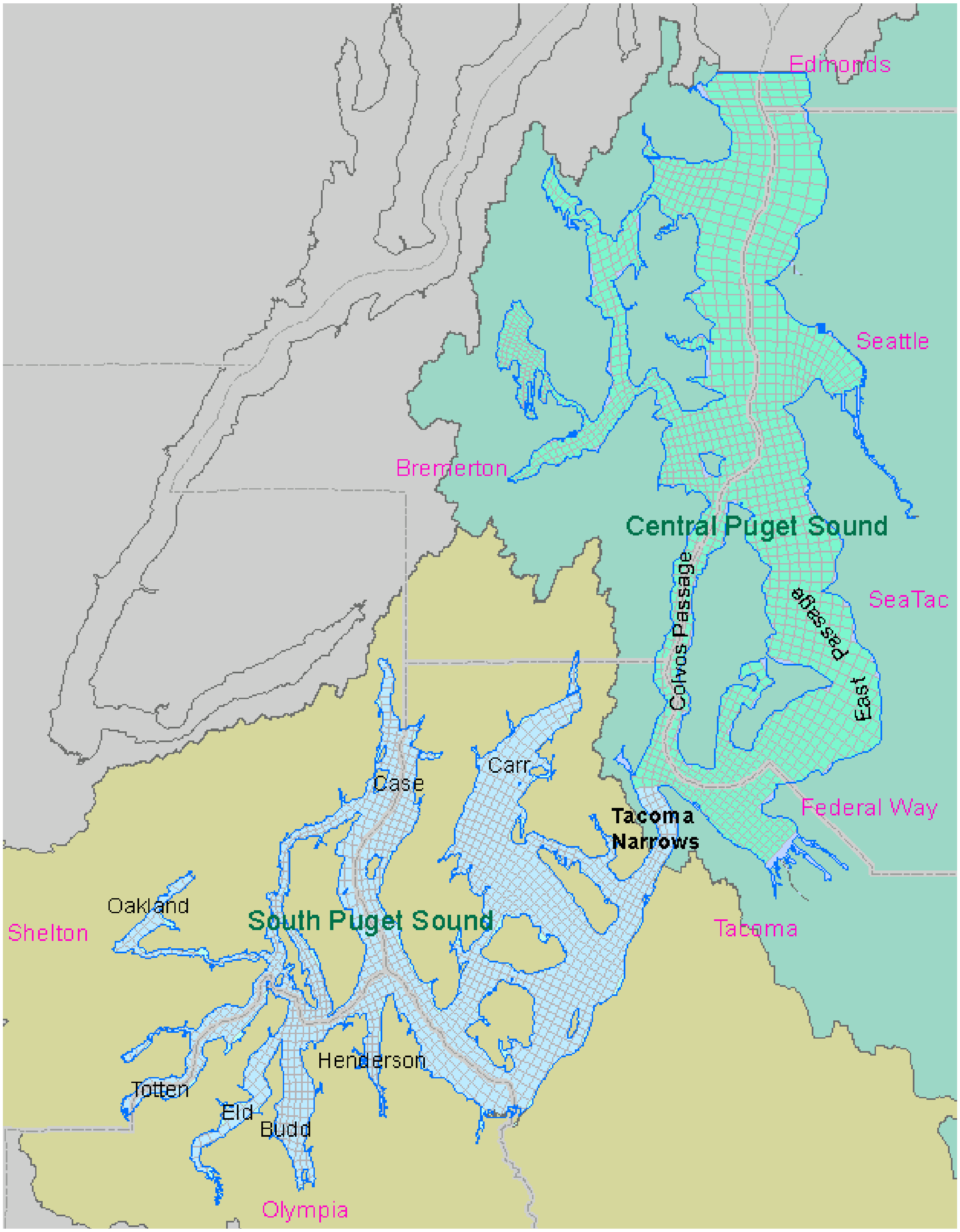


Figure 1**. South Puget Sound Dissolved Oxygen Study water bodies and place names**

Sources of Nitrogen

Nitrogen enters Puget Sound from many different human and natural sources. The dominant source of nitrogen is marine water that enters with the tides that is defined as the estuarine exchange multiplied by the observed concentrations. Other sources add to the marine nitrogen. For this study, Ecology grouped the sources of nitrogen into five main categories (Figure 2).

1. **Exchange of Marine Water**
   The exchange of marine water is the nitrogen that enters and leaves Central Puget Sound at Edmonds as tides move water to and from northern parts of Puget Sound and the Pacific Ocean.

2. **Marine Point Sources**
   For this study, marine point sources refer to the subset of municipal WWTPs and industrial facilities that discharge directly to South or Central Puget Sound. WWTPs that discharge to freshwater are not included in this category, but are part of watershed sources. The South Puget Sound Dissolved Oxygen Study includes 31 municipal wastewater treatment plants and 2 industrial facilities that discharge nitrogen directly to Puget Sound.

3. **Watershed Inflows**
   Watershed inflows include all natural, nonpoint, and point sources of nitrogen that reach South or Central Puget Sound through rivers, streams, lakes, stormwater infrastructure, shoreline areas, or marine discharges of groundwater. Watershed inflows were monitored at the mouths of rivers, streams, and lakes and extrapolated to the shoreline areas (Mohamedali et al., 2011). This study includes 45 watershed inflows representing rivers, streams and lakes that flow into South and Central Puget Sound. Watershed inflows include septic systems, stormwater, WWTPs discharging to rivers, upland atmospheric deposition, other point and nonpoint sources, and natural sources.

4. **Atmospheric Deposition**
   Atmospheric deposition is the addition of nitrogen directly to South and Central Puget Sound from rain and the atmosphere. Atmospheric deposition to the watershed and freshwater bodies are included with watershed inflows.

5. **Sediment Fluxes to Marine Water**
   Benthic (sediment) release is an indirect, but important, source of water column nutrients. Detritus from algae growth and external loads accumulates in the sediments. Organic nitrogen from the water column is converted to dissolved inorganic nitrogen (DIN) in the sediments through chemical and biological transformations. The DIN is then released to the water column.

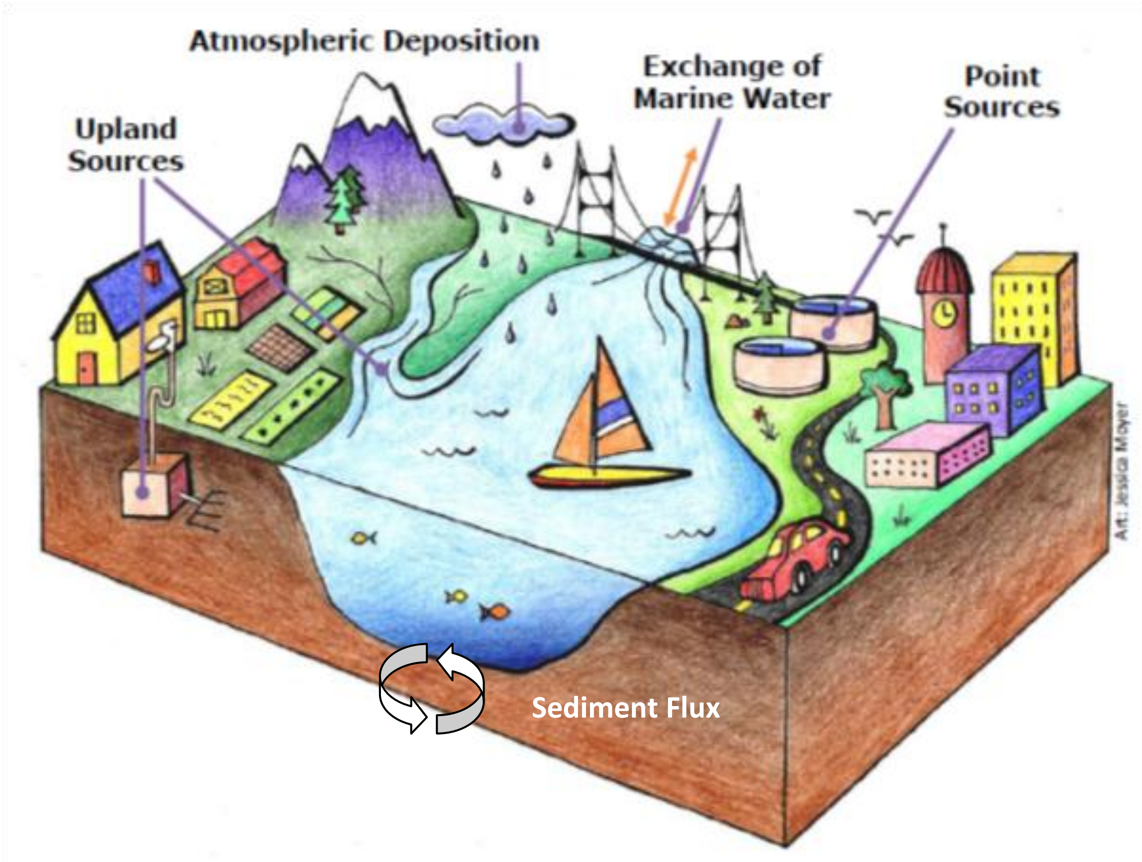


Figure 2. Sources of nitrogen in South and Central Puget Sound.

Mohamedali et al. (2011) summarized DIN loads from marine point sources, watershed inflows, and atmospheric deposition. Figure 3 and Figure 4 present individual marine point source and watershed inflows DIN loads, while Figure 5 summarizes the proportions contributed by watershed inflows (rivers), marine point sources (WWTPs), and atmospheric deposition to the surface of South and Central Puget Sound. Marine and sediment contributions are not estimated in Mohamedali et al. (2011) because these require model output.

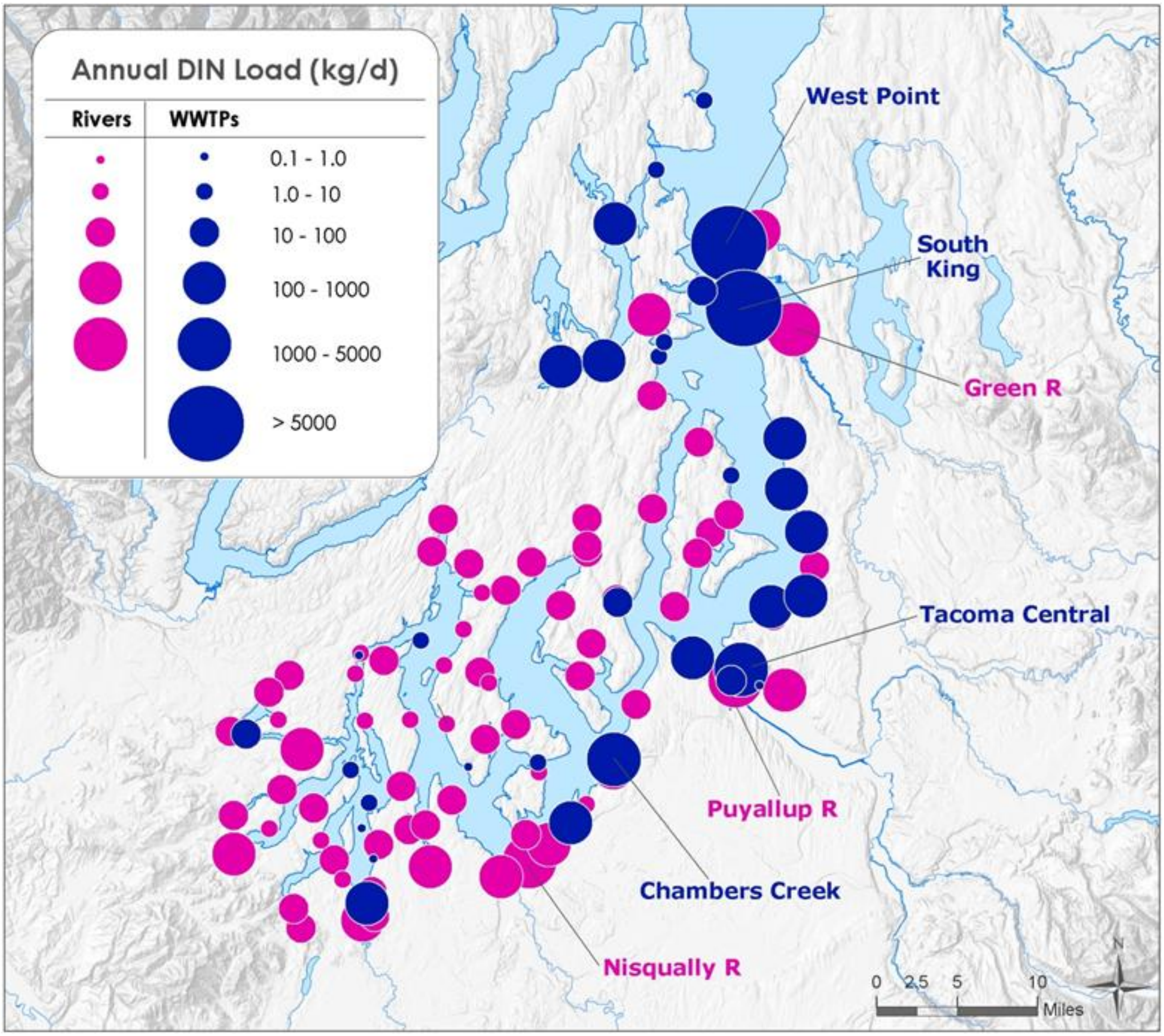


Figure 3. Mean annual dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into South and Central Puget Sound. from 2006-07.

Source: Mohamedali et al. (2011).

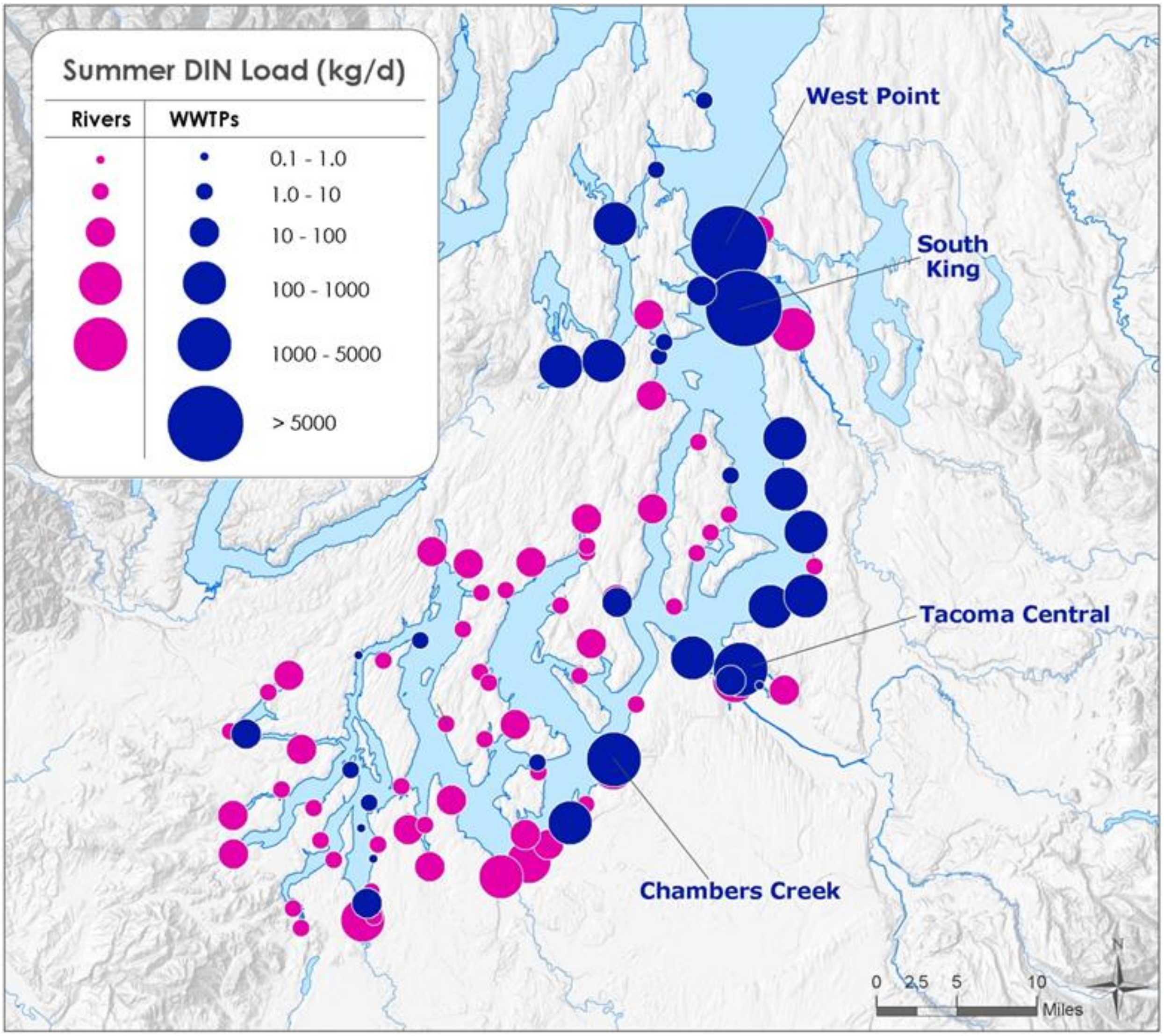


Figure 4. Mean summer dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into South and Central Puget Sound from 2006-07.

Source: Mohamedali et al. (2011).

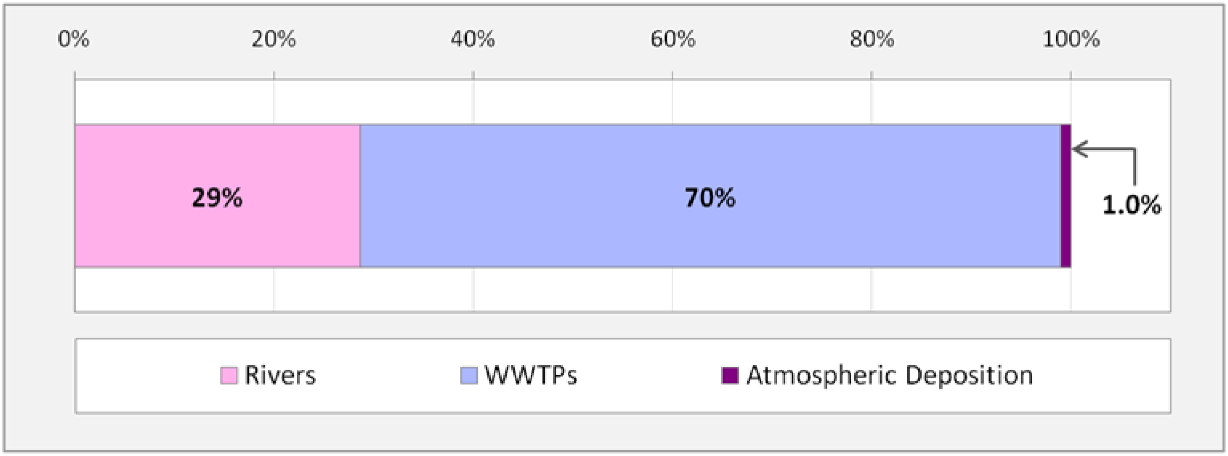


Figure 5. Annual dissolved inorganic nitrogen (DIN) loads from rivers, WWTPs, and atmospheric deposition to the surface of South and Central Puget Sound from 2006-07.

Source: Mohamedali et al. (2011).

Sources and Sinks of Dissolved Oxygen

1. **Exchange of Marine water**
   The exchange of marine waters that enters Central Puget Sound near Edmonds due to tidal movement brings water from northern parts of Puget Sound and the Pacific Ocean. The water coming into the model domain is at the bottom and generally is of lower DO compared with DO near the surface.

2. **Re-aeration and DO saturation**
   When DO in the surface layers of the water column is lower than the partial pressure of O2 in the atmosphere, there is a net transfer of DO from the air into the water (re-aeration). Oxygen is transferred from water to the air when DO in the water is higher than the partial pressure of O2 in the atmosphere, usually due to photosynthesis. The solubility of DO in water is affected by temperature, salinity and atmospheric pressure. DO saturation is the ratio of DO to the amount of DO that would be completely saturated at the ambient temperature, salinity, and pressure. Both re-aeration and DO saturation define how much DO is retained by the water column.

3. **Rainfall and other freshwater sources**
   Rainfall, rivers, and other freshwater sources add DO depending on the DO and flow of the source. DO in rainfall is likely near the 100% saturation level.

4. **Nitrogenous Biochemical Oxygen Demand**
   When ammonia is converted to nitrate in a process called "nitrification", oxygen is consumed by the microorganisms conducting this process.

5. **Carbonaceous Biochemical Oxygen Demand**

DO is consumed by microorganisms during the oxidation of dissolved organic carbon originating from dissolved and particulate organic matter delivered by the Marine Point Sources, Watershed Inflows, and produced by photosynthesis within water column decay.

6. **Algal respiration**
   Phytoplankton and zooplankton respire and consume DO.

7. **Algal photosynthesis**
   In presence of sunlight, algae use the inorganic carbon from dissolved carbon dioxide (CO_2) to produce organic carbon while releasing the oxygen (O_2) into the water column.

8. **Sediment Oxygen Demand:**
   Oxygen is consumed by microorganisms when dead algae and settled organic matter in the sediments decomposes.

Federal Clean Water Act Requirements

The Clean Water Act (CWA) establishes a process to identify and clean up polluted waters. The CWA requires each state to have its own water quality standards that protect, restore, and preserve water quality. Water quality standards consist of (1) designated uses for protection, such as marine life, and (2) criteria, usually numeric criteria, to achieve those uses.

Water Quality Standards and Numeric Targets

South and Central Puget Sound waters are protected for numerous uses including all four levels of aquatic life (extraordinary, excellent, good, and fair), shellfish harvesting, recreational uses, and miscellaneous uses.

Having adequate levels of DO is essential for aquatic life. The water quality standards for marine DO are found in WAC 173-201A-210(1)(d) and have two parts. Numeric DO criteria are applied as a 1-day minimum DO concentration in milligrams per liter (mg/L). The criteria are applied such that concentrations must be greater than a specific threshold, which varies by location and aquatic life category to be protected, at all times of year and locations in the water column (Figure 6):

- Extraordinary quality: 7.0 mg/L
- Excellent quality: 6.0 mg/L
- Good quality: 5.0 mg/L
- Fair quality: 4.0 mg/L

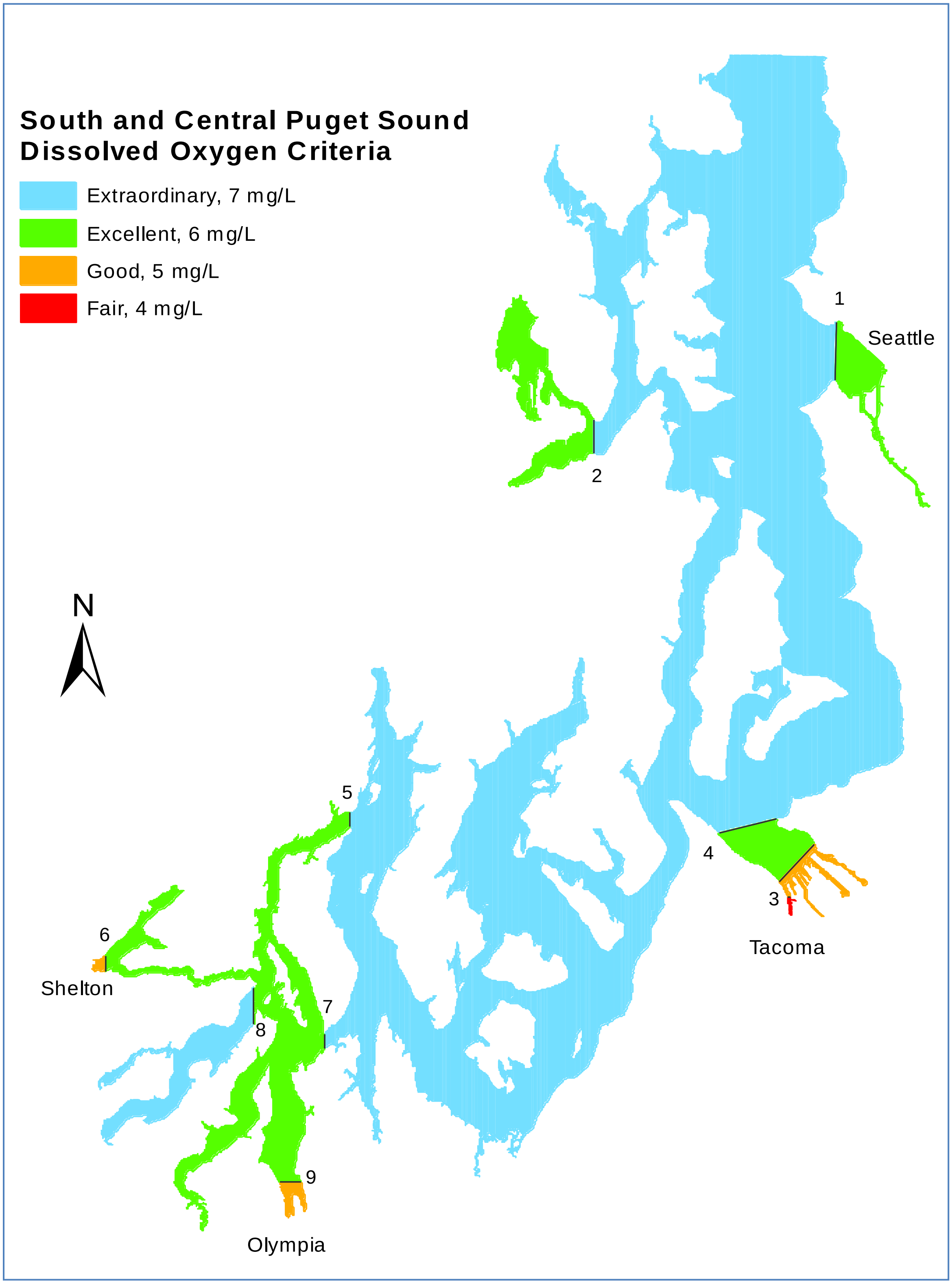


Figure 6. Marine DO standards in South and Central Puget Sound.

See following page for more detail corresponding to each line and number on map.

The numeric DO criteria vary from 4 mg/L in the inner Commencement Bay to 7 mg/L in most of South and Central Puget Sound. Lines of demarcation are determined in the WAC:

1. Line 1 divides excellent waters in Elliot Bay east of Duwamish Head and Pier 91 from extraordinary waters in the main channel west of this line.

2. Line 2 divides excellent waters in Dyes and Sinclair Inlets west of longitude 122˚ 37′ 0″ from extraordinary waters in the main channel east of this line.

3. Line 3 divides the good waters in Inner Commencement Bay from Excellent waters in the Outer Commencement Bay along southeast of line through Hylebos. The inner bay also contains an area of fair water quality. The Inner commencement Bay is not included in the model.

4. Line 4 is at the edge of the outer Commencement Bay at Brown's point and it divides excellent waters in the outer Commencement Bay from extraordinary waters in the main channel north of this line.

5. Line 5 separates excellent waters in Pickering Passage from extraordinary waters in Case Inlet and the main channel

6. Line 6 divides the good waters in the inner Shelton Harbor from excellent waters in Oakland Bay and Hammersley Inlet along Longitude 122˚ 5′ 0″

7. Line 7 divides Dana Passage with excellent waters east of the line from extraordinary waters west of this line

8. Line 8 divides extraordinary waters in Totten and Little Skookum Inlets west of longitude 122˚ 56′ 32″ from excellent waters east of this longitude

9. Line 9 divides the good waters in Inner Budd Inlet from excellent waters in Outer Budd Inlet along Latitude 47˚ 4′ 0″.

We mapped these definitions to the model grid cells, but they do not align with the demarcation lines described above. Therefore, if a grid cell has more than one numeric criterion within it, then the more restrictive of the two is assigned to the entire grid cell. This results in a modification of the boundary lines (as specified in WAC 173-201A-210(1)(d)) to conform to the grid cell boundaries (Figure 7).

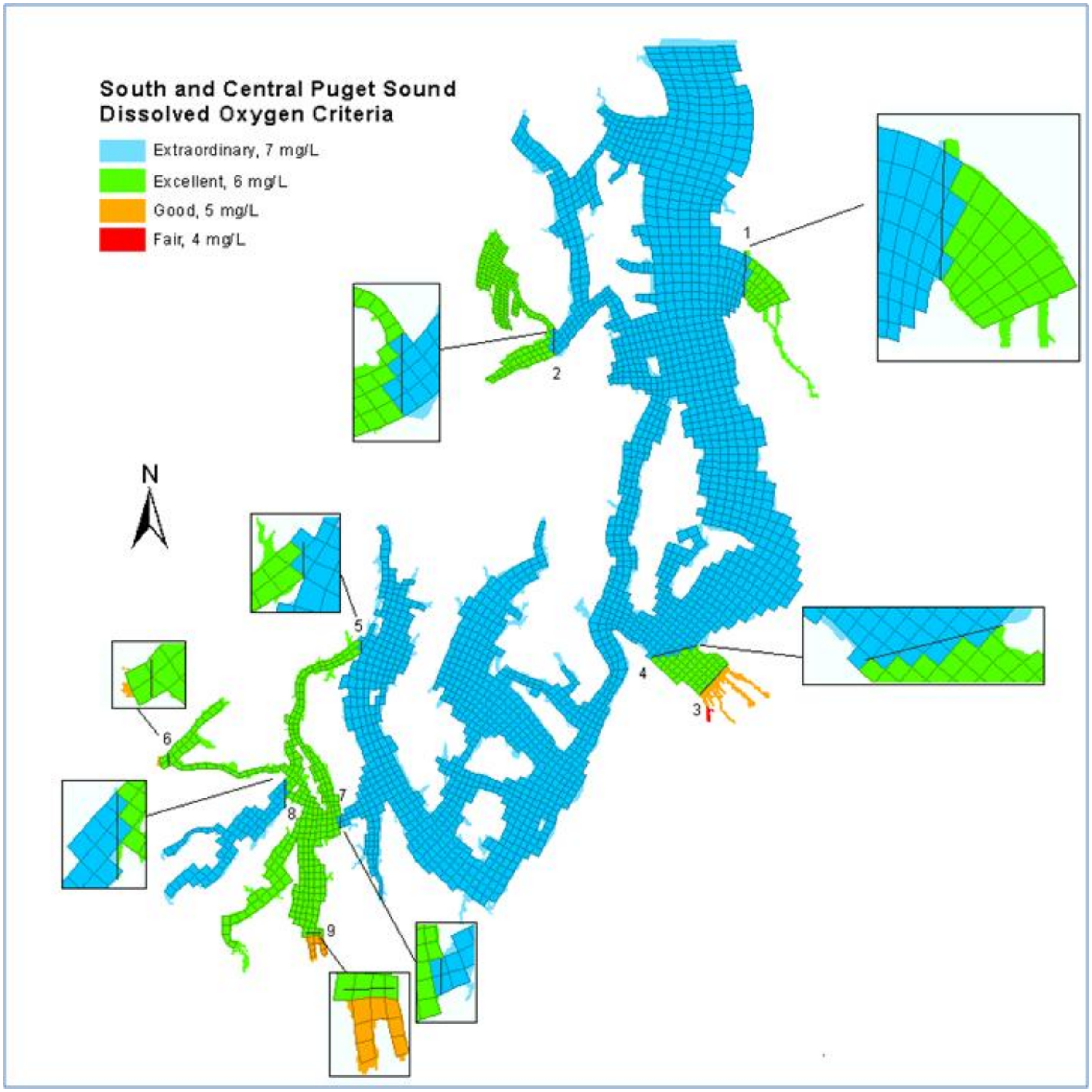


Figure 7. DO standards delineations applied to South and Central Puget Sound model grid.

The second part of the DO standard in WAC 173-201A-210(1)(d)(i) overrides numeric DO criteria. The second part states: "When a water body's dissolved oxygen (DO) is lower than the numeric criterion in the dissolved oxygen standard (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the DO of that water body to decrease more than 0.2 mg/L."

Because DO measurements include the combined effect of natural and human influences, the second part of the standard cannot be evaluated using data alone. The South and Central Puget Sound DO model was developed to determine whether human sources cause >0.2 mg/L decrease in DO in waters naturally below the criterion or cause any areas with DO naturally above the numeric criterion to fall below the threshold.

The Water Quality Assessment and the 303(d) List

Under Section 303(d) of the Clean Water Act, states are required to prepare a list of water bodies that do not meet water quality standards. In Washington State, the 303(d) list is part of the Water Quality Assessment (WQA) process. The U.S. Environmental Protection Agency (EPA) approved the most recent list on December 21, 2012. Further information is available at Ecology's Water Quality Assessment website.

To develop the WQA, the Washington State Department of Ecology (Ecology) compiles its own water quality data along with data from local, state, and federal governments, tribes, industries, and citizen monitoring groups. All data in this WQA are reviewed to ensure that they were collected using appropriate scientific methods before they are used to develop the assessment. Waterbodies are placed in one of five categories based on the WQA:

- Category 1 – Meets standards for parameter(s) for which it has been tested.
- Category 2 – Waters of concern.
- Category 3 – Waters with no data or insufficient data available.
- Category 4 – Polluted waters that do not require a TMDL because they:
  - 4a – Have an approved TMDL being implemented.
  - 4b – Have a pollution control program in place that should solve the problem.
  - 4c – Are impaired by a non-pollutant such as low water flow, dams, or culverts.
- Category 5 – Polluted waters that require a TMDL – the 303(d) list.

Only Category 5 listings from the WQA constitute the 303(d) list. These include marine waters that do not meet the numeric DO criteria. Because a model is needed to distinguish human influences from naturally occurring low DO, not all of these listings may violate both parts of the standards.

Figure 8 presents the Category 5 listings for marine DO in South and Central Puget Sound. Appendix A contains the complete list. South and Central Puget Sound has over 70 Category 5 listings for marine DO. Additional Category 2 listings (waters of concern) exist throughout the study area.

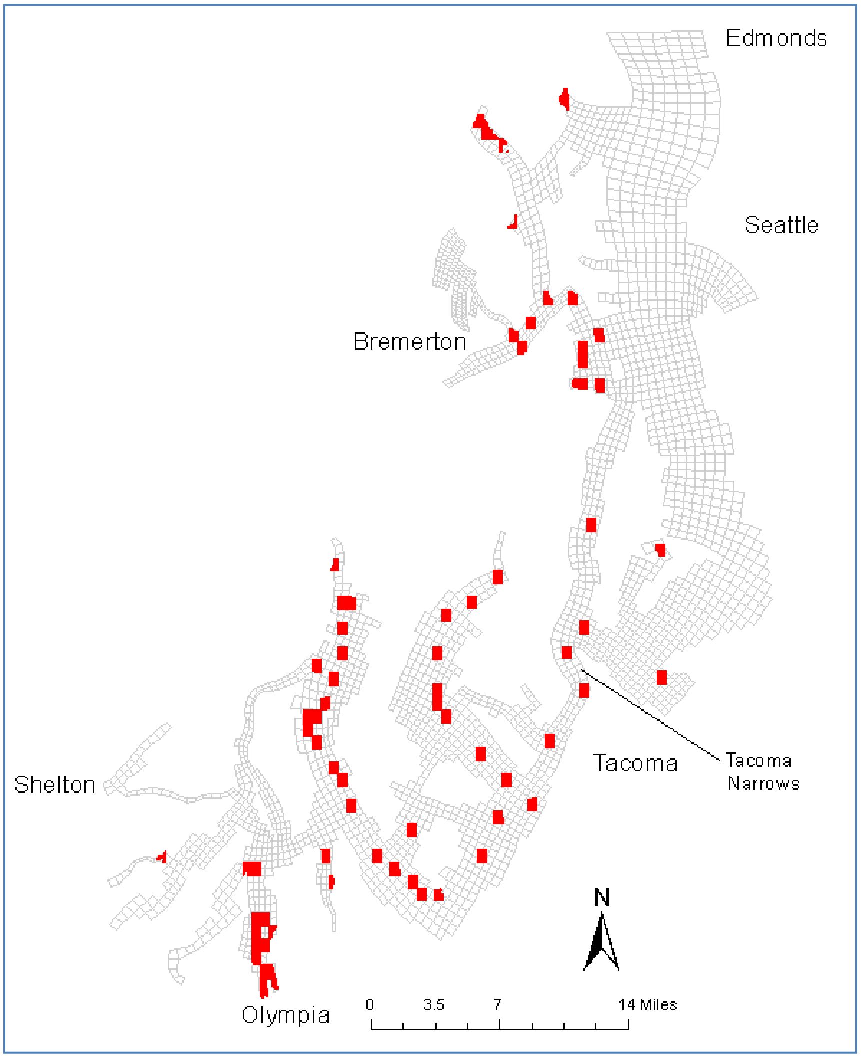


Figure 8. 2012 Category 5 (impaired waters) listings of marine DO in South and Central Puget Sound.

How Ecology Determines a Dissolved Oxygen Violation

A computer model is required to determine whether the waterbodies identified as Category 5 on the 303(d) list in Appendix A violate both parts of the water quality standards. Each waterbody was added to the 303(d) list based on measurements that fall below the numeric DO standards. To apply the second part of the standards, we determine natural nitrogen loading to marine waters and apply the water quality model with natural loading only. Predicted DO is compared against current conditions to evaluate whether current sources cause >0.2 mg/L depletion in minimum daily DO. Note that "current conditions" for this report are as of 2007 because that is the year data are available.

To determine whether water quality standards are violated, the water quality model is run first with natural conditions only and then with current (2007) loads. If the difference in predicted DO between the two model runs is >0.2 mg/L, then a violation occurs. The water quality model predicts DO in every layer in every model grid cell for every time step with a frequency smaller than hourly. The water quality standards do not establish a specific water volume or time period to consider. In general, averaging over space or time cannot be used to mask violations.

To apply the water quality standards with the South Puget Sound DO model, we process model output from both the natural condition and current condition model runs:

- Save instantaneous model predictions of DO (every grid cell and every layer) every hour for every day of the simulation period.
- Calculate the daily minimum DO for each layer of each grid cell for the entire simulation period.
- If the current condition minimum DO in any layer or any grid cell is below or within 0.2 mg/L of the numeric DO criterion, calculate the difference in daily water column minimum DO for each layer within each grid cell between the natural condition and current condition.
- Identify any grid cell where current condition minimum DO >0.2 mg/L in any layer. The highest depletion in the worst layer is identified and assigned to the grid cell.

A violation of the DO standard is then defined as any grid cell that meets one of two criteria:

1. The DO under natural conditions is <u>greater</u> than the numeric DO criterion plus 0.2 mg/L, and the predicted DO for current conditions falls below the numeric DO criteria.
2. The DO under natural conditions is <u>below</u> the numeric DO criterion plus 0.2 mg/L, and the predicted DO for current conditions falls below the natural condition DO by at least 0.2 mg/L

To apply the standards to scenarios, we apply the same method but replace “current conditions” with “scenario condition”.

Water Quality Model Description and Setup for Current Conditions

This section describes the model used to assess DO in South and Central Puget Sound. We also document the information used to set up the model, including both boundary conditions and initial conditions. Finally, we describe the marine data used to compare against model predictions.

Water Quality Model Description

Ecology applied the Generalized Environmental Modeling System for Surface Waters (GEMSS) to simulate current and potential water quality in South and Central Puget Sound. GEMSS is an integrated system of three dimensional (3-D) hydrodynamic and transport models embedded in a geographic information and environmental data system (GIS) and set of pre- and post-processing tools to support 3-D modeling. The theoretical basis of the three dimensional model was first presented in Edinger and Buchak (1980) and subsequently in Edinger and Buchak (1985) under the previous name called GLLVHT for the Generalized Longitudinal, Lateral, and Vertical Hydrodynamic Transport model.

GEMSS has been peer reviewed and published (Edinger and Buchak, 1995; Edinger, et al., 1994 and 1997). The fundamental computations are an extension of the well known longitudinal-vertical transport model that was developed by J. E. Edinger Associates, Inc. beginning in 1974 and summarized in Buchak and Edinger (1984). This model forms the hydrodynamic and transport basis of the Corps of Engineers' water quality model CE-QUAL-W2 (U.S. Army Engineer Waterways Experiment Station, 1986). GEMSS has previously been applied in Budd Inlet (Roberts et al., 2012) and many other waterbodies (e.g., Fischera et al., 2005).

The circulation model simulates water surface elevations, velocity, temperature, and salinity throughout the model domain (Roberts et al., 2013, in press). The northern boundary was established at Edmonds to capture the largest nutrient sources within Central Puget Sound but to avoid the complicated circulation patterns north of Edmonds.

Ecology used the three dimensional GLLVHT numerical model within GEMSS to simulate water surface elevations, velocity components, temperature and salinity in the South and Central Puget Sound model domain. Hydrodynamic model description using GLLVHT and calibration to these physical parameters measured in the field are presented in the water circulation report (Roberts et al., 2013, in press).

The Water Quality Carbon Based Module (WQCBM) within GEMSS was used to simulate the concentrations and transformations of DO, ammonia, nitrate, dissolved and particulate organic nitrogen (DON and PON), dissolved and particulate organic phosphorus (DOP and POP), dissolved and particulate organic carbon (DOC and POC), as well as chlorophyll concentrations tied to the GAM (generalized algae) module. The kinetic rates and constants for water quality variables were regionalized between shallow inlets and the deeper channel (see Appendix D).

The state variables used in GEMSS/WQCBM are listed in Table 1. The flowchart of kinetic processes for WQCBM/GAM modules is presented in Figure 9. Over 50 kinetic processes are simulated including auxiliary functions for light attenuation, reaeration rate as a function of wind speed, sediment exchange for NH3, NO3, PO4, and sediment oxygen demand (SOD), light, nutrient and temperature limitation of phytoplankton, settling of phytoplankton and detritus, and other processes.

Table 1. List of water quality state variables in WQCBM

Variable	Notation	Units
Ammonium N	NH3	gN/m^3
Nitrate + nitrite N	NO3	gN/m^3
Inorganic P	PO4	gP/m^3
Phytoplankton (GAM1 and GAM2)	PHYT	gC/m^3
Fast-reacting dissolved CBOD	CBOD_F	gO2/m^3
Slow-reacting dissolved CBOD	CBOD_S	gO2/m^3
Dissolved Oxygen	DO	gO2/m^3
Dissolved organic N	ON_D	gN/m^3
Particulate organic N	ON_P	gN/m^3
Dissolved organic P	OP_D	gP/m^3
Particulate organic P	OP_P	gP/m^3
Fast-reacting particulate organic C	OC_P_F	gC/m^3
Slow-reacting particulate organic C	OC_P_S	gC/m^3
Refractory particulate organic C	OC_P_R	gC/m^3

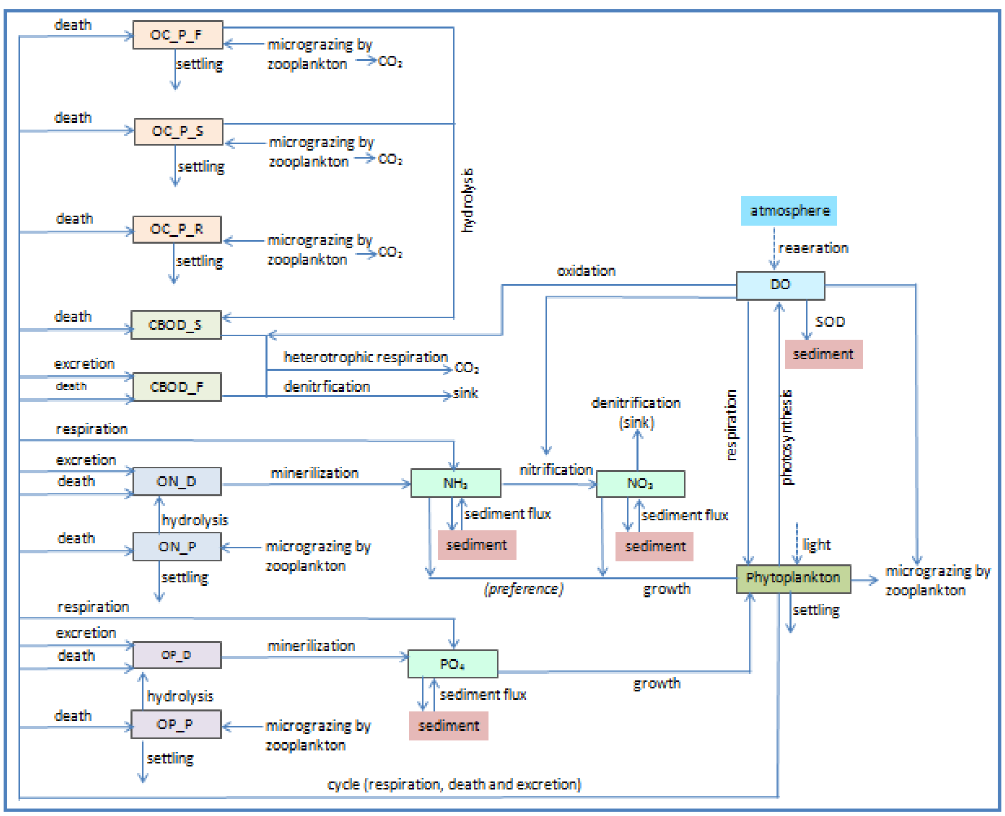


Figure 9. Flowchart of GEMSS-WQCBM model

The Generalized Algae Module (GAM) was used to define two phytoplankton groups, GAM1 and GAM2. These are not specific species but generally represent the diatom-dominated spring blooms and the dinoflagellate-dominated growth in late summer. Different rates were used for different regions in the model domain for algal growth, respiration, settling velocities, light constants, and optimum temperature for growth. These regions were inner and outer areas of shallow inlets (Oakland Bay, Henderson, Budd, Eld, and Totten Inlets) and the main channel.

The optimum temperatures were calibrated separately for GAM1 and GAM2. Values were lower for GAM1 than GAM2 to simulate early and late chlorophyll peaks during the model simulation period. The settling velocity was also treated separately for GAM1 and GAM2. Settling velocities were higher for GAM1 than GAM2 to represent early blooming species with higher settling velocities dominated by diatoms with a relatively higher peak while GAM2 represents later blooming species dominated by dinoflagellates with slower settling velocities and a relatively flatter peak. To preserve mass balance, the carbon-to-chlorophyll ratios were kept constant for each algal group for the whole model domain and did not vary with time. The carbon to nitrogen ratio was specified and kept constant for all algal groups.

Model Domain and Grid

A detailed description of how the model grid was developed, bathymetry used, grid layering and smoothing procedures involved is included in the circulation report (Roberts et al., 2013, in press). Figure 10 shows the grid used to define the extent of Central and South Puget Sound. The model domain extends from Oakland Bay in the south to the open boundary at Edmonds in the north. Depths range from very shallow inlets less than 20 m deep in several inlets to over 200 m deep in the main basin of Central Puget Sound. The orthogonal grid was developed to describe the complicated shapes of South and Central Puget Sound and captures most features. However, not all features are included, such as Gig Harbor near the Tacoma Narrows.

The model uses grid cells with a typical resolution of 600 m although individual cells range in size from 300 to 1300 m. Each grid cell has up to 17 layers that are 4 m thick in the intertidal zone and increase in thickness with water depth up to 29 m in the deepest locations. Shallow inlets have fewer layers than deeper inlets. The model grid resolution represents a balance between sufficient detail to capture key processes and model run time.

GEMSS runs on a 64-bit Windows server with 2 Xeon 5680 (3.33 GHz) processors (each has 6 cores with 2 logical processors for a total of 24 processors) with 64 Gigabyte of random access memory. Each run requires 10 days to simulate 10 months. Increasing the resolution or layering would have extended run times, limiting usefulness for model calibration.

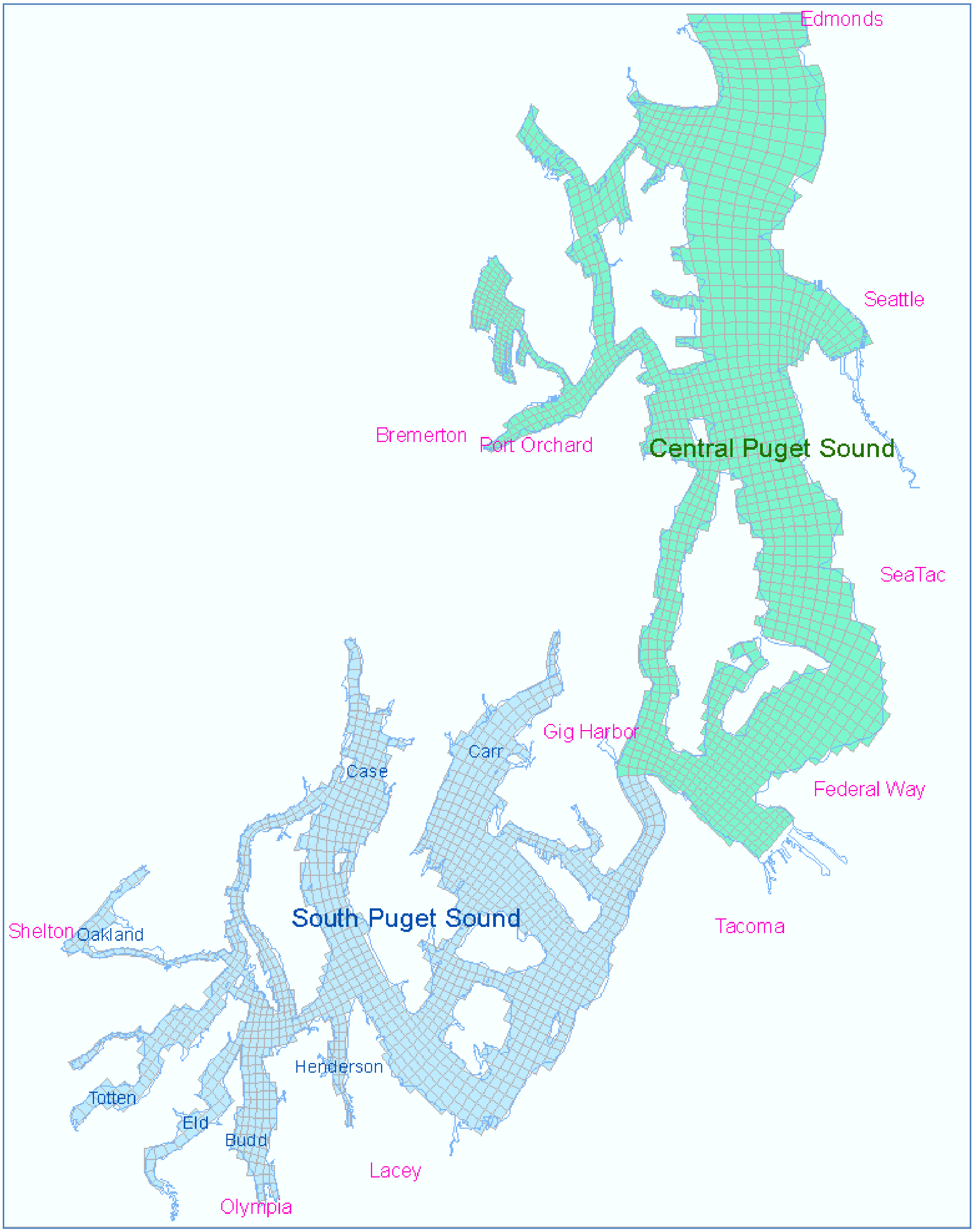


Figure 10. GEMSS model grid for South and Central Puget Sound showing major cities and inlet names.

Boundary Conditions

Point Sources Discharging to Marine Waters

Roberts et al. (2008) describes data collected in 2006 and 2007 on marine point source discharges. Ecology collected 24-hour composite samples each month at 29 municipal wastewater treatment plants (WWTPs) and industrial plants discharging to South and Central Puget Sound (Figure 11). Ecology sampled 17 plants from August 2006 through October 2007 and 12 additional plants from August 2007 through October 2007.

Mohamedali et al. (2011) developed daily time series for each of the facilities using linear regression to describe concentrations as a function of flow and time of year. Flows were obtained from discharge monitoring reports submitted to Ecology or to EPA (for federal or tribal facilities). Two small municipal plants (Taylor Bay, McNeill Island) were not monitored directly. Results from other small plants were used to describe these facilities. In addition, constituents were estimated for US Oil.

Current marine point source discharges (as of 2007) were mapped to either the surface layer or multiple layers depending upon whether the outfalls are located in shallow or deep waters (for a discussion on trapping levels of marine point source discharge see Roberts et al. (2013 in press). On an annual average basis (2006-2007), marine point sources discharge a flow of 37 million gallons per day (mgd) with a dissolved inorganic nitrogen (DIN) load of 2,700 kg/d to South Puget Sound. For Central Puget Sound, marine point sources discharge 266 mgd with 24,000 kg/d of annual average DIN (2006-2007).

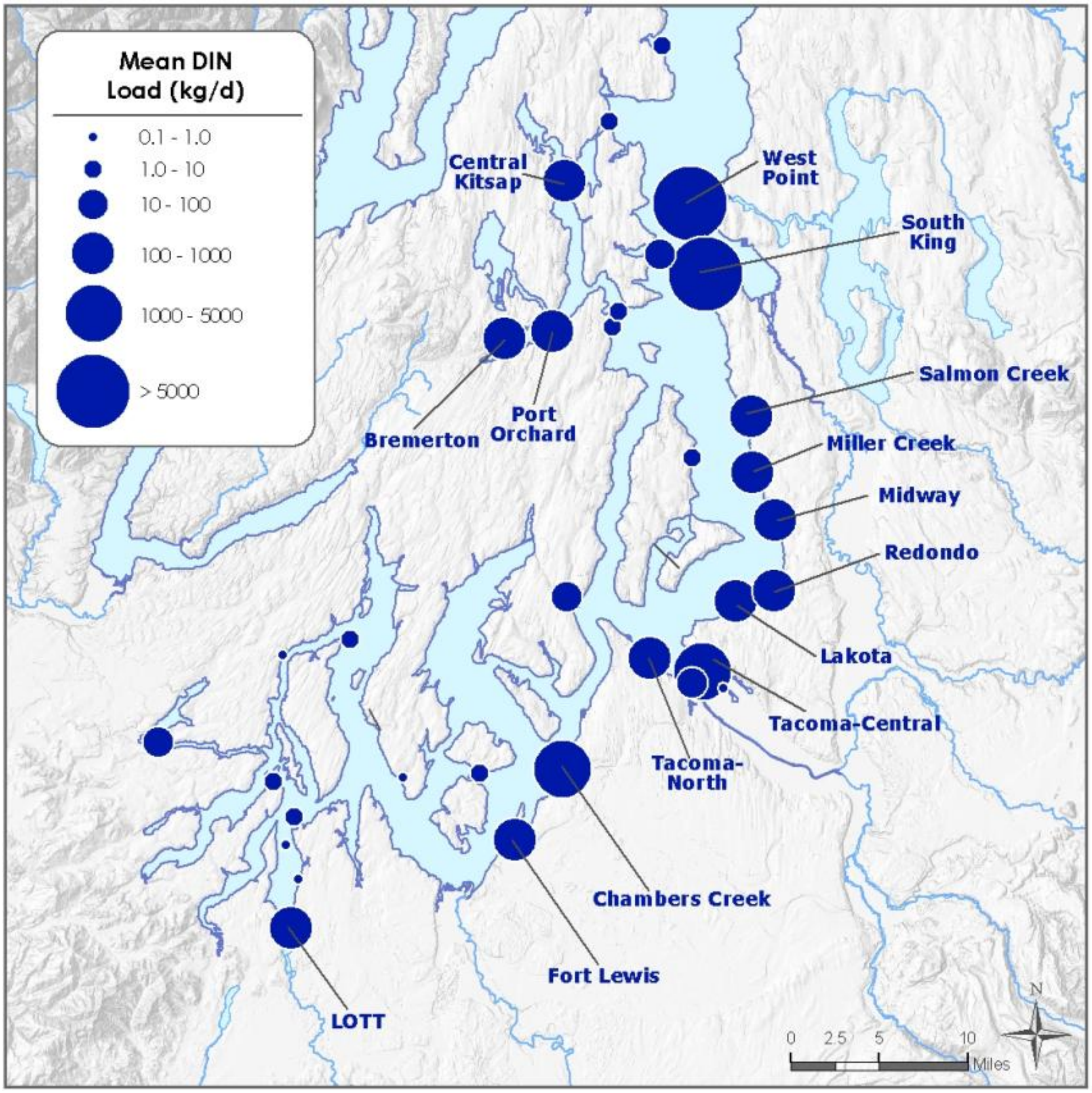


Figure 11. Mean annual dissolved inorganic nitrogen (DIN) loads from marine point sources discharging to South and Central Puget Sound (2006-07). Source: Mohamedali et al. (2011).

Watershed Inputs

Rivers and Streams

Roberts et al. (2008) also summarized data collected from rivers and streams in 2006 and 2007. Ecology collected grab samples each month at 38 streams and rivers flowing to Puget Sound (Figure 12). Ecology sampled 17 rivers from August 2006 through October 2007 and 21 additional rivers from July 2007 through October 2007. Mohamedali et al. (2011) describes how multiple linear regression was used to develop daily time series of concentrations. Flows for large rivers and streams were obtained from USGS flow gaging networks.

On an annual average basis, watershed inflows deliver 4600 cfs and 5100 kg/d of DIN to South Puget Sound, and 8000 cfs and 5,800 kg/d of DIN to Central Puget Sound (Figure 3). Monitoring locations represent 82% of the watershed tributary to South and Central Puget Sound. Mohamedali et al. (2011) details the method to extrapolate to unmonitored areas using geographic proximity and normalized flow. This ensured that all freshwater from the watershed was accounted for in the model. Inputs from the Lake Washington and Cedar River watersheds were estimated from sparse information in the Ship Canal. Contributions to Sinclair and Dyes inlets were simplified to one large watershed and pour point because they receive inflow from dozens of smaller streams. Each input was mapped to 75 separate pour points.

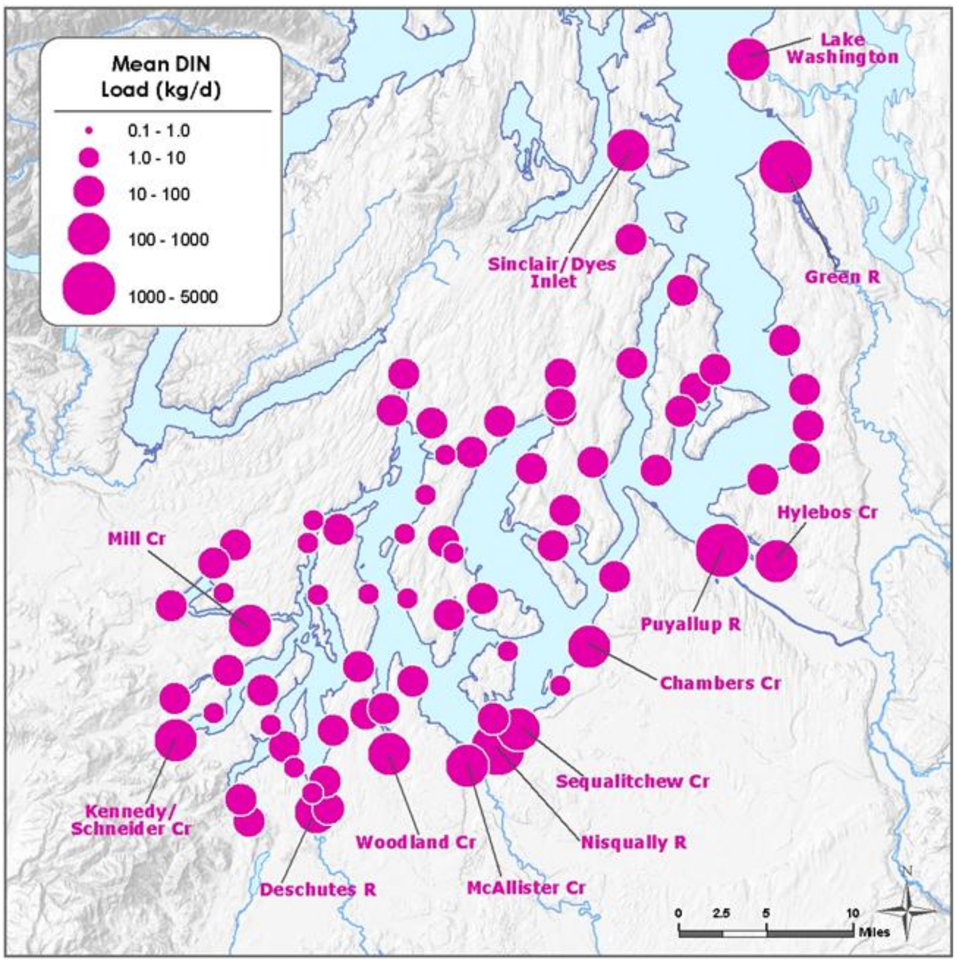


Figure 12. Mean annual dissolved inorganic nitrogen (DIN) loads from watersheds into South and Central Puget Sound (2006-07). Source: Mohamedali et al. (2011).

Septics in Unmonitored Areas

On-site septic system nutrient loads upstream of the monitoring locations are included in estimates of watershed loads, along with other human and natural contributions. By extrapolating from monitored locations to the entire watershed, we accounted for all unmonitored areas downstream of stations and the areas along the shoreline that flow directly to marine waters. This should reflect septic systems near the marine shoreline. Mohamedali et al. (2011) includes an analysis in Appendix C of that report that compared loads from septic systems in these shoreline regions to the loads extrapolated from nearshore areas. Mohamedali et al. (2011) concluded that the extrapolated watershed loads adequately captured nutrient loads from on-site septic systems in shoreline fringe areas.

Groundwater

Groundwater nutrient loads are included in the estimates of watershed load and were not considered as a separate load. Mohamedali et al. (2011) describes a USGS analysis that estimates 100 to 1000 cfs of groundwater discharges directly to the marine waters of the entire Puget Sound and a separate report by Pitz (2010) that included nutrient concentrations. The extrapolation of watershed loads from the monitoring location to the mouth of each watershed also includes the groundwater loads into Puget Sound from shallow near-shore areas (Mohamedali et al., 2011). No additional nutrient loads from groundwater were included since they are likely within the error range of surface water flow measurements and not a major nitrogen contributor. Groundwater that surfaces as baseflow in rivers and streams is included in the watershed inflows.

Atmospheric Deposition

We estimated atmospheric deposition based on available measurements. Wet atmospheric deposition rates of ammonium and nitrate were obtained from four National Trend Network (NTN) sites (WA14, WA19, WA21, and WA99, Figure 13) in Washington State operated by National Atmospheric Deposition Program (NADP, http://nadp.sws.uiuc.edu/). Wet deposition rates for the South Puget Sound DO model were estimated as the average of the rates of these four stations and applied as monthly values throughout the year. These are described in Mohamedali et al. (2011).

We also evaluated dry deposition, following the methods of DeGasperi (2010) for ammonium and nitrate. The dry deposition rates were obtained from EPA's Clean Air Status and Trends Network (CASTNet, http://epa.gov/castnet) stations OLY421 (location same as NTN site WA14), station MOR409 (location same as NTN site WA99), and station NCS415 (location same as NTN site WA19).

The dry (in absence of rain) and wet deposition (during rainfall) rates were added to establish bulk atmospheric deposition rates for ammonium and nitrate with prior conversion of wet deposition rates to its associated dry rates based on available precipitation data.

Bulk monthly total Kjeldahl nitrogen (TKN) and total phosphorus (TP) deposition rates were obtained from Ebbert et al. (1985) who measured wet and dry atmospheric deposition rates in Bellevue, Washington at three locations (Figure 14). The TP data was assumed to be 50% organic phosphorus and 50% inorganic (PO_4). Organic nitrogen deposition rates were obtained from subtracting ammonia-N from total Kjeldahl nitrogen (TKN) for both dry and wet deposition rates. The dry deposition rates represent a flux of all particulate organic nitrogen. However, wet deposition rates would include some particulate forms but were assumed to be entirely dissolved organic nitrogen. This assumption was deemed appropriate given that the atmospheric load was an insignificant portion of the total nitrogen loading to the model domain (Mohamedali et al. 2011). We used the same assumptions for dissolved and particulate organic phosphorus.

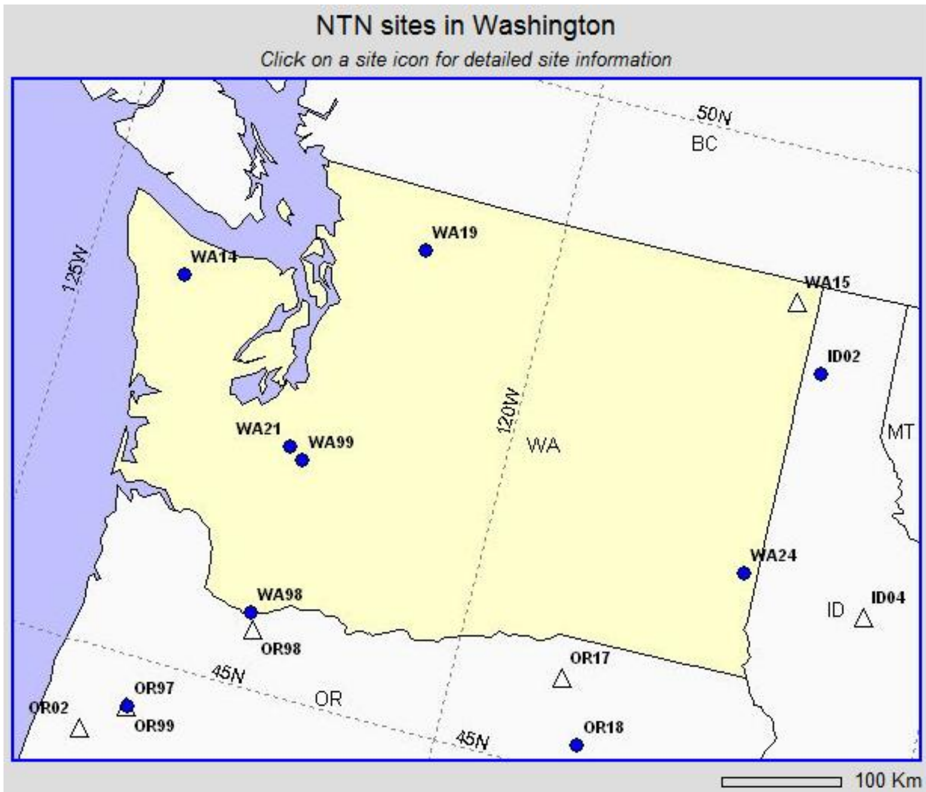


Figure 13. Location of NADP stations in Washington State used for atmospheric deposition load estimates.

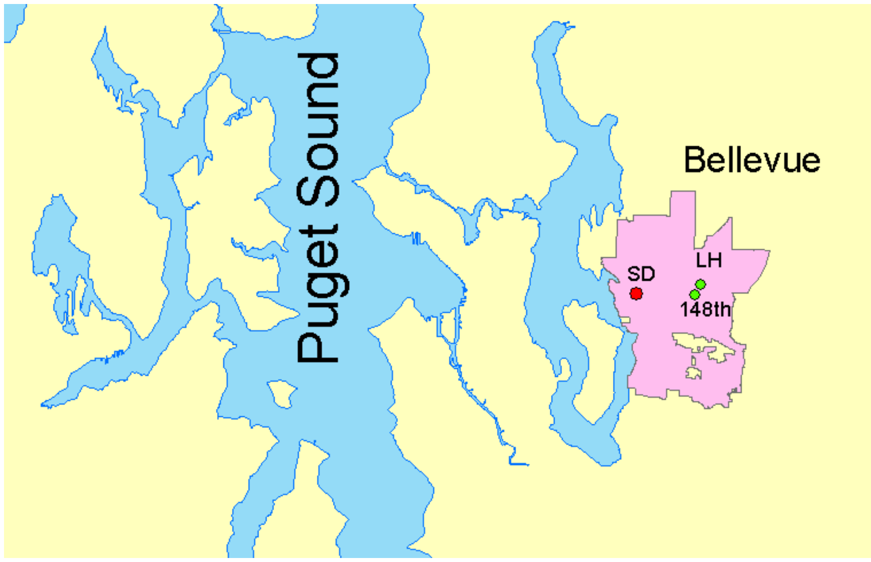


Figure 14. Locations of stations in the city of Bellevue, WA where atmospheric deposition rates were measured by Ebbert et al. (1985).

SD = Surrey Downs; LH = Lake Hills; 148th = 148th Avenue S.E.

Meteorology

Meteorological data were the same as those discussed in detail in the South and Central Puget Sound water circulation report (Roberts et al., 2013, in press). DO concentrations were estimated by assuming 100% saturation for the rainfall temperature. We assumed the rainfall temperature was the average of the air temperature and dew point temperature; any negative average temperatures were assumed to be zero. All other water quality parameters were assumed to be zero since they were captured in the atmospheric deposition rates applied to the whole model domain.

Northern Boundary Conditions

Roberts et al. (2008) describes water quality parameters monitored from July 2006 through October 2007 at two stations (Edmonds East and Edmonds West) representing the model open boundary. Monthly monitoring provided a total of 16 vertical profiles for water quality parameters.

> All data, including discrete lab results and continuous CTD profiles, were binned to the model grid layers. Depths associated with vertical profiles were converted to NAVD88 using a combination of PSTide predictions and NOAA's VDatum translation. Edmonds East (EdmE) water quality parameter concentrations were assigned to the four eastern boundary grid cells at the open boundary, while Edmonds West (EdmW) station was assigned to the three western grid cells (
> Figure 15).

Chlorophyll concentrations were split into two algal groups GAM1 and GAM2 that represent diatoms and dinoflagellates. CBOD data were split equally between CBOD_fast and

CBOD_slow, the two forms of BOD required by the GEMSS model. Particulate organic carbon was split equally three ways into slow, fast and refractory fractions.

Station temporal plots for stations EdmE and EdmW are shown in Figure 16 and Figure 17. EdmE and EdmW exhibit comparable water quality characteristics and do not indicate large east-west variation near Edmonds. Data show a seasonal increase in DO associated with an increase in chlorophyll-a concentrations during spring and early summer. This period also shows a decrease in ammonia and phosphorus concentrations. Salinity differences from higher spring river flow induce water column stratification during this time as well.

Water quality characteristics of the incoming tide at the open boundary were assigned from field data for stations EdmE and EdmW as discussed above. The quality of water leaving the open boundary would be a result of the chemical, physical, and biological transformations that occur within the model domain during a given time step.

Figure 15. Open boundary stations at Edmonds.

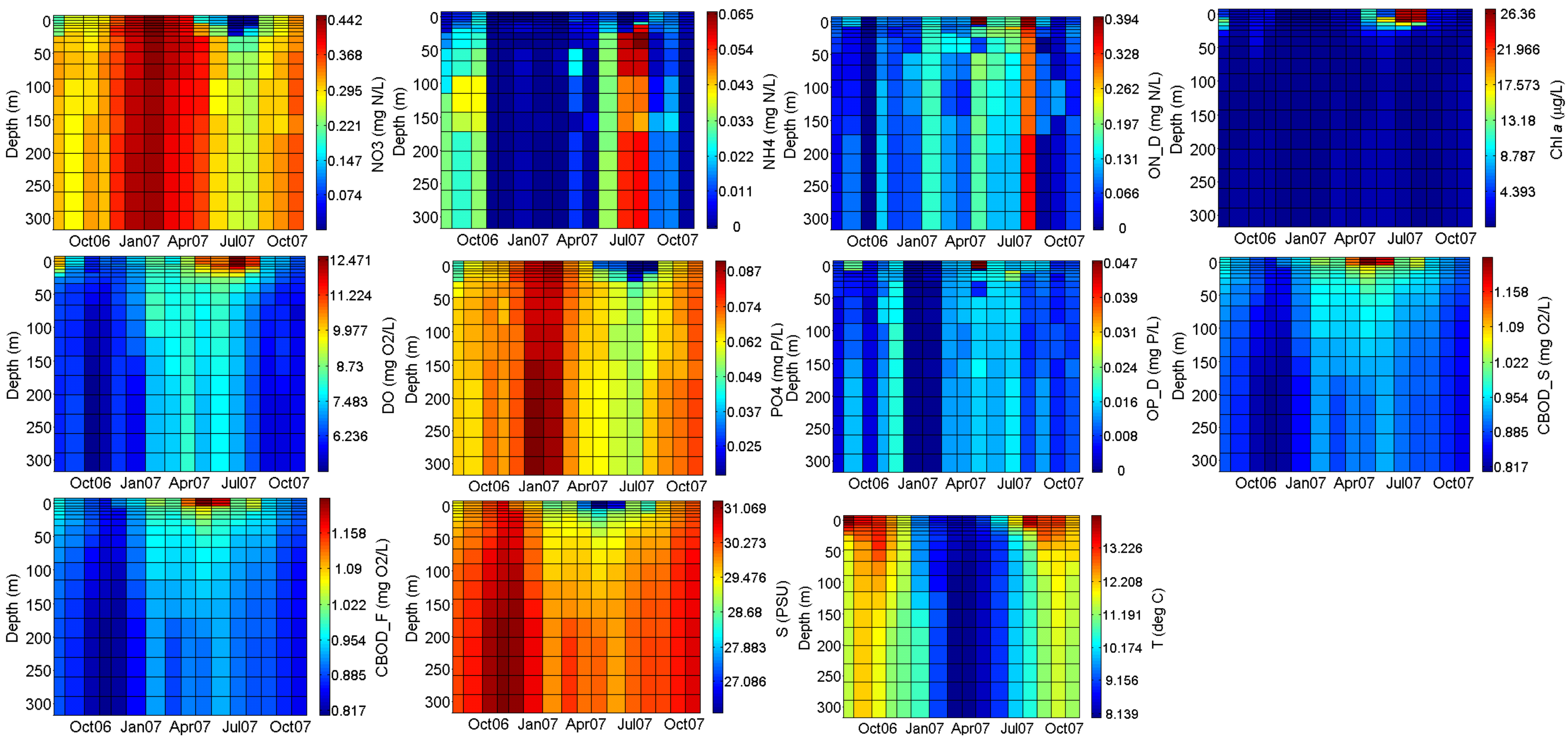


Figure 16. Water quality characteristics of open boundary station EdmE based on monthly profiles.

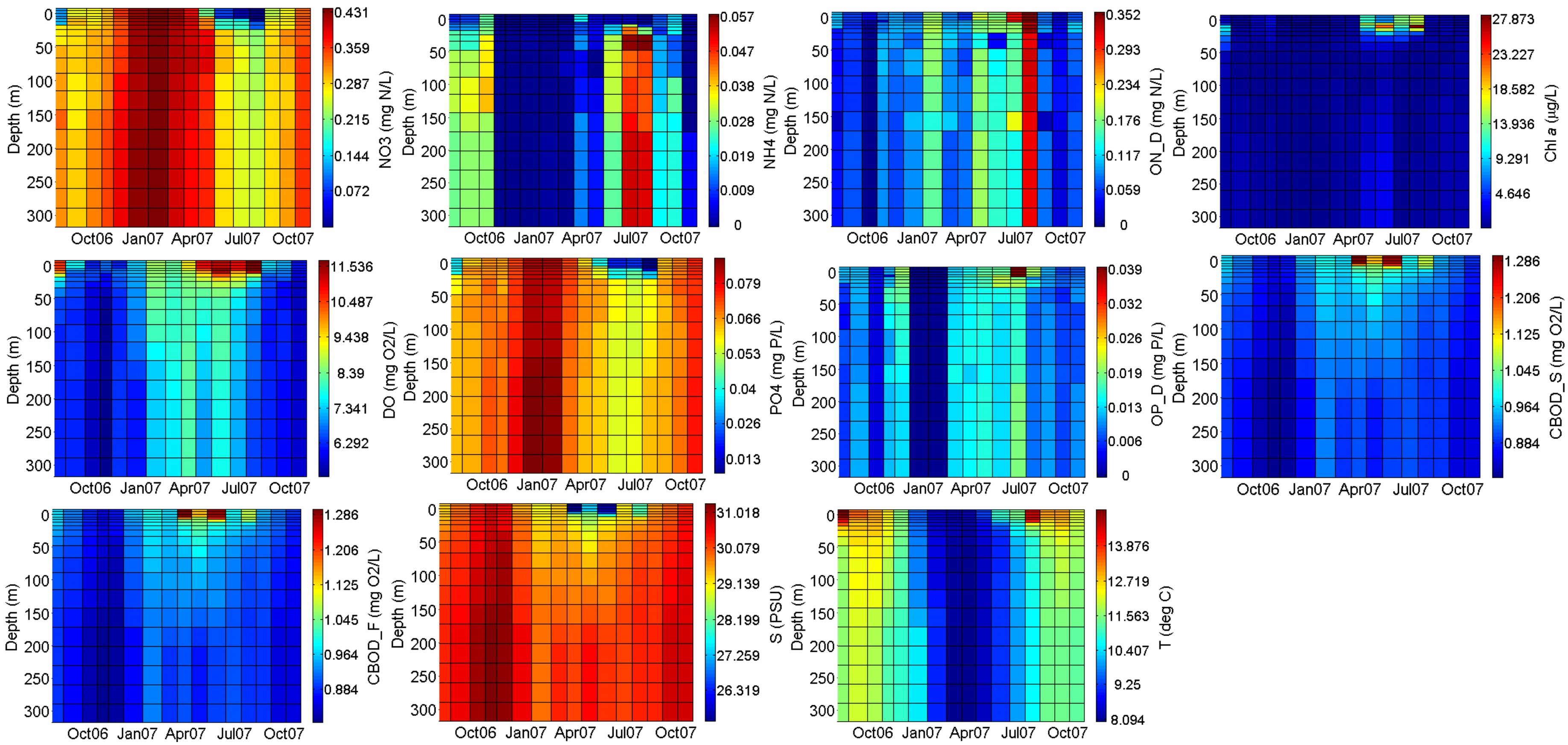


Figure 17. Water Quality characteristics at open boundary station EdmW based on monthly profiles.

Sediment Exchanges

GEMSS does not simulate sediment-water fluxes internally. Vertical fluxes of oxygen, nitrogen, and phosphorus are specified as boundary conditions. Roberts et al. (2008) describes sediment flux measurements in South Puget Sound, but little quantitative information exists for Puget Sound fluxes (Sheibley and Paulson, 2013, in press). We divided South and Central Puget Sound into 17 regions to capture expected variability (Figure 18).

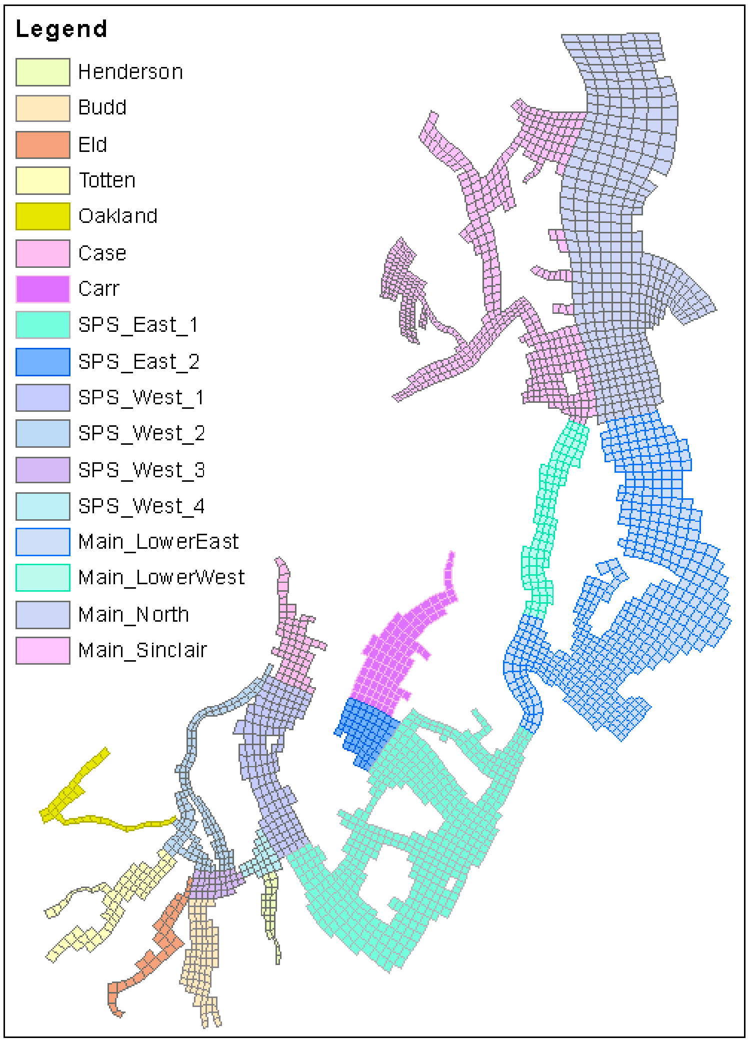


Figure 18. Sediment flux regions in the South Puget Sound Model.

Initial sediment fluxes for the model were based upon field measurements conducted in four Inlets (Budd, Carr, Case and Eld) as outlined in Roberts and Coomes (2007) and Roberts (2007). While the observed sediment fluxes of nutrients were used in the model without adjustment, the measured sediment fluxes of DO (or sediment oxygen demand, SOD) were increased for model calibration. This was deemed appropriate since the results of the benthic flux study may underestimate SOD due to the effects of productivity in sediment chambers.

To develop sediment fluxes in the various regions, measured sediment fluxes in Budd and Eld Inlets were combined and average values were assumed to represent sediment fluxes in other smaller inlets (Totten, Oakland Bay/Hammersley, and Henderson Inlets). Measured sediment fluxes in Case and Carr Inlets were combined and average values were assumed for the rest of the model domain including Tacoma Narrows and the Main Basin of Central Puget Sound. During the course of model calibration to water quality parameters, the SOD values were adjusted upward.

The final calibrated SOD in the finger inlets was 2 g/m^2-day. This is similar to SOD used to calibrate the Budd Inlet model (Roberts et al., 2012) and values used in Chesapeake Bay (Cerco et al., 2004) and recommended by Chapra (1997). The final calibrated SOD in Case and Carr Inlets as well as other areas south of Tacoma Narrows were 1.5 times the observed values. The remainder of the main basin including Tacoma Narrows remained at measured SOD values. The final sediment fluxes used in the calibrated model are shown in Table 2. These were applied as constant values throughout the year. A positive number indicates a net flux into the water column while a negative number indicates a net flux out of the water column.

Table 2. Sediment flux in regions of the model.

Region	NH3, g/m^2_d	NO3, g/m^2_d	PO4, g/m^2_d	SOD, g/m^2_d
Budd Inlet	0.048	-0.010	0.015	-2.000
Eld Inlet	0.092	-0.012	0.043	-2.000
Oakland Bay, Totten and Henderson Inlet	0.070	-0.011	0.029	-2.000
Case Inlet	0.069	-0.009	0.020	-0.777
Carr Inlet	0.046	-0.008	0.021	-0.720
SPS_East_1 &2, SPS_West_1 through 4	0.057	-0.009	0.021	-0.749
Main_LowerEast & West, Main_North, Main_Sinclair	0.057	-0.009	0.021	-0.499

Initial Conditions

Field data from December 2006 (Roberts et al., 2008) were used to establish initial conditions for model runs commencing on January 1, 2007. Different initial conditions were established separately for three regions to reflect water quality variations (Figure 19). Data were averaged over all field stations for each of these regions. Depths associated with all field stations were converted to NAVD88 using a combination of PSTide predictions and NOAA's vertical datum (VDatum) translation.

All data, including discrete lab results and continuous CTD profiles, were binned according to the model grid layers. All water column field data falling within a grid layer (bin) were averaged and this single value was assigned to the grid layer. The water column was divided into three vertical sub-regions for each of the horizontal regions to characterize large vertical gradients.

Field data in each of these vertical sub-regions were averaged over both vertical and horizontal extent and assigned a single average initial value. Initial conditions for temperature and salinity were previously described in the hydrodynamic calibration report (Roberts et al., 2013, in press). However, these are presented again in Table 3 along with other water quality variables.

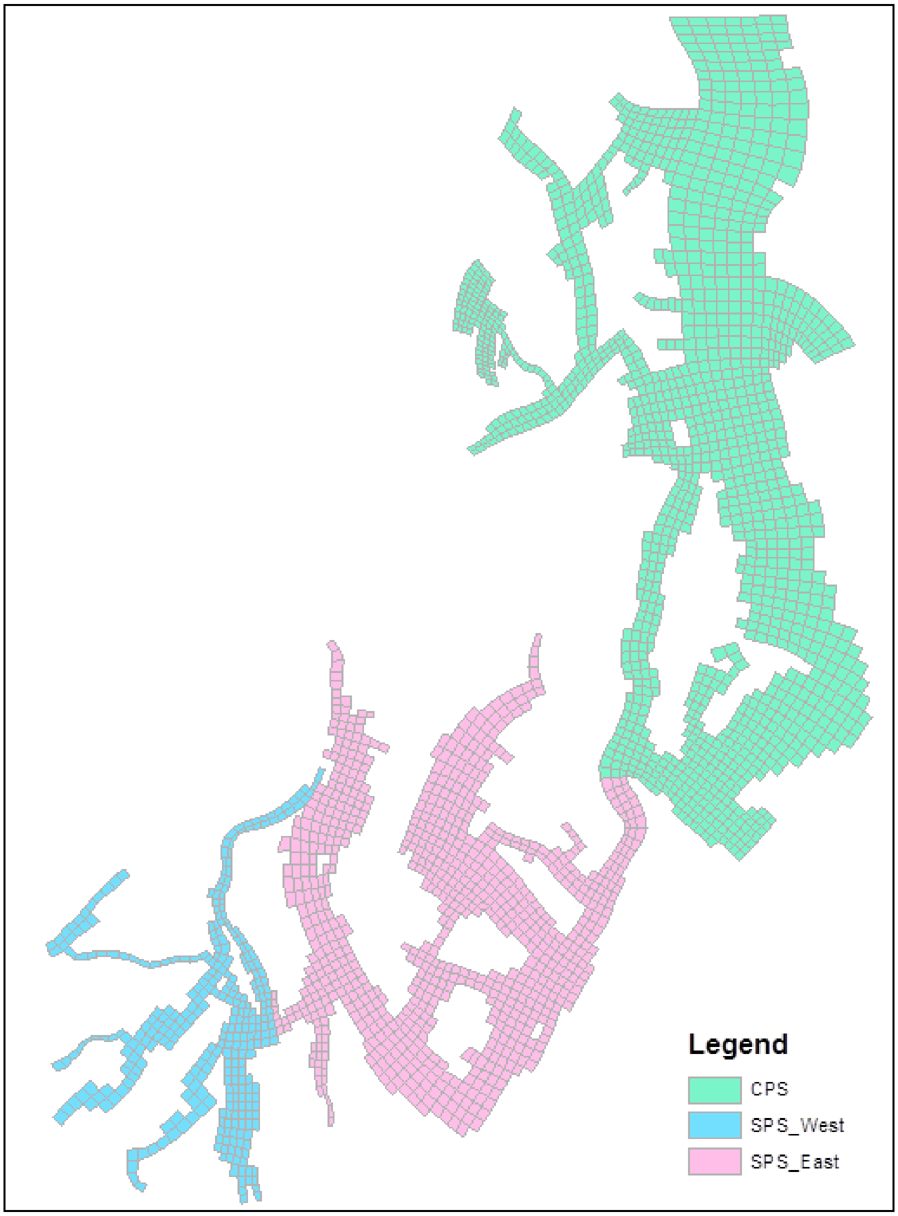


Figure 19. Regions used to assign initial conditions.

CPS = Central Puget Sound (model domain north of Tacoma Narrows).
SPS_West = South Puget Sound West (region including most of the finger Inlets west of Dana Passage).
SPS_East = South Puget Sound East (region between Dana Passage and Tacoma Narrows.

Table 3. Initial conditions for domain-wide water quality characteristics (January 1, 2007).

K_start and K_end represent the assigned starting and ending layers (Appendix B). KT is the top layer, KB is the bottom layer, and K2-Kx are the intermediate layers from top to bottom.

variable	unit	CPS (I = 1:83; J = 91:202)			SPS_East (I = 1:83; J = 33:90)			SPS_west (I = 1:83; J = 1:32)		
		value	K_start	K_end	value	K_start	K_end	value	K_start	K_end
Temp	C	10.1328	KT	K7	8.8052	KT	K6	9.3592	KT	K4
Temp	C	10.2122	K8	K13	9.3299	K7	K11	9.8230	K5	K6
Temp	C	10.6596	K14	KB	9.7077	K12	KB	9.9675	K7	KB
Saln	ppt	29.8330	KT	K7	26.6058	KT	K6	28.6602	KT	K4
Saln	ppt	29.9131	K8	K13	28.0456	K7	K11	29.2946	K5	K6
Saln	ppt	30.4827	K14	KB	28.9909	K12	KB	29.5527	K7	KB
NH3	mg/l	0.0024	KT	K7	0.0287	KT	K6	0.0066	KT	K4
NH3	mg/l	0.0016	K8	K13	0.0155	K7	K11	0.0031	K5	K6
NH3	mg/l	0.0042	K14	KB	0.0014	K12	KB	0.0009	K7	KB
NO3	mg/l	0.4203	KT	K7	0.3957	KT	K6	0.4015	KT	K4
NO3	mg/l	0.4221	K8	K13	0.3999	K7	K11	0.4045	K5	K6
NO3	mg/l	0.4288	K14	KB	0.3888	K12	KB	0.4041	K7	KB
PO4	mg/l	0.0873	KT	K7	0.0740	KT	K6	0.0763	KT	K4
PO4	mg/l	0.0878	K8	K13	0.0769	K7	K11	0.0769	K5	K6
PO4	mg/l	0.0903	K14	KB	0.0721	K12	KB	0.0766	K7	KB
DO	mg/l	7.0912	KT	K7	7.7825	KT	K6	7.5556	KT	K4
DO	mg/l	6.9459	K8	K13	7.3659	K7	K11	7.1550	K5	K6
DO	mg/l	6.1278	K14	KB	7.1031	K12	KB	7.0239	K7	KB
ON_D	mg/l	0.0816	KT	K7	0.0867	KT	K6	0.1028	KT	K4
ON_D	mg/l	0.0759	K8	K13	0.0919	K7	K11	0.0838	K5	K6
ON_D	mg/l	0.0760	K14	KB	0.0919	K12	KB	0.0943	K7	KB
ON_P	mg/l	0.0145	KT	KB	0.0145	KT	KB	0.0145	KT	KB
OP_P	mg/l	0.0014	KT	KB	0.0014	KT	KB	0.0014	KT	KB
OP_D	mg/l	0.0000	KT	K7	0.0184	KT	K6	0.0159	KT	K4
OP_D	mg/l	0.0000	K8	K13	0.0177	K7	K11	0.0156	K5	K6
OP_D	mg/l	0.0000	K14	KB	0.0177	K12	KB	0.0161	K7	KB
CBOD_F	mg/l	0.9272	KT	K7	1.2032	KT	K6	1.0275	KT	K4
CBOD_F	mg/l	0.9204	K8	K13	1.0801	K7	K11	0.9733	K5	K6
CBOD_F	mg/l	0.8717	K14	KB	0.9993	K12	KB	0.9512	K7	KB
CBOD_S	mg/l	0.9272	KT	K7	1.2032	KT	K6	1.0275	KT	K4
CBOD_S	mg/l	0.9204	K8	K13	1.0801	K7	K11	0.9733	K5	K6
CBOD_S	mg/l	0.8717	K14	KB	0.9993	K12	KB	0.9512	K7	KB
OC_P_F	mg/l	0.0387	KT	KB	0.0387	KT	KB	0.0387	KT	KB
OC_P_S	mg/l	0.0387	KT	KB	0.0387	KT	KB	0.0387	KT	KB
OC_P_R	mg/l	0.0387	KT	KB	0.0387	KT	KB	0.0387	KT	KB
GAM1	ug/l	1.0000	KT	KB	1.0000	KT	KB	1.0000	KT	KB
GAM2	ug/l	0.2584	KT	K7	0.2335	KT	K6	0.2833	KT	K4
GAM2	ug/l	0.2255	K8	K13	0.1517	K7	K11	0.2175	K5	K6
GAM2	ug/l	0.1342	K14	KB	0.1517	K12	KB	0.2175	K7	KB

Marine Data for Calibration

Stations selected for hydrodynamic calibration (water surface elevation, temperature, salinity, and currents) were discussed in the hydrodynamic calibration report (Roberts et al., 2013, in press). Water quality data gathered at 90 marine stations between 2006 and 2007 in South and Central Puget Sound is discussed in detail by Roberts et al. (2008).

All field data, discrete laboratory results, and continuous temperature, salinity and DO profiles were binned according to the South and Central Puget Sound model grid layers with average values assigned to the center of each grid cell. These average observed data from all marine stations were used to compare model predicted values in each model run for salinity, temperature, DO, DIN (ammonia + nitrate), total chlorophyll, organic nitrogen, CBOD, and particulate organic carbon. Differences between the observed and predicted values at all stations were tabulated into a single root mean square error (RMSE) and associated mean bias for each variable. Subsequent model runs were aimed at improving the overall RMSE for each variable for all marine stations.

Low DO concentrations were observed in Budd, Carr, Case and Henderson Inlets, as well as Pickering and Dana Passages and Nisqually Reach. Areas of high chlorophyll levels in spring and early fall included Budd, Totten, Eld, Henderson, Case and Carr Inlets; north Pickering Passage; and Oakland Bay. Blooms of chlorophyll occurred one month earlier in South Puget Sound compared with Central Puget Sound. For water quality calibration (time-series and profiles), eleven stations, covering the whole model domain from Budd Inlet to the open boundary at Edmonds, were selected for graphical review of goodness of fit of model predictions as shown in Figure 20. These also include stations north of Tacoma Narrows that were independently monitored by King County. Additional stations were used, where applicable, for plan-view water quality maps.

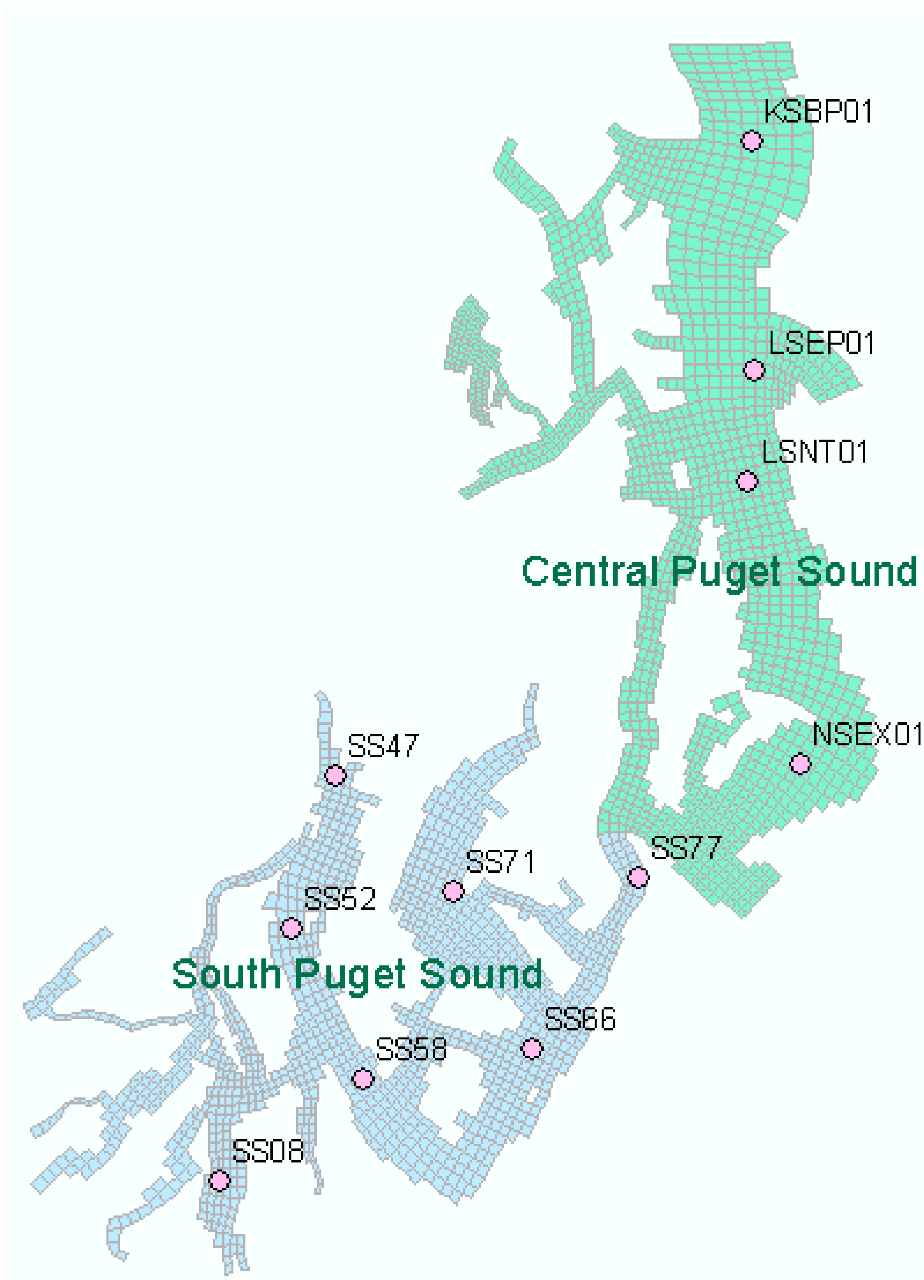


Figure 20. Selected stations in the model domain for time-series model output for water quality calibration.

Water Quality Model Calibration to Current Conditions

Circulation Model Calibration

Roberts et al. (2013, in press) details the hydrodynamic model calibration. Calibration plots of tidal elevations, current velocities, temperature and salinity for many stations in the model domain are presented in the report. Overall, the circulation model reproduces water surface elevations and tidal constituents well throughout the model domain. The only exception is Oakland Bay, where the two 90-degree bends in Hammersley Inlet were straightened out to avoid numerical instability with the sharp turns. The RMSE for predicted tidal elevations is approximately 10% of tidal range in Oakland Bay. Salinity and temperature predictions are within 1 psu and 1°C, respectively.

Water Quality Model Calibration Approach

A total of approximately 1190 model runs in batches of 50 to 70 were simulated during the calibration process. The calibration process involved using as a first cut many of the same key kinetic parameter values in the WQCBM and GAM modules as those used in a previously calibrated Budd Inlet model (Roberts et al., 2012). Each run was assigned a fitness score calculated as a weighted average of the root mean squared error (see Appendix C) of predicted vs. observed values across all sampling stations, combining DO, DIN, chlorophyll, organic nitrogen, particulate organic carbon (POC), and carbonaceous biochemical oxygen demand (CBOD) to select the best run within a batch. This was then used as a base run for the next batch. Key parameters were then further changed based on a review of the calibration plots in the last batch.

Model output was shared with Robert Ambrose who worked with the project team to identify kinetic constants for trial in the next iterative model run (personal communication 2011). Most of the calibration effort focused on the algal kinetics (growth, respiration, and decay rates, as well as optimum temperature for growth, settling velocity, and carbon-to-chlorophyll ratios). In later runs, bottom DO calibration issues were resolved by increasing sediment oxygen demand, POC settling rates, and BOD decay rates. The final water quality and algal kinetic rates and constants are included in Appendix D. Since continuous field data were available for most of 2007, each model run was simulated for January through October and no distinction was made between calibration and confirmation runs.

Seasonal Water Quality Patterns

Figure 21 and Figure 22 show hourly model-predicted water column DO concentrations throughout the simulation period of January - October 2007. These are the time-depth plots that show time-varying concentrations of DO throughout the water column from surface to bottom. Observed DO data throughout the simulation period are also plotted for comparison with predicted values. The predicted time-depth plots indicate that there is a period of high DO during spring and summer which is limited to the upper water column in deeper waters north of Tacoma Narrows and throughout the water column in well-mixed shallow areas. The location and times of higher DO is associated with increased algal productivity. In early fall, low DO is predicted, which results from low algal productivity, algal die-off and decomposition, and low DO in the incoming marine waters.

Comparing the predicted and observed results, the lowest root mean square error is observed in deeper waters while the highest RMSEs were observed in shallow waters. In shallower inlets like Budd, there were only two grid layers which created an overprediction of DO attributed to numerical dispersion (a term used to explain dilution/dispersion occurring merely due to large gird size cells). However, this overprediction was not statistically significant (see section on Model Uncertainty).

Figure 23 and Figure 24 show hourly model-predicted water column DIN concentrations throughout the simulation period of January - October 2007. Observed DIN data throughout the simulation period are also plotted for comparison with predicted values. The plots shows a decrease in DIN concentrations in surface layers during times coinciding with high DO concentrations. This is attributed to DIN consumption during algal productivity. The lowest RMSEs were observed for deeper waters while the higher RMSEs were observed in shallow waters. As with DO, fewer layers in shallow areas may be contributing to the higher RMSEs for DIN.

Figure 25 and Figure 26 show hourly model-predicted water column total chlorophyll concentrations throughout the simulation period of January - October 2007. Observed chlorophyll data throughout the simulation period are also plotted for comparison with predicted values. In general the model predicts magnitudes better in deeper waters than in shallow waters. The plots shows an increase in chlorophyll concentrations in surface layers during times coinciding with high DO concentrations and low DIN concentrations, as expected. The lowest RMSEs were observed for deeper waters while the higher RMSEs were observed in shallow waters.

Statistical measures of goodness-of-fit will be discussed in a later section.

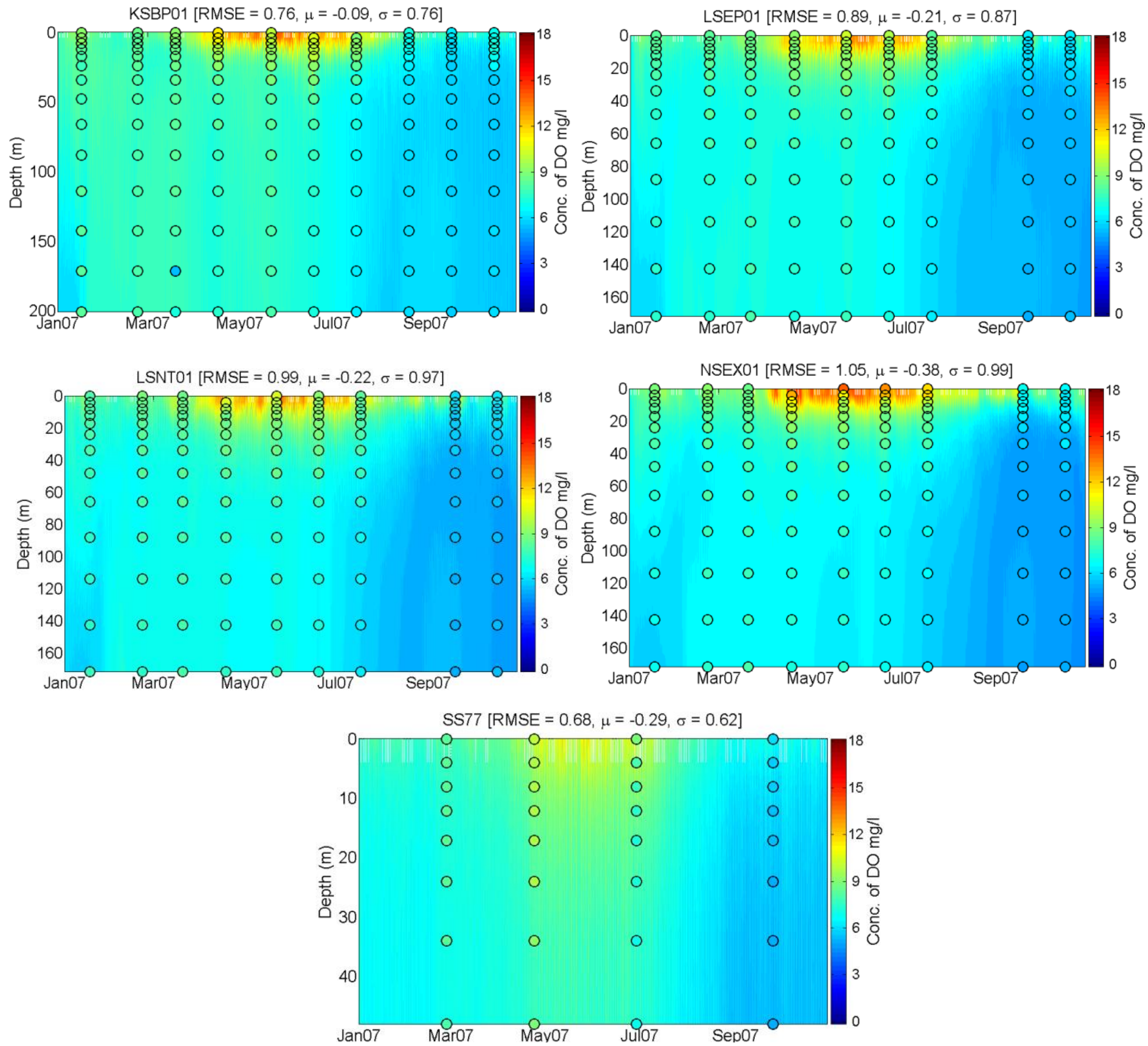


Figure 21. Time-depth contour plots of predicted and observed DO at Central Puget Sound calibration stations. See Figure 20 for station locations.

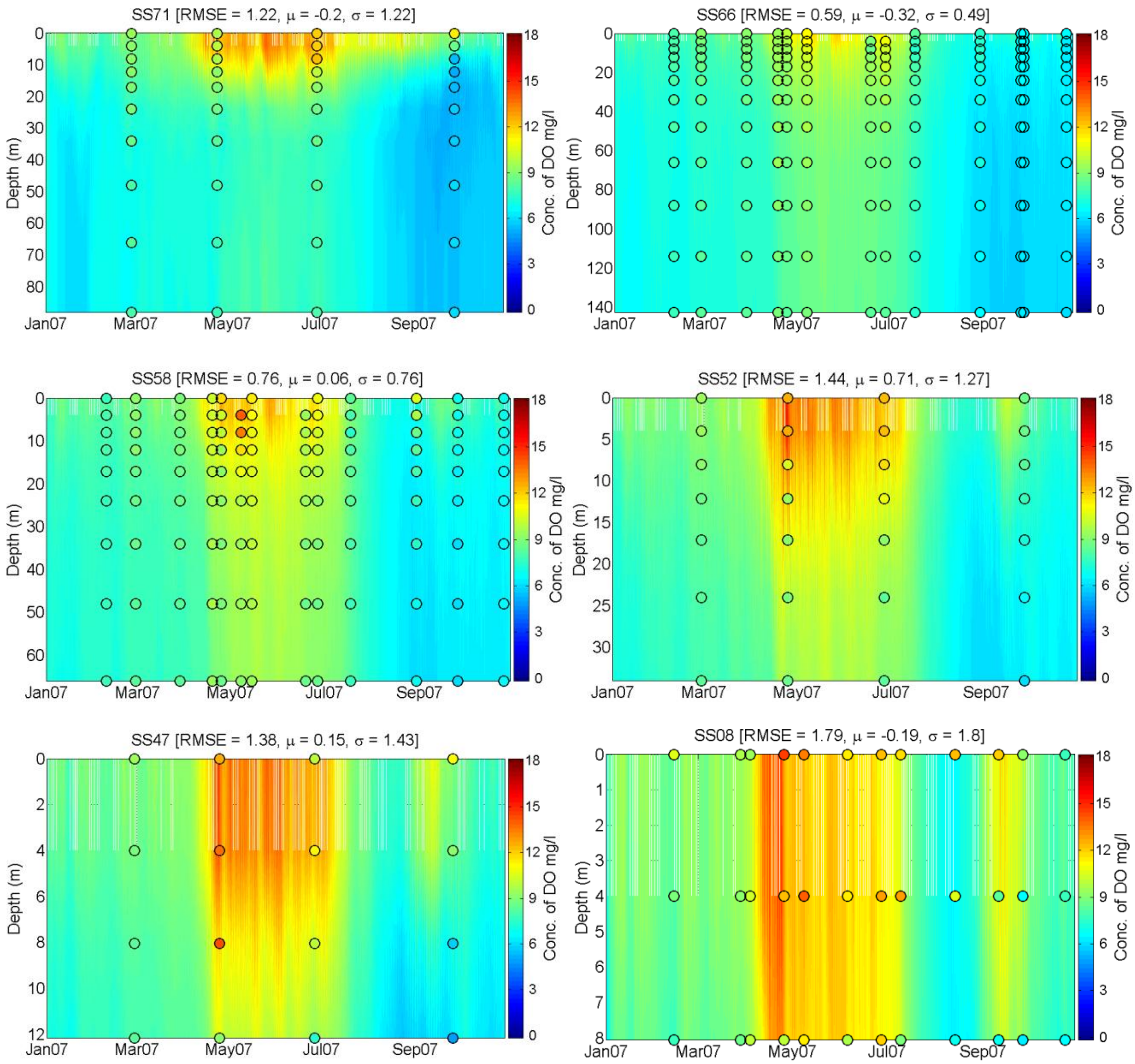


Figure 22. Time-depth contour plots of predicted and observed DO at South Puget Sound calibration stations. See Figure 20 for station locations.

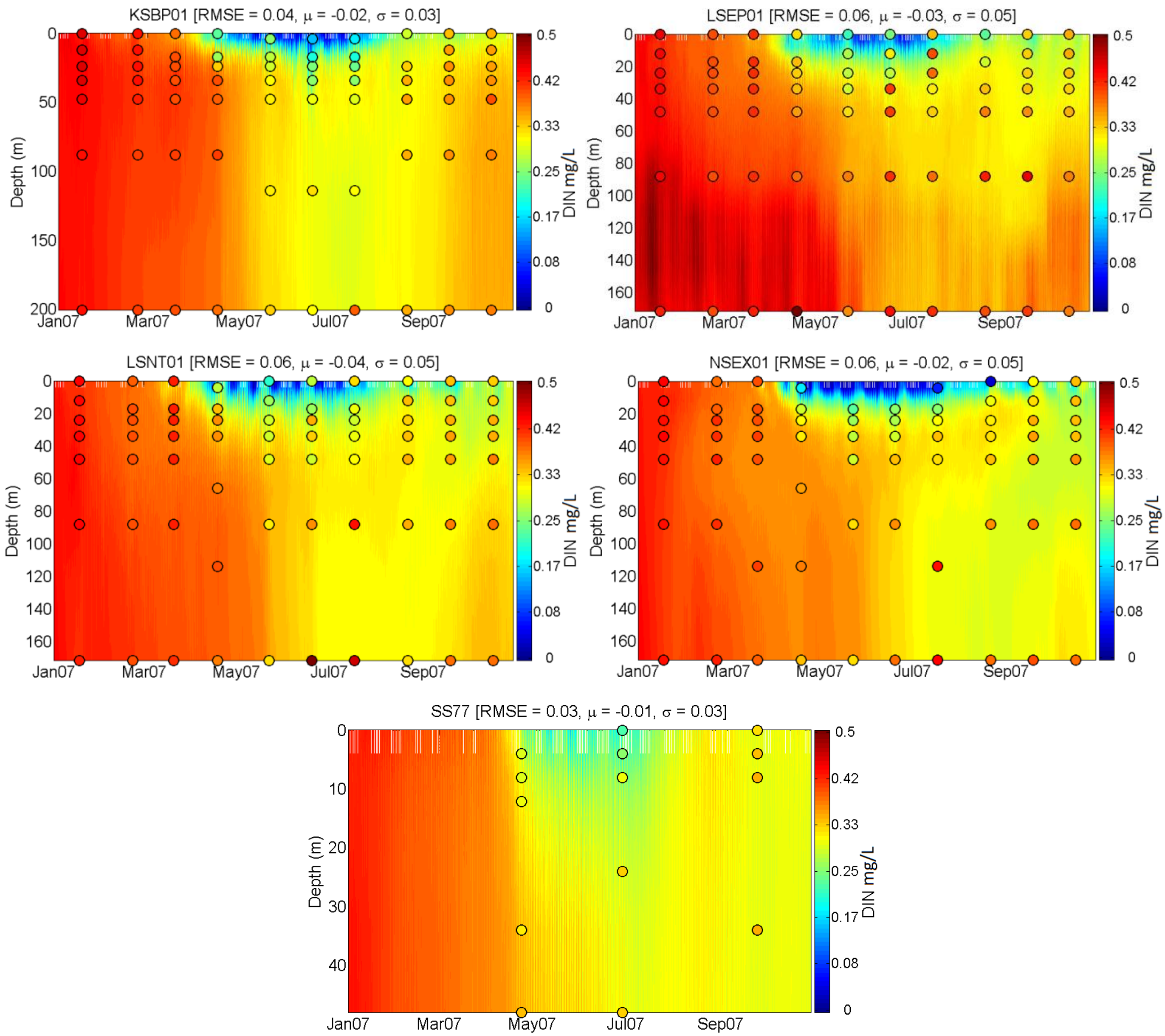


Figure 23. Time-depth contour plots of predicted and observed DIN at Central Puget Sound calibration stations. See Figure 20 for station locations.

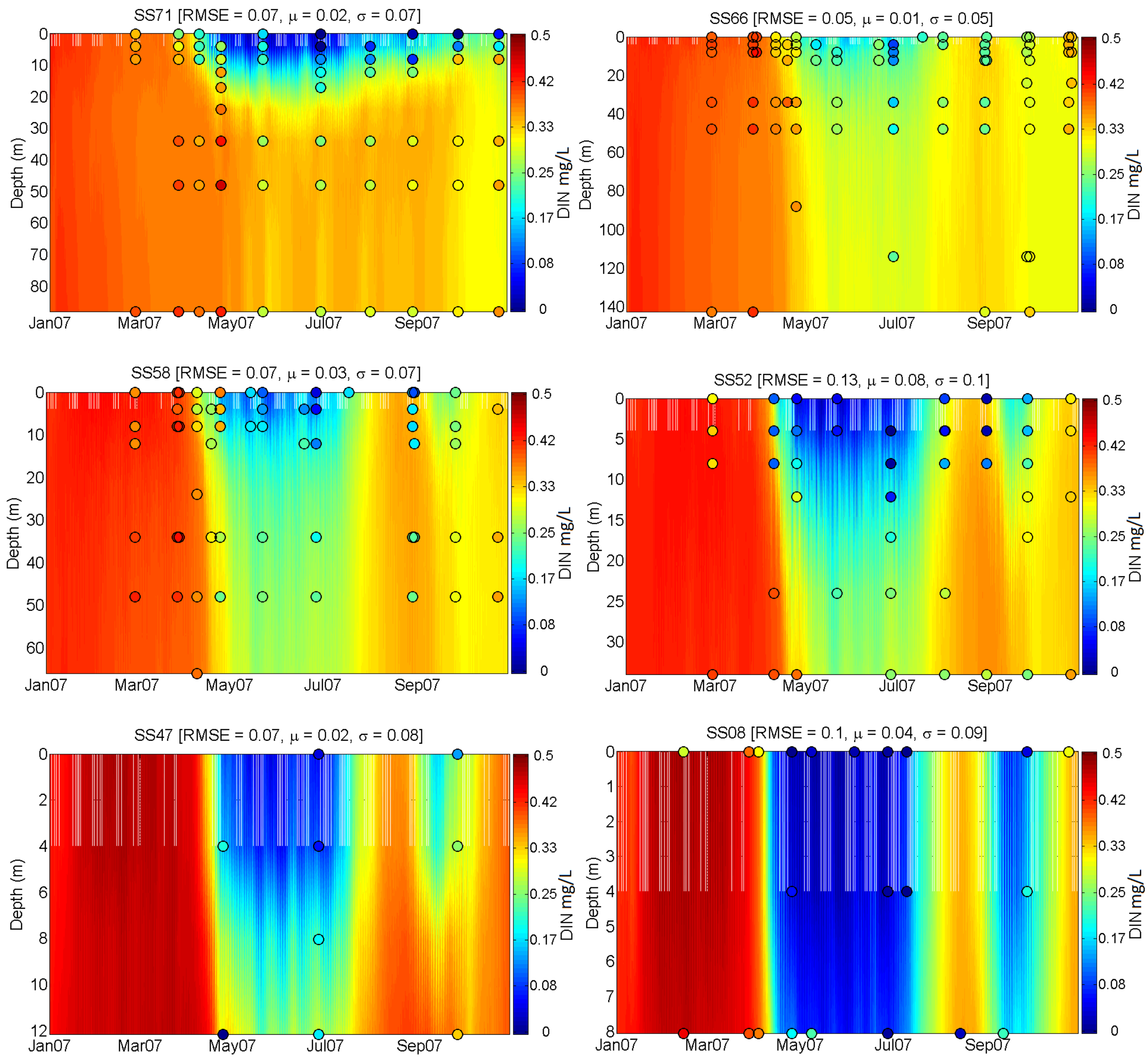


Figure 24. Time-depth contour plots of predicted and observed DIN at South Puget calibration stations. See Figure 20 for station locations.

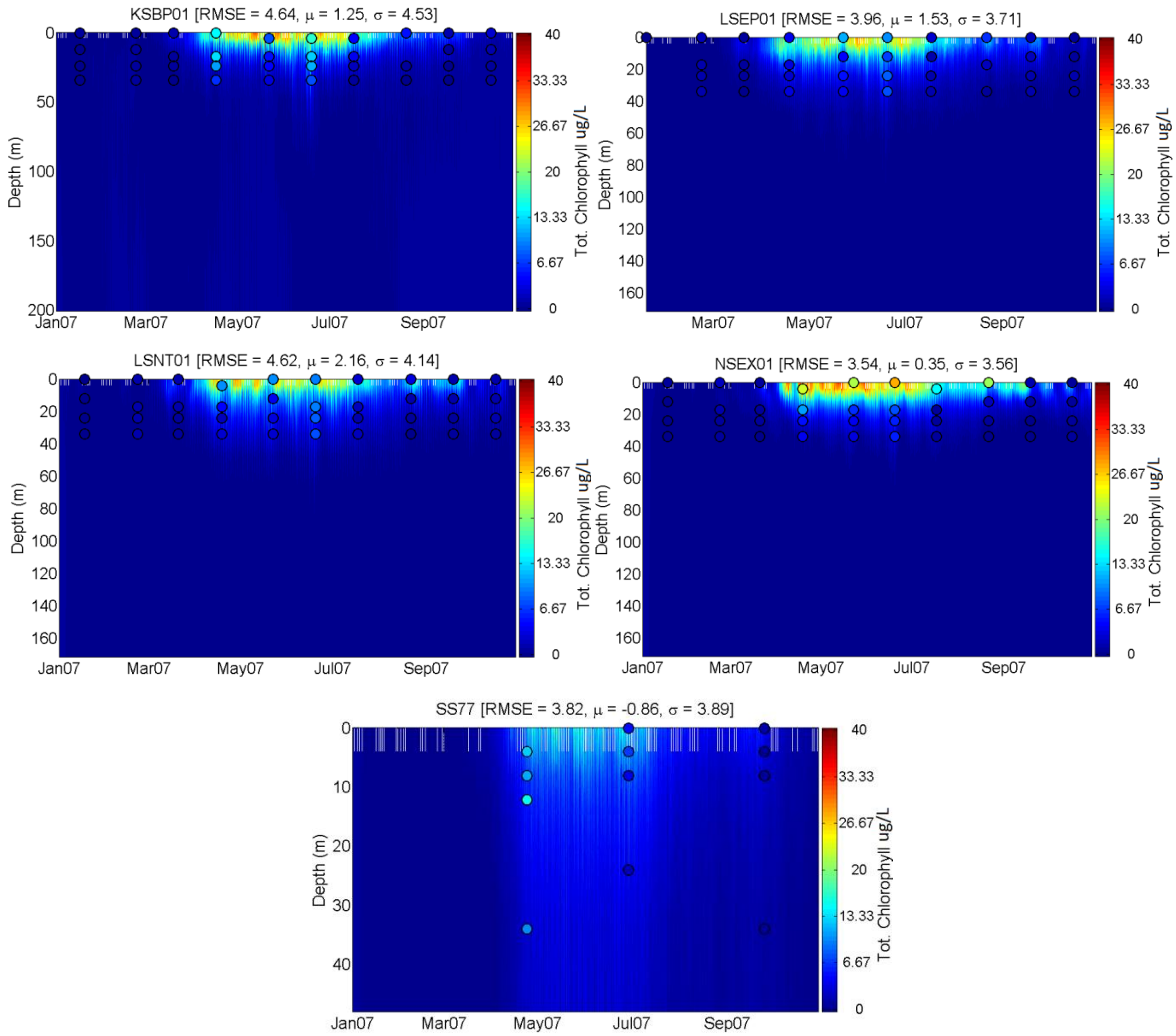


Figure 25. Time-depth contour plots of predicted and observed chlorophyll at Central Puget Sound calibration stations. See Figure 20 for station locations.

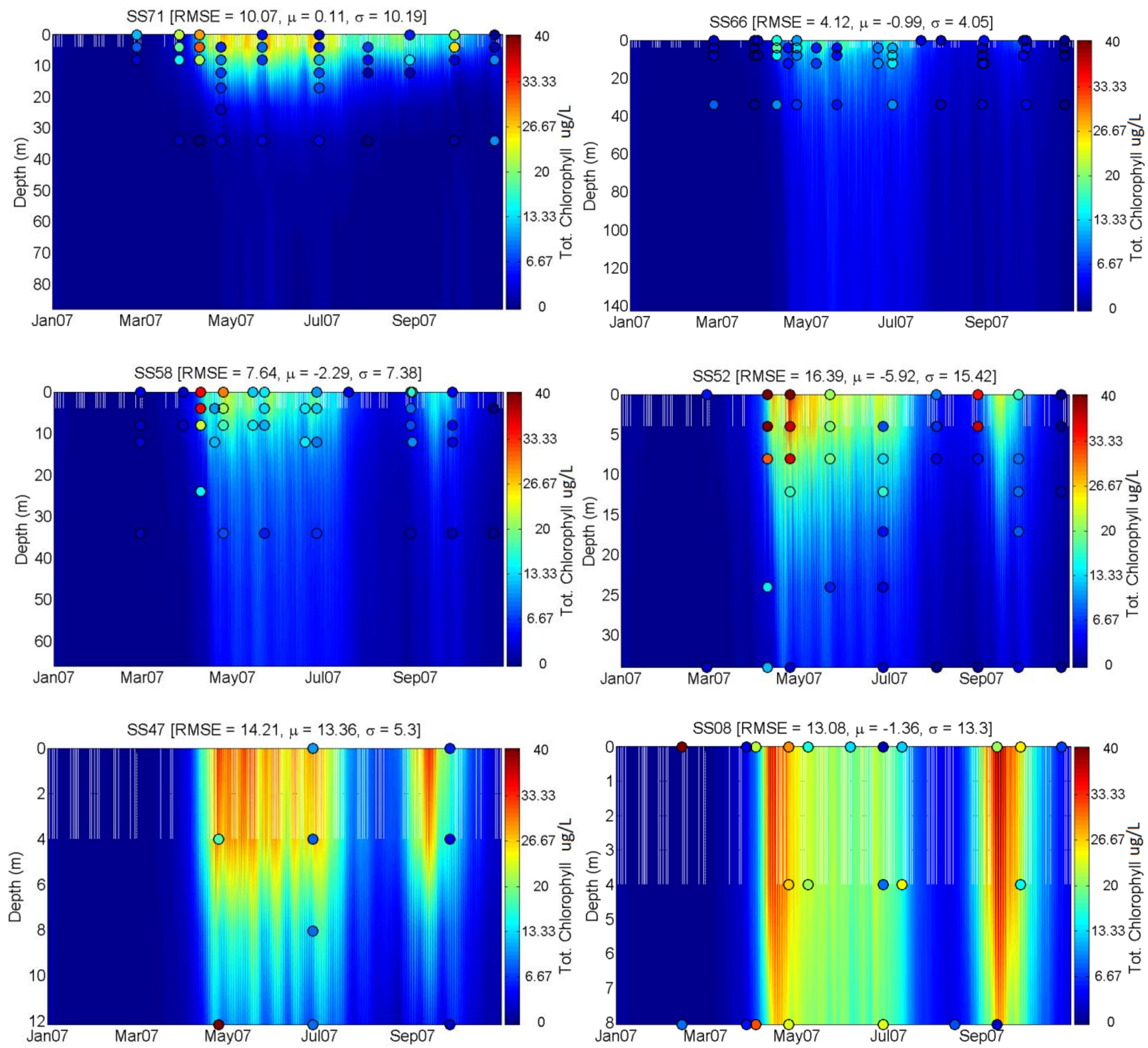


Figure 26. Time-depth contour plots of predicted and observed chlorophyll at South Puget Sound calibration stations.

See Figure 20 for station locations.

Water Quality Time-Series Plots

Figure 27, Figure 28 and Figure 29 show the time-series plot of DO, DIN and chlorophyll at both surface and bottom layer for all the calibration stations (Figure 20). The seasonal pattern of DO shows a gradual increase in the early part of summer and then a gradual decrease into fall. This pattern is true for surface layers in deeper regions but is reflected in both surface and bottom layers of shallow waters. The seasonal trend for chlorophyll also follows this pattern but is reversed for DIN which is consumed during algal growth. In deeper waters there is no algal productivity due to lack of light as predicted by the model and measured data. In shallow Inlets however, algal productivity exists throughout the water column. The model captures the seasonal trend for DO, DIN and chlorophyll.

The model did a better job at simulating bottom DO (maximum RMSE of 1.6 mg/L with an average RMSE of 0.86 mg/L) compared to surface DO (maximum RMSE of 2 mg/L with an average RMSE of 1.4 mg/L). These RMSEs are comparable to those observed for DO in Budd Inlet (maximum RMSE of 2.4 mg/L with an average RMSE of 1.2 mg/L for bottom layer) (Roberts et al., 2012) using the same modeling framework but with a higher resolution grid.

DIN time-series plots show that during peak algal growth, nutrients are reduced to near limiting conditions in surface layers of deeper waters and throughout the water column in shallow waters. For surface layers the maximum RMSE was 0.18 mg/L (average of 0.09 mg/L) which is slightly more than previously observed surface layer maximum RMSE of 0.11 mg/L (average of 0.08 mg/L) in a higher resolution Budd Inlet model (Roberts et al., 2012).

Chlorophyll time-series show algal productivity in surface layers of deeper waters. Shallow waters show algal productivity throughout the water column, which is perhaps an artifact of mathematical dispersion due to fewer layers in the inlets. The maximum RMSE was 26 ug/L in Case Inlet while the overall average RMSE was 10 ug/L. These values are comparable to a higher resolution Budd Inlet DO model where a maximum RMSE of 18 ug/L (average RMSE of 13 ug/L) was observed (Roberts et al., 2012).

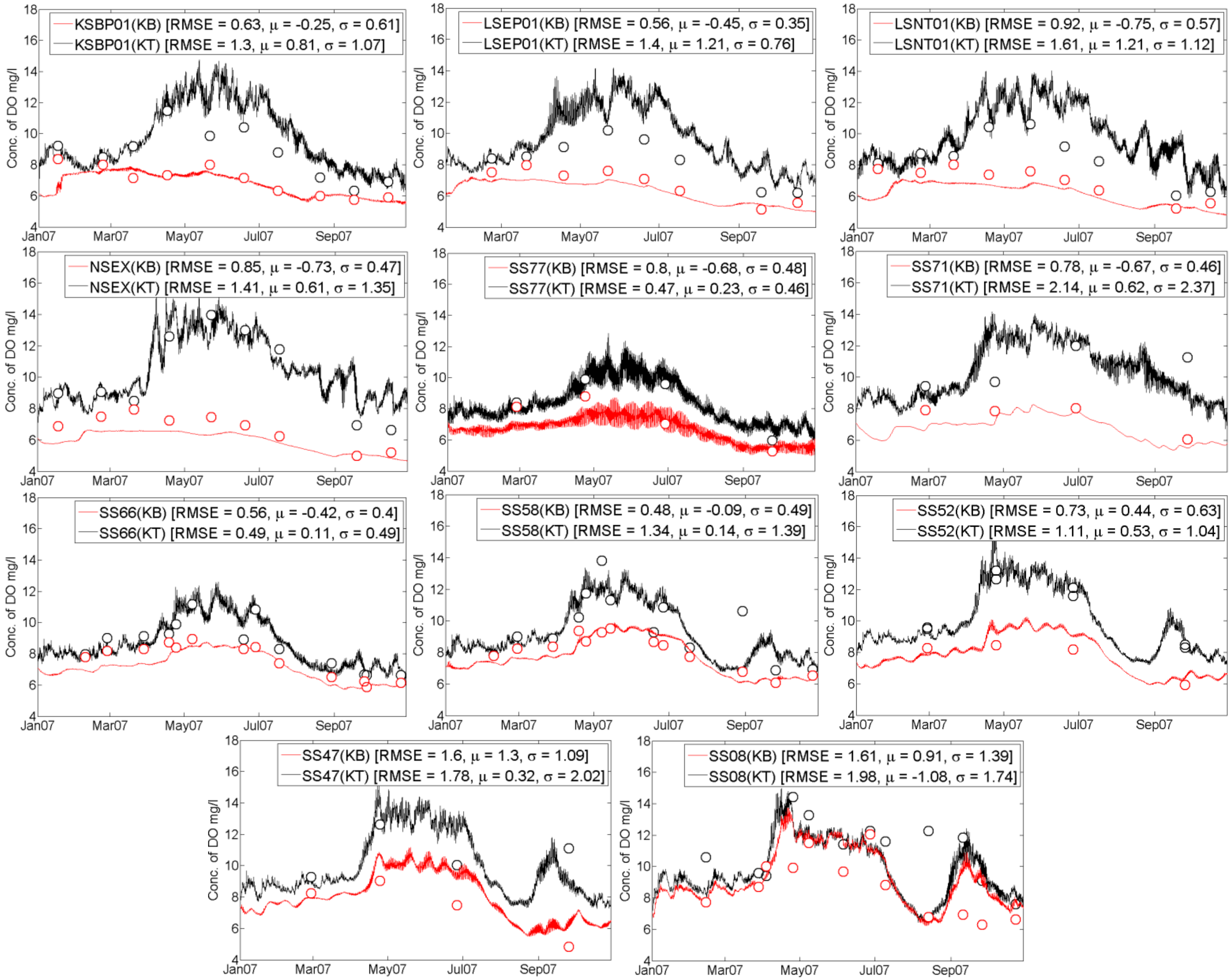


Figure 27. Time-series plot of DO at surface (KT) and bottom (KB) layers (See Figure 20 for station locations)

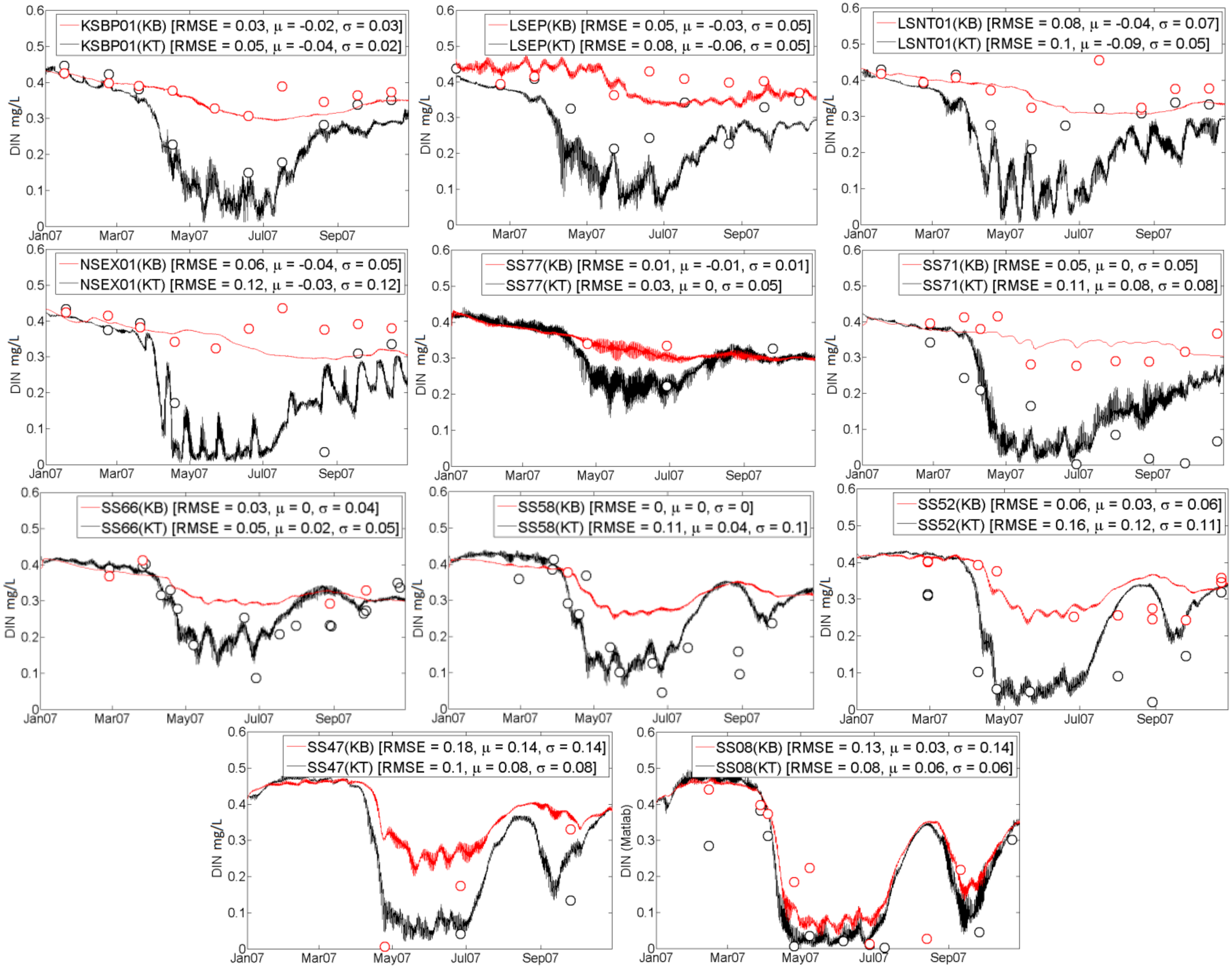


Figure 28. Time-series plot of DIN at surface (KT) and bottom (KB) layers (See Figure 20 for station locations)

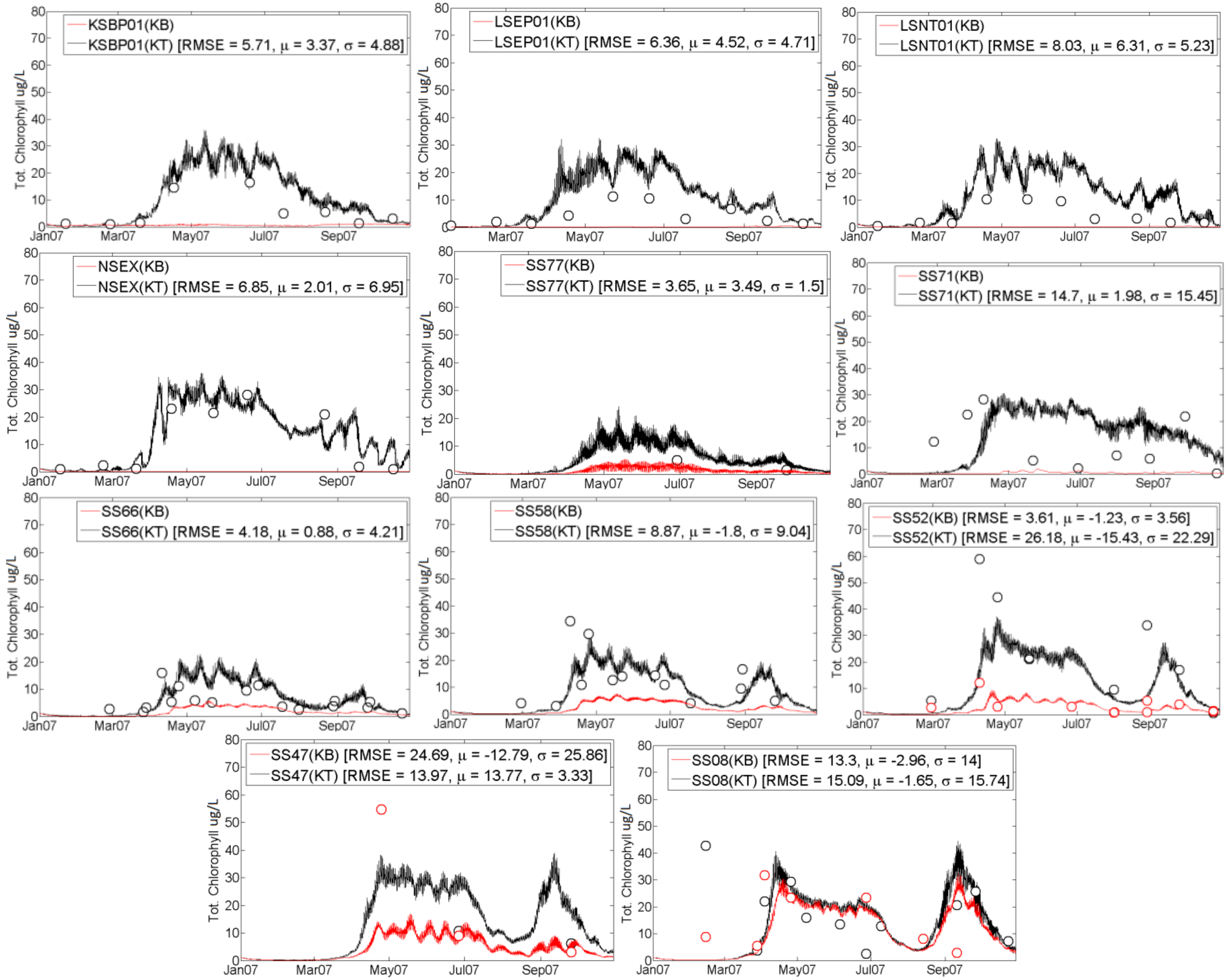


Figure 29. Time series plot of chlorophyll at surface (KT) and bottom (KB) layers (See Figure 20 for station locations)

Water Quality Profiles at Selected Stations

Figure 30 shows the stations where model-predicted water quality profiles were compared with observed data for DO, DIN and chlorophyll. At each station, three seasonal profiles were compared, in spring, summer and fall for DO, DIN, and chlorophyll (Figure 31, Figure 32, and Figure 33). Depths are shown with respect to water surface. In some cases the deepest measured data do not coincide with the bottom of the model profile where the field data may have been measured in a deeper-than-average location.

In general, the model was able to simulate the vertical observed profiles. The maximum RMSE for DO profiles was 2 mg/L with an overall average of 1.1 mg/L. The maximum RMSE for DIN profiles was 0.1 mg/L with an overall average of 0.06 mg/L. The maximum RMSE for total chlorophyll profiles was 21 ug/L with an overall average of 7 ug/L. These error statistics were comparable to those obtained in a higher resolution Budd Inlet DO model (Roberts et al., 2012) For vertical profiles, the Budd Inlet model had an average RMSEs for DO, DIN, and chlorophyll of 1.2 mg/L, 0.1 mg/L, and 12.8 ug/L, respectively. Further discussion on error statistics is included in the section titled "Model Uncertainty" following this section.

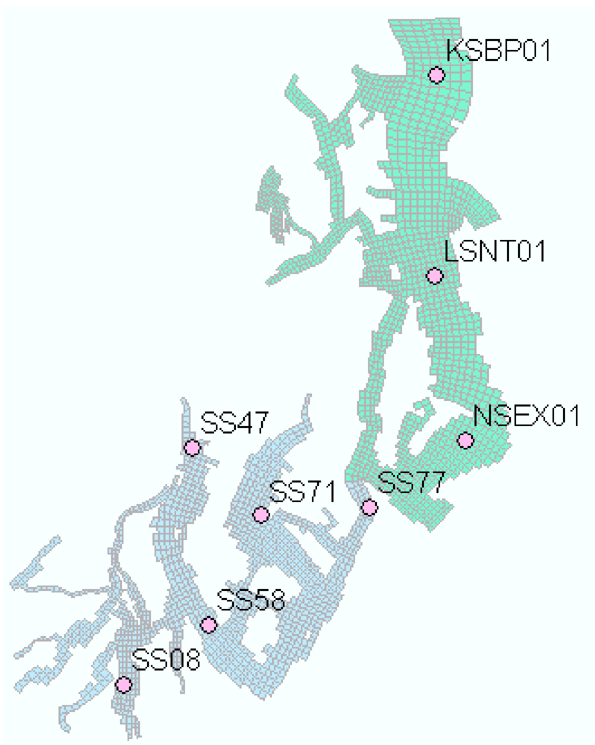


Figure 30. South Puget Sound and Central Puget Sound stations where water quality profiles were evaluated.

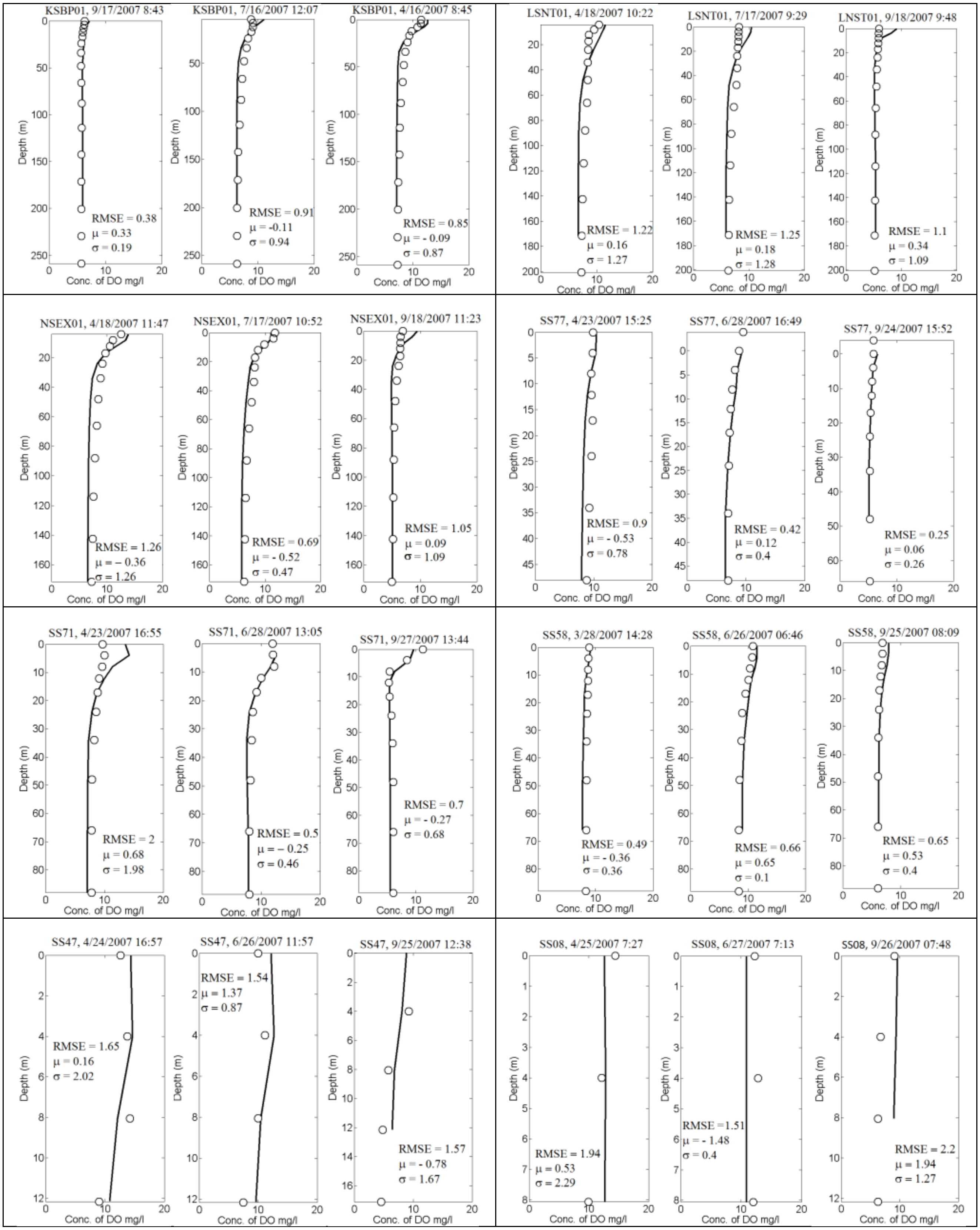


Figure 31. DO profiles at selected stations in South and Central Puget Sound for spring, summer, and fall.

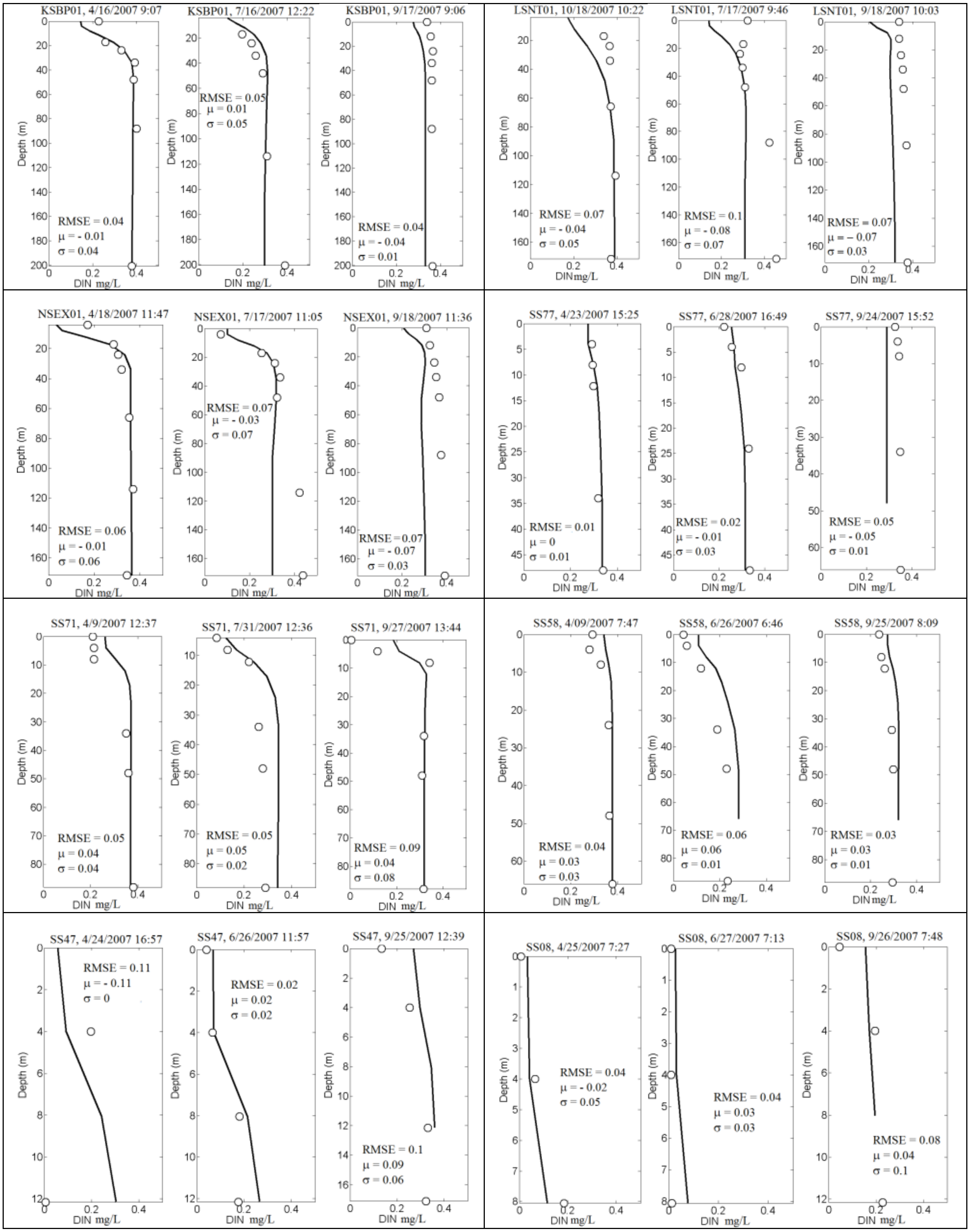


Figure 32. DIN profiles at selected stations in South and Central Puget Sound for spring, summer, and fall.

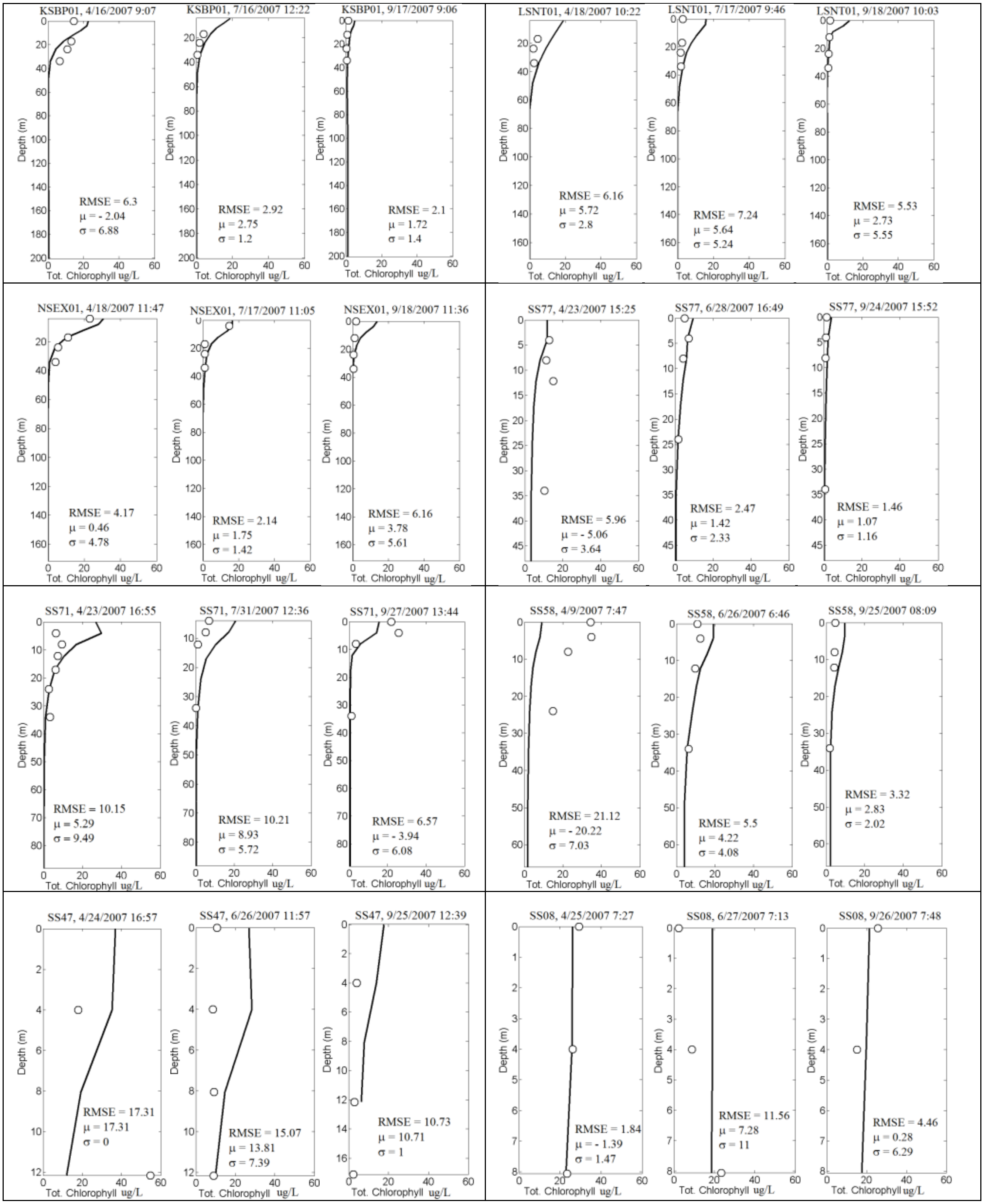


Figure 33. Chlorophyll profiles at selected stations in South and Central Puget Sound for spring, summer, and fall.

Model Uncertainty

Figure 34 shows the overall error statistics for DO, DIN, and total chlorophyll for calibration stations. The root mean square error (RMSE) is an unbiased statistic of how well the model is predicting observed values. It is mathematically defined as the square-root of the average squared difference between paired observed and predicted data, as defined below:

$$RMSE = \sqrt{\frac{\sum \left(X_o - X_p\right)^2}{n}}$$

Where X_0 = observed data; X_p = predicted data; n = number of paired data sets

We also evaluated bias, or the tendency to overpredict or under predict water quality patterns. The mean bias (μ) of the predictions is the average of the differences between predicted and measured values, while σ is the standard deviation of the bias. If the range (μ ± 2 σ) does not contain zero, then model would be biased.

$$bias = average\left\{\left(X_{pred,1} - X_{obs,1}\right) + \left(X_{pred,2} - X_{obs,2}\right) \ldots + \left(X_{pred,n} - X_{obs,n}\right)\right\}$$

If the range is below zero, then the model underpredicts. If the range is above zero, then the model overpredicts. In reviewing the error statistics it should be noted that the model predictions are average values within a given grid-cell layer. The field data were binned to the model layers.

The highest RMSE for DO was approximately 1.8 mg/L at the Budd Inlet station (SS08). Using the confidence interval of μ ± 2 σ, the model does not have a bias in predicting observed DO concentrations. The highest RMSE for DIN was approximately 0.1 mg/L at both Budd Inlet station (SS08) and in Case Inlet (station SS52). The model does not have a bias in predicting observed dissolved inorganic nitrogen (DIN) concentrations. The highest RMSE for total chlorophyll was approximately 16 ug/L at station SS52 in Case Inlet. The Budd Inlet (SS08) and northern Case Inlet (SS47) stations also had high RMSE. There is a positive bias (i.e., over prediction) for total chlorophyll at the Case Inlet station (SS47).

Overall goodness of fit for DO, DIN, and chlorophyll is depicted in Figure 35. Data from all field stations at all depths and times were plotted along with model predicted values between the dates of January 2007 and October 2007. A perfect match would be when all data lie on the 1:1 line and predicted values and measured values match exactly. The histogram shows the frequency distribution of the residuals, which are the differences between predicted and observed values, with the mean and standard deviation of the bias.

The overall root mean square error for DO was 1.2 mg/L (n = 3718) with a mean bias of 0.04 mg/L. However, the bias for DO is not significant because it lies within 2 standard deviations of zero difference (i.e., at the 95% confidence interval). For predicted DIN, the overall RSME is 0.07 mg/L (n = 1744) with a mean bias of -0.005 mg/L. Again within the 95 percentile confidence interval, the bias for DIN is not significant. The overall RMSE for total chlorophyll was 8.2 ug/L (n = 1257) with a mean bias of 1.2 ug/L. The bias for total chlorophyll was not significant because it falls within 2 standard deviations of zero difference.

Station	Dissolved Oxygen, mg/L					Dissolved Inorganic Nitrogen, mg/L					Total Chloropyll, ug/L				
	RMSE	μ	σ	μ + 2σ	μ - 2σ	RMSE	μ	σ	μ + 2σ	μ - 2σ	RMSE	μ	σ	μ + 2σ	μ - 2σ
KSBP01	0.76	-0.09	0.76	0.67	-0.85	0.04	-0.02	0.03	0.01	-0.05	4.64	1.25	4.53	5.78	-3.28
LSEP01	0.89	-0.21	0.87	0.66	-1.08	0.06	-0.03	0.05	0.02	-0.08	3.96	1.53	3.71	5.24	-2.18
LSNT01	0.99	-0.22	0.97	0.75	-1.19	0.06	-0.04	0.05	0.01	-0.09	4.62	2.16	4.14	6.3	-1.98
NSEX01	1.05	-0.38	0.99	0.61	-1.37	0.06	-0.02	0.05	0.03	-0.07	3.54	0.35	3.56	3.91	-3.21
SS77	0.68	-0.29	0.62	0.33	-0.91	0.03	-0.01	0.03	0.02	-0.04	3.82	-0.86	3.89	3.03	-4.75
SS71	1.22	-0.2	1.22	1.02	-1.42	0.07	0.02	0.07	0.09	-0.05	10.07	0.11	10.19	10.3	-10.08
SS66	0.59	-0.32	0.49	0.17	-0.81	0.05	0.01	0.05	0.06	-0.04	4.12	-0.99	4.05	3.06	-5.04
SS58	0.76	0.06	0.76	0.82	-0.7	0.07	0.03	0.07	0.1	-0.04	7.647	-2.29	7.38	5.09	-9.67
SS52	1.44	0.71	1.27	1.98	-0.56	0.13	0.08	0.1	0.18	-0.02	16.39	-5.92	15.42	9.5	-21.34
SS47	1.38	0.15	1.43	1.58	-1.28	0.07	0.02	0.08	0.1	-0.06	14.21	13.36	5.3	18.66	8.06
SS08	1.79	-0.19	1.8	1.61	-1.99	0.1	0.04	0.09	0.13	-0.05	13.08	-1.36	13.3	11.94	-14.66

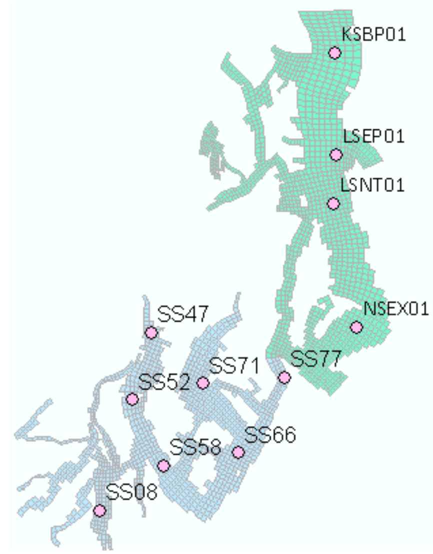


Figure 34. Error statistics for DO, DIN, and chlorophyll predictions (2007) for calibration stations.

Colors indicate lowest value in each category (RMSE or σ) as bright green while highest value in bright red.

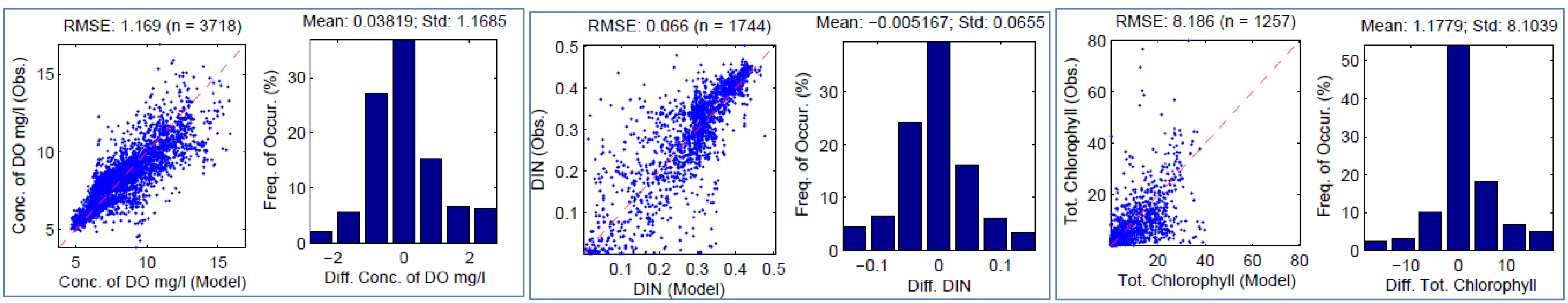


Figure 35. Goodness of fit for DO, DIN, and total chlorophyll predictions for 2007 across all stations used in model calibration.

Regional Water Quality Patterns

Figure 36, Figure 37, Figure 38, Figure 39, Figure 40 and Figure 41 show the spatial pattern of DO, DIN, and total chlorophyll concentrations in the model domain under various times of the year. Observed data from a ± 5 day window were plotted with instantaneous model predictions for several time periods. All data were gathered during day time. So, the spatial data reflects day time data only. However, diurnal data within the daylight hours are grouped in each plot. A 5-day window around noon time would include data from as early as 7 am to as late as 5 pm.

The plots show that both model predictions and observed data vary seasonally, with lowest surface concentrations of DO during winter and fall and highest during spring and summer. Similar patterns are observed for chlorophyll concentrations while the reverse is the case for DIN which is consumed by algae during spring and summer. The seasonal DO pattern is generally more pronounced in the surface layer compared to the bottom layer because surface levels respond immediately to algal productivity. However, the finger inlets still show elevated DO in the bottom layers seasonally, which can be attributed to fewer layers and large grid cells that promoted numerical dispersion in the shallow areas. Similar patterns are observed for DIN and total chlorophyll.

Figure 42 and Figure 43 compare a plan view map of predicted chlorophyll concentrations in the surface layer for April and June 2007, respectively, with photos taken in April and June 2013 by Ecology's "Eyes Over Puget Sound" (EOPS) project (http://www.ecy.wa.gov/programs/eap/mar_wat/surface.html). EOPS had not begun in 2007 when the data collection program occurred, so 2007 model results are compared with 2013 photos for general patterns only.

The April model predictions include algal blooms in Sinclair Inlet, Oakland Bay and Totten Inlet. EOPS aerial photos show a red phytoplankton bloom in Sinclair Inlet, brown algal bloom in Oakland Bay and red-brown bloom in Totten Inlet. The June model predictions include algal blooms in Port Madison (Central Puget Sound), Filucy Bay (near McNeil Island), and Henderson Inlet. EOPS aerial photos show a Noctiluca (a dinoflagellate) bloom in Port Madison accumulating at surface in filaments following large eddies, phytoplankton bloom in Filucy Bay across from McNeil Island in colors of green and brown, and green and red phytoplankton bloom in Henderson Inlet. The EOPS photos represent ground truth of algal blooms in these two periods as predicted by the model.

EOPS was not used in the calibration process. Instead, images were compared after calibration to compare model predictions against patterns observed in the marine flight program. These surface observations generally corroborate model-predicted patterns.

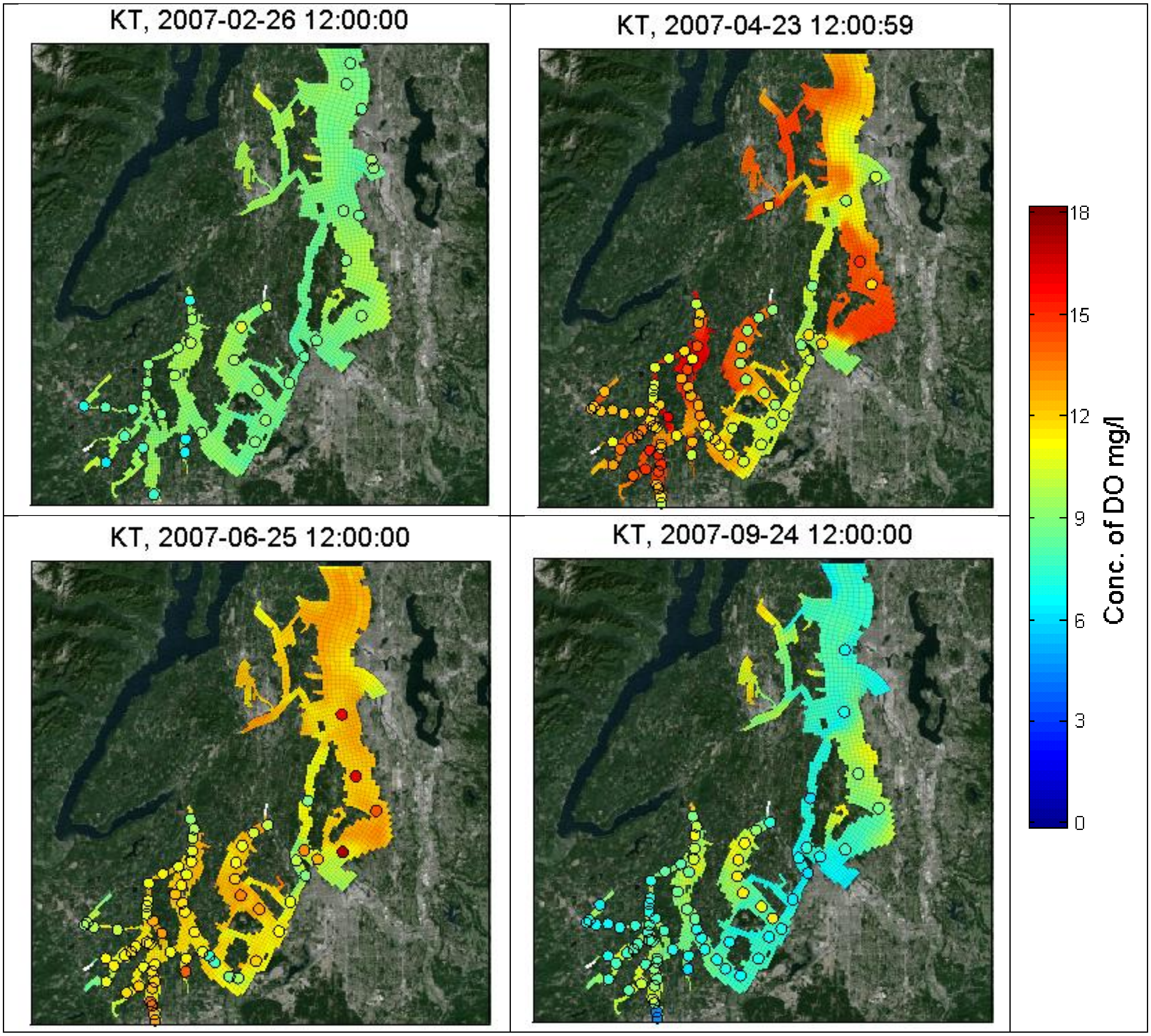


Figure 36. Spatial patterns for DO in the surface (KT) layer during different times of the year (2007).

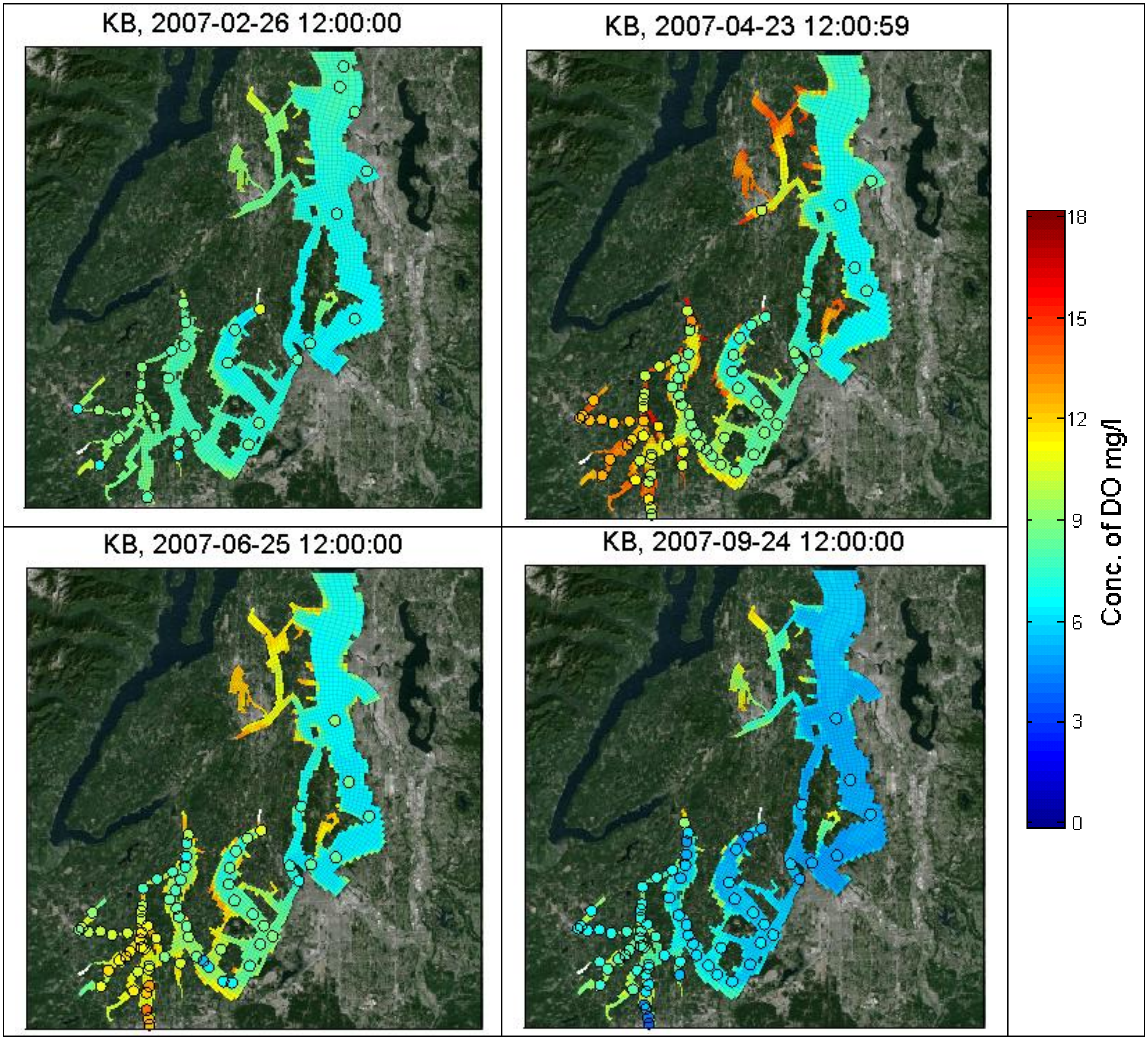


Figure 37. Spatial patterns for DO in the bottom (KB) layer during different times of the year (2007).

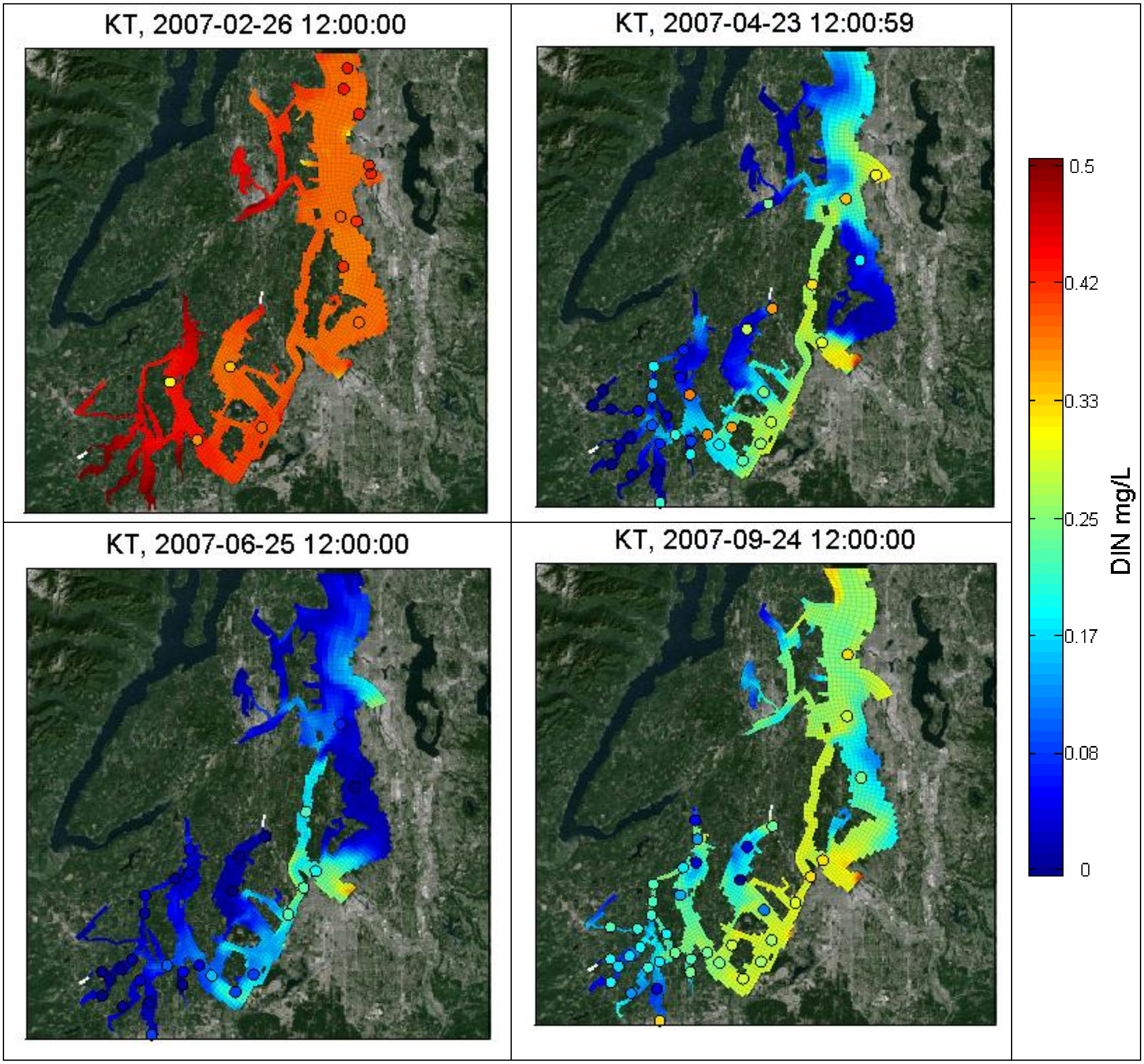


Figure 38. Spatial patterns for DIN in the surface (KT) layer during different times of the year (2007).

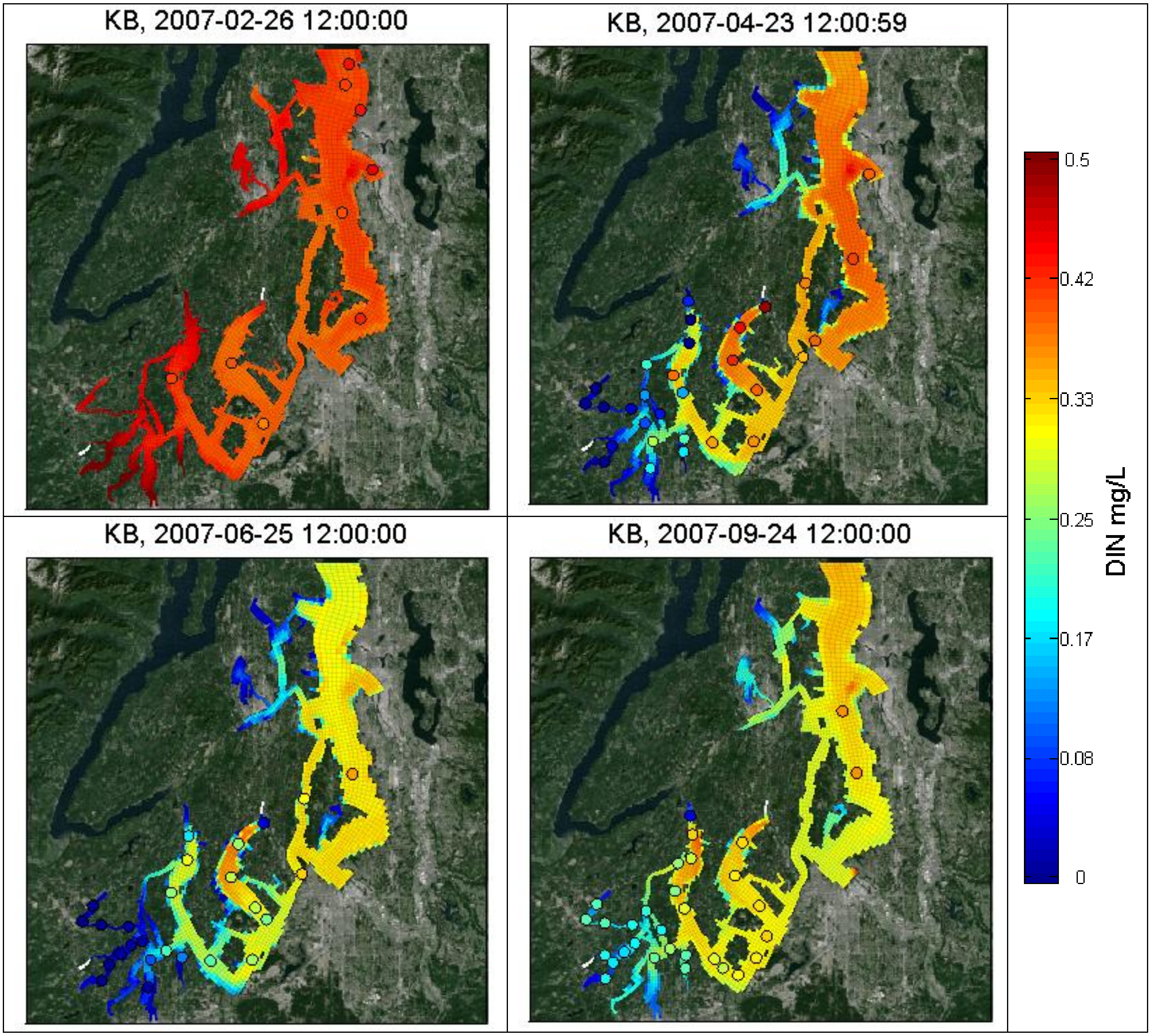


Figure 39. Spatial patterns for DIN in the bottom (KB) layer during different times of the year (2007).

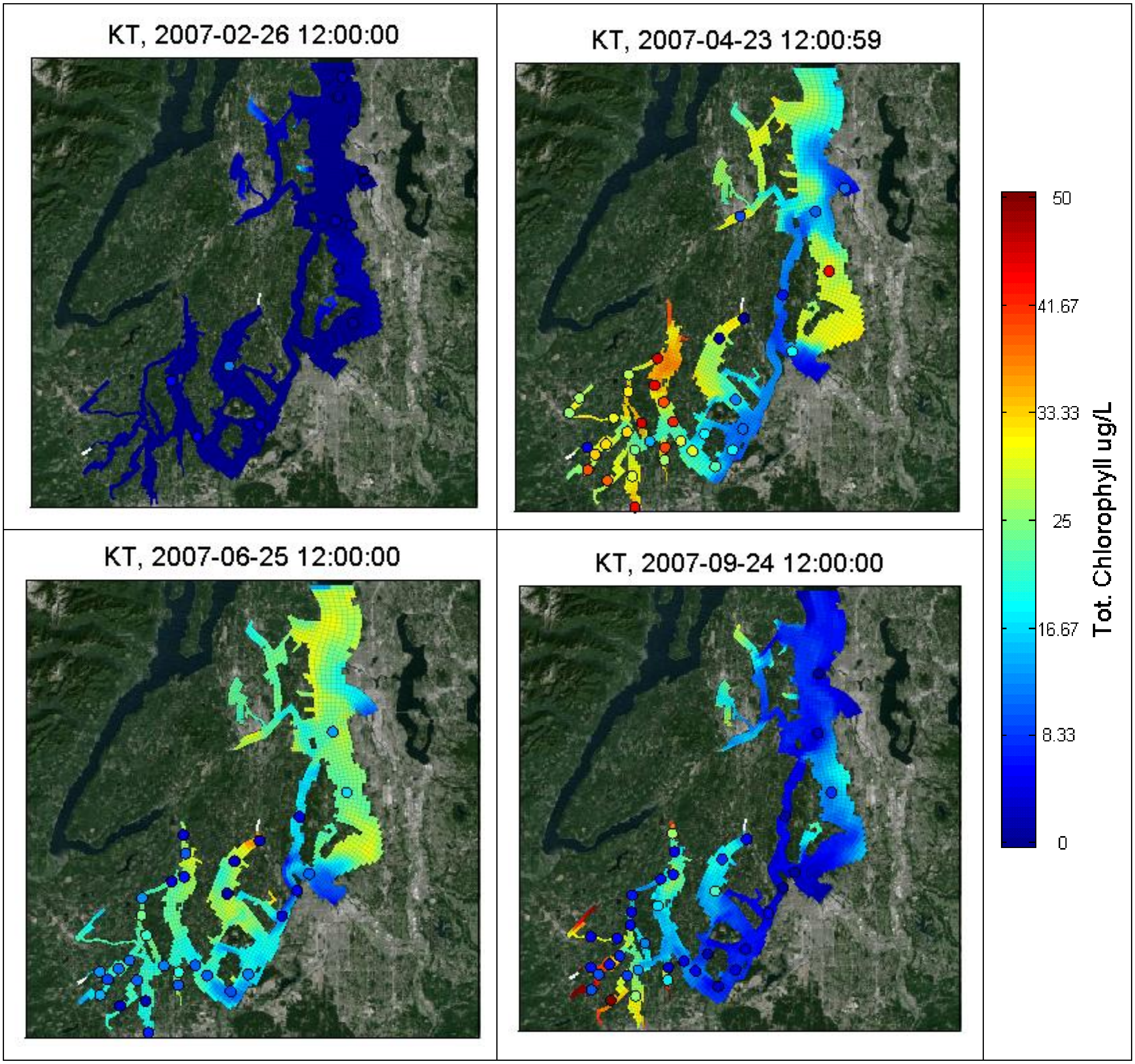


Figure 40. Spatial patterns for total chlorophyll in the surface (KT) layer during different times of the year (2007).

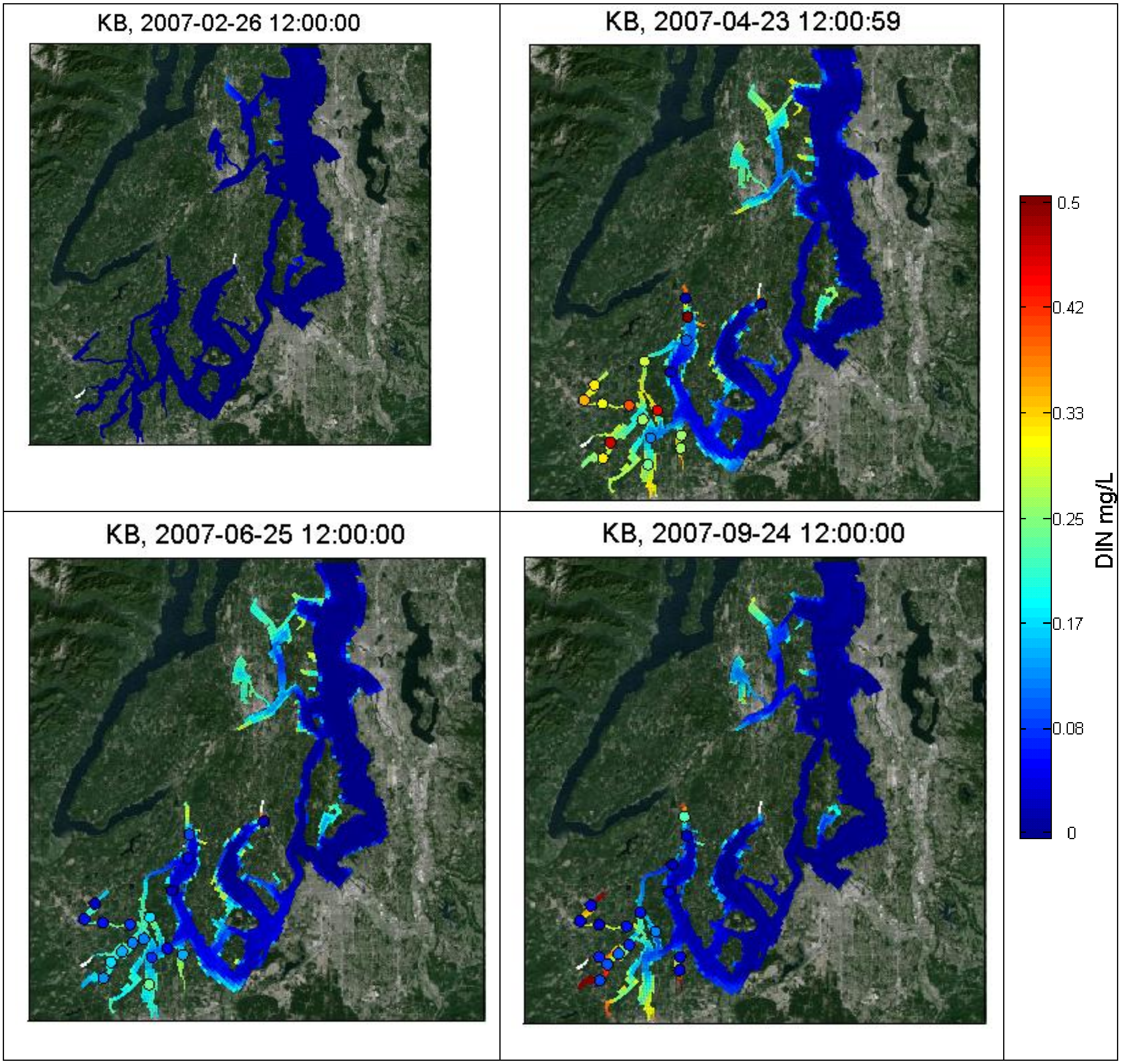


Figure 41. Spatial patterns for total chlorophyll in the bottom (KB) layer during different times of the year (2007).

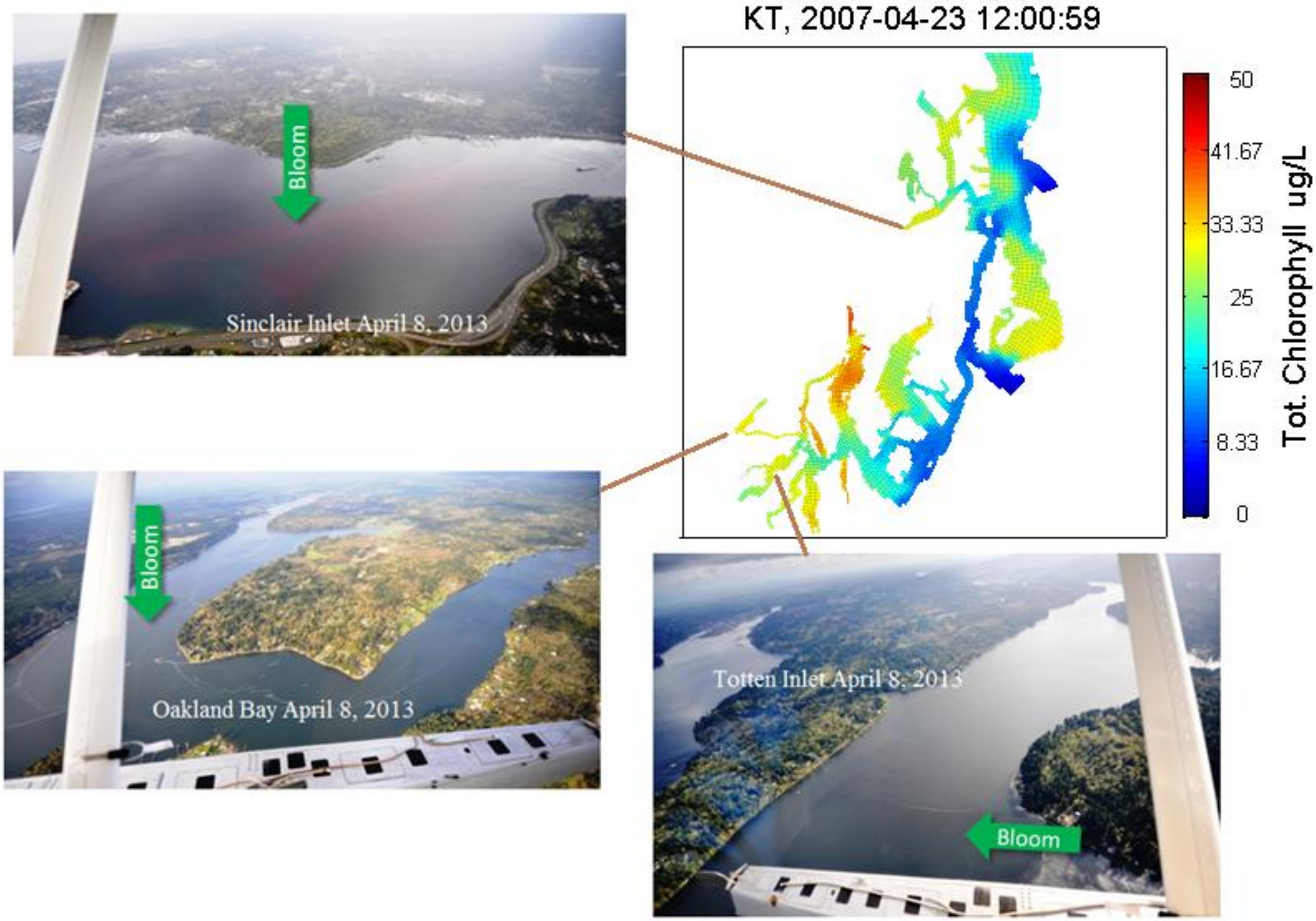


Figure 42. Comparing surface photos (April 8, 2013) from Eyes Over Puget Sound (EOPS) to model predictions (April 8, 2007).

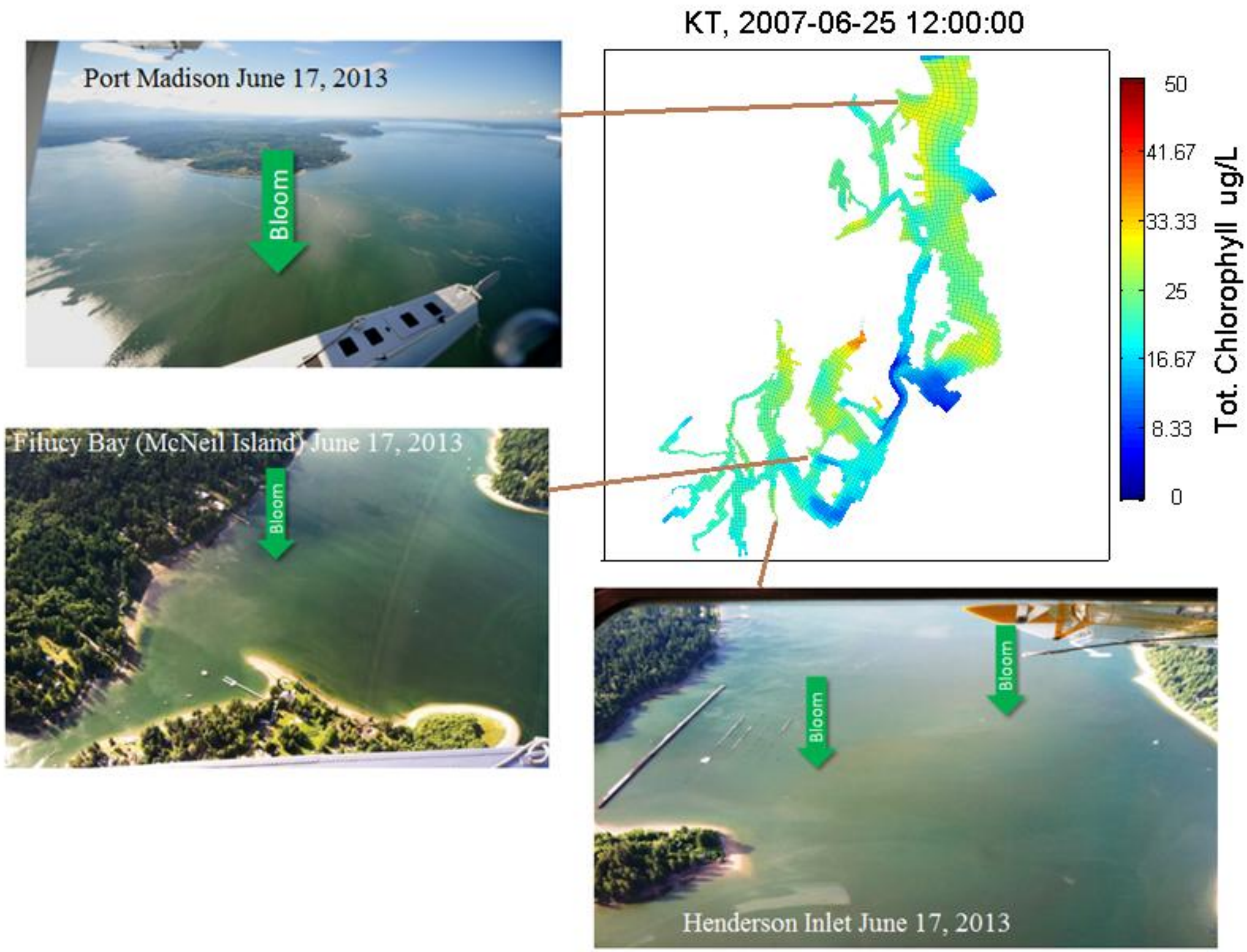


Figure 43. Comparing surface photos (June 17, 2013) from Eyes Over Puget Sound (EOPS) to model predictions (June 25, 2007).

Scenario Setup and Results

The goal of the South Puget Sound Dissolved Oxygen Study was to determine how human activities – along with natural factors – affect low DO levels in South Puget Sound. We evaluated current impacts by comparing predicted DO under current conditions with concentrations that would occur with only natural sources of nitrogen. We also evaluated the relative impacts of current marine point sources and human sources within watershed inflows, as well as impacts that could occur if permitted facilities discharged at maximum permitted levels. Finally, we explored the implications of reducing various groups of sources. Future work will evaluate the impacts from individual sources of nitrogen. This section summarizes scenario set up and the results for groups of sources.

The seven scenarios evaluated in this report are listed in Table 4. Detailed loading data for each of these scenarios is presented in Table 9 (later in the section) and Appendix G. Scenarios 2 through 7 were each compared with scenario 1 and the numeric DO standard to determine the extent of violations of the DO water quality standard.

Table 4. Scenario descriptions for current and alternative loads

Scenario Number	Scenario Name	Scenario Description
1	Natural conditions	No marine point source loads and no anthropogenic watershed loads
2	Existing conditions	Existing anthropogenic marine point source and watershed loads
3	Watershed loads only	Anthropogenic watershed loads only with no marine point source loads
4	Marine point source loads only	Anthropogenic marine point source loads only with no anthropogenic watershed loads
5	Maximum permitted marine point source laods	Marine point source loads at maximum permitted values with watershed loads at existing conditions
6	Overall Reductions in Loads	Reduce marine point source and watershed loads by 25%, 50%, and 75%
7	No anthropogenic sources in Central Puget Sound	South Puget Sound: Existing conditions for marine point sources and watershed loads. Central Puget Sound: Natural conditions (no anthropogenic marine point source and watershed loads)

Natural Conditions

As described earlier, the Washington State water quality standards have two parts. Where natural conditions are above the numeric criteria, human contributions cannot cause DO to fall below the criteria. Where natural conditions are below the numeric criteria, human contributions cannot cause DO to decrease by more than 0.2 mg/L below the natural condition. The first step is to determine the minimum DO that would occur under natural conditions.

The natural condition DO concentrations for the model domain was established by running the hydrodynamic and water quality calibrated model with:

1. Watershed loads set to natural conditions.
2. Marine point source concentrations set to average natural watershed conditions.
3. Open boundary conditions at Edmonds set to natural conditions.
4. Sediment fluxes set to natural conditions.
5. No changes made to atmospheric loads or meteorology.

Watershed Loads

A detailed procedure on how natural watershed loads were estimated is included in Mohamedali et al. (2011). While flows in rivers and streams were kept at current conditions, the concentrations were set to natural conditions. This entailed creating new time-series files for water quality parameters for each watershed inflow. These time-series files included constant monthly values for different forms of nitrogen (NH3, NO3, dissolved and particulate organic nitrogen; see example plots in Figure 32 in Mohamedali et al 2011). We did not adjust other boundary condition input parameters, such as temperature or DO, from current conditions.

Marine Point Sources

Under natural conditions, marine point sources were assumed to discharge flow at the same level as current conditions because all of the water comes from the South and Central Puget Sound watersheds and would eventually reach these marine water bodies. This ensured that the hydrodynamic conditions remained the same. Because zero values could dilute ambient marine concentrations in and near the grid cells where marine point sources discharge, we assigned non-zero concentrations. Water quality of these discharges was assumed to be equal to that of the natural watershed inflow concentrations. This entailed creating a single time-series water quality file that was used for every marine point source. While this introduces some nutrients to the model domain under natural conditions, the loads are several orders of magnitude lower than either the current marine point sources or watershed inflows.

Open Boundary Natural Condition

Puget Sound is a partially mixed estuary that has a net landward inflow of denser water into the subsurface layer and a net seaward outflow of fresher water from the surface. The subsurface layer was defined as all water deeper than the depth of no net motion, determined through examination of the long-term average flow pattern at the Edmonds boundary. This varied from a depth of 12 m near shore to 88 m in the thalweg. The net inflow of water into the subsurface layer also carries a relatively large nutrient loading into Central Puget Sound from sources north of the open boundary at Edmonds and from the Pacific Ocean.

A portion of the open boundary inflow load is from anthropogenic sources. The anthropogenic load of nutrients into Central Puget Sound across the open boundary originates from two categories of sources:

1. Sources within the model domain (e.g., rivers and point sources directly discharging into South Puget Sound and central Puget Sound) that are transported north across the Edmonds

boundary in the surface layer, and then re-circulate back into Central Puget Sound into the subsurface layer in a process known as refluxing.

2. Sources from north of the Edmonds boundary (e.g., rivers and human sources north of Edmonds and ocean inputs).

In order to run the natural condition scenario it is necessary to estimate the loading of nutrients from across the open boundary that would occur if anthropogenic loading sources were eliminated. It is necessary to use a model with a larger domain that includes all of the external loading sources north of the Edmonds boundary in addition to the sources within the South and Central Puget Sound regions.

Khangaonkar et al. (2012) developed a model that simulates the entire Salish Sea including South Puget Sound plus all regions north of Edmonds. As part of that project, the water quality concentrations under current and natural conditions were simulated. Roberts et al. (2013, in press) summarizes that model application. The Puget Sound / Salish Sea model predictions of water quality concentrations across a transect at Edmonds under current and natural conditions were compared to estimate a ratio of concentrations at natural versus current conditions. The resulting ratio was called the "open boundary water quality scalar" for natural conditions.

The open boundary water quality scalar from the Puget Sound / Salish Sea model was multiplied by the current water quality conditions at the open boundary in the South and Central Puget Sound model to approximate the open boundary inputs that would occur under natural conditions. A detailed procedure on how we calculated the open boundary water quality scalars is included in Appendix E. The open boundary water quality scalars are shown in Table 5. Temperature and salinity remain unchanged between current and natural conditions. Therefore a scalar of one is used. Dissolved and particulate organic phosphorus results are not available as an output of the Salish Sea model. Therefore, dissolved and particulate organic phosphorus remain unchanged between current and natural conditions and a scalar of one is used.

Table 5. Water quality scalars for natural condition at the Edmonds open boundary.

Variables used in GEMSS		
Variable	Variable name	Scaling factor
Temp	Temperature	1.0000
Saln	Salinity	1.0000
DO	Dissolved oxygen	1.0035
CBOD_F	Fast carbonaceous biochemical oxygen demand	0.9821
CBOD_S	Slow carbonaceous biochemical oxygen demand	0.9821
GAM1	Algae 1	0.9676
GAM2	Algae 2	0.9476
NH3	Ammonia	0.8557
NO3	Nitrate	0.9353
PO4	Phosphate	0.9625
ON_D	Dissolved organic nitrogen	0.9132
OP_D	Dissolved organic phosphorus	1.0000
ON_P	Particulate organic nitrogen	0.9158
OC_P_F	Fast particulate organic carbon	0.9568
OC_P_S	Slow particulate organic carbon	0.9568
OC_P_R	Refractory particulate organic carbon	0.8952
OP_P	Particulate organic phosphorus	1.0000

Sediment Fluxes under Natural Conditions

Sediment fluxes under natural conditions were reduced using scalars to adjust sediment fluxes from those under current conditions. First, the South and Central Puget Sound model was run twice under natural conditions for watershed loads, marine point sources, and the open boundary. The first run had a sediment scalars of 1.0; the second run had a sediment scalar 0.5, which is the same as 50% of current conditions.

For the two runs, a domain-wide particulate nitrogen flux for the bottom grid layer was estimated. This value was divided by the particulate nitrogen flux under current conditions to give a predicted scalar that was expected to be equivalent to the assumed sediment scalar for that run. This is because sediment fluxes are driven by particles settling to the bottom. We assumed that the ratio of fluxes from sediments to water under natural and current conditions would be the same as the ratio of settling PON between the natural and current condition.

The difference between assumed and predicted sediment scalars was plotted against predicted sediment scalar (Figure 44).The sediment scalar with zero difference between the predicted and assumed scalar (0.886) was selected as the actual sediment scalar for the natural condition. A final run was made using this sediment scalar to confirm the difference between the assumed and predicted sediment scalar was zero. Appendix F includes additional detail on the approach to estimate sediment scalars for natural conditions using particulate nitrogen flux for the grid bottom layer. The procedure was repeated using a mass balance that includes the incoming total nitrogen load from marine waters (see Appendix F). The calculated scalar was similar to 0.886, as shown in Figure 44. Therefore, a sediment scalar of 0.886 was applied to all nitrogen and oxygen fluxes throughout the model domain to simulate natural conditions.

The sediment flux scalar for SOD for natural conditions was estimated assuming that the ratio of natural/current SOD would be equivalent to the ratio of natural/current deposition of PON. This assumption was checked at a location in Carr Inlet using Ecology's spreadsheet sediment diagenesis model (Ecology, 2013) to calculate the ratio of natural/current SOD in response to changes in deposition of organic C and N and overlying water column concentrations of DO, ammonia, and nitrate. The sediment diagenesis model predicted a ratio of natural/current SOD of 0.918 which was similar to the ratio of natural/current deposition of PON of 0.904 at the same location. The close agreement of <2% difference corroborates the assumption of equivalence of the ratios of natural/current SOD and deposition of PON.

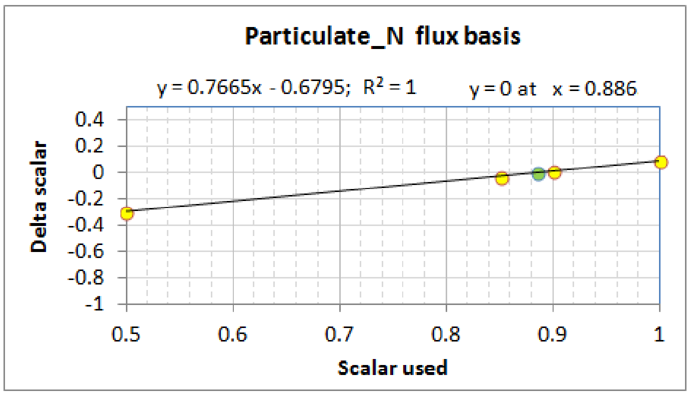


Figure 44. Plot of difference between used and predicted sediment scalars versus scalar used.

The yellow dots represent the different trials on which the regression equation is based.
The green dot signifies the final scalar for which the difference between used and predicted scalar is zero.

Predicted Dissolved Oxygen Concentrations under Natural Conditions

DO concentrations were predicted under natural conditions using the GEMSS model under natural watershed loads, natural discharges from marine point sources, natural loading at the open boundary and natural sediment fluxes. Minimum DO in each layer of each grid cell was then used to evaluate whether water quality standards were being violated or not. Figure 45 shows the minimum DO concentration that would occur under natural conditions for each grid cell where DO was below the numeric DO criterion. The numeric regional DO criterion is also included in the figure. The minimum DO naturally falls below the applicable numeric criterion throughout most of South and Central Puget Sound.

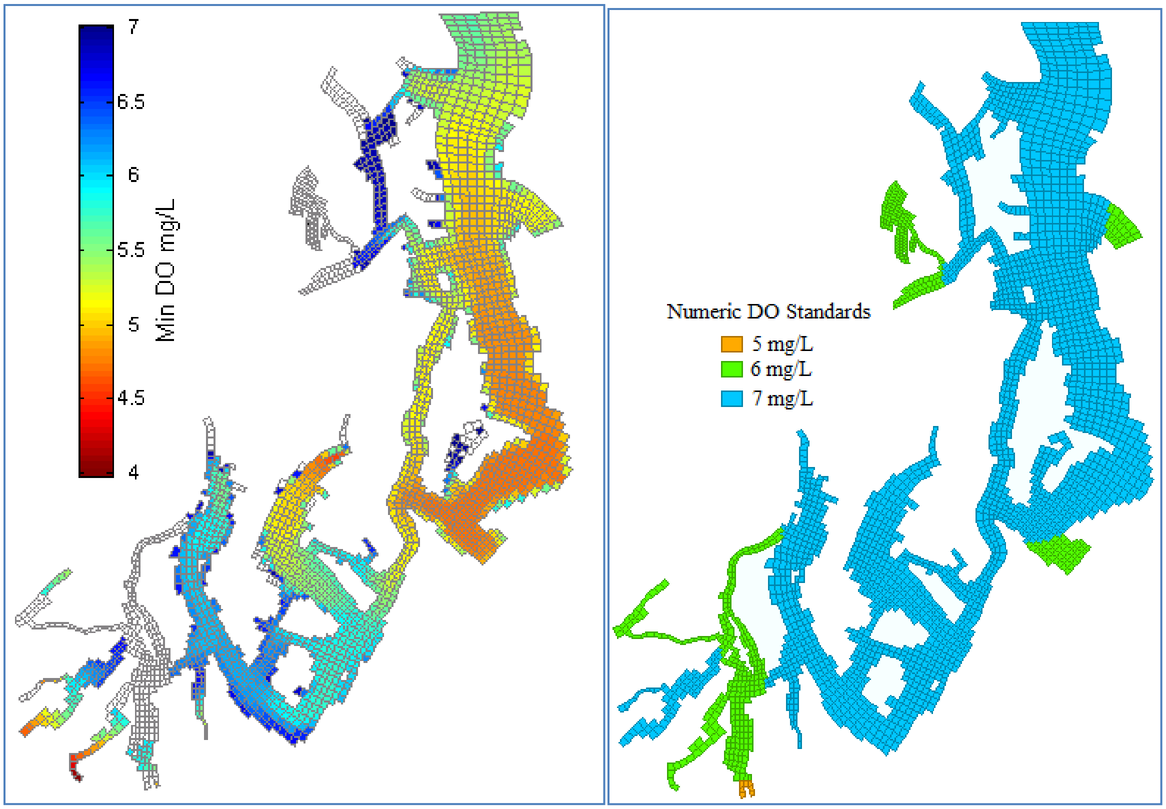


Figure 45. Grid cells with minimum DO below the numeric standard under natural conditions. Cells in white are above the numeric standards under natural conditions.

Table 6 summarizes the areas and duration where natural conditions fall below the applicable numeric criterion. For instance, 2 km^2 of South and Central Puget Sound has a numeric criterion of 5 mg/L, and 0.2 km^2 falls below that value, or 12% of the area. However, this occurred on only 1 day out of the 302-day simulation, or 0.3% of the time. The minimum predicted instantaneous hourly value was 4.95 mg/L. Within areas with a numeric criterion of 6 mg/L, 33% of the 135 km^2 falls below 6 mg/L, and this occurs from 1 to 143 days depending on the grid cell. The lowest predicted DO was 3.92 mg/L. For areas with a numeric criterion of 7 mg/L, 96% of the area falls below the criterion. This occurs throughout the simulation for some grid cells, and the minimum predicted DO was 4.58 mg/L.

Table 6. Percent areas and days when natural DO was below the applicable numeric criterion under natural conditions.

Category	Numerical DO criterion	Total area for category, km^2	area with DO below criterion, km^2	% area below criterion	Days below criteria		Minimum predicted DO, mg/L
					no. of days	% of days	
Good	5	2	0.2	12	1	0.3	4.95
Excellent	6	135	44	33	1 - 143	0.3- 47	3.92
Extraordinary	7	927	893	96	1 - 302	0.3 - 100	4.58

Alternative Loading Scenario Setup

The following discussion pertains to Scenarios 3 through Scenario 7 (see Table 4) where different current anthropogenic loads are being reduced or increased.

Point Sources Discharging to Marine Waters

Current marine point source discharges (as of 2007) were mapped to either the surface layer or multiple layers depending upon whether the outfalls are located in shallow or deep waters (for a discussion on trapping levels of marine point source discharge see Roberts et al., 2013 in press). Under natural conditions or scenarios that eliminate marine point sources, the quantity of flow is the same as 2007 but the quality is set to the average concentrations of natural watershed inflows.

The total nitrogen (TN) load from point source discharges to marine waters under current conditions during April-September was 28,000 kg-TN/day for the entire South and Central Puget Sound region (Table 7). Under natural conditions the load is 200 kg-TN/d; several orders of magnitude lower. Therefore the anthropogenic portion of the load is the difference, or 27,800 kg-TN/d. For scenarios where marine point sources were reduced, we kept the flow constant but reduced the concentrations to reflect a load reduction. Under the various scenarios, only the anthropogenic portion changes.

Table 7. Total nitrogen loads (kg/d) within model domain from marine point sources

Scenario	Region	Marine Point Sources
Natural	Total	200
	South Puget Sound	20
	Central Puget Sound	180
Current	Total	28000
	South Puget Sound	3300
	Central Puget Sound	24700

We did not change the salinity or temperature of the marine point source discharges in any scenario. DO was set to natural watershed concentrations where marine point sources were eliminated but was not changed for other scenarios. We did not change how the marine point sources were mapped to grid cells and layers for any scenarios.

Watershed Inputs

Watershed loads include the loadings from rivers, streams, and all upstream watersheds. For current conditions these are the 2007 loads. Under natural conditions the river and stream loads were obtained from Mohamedali et al. (2011). We have little information to characterize loads from the Cedar River watershed as it flows through Lake Washington and to Central Puget Sound through the Ship Canal. Therefore, we did not change the Lake Washington contributions and the same values were used under both current and natural conditions. The total watershed loads under current and natural conditions were 5300 kg-TN/d and 3800 kg-TN/d (Table 8), respectively, for the entire South and Central Puget Sound watershed. Therefore the anthropogenic portion of watershed load amounted to 1500 Kg TN/d. Only the anthropogenic portion changes under the various scenarios.

Table 8. Total nitrogen loads (kg/d) within model domain from watershed inflows

Scenario	Region	Watershed Inflows
Natural	Total	3800
	South Puget Sound	1500
	Central Puget Sound	2400
Current	Total	5300
	South Puget Sound	2400
	Central Puget Sound	2900

Atmospheric Deposition

Atmospheric deposition was kept constant at current conditions and for all scenarios. However, it was used in calculations for scaling the sediment fluxes. The total nitrogen loading from atmospheric deposition during the April-September period was 360 kg-TN/d.

Meteorology

Meteorology was kept constant for all scenarios.

Northern Boundary

As described in the Natural Conditions Section, the Puget Sound / Salish Sea model (Khangaonkar et al. 2012) was used to estimate open boundary scalars to account for the absence of human sources under natural conditions south and north of Edmonds. The total incoming nitrogen loading under current conditions at the Edmonds open boundary during the April-Sept period was 678,100 kg-TN/day. Under natural conditions, the incoming loading at the open boundary was estimated at 634,800 kg-TN/day. The difference between these two numbers is the anthropogenic portion of the incoming loading, or 43,300 kg-TN/d (see discussion on uncertainty around this number in a later section). A portion of this anthropogenic load is from external sources north of the Edmonds boundary while some portion reflects the reflux of anthropogenic sources internal to the model south of Edmonds boundary.

To assist with the Budd Inlet TMDL, we estimated the reflux of anthropogenic nutrients within Budd Inlet to evaluate how influential this process might be. In order to measure the magnitude of the reflux, an internal boundary at Boston Harbor was selected. This defined an open boundary for Budd Inlet (Figure 46). The South and Central Puget Sound model was then run at natural conditions with and without LOTT wastewater treatment plant. The total nitrogen loading entering Budd Inlet from across the open boundary at Boston Harbor was estimated under the two scenarios.

With the addition of LOTT, there was an increase in TN loading entering Budd Inlet from across the open boundary that was equal to approximately 20% of the TN load from LOTT. Therefore the model predicted reflux of about 20% of the TN that was discharged from LOTT returning back into Budd Inlet after it was flushed out of Budd Inlet. Reflux at the open boundary at Edmonds was therefore estimated to be about 20% based on results from Budd Inlet. This refluxed load is 1% of the total incoming nutrient load at Edmonds under current conditions and 1.3% of the total incoming load under maximum permit conditions for marine point source discharges (see Appendix G). A sensitivity analysis on reflux is included in Scenario Uncertainty section later in the report.

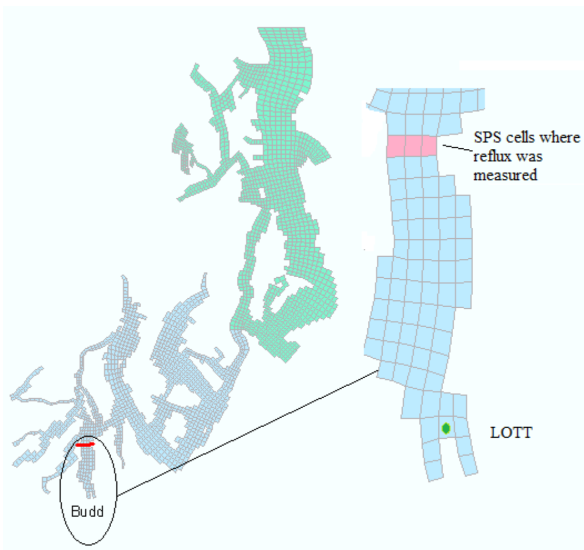


Figure 46. Northern boundary of Budd Inlet where reflux was measured when LOTT was turned off.

There are no anthropogenic loads at the open boundary under natural conditions by definition. Under current conditions, however, the anthropogenic load is apportioned between external loads outside the model domain and internal load (within model domain) that is refluxed at the open boundary. For any given scenario involving reductions in loads of internal sources, only the refluxed amount would change. For scenarios involving reductions in anthropogenic sources external to the model domain, only the external anthropogenic loading would change. In either case, the total incoming open boundary load changes.

The water quality scalar at the open boundary at Edmonds for any scenario is prorated based on total incoming load at Edmonds open boundary (see Table 9) for current, natural, and the respective scenario.

Table 9. Total internal and external model domain TN loading (Kg/d) under various scenarios (April-September 2007).

Source	natural/anthropogenic	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6a	Scenario 6b	Scenario 6c	Scenario 7
		natural	current	Watershed Loads Only	Marine Point Source Loads Only	Maximum Permitted Marine Point Source Loads	Reducing Human Loads in South and central Puget Sound by			No Human Sources in Central Puget Sound
							25%	50%	75%	
Atmospheric load	Natural	400	400	400	400	400	400	400	400	400
Point Source Load to Marine Waters	Natural	200	200	200	200	200	200	200	200	200
	Anthropogenic	0	27800	0	27800	41500	20800	13900	6900	3200
Watershed Loads	Natural	3800	3800	3800	3800	3800	3800	3800	3800	3800
	Anthropogenic	0	1500	1500	0	1500	1100	700	400	900
Total Marine Point source and Watershed loads	Natural	4400	4400	4400	4400	4400	4400	4400	4400	4400
	Anthropogenic	0	29300	1500	27800	43000	22000	14600	7300	4200
	Total	4400	33700	5900	32200	47400	26400	19000	11700	8500
External anthropogenic at open boundary	Anthropogenic	0	37500	37500	37500	37500	37500	37500	37500	37500
Internal anthropogenic load refluxed at open boundary (20%)	Anthropogenic	0	5900	300	5600	8600	4400	2900	1500	800
Total load coming in at Edmonds open boundary	Natural	634800	634800	634800	634800	634800	634800	634800	634800	634800
	Anthropogenic	0	43300	37800	43000	46100	41900	40400	38900	38300
	Total	634800	678100	672500	677800	680800	676600	675200	673700	673100
Total Incoming Load for model domain	Natural	639100	639100	639100	639100	639100	639100	639100	639100	639100
	Anthropogenic	0	72600	39300	70800	89000	63800	55000	46200	42500
	Total	639100	711700	678400	709900	728100	702900	694100	685300	681600

Sediment Exchanges

The sediment fluxes under current conditions were based on model calibration while those under natural conditions were established through the use of scalars based on a comparison of particulate nitrogen flux to the sediments under current and natural conditions as discussed in the Natural Conditions section. An alternate method adjusting the sediment scalars based on incoming total nitrogen loads resulted in a similar scalar as that based on particulate nitrogen fluxes.

When assessing sediment scalars for alternative load scenarios, the incoming total nitrogen load was used to prorate scalars. When the incoming total nitrogen load at the open boundary discussed above is added to loads from point source discharge to marine waters and watershed loads within the model domain, the sum is the total TN load to the model domain (see Table 9). Under different scenarios, the anthropogenic TN loads would change, which in turn would change the total incoming load from all sources. Sediment scalars for each scenario were prorated based on total incoming nitrogen load for model domain for each scenario when compared with those under current and natural conditions.

Effects of Current Anthropogenic Sources: Current Watershed Loads and Marine Point Sources

Scenario 2 represents current watershed loads and marine point sources. Model-predicted DO concentrations under current anthropogenic loading condition (2007) were compared with Washington State water quality standards for DO and with predicted DO concentrations under natural conditions (Scenario 1) to determine which cells in the model domain were in violation of the standards. Figure 47 shows the areas and magnitudes of DO standards violations. DO violations are present in East Passage of Central Puget Sound, Carr and Case Inlets, and the smaller finger Inlets (Budd, Eld, Totten, and Henderson). DO violations in Eld Inlet are the highest in magnitude at 0.38 mg/L.

Figure 47 also includes the 303(d) listing locations. However, these locations are only based on whether measured concentrations were below the applicable numeric criterion for DO. An assessment of whether these constitute violations below the natural conditions could not be made until natural conditions for DO were established.

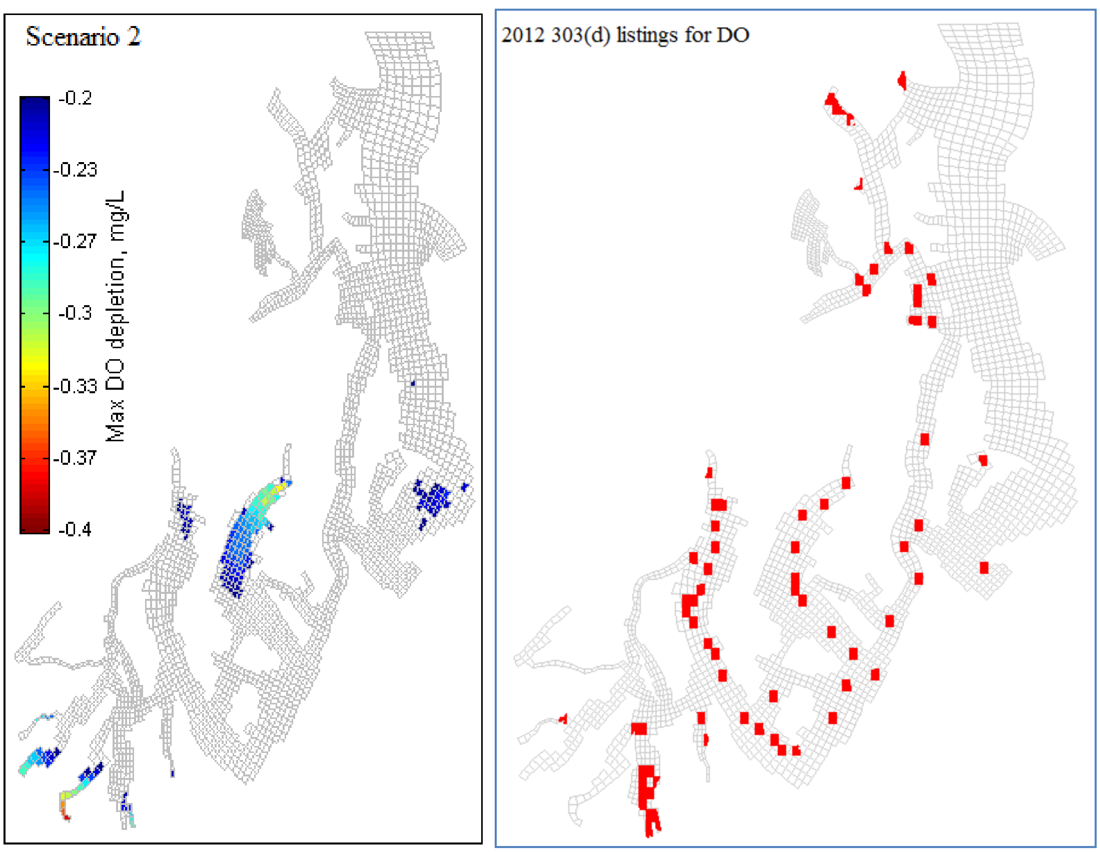


Figure 47. Regions of DO violations (both parts of standards) due to current anthropogenic loads (2007 conditions) and the 2012 303(d) listing locations.

Effects of Current Watershed Loads Only

Scenario 3 represents the effect of human sources within the watersheds (Table 9). In this scenario, all of the point sources to marine waters within the model domain have been turned off while the watershed loads are at current conditions (2007). It should be noted that the external nutrient loads at the Edmonds open boundary are still present. DO violations are found by comparing the results of this scenario to Scenario 1, natural conditions (Figure 48). Human sources within watersheds alone (in conjunction with external loads at the open boundary) do not cause any DO violations except in a small cell at the head of Eld Inlet, where the maximum depletion is 0.204 mg/L.

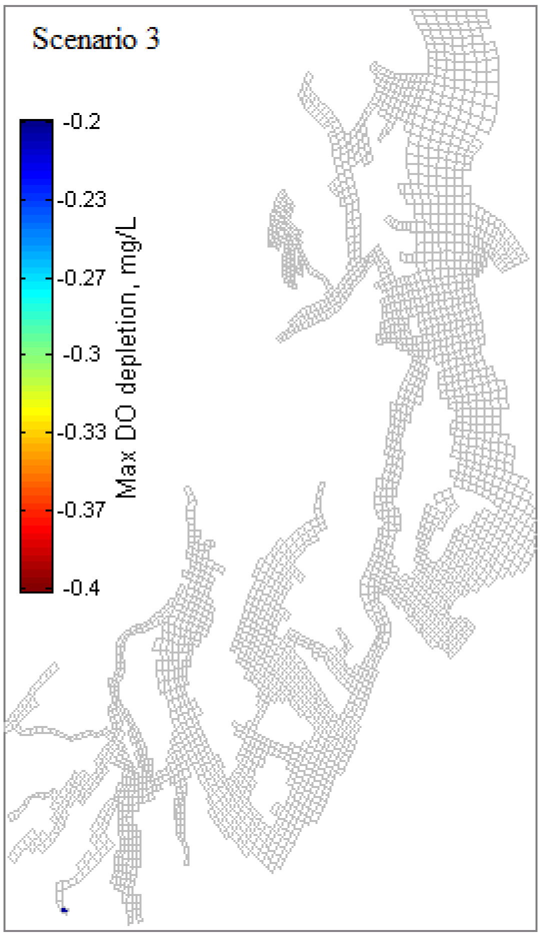


Figure 48. Regions of DO violations due to human sources within watersheds only.

Point sources to marine waters have been turned off, external anthropogenic sources at Edmonds open boundary are still present.

Effects of Current Marine Point Source Loads Only

Scenario 4 represents the effect of internal marine point sources (i.e., no internal anthropogenic watershed loads, see Table 9). However, external anthropogenic loads at the Edmonds open boundary are present. All the internal watershed loads have been turned to natural conditions. With only the internal point source discharges to marine waters turned on, the DO violations are similar to those under current conditions. The maximum depletion is 0.368 mg/L in Eld Inlet. Comparison of Scenarios 2, 3, and 4 indicates that the dominant contributors to DO violations are the point sources to marine waters.

Watershed sources cause some DO depletion, but the marine point sources alone cause more than 0.2 mg/L depletion compared with natural conditions. The two contributions are added together in Scenario 2. Note the high anthropogenic total nitrogen loading (April-September 2007) from the Marine point sources contributed 27,800 kg/d during the period April-September 2007, while human sources in the watersheds contributed 1,500 kg/d. In addition external anthropogenic load contribute approximately 40,000 kg/d. The maximum depletion scales with the relative anthropogenic contribution, and internal marine point sources have greater impact than human sources in internal watersheds.

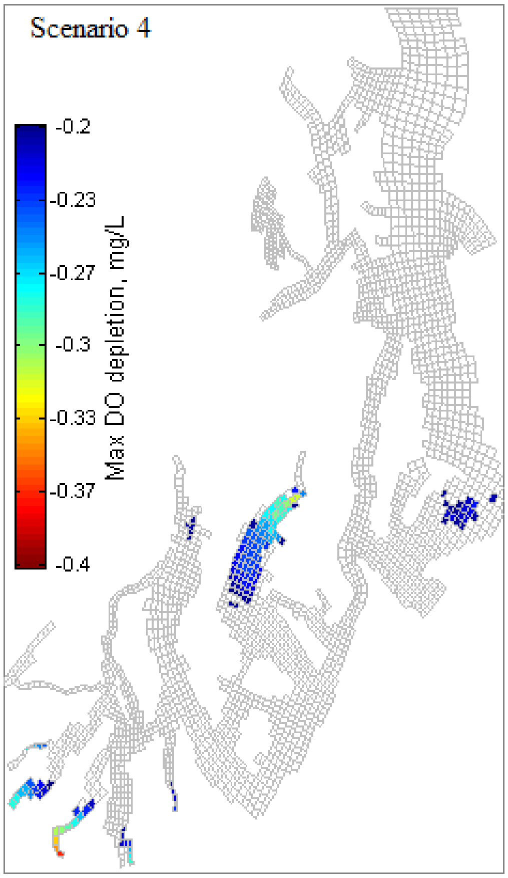


Figure 49. Regions of DO violations due to marine point sources only.

Effects of Maximum Permitted Point Source Loads

NPDES permits set limits for various parameters in discharges, such as BOD load or ammonium concentration. Plants typically operate far below these limits but can legally discharge continuously at the limits. Most plants do not have flow limits. If the point sources discharged at maximum permit values continuously, the extent and magnitude of DO violations would significantly increase. No plants are operated in this mode, however. For this scenario, internal watershed loads are kept at current conditions. External anthropogenic nutrient load was also kept at current conditions. To increase marine point source loadings to permitted values, concentrations of nutrients were increased while keeping the flows at current conditions. This ensured that circulation was kept the same as natural conditions.

Scenario 5 results indicate that maximum violations would increase to 0.468 mg/L in Eld Inlet. The area with depletions above 0.2 mg/L would grow in Oakland Bay, Totten Inlet, Eld Inlet, Budd Inlet, Case Inlet, and Carr Inlet in South Puget Sound. In Central Puget Sound, Colvos Passage and the region between Tacoma and Seattle would violate standards.

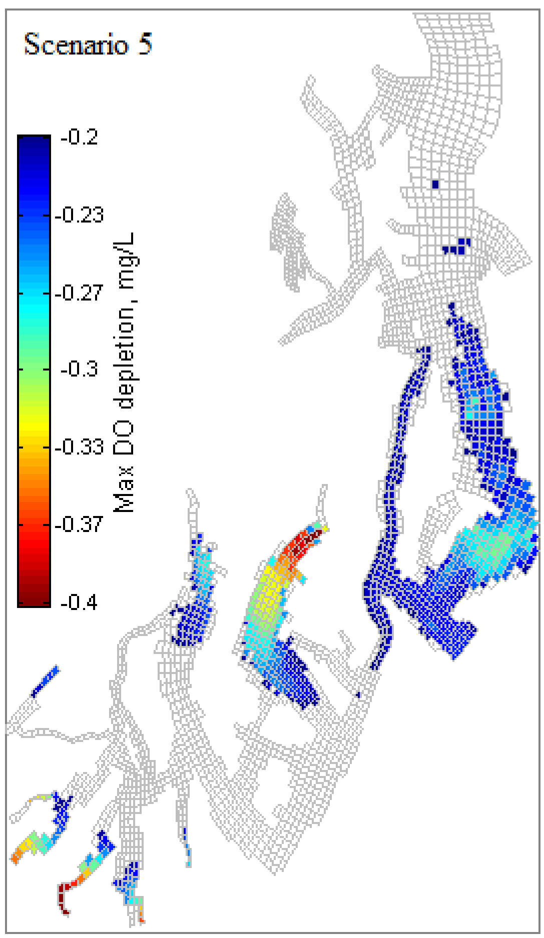


Figure 50. Regions of DO violations due to marine point sources at maximum permit values.

Effect of Reducing Human Loads in South and Central Puget Sound by 25, 50, and 75 Percent

In this scenario anthropogenic nutrient sources are reduced by 25% (Scenario 6a), 50% (Scenario 6b), and 75% (Scenario 6c). However, external anthropogenic loads at the Edmonds open boundary remained at current conditions. With 25% reductions, almost all the DO violations in Central Puget Sound and all violations in Case Inlet are eliminated. The magnitude and extent of DO violations in other inlets are reduced (Figure 51) as well. The magnitude and extent of violations in inlets is further reduced with 50% reductions in internal nutrient loading. Finally with 75% reductions only a small region in Eld Inlet remains in violation.

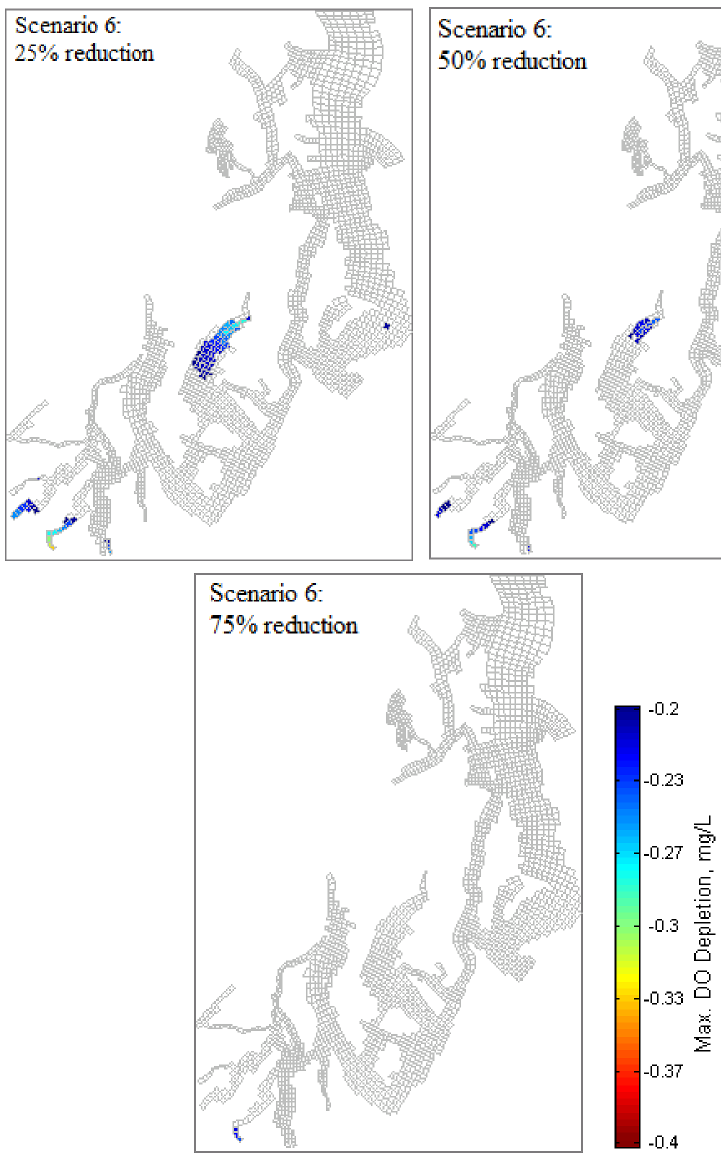


Figure 51. Regions of DO violations with 25, 50 and 75 percent reductions of both human watershed loads and marine point sources loads.

Effect of Reducing Human Loads in Central Puget Sound

Scenario 7 evaluates the effect of eliminating anthropogenic sources in Central Puget Sound. In this scenario, Central Puget Sound watersheds discharge at natural condition while the anthropogenic sources in South Puget Sound remain at current levels. In addition, external anthropogenic nutrient load at the Edmonds open boundary remain at current conditions. Since the sediment scalars are prorated based on magnitude of incoming load into the entire domain, two different assumptions were made to evaluate this scenario:

1. Sediment scalars were prorated by the change in loading and applied to both Central and South Puget Sound. This assumes that the sediment fluxes in the whole model domain are affected by nutrient load reductions in Central Puget Sound.

2. Sediment scalars were prorated by the change in loading and applied to Central Puget Sound only. Sediment fluxes in South Puget Sound were assumed to be the same as for current conditions. This assumes that the sediment fluxes in only Central Puget Sound is affected by load reductions in Central Puget Sound.

The plot on the left of Figure 52 shows the effect of the first assumption (sediment fluxes adjusted in both South and Central Puget Sound). Model results indicate that the maximum depletion would decline to <0.2 mg/L in all areas except a portion of Eld Inlet.

The plot on the right side of Figure 52 shows the effect of the second assumption (adjusting the sediment fluxes in only Central Puget Sound). Model results under this assumption indicate that the maximum depletion would decline to <0.2 mg/L in East Passage and Case Inlet and would decrease to 0.22 mg/L in Carr Inlet. Maximum depletion in the finger inlets would not change.

The true extent of DO violations is most likely somewhere between the results shown in the left and right sides of Figure 52. The two methods bracket the potential response.

Refinement of these results to account for disproportionate changes in sediment fluxes in various regions would require a more sophisticated model (e.g., sediment diagenesis model). Additional model development and application would be needed to reduce this source of uncertainty.

Tracer studies using the calibrated hydrodynamic model (Roberts et al., 2013, in press) shows that tracer injected at all Central Puget Sound marine point source discharges shows up in all of South Puget Sound areas (Figure 53). A load analysis of dye released at the marine point sources in Central Puget Sound and that crossing Tacoma Narrows into South Puget Sound (April – September) indicates only 14% of dye reaching South Puget Sound. Although this finding may be a potential avenue in estimating sediment scalar for South Puget Sound region, additional study needs to be conducted to include watershed inflows, reflux at open boundary, as well as nutrient uptake in Central Puget Sound (tracer is conservative) before such numbers can be utilized to estimate sediment scalars.

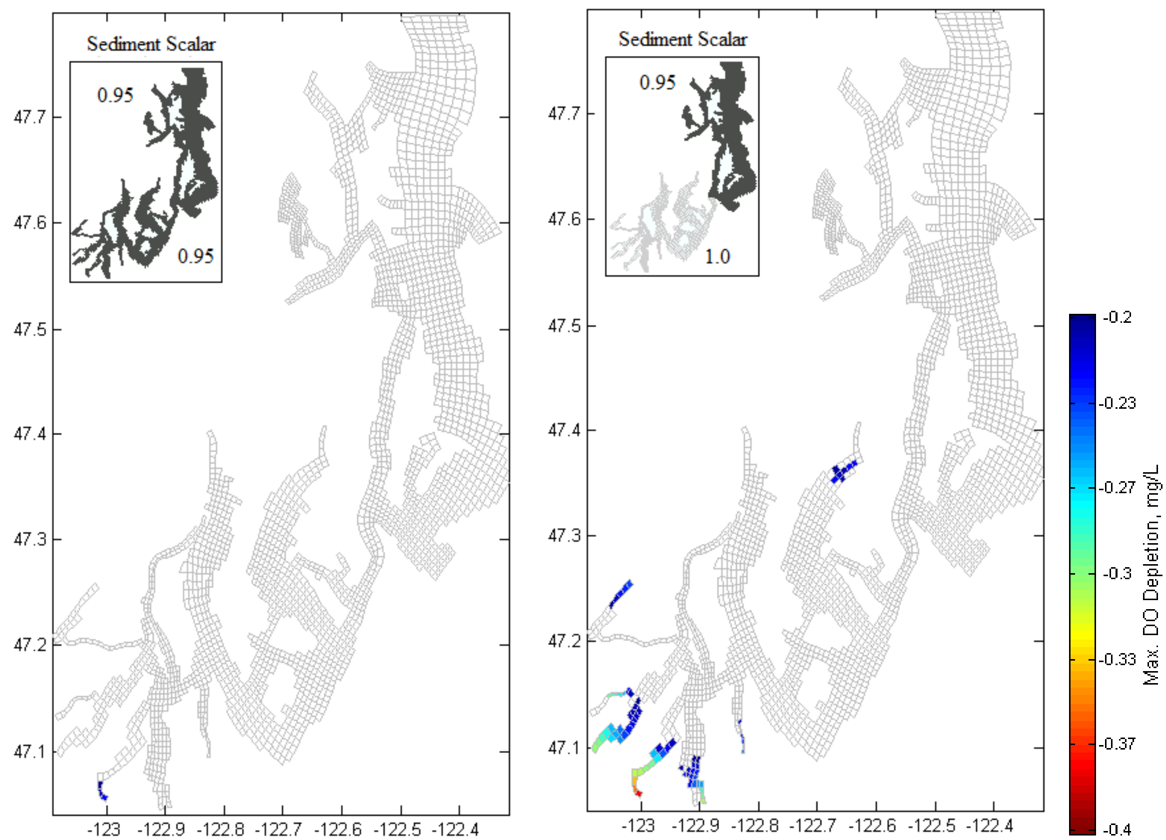


Figure 52. Regions of DO violations due to South Puget Sound sources only with Central Puget Sound at natural condition for sediment scalars adjusted in (a) both South and Central Puget Sound and (b) Central Puget Sound only.

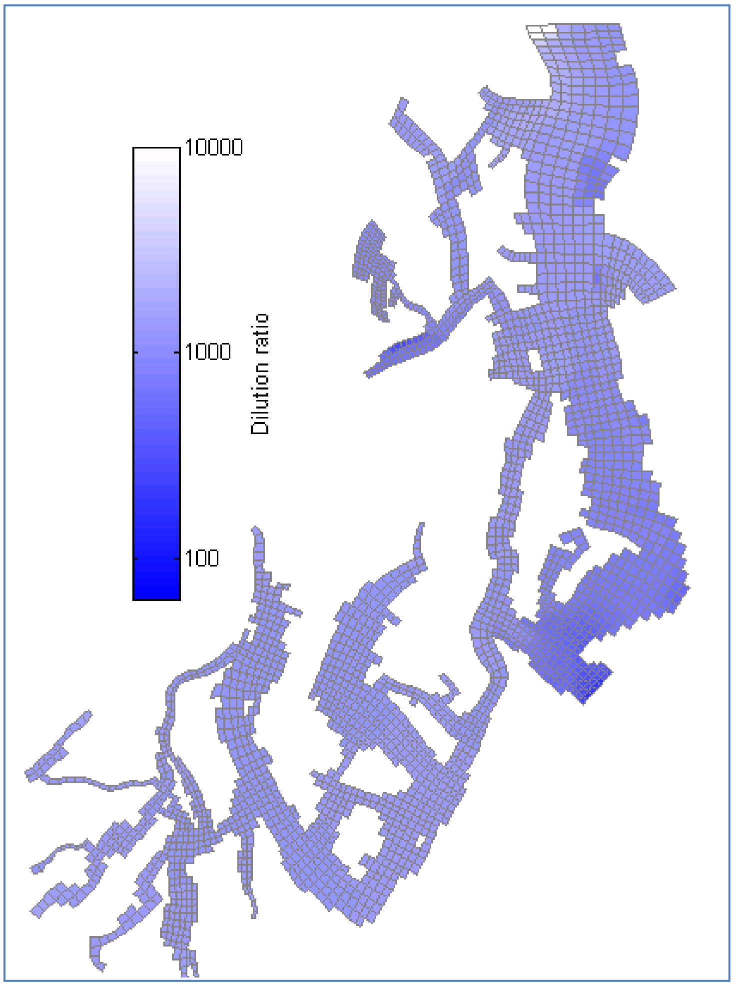


Figure 53. Dilution factors calculated from maximum water-column dye concentrations for Central Puget Sound wastewater discharge tracer simulations (September 2007).

Source: Roberts et al. (2013 in press).

Summary of Scenario Results

Table 10 includes a summary of DO standard violations for each scenario. The table includes the percent of domain area that is below the DO standard, how long these areas stay below the standard, and the magnitude of these violations. Under current conditions, 7% of the domain area violates the DO standard with the worst frequency of violations occurring 30% of the time (January - October 2007) with a maximum depletion of 0.38 mg/L below DO criterion (below natural conditions in Eld Inlet). With point sources removed the domain area violating the standard reduces to 0.03%, while increasing the point sources to maximum permit conditions the domain area in violation increase to 33%.

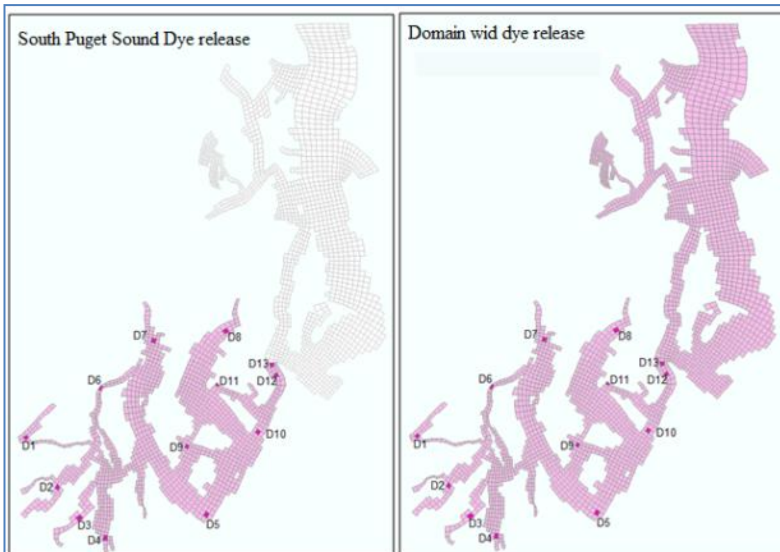
Table 10. Summary of model scenarios with domain areas and time-periods of DO violations

Scenario	Title	Model Scenario		Calculation (compare dissolved oxygen levels)	
		Description	Result	Calculation	Result
1	Natural Conditions	No anthropogenic nitrogen sources in either South or Central Puget Sound, or at the open boundary at Edmonds	See Table 6		
2	Current Marine Point and Watershed Sources	Current nitrogen sources in both South and Central Puget Sound (current condition)	7 % of the domain area are in violation of the DO standard for up to 30 % of the time with up to 0.38 mg/L below DO standard	Scenario 2 minus 1	Current human sources (both marine point sources and human watershed sources) are causing violations of dissolved oxygen standards.
3	Human Watershed Sources	No point sources and current levels of human watershed nitrogen in both South and Central Puget Sound.	0.034 % of the domain area are in violation of the DO standard for up to 1.3% of the time with up to 0.204 mg/L below DO standard	Scenario 3 minus 1	Current internal human watershed sources and external anthropogenic sources are causing small violation of dissolved oxygen standards in one cell in Eld Inlet
4	Marine Point Sources	No human watershed sources but current levels of marine point sources in both South and Central Puget Sound	6.1 % of the domain area are in violation of the DO standard for up to 32 % of the time with up to 0.37 mg/L below DO standard	Scenario 4 minus 1	Current internal marine point sources and external anthropogenic sources are causing violations of dissolved oxygen standards.
5	Maximum Permitted Marine Point Sources	Maximum permitted marine point sources and current watershed sources in both South and Central Puget Sound.	32.9 % of the domain area are in violation of the DO standard for up to 65 % of the time with up to 0.47 mg/L below DO standard	Scenario 5 minus 1	Maximum permitted loading from marine point sources cause dissolved oxygen levels to violate dissolved oxygen standards.
6	Overall Reductions in Loads	Reduce marine point sources and human watershed sources by 25% (Scenario 6a) , 50% (Scenario 6b), and 75% (Scenario 6c) in both South and Central Puget Sound	3.8 %, 1.5%, and 0.13% of the domain area are in violation of the DO standard for up to 74 %, 33%, and 24% of the time with up to 0.34 mg/L, 0.29 mg/L, and 0.24 mg/L below DO standard for Scenarios 6a, 6b, and 6c, respectively.	Scenario 6a minus 1 Scenario 6b minus 1 Scenario 6c minus 1	In excess of 75% region-wide reduction in marine point sources and human watershed sources would be needed to meet dissolved oxygen standards without any reductions in external sources
7	South Puget Sound sources; Central Puget Sound off	Current conditions in South Puget Sound and natural conditions in Central Puget Sound, with either domain wide sediment scalar (Scenario 7a) or Central Sound only sediment scalar (Scenario 7b)	0.13 % and 3% of the domain area are in violation of the DO standard for up to 4.3 % and 15.6% of the time with up to 0.22 mg/L, and 0.38 mg/L below DO standard for Scenarios 7a and 7b, respectively	Scenario 7a minus 1 Scenario 7b minus 1	Human sources in both South and Central Puget Sound contribute to violations of dissolved oxygen standards in South Sound. The relative impact depends on the sediment scalar.

Eld Inlet DO Violations

We explored why Eld Inlet appears to be the most critical area for magnitude of DO violations and resistance to DO changes from domain-wide nutrient load reductions.

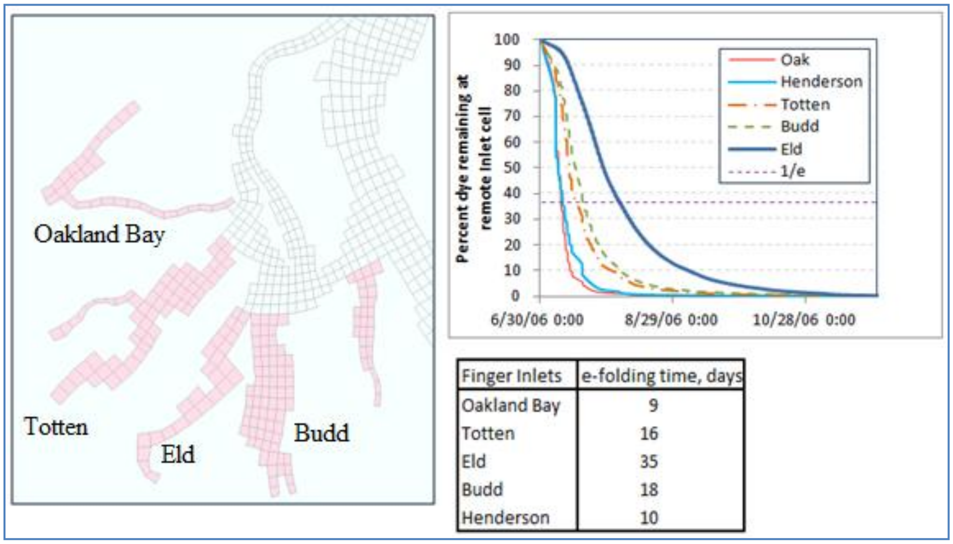
From a hydrodynamic point of view, Eld Inlet appears to be the most stagnant inlet based on tracer studies using the calibrated hydrodynamic model (Roberts et al., 2013, in press). Beginning with an initial condition where the whole South Puget Sound was dyed, the Eld Inlet residence time was the longest among all finger inlets. Stations D1, D2, D3 and D4 are in the finger inlets Oakland Bay, Totten Inlet, Eld Inlet and Budd Inlet respectively (Figure 54). Station D3 in Eld Inlet had the longest residence time among all the finger inlets. Results from individual inlet dye study showed that residence time for Eld Inlet was almost twice that of Budd Inlet (see Figure 55).



Station	e-folding time, days	
	Dye_south of TN	Domain wide dye
D13	3.1	70.4
D12	17.6	70.4
D11	56.4	98.3
D10	24.3	80.2
D9	66.1	99.6
D8	81.8	112.3
D7	107.7	157.1
D6	103.8	153.7
D5	65.2	111.5
D4	100.8	129.6
D3	104.5	145.0
D2	99.1	137.2
D1	93.6	129.4

Figure 54. Flushing times at stations following South Puget Sound and domain wide initial dye release.

e-folding time = time to dilute to 1/e level, i.e., 37% of original concentration.



Finger Inlets	e-folding time, days
Oakland Bay	9
Totten	16
Eld	35
Budd	18
Henderson	10

Figure 55. e-folding time for remote cell in each inlet.
Time to dilute to 1/e level, i.e., 37% of original concentration.

Flows in McLane and Perry Creeks, the two creeks that enter the south end of Eld Inlet, were at the lowest seasonal values during critical periods of low DO in late August/early September (Figure 56). With low freshwater inflows, flushing of the inlet is at its minimum.

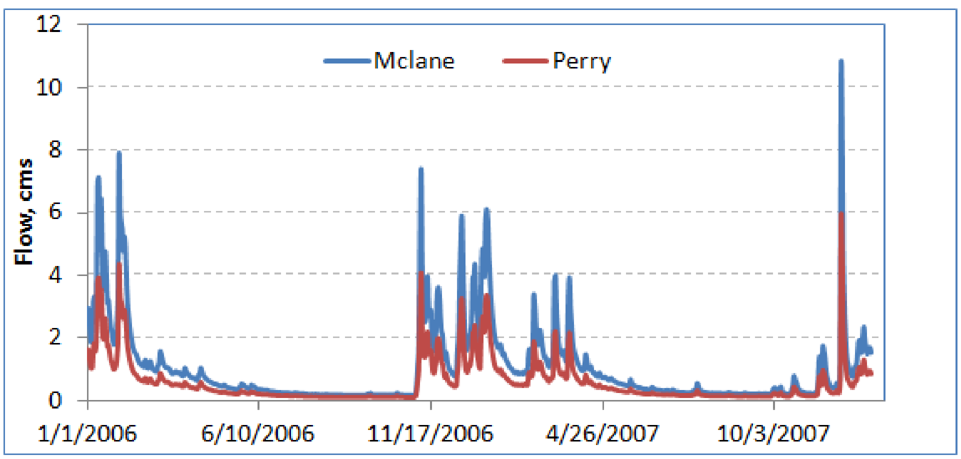


Figure 56. Flows in McLane and Perry Creeks.

Model prediction statistics for time-series of DO, chlorophyll, and dissolved inorganic nitrogen (DIN) concentrations at Eld Inlet stations were comparable to other stations in the calibrated model (see Figure 57). Therefore, the model captures the overall patterns in Eld Inlet.

The low DO in Eld Inlet is likely related to poor circulation. The highest DO violations occur at the south end of Eld Inlet where circulation is the worst partly due to low watershed inflows during the critical summer/fall period. Poor circulation causes limiting nutrient conditions, with algal die-off and decomposition resulting in low DO in the water column. Poor circulation also prevents higher DO waters from surrounding areas to flow in.

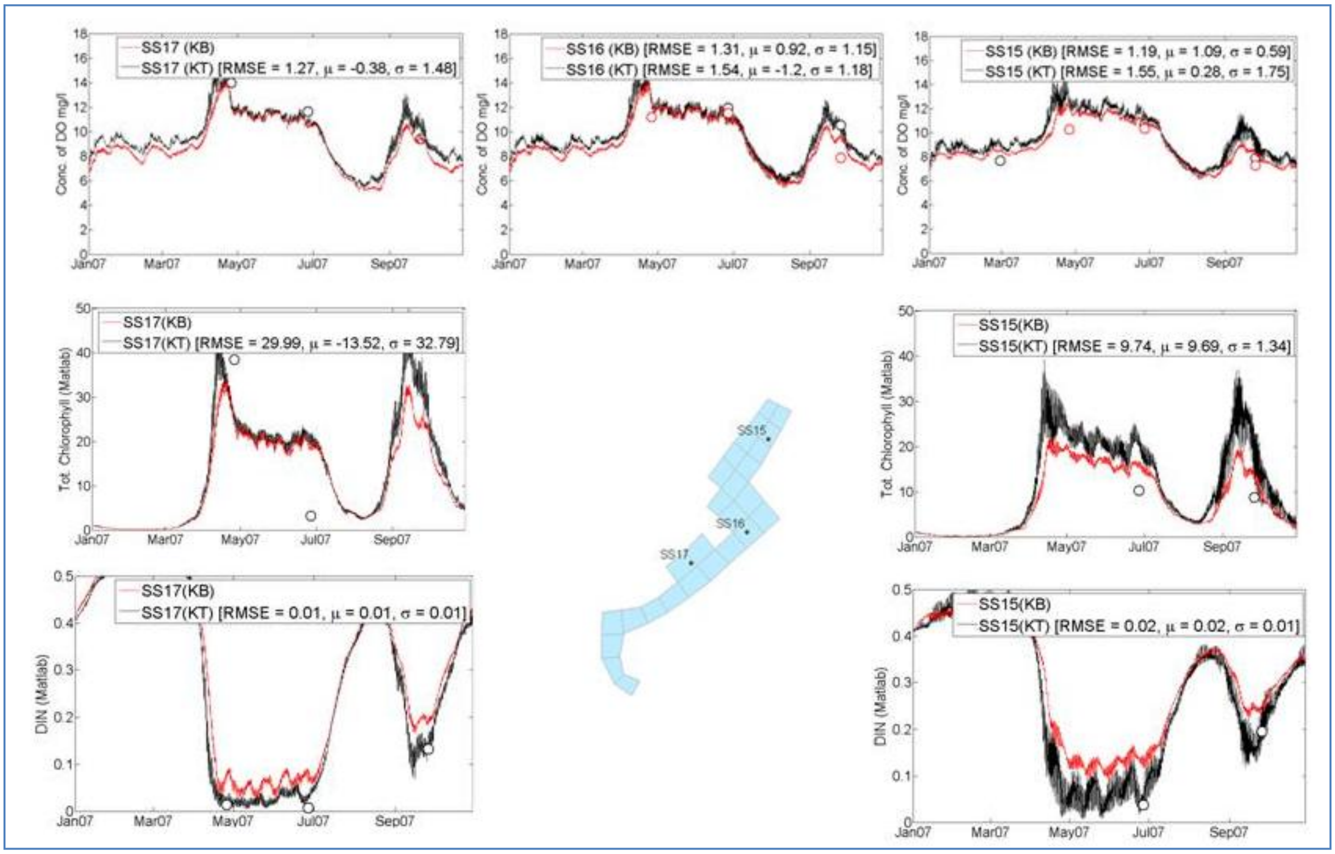


Figure 57. Time-series plots for DO, chlorophyll, and dissolved inorganic nitrogen (DIN) in Eld Inlet stations.

KT= surface layer; KB = bottom layer

Comparing Budd Inlet Predictions between Models

Ecology has developed a water quality model tuned to Budd Inlet DO to support the development of a TMDL (Roberts et al., 2012). The model has been calibrated and applied to similar scenarios as in this study.

The Budd Inlet model predicts larger impacts from current human sources than the South and Central Puget Sound model for the same region of Budd Inlet (Figure 59). Both predict the highest depletions to occur in East Bay, in the southeast corner of Budd Inlet, and extend through southern Budd Inlet. The RMSEs of DO predictions compared to observed data were comparable between the models. Several factors could contribute to the differences.

First, the Budd Inlet model grid is more detailed both horizontally and vertically. Figure 58 shows the size and distribution of grid cells used to define Budd Inlet in the South and Central Puget Sound model (left grid) and Budd Inlet model (right grid, Roberts et al., 2012). The Budd Inlet model uses 159 cells to characterize Budd Inlet, compared to 71 cells for the South and Central Puget Sound model.

Fewer cells meant depths were averaged over larger areas resulting in shallower water column. This resulted in maximum depth of the critical cell in East Bay to be more “smoothed” out in the South and Central Puget Sound model with a maximum depth of -2 m below the North American Vertical Datum (NAVD88) compared with a maximum depth of -3 m NAVD88 in the Budd Inlet model. There were also more vertical layers in the Budd inlet model. For example, in the East Bay cell (see Figure 58), there were 10 layers, compared to 3 layers in the South and Central Puget Sound model. The larger cell areas and fewer cell layers mean that predicted water quality variable concentrations are averaged over a relatively larger volume in the South and Central Puget Sound model compared to the Budd Inlet model.

A fundamental difference between the two models is that the Budd Inlet model accounts for the effect of the current Capitol Lake dam and is capable of evaluating the effects of the Deschutes River either with or without the dam in place. The Budd Inlet project has determined that the natural condition against which scenarios are compared is without the Capitol Lake dam. The Capitol Lake dam has a large impact on DO in southern Budd Inlet (Roberts et al., 2012) and is best assessed with the Budd Inlet model.

In the South and Central Puget Sound model, the Capitol Lake flows were present in both the current and natural conditions. In other words the impact of lake was not evaluated. Figure 59 shows the DO standard violations in Budd Inlet as predicted by the two models. Note that in the Budd Inlet model Capitol Lake is not included in either of the current and natural conditions, where as it is included in both the current and natural conditions in the South and Central Puget Sound model.

In addition, the Budd Inlet model is evaluating impacts of 1996-97 loads. The largest marine point source had reduced its discharge by half by 2007. Loads have decreased due to operational changes at the plant.

Ecology will continue to use the Budd Inlet model to set load and waste load allocations for Budd Inlet.

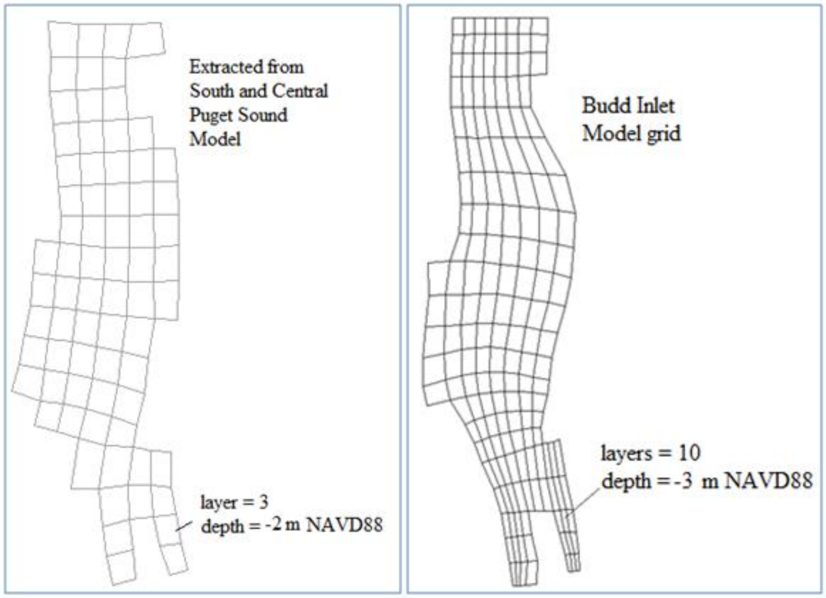


Figure 58. Budd Inlet grid distribution in South and Central Puget Sound Model (left) and Budd Inlet Model (right).

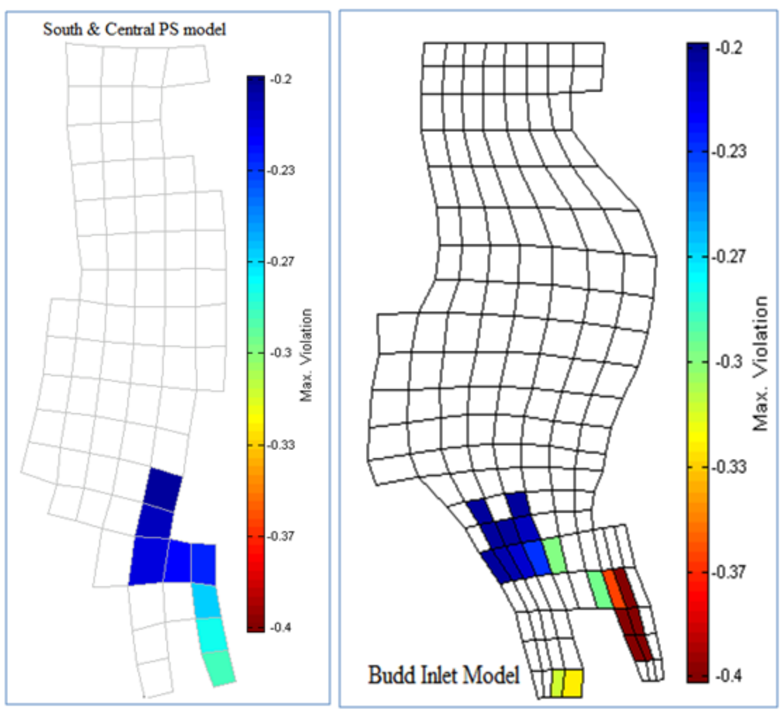


Figure 59. DO violations in Budd Inlet in South and Central Puget Sound model (with Capitol Lake) and Budd Inlet Model (without Capitol Lake) (Roberts et al., 2012).

Scenario Uncertainty

Scenarios that isolate groups of sources were developed using the best available information and approaches. Alternative loading scenarios are intended to illustrate relative impacts from different sources. Uncertainty results from data used to develop the current and alternative load estimates, assumptions regarding how these would affect other model parameters, and the model performance in general.

Marine Point Source and Watershed Inflow Load Uncertainty

Uncertainty in specifying alternative loads is low overall. Loads described in Mohamedali et al. (2011) focus on the watershed inflows at the point they reach marine water and marine point source discharges at the outfall location. Development of natural conditions for watershed inflows is discussed in Mohamedali et al. (2011). Natural conditions of water quality for marine point source discharges were assumed to be the average of the natural water quality of the watershed inflows.

The two largest areas of uncertainty in watershed inflows are the establishment of natural conditions and identification of which specific sources upstream in the watershed are the dominant human sources at the mouth. If human watershed sources require reductions, then additional study is needed to identify specific contributions. We focused on the mouths of rivers and streams and based loads on actual data rather than develop watershed models that simulate the sources, transport, and fate of nutrients. This would have added uncertainty and would have required additional resources.

The largest uncertainty in the marine point sources is the initial dilution of effluent that occurs when freshwater first mixes with estuarine water. The South and Central Puget Sound does not optimize buoyant plume simulations, which are critical to identifying nearfield mixing. We reduced uncertainty by externally modeling mixing zone dynamics using plume models for the largest marine point sources.

Overall, the watershed inflow and marine point source approach minimizes uncertainty.

Uncertainty in Open Boundary and Sediment Flux Adjustments under Alternative Loading Scenarios

The second area of uncertainty involves how other model parameters were adjusted in response to alternative loads. We adjusted both water quality at the open boundary and sediment fluxes within the model domain. While these add uncertainty, not accounting for these factors would have underestimated human impacts in the various scenarios.

In building the scenarios, the marine point sources and human watershed sources were either decreased or increased individually or collectively. The primary effects of these changes were changes in nutrient loadings to the model domain. Secondary effects of these changes were the changes to the water quality at the open boundary and the sediment fluxes. For each of the scenarios these secondary effects were defined by prorating the open boundary and sediment flux nutrient loads between natural and current conditions or the conditions in alternative loading scenarios.

Adjusting the open boundary entailed using scalars based on anthropogenic load increases within the model domain and adjusting how much of it refluxed back into the model domain at the open boundary.

The sediment fluxes under different scenarios were prorated between current and natural conditions based on changes in nutrient fluxes within the model domain. A sediment diagenesis model is an alternative approach for estimating the sediment fluxes under the various scenarios. However, this capability was not available in the model. Adjusting sediment fluxes was deemed appropriate since changes in nutrient loading would affect algal production and ultimately the flux of particulate nitrogen to the sediments.

Uncertainty in Reflux

The total anthropogenic load can be divided into three categories: 1) internal anthropogenic sources that discharge directly into the model domain south of Edmonds, 2) reflux of internal anthropogenic sources that flow out of the model domain and then return back across the open boundary, and 3) sources that originate from outside of the model domain north of Edmonds.

To directly estimate reflux it would be necessary to use a model like Ecology's Puget Sound/Salish Sea model that includes not only the model domain of South and Central Puget Sound, but also extends beyond to simulate the fate of local anthropogenic loads after they flow beyond the Edmonds boundary. It was not possible to use the Puget Sound/Salish Sea model for this purpose due to budget constraints. The South and Central Puget Sound model was used to estimate about 20% reflux of local primary anthropogenic load to Budd Inlet back across the mouth of Budd Inlet.

We assumed that reflux of local anthropogenic loads to South and Central Puget Sound across the Edmonds boundary were similar to reflux of local anthropogenic loads to Budd Inlet across the mouth of Budd Inlet. This refluxed load is 1% of the total incoming nutrient load at Edmonds under current conditions a (see Appendix G) Not accounting for it would have underestimated the differential human impact.

We tested the sensitivity of the model results to uncertainty in the assumed reflux of internal anthropogenic sources using Scenario 4 with various amounts of reflux (20%, 10%, and 5%) (Figure 60). The difference in DO violations between a reflux of 20% and 5% is in the order of 0.02 mg/L at the critical cell in Eld Inlet (6% of the predicted depletion), and between reflux of 20% and 10% is 0.01 mg/L (4%). Therefore the effect of uncertainty in reflux on predicted DO depletion for the critical Eld Inlet cell is considered to be small.

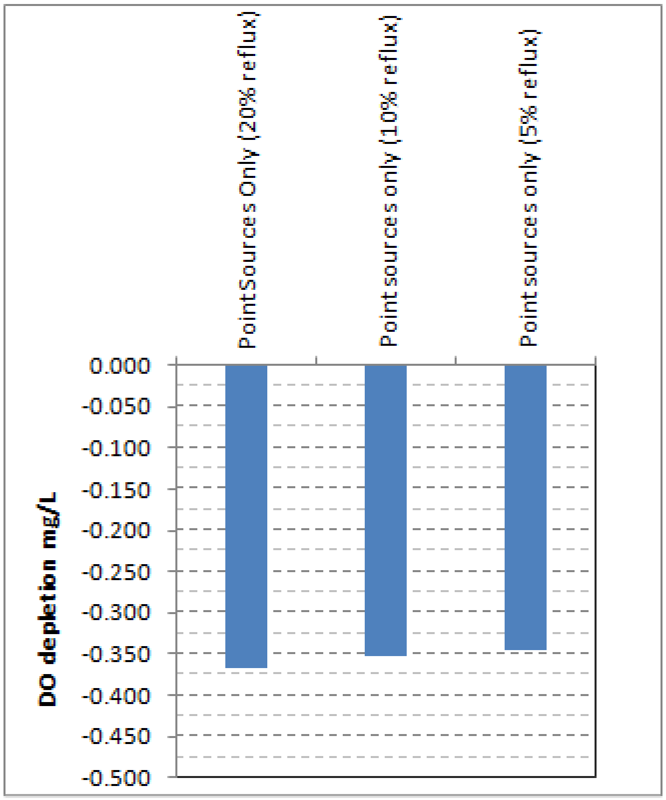


Figure 60. Sensitivity analysis for different percent reflux on DO depletion at the critical Eld Inlet cell.

Model Uncertainty

We calibrated the model to 2007 current conditions, mostly by tuning rate parameters influenced by biological processes. This provides a virtual environment to evaluate potential impacts from changing nutrient loads. We do not adjust internal model parameters and we assume that the system will respond using the kinetics based on the best available understanding of relationships between nutrients, algae, and DO. There is no other known basis for changing these internal processes, and our approach minimizes uncertainty.

Uncertainty of Incoming Nutrient Load at Edmonds open Boundary

The Puget Sound / Salish Sea model was used to establish ratios of water quality variables at Edmonds between natural and current conditions. These ratios were then used with current conditions in the South and Central Puget Sound GEMSS model to define natural conditions at Edmonds open boundary. The Puget Sound / Salish Sea model was also used to establish the incoming total nitrogen load at the Edmonds open boundary under both current and natural conditions. The mean tidal inflow used in calculations for the load was obtained from Table 3.2 in Khangaonkar et al. (2012). The difference between the incoming TN load under current and natural conditions is an estimate of the sum of the external anthropogenic load and reflux of internal loads.

Incoming TN loads were also estimated using the South and Central Puget Sound GEMSS model at a transect 5 grid-cells south of the Edmonds open boundary, away from boundary effects. At the Edmonds open boundary, any mass of nutrients or other water quality variables leaving the boundary during an ebb tide is lost. The mass coming in during a flood tide is equal to the specified concentration at the Edmonds open boundary times the tidal flows. The difference between current and natural incoming nutrient loads, as predicted by the South and Central Puget Sound model is also an estimate of the anthropogenic load at the Edmonds open boundary. This approach relies on water quality ratios developed using the Salish Sea model to define natural conditions at Edmonds open boundary for the South and Central Puget Sound model.

The estimates of external anthropogenic load without reflux from the two approaches (Puget Sound / Salish Sea and GEMSS South and Central Puget Sound model) are listed in Table 11. The difference between the two approaches is approximately 10%. The estimate based on the Puget Sound/Salish Sea model was used for calculation of sediment flux scalars for model scenarios.

The 10% difference is attributed in large part to the differences in estimated residual flows between the two models since the nitrogen scalars between natural and existing conditions for both the Salish Sea and South and Central Puget Sound model are the same. However, the total uncertainty is likely higher since there is uncertainty in nitrogen concentrations themselves between existing and natural conditions.

The total uncertainty can only be resolved by developing a method for the Salish Sea model to better estimate residual flows and loads across a transect at Edmonds. In addition, simulated dye studies using the Salish Sea model with dye in anthropogenic sources north of Edmonds would improve understanding of the quantity of external anthropogenic loading that crosses the Edmonds boundary. The Salish Sea model simulates the portion of anthropogenic loading from sources north of Edmonds that crosses the Edmonds boundary. Use of the Salish Sea model to evaluate scenarios would eliminate the uncertainty caused by translating between models to estimate the response to external anthropogenic load into Central and South Puget Sound.

Table 11. External total nitrogen load at Edmonds open boundary

Incoming external anthropogenic load at Edmonds open boundary (Kg TN/d)	
Salish sea Model	37400
South and Central Puget Sound Model	41800

The anthropogenic total nitrogen load in the Salish Sea north of the Edmonds was estimated by Mohamedali (2013) as 79,400 Kg TN/d. Therefore, based on values in Table 11 approximately 47-53% of the external anthropogenic load north of Edmonds is entering the model domain.

Summary of Uncertainty Factors

Sources of uncertainty in decreasing order of likely influence on results are as follows:

- Impacts of external anthropogenic loading
- Relationship between changes in nutrient loading and corresponding changes in sediment flux. This is more significant for scenarios involving reduction of loading from selected sources or within partial regions (e.g., Scenario 7). This uncertainty is likely less influential for scenarios involving across-the-board reductions from all sources in all regions.
- Possible under-estimation of violations due to possible over-prediction of DO (though not statistically significant) in the bottom layers of shallow inlets.
- Changes in open boundary loading of nutrients from sources external to the model domain.
- Estimated reflux of current loads back across the open boundary.
- Changes in open boundary loading from reflux of loads in different scenarios within the model domain.

Discussion and Conclusions

Some areas in South and Central Puget Sound are on the Clean Water Act Section 303(d) list of impaired waters because they do not meet the numeric criteria in the water quality standards for DO. This report summarizes the development and calibration of GEMSS, a 3-dimensional water quality model. Determining violations of the water quality standards depend in part on natural conditions, which we established using the calibrated model. The model was also applied to alternative loading scenarios to isolate the influences of different groups of sources.

Seasonal and Regional Dissolved Oxygen Profiles

Overall the model appropriately describes the regional and seasonal patterns of DO in a highly variable system. As described in Roberts et al., (2013 in press), the model reproduces the water surface elevations and the tides throughout South and Central Puget Sound as well as the profiles of salinity and temperature. The latter are important to characterize estuarine circulation patterns fundamental to nutrient transport and fate.

The calibrated model appropriately predicts the spatial and seasonal patterns in DO, nitrogen, and chlorophyll a concentrations throughout the model domain. Overall the model optimizes predictions of deeper DO concentrations. In the shallower inlets of South Puget Sound, the model somewhat overpredicts bottom-layer DO. While calibration focused on the RMSE for time series and profiles at key locations, we also compared detailed depth-time plots to monitoring data at 106 stations and evaluated surface and bottom DO, nitrogen, and chlorophyll in South and Central Puget Sound.

In Central Puget Sound, algae growth in the euphotic zone produces high-oxygen concentrations near the surface from spring through summer (Figure 61). Near the Edmonds boundary, the bottom-layer DO levels decline in the fall as marine water intrudes into Central Puget Sound. Both the model predictions and observed data indicate that the lowest DO concentrations in Central Puget Sound occur in East Passage. These patterns reflect algae growth, settling, and decomposition within Central Puget Sound in addition to the advection of low-oxygen water into the model domain past Edmonds. The sill at the Tacoma Narrows induces strong vertical mixing.

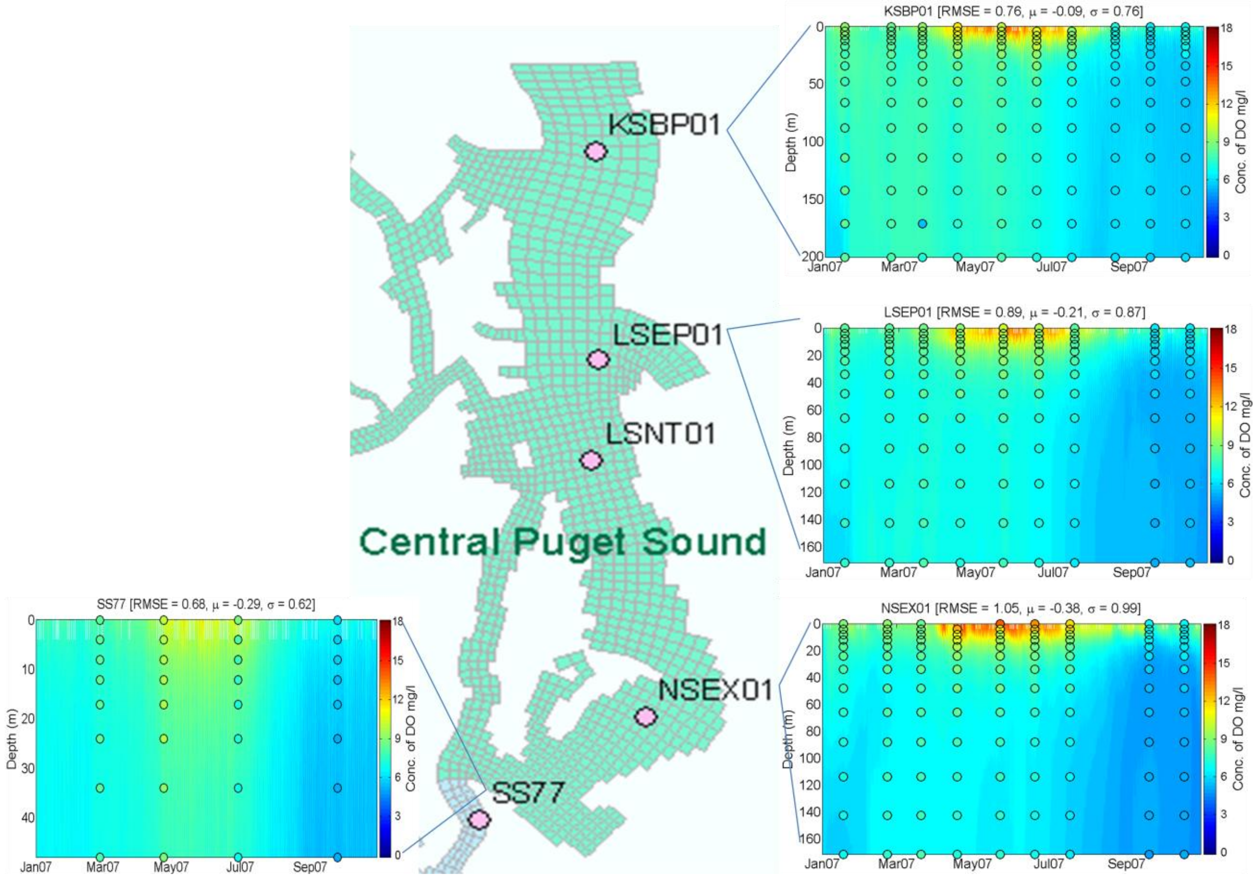


Figure 61. Predicted DO depth-time plots for key stations in Central Puget Sound.

Observation data are indicated with circles.

Within South Puget Sound, the lowest oxygen concentrations occur in northern Carr Inlet and at the ends of the finger inlets (Figure 62). The deeper waters of central Carr Inlet and southeast of McNeil and Fox Islands stratify during the summer and fall, with higher summer surface water and lower fall deeper water oxygen concentrations in Carr Inlet.

Oxygen profiles in shallow inlets such as northern Case and Budd result from algal productivity throughout the water column as light can penetrate to the bottom. Low DO water lags algae blooms in the surface layers by several months and likely reflects a combination of advection of low-oxygen water into South Puget Sound and formation from algae growth, settling, and decomposition, especially in regions of low water exchanges. However, the model over predicts near-bottom oxygen levels in the fall. This occurs where algae respiration offsets sediment oxygen demand in the model. The model also predicts more mixing than observations indicate, which leads to the over prediction of minimum oxygen concentrations.

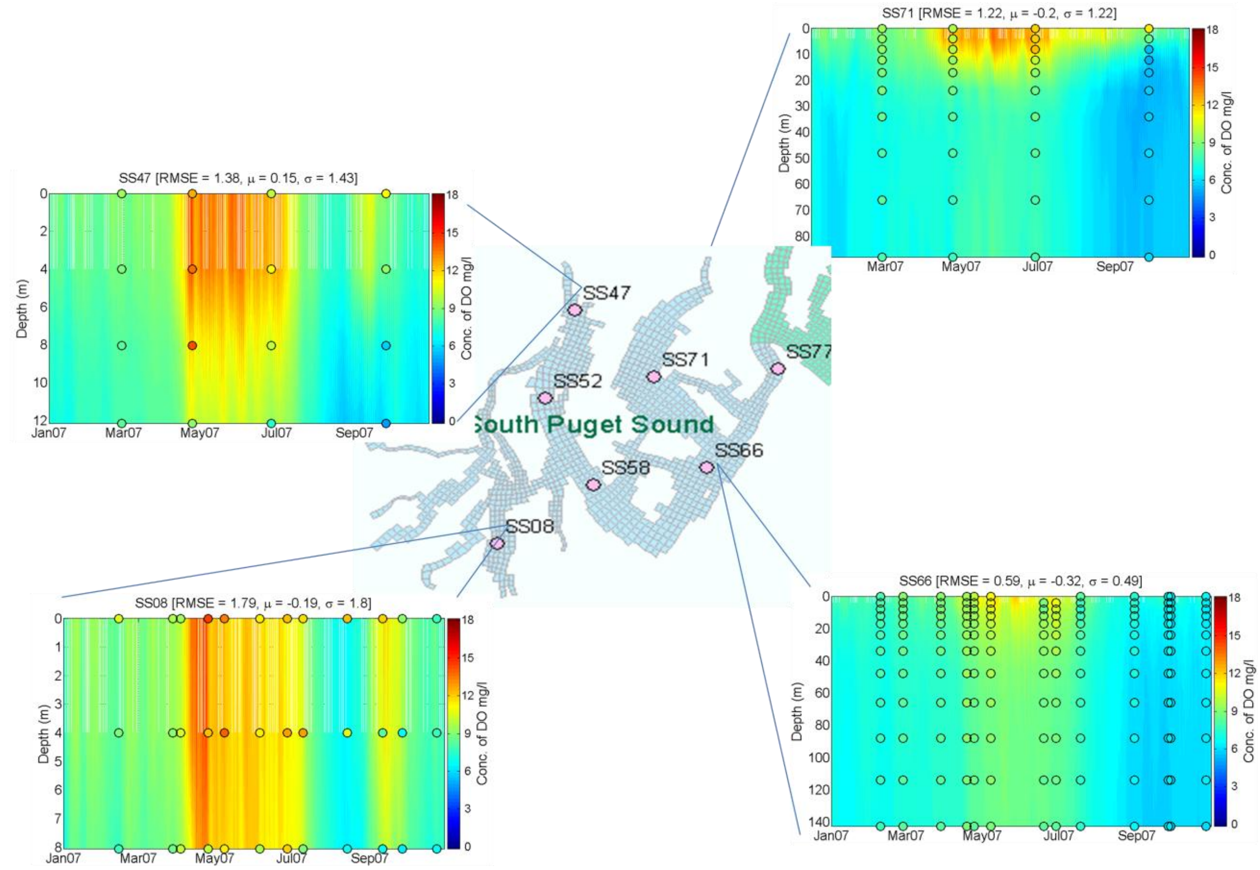


Figure 62. Predicted DO depth-time plots for key stations in South Puget Sound.
Observation data are indicated with circles.

Seasonal Patterns of Dissolved Oxygen in the Surface and Bottom Layers

The calibrated model predicts the seasonal patterns in DO and related parameters (Figure 63, Figure 64, and Figure 65). The root mean squared error (RMSE) statistic on each plot shows the goodness of fit between model-predicted values and observed data for the top (KT) and bottom (KB) layers. The model predicts a gradual increase in surface DO followed by a rapid increase into May, peaking with the spring algal bloom. Surface DO declines in summer into fall. For smaller inlets, there appears to be a secondary early fall increase in DO corresponding to algal blooms during this time. Bottom-layer DO declines from spring to fall near the Edmonds boundary and through the Tacoma Narrows. The calibrated model was able to reproduce the seasonal pattern quite well at all stations in the model domain with an average RMSE for DO of 1.05 mg/L. This is comparable to previous DO studies (Roberts, et al. 2012).

In general, the RMSE is better for the bottom layer compared to the top layer. The bottom layer concentrations reflect seasonal decreases and do not respond to specific algae blooms except in shallow inlets. Surface layer DO concentrations reflect what is happening on short time scales, since any supersaturation of DO would off-gas to the atmosphere on time scales of days. Most low DO concentrations are associated with the bottom layer. In shallow inlets like Budd Inlet, the model predicted DO concentrations for the bottom layer are very close to those for the top layer, although observed data show some differences between the layers. This is likely due to fewer layers in this shallow inlet that allowed for relatively more mixing between the layers.

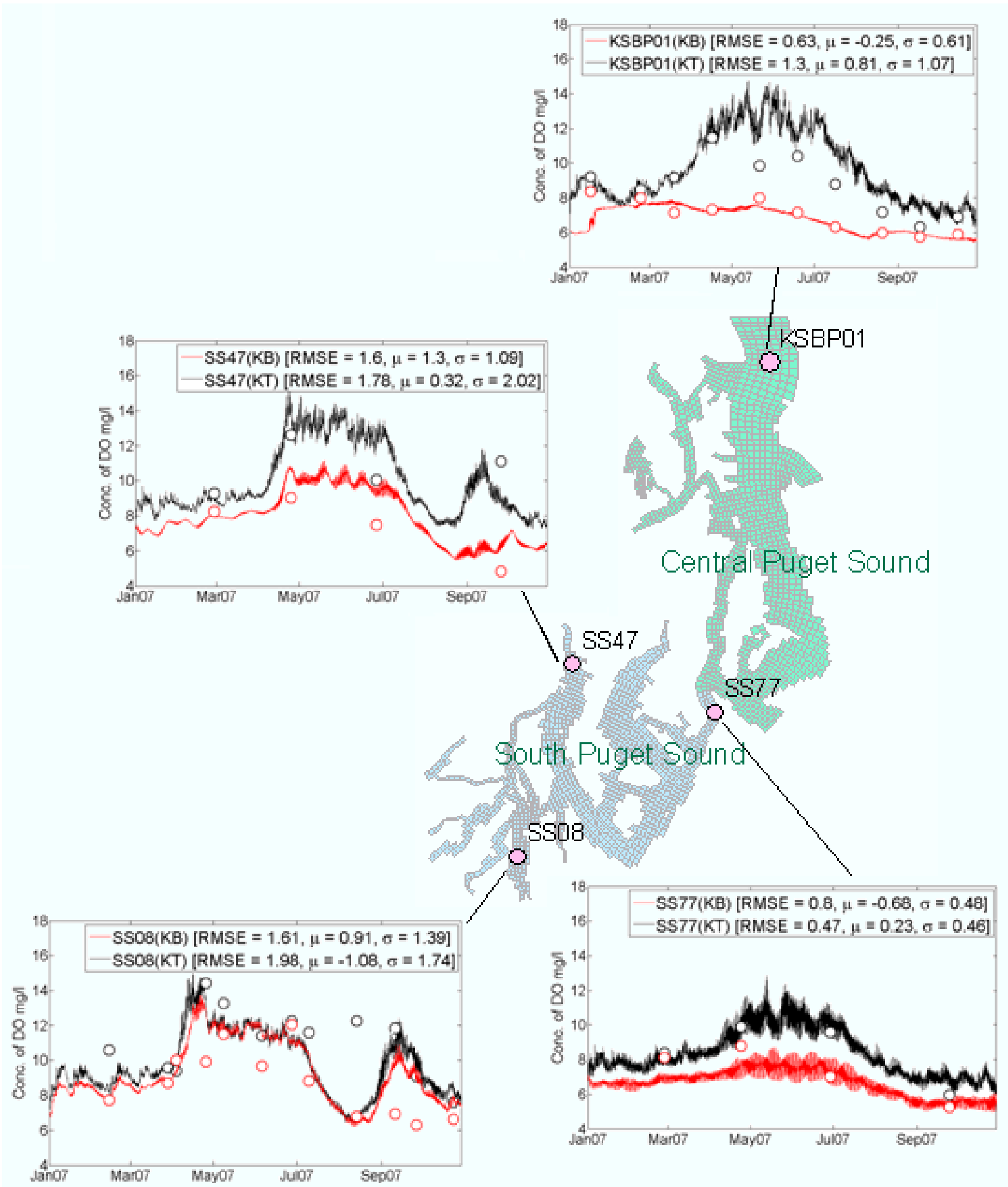


Figure 63. Measured and predicted DO concentrations in the surface (KT) and bottom layer (KB).

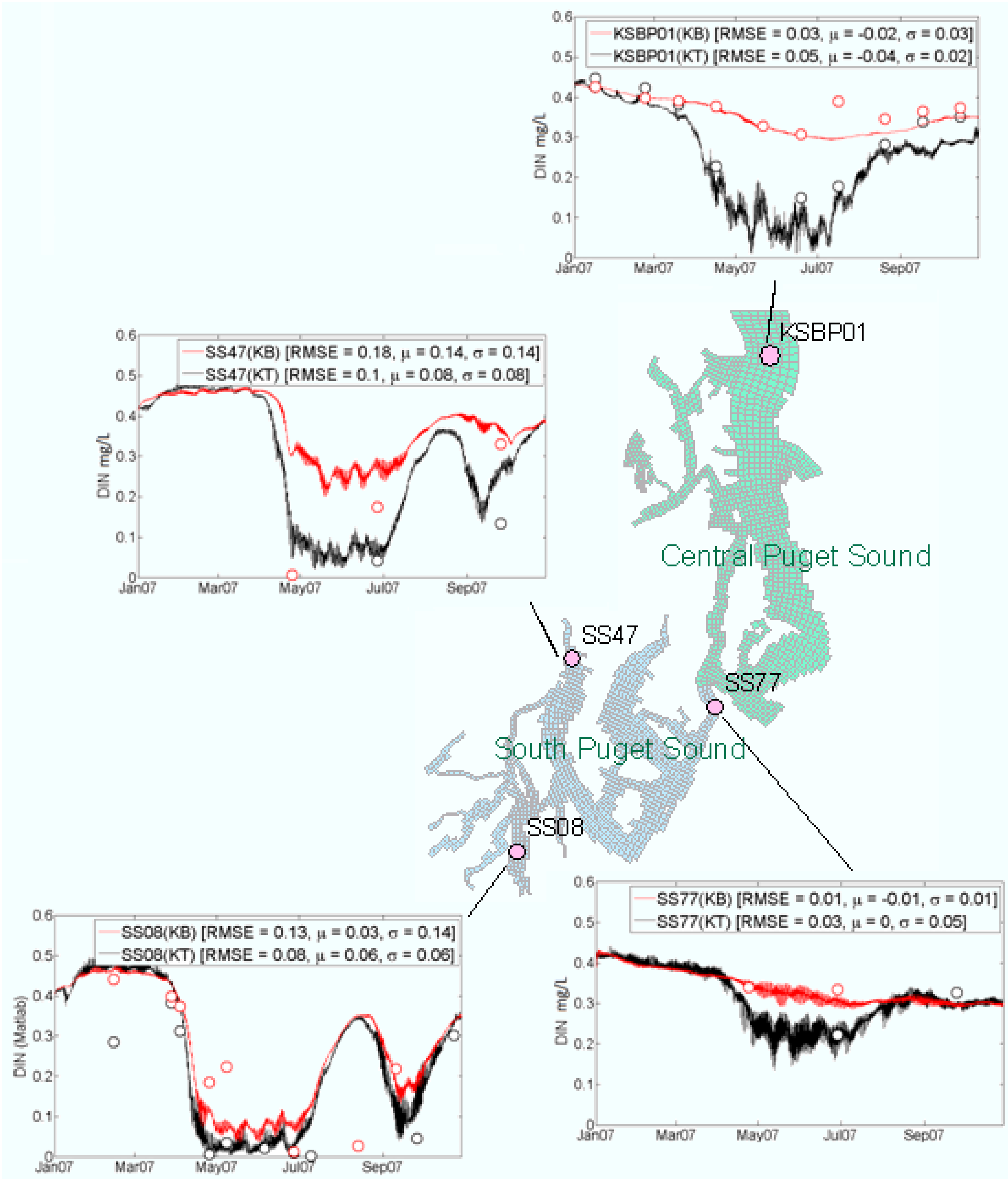


Figure 64. Measured and predicted dissolved inorganic nitrogen (DIN) concentrations in the surface (KT) and bottom layer (KB).

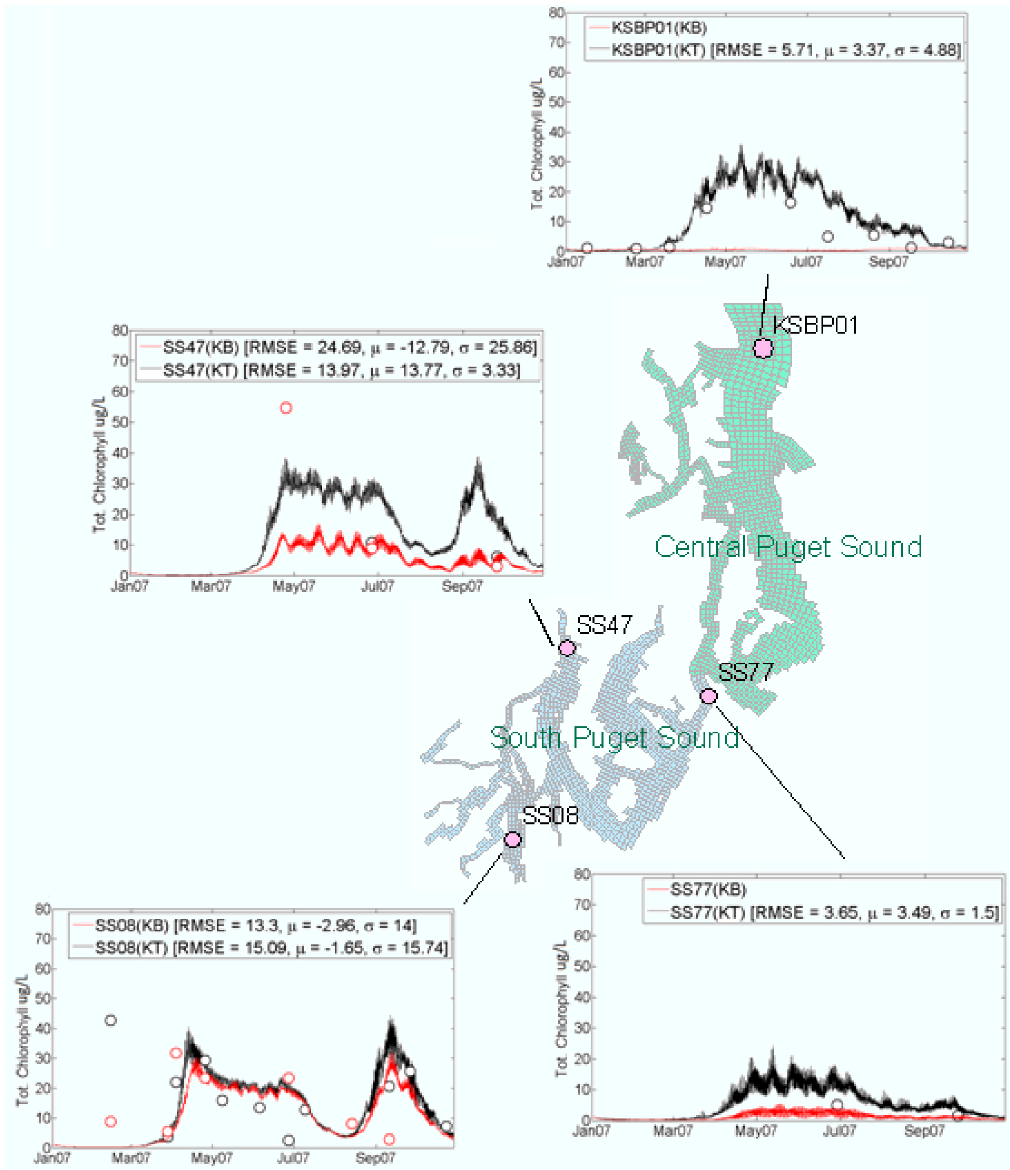


Figure 65. Measured and predicted chlorophyll concentrations in the surface (KT) and bottom layer (KB).

Regional Patterns in Surface and Bottom Dissolved Oxygen, Chlorophyll, and Dissolved Inorganic Nitrogen

Model predictions and observations of South and Central Puget Sound DO, chlorophyll, and nitrogen exhibit high spatial variability in addition to the strong seasonal variation. Surface chlorophyll levels represent a proxy for algae growth. Low light drives low algae growth in the winter months (Figure 66 (a)), but increased light in the spring produces blooms (Figure 66 (b)). Blooms produce oxygen in the surface layers (Figure 67) and draw down DIN (Figure 68) as algae convert it to organic matter. In the fall, chlorophyll levels decline, although the model predicts continued growth in the shallow inlets and in Central Puget Sound.

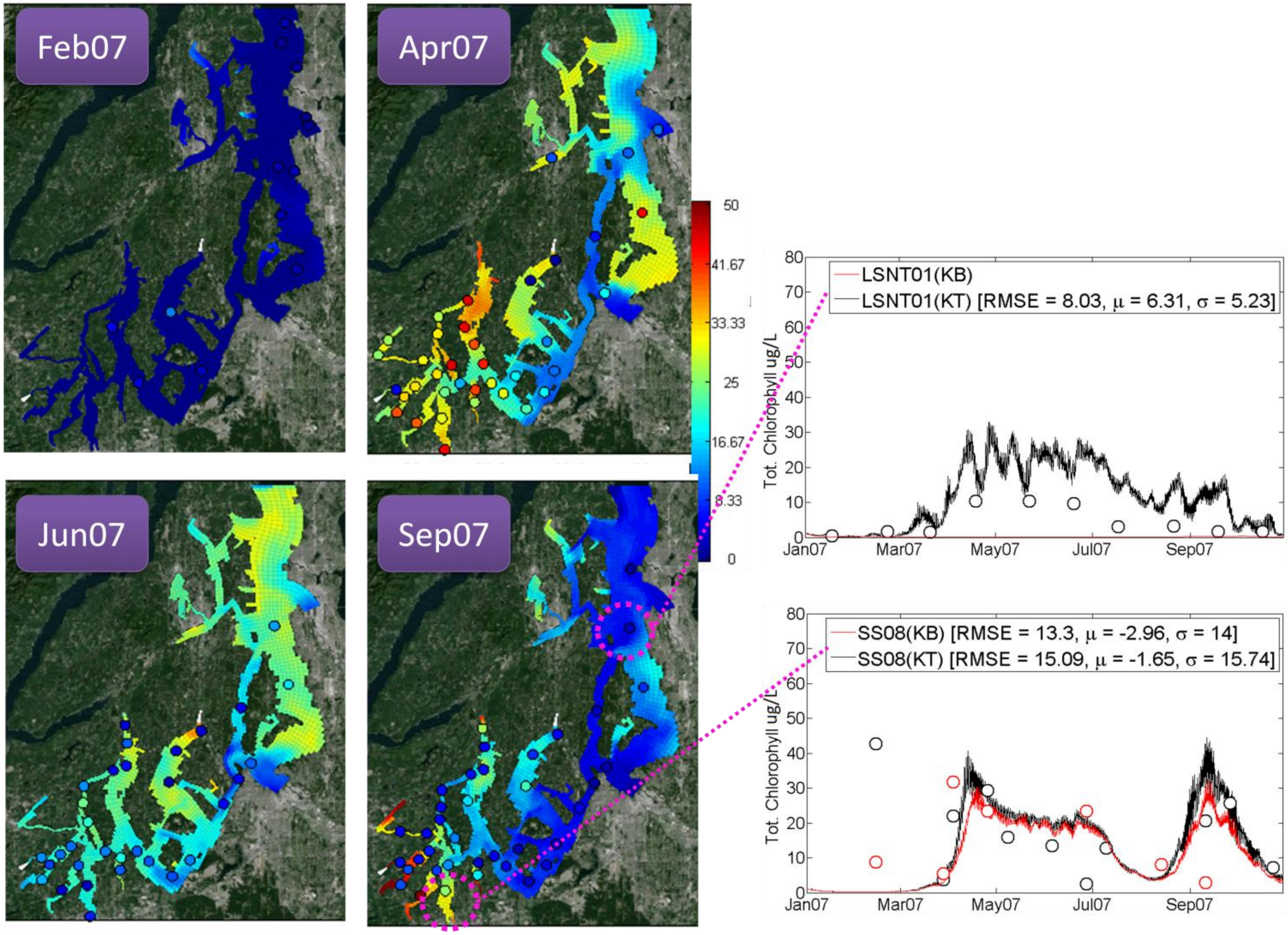


Figure 66. Hourly predictions of surface layer chlorophyll a concentrations (ug/L) for (a) February 2007, (b) April 2007, (c) June 2007, and (d) September 2007 with data collected within 5 days of the simulated date and time in circles.

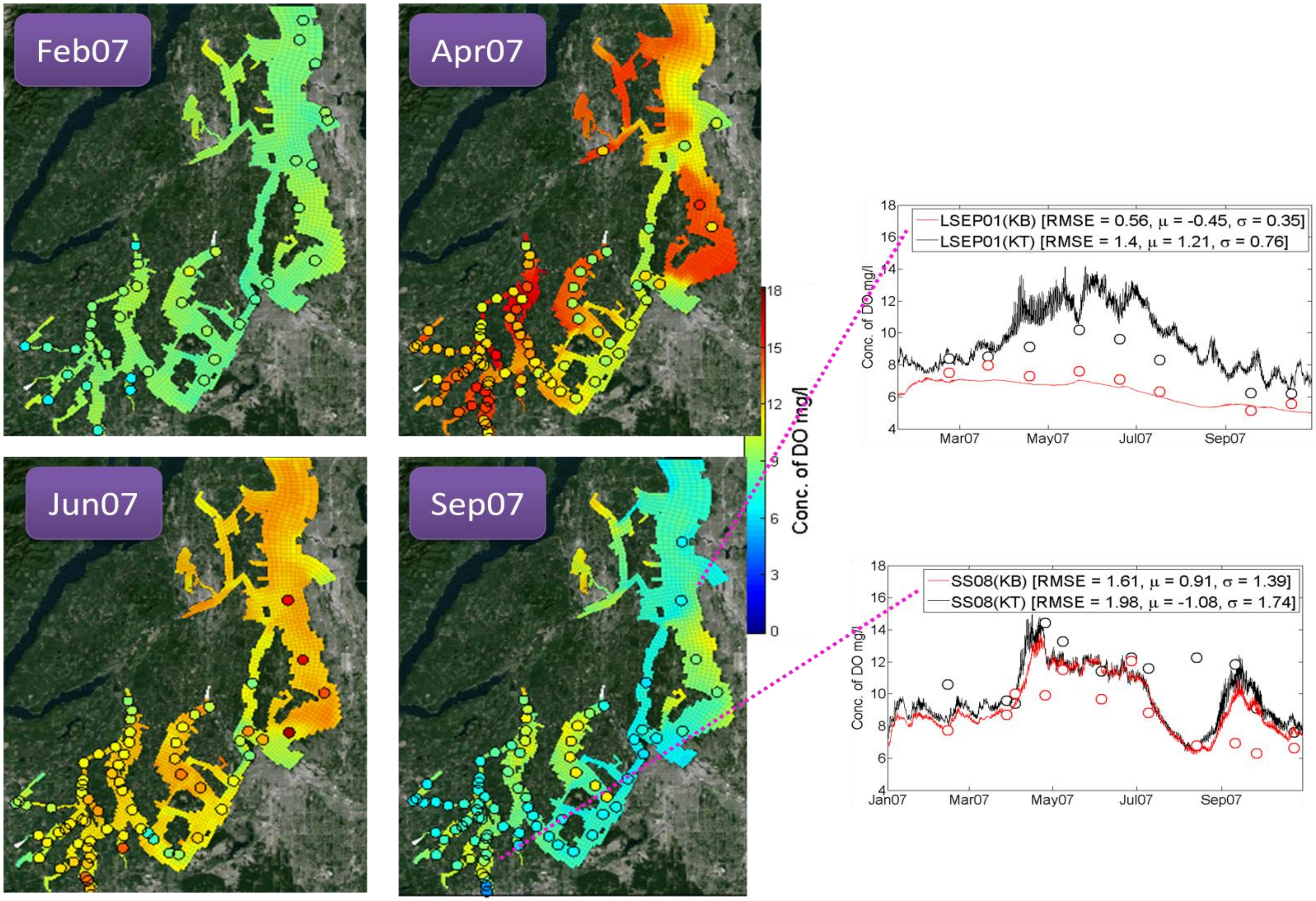


Figure 67. Hourly predictions of surface layer DO concentrations (mg/L) for (a) February 2007, (b) April 2007, (c) June 2007, and (d) September 2007 with data collected within 5 days of the simulated date and time in circles.

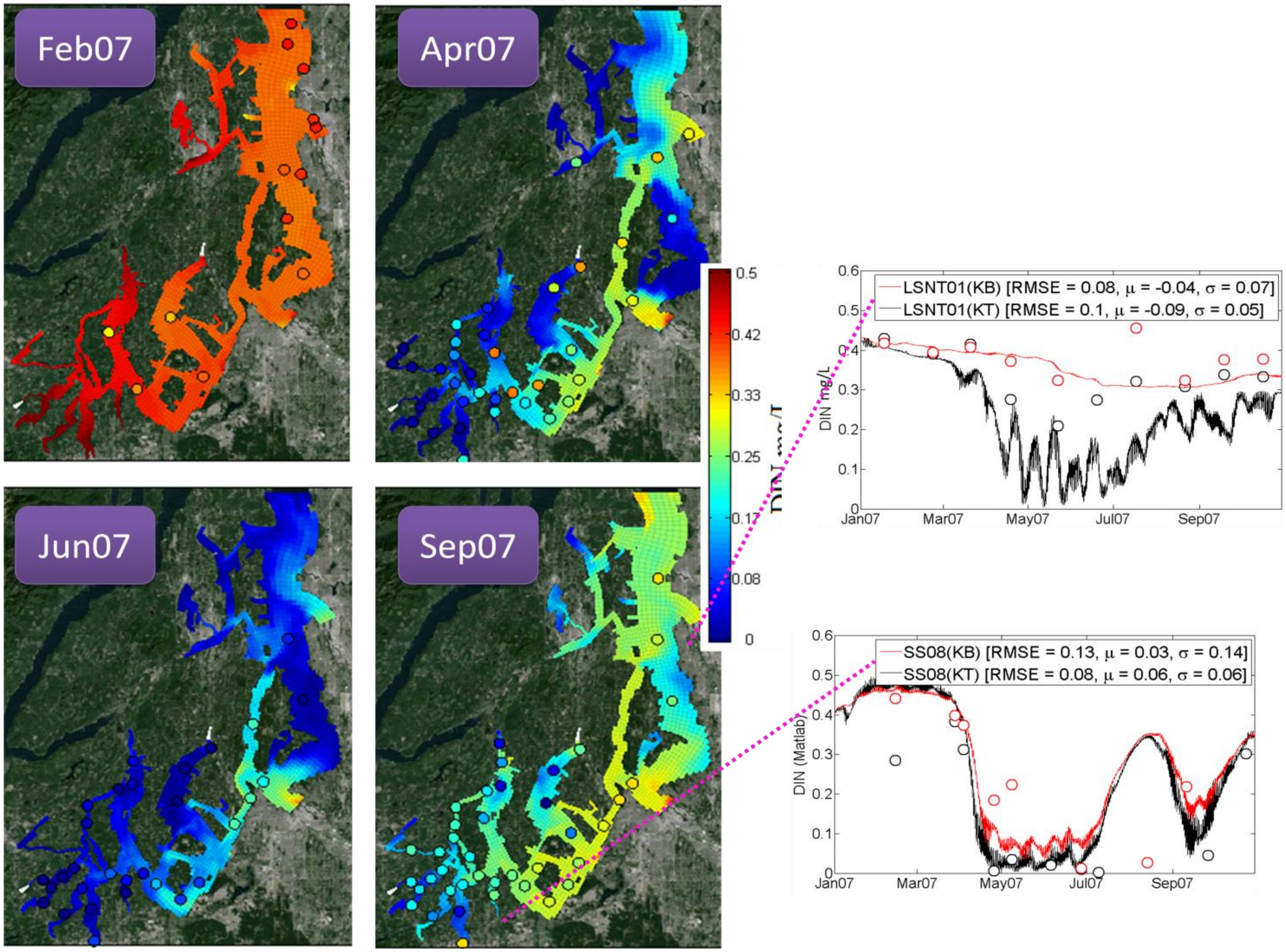


Figure 68. Hourly predictions of surface layer dissolved inorganic nitrogen (DIN) concentrations (mg/L) for (a) February 2007, (b) April 2007, (c) June 2007, and (d) September 2007 with data collected within 5 days of the simulated date and time in circles.

While these represent hourly snapshots of model predictions combined with 10-day composites of observations, they confirm that the predicted and observed blooms show very strong spatial variability. In Central Puget Sound, the regions east of Vashon Island and west of Bainbridge Island show the highest spring algae concentrations. High surface oxygen levels and low DIN coincide. In June and September the surface patterns are more homogeneous but still reflect higher algae growth in Sinclair and Dyes Inlets and the region east and south of Vashon Island.

The Tacoma Narrows surface layer characteristics extend north through Colvos Passage, west of Vashon Island, and south into the area southeast of Fox and McNeil Islands. Higher algae growth occurs in Carr, Case, and the finger inlets of South Puget Sound, with corollary increases in surface DO and decreases in surface DIN concentrations in summer and fall.

Near-bottom water quality parameters reflect seasonal patterns as well as variations in depth and circulation (Figure 69). Near-bottom conditions are more homogeneous than surface water characteristics. Deeper waters show very low chlorophyll a levels throughout the year. DO concentrations are more homogeneous in the deeper bottom waters of South and Central Puget Sound, with a seasonal decline from April through September. DIN in deep waters reflect the combined effects of advection of marine water at the northern boundary, deep discharges of marine point sources in Central Puget Sound, and a seasonal decline.

In shallow inlets and bays, sunlight penetrates to the bottom and chlorophyll a levels reflect seasonal variability. Algae respiration increases in the spring, coinciding with lower DIN concentrations in the bottom-waters of shallow inlets compared to deeper regions. Model predictions of surface layer chlorophyll exhibit strong spatial gradients in the South Puget Sound finger inlets, with higher levels near the ends of the inlets. The surface layer chlorophyll data generally corroborate the finding but indicate very high patchiness, particularly in spring. By September, the model predicts continued high chlorophyll levels.

The model predictions match observed DO and related parameters well, although it does not reproduce each observation perfectly. The goal was to appropriately simulate the dominant processes governing DO in South Puget Sound and to describe the seasonal progression of low oxygen concentrations.

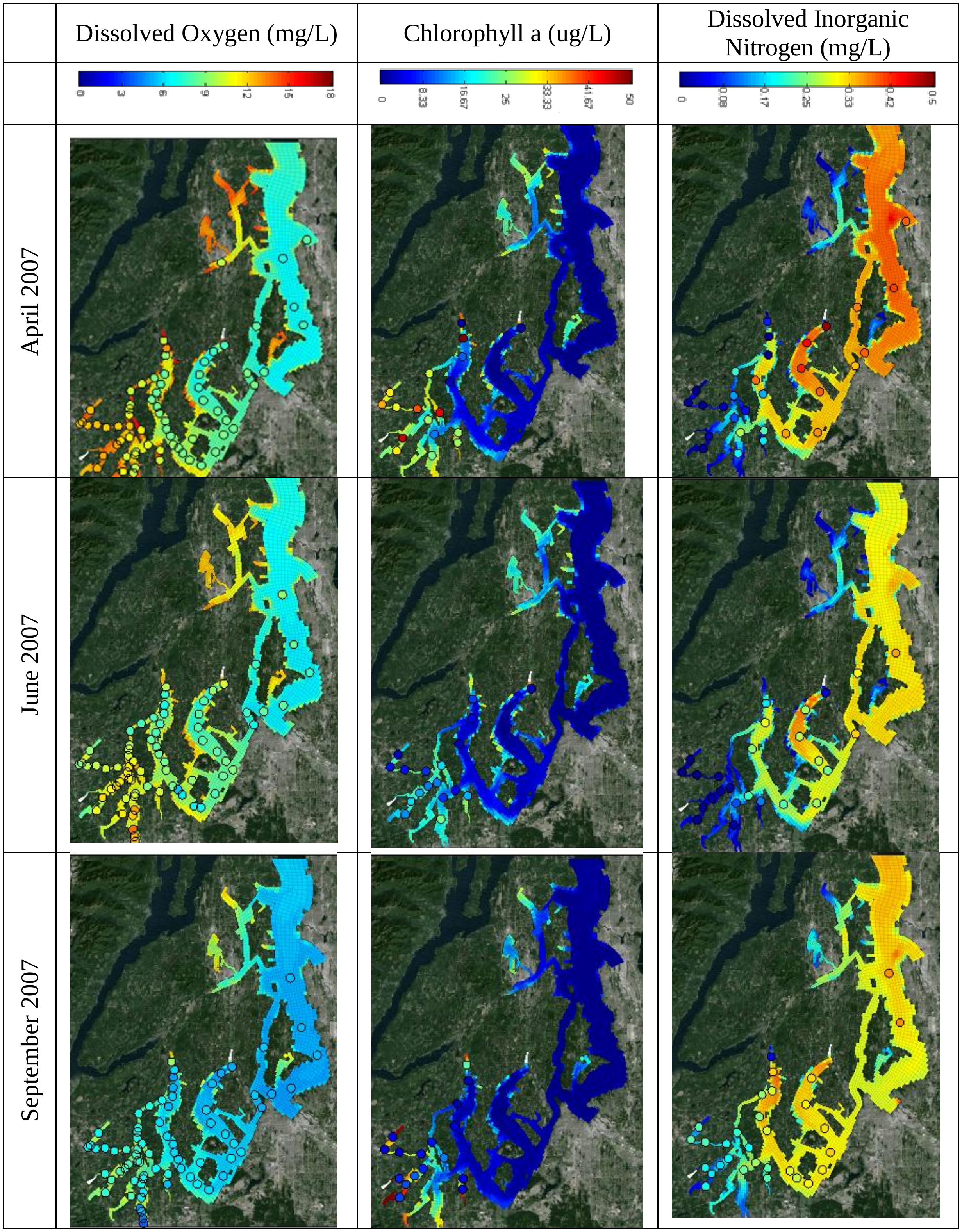


Figure 69. Predicted and observed bottom-layer DO, chlorophyll a, and DIN.

Model Errors and Uncertainty

Model skill refers to how well the model reproduces the underlying processes and observational data in a system. We used several indicators of skill to assess model performance during calibration to supplement visual interpretation. However, calibration relied on two measures in particular. The root mean square error is the square root of the average squared difference between predicted and observed values. It evaluates the model capability in reproducing observed conditions using. We also evaluated the mean bias, or the average of differences between predicted and observed concentrations.

The RMSE between predicted and observed DO, DIN, and chlorophyll data is comparable to a previously published report (Roberts et al., 2012). The mean bias across all stations is much lower than the RMSEs indicating that the model is not significantly biased overall (the bias is negligible within the 95% confidence interval). However, a single station in Case Inlet suggests a slight but significant tendency to over predict chlorophyll.

The model is suitable for the purposes of this project to predict critical bottom DO in response to variation in nutrient loading and for predicting DO standards violations when comparing scenario predictions to natural conditions and to the numerical DO criteria.

Natural Conditions Fall below Numeric Criteria

Natural conditions were defined using the natural loadings defined by Mohamedali et al. (2011). We also adjusted water quality concentrations at the open boundary at Edmonds using the Puget Sound / Salish Sea model (Khangaonkar et al., 2012) and sediment fluxes to reflect decreased loads. The minimum DO under natural conditions falls below the numeric water quality criteria for DO (Figure 70).

In Central Puget Sound, minimum DO concentrations fall below 5 mg/L in the deep waters east and south of Vashon Island and into Commencement Bay. Lower concentrations occur further south, away from the Edmonds boundary. Minimum DO concentrations are higher in the shallow inlets of Central Puget Sound where algal productivity extends to the sediments and can offset SOD. Colvos Passage minimum DO concentrations reflect levels in the Tacoma Narrows. In South Puget Sound, lowest concentrations occur near the landward ends of Carr, Totten, Eld, and Budd Inlets and fall below the criteria. In these regions, human contributions cannot cause DO to fall by more than 0.2 mg/L below natural conditions. In the areas where natural conditions are above the criteria, human impacts cannot cause DO to fall below the numeric criteria.

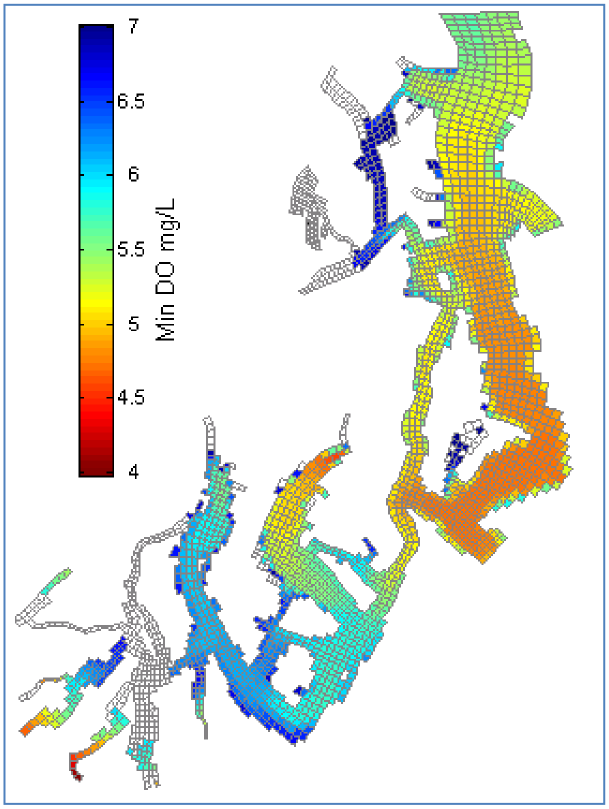


Figure 70. Annual minimum DO concentrations under natural conditions predicted by the model where they are lower than the numeric criteria in the water quality standards.

Current Human Sources Violate DO Standards

We compared model-predicted DO concentrations with both the numeric criteria for DO as well as with model predicted natural DO concentrations to delineate areas where DO standards are not met. The 303(d) listings are strictly based upon the numeric criteria for DO. Figure 71 shows the DO violations under current conditions compared with both the numeric criteria and the DO under natural conditions. It also shows regions for the 2012 303(d) listings (red squares) for DO. Locations where 303(d) listings exist but model predicts no violation are areas where observed DO is lower than the numeric criteria, but natural conditions are also below the numeric criteria and the DO depletion is within 0.2 mg/L of the natural DO.

We also evaluated loading scenarios that isolate the impacts from only watershed inflows and only marine point sources. Human sources within watershed inflows in the model domain along with external anthropogenic sources alone do not cause DO depletions above 0.2 mg/L except at the southern end of Eld Inlet. However, the magnitude and extent of DO violations from marine point sources and external anthropogenic sources is similar to those of the combined human sources (watershed inflows, marine point source discharges, and external anthropogenic sources). Therefore, while in conjunction with external anthropogenic sources, watershed inflows do cause some DO depletion, marine point sources exert a greater impact on minimum DO in South and Central Puget Sound.

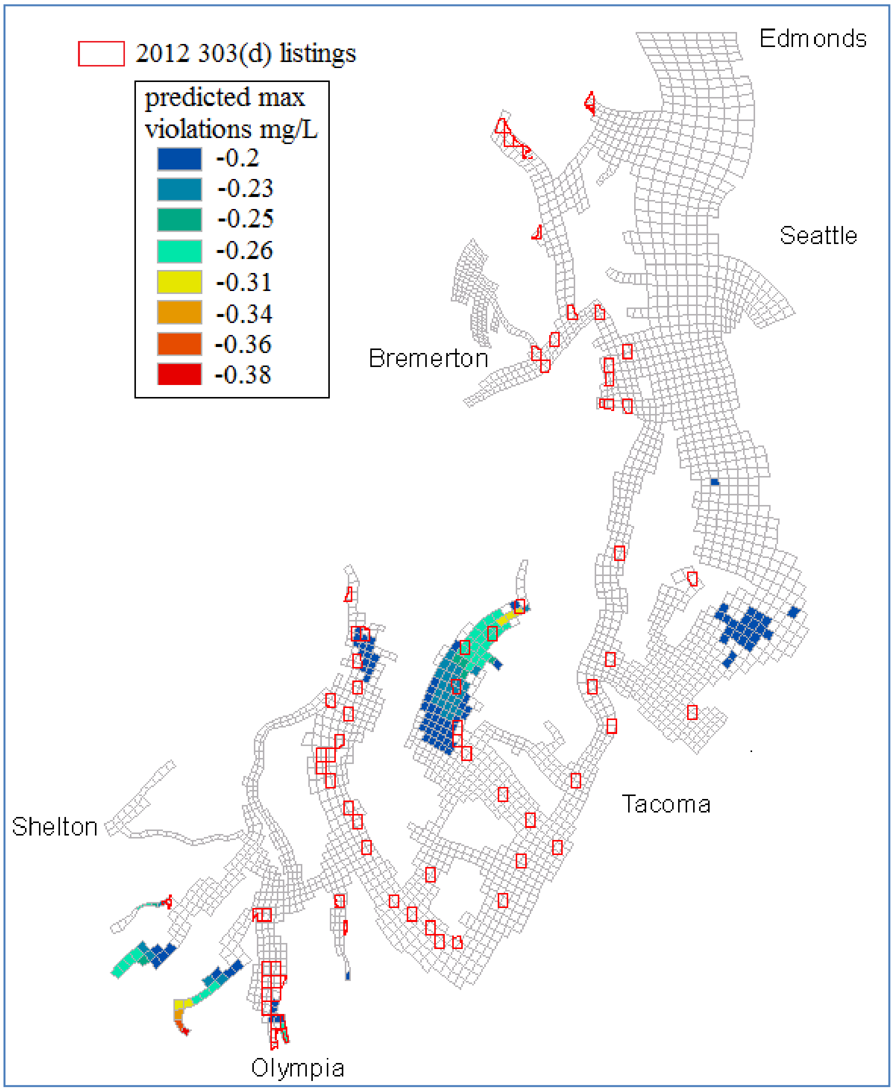


Figure 71. Predicted violations of water quality standards for DO (based on limiting numeric criteria and/or natural conditions) and 303(d) listings (based on numeric standards)

Reducing Human Nutrients Reduces DO Impacts

Scenarios that represent 25, 50, and 75% reductions of all human sources to South and Central Puget Sound decrease the DO impacts compared with current contributions (Figure 52). Both the maximum depletion and the region above 0.2 mg/L depletion decrease with decreasing human contributions. A 25% reduction eliminates the violations in East Passage and Case Inlet. While a 50% reduction decreases depletions, it does not eliminate violations in additional inlets. A 75% reduction would decrease the maximum depletion to less than 0.2 mg/L in all but Eld Inlet. The remaining human contributions, 25% of the current contributions to both South and Central Puget Sound and external anthropogenic sources, would still cause some DO depletions, but maximum depletions would be below 0.2 mg/L.

Low circulation strongly influences Eld Inlet oxygen levels. The remaining violations in Eld Inlet likely reflect a combination of nearby human sources within watersheds and dispersed nutrients from other human sources outside of Eld Inlet. The residence time is the highest of the South Puget Sound inlets due a combination of physical shape and low freshwater inputs at its southern end from small watersheds. Additional scenarios would be needed to determine nutrient reductions required to eliminate violations in Eld Inlet.

Both South and Central Puget Sound Sources Contribute to South Puget Sound DO Impacts

We evaluated the relative contributions of South and Central Puget Sound Sources to DO impacts in South Puget Sound by turning off all human sources to Central Puget Sound. DO depletions in South Puget Sound decline but are not completely eliminated. This indicates that both South and Central Puget Sound sources contribute to DO impacts in South Puget Sound. Maximum depletions fall below 0.2 mg/L in both East Passage and Case Inlet.

The magnitude of the remaining DO depletions depends on how the sediment scalars are applied. Decreasing the external loads to South and Central Puget Sound would decrease algal productivity. This would decrease the amount of nitrogen settling in particles to the sediments, which would decrease the sediment oxygen demand and nitrogen fluxes back to the water column. Sediment fluxes are scaled from current conditions using mass balances of nutrients to account for this process.

We do not know what proportion of Central Puget Sound sources reaches South Puget Sound. We bounded the effect by applying the sediment flux scalar to (a) both South and Central Puget Sound and (b) only Central Puget Sound (Figure 53). Based on the pattern of simulated tracers released from Central Puget Sound sources, some fraction of loading to Central Puget Sound would reach South Puget Sound (Roberts et al., 2013, in press). The fraction reaching South Puget Sound was estimated to be 14% when only the marine point sources were dyed.

The fraction of Central Puget Sound nutrients reaching South Puget Sound could be lower than a conservative tracer indicates because of uptake within Central Puget Sound. With low fractions of nutrients from Central Puget Sound reaching South Puget Sound, applying the sediment scalars only to Central Puget Sound (with a minor change in scalars for South Puget Sound) would be more appropriate.

In case where sediment scalars are applied only to central Puget Sound, the maximum depletions would still decrease to less than 0.2 mg/L in East Passage and Case Inlet, but maximum depletions above 0.2 mg/L would remain in the other inlets. Maximum depletions would decrease from 0.32 to 0.22 in Carr Inlet and from 0.22 to 0.16 mg/L in Case Inlet. Maximum depletions would not change in Totten, Eld, or Budd Inlets, indicating that South Puget Sound sources contribute to maximum depletions only. The decreases in Carr and Case Inlets indicate that Central Puget Sound sources would cause about 30% of the DO depletion there, and South Sound sources would cause the remaining 70%.

In summary, Central Puget Sound sources, through a combination of water and sediment processes, potentially contribute 30 to 40% of the DO depletions in Carr and Case Inlets. South Puget Sound sources potentially contribute 60 to 70%. Eliminating Central Puget Sound sources could decrease maximum depletions in those inlets but portions of Carr Inlet would still likely have maximum depletions above 0.2 mg/L. South Sound sources potentially contribute at least 60% and possibly all of the depletions in Totten, Eld, and Budd inlets.

Comparing Maximum Depletion in Eld Inlet under Alternative Loading Scenarios

Under current conditions, DO standards are violated in Budd, Eld, Totten, Case and Carr Inlets as well as some limited portions of Central Puget Sound. However, the critical area for DO standards violation is at the mouth of Eld Inlet. Figure 72 shows a time series plot of DO at this location for current and natural conditions.

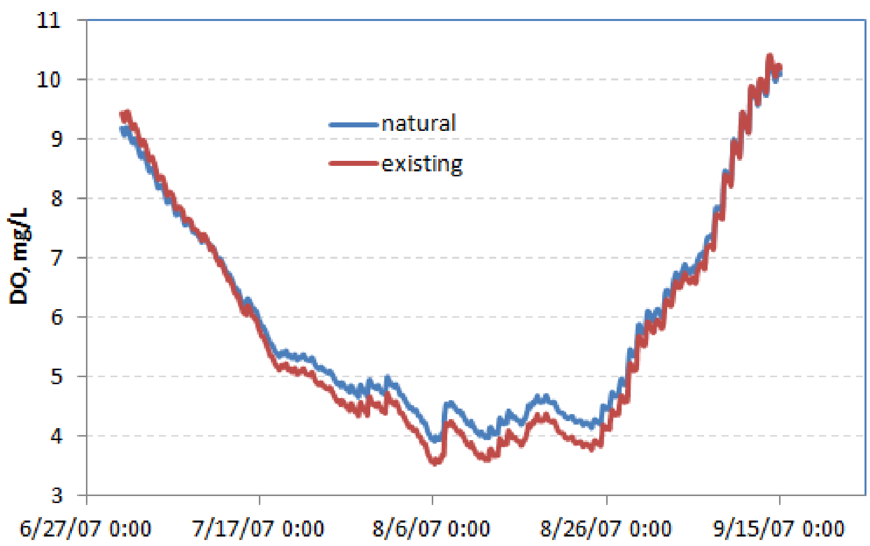


Figure 72. DO concentrations at critical cell in Eld Inlet under current and natural conditions

Figure 73 shows the DO depletions in critical cell at the mouth of Eld Inlet under various scenarios. The red line shows the critical depletion of 0.2 mg/L. Any depletion below this line is a violation of the water quality standard. Under current conditions (the first bar from left) the DO is depleted by 0.38 mg/L below natural conditions. When external nutrient loads are kept constant, the majority of the depletion is caused by internal marine point sources and to a much lesser extent by the internal watershed loads (the nest two bars from left).

The depletions get much worse when nutrients in point sources are increased to their permit levels (fourth bar from left). The next three bars show the cumulative effect of reducing both the point and non-point internal sources by 25%, 50% and 75% with the latter showing the least depletions. With Central Puget Sound at natural conditions (the last two bars) and both the external and South Puget Sound anthropogenic sources at current conditions , the effect on DO depletion in Eld Inlet varies based on whether the sediment scalar is applied to only the Central Sound area or the whole model domain.

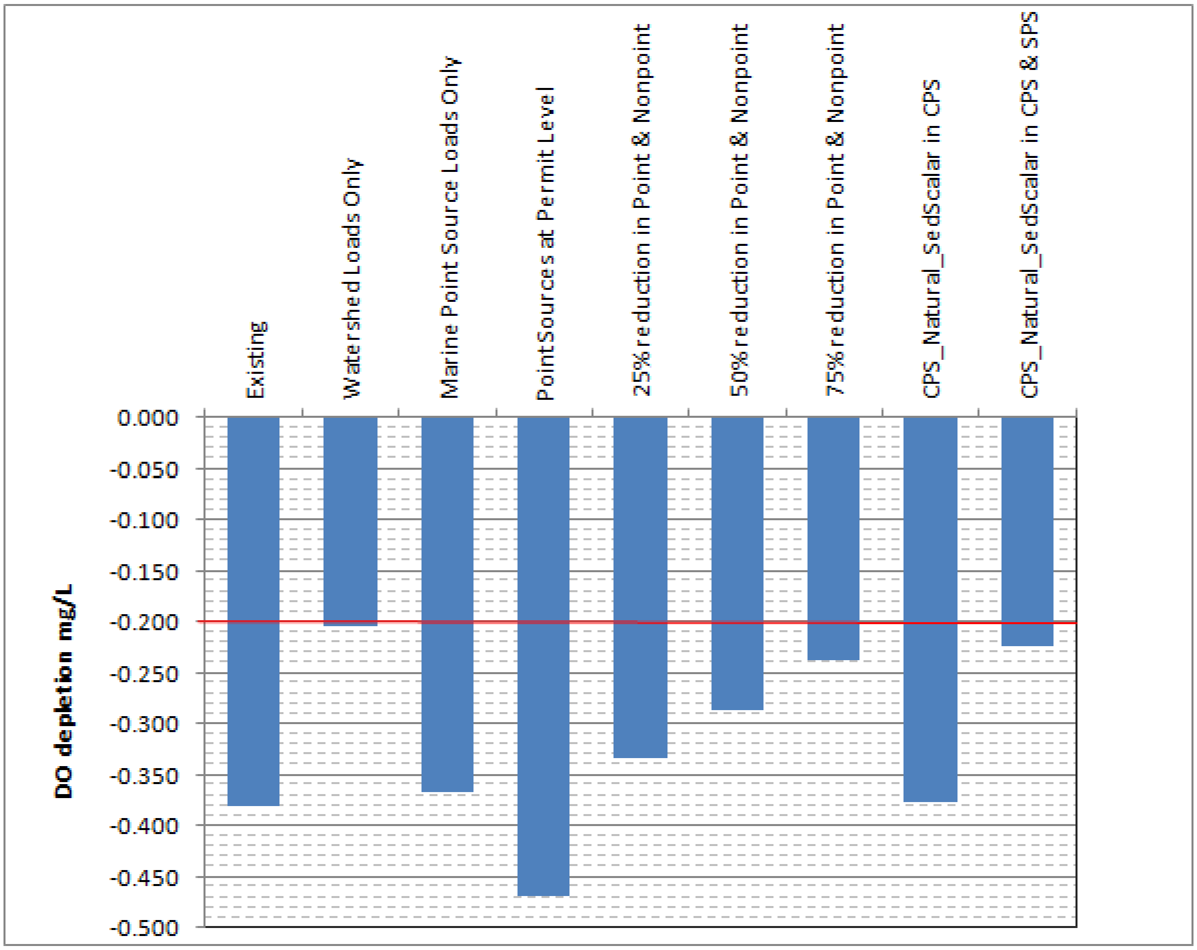


Figure 73. DO depletion in excess of 0.2 mg/L in the critical Eld Inlet cell.

In order to get a sense of the impact of external anthropogenic sources on magnitude of DO depletion in the critical Eld Inlet cell, DO depletion is plotted against percent reduction of internal nutrient loads as shown in Figure 74. The zero percent reduction in internal anthropogenic nutrient loads corresponds to current conditions and the extrapolated 100% reduction corresponds to a scenario where only external anthropogenic loads exist. With no internal anthropogenic nutrient loads the DO is depleted by 0.19 mg/L below natural conditions. Therefore, with a total DO depletion of 0.38 mg/L under current conditions, the model predicts that about 50% of the depletion is caused by sources from north of the Edmonds open boundary.

A model run with external anthropogenic load added to natural conditions confirmed this DO depletion to be 0.19 mg/L (with no depletions greater than 0.2 mg/L in the model domain, see Figure 75.

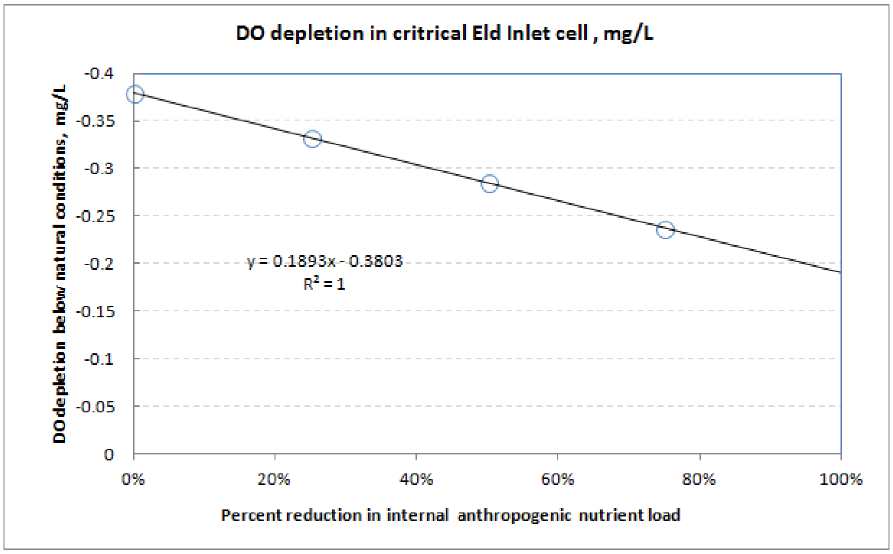


Figure 74. DO depletion in critical Eld Inlet cell in response to percent reductions in internal anthropogenic nutrient load.

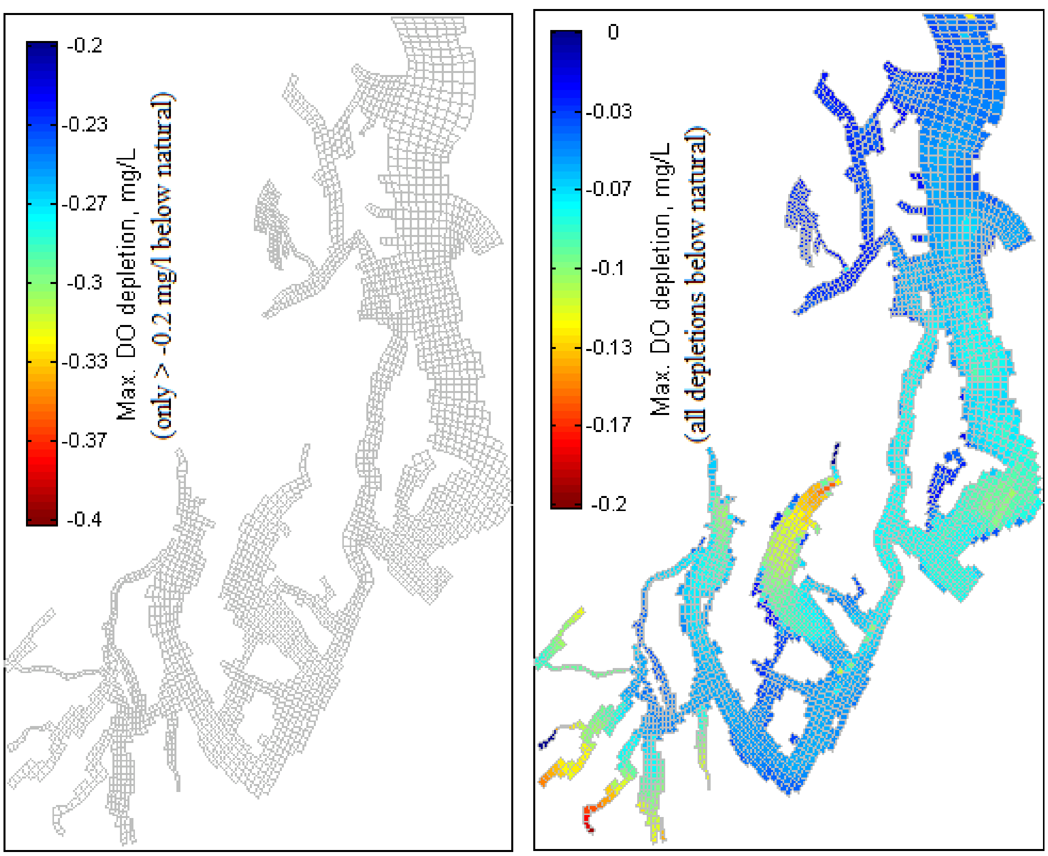


Figure 75. Regions of DO violations with external anthropogenic sources present at the Edmonds open boundary under natural conditions.

Scenario Uncertainty

The scenarios are developed using the best available information and approaches. Sources of uncertainty in decreasing order of likely influence on results are as follows:

- Relationship between changes in nutrient loading and corresponding changes in sediment flux. This is more significant for scenarios involving reduction of loading from selected sources or within partial regions (e.g., Scenario 7). This uncertainty is likely less influential for scenarios involving across-the-board reductions from all sources in all regions.
- Possible under-estimation of violations due to possible over-prediction of DO (though not statistically significant) in the bottom layers of shallow inlets.
- Changes in open boundary loading of nutrients from sources external to the model domain.
- Estimated reflux of existing loads back across the open boundary.
- Changes in open boundary loading from reflux of loads in different scenarios within the model domain.

Recommendations and Next Steps

We recommend several next steps.

Additional Scenarios

Additional scenarios are needed to isolate the influences of different sources. We recommend applying the calibrated model to a series of scenarios.

We determined that South Puget Sound sources cause most or all of the impacts to the finger inlets (Totten, Eld, and Budd Inlets). We recommend additional scenarios to isolate these influences. This would include a combination of dye tracer simulations using just the circulation model as well as water quality runs that isolate the larger marine point sources in South Puget Sound. We recommend continuing to adjust the sediment flux scalars using the method described in this report.

One of the remaining uncertainties involves the impact of Central Puget Sound human sources of nitrogen on South Puget Sound DO concentrations. By leaving the sediment flux scalars at current conditions for South Puget Sound or scaling them to 95% of the current levels as in Central Puget Sound, we bracketed the range of impacts of Central Puget Sound sources on South Sound water quality. Although preliminary evaluation with dye studies showed 14% of Central Puget Sound Marine Point Source discharge reaching South Puget Sound areas, we recommend additional study be conducted to include watershed inflows as well as reflux at open boundary, along with some provision to reflect nutrient uptake in Central Puget Sound (tracer is conservative) before such numbers can be utilized to estimate sediment scalars.

The northern boundary of the South Puget Sound model was adjusted to reflect increased or decreased loading by coupling with the larger Puget Sound / Salish Sea modeling effort (Roberts et al., 2013, in press). We recommend additional sensitivity analyses to characterize boundary effects.

We also recommend additional sensitivity analyses on sediment fluxes of oxygen and nitrogen.

Coordination with Puget Sound / Salish Sea Modeling

We recommend continued coordination with the larger Puget Sound / Salish Sea model efforts. The Puget Sound / Salish Sea model has additional layers in shallow inlets that could be used to refine predictions in both models. An upcoming effort will also add the capability to simulate sediment-water exchanges interactively.

Data Needs

A recent compilation of sediment fluxes in the Puget Sound region found relatively little site-specific data (Sheibley and Paulson, 2013 in press). Most of the Puget Sound data were developed for shallow waters during the summer months. We recommend that data collection programs focus on sediment-water exchanges in areas with low human inputs and in areas with high human inputs. If a marine point source outfall location shifts in the near future, we recommend sediment flux monitoring before and after the shift at both the current and the new locations. This would provide insight on how sediment fluxes respond to changes in external loading.

Sediment fluxes are fueled by the deposition of particulates from the water column to the sediments. We recommend field studies that quantify particle fluxes in the lower water column in a range of depositional environments. Measurements should occur in all four seasons.

Next Steps to Guide Management Actions

Additional scenarios will be needed to refine the relative contributions of different sources to the DO depletions predicted for South Puget Sound. These should be combined into potential sets of management actions to support the future development of load and wasteload allocations if a TMDL is pursued. Ecology may decide to not conduct a TMDL if alternative management approaches are used to address violations.

We also identified several regions where Category 5 303(d) listings occur yet we do not predict that human sources cause >0.2 mg/L depletion. DO listings should be reconsidered in these regions.

Summary of Public Involvement

Ecology posts South Puget Sound Dissolved Oxygen Study information on its website at www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html. The website includes raw data, the data report, the circulation report, independent audit reports, advisory committee information, outreach material, a video describing the project, related links, and other information.

Ecology initiated the South Puget Sound Dissolved Oxygen Study with a mass mailing and public meeting in November, 2006. Ecology formed an advisory committee that met on an as-needed basis eight times since 2006. Advisory committee attendance changed over time. The following organizations were included on the advisory committee:

Name	Organization
Dave Adams	Citizens for a Healthy Bay
John Bolender	Mason Conservation District
Seth Book	Mason County Department of Health Services
Kevin Buckley	Snoqualmie Tribe
Roma Call	Puget Sound Partnership
Ben Cope	EPA Region 10
Joe Gibbens	Fort Lewis Public Works
Bill Dewey	Taylor Shellfish Co.
Larry Ekstrom	Pierce County Public Works and Utilities
John Eliasson	Washington State Dept. of Health
Duane Fagergren	Puget Sound Partnership
Bill Fox	Cosmopolitan Engineering Group
Cheryl Greengrove	University of Washington – Tacoma
Keith Grellner	Kitsap
Mitsuhiro Kawase	University of Washington
Bill Kingman	City of DuPont
Andrew Kolosseus	Department of Ecology
John Konovsky	Squaxin Island Tribe / NWIFC
Dave Lenning	Washington State Dept. of Health
Lincoln Loehr	Stoel Rives
Tom Moore	Mason County Department of Utilities and Waste Management
Bruce Nairn	King County WTD
Greg Narum	Simpson Tacoma Kraft
Anthony Paulson	U.S. Geological Survey
Dave Ragsdale	EPA Region 10
Debbie Riley	Mason County Environmental Health
Wayne Robinson	LOTT Alliance
Lynn Schneider	WA State Dept of Health
Dan Thompson	Tacoma Wastewater Treatment Plant
Dave Peeler	People for Puget Sound
Bruce Wishart	People for Puget Sound
Dan Wrye	Pierce County Public Works and Utilities
Tyle Zuchowski	LOTT Alliance
Char Naylor	Puyallup Tribe
Dave Clark	HDR

Ecology also conducted outreach directly with WWTPs that are in the study area:

Name	*Organization*
Steve Pyke	Bainbridge Island WWTP
Mark Petrie	Boston Harbor and Tamoshan STPs
Pat Coxon	Bremerton STP
Lee Schumacher	Carlyon Beach
Kirk Zempel	City of Tacoma
Nate Barto	Fort Lewis Public Works
Phil Crawford	Fort Lewis Public Works
Darrell Winans	Gig Harbor STP
Rick Butler	King County - South Plant
Teresa Schoonejans	King County - South Plant
Betsy Cooper	King County WTD
Eugene Sugita	King County WTD - West Point WWTP
Rick Hammond	King County WTD - West Point WWTP
Bob Thurston	Kitsap Co Sewer Dist 7
John Gardner	Kitsap County (Central Kitsap, Manchester, etc)
Stella Vakarcs	Kitsap County (Central Kitsap, Manchester, etc)
Chris McCalib	Lakota and Redondo WWTPs
Tyle Zuchowski	LOTT Alliance
Wayne Robinson	LOTT Alliance
Tom Moore	Mason Co. Dept. of Utilities and Waste Management
Charri Garber	McNeil Island Correction Center WWTP
Jeff Griffith	Midway Sewer District
Tim Berge	Miller Creek WWTP
Larry Ekstrom	Pierce County Public Works and Utilities
John Poppe	Port Orchard STP
Larry Curles	Port Orchard STP
Mark Dorsey	Port Orchard STP
Randy Screws	Port Orchard STP
Char Naylor	Puyallup Tribe
Don Lange	Puyallup WWTP
Terry Hoefle	Salmon Creek WWTP
Rob Koden	SEASHORE VILLA STP
John Ozga	Shelton STP
Dan Thompson	Tacoma Wastewater Treatment Plant
Greg Burnham	Vashon WWTP

Ecology also held separate informational meetings with the following organizations on the South Puget Sound Dissolved Oxygen Study:

Ecology held informational meetings with the following organizations on the South Puget Sound Dissolved Oxygen Study:

- Nisqually River Council
- Chambers-Clover Watershed Group
- Puyallup River Watershed Council
- South Sound Core Group
- Nisqually/Henderson Shellfish Protection Districts
- Capitol Lake Adaptive Management Plan
- Citizens for a Healthy Bay
- Port of Olympia
- Port of Tacoma
- Northwest Indian Fisheries Commission
- EPA
- Water Quality Partnership
- West Sound Stormwater
- Coalition for Clean Water
- WWTP Operators Group
- Washington Operator Workshop for Wastewater Operators
- Chambers Creek WWTP
- Tacoma Central and North WWTP
- Fort Lewis WWTP
- Midway and McNeil Island WWTPs
- Gig Harbor WWTP
- LOTT WWTP
- Puyallup WWTP
- Shelton WWTP
- Boston Harbor, Carlyon Beach, Harstene Pointe, Rustlewood, Seashore Villa, and Tamoshan WWTPs

Ecology posts all information relevant to the South Puget Sound Dissolved Oxygen Study on the website www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html. The website includes reports, advisory committee information, outreach material, related links, and other information.

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Appendices

Appendix A. Category 5 Listings of Marine Dissolved Oxygen in South and Central Puget Sound (303(d) list)

Table A - 1. 303(d) listings for dissolved oxygen (DO) in South and Central Puget Sound

Listing Number	Name
South Puget Sound (south and west of Tacoma Narrows)	
3770	Squaxin, Peale, and Pickering Passages
5852	Budd Inlet (Inner)
5853	
5863	
5864	
3769	Budd Inlet (Outer)
5862	
7582	
7583	
7584	
7585	
7586	
7587	
10188	
66263	Little Skookum Inlet
10241	Henderson Bay
43004	
10192	Henderson Inlet
66164	
10233	Case Inlet and Dana Passage
10244	
42985	
42986	
42987	
42988	
42989	
42990	
43020	
43022	
66082	
66084	
66085	
66086	
66088	

Listing Number	Name
South Puget Sound (south and west of Tacoma Narrows)	
10222	Balch and Cormorant Passages
42998	
43006	
10229	Carr Inlet
42999	
43000	
43001	
43002	
43003	
66075	
42993	Nisqually Reach/Drayton Passage
42994	
42995	
66307	
66309	
66312	
66318	
43007	Tacoma Narrows
43008	
Central Puget Sound (north and east of Tacoma Narrows and south of Edmonds)	
10175	Commencement Bay (Outer)
43009	Colvos Passage
66090	
10178	Quartermaster Harbor
12702	Duwamish Waterway
12703	
38840	Puget Sound (S-Central) and East Passage
38939	
52995	
52996	
52997	
52998	

Listing Number	Name
Central Puget Sound (north and east of Tacoma Narrows and south of Edmonds)	
38463	Port Orchard, Agate Passage, and Rich Passage
38547	
38847	
52999	
53000	
53002	
10268	Liberty Bay
23537	
23540	
23541	
38682	
38710	Port Madison
38714	

Appendix B. Model Grid Layer Elevations

Table B – 1 shows the maximum number of layers and their elevations used in the South and Central Puget Sound model. The layers in the upper water column are shallow and gradually become deeper with depth. The surface or top layer in any given grid cell is named “KT” while the bottom layer is labeled “KB”. Any intermediate layer is labeled K2 through Kx until it reached KB. For example, for a water column that is 5 layers deep and the water surface starts in layer 2

Surface layer, or KT = K2
Bottom layer, or KB = K5
Intermediate layers are
K3 and K4

Table B - 1. Grid layers and their elevations (NAVD88)

Layer number	Layer thickness, m	Layer_elevation (m) NAVD88	
		Top of layer	Bottom of layer
1	4	10	6
2	4	6	2
3	4	2	-2
4	4	-2	-6
5	4.1	-6	-10.1
6	4.1	-10.1	-14.2
7	5.8	-14.2	-20
8	8	-20	-28
9	12	-28	-40
10	16	-40	-56
11	20	-56	-76
12	24	-76	-100
13	28	-100	-128
14	29	-128	-157
15	29	-157	-186
16	29	-186	-215
17	29	-215	-244

Appendix C. Water Quality Calibration Approach: Using Weighted Average Root Mean Square Errors

Two approaches were used in the calibration process:

Approach 1. Station average RMSE: Root mean square errors (RMSE) were first estimated for each variable for each station over the simulation period. These were then divided by normalization factors (Table C-1) which are the average concentrations of all field data for each variable. The normalized RMSE is unitless for each variable. The average of the normalized RMSE for each variable at all stations gives the aggregate station average for each variable. The aggregate station average was then multiplied by its associated weighting factor (Table C-1). This product for each variable was summed and divided by the sum of the weighting factors to give the station average fitness score for each model run. In other words the fitness score is a single number that gives an indication of how well the model predictions matched observed data across all variables and all stations.

The weighting factors give importance to each variable as the overall fitness score was being estimated. For example, the weighting factor for DO (in deep layers) was 20 and that of CBOD was 1 indicating that DO was 20 times more important for calibration compared with CBOD.

Approach 2. Station depth-average RMSE: This is the same as Approach 1 except the RMSE for each variable and the overall fitness score were based on all data.

Table C-2 shows both the station average and station depth-average RMSE as per the two approaches discussed above for individual runs (using the assigned weighting factors for each variable) as well as for individual variables (using the normalization factors only).

Table C-1. Normalization and weighting factors for RMSE during calibration process.

Notes for normalization and weighting factors

Variable	Normalization Factor (1)	Assigned Weight (2)
DO Deep (> 30 m or half water column; whichever deeper) (mg/l)	7.6967	20
DO (all depths) (mg/l)	8.2614	10
DIN (mgN/L)	0.2729	10
Chloropyhyll (surface layer) (ugA/L)	9.8277	10
Chlorophyll (all depths) (ugA/L)	8.0315	5
ON (mgN/L)	0.18258	2
POC (mgC/L)	0.28472	2
CBOD (mg/L)	1.9645	1
Temperature (C)	11.1256	0
Salinity (ppt)	29.1907	0

1)To convert normalized RMSE to engineering units, multiply by normalization factor
2) Weighted-average RMSEs were calculated by summing across products of all variable RMSEs and weighting factors divided by the sum of the weighting factors

Table C-2. Sample table used in evaluating each model run for a given batch of runs based on station average RMSE or station depth-average RMSE.

Station	Station average	Station-depth average	Aggregated station average for each variable								Aggregated station-depth average for each variable							
Variable	Wtd-avg RMSE	Wtd-avg RMSE	DO (deep)	DO (all)	DIN	Tot Chla (surf)	Tot Chla (all)	ON	POC	CBOD	DO (deep)	DO (all)	DIN	Tot Chla (surf)	Tot Chla (all)	ON	POC	CBOD
base18d_XPI13_subset_rmse	0.45	0.44	0.15	0.15	0.26	0.87	0.98	0.64	2.16	0.48	0.13	0.13	0.27	1.00	0.95	0.60	1.69	0.44
base18d_XPI15_subset_rmse	0.45	0.44	0.15	0.15	0.27	0.86	0.97	0.65	2.26	0.49	0.13	0.13	0.27	0.98	0.93	0.60	1.76	0.44
base18b_XPJ15_subset_rmse	0.45	0.44	0.14	0.15	0.27	0.87	0.98	0.66	2.37	0.46	0.13	0.13	0.27	0.99	0.94	0.60	1.86	0.42
base18d_XPI16_subset_rmse	0.45	0.44	0.15	0.15	0.27	0.86	0.98	0.66	2.33	0.49	0.13	0.13	0.27	0.98	0.93	0.60	1.79	0.44
base18b_XPJ11_subset_rmse	0.45	0.44	0.15	0.15	0.27	0.88	0.99	0.64	2.31	0.46	0.13	0.13	0.27	0.99	0.94	0.60	1.83	0.42
base18a_XPJ17_subset_rmse	0.46	0.44	0.15	0.15	0.24	0.83	0.98	0.63	2.70	0.51	0.13	0.13	0.24	0.98	0.92	0.55	2.07	0.44
base18d_XPI09_subset_rmse	0.46	0.44	0.15	0.15	0.27	0.88	0.98	0.65	2.28	0.49	0.13	0.13	0.27	0.99	0.94	0.60	1.79	0.44
base18c_XPB02_subset_rmse	0.46	0.45	0.16	0.16	0.24	0.85	0.98	0.62	2.53	0.55	0.14	0.13	0.24	1.01	0.95	0.55	1.93	0.47
base18b_XPJ09_subset_rmse	0.46	0.44	0.14	0.15	0.27	0.89	0.99	0.66	2.38	0.46	0.13	0.13	0.27	1.00	0.94	0.60	1.90	0.42
base18d_XPI11_subset_rmse	0.46	0.44	0.16	0.16	0.27	0.88	0.99	0.63	2.22	0.50	0.13	0.13	0.27	1.00	0.95	0.60	1.76	0.45
base18b_XPJ16_subset_rmse	0.46	0.45	0.14	0.15	0.27	0.88	0.99	0.67	2.46	0.47	0.12	0.13	0.27	1.00	0.94	0.60	1.93	0.42
base18c_XPB06_subset_rmse	0.46	0.45	0.17	0.16	0.23	0.86	0.98	0.61	2.51	0.55	0.14	0.13	0.24	1.03	0.97	0.55	1.90	0.48
base18b_XPJ07_subset_rmse	0.46	0.45	0.15	0.15	0.28	0.90	0.99	0.66	2.42	0.47	0.13	0.13	0.27	1.00	0.94	0.60	1.93	0.42
base18a_XPC09_subset_rmse	0.46	0.45	0.15	0.15	0.24	0.87	0.99	0.63	2.68	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.07	0.46
base18c_XPB11_subset_rmse	0.46	0.45	0.16	0.16	0.24	0.85	0.97	0.63	2.67	0.57	0.14	0.13	0.24	1.00	0.94	0.55	2.04	0.48
base18c_XPB13_subset_rmse	0.46	0.45	0.17	0.16	0.24	0.84	0.96	0.63	2.70	0.58	0.14	0.13	0.24	1.00	0.94	0.55	2.07	0.48
base18a_XPC13_subset_rmse	0.46	0.45	0.15	0.15	0.25	0.86	0.98	0.63	2.79	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.14	0.46
base18a_XPC11_subset_rmse	0.46	0.45	0.15	0.15	0.25	0.87	0.98	0.64	2.77	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.14	0.45
base18d_XPI08_subset_rmse	0.47	0.44	0.16	0.16	0.28	0.90	1.00	0.65	2.34	0.50	0.13	0.13	0.27	0.99	0.94	0.60	1.86	0.44
base18c_XPJ19_subset_rmse	0.47	0.44	0.17	0.17	0.24	0.84	0.98	0.62	2.67	0.57	0.14	0.13	0.24	0.99	0.94	0.55	2.04	0.47
base18b_XPJ03_subset_rmse	0.47	0.45	0.15	0.15	0.28	0.90	1.00	0.66	2.48	0.48	0.13	0.13	0.31	1.00	0.94	0.60	2.00	0.43
base18a_XPC04_subset_rmse	0.47	0.45	0.15	0.15	0.25	0.88	0.99	0.63	2.79	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.14	0.46
base18a_XPC01_subset_rmse	0.47	0.45	0.15	0.15	0.25	0.88	0.99	0.63	2.79	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.14	0.46
base18a_XPI17_subset_rmse	0.47	0.45	0.15	0.15	0.25	0.88	0.99	0.63	2.79	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.14	0.46
base18a_XPI18_subset_rmse	0.47	0.45	0.15	0.15	0.25	0.88	0.99	0.63	2.79	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.14	0.46
base18a_XPC12_subset_rmse	0.47	0.45	0.15	0.15	0.25	0.88	1.00	0.64	2.77	0.52	0.13	0.13	0.24	1.02	0.95	0.55	2.14	0.45
base18a_XPC05_subset_rmse	0.47	0.45	0.16	0.15	0.25	0.88	0.99	0.63	2.79	0.53	0.13	0.13	0.24	1.01	0.94	0.55	2.14	0.46
base18c_XPB09_subset_rmse	0.47	0.46	0.17	0.17	0.24	0.87	1.00	0.61	2.62	0.57	0.14	0.14	0.24	1.03	0.97	0.55	2.00	0.49
base18c_XPB04_subset_rmse	0.48	0.45	0.17	0.17	0.25	0.87	0.99	0.62	2.73	0.58	0.14	0.14	0.24	1.01	0.95	0.55	2.11	0.48
base18c_XPB01_subset_rmse	0.48	0.45	0.17	0.17	0.25	0.87	0.99	0.63	2.73	0.58	0.14	0.14	0.24	1.01	0.95	0.55	2.11	0.48
base18b_XPJ08_subset_rmse	0.48	0.46	0.15	0.15	0.29	0.93	1.01	0.67	2.56	0.49	0.13	0.13	0.31	1.02	0.95	0.60	2.07	0.42
base18c_XPB05_subset_rmse	0.48	0.45	0.17	0.17	0.25	0.87	0.99	0.63	2.73	0.58	0.14	0.14	0.24	1.01	0.95	0.55	2.11	0.48
base18c_XPB12_subset_rmse	0.48	0.46	0.17	0.17	0.25	0.89	1.00	0.63	2.70	0.57	0.14	0.14	0.24	1.02	0.96	0.55	2.07	0.48
base18a_XPC10_subset_rmse	0.48	0.45	0.16	0.16	0.25	0.90	1.01	0.62	2.83	0.54	0.13	0.13	0.24	1.02	0.95	0.55	2.18	0.46
base18a_XPC14_subset_rmse	0.48	0.46	0.15	0.15	0.26	0.89	1.01	0.64	2.90	0.54	0.13	0.13	0.27	1.03	0.95	0.55	2.25	0.46
base18c_XPB14_subset_rmse	0.48	0.45	0.17	0.17	0.25	0.88	1.00	0.64	2.82	0.58	0.14	0.14	0.24	1.01	0.95	0.55	2.14	0.48
base18a_XPC08_subset_rmse	0.48	0.46	0.15	0.15	0.26	0.90	1.01	0.64	2.92	0.55	0.13	0.13	0.27	1.02	0.95	0.55	2.28	0.46
base18c_XPB08_subset_rmse	0.49	0.46	0.17	0.17	0.26	0.89	1.00	0.63	2.85	0.59	0.14	0.14	0.27	1.00	0.94	0.55	2.21	0.48
base18b_XPJ04_subset_rmse	0.49	0.46	0.15	0.16	0.30	0.93	1.02	0.67	2.65	0.51	0.13	0.13	0.31	1.02	0.95	0.60	2.14	0.44
base18c_XPI01_subset_rmse	0.49	0.46	0.17	0.17	0.26	0.88	1.01	0.64	2.93	0.59	0.14	0.14	0.27	1.01	0.95	0.60	2.21	0.49
base18a_XPC06_subset_rmse	0.49	0.47	0.16	0.16	0.26	0.92	1.02	0.64	2.97	0.56	0.13	0.13	0.27	1.03	0.96	0.55	2.32	0.46
base18c_XPB10_subset_rmse	0.49	0.46	0.18	0.18	0.26	0.90	1.02	0.62	2.79	0.59	0.14	0.14	0.24	1.03	0.96	0.55	2.14	0.49
base18a_XPJ01_subset_rmse	0.49	0.47	0.15	0.15	0.26	0.92	1.04	0.66	3.03	0.56	0.13	0.13	0.27	1.05	0.97	0.60	2.32	0.47
base18c_XPB07_subset_rmse	0.50	0.47	0.18	0.17	0.26	0.92	1.03	0.63	2.94	0.61	0.14	0.14	0.27	1.02	0.95	0.60	2.28	0.49
base18a_XPC02_subset_rmse	0.50	0.47	0.16	0.16	0.27	0.93	1.03	0.64	3.08	0.58	0.14	0.14	0.27	1.04	0.96	0.55	2.42	0.48
base18a_XPC07_subset_rmse	0.51	0.48	0.16	0.16	0.27	0.96	1.05	0.65	3.14	0.59	0.13	0.14	0.27	1.06	0.98	0.60	2.49	0.48
base18a_XPC03_subset_rmse	0.53	0.49	0.17	0.17	0.28	0.98	1.08	0.65	3.32	0.63	0.14	0.14	0.27	1.07	0.99	0.60	2.63	0.50

Conditional Formatting Notes:

RMSE statistics colored SEPARATELY for each column: Green --> Red (Min == Green, 50% == Yellow, Max == Red)

RMSE statistics sorted based on station averaged/weighted statistic (Column B)

Base case highlighted for reference

Appendix D. Kinetic Rates and Constants used in GEMSS

Table D - 1. Kinetic rates and constants for water quality carbon based model (WQCBM).

Parameter	Unit	General	Shallow Inlets
Ke_a, Background non-algal light extinction	0 : 1/m	0.336	
Ke_b, Coefficient for chlorophyll for light extinction	0 : 1/m/(ugA/L)^Ke_c)	0.0365	
Ke_c, Exponent for chlorophyll for light extinction	0 : No Units	0.64	
NH3 (Ammonia),			
anc, Nitrogen to carbon ratio	0 : g N/g C	0.1	
k71, Organic nitrogen mineralization rate	0 : 1/day	0.1	
th71, Temperature coefficient	No Units	1.07	
k12, Nitrification rate	0 : 1/day	0.07	
th12, Temperature coefficient	No Units	1.08	
knit, Half saturation constant for oxygen limitation of nitrification	0 : g O2/m^3	1	
kmnc, Half saturation constant for nitrogen mineralization	0 : g C/m^3	0.09	
NO3 (Nitrate),			
k2d, Denitrification rate @ 20 °C	0 : 1/day	0.15	
th2d, Temperature coefficient	No Units	1.05	
kno3, Michaelis constant for denitrification	0 : g O2/m^3	0.5	
PO4, Inorganic Phosphorous			
apc, Phosphorus to carbon ratio	0 : g P/g C	0.001	
k83, Dissolved organic phosphorus mineralization @ 20 °C	0 : 1/day	0.2	
th83, Temperature coefficient	No Units	1.07	
kmpc, Half saturation constant for phosphorus mineralization	0 : g C/m^3	0.05	
plc, Phosphorus limiting switch	No Units	0	
DO (Dissolved Oxygen),			
SDOEMethod (Surface DO reaeration formulation),	View Equation	1 : Wanninkohf 1991	
kdf, deoxygenation rate @ 20°C for fast CBOD	0 : 1/day	0.2	
kds, deoxygenation rate @ 20°C for slow CBOD	0 : 1/day	0.02	
ReaerationFactor (Factor to increase the reaeration rate),	No Units	1	
Thtk2, Temperature correction for reaeration	No Units	1.024	
CBOD_F (Fast Reacting Dissolved Carbonaceous BOD),			
aoc, Oxygen to carbon ratio	0 : g O2/g C	2.67	
thd, Temperature coefficient	No Units	1.06	
kbod, Half saturation constant for oxygen limitation	0 : g O2/m^3	0.5	
foc, Oxygen from dead algae	No Units	0.5	0.25
r_CBODP, Stoichiometric equivalent between CBOD and phosphorous	No Units	0.004	
r_CBODN, Stoichiometric equivalent between CBOD and nitrogen	No Units	0.006	
r_CBODC, Stoichiometric equivalent between CBOD and carbon	No Units	0.32	

Table D - 2. Kinetic rates and constants for water quality carbon based model (WQCBM) (continued).

Parameter	Unit	General	Shallow Inlets
CBOD_S (Slow Reacting Dissolved Carbonaceous BOD),			
fd5, Fraction of dead phytoplankton recycled to fast reacting CBOD	No Units	0.75	1
ON_D and ON_P (Dissolved and Particulate Organic Nitrogen),			
kh7p, Hydrolysis rate for particulate organic nitrogen	0 : 1/day	0.086	
thh7p, Temperature coefficient	No Units	1.047	
fon, Organic nitrogen from dead algae	No Units	0.5	
vs7, Organic matter settling velocity	5 : m/day	0.2	
ancp, Particulate organic nitrogen to carbon ratio	No Units	0.25	
OP_D and OP_P (Dissolved and Particulate Organic Phosphorus),			
kh8p, Hydrolysis rate for particulate organic phosphorus	0 : 1/day	0.086	
thh8p, Temperature coefficient	No Units	1.047	
fop, Organic phosphorus from dead algae; Fraction to dissolved component	No Units	0.5	
vs8, Organic matter settling velocity	5 : m/day	0.2	
apcp, Particulate organic phosphorus to carbon ratio	No Units	0.75	
OC_P_F (Fast Reacting Particulate Organic Carbon),			
fd9f, Fraction of dead phytoplankton to recycled to fast reacting particulate organic carbon	No Units	0.4	1
fg9f, Fraction of micro-Grazing to fast reacting particulate organic carbon	No Units	0.4	0.5
kpd9f, Hydrolysis rate for fast reacting particulate organic carbon	0 : 1/day	0.08	
thpd9p, Temperature coefficient for the hydrolysis rate	No Units	1.04	
vs9, Settling velocity of particulate organic carbon	5 : m/day	0.2	
OC_P_S (Slow Reacting Particulate Organic Carbon),			
fd9s, fraction of dead phytoplankton to recycled to slow reacting particulate organic carbon	No Units	0.4	0
fg9s, fraction of micro-grazing to slow reacting particulate organic carbon	No Units	0.4	0.5
kpd9s, Hydrolysis rate for slow reacting particulate organic carbon	0 : 1/day	0.02	
thpd9s, Temperature coefficient for the hydrolysis rate	No Units	1.04	
OC_P_R (Refractory Particulate Organic Carbon),			
fd9r, fraction of dead phytoplankton to recycled to refractory particulate organic carbon	No Units	0.2	0
fg9r, fraction of micro-grazing to refractory particulate organic carbon	No Units	0.2	0

Table D - 3. Kinetic rates and constants for general algae module (GAM).

Parameter	Unit	GAM1			GAM2		
		General	Inner Shallow Inlets	Outer Shallow Inlets	General	Inner Shallow Inlets	Outer Shallow Inlets
Use nutrient limit function in growth computations	No Units	1			1		
Use temperature limit function in growth computations	No Units	1			1		
Use saline toxicity limit function in growth computations	No Units	0			0		
Use light limit function in growth computations	No Units	1			1		
k1r, Respiration rate @t 20 °C	0 : 1/day	0.07	0.08	0.08	0.07		
Tht_k1r, Temperature Coefficient	No Units	1.05			1.05		
k1c, Growth rate @ 20 °C	0 : 1/day	2.3			2.5	1.5	2.3
Tht_k1c, Temperature Coefficient	No Units	1			1		
k1d, Death rate @ 20 °C	0 : 1/day	0.03			0.03	0.04	0.04
fe, Excretion fraction	No Units	0.05			0.05	0.08	0.05
as, Assimilaion efficiency of zooplankton grazing	No Units	0.5			0.5		
ws, Settling velocity	5 : m/day	0.4	0.5	0.5	0.2	0	0
ZPGMode, Zooplankton grazing mode	No Units	1 : LinearGrazing			1 : LinearGrazing		
kgmicro, Grazing rate due to micro zooplankton	0 : 1/day	0.11			0.11	0.04	0.11
Tht_kgmicro, Temperature Coefficient	No Units	1.04			1.04		
kgmacro, Grazing rate due to macro zooplankton	0 : 1/day	0.01			0.01		
Tht_kgmacro, Temperature Coefficient	No Units	1.04			1.04		
cchl, Carbon to chlorophyll ratio	0 : gC/gChl-a	60			50		
Light model	No Units	3 : Steele Equation			3 : Steele Equation		
kke, Light extinction coefficient	No Units	1			1		
kechl, Light attenuation coefficient	0 : m^2/mg	17			17		
Isat, Light constant	1 : W/m^2	30	40	40	75	70	70
khn, Constant for algae nitrogen uptake	0 : gm N/m^3	0.024			0.028		
khp, Constant for algae phosphorous uptake	0 : gm P/m^3	0.00001			0.00001		
stMethod, Salinity toxicity method	Equation	1 : Equation_1			1 : Equation_1		
stf, Maximum mortality due to salinity toxicity	0 : 1/day	0.01			0.01		
khst, Salinity at which toxicity is half the maximum value	0 : ppt	0.5			0.5		
tm, Optimum temperature for algae growth	0 : C	10	11	11	16	16.5	16
ktg1, Suboptimal temperature effect for algae growth	No Units	0.024			0.02	0.03	0.02
ktg2, Superoptimal temperature effect for algae growth	No Units	0.024			0.02	0.03	0.02
fd5, Fraction of dead phytoplankton recycled to fast CBOD	No Units	0.75			0.75		
fon, Organic nitrogen from dead algae	No Units	0.5			0.5		
fop, Organic phosphorous from dead algae	No Units	0.5			0.5		
foc, Organic carbon from dead algae	No Units	0.5			0.5		

Appendix E. Procedure for Calculating Open Boundary Water Quality Scalars at Edmonds under Natural Conditions

Water quality scalars at the Edmonds open boundary under natural conditions were obtained from a model of the Salish Sea (Khangaonkar et al. 2012). Figure E-1 shows the extent of the Salish Sea model including location of Edmonds, the open boundary for the South and Central Puget Sound (SCPS) Model. The zoom-in view at Edmonds shows that the Salish Sea grid cells (elements) are not aligned to the Edmonds open boundary of the SCPS model. Projected flows were estimated for each element in the seaward direction. At each element layer the long term seaward residual flow (April_Sept) was calculated.

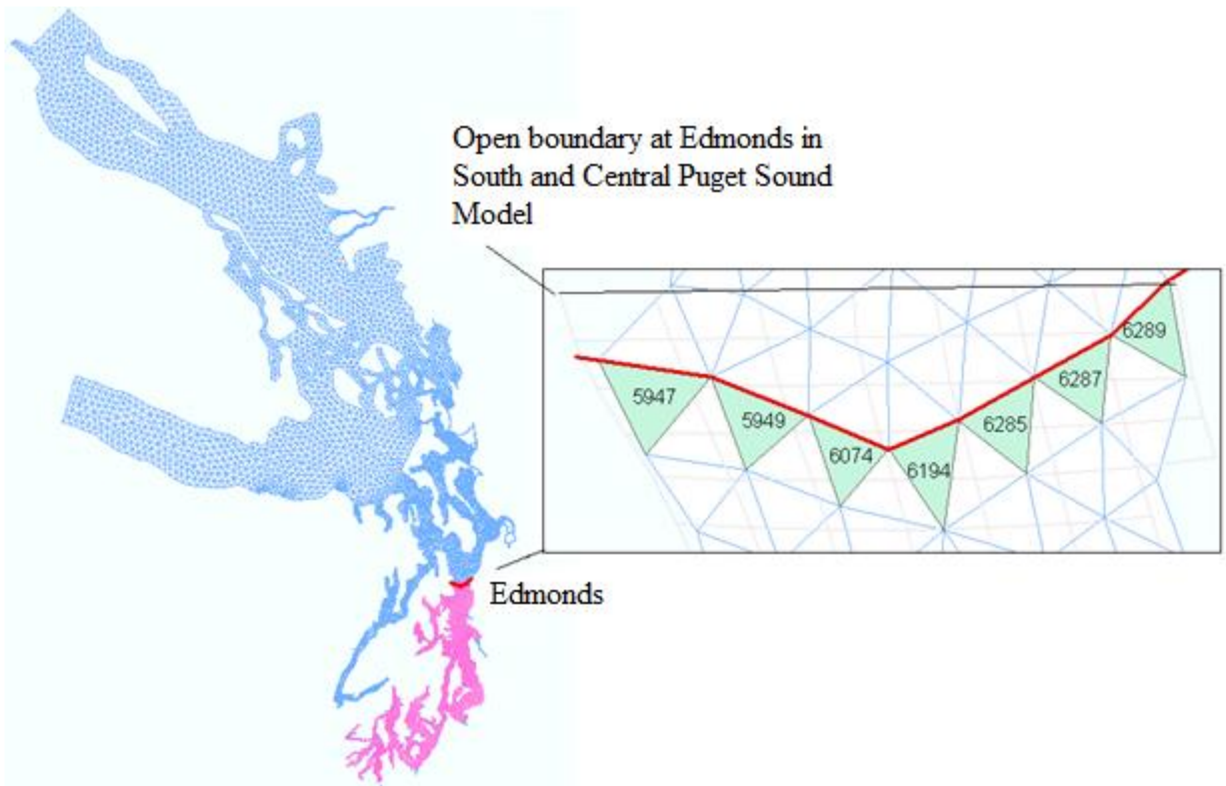

Figure E-1. Salish Sea model grid domain showing location of Edmonds open boundary for the South and Central Puget Sound model.

For each element layer and for each time-step, water quality concentrations were summed for each variable, if the seaward residual flow was negative (i.e. incoming) and seaward flow in each time step was negative. The sum was then divided by the number of data to obtain the arithmetic mean. This was done for both natural and current conditions.

The ratio of concentrations of each water quality variable between natural and current conditions was the scalar for that variable. Since no changes were made to salinity or temperature between current and natural conditions, the scalar for these two variables was equal to one. The Salish Sea model did not provide any output of dissolved and particulate organic phosphorus and given that the system is not phosphorus limited, the scalar for these two variables were assumed to be one also. Both CBOD_fast and slow variables used in GEMSS were assumed to have the same scalar as dissolved organic carbon (DOC). Fast and slow particulate organic carbon (OC_P_F and OC_P_S) in GEMSS were assumed to have the same scaling factor as labile particulate organic carbon (LPOC) in the Salish Sea model.

Table E - 1. Open Boundary Scalars for South and Central Puget Sound model at Edmonds.

water quality varaiables in Salish Sea model	Average when seaward flow is negative and residual flow is negative, Sed_Scalr = 0.89		Open boundary scalar for natural conditions
	Run#23, natural	Run#20 existing	incoming water
DO (mg/l)	6.1827	6.1613	1.0035
OC_D (mg/l)	0.6884	0.7010	0.9821
GAM1 C (mg/l)	0.0259	0.0267	0.9676
GAM2 C (mg/l)	0.0250	0.0264	0.9476
NH4N (mg/l)	0.0150	0.0175	0.8557
NO23N (mg/l)	0.3163	0.3382	0.9353
PO4P (mg/l)	0.0594	0.0617	0.9625
RDOC (mg/l)	0.1312	0.1403	0.9348
LPOC (mg/l)	0.1580	0.1651	0.9568
RPOC (mg/l)	0.0754	0.0842	0.8952
LDON (mg/l)	0.0262	0.0291	0.9028
RDON (mg/l)	0.0088	0.0093	0.9455
LPON (mg/l)	0.0122	0.0134	0.9085
RPON (mg/l)	0.0105	0.0114	0.9245
DON=LDON+RDON (mg/l)	0.0350	0.0383	0.9132
PON=LPON+RPON (mg/l)	0.0227	0.0248	0.9158

variables used in GEMSS	
ID	Scaling Factor
Temp	1
Saln	1
DO	1.0035
CBOD_F	0.9821
CBOD_S	0.9821
GAM1	0.9676
GAM2	0.9476
NH3	0.8557
NO3	0.9353
PO4	0.9625
ON_D	0.9132
OP_D	1
ON_P	0.9158
OC_P_F	0.9568
OC_P_S	0.9568
OC_P_R	0.8952
OP_P	1

DO = dissolved Oxygen
OC_D = dissolved Organic Carbon
GAM1 C = algae 1 carbon
GAM2 C = algae 2 carbon
NH4N, NH3 = ammonia nitrogen
NO23N, NO3 = nitrate/nitrite nitrogen
PO4P, PO4 = phosphate phosphorus
RDOC = refractory dissolved organic carbon
LPOC = labile particulate organic carbon
RPOC = refractory particulate organic carbon
LDON = labile dissolved organic nitrogen
RDON = refractory dissolved organic nitrogen
LPON = labile particulate organic nitrogen
RPON = refractory particulate rganic nitrogen

Temp = temperature
Saln = salinity
CBOD_F = fast carbonaceous biochemical oxygen demand = assumed to have same scalar as OC_D
CBOD_S= slow carbonaceous biochemical oxygen demand= assumed to have same scalar as OC_D
GAM1 = algae 1
GAM2 = algae 2
ON_D = dissolved organic nitrogen = LDON + RDON
OP_D = dissolved organic phosphorus
ON_P = particulate organic nitrogen = LPON + RPON
OC_P_F = fast particulate organic carbon = assumed to have same sacalar as LPOC
OC_P_S = slow particulate organic carbon= assumed to have same sacalar as LPOC
OC_P_R = refractory particulate organic carbon = RPOC
OP_P = particulate organic phosphorus

Appendix F. Procedure for Calculating Sediment Flux Scalar under Natural Condition

Figure F-1 shows the sediment scalar used for each model run under natural conditions and the domain-wide particulate nitrogen flux at the bottom layer for each run. The nitrogen flux in g/m2/d was obtained through summing the product of each particulate nitrogen type (organic nitrogen and nitrogen equivalent of all the algal groups) and their settling velocities. Care was taken to account for different settling velocities of algal groups in different regions of the model domain. The domain wide nitrogen flux in Kg/d was obtained by first multiplying nitrogen flux (in g/m2/d) with the respective cell area and then summing up all the fluxes and finally applying a unit conversion.

The imbedded table in Figure F-1 also includes the particulate nitrogen flux for current conditions. The ratio of particulate nitrogen flux under natural condition to that under current conditions gives the predicted sediment scalar for the model run. The difference between the scalar assumed and predicted is then plotted against scalar used. The scalar for which the difference is zero is then extracted from the plot as 0.886 and re-used in a final natural condition run to confirm if the difference between assumed and predicted scalar was zero based on particulate nitrogen fluxes.

Run	Scalar Used	partiulate N flux Kg/d	benthic scalar particulate flux basis	
			predicted	delta
Existing	1	21662	1.00	0
Natural	0.5	17245	0.796	-0.296
Natural	0.85	19025	0.878	-0.028
Natural	0.9	19275	0.890	0.010
Natural	1	19769	0.913	0.087
Natural	0.886	19204.95	0.886594	-0.00059

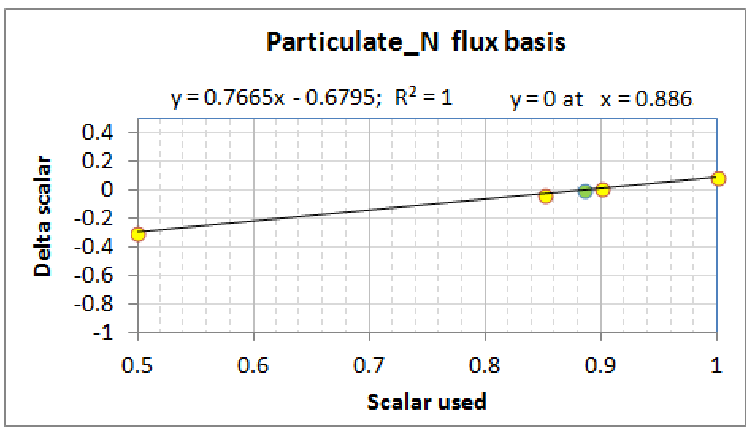

Figure F-1. Sediment scalar under natural conditions based on particulate nitrogen flux

The procedure above was confirmed using incoming total nitrogen load instead of the particulate nitrogen flux. The final scalar was similar as shown below in Figure F-2. The incoming total nitrogen load was estimated for cells across a transact that was five cells south of Edmonds (Figure F-3). This reduced the effects of open boundary where concentrations of nitrogen type leaving the domain were predicted by the model but the incoming was defined by the boundary condition.

For each cell layer the negative residual flow (i.e. landward) between Apr-Sept was estimated based on model predicted velocities, seaward cell cross sectional area, and cell angles and orientations. The final landward flow would be the sum of all the negative seaward flows in all the cell layers across transact. The residual flows would then be multiplied by the mean total nitrogen concentrations obtained when the seaward residual flow for a given cell layer was negative and the time-step seaward flow was also negative. The product of the negative seaward residual flows and the mean total nitrogen concentration of the incoming flow would give the incoming load for total nitrogen. Total nitrogen was defined as the sum of concentrations of ammonia (NH3), nitrate (NO3), dissolved organic nitrogen (DON), particulate organic nitrogen (PON), and nitrogen associated with all algal groups.

Run	Scalar Used	Open BC Import (kg/d)	Atmospheric load, Kg/d	River Load, Kg/d	WWTP load, Kg/d	Total Incoming, Kg/d	benthic scalar incoming TN basis	
							predicted	delta
Existing	1	642017	358	5324	27990	675689	1	0
Natural	0.5	594748	358	3825	204	599135	0.887	-0.387
Natural	0.85	594340	358	3825	204	598727	0.886	-0.036
Natural	0.9	594294	358	3825	204	598681	0.886	0.014
Natural	1	594202	358	3825	204	598589	0.886	0.114

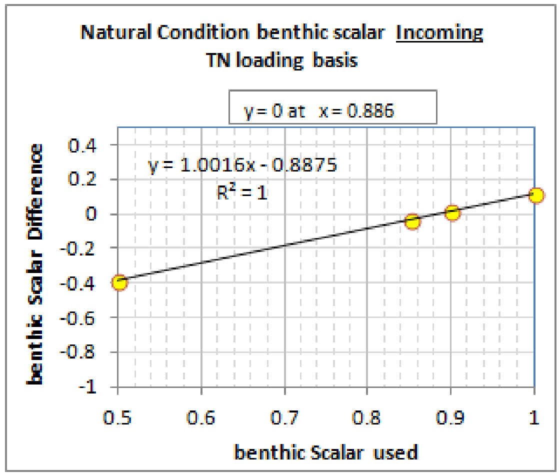

Figure F-2. Sediment scalar under natural conditions based on incoming total nitrogen load.

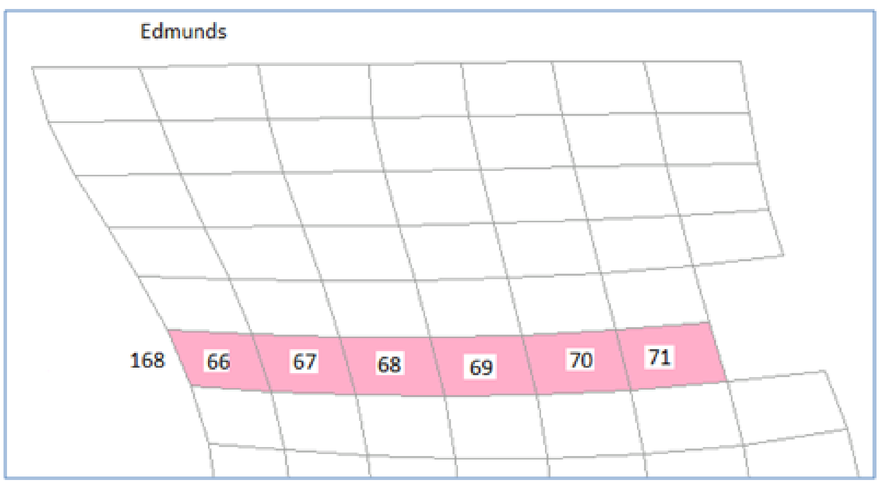

Figure F-3. Grid cells south of Edmonds where incoming total nitrogen load was estimated.

Appendix G. Scenario Loading Information and Associated Open Boundary and Sediment Scalars

Table G-1. Scenario loading (kg TN/d) and associated open boundary and sediment scalar Information.

Source	natural/anthropogenic	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6a	Scenario 6b	Scenario 6c	Scenario 7
		natural	current	Watershed Loads Only	Marine Point Source Loads Only	Maximum Permitted Marine Point Source Loads	Reducing Human Loads in South and central Puget Sound by			No Human Sources in Central Puget Sound
							25%	50%	75%	
Atmospheric load	Natural	358	358	358	358	358	358	358	358	358
Point Source Load to Marine Waters	Natural	204	204	204	204	204	204	204	204	204
	Anthropogenic	0	27786	0	27786	41471	20840	13893	6947	3226
Watershed Loads	Natural	3825	3825	3825	3825	3825	3825	3825	3825	3825
	Anthropogenic	0	1499	1499	0	1499	1124	750	375	934
Total Marine Point source and Watershed loads	Natural	4387	4387	4387	4387	4387	4387	4387	4387	4387
	Anthropogenic	0	29285	1499	27786	42970	21964	14643	7321	4159
	Total	4387	33672	5886	32173	47357	26350	19029	11708	8546
External anthropogenic at open boundary	Anthropogenic	0	37461	37461	37461	37461	37461	37461	37461	37461
Internal anthropogenic load refluxed at open boundary (20%)	Anthropogenic	0	5857	300	5557	8594	4393	2929	1464	832
Total load coming in at Edmonds open boundary	Natural	634763	634763	634763	634763	634763	634763	634763	634763	634763
	Anthropogenic	0	43318	37761	43018	46055	41854	40390	38925	38293
	Total	634763	678081	672524	677781	680818	676617	675153	673688	673056
Total Incoming Load for model domain	Natural	639150	639150	639150	639150	639150	639150	639150	639150	639150
	Anthropogenic	0	72603	39260	70804	89025	63818	55032	46247	42452
	Total	639150	711753	678410	709954	728175	702967	694182	685396	681602
Sediment flux scalar		0.886	1	0.948	0.997	1.026	0.986	0.972	0.959	0.953
Open boundary Scalars	Temp	1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Saln	1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	DO	1	1.0035	1.0004	1.0000	0.9998	1.0001	1.0002	1.0004	1.0004
	CBOD_F	1	0.9821	0.9977	0.9999	1.0011	0.9994	0.9988	0.9982	0.9979
	CBOD_S	1	0.9821	0.9977	0.9999	1.0011	0.9994	0.9988	0.9982	0.9979
	GAM1	0.5	0.4838	0.4979	0.4999	0.5010	0.4995	0.4989	0.4984	0.4981
	GAM2	0.5	0.4738	0.4966	0.4998	0.5017	0.4991	0.4982	0.4973	0.4970
	NH3	1	0.8557	0.9815	0.9990	1.0091	0.9951	0.9902	0.9854	0.9833
	NO3	1	0.9353	0.9917	0.9996	1.0041	0.9978	0.9956	0.9934	0.9925
	PO4	1	0.9625	0.9952	0.9997	1.0024	0.9987	0.9975	0.9962	0.9956
	ON_D	1	0.9132	0.9889	0.9994	1.0055	0.9971	0.9941	0.9912	0.9899
	OP_D	1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	ON_P	1	0.9158	0.9892	0.9994	1.0053	0.9972	0.9943	0.9915	0.9902
	OC_P_F	1	0.9568	0.9945	0.9997	1.0027	0.9985	0.9971	0.9956	0.9950
	OC_P_S	1	0.9568	0.9945	0.9997	1.0027	0.9985	0.9971	0.9956	0.9950
	OC_P_R	1	0.8952	0.9866	0.9993	1.0066	0.9965	0.9929	0.9894	0.9878
	OP_P	1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

The sediment scalar for natural condition was obtained from South and central Puget Sound model. The water quality scalars at the open boundary for natural conditions were obtained from the Salish Sea model (Khangaonkar et al., 2012). However, the prorating of scalars were done based on total incoming load for sediment scalars and on total load at open boundary for the water quality scalars.

Appendix H. Glossary, Acronyms, and Abbreviations

Glossary

303(d) List: Section 303(d) of the federal Clean Water Act requires Washington State periodically to 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 water bodies (ocean waters, estuaries, lakes, and streams) that fall short of state surface water quality standards and are not expected to improve within the next two years.

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.

Critical condition: When the physical, chemical, and biological characteristics of the receiving water environment interact with the effluent to produce the greatest potential adverse impact on aquatic biota and existing or designated water uses. For steady-state discharges to riverine systems, the critical condition may be assumed to be equal to the 7Q10 (see definition) flow event unless determined otherwise by the department.

Designated uses: Those uses specified in Chapter 173-201A WAC (Water Quality Standards for Surface Waters of the State of Washington) for each water body or segment, regardless of whether or not the uses are currently attained.

Dilution factor: The relative proportion of effluent to stream (receiving water) flows occurring at the edge of a mixing zone during critical discharge conditions as authorized in accordance with the state's mixing zone regulations at WAC 173-201A-100. http://apps.leg.wa.gov/WAC/default.aspx?cite=173-201A-020

Dissolved Oxygen Standards. These standards include both parts: the numeric dissolved oxygen standard and the human actions dissolved oxygen standard.

Exceeded criteria: Did not meet criteria.

Existing uses: Those uses actually attained in fresh and marine waters on or after November 28, 1975, whether or not they are designated uses. Introduced species that are not native to Washington, and put-and-take fisheries comprised of non-self-replicating introduced native species, do not need to receive full support as an existing use.

Human Actions Dissolved Oxygen Standard: The second part of the dissolved oxygen standard in WAC 173-201A-210(1)(d)(i) that states: When a water body's DO is lower than the criteria in Table 210 (1)(d) (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the DO of that water body to decrease more than 0.2 mg/L.

Human Watershed Sources: The point and nonpoint sources caused by humans (such as all septics, fertilizer use, and stormwater; it also includes the point sources that discharge to rivers).

National Pollutant Discharge Elimination System (NPDES): National program for issuing and revising permits, as well as imposing and enforcing pretreatment requirements, under the Clean Water Act. The NPDES permit 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.

Natural Watershed Sources: The sources not caused by humans (natural sources such as atmospheric deposition). Natural watershed sources are included in every scenario.

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 National Pollutant Discharge Elimination System 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.

Numeric Dissolved Oxygen Criteria: The first part of the dissolved oxygen standards in WAC 173-201A Table 210(1)(d) that are the lowest one-day minimums of 7.0, 6.0, 5.0, or 4.0 mg/L.

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

Plume: Describes the three-dimensional concentration of particles in the water column (example, a cloud of sediment).

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites that clear more than five acres of land.

Point Sources: The subset of municipal WWTPs and industrial facilities that discharge directly to Puget Sound. WWTPs that discharge to rivers are not included in this category.

Pollution: Such 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.

Total maximum daily load (TMDL): A distribution of a substance in a water body designed to protect it from exceeding water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload 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 wasteload determination. A reserve for future growth is also generally provided.

Watershed Sources: The point, nonpoint, and natural sources of nitrogen that reach Puget Sound through rivers, overland flow, or groundwater. Watershed sources were measured at the mouths of the rivers and calculated for the shoreline fringes.

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.

Acronyms and abbreviations

Following are acronyms and abbreviations used frequently in this report.

DO	dissolved oxygen
DIN	dissolved inorganic nitrogen
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
NPDES	National Pollutant Discharge Elimination System
TMDL	total maximum daily load (water cleanup plan)
USGS	United States Geological Survey
WAC	Washington Administrative Code
WRIA	Water Resources Inventory Area
WWTP	wastewater treatment plant

Units of Measurement

cfs	cubic feet per second
kg/d	kilograms per day
km	kilometer, a unit of length equal to 1,000 meters.
mgd	million gallons per day
mg/L	milligrams per liter (parts per million)