South Puget Sound Dissolved Oxygen Study

Interim Data Report

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For more information contact:

Publications Coordinator
Environmental Assessment Program
P.O. Box 47600
Olympia, WA 98504-7600
Phone: 360-407-6764

Washington State Department of Ecology - www.ecy.wa.gov/

o Headquarters, Olympia	360-407-6000
o Northwest Regional Office, Bellevue	425-649-7000
o Southwest Regional Office, Olympia	360-407-6300
o Central Regional Office, Yakima	509-575-2490
o Eastern Regional Office, Spokane	509-329-3400

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South Puget Sound Dissolved Oxygen Study

Interim Data Report

by

Mindy Roberts, Julia Bos, and Skip Albertson

Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

Waterbody Numbers:

WA-13-0010, -0020, -0030
WA-14-0010, -0020, -0050, -0100, -0110

Budd Inlet (outer): 47122B9E1, 47122B9E2, 47122B9A1, 47122B9A0, 47122A8J9, 47122A9I0, and 47122A9I1.
Budd Inlet (inner): 47122A9H1, 47122A9G0, 47122A9G9, 47122A8F9, 47122A9F0, and 47122A9E0.
Carr Inlet: 47122D6D9, 47122D7B0, 47122C7H0, 47122C6F9, 47122C6D5, and 47122C6B2.
Commencement Bay: 47122C4J4.
Sinclair Inlet: 47122F6D8.
Central Puget Sound: 47122H3H9.

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Abstract

The Washington State Department of Ecology began this study to determine how nitrogen from a variety of sources affects dissolved oxygen in South Puget Sound. Portions of South Puget Sound do not meet Washington State water quality standards for dissolved oxygen.

The study includes collecting and analyzing data, developing hydrodynamic and water quality models, and assessing alternative management scenarios. This report summarizes nitrogen (nutrient) and related data collected from July 2006 through October 2007. The data were collected from 90 marine stations within South and Central Puget Sound, 29 wastewater treatment plants (WWTPs) and industrial discharges directly to Puget Sound, and 39 rivers and streams.

Future reports will describe hydrodynamics, water quality model development, and alternative management scenarios. If the results show that human-related sources of nitrogen must be reduced to keep South Sound healthy, the final technical report will identify what reductions are needed.

Of the nutrient loads from the land surface, rivers and WWTPs are significant sources of dissolved inorganic nitrogen (DIN; the sum of ammonium and nitrate + nitrite). Nutrients recycled from sediments are an important influence and during late summer may release loads comparable to those from WWTPs and rivers. Other sources of nitrogen include atmospheric inputs which are small in comparison to watershed sources, and septic systems which are included in the watershed loads within the sites monitored.

Water circulation and velocity patterns are complex. Stratification was most intense in Budd, Carr, and Case Inlets, and Oakland Bay. Low near-bottom dissolved oxygen occurred in many parts of South Sound, including but not limited to Budd, Carr, and Case Inlets. DIN levels varied seasonally and spatially, and also reflected surface oxygen depletion associated with productivity. Chlorophyll levels were highest in shallow inlets as well as in north Pickering Passage and Oakland Bay.

Acknowledgements

The authors of this report would like to thank the following people and organizations for their contributions to this study:

- Evans Hamilton staff (Carol Coomes, Maya Whitmont, Rachel Halfhill) conducted benthic flux studies and meteorological station operations.
- Bob Kruger and King County staff provided *R/V Liberty* field operations and sampling assistance as well as post-field processing of conductivity, temperature, and depth (CTD) data.
- Ray McQuin, Nikki Hix, Floyd McCroskey, Tor Bjorklund, and other University of Washington (UW) staff provided *R/V Barnes* operations as well as CTD operations and sampling support.
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  - Ken Peer conducted benthic flux studies and meteorological station operations
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- Ryan McEliece, Chris Moore, and Brandon Slone conducted all freshwater monitoring, including coordinating with WWTP staff for composite sample collection.
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  - John Eliasson (Washington State Department of Health)
  - Stuart Glasoe (former Puget Sound Action Team)
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Executive Summary

Marine life needs dissolved oxygen (DO) to survive, but portions of South Puget Sound do not meet the Washington State water quality standards for dissolved oxygen levels. When significant quantities of nitrogen enter Puget Sound and stimulate extensive algae growth, near-bottom DO levels decrease. The form of nitrogen of greatest interest is dissolved inorganic nitrogen (DIN), which is the sum of nitrate, nitrite, and ammonium. Algae bloom and die off, and organic matter decomposition decreases near-bottom DO in the process.

The Washington State Department of Ecology began this study to determine the extent of low DO and how nitrogen from a variety of sources affects DO levels. The study includes collecting data, developing hydrodynamic and water quality models, and simulating alternative management scenarios. This report summarizes data collected from July 2006 through October 2007 from 90 marine stations within South and Central Puget Sound, 29 wastewater treatment plants (WWTPs) and industrial plants discharging to Puget Sound, and 39 rivers and streams. Future reports will describe model development. If the results show that human-related sources of nitrogen must be reduced to keep South Sound healthy, the final technical report will identify what reductions are needed.

This study focuses on South Puget Sound, south of the Tacoma Narrows (Figure ES-1). However, because Central Puget Sound sources may influence South Puget Sound water quality, the entire South and Central Sound area will be modeled initially. The results of the hydrodynamic model will be used to select the northern boundary for water quality model development.

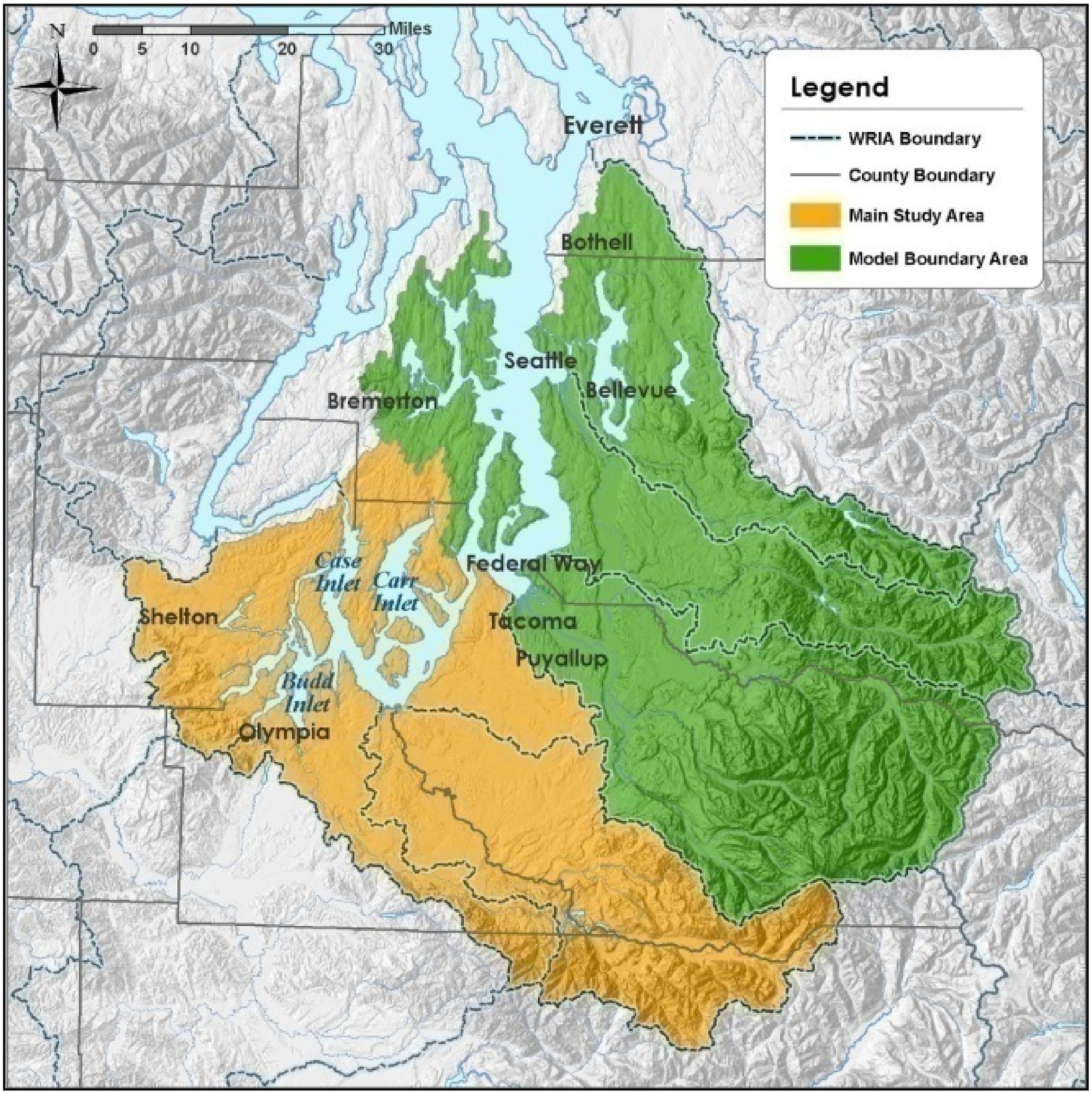


Figure ES-1. Study area, including South Sound as the primary area of interest. (WRIA – Water Resource Inventory Area.)

Freshwater Results

The project included sampling of major rivers and streams, domestic WWTP effluent, and nutrient fluxes from sediments. Flows were developed from U.S. Geological Survey (USGS) gaging stations and WWTP monitoring data. Instantaneous loads were developed from the monthly data, although more detailed loads will be developed with the water quality model. Septic system inputs were included within the river inputs.

On an annual basis, watershed loads from river and stream tributaries and domestic WWTPs produced comparable DIN loads to South Sound, south of the Tacoma Narrows (Figure ES-2). In September 2007, when the lowest DO levels occurred during the marine data collection program (see below), WWTPs contributed 80% of the DIN load to South Puget Sound.

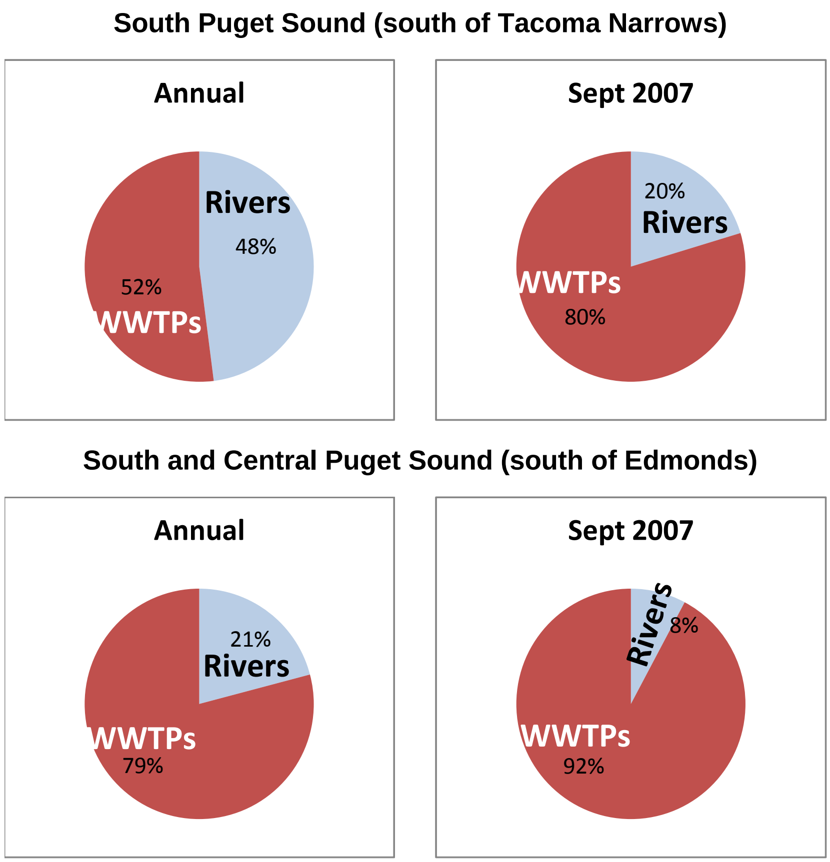


Figure ES-2. Annual and late summer (September 2007) contributions of DIN load from rivers and wastewater treatment plants (WWTPs) that discharge directly to Puget Sound.

However, the ratio of tributary-to-WWTP contribution shifts when the entire South and Central Puget Sound south of Edmonds is considered, due to the larger population centers in Central Puget Sound. On an annual basis, WWTPs contributed 79% and rivers 21% of the DIN load south of Edmonds, but in September 2007, WWTPs contributed over 90% of the watershed DIN load to Central and South Puget Sound. Figure ES-3 summarizes monthly river and WWTP DIN loads.

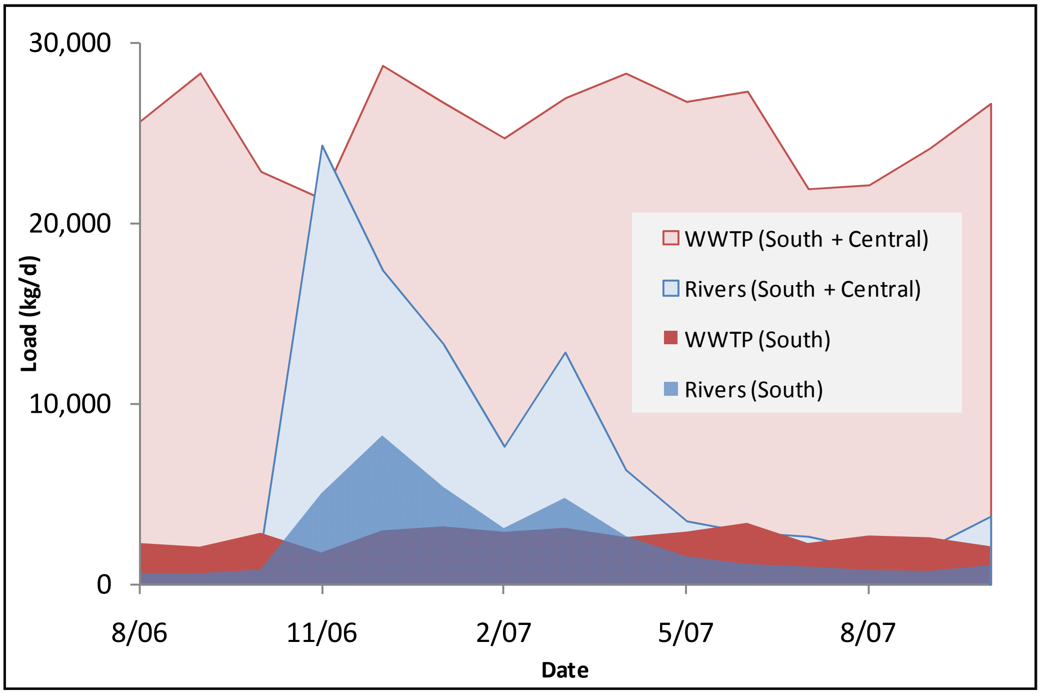


Figure ES-3. Monthly DIN loads for rivers and wastewater treatment plants (WWTPs) tributary to South Sound and the combined South and Central Puget Sound.

Rivers and stream contributions were low but dominated annual loads to many of the western inlets, including Totten, Eld, Henderson, northern Case, and northern Carr (Figure ES-4). Wastewater treatment plant and river inputs were comparable in Hammersley Inlet, Budd Inlet, and near Chambers Creek, but WWTPs dominated loads throughout Central Puget Sound. Figure ES-5 summarizes contributions for September 2007, at which time the river contributions were much lower but wastewater contributions similar to annual means.

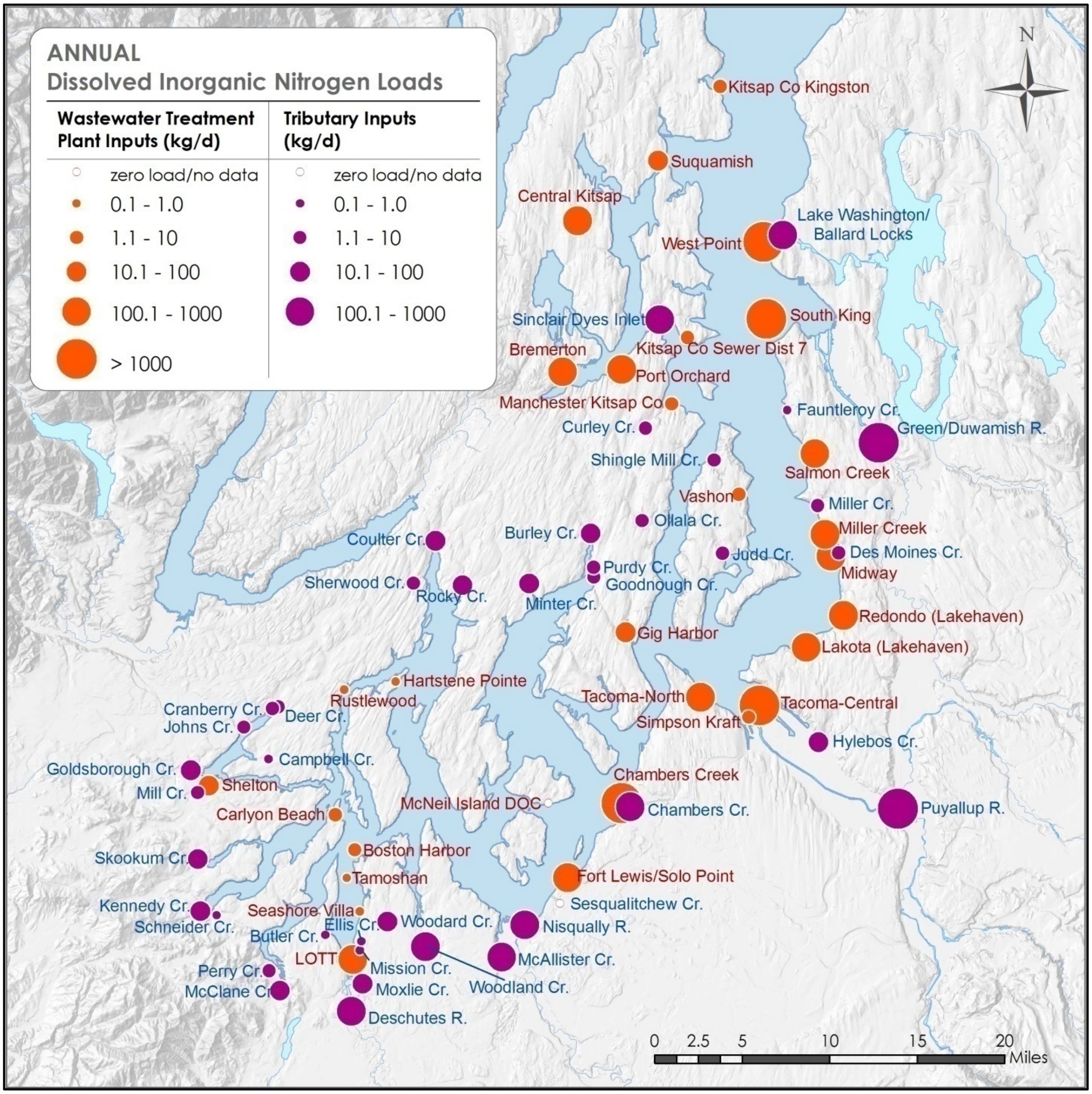


Figure ES-4. Annual DIN loads from rivers and wastewater treatment plants.

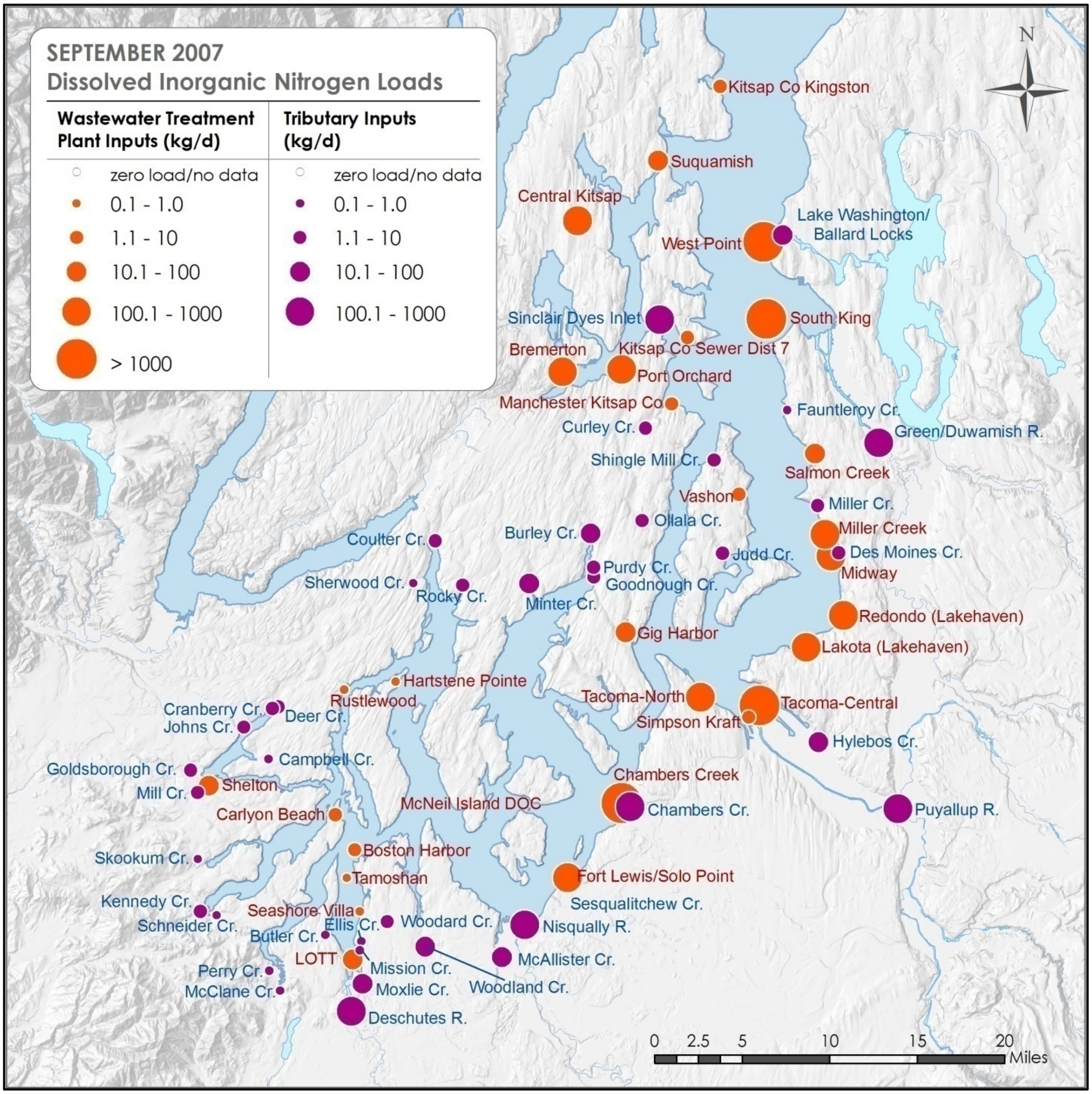


Figure ES-5. September 2007 DIN loads from rivers and wastewater treatment plants.

Rivers and streams produced an annual mean of 2,720 kg/d of DIN, primarily in the form of nitrate + nitrite, to South Puget Sound. The entire area south of the Edmonds boundary produced 7,160 kg/d of DIN, including estimates for watersheds tributary to Sinclair and Dyes Inlets as well as to Lake Washington. The initial estimates from monthly data will be refined in subsequent efforts. Seasonally, higher loads occur in the wet winter months, when loads could be twice the annual mean. Creeks with high nitrogen concentrations included those in southern King County; Goodnough Creek in northern Carr Inlet; Hylebos, Chambers, and McAllister Creeks, all strongly influenced by groundwater; and tributaries to Henderson and Budd Inlets.

Loads estimated for the Puyallup River, Green/Duwamish, and Lake Washington watersheds include WWTPs that discharge to fresh waterbodies upstream of Puget Sound. These WWTPs were not monitored during this phase of the study. However, watersheds that strongly influence marine DO levels will be the focus of follow-up work to isolate these sources.

Annual mean river and stream estimates are based on time-weighted loads derived from individual sampling days. A future effort will use a statistical technique called multiple linear regression to extrapolate monitoring data to daily time series of inflows for the water quality model. However, because the sampling days coincided with a variety of wet-weather and baseflow events, the presented estimates are a reasonable step toward understanding nitrogen loads to South and Central Puget Sound.

WWTPs produced an annual mean of 2,950 kg/d of DIN, primarily in the form of ammonium, to South Puget Sound. The entire area south of Edmonds produced a total of 27,100 kg/d of DIN. Wastewater loads do not exhibit an obvious seasonal pattern. Variability in the monthly totals resulted mostly from occasional missing plant data.

Annual mean estimates of WWTP loads were based on time-weighted values derived from individual sampling days, and no attempt was made to fill missing information for this report. Early discussions with wastewater specialists indicated that the variable nature of sludge dewatering, which varies by plant, could result in highly variable ammonium levels in the effluent. However, at most plants, monthly variation was relatively low, indicating that the effect of sludge dewatering on effluent quality was not as variable as anticipated, and time-weighted estimates were acceptable. Only the Tacoma Central plant showed a wide range between the 25th and 75th percentile DIN concentrations that may reflect sludge dewatering patterns. A future effort will develop daily flows and loads for each WWTP to provide detailed water quality model input.

Marine Results

Low levels of DO occurred throughout South Puget Sound near-bottom waters (Figure ES-6). Concentrations below the water quality standards were recorded in Budd, Carr, Case, and Henderson Inlets; Pickering Passage; Dana Passage; and the Nisqually Reach. Central Puget Sound and the Tacoma Narrows also exhibited low near-bottom DO in summer 2007. Lowest levels occurred in southern Budd Inlet, but levels near or below 5 mg/L occurred in Case and Carr Inlets as well as through the Tacoma Narrows in September 2006. Low levels persisted until December 2006 and returned again in June 2007. The unusually cool and wet summer in

2007 likely contributed to the moderate DO depletion in September 2007 compared with the previous year. Winkler DO values confirm the patterns. Highest DO values occurred in the upper water column in the summer months, consistent with high algal productivity.

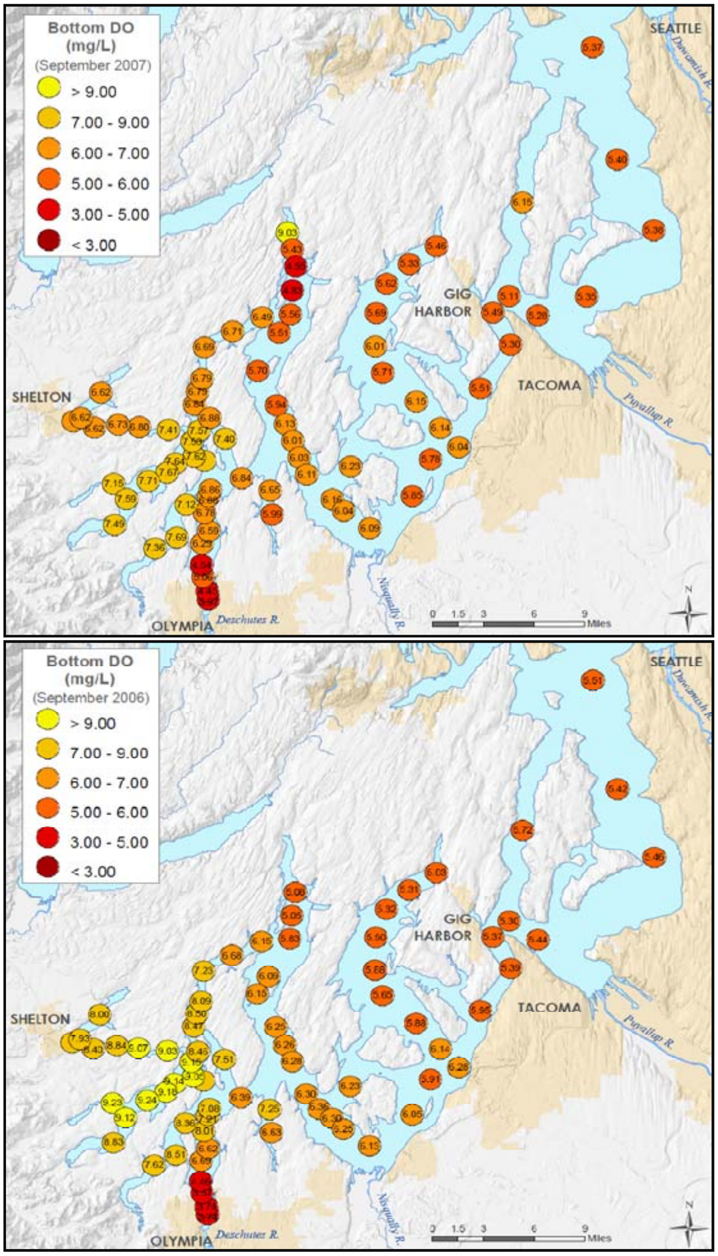


Figure ES-6. Near-bottom dissolved oxygen concentrations in late summer 2006 and 2007.

Biochemical characteristics such as DIN, ammonium, and chlorophyll-a, and hydrodynamics (stratification, circulation, residence time) often differed between the Central Basin, Tacoma Narrows, the deeper eastern South Sound inlets (Carr and Central Case), and the shallow western inlets (Budd, Totten, Eld, Oakland Bay, and the head of Carr). For examples, Figure ES-7 presents maximum water column ammonium concentrations for December 2006 and September 2007. Differences in levels of ammonium, plankton growth, and the long residence times make the western inlets and the heads of Case and Carr Inlets more prone to degraded water quality conditions, including occurrences of low DO. Dissolved inorganic nitrogen values indicated surface water depletion in the summer months.

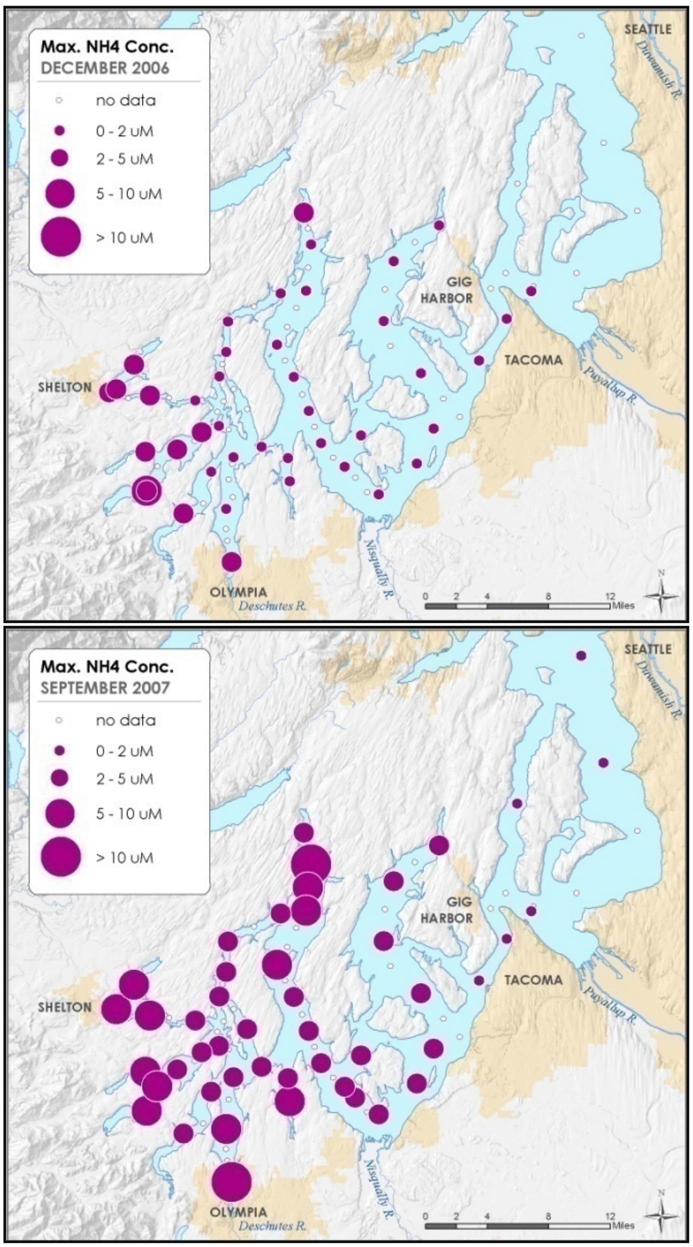


Figure ES-7. Maximum water column ammonium (NH4) concentration in winter and late summer conditions.

Chlorophyll levels were generally higher in 2007 than 2006 (Figure ES-8). Blooms of chlorophyll occur about one month earlier in South Puget Sound compared to Central Puget Sound. The highest chlorophyll levels were recorded in September 2007. The areas with the highest chlorophyll levels include Budd, Totten, Eld, Henderson, Carr, and Case Inlets; north Pickering Passage; and Oakland Bay. The lowest levels occurred within the Nisqually Reach and at the Tacoma Narrows.

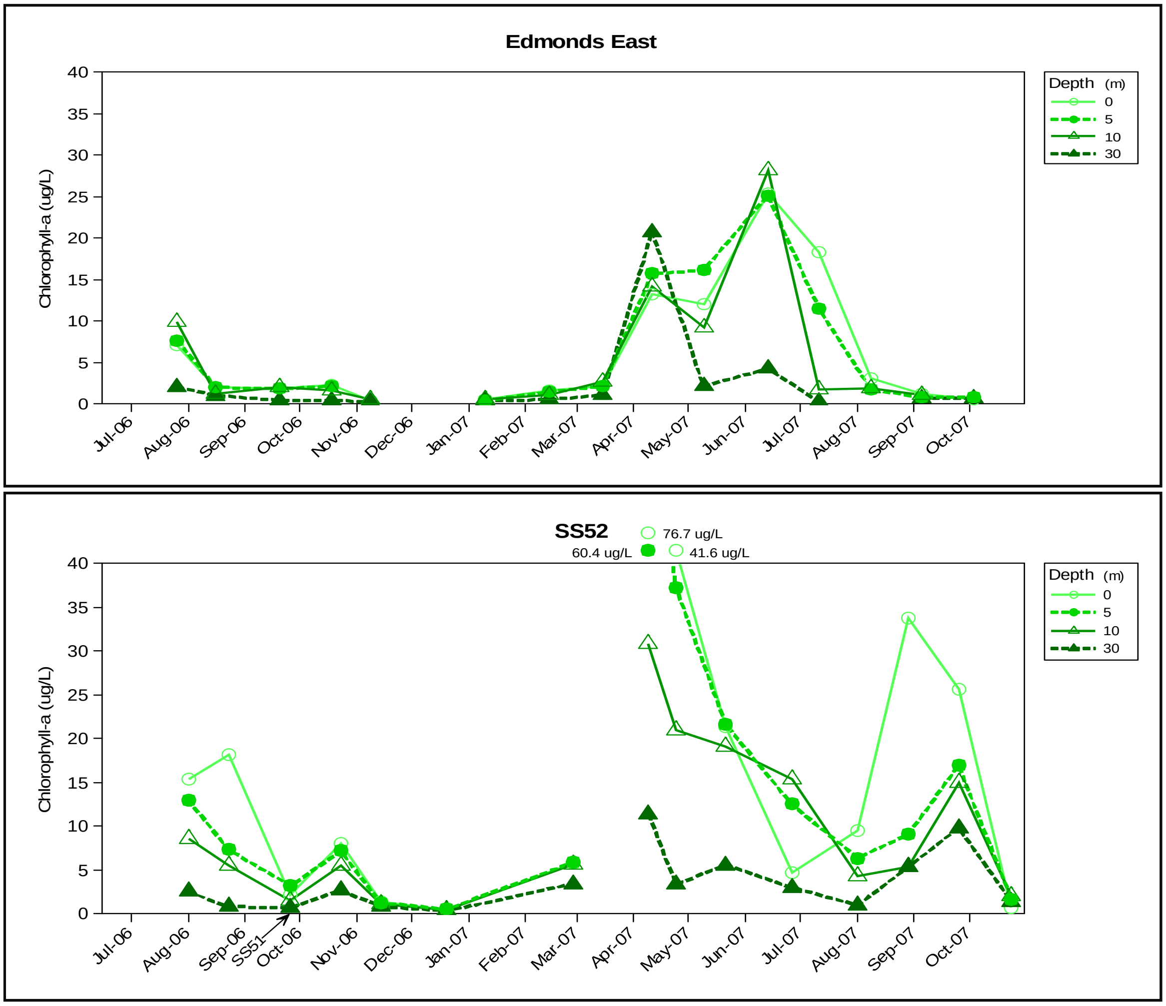


Figure ES-8. Monthly chlorophyll-a concentrations from Edmonds east in Central Puget Sound and a station in central Case Inlet (SS52) within South Puget Sound.

Water column velocity profiles were used to quantify cross-channel hydrodynamic complexity and variation with depth. To develop instantaneous mass flux, results were integrated across a section. Cross sections reflect structures such as gyres and particularly complex patterns around Hope Island. Budd, Carr, and Case Inlets show low water exchanges near the heads of each inlet, even with the temporal offsets of the cross sections. The northern end of Case Inlet was isolated by circulation patterns where most of the water flux travels north around Harstine Island. In addition, high water exchanges north around Fox Island hydrodynamically isolate northern Carr Inlet as well as a zone west of Fox Island.

Based on the September transects, Totten Inlet outflows split on the ebbing tide and flowed both north through Pickering Passage and east past Hope Island. On a flood tide, Totten receives inflows from both Pickering Passage and around Hope Island. Therefore, a tidal node existed west of Hope Island, and the increased friction caused by Hope Island forces water to travel around Pickering Passage. Bottom-mounted velocity profiles indicated that Carr Inlet circulation was highly influenced by wind, whereas Case and Budd Inlet patterns reflect more of the smooth tidal forcing.

Benthic flux chambers installed in Budd, Carr, Case, and Eld Inlets provide local information on sediment fluxes of oxygen, nitrogen, and phosphorus. Sediment oxygen demand (SOD) was highest in Eld Inlet, which also produced the highest rates of phosphorus, ammonium, and DIN (Figure ES-9). Although SOD rates were fairly constant over the three survey periods, nitrogen releases were lower in late October than in September. Rates indicate that sediment flux is a seasonally important process.

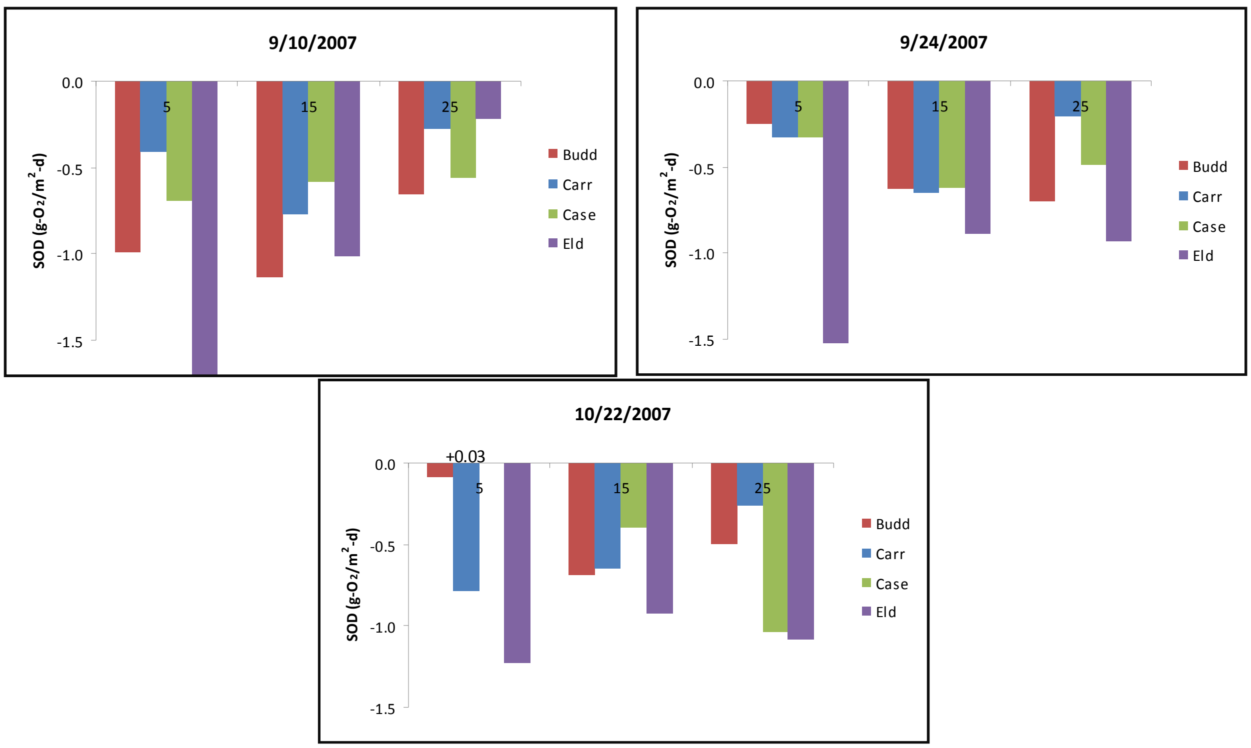


Figure ES-9. Sediment oxygen demand estimates for late summer 2007 from benthic flux chambers located in 5, 15, and 25 meters nominal water depths.

Extrapolating rates to Budd Inlet, sediments produce approximately 1,100 kg/d of DIN. Extensive sediment flux monitoring during the *Budd Inlet Scientific Study* (Aura Nova Consultants et al., 1998) found an annual mean of 890 kg/d and a summer peak of 2400 kg/d of DIN. Because the historical flux rates used a different methodology, direct comparisons can be qualitative only. Historical results corroborate estimates found in this study and underscore the overall importance of sediment processes in South Puget Sound. Sediment fluxes alone are not responsible for the low levels of DO found in Budd Inlet, since higher SOD and DIN rates were found in neighboring Eld Inlet which does not have extensive DO depletion.

Two continuous mooring stations have been installed in South Puget Sound as part of a separate ambient monitoring program. Results indicate that while near-bottom DO concentrations remain near 8 mg/L throughout 2007 at Squaxin Passage, levels consistently fell below 5 mg/L from July through September in Budd Inlet (Figure ES-10).

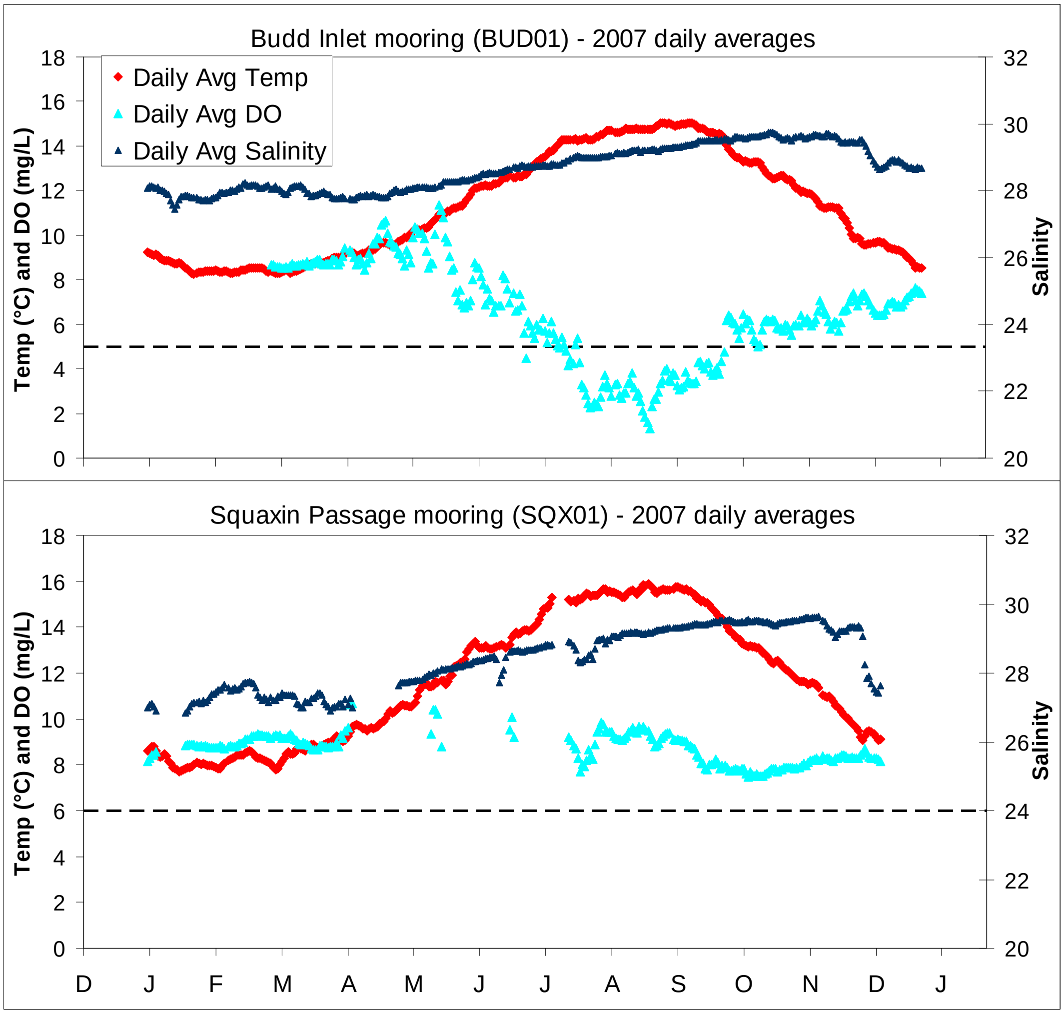


Figure ES-10. Continuous data (preliminary) for stations located in southern Budd Inlet and Squaxin Passage. The dashed lines indicate the water quality standard for each location.

Nutrient sources other than the rivers and WWTPs contribute additional loads to South and Central Puget Sound. Septic systems were included with measured river inputs. Atmospheric deposition to the water surface increased DIN loads to Puget Sound by 5%. Nutrient fluxes into and out of the northern model boundary will be quantified using the water quality model later in the project. Internal sources from sediments are locally important, particularly during the late summer. In shallow inlets, sediment releases of DIN are comparable to external watershed loads. Figures ES-11 and ES-12 summarize DIN loads to South and Central Puget Sound as annual averages and late summer (September 2007) conditions, respectively.

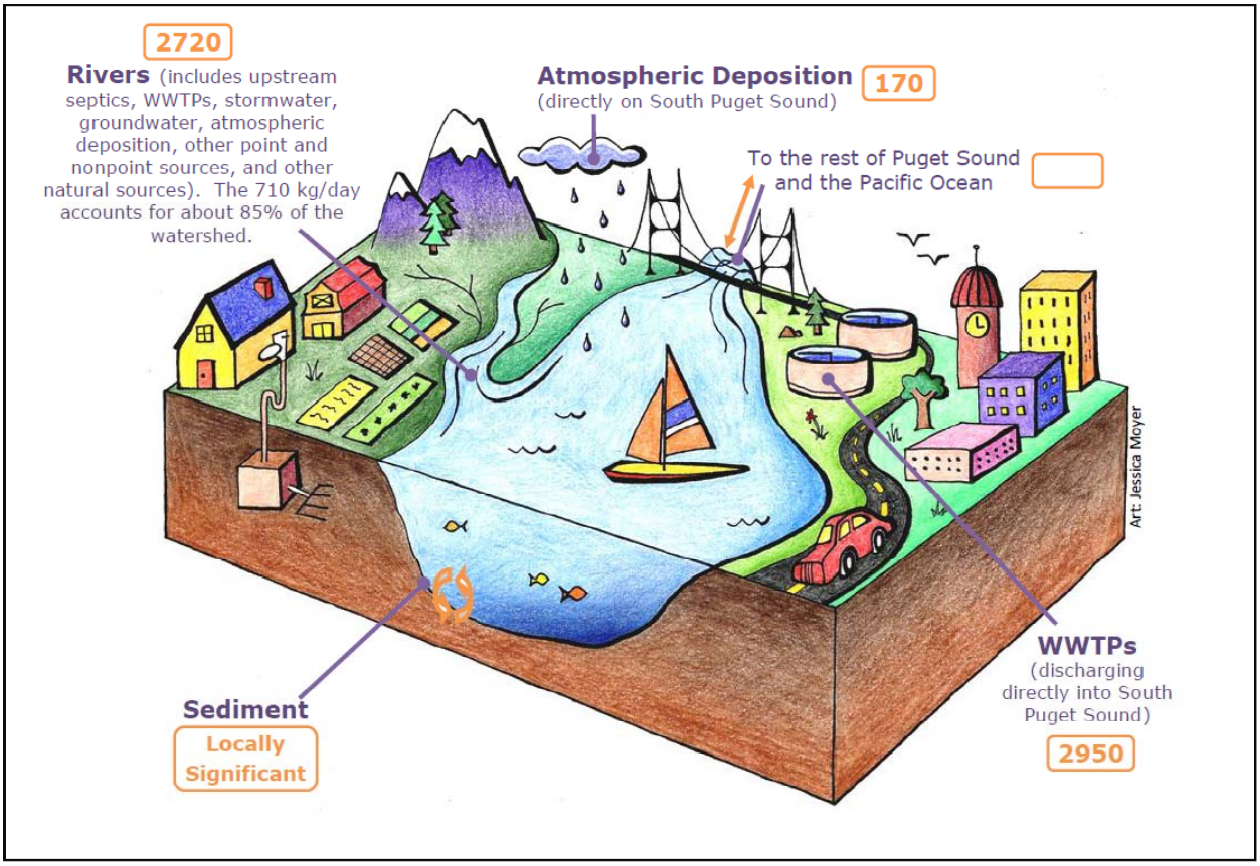


Figure ES-11. Annual average dissolved inorganic nitrogen (DIN) loading to South Puget Sound (kg/d). Nutrient fluxes with the rest of Puget Sound will be determined using the model.

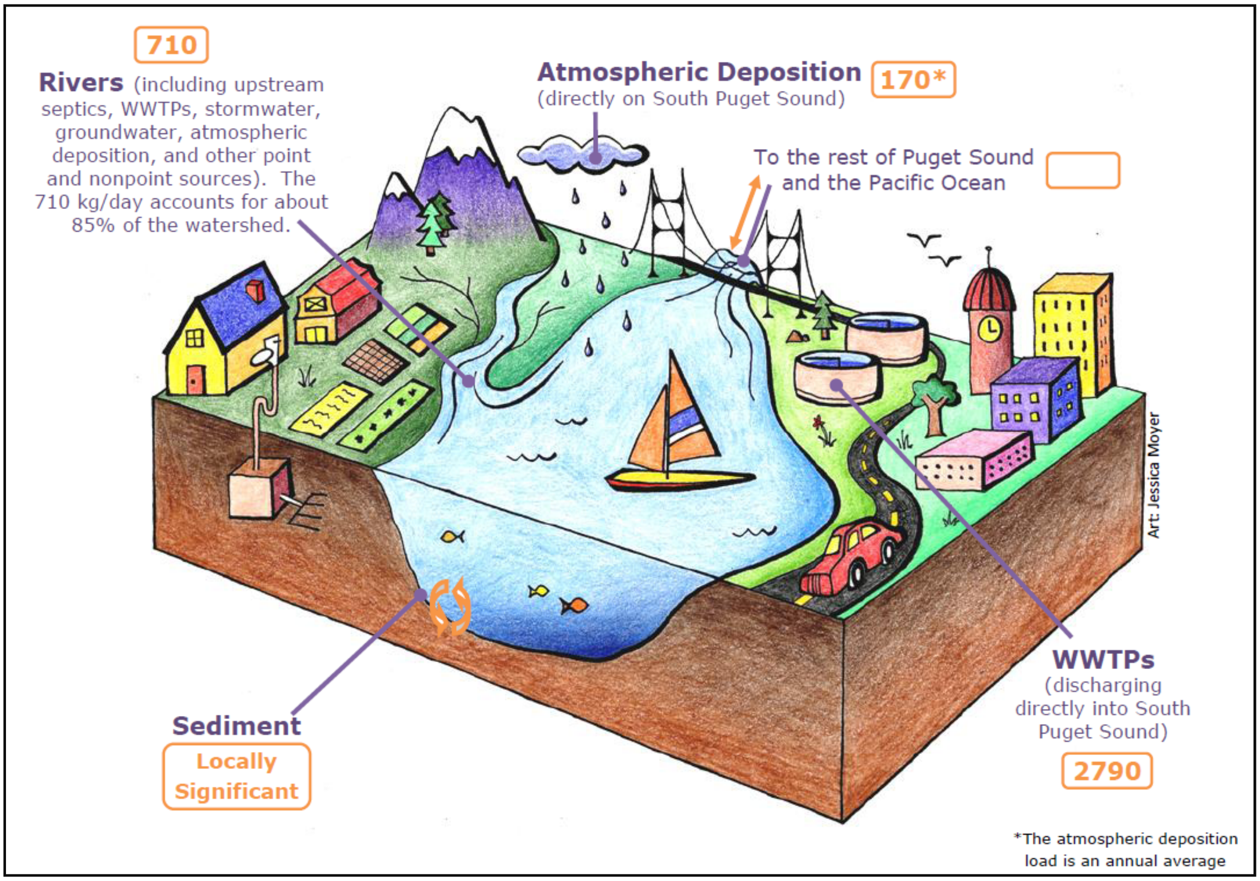


Figure ES-12. September 2007 dissolved inorganic nitrogen (DIN) loading to South Puget Sound (kg/d). Nutrient fluxes with the rest of Puget Sound will be determined using the model.

Additional Data

Some data were not finalized for the present report and will be summarized in addendum form. Data programs include the following:

- Sediment traps deployed through May 2008
- Phytoplankton samples
- Productivity
- Dissolved organic carbon and particulate carbon and nitrogen

In addition, bottom-mounted acoustic Doppler current profiler (ADCP) results for fall 2007 will be presented in the hydrodynamic model report.

Introduction

The Washington State Department of Ecology (Ecology) began this study of low dissolved oxygen (DO) levels in South Puget Sound in 2006. Fish and other marine life need DO to survive. Dissolved oxygen levels decrease when excess nitrogen enters Puget Sound, stimulating algae growth. When these algae die off and begin to decay, microbes consume DO.

The purpose of this study is to determine how nitrogen from a variety of sources affects DO levels in South Puget Sound. The overall project includes collecting marine and freshwater data, developing a three-dimensional hydrodynamic and water quality model, running alternative management scenarios using the calibrated models, and summarizing the findings in a technical report.

This report summarizes water quality data collection from July 2006 through October 2007. The experimental design was published in the Quality Assurance (QA) Project Plan (Albertson et al., 2007), including three addenda that cover supplemental velocity profiles (Roberts, 2007), benthic fluxes (Roberts and Coomes, 2007), and sediment traps (Roberts and Pelletier, 2007). Over 90 marine stations were sampled, along with 29 wastewater treatment plants (WWTPs) and industrial discharges directly to Puget Sound and 35 tributaries. Water quality data were used to estimate instantaneous loads of nitrogen and other parameters.

A separate hydrodynamic model report will summarize the status of model development. Data for certain project components – such as phytoplankton biovolumes, primary productivity studies, and meteorological data – were not available at the time of publication. These data will be published as an addendum to this report. In addition, dissolved organic carbon did not pass initial quality control and will be presented in an addendum to this report.

This study is a critical first step in determining what might need to be done to improve South Puget Sound water quality. The study results may show that human-related sources of nitrogen need to be reduced to keep South Puget Sound healthy. If reductions are needed, the study also will help determine where the reductions need to occur. The final technical report will be developed in 2010 following water quality model calibration.

Study Area

This study focuses on the marine waters of South Puget Sound, defined as the area south of the Tacoma Narrows (Figure 1), and the watersheds that drain to these marine waters. Due to the much higher population in the watershed tributary to Central Puget Sound, these sources will be evaluated for potential impacts on South Puget Sound water quality. The entire South and Central Puget Sound will be modeled initially, although Central Puget Sound is not the primary area of interest of the study. If the Central Puget Sound sources do not influence water quality in South Puget Sound, only the Alki boundary will be used. However, if preliminary modeling indicates these sources could influence South Puget Sound water quality, the final model boundary may be as far north as Edmonds.

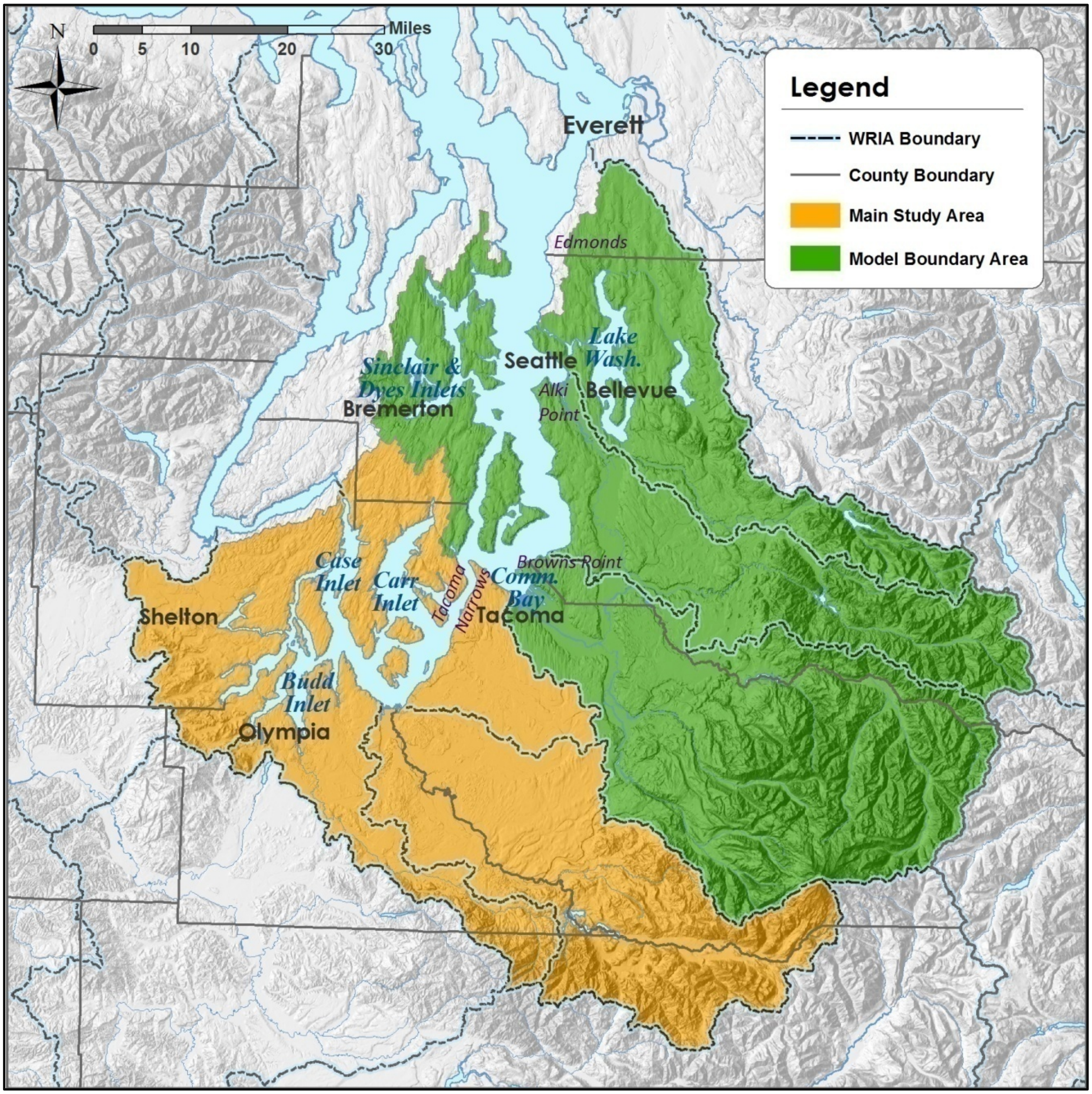


Figure 1. Study area for the South Puget Sound Dissolved Oxygen Study.

Earlier work by Ecology demonstrated the occurrence of low levels of DO in some portions of South Puget Sound (Albertson et al., 2002). While low DO levels in Budd Inlet had been well described, interim monitoring in the Phase 1 study identified additional low levels below Washington State water quality standards in Case and Carr Inlets (Figure 2). The standards establish minimum DO levels throughout Puget Sound ranging from 5 mg/L in southern Budd Inlet to 7 mg/L in Case and Carr Inlets (see below). Low DO concentrations are found naturally in some areas of Puget Sound, but may be exacerbated by human nitrogen inputs that stimulate algae growth and lead to water quality problems such as low DO. The near-bottom DO spatial patterns and overall magnitudes vary annually as well.

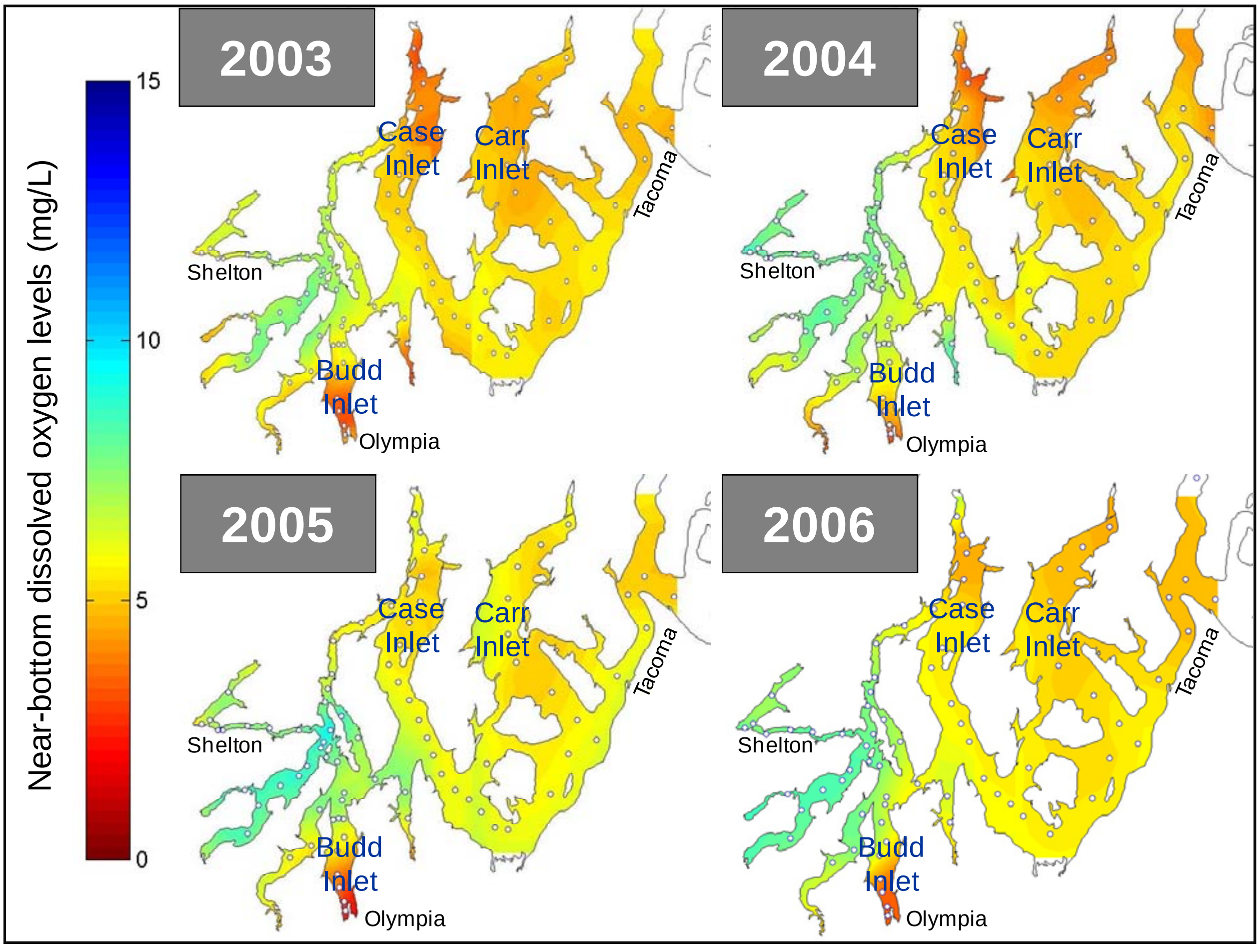


Figure 2. Near-bottom dissolved oxygen levels for South Puget Sound in September of four consecutive years. Values have not been corrected with laboratory Winkler results.

Ecology develops a list of impaired waters every two years, as defined under Section 303(d) of the federal Clean Water Act. The impaired waters list is part of the larger Water Quality Assessment. In the 2004 Water Quality Assessment, 22 locations in South Puget Sound were impaired by levels of DO that fell below the water quality standards. Another 43 locations were identified as areas of concern. Overall, Budd, Carr, and Case Inlets remain the areas of greatest concern (Figure 3).

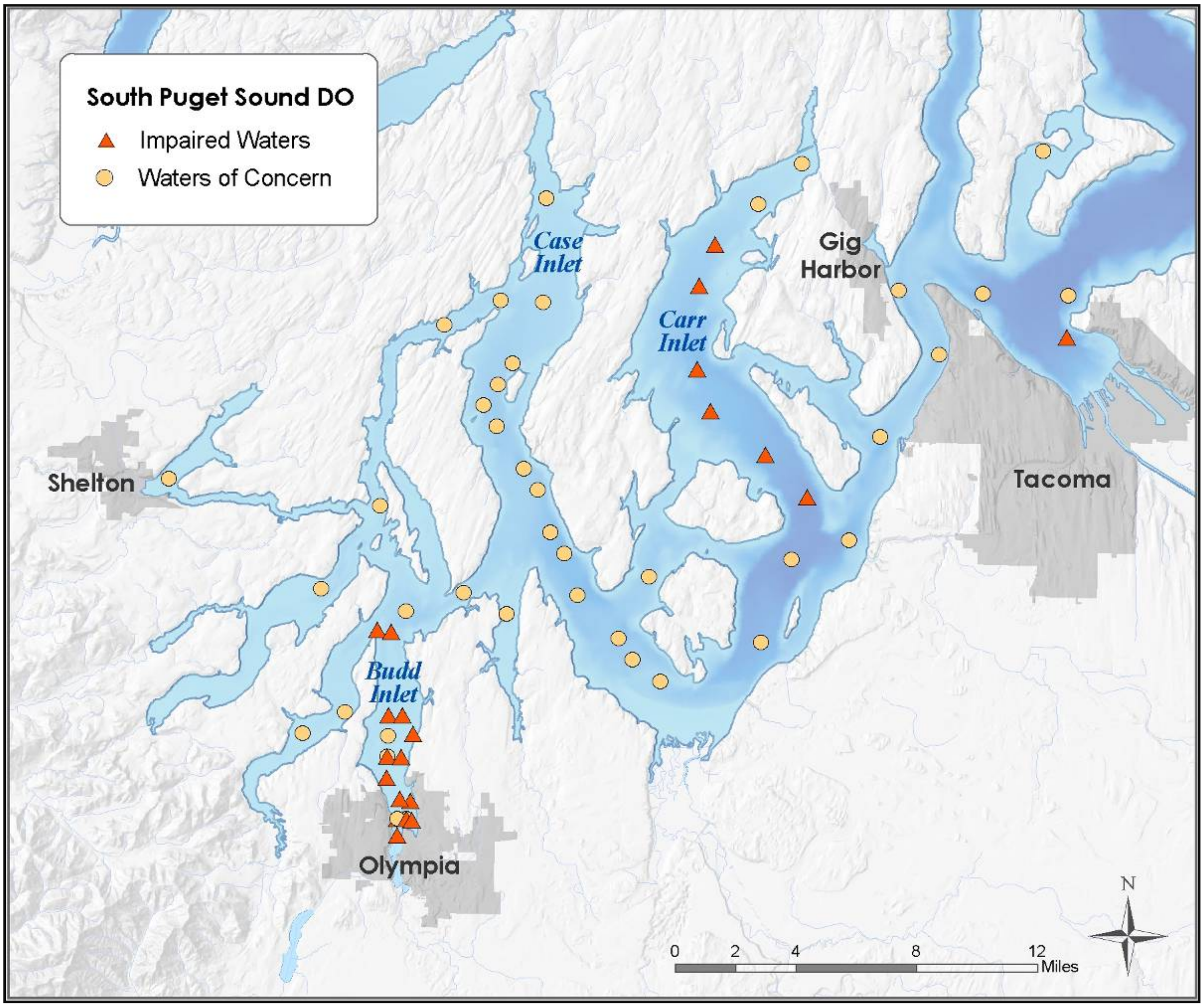


Figure 3. 2004 Water Quality Assessment for dissolved oxygen in South Puget Sound.

Several factors control nutrient (e.g., nitrogen) enrichment and DO depletion. Processes that contribute nutrients to South Puget Sound include atmospheric deposition, river and stream inflows, point source discharges, nonpoint source inputs, nutrient fluxes with Puget Sound into and out of the northern study boundary, and sediment-water exchanges. Hydrodynamic characteristics such as tides, stratification, mixing, and freshwater inflows govern transport of nutrients and other parameters. Photosynthesis rates govern biological nutrient transformations and DO dynamics. Light, nutrient availability, temperature, and phytoplankton species influence photosynthesis rates as well as algae growth, respiration, death, and settling. Therefore, this study was designed to quantify each of these processes, both to understand the dynamics of South Puget Sound and to develop a model to simulate those dynamics.

Direct Wastewater Treatment Plant (WWTP) Discharges

Domestic WWTPs and industrial discharges operate under individual National Pollutant Discharge Elimination System (NPDES) permits. Within the project domain, 31 domestic WWTPs and two industrial facilities discharge directly to South and Central Puget Sound. Several other facilities discharge to rivers or directly to groundwater within the watershed, but these were not sampled as part of this study. Each facility is required to test effluent on a routine basis, generally daily to weekly depending on the parameter, and to report concentrations of these parameters to Ecology as a condition of the permit. However, while all plants test for biochemical oxygen demand (BOD) and total suspended solids, most permits do not require tests for nutrients, including nitrogen, phosphorus, or carbon.

Figure 4 identifies the participating plant locations. These facilities include 28 domestic WWTPs and one industrial plant, which represent all major NPDES plants and nearly all of the minor plants. We did not pursue monitoring at the McNeil Island Department of Corrections WWTP because of the logistical difficulties related to ferry travel. In addition, several plants listed in the QA Project Plan had ceased discharging prior to sampling and were not included (Beverly Beach, Washington Parks Blake Island, Kitsap County Sewer District No. 7). The Taylor Bay Longbranch plant could not be reached. The City of Bainbridge Island discharge was inadvertently excluded from the sampling plan. Finally, the King County Alki plant is exclusively a combined sewer overflow plant and was not monitored.

In addition, U.S. Oil and Refining in Tacoma discharges to Commencement Bay but was not monitored directly. The facility's NPDES permit requires effluent reporting of flows, ammonium, and biological oxygen demand (BOD). Based on long-term monitoring (U.S. Oil and Refining, 2006), the facility discharges very small loads of ammonium (0.3 mg/L and 0.5 kg/d) and BOD (1.8 mg/L and 2.8 kg/d). Finally, one industrial facility has an NPDES permit but is currently inactive (Abitibi in Steilacoom).

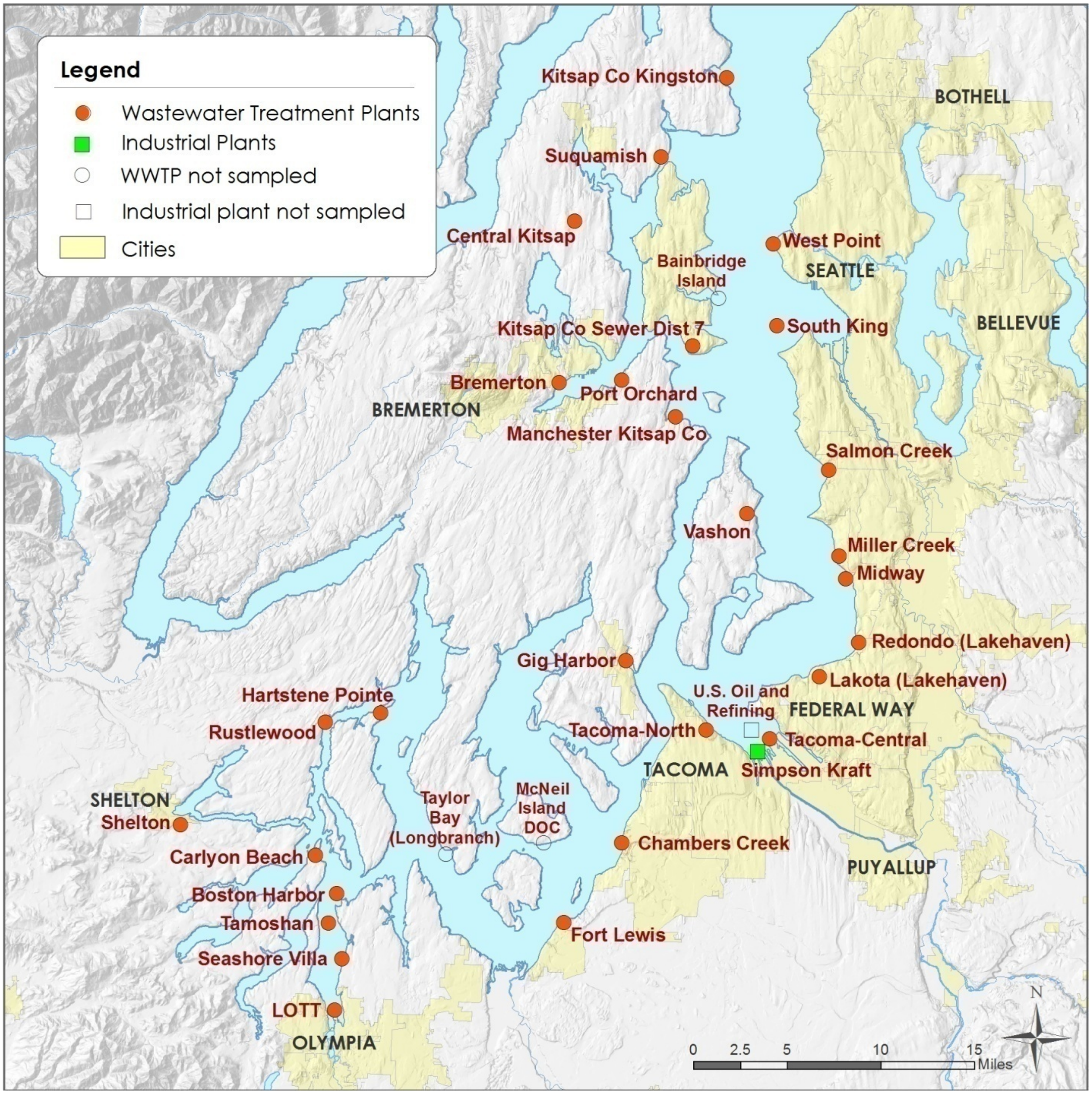


Figure 4. Domestic wastewater treatment plants and industrial facilities that participated in supplemental effluent monitoring.

NPDES permits are administered by Ecology for non-federal facilities, while EPA administers NPDES permits for federal and tribal facilities. Table 1 lists the permitted dischargers within the study domain.

Table 1. Active facilities with NPDES permits for continuous domestic wastewater treatment plant and industrial effluent discharges within the study domain. Abbreviations are included in the *Glossary*. NS indicates the facility was not sampled.

Plant Name	Permit No.	Effective Date	Expires	Parameter limits	Reporting parameters	Design criteria
Municipal WWTP permits managed by Ecology's Southwest Regional Office						
Boston Harbor	WA0040291	7/1/06	6/30/11	BOD, TSS, FC, pH	Q, BOD5, TSS, FC, NH3 (A), DO, pH, sludge quantity (gal, %solids)	Q_{maxmo} 0.054 mgd; 600 people
Carlyon Beach	WA0037915	7/1/07	6/30/12	BOD5, TSS, FC, pH	Q, pH, CBOD5, TSS, Cl, FC, NH3 (H)	Q_{maxmo} 0.060 mgd
Chambers Creek	WA0039624	1/1/03	12/31/07	BOD5, TSS, FC, pH, toxicity	Q, CBOD5, BOD5, TSS, PPM, Temp, FC, pH, chlorine, NH3 (B), DO	Q_{maxmo} 28.7 mgd
Hartstene Pointe	WA0038377	7/1/05	6/30/10	BOD5, TSS, FC, pH, Cl	Q, pH, CBOD5, TSS, Cl, FC, NH3 (H)	Q_{maxmo} 0.186 mgd
LOTT	WA0037061	10/1/05	9/30/10	BOD5 (w, sp/f, su), TSS, TIN (sp/f, su), FC, pH	Q, BOD5, TSS, pH, FC, Temp, NH3 (E), NO23N (F), TKN (G), TRM	Q_{maxmo} 28 mgd; Q_{maxday} 55 mgd; Q_{in} 64 mgd
Rustlewood	WA0038075	5/1/02	6/30/07	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, FC, Cl, NH3 (D)	Q_{maxmo} 55,000 gpd
Tacoma-Central	WA0037087	6/1/04	5/31/09	BOD5, TSS, FC, pH, toxicity, Cl	Q, BOD5, TSS, PPM, Temp, FC, pH, Cl, NH3 (C), DO, toxicity	Q_{maxmo} 60 mgd; Q_{maxday} 150 mgd
Tacoma-North	WA0037214	12/1/03	11/30/08	BOD5, TSS, FC, pH, toxicity, Cl	Q, BOD5, TSS, pH, Cl, FC	Q_{maxmo} 7.2 mgd; Q_{maxday} 15.8 mgd; 54300 people
Tamoshan	WA0037290	1/1/03	12/31/07	BOD5, TSS, FC, pH	Q, BOD5, TSS, pH, FC	Q_{maxmo} 0.050 mgd
Industrial discharge permits managed by Ecology's Southwest Regional Office						
Simpson Kraft	WA0000850	11/1/01	11/1/06	BOD5, TSS, pH	BOD5, TSS, pH, COD, Q, Temp	Q_{avg} 28 to 34 mgd
U.S. Oil and Refining (NS)	WA0001783	8/1/08	8/1/13	BOD5, COD, TSS, NH4, TOC, pH	Q, BOD5, COD, TSS, NH4, TOC, Temp, pH	Q_{maxday} 1.08 mgd
Municipal WWTP permits managed by Ecology's Northwest Regional Office						
Bainbridge Island (NS)	WA0020907	7/1/07	6/29/12	BOD5, TSS, FC, pH, Cl	Q, CBOD5, TSS, FC, TSS, pH, Cl; DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 1.2 mgd
Bremerton	WA0029289	10/1/06	9/28/11	BOD5, TSS, FC, pH, toxicity, Cl	Q, BOD5, TSS, pH, Cl, FC, NH3 (H), DO, TKN or TN (I), TP (J), NO23N (I)	Q_{maxmo} 10.1 mgd
Central Kitsap	WA0030520	6/1/07	5/31/12	CBOD5, TSS, FC, pH	Q, pH, CBOD5, TSS, Cl, FC, NH3 (H); DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 6.0 mgd
Gig Harbor	WA0023957	8/1/04	7/28/09	CBOD5, TSS, FC, pH, Cl	Q, pH, CBOD5, TSS, Cl, FC, NH3 (D); DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 1.6 mgd
Kitsap Co Kingston	WA0032077	5/2/05	5/2/10	CBOD5, TSS, FC, pH	Q, pH, CBOD5, TSS, FC; DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 0.292 mgd
Kitsap Co Sewer Dist 7 (Bainbridge/ Fort Ward)	WA030317	7/1/06	6/30/11	BOD5, TSS, FC, pH, Cl	Q, pH, CBOD5, TSS, FC; DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 0.14 or 0.28* mgd
Lakota (Lakehaven)	WA0022624	8/1/03	7/15/08	CBOD5, TSS, FC, pH, toxicity, Cl	Q, CBOD5, TSS, FC, TSS, pH, Cl; DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 10 mgd

Plant Name	Permit No.	Effective Date	Expires	Parameter limits	Reporting parameters	Design criteria
Manchester Kitsap Co	WA0023701 D	8/1/02	7/22/07	BOD5, TSS, FC, pH	Q, pH, CBOD5, TSS, FC, Temp; DO, NH3 (A), TKN, NO23N, TP (J)	Q_{maxmo} 0.46 mgd
McNeil Island/DOC (NS)	WA0040002	8/1/05	7/15/10	BOD5, TSS, FC, pH	Q, pH, CBOD5, TSS, FC, NH3 (H)	Q_{maxmo} 0.45 mgd
Midway	WA0020958	12/1/05	11/30/10	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, FC, Cl, pH	Q_{maxmo} 9 mgd
Miller Creek	WA0022764	5/1/03	4/25/08	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, FC, Cl, pH	Q_{maxmo} 7.1 mgd
Port Orchard	WA0002034 6	updating	updating	BOD5, TSS, FC, pH, Cl	Q, pH, BOD5, TSS, Cl, FC, NH3 (D); DO, TKN, TP (J); NO3+NO2, TKN or TN (I)	Q_{maxmo} 4.2 mgd
Redondo (Lakehaven)	WA0002345 1(M)	8/1/03	7/15/08	CBOD5, TSS, FC, pH, Cl	Q, CBOD5, TSS, pH, FC, Cl; DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 5.6 mgd
Salmon Creek	WA0022772	5/1/03	4/25/08	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, FC, Cl	Q_{maxmo} 8.1 mgd
Seashore Villa	WA0037273	1/1/03	12/31/07	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, FC, Cl	Q_{maxmo} 15,000 gpd
Shelton	WA0023345	10/1/02	6/30/07	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, FC, Cl, NH3 (D)	Q_{maxmo} 4.02 mgd
South King	WA0029581	10/1/04	9/30/09	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, FC, Cl	Q_{maxmo} 144 mgd
Taylor Bay (Longbranch) (NS)	WA0037656	11/1/05	10/31/10	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, Cl, FC	Q_{maxmo} 29,000 gpd
Vashon	WA0022527	9/1/06	8/31/11	BOD5, TSS, FC, pH, Cl	Q, CBOD5, TSS, pH, FC, Cl; DO, NH3, TKN, NO23N, TP (J)	Q_{maxmo} 0.52 mgd
West Point	WA0029181	1/1/04	12/31/08	BOD5, TSS, FC, pH, Cl	Q, BOD5, CBOD5, TSS, pH, Cl, FC	Q_{maxmo} 215 mgd
Municipal WWTP permits managed by the U.S. Environmental Protection Agency (EPA)						
Fort Lewis/ Solo Point	WA0021954	12/30/03	2/1/09	CBOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, Cl, FC, TN (K)	(not listed in permit)
Kitsap Co Suquamish	WA002325-6	Draft	Draft	BOD5, TSS, FC, pH, Cl	Q, BOD5, TSS, pH, FC, Temp, NH4N, Alk	Q_{design} 0.4 mgd

* After fall 2007 Q_{maxmo} expands to 0.28 mgd
(A) Monthly grab sample
(B) 3 grabs per week
(C) 1 grab per week
(D) 1 per week, 24-hr composite
(E) 5 days/wk 4/1-10/31; 1 day/wk 11/1-3/31; 24-hr composite
(F) 5 days/wk 4/1-10/31; 1 day/wk 11/1-3/31; 24-hr composite
(G) 1 day/wk; 24-hr composite
(H) 1/mo; 24-hr composite
(I) 1/week, 24-hr composite; 2007, 2008, 2009 for July, August, September, October
(J) 3 grabs per permit term
(K) 1/year
(L) 1/permit cycle

Permit requirements and plant operations evolve over time. A variety of plant upgrades have been planned, designed, or are in construction. These will be considered in alternative future scenarios planned once the water quality model is developed.

River and Tributary Inflows

Four major rivers discharge to South and Central Puget Sound (Deschutes, Nisqually, Puyallup, and Green/Duwamish). The Cedar River, Lake Washington, and Lake Union watersheds discharge through the Ballard Locks to Central Puget Sound. Dozens of large streams and hundreds of small streams flow into the study domain.

The total study area (South and Central Puget Sound) including land and water constitutes 4780 km^2 (1850 mi^2) south of the Tacoma Narrows and 11,600 km^2 (4,480 mi^2) south of the Edmonds boundary. Within the total study area, marine water covers 439 km^2 (169 mi^2) south of the Tacoma Narrows and 985 km^2 (380 mi^2) south of Edmonds.

Previous efforts by the USGS estimated annual loads of total phosphorus and total nitrogen by the major rivers of Puget Sound, including the five major inflows included in this study (Embrey and Inkpen, 1998). Phase 1 of this Ecology project estimated loads of various nutrient parameters for 71 inflows to South Puget Sound (Roberts and Pelletier, 2001; Albertson et al., 2002).

Ecology conducts ambient monthly monitoring near the mouths of the Deschutes, Nisqually, Puyallup, and Green Rivers. Because the sites were already visited monthly, only supplemental monitoring for total organic carbon, dissolved organic carbon, dissolved total phosphorus, and dissolved total persulfate nitrogen was included for this study. In addition, supplemental sampling for all study parameters was conducted on 18 tributaries for the entire 15 months of the 2006-07 sampling period and another 17 smaller tributaries were included for 4 months. Figure 5 presents the major and minor freshwater inflows included for supplemental monitoring.

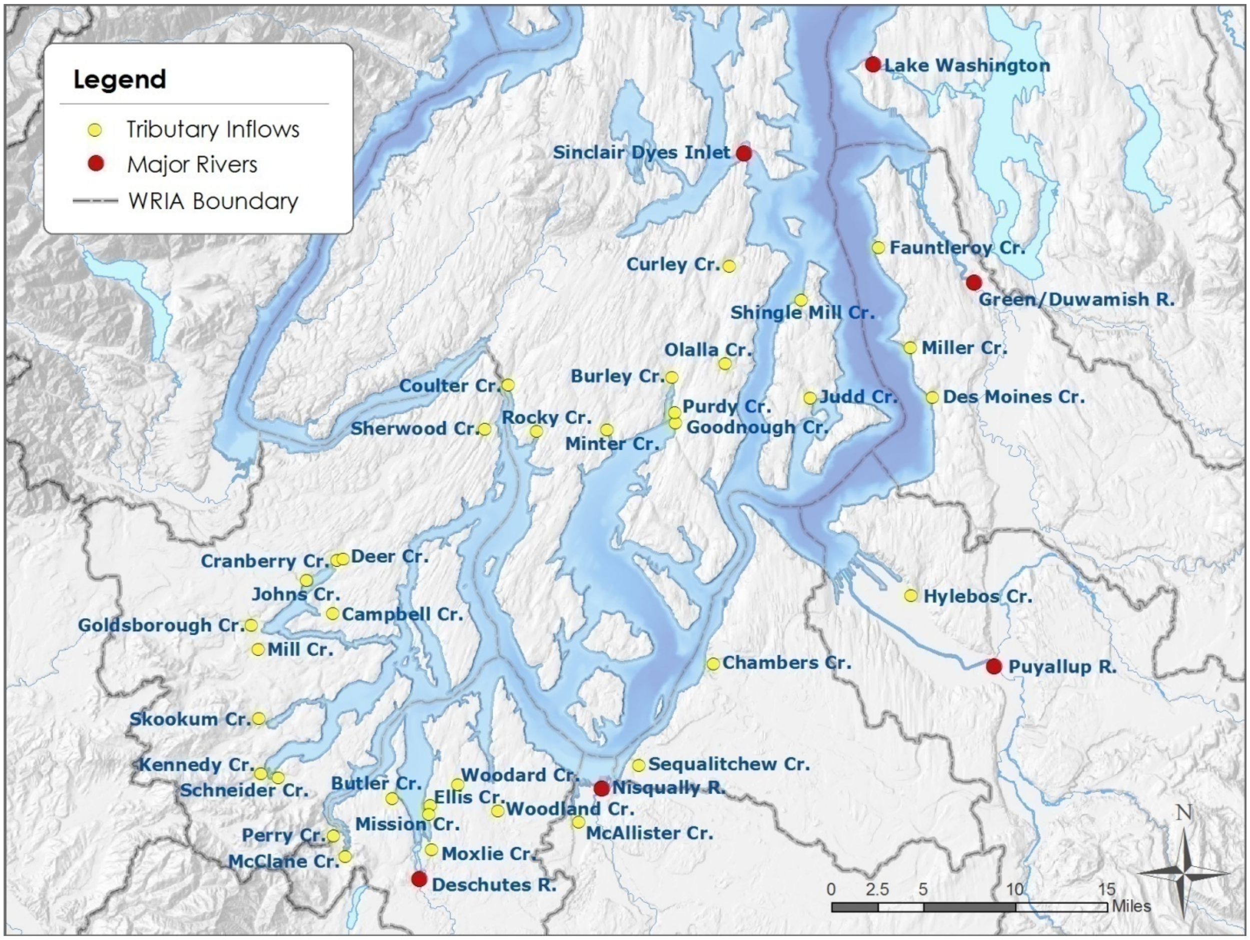


Figure 5. Freshwater inflows monitored within the South Puget Sound model domain, including portions of Central Puget Sound. Red dots indicate Ecology ambient monitoring sites at major rivers.

Water Quality Standards

Under the federal Clean Water Act, each state maintains water quality standards designed to protect, restore, and preserve water quality. Water quality standards consist of both designated uses for protection (such as aquatic life) and criteria, usually numeric, required to achieve those uses. Water quality standards are found in the Washington Administrative Code (WAC), Section 173-201A.

Designated uses for South and Central Puget Sound are established in WAC 173-201A-612 and are shown in Figure 6:

- **Extraordinary Aquatic Life Use, Shellfish Harvest, and Primary Contact Recreation**
  - Puget Sound through Admiralty Inlet and South Puget Sound, south and west to longitude -122°52'30"W (Brisco Point) and longitude -122°51'W (northern tip of Harstine Island).
  - Totten Inlet and Little Skookum Inlet, west of longitude -122°56'32" (west side of Steamboat Island).
- **Excellent Aquatic Life Use, Shellfish Harvest, and Primary Contact Recreation**
  - South Puget Sound west of longitude -122°52'30"W (Brisco Point) and longitude -122°51'W (northern tip of Harstine Island, except as otherwise noted).
  - Dyes and Sinclair Inlets west of longitude -122°37'W.
  - Elliott Bay east of a line between Pier 91 and Duwamish Head.
  - Commencement Bay south and east of a line bearing 258° true from Brown's Point and north and west of a line bearing 225° true through the Hylebos waterway light.
- **Good Aquatic Life Use and Secondary Contact Recreation**
  - Commencement Bay, inner, south, and east of a line bearing 225° true through Hylebos waterway light except the city waterway south and east of south 11th Street.
  - Budd Inlet south of latitude 47°04'N (south of Priest Point Park).
  - Oakland Bay west of longitude -123°05'W (inner Shelton harbor).

Aquatic organisms are very sensitive to reductions in DO levels in water. The health of fish and other aquatic species depends on maintaining an adequate supply of DO in the water. Growth rates, swimming ability, susceptibility to disease, and the relative ability to endure other environmental stressors and pollutants are all affected by DO levels. The State's criteria are designed to maintain conditions that support healthy populations of fish and other aquatic life well above lethal limits.

Dissolved oxygen levels fluctuate seasonally and between day and night in response to changes in weather conditions as well as the respiration and photosynthesis rates of aquatic plants, algae, phytoplankton, and bacteria. Since the health of aquatic species is tied predominantly to the pattern of daily minimum DO concentrations, the criteria are expressed as the lowest one-day minimum DO concentration that occurs in a waterbody.

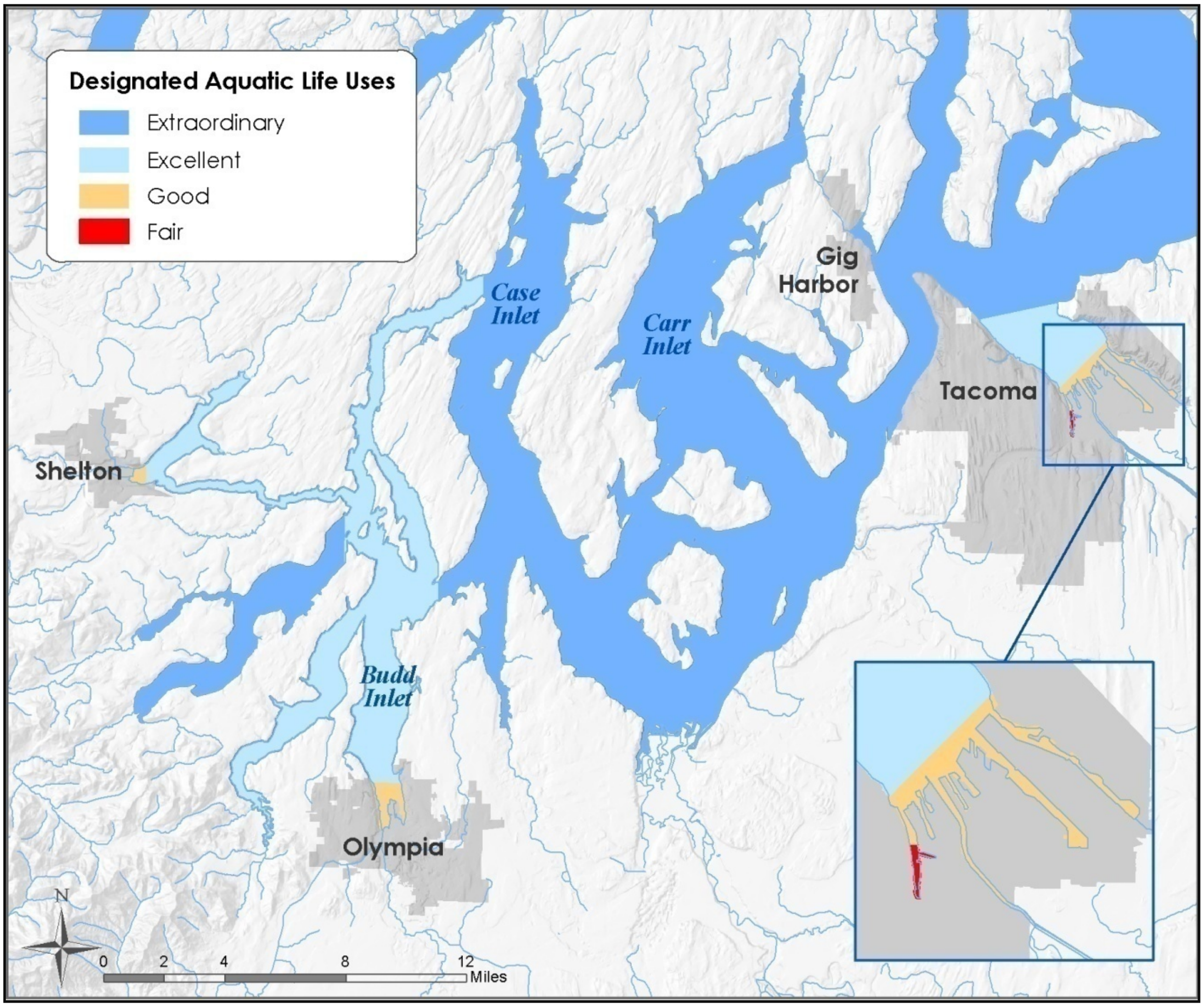


Figure 6. Designated aquatic life uses for South and Central Puget Sound from WAC 173-201A. An inset of Commencement Bay is included for clarity.

The numeric criteria for South Puget Sound are as follows:

1. To protect the designated "*Extraordinary quality*" category of aquatic life use, the lowest one-day minimum DO level must not fall below 7.0 mg/L more than once every ten years on average.
2. To protect the designated "*Excellent quality*" category of aquatic life use, the lowest one-day minimum DO level must not fall below 6.0 mg/L more than once every ten years on average.
3. To protect the designated "*Good quality*" category of aquatic life use, the lowest one-day minimum DO level must not fall below 5.0 mg/L more than once every ten years on average.

The numeric oxygen criteria are established to ensure that a waterbody provides full support for its designated aquatic life uses where it is naturally capable. The standards recognize, however, that not all waters are naturally capable of remaining above the fully protective DO criteria. When a waterbody naturally falls below the DO criteria, an additional provision for human activities is included. In this case, the combined effects of all human activities (including both point and nonpoint sources) must not cause more than a 0.2 mg/L decrease below the natural lower (inferior) DO condition.

Technical Advisory Committee

An independent Technical Advisory Committee (TAC) was established in 2006. Scientifically knowledgeable individuals representing a wide range of interests in South Puget Sound are involved in the TAC. Committee members include representatives from Tribes, WWTPs, conservation districts, the Washington State Department of Health, universities, business interests, environmental groups, municipalities, counties, and the federal government. (See the *Acknowledgements* section of this report.)

The role of the TAC is to provide recommendations on the initial project findings, encourage discussion of key issues, and promote South Puget Sound scientific education for decision-makers at all levels. Ecology's role is to make final decisions on project elements and to apply the study findings. The group meets on an as-needed basis, generally quarterly. The TAC commented on the draft QA Project Plan and the draft Interim Data Report.

Data Availability and Storage

The data collected by Ecology and provided in this report are available through electronic databases.

- Wastewater treatment plant supplemental data are available through the Environmental Information Management (EIM) system (www.ecy.wa.gov/eim/), under User Study ID MROB0004. Results for specific treatment plants can be found using the Location Name field.
- Monthly data from the four largest rivers (Deschutes, Nisqually, Puyallup, and Green) are available through EIM or the ambient monitoring database (www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html#4).
- Monthly supplemental tributary data are available through the EIM system (www.ecy.wa.gov/eim/), under User Study ID MROB0004. Results for specific creeks can be found using the Location Name.
- Marine flight data from monthly ambient monitoring are available through the Marine Flights database (www.ecy.wa.gov/apps/eap/marinewq/mwdataset.asp), which includes long-term results for several locations within South Puget Sound.
- Marine water column CTD and lab data for the South Puget Sound study are available (www.ecy.wa.gov/programs/eap/mar_wat/focused_south.html).

- Winter and summer cruise data collected under the PRISM program, a cooperative consortium that includes the University of Washington and Ecology, can be found on the PRISM web site (prism.washington.edu).
- Mooring data from southern Budd Inlet are available through the Ecology Mooring database (http://aww.ecydev/programs/eap/mar_wat/data.html).

Other data used in this report but collected by others include the following:

- Wastewater treatment plant monthly data reported under NPDES permits are available through Water Quality Permit Life Cycle System (WPLCS) (www.ecy.wa.gov/programs/wq/permits/wplcs/index.html). Daily data are available through a public disclosure request.
- Streamflow data from USGS for the four major rivers and several minor streams are available on the Real-Time Data for Washington Streamflow web page (waterdata.usgs.gov/wa/nwis/current?type=flow).
- National Atmospheric Deposition Program monitoring data are available at nadp.sws.uiuc.edu/.
- Meteorology data are available at several locations around South Puget Sound. Data sources and data will be summarized in the hydrodynamic model report, in development.

Methods

The QA Project Plan (Albertson et al., 2007) details the methods used to collect and analyze the data. An overview is provided below.

Freshwater

Tributary Monitoring

Sample collection from tributaries followed protocols described in Ecology (1993). In summary, nutrient samples were collected by quickly submerging the sample bottles facing upstream. Sample bottles, storage, and hold times are presented in Table 2. Ecology field-filtered samples analyzed for dissolved parameters. In-situ values for temperature, DO, and pH were determined using a Hydrolab calibrated according to standard operating procedures (Swanson, 2007). Streamflow was measured during each site visit according to established protocols (Ecology, 1993), with the exception of the major rivers that are gaged by USGS.

Wastewater Treatment Plant Monitoring

Wastewater samples were collected according to the methods in the QA Project Plan. Extra samples from each plant's 24-hour composite sampling equipment were retained for Ecology staff on a monthly basis. The specific location within the treatment process varied somewhat from plant to plant and was selected as the most accessible downstream location.

Autosamplers were operated by treatment plant staff for the purposes of NPDES compliance. No changes were made to the compositing strategies, which are specified in each permit. Most samplers use a peristaltic pump and Teflon-lined collection tubing, which are maintained by each plant on a regular schedule. In some cases, the composite sample was inadvertently discarded prior to the arrival of Ecology staff, and no sample was analyzed by Ecology. For smaller plants without 24-hour compositing capabilities, Ecology staff collected grab samples. Ecology staff filtered samples at the end of each sampling day. Sample bottles, storage, and hold times are presented in Table 2.

Table 2. Freshwater information by parameter for samples collected from tributaries and wastewater treatment plants. See *Glossary* for abbreviations.

Parameter Name	Code	Method	Laboratory	RSD	Lowest value of interest	Bottle	Preservative	Hold Time
Laboratory								
Ammonium	NH4N	SM 4500 NH3H	MEL	10%	10 ug/L	C	Filter; Cool to 4ºC	28 days
Nitrate + nitrite	NO23N	SM 4500NO3I	MEL	10%	10 ug/L	C	Filter; Cool to 4ºC	28 days
Total dissolved persulfate nitrogen	TDN	SM 4500NO3B	MEL	10%	25 ug/L	C	Filter; Cool to 4ºC	28 days
Total persulfate nitrogen	TN	SM 4500NO3B	MEL	10%	25 ug/L	C	Cool to 4ºC	28 days
Soluble reactive phosphorus	SRP	SM 4500P G	MEL	10%	3 ug/L	D	Filter; Cool to 4ºC	48 hours
Total dissolved phosphorus	TDP	EPA 200.8	MEL	10%	1 ug/L	C	Filter; Cool to 4ºC	28 days
Total phosphorus	TP	EPA 200.8	MEL	10%	1 ug/L	C	Cool to 4ºC	28 days
Total organic carbon	TOC	EPA 415.1	MEL	10%	1 mg/L	E	Cool to 4°C, acidify with 1:1 HCl to pH <2	28 days
Dissolved organic carbon	DOC	EPA 415.1	MEL	10%	1 mg/L	E	Filter; Cool to 4°C, acidify with 1:1 HCl to pH <2	28 days
Carbonaceous BOD5*	BOD5	405.1/521 OB	MEL	25%	2 mg/L	F	Cool to 4ºC, dark	48 hours
Alkalinity	ALK	SM 2320	MEL	10%	10 mg/L	A	Cool to 4ºC	14 days
Dissolved oxygen	DO	Winkler titration	ML	10%	0.1 mg/L	B	Cool to 4ºC, dark	7 days
Field			Equipment					
Temperature	TEMP		Hydrolab	0.025ºC	0.1ºC	NA	NA	NA
Conductivity	COND		Hydrolab	5%	1 umhos/cm	NA	NA	NA
pH	pH		Hydrolab	0.05 SU	1 to 14 SU	NA	NA	NA
Discharge	Q			0.1 ft/s**	0.05 ft/s**	NA	NA	NA

* BOD5 only measured in WWTP effluent, not in tributaries.
** Streamflow measured with velocity meter. Equipment native units are in the English system; 0.1 ft/s = 0.0305 m/s.
Bottle codes:
A. 500-mL wide-mouth polyethylene
B. Nominal 140-mL glass
C. 125-mL clear wide-mouth polyethylene, pre-acidified
D. 125-mL amber wide-mouth polyethylene
E. Pre-acidified 60 mL
F. 1-gallon (4-liter) Cubitainer

Marine Water

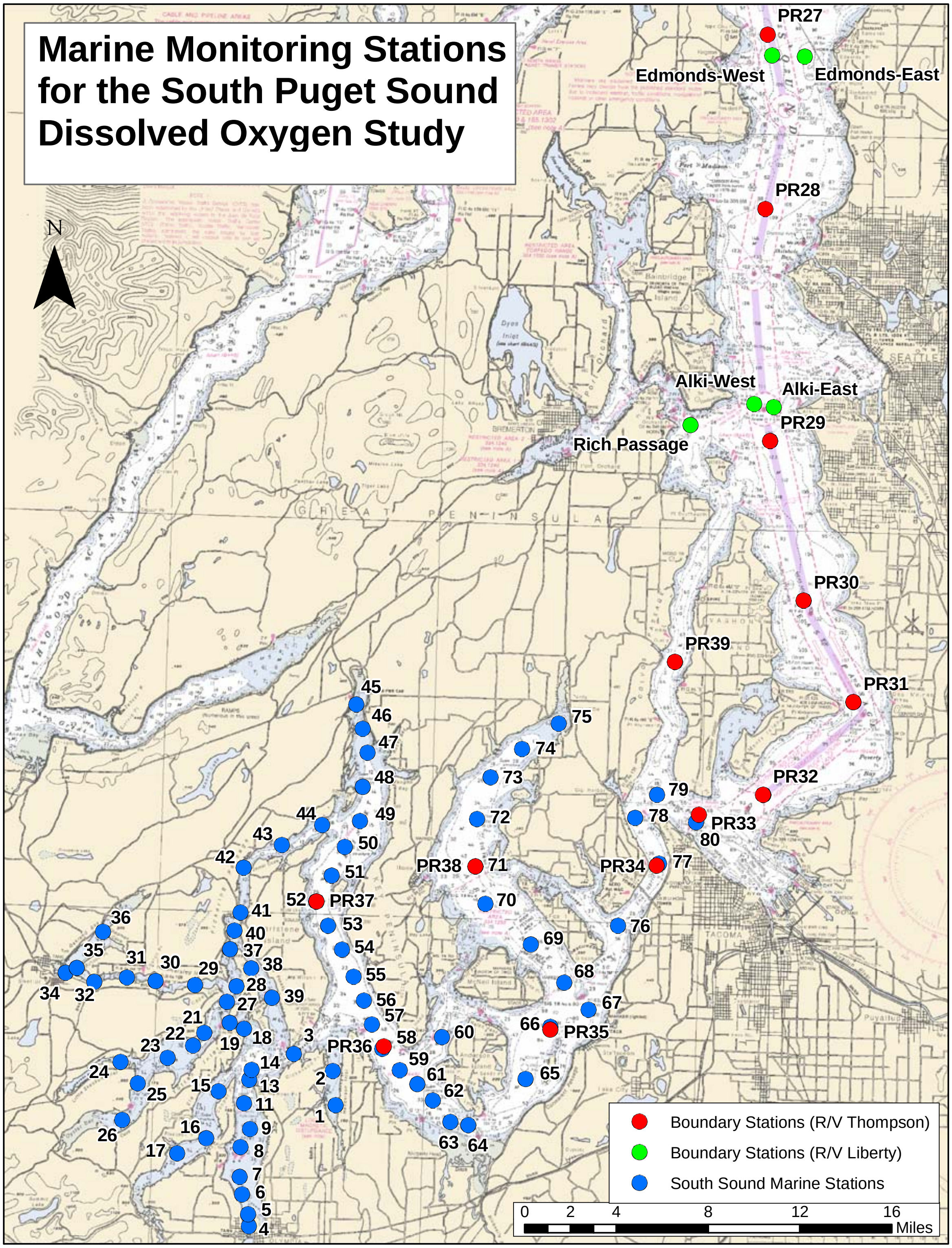
Boundary Station Monitoring

Boundary conditions were assessed during cruises in cooperation with King County using the *R/V Liberty*. Five stations, shown in Figure 7, were sampled approximately monthly between July 2006 and October 2007. PRISM cruises in June and December 2006 and June 2007 provided additional boundary condition data. At each station, vertical conductivity, temperature, and depth (CTD) profiles were taken for temperature, salinity, density, DO, in-situ fluorescence, light transmission, pH, and PAR (photosynthetically active radiation). CTD casts were conducted in accordance with manufacturer protocols (SBE, 2007). In addition, discrete water samples were collected at depths of 0, 5, 10, 30, 50, 100, and 150 meters as depths permitted and near-bottom at all stations, according to methods described in the QA Project Plan. Sample bottles, storage, and holding times are presented in Table 3.

A Secchi disk measurement (called Secchi depth) was recorded at all stations occupied during daylight hours by lowering a standard non-glossy white disk to the depth of its disappearance. Secchi depths, measured to the nearest 0.5 m, were used to calculate the light extinction coefficient. These coefficients were used to estimate euphotic zone depths, or the portion of the water column where there is sufficient light to support photosynthesis. Euphotic zone depths were calculated according to standard equations (Poole and Atkins, 1929; Newton et al., 2002). For the purposes of this study, the euphotic zone is defined as the depth at which 1% of the incident radiation is present (Steemann Nielsen, 1975).

In addition, samples were collected for phytoplankton species identification and biovolume measurements. Results were not available for the present report and will be summarized in a future addendum.

While the water quality criteria generally apply throughout a waterbody, they are not intended to apply to discretely anomalous areas such as in shallow stagnant areas where natural features unrelated to human influences are the cause of not meeting the criteria. For this reason, the standards direct that measurements be taken from well-mixed portions of the waterbody. For the same reason, samples should not be taken from anomalously high DO areas for direct comparison to water quality standards. For example, in a poorly flushed embayment with high nutrient loading, sampling the surface layer during mid-day may produce an anomalously high reading that is caused by the peak photosynthesis cycle of algae. In marine areas in general, the lowest DO levels are expected near the bottom during late summer.



R/V = research vessel

Figure 7. Marine station locations for South and Central Puget Sound. Data collected from six stations common to the project and the Puget Sound Regional Synthesis Model (PRISM) cruises are labeled with the PRISM station location if not collected during a project cruise.

Table 3. Marine sample information by parameter. Group refers to which parameter was measured at each station and cruise. See table codes below and the *Glossary* for abbreviations.

Parameter Name	Code	Group	Method	Labora-tory	RSD	Lowest value of interest	Bottle	Preservation	Hold Time
Laboratory									
Ammonium	NH4N	I, II	6	UW MCL	10%	0.05 uM	C	Filter; Freeze	1-3 months
Nitrate	NO3N	I, II	1	UW MCL	10%	0.15 uM	C	Filter; Freeze	1-3 months
Nitrite	NO2N	I, II	1	UW MCL	10%	0.01 uM	C	Filter; Freeze	1-3 months
Total dissolved nitrogen	TDN	I	8	UW MCL	10%	0.38 uM	D	Filter; Cool to 4ºC	1-3 months
Total nitrogen	TN	I, II	8	UW MCL	10%	0.38 uM	D	Cool to 4ºC	1-3 months
Soluble reactive phosphorus (orthophosphate)	SRP	I, II	2	UW MCL	10%	0.02 uM	C	Filter; Freeze	1-3 months
Total dissolved phosphorus	TDP	I	8	UW MCL	10%	0.02 uM	D	Filter; Cool to 4ºC	1-3 months
Total phosphorus	TP	I, II	8	UW MCL	10%	0.02 uM	D	Cool to 4ºC	1-3 months
Particulate organic carbon and nitrogen	PCN	I	5	UW MCL	10%	10 ug C	G	Filter; Freeze	1-2 months
Dissolved organic carbon	DOC	I	5	UW MCL	10%	50 ug/L	G	Filter; Freeze	1-2 months
Chlorophyll-a	CHLA	I, II	4	ML	10%	0.02 ug/L	F	Filter; Freeze in 90% acetone	1 month
Silicon	SIO2	I, II	1	UW MCL	10%	0.21 uM	C	Filter; Freeze	1-3 months
Alkalinity	ALK	I	7	MEL	10%	1 uM/kg	A	Filter; Cool to 4ºC	1 month
Dissolved oxygen	DO	I, II	3	ML	5%	0.05 mg/L	B	Seal; keep cold and dark	1-5 days
Salinity	SAL	I, II	5	MCL	5%	0.002 PSU	E	Keep dark	1-3 months
Field				Equip-ment					
Temperature	TEMP	III		CTD	0.025 C	0.1 C	NA	NA	NA
pH	pH	III		CTD	0.05 SU	1 to 14 SU	NA	NA	NA
Conductivity	Cond	III		CTD	10%	1 uS/cm	NA	NA	NA
Dissolved oxygen	DO_Raw	III		CTD	5%	0.05 mg/L	NA	NA	NA
Secchi depth	Secchi	III			0.5 m	N/A	NA	NA	NA
Pressure	Pressure	III		CTD	5%	0.1 db	NA	NA	NA
Density	Sigma-T	III		CTD	10%	0.1 σt	NA	NA	NA
Chlorophyll fluorescence	Fluor	III		CTD	10%	0.1 FU	NA	NA	NA
Light transmission	Transmission	III		CTD	10%	0.01 %	NA	NA	NA
Photosynthetically Active Radiation	PAR	III		CTD	Not specified	Not specified	NA	NA	NA

Codes for Table 3

Group:
I. Nutrients monitored at a subset of marine stations
II. Supplemental nutrients sampled from all marine stations during the *R/V Barnes* and *Skookum* cruises
III. CTD casts only

Method
1. Armstrong et al., 1967
2. Bernhardt and Wilhelms, 1967
3. Carpenter, 1966
4. EPA, 1977
5. Grasshoff et al., 1999
6. Slawyk and MacIsaac, 1972
7. Strickland and Parsons, 1968
8. Valderrama, 1981

Bottles
A. 500-mL wide-mouth HDPE
B. Nominal 125-mL glass iodine determination flask
C. 60-mL narrow-mouth HDPE
D. 60-mL wide-mouth HDPE
E. 125-mL amber wide-mouth HDPE (pre-treated w/ salt water)
F. 65-mL amber narrow-mouth HDPE
G. 1-L wide-mouth HDPE

South Sound Station Monitoring

Sixteen data collection cruises were conducted between July 2006 and October 2007 using the *R/V Barnes* or the *Skookum*. The *R/V Barnes* collected data from over 80 stations while the *Skookum* collected data from a subset of 40 stations. Table A-1 in the QA Project Plan (Albertson et al., 2007) provides details on the sampling plan for each station.

More intensive sampling was conducted in September 2006 and September 2007 to coincide with expected critical conditions. At each station, vertical CTD profiles were taken for temperature, salinity, density, DO, in-vivo fluorescence, light transmission, pH, and PAR. CTD casts were conducted in accordance with manufacturer protocols (SBE, 2007). Discrete water samples were collected at depths of 0, 5, 10, 30, 50, and 100 meters, and near-bottom, according to methods described in the QA Project Plan. A sub-set of these depths, including near-bottom, were sampled for shallow stations. Sample bottles, storage, and holding times are presented in Table 3. Figure 7 and Table 3 summarize the locations and logistics for South Sound station monitoring.

In addition, samples were collected for phytoplankton species identification as well as biovolume and primary productivity measurements. These data were not available for the present report and will be summarized in a future addendum.

Acoustic Doppler Current Profilers (ADCPs)

The first addendum to the QA Project Plan summarized the experimental design for ADCP deployments. The plan included both instantaneous surface-mounted transects and longer-term bottom-mounted deployments of ADCPs in key locations. Resulting measurements will help scientists understand circulation and currents in South Puget Sound. Transects were conducted to (1) assess current variability across each transect and with depth, and (2) develop instantaneous mass fluxes of water to compare with model output. Bottom-mounted ADCPs were deployed to evaluate temporal velocity patterns and factors influencing circulation patterns such as wind events.

Transects

Surface transects were conducted at five inlets (Budd, Carr, Case, Eld, and Totten) on a rising tide on July 10-12, 2007. Each transect consisted of a single pass, as near to shore as possible. An additional transect was conducted in June 2007 across Dana Passage to verify the maximum depth achievable, assess potential error incurred with a single pass, and serve as a field replicate. Figure 8 presents the July 2007 transect locations. Transects were recorded within several hours but do not represent synoptic conditions.

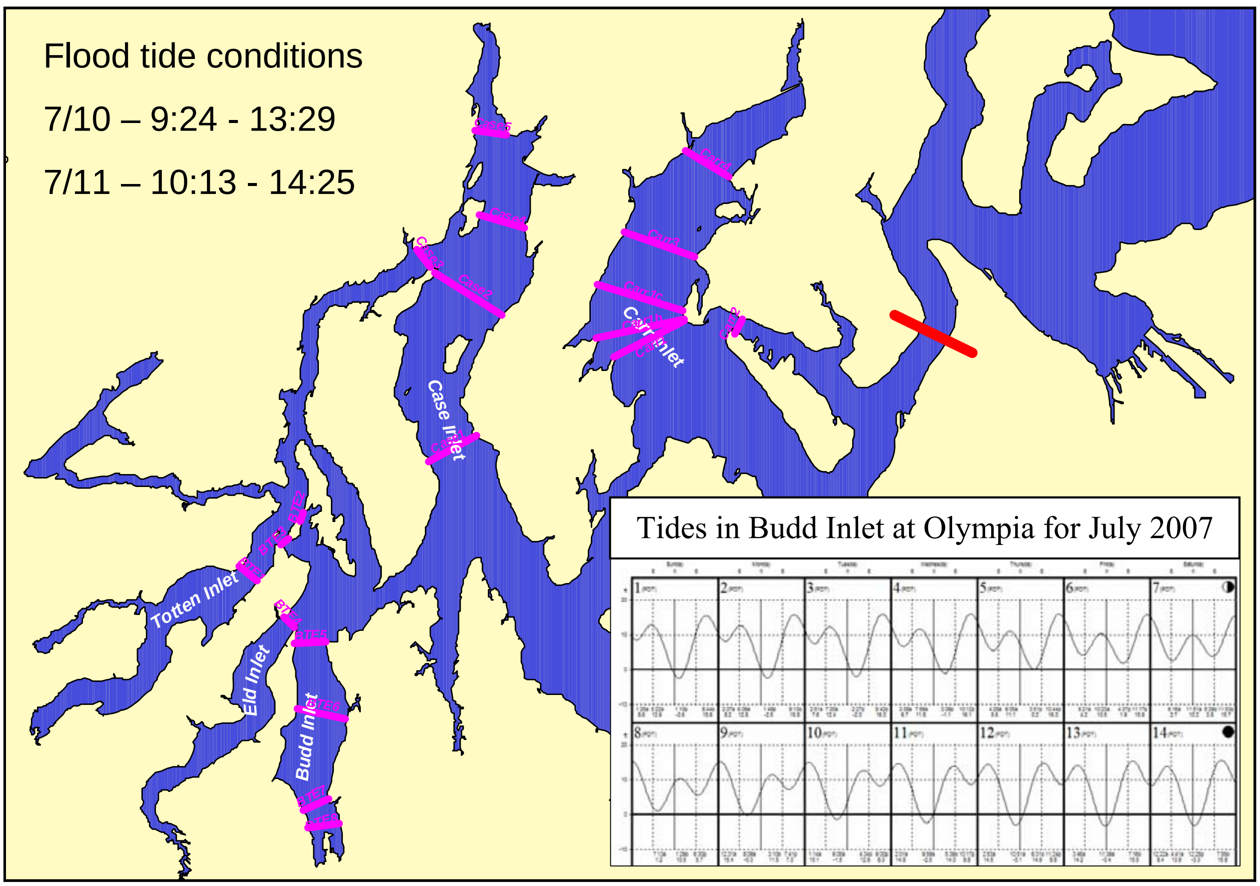


Figure 8. Surface-mounted ADCP transect locations for July 10-12, 2007. Times for high tide and low tide at Budd Inlet each day are indicated in the top left. On July 10 and 11, low tide occurred at 9:05 and 9:59 a.m., and high tide at 4:34 and 5:39 p.m., respectively, based on predictions for Budd Inlet at Olympia.

In addition, to understand transport patterns near Hope Island, supplemental transects were recorded on September 26, 2007, both during flood and ebb tide. These transects were not synoptic, but the time lag between adjacent transects was minimized to enable flux comparisons between transects. Figure 9 presents the September 2007 Hope Island transect locations. Ebb-tide surveys were conducted between 8:00 a.m. and 12:00 p.m., while flood-tide surveys were conducted between 1:10 p.m. and 4:30 p.m. Slack low tide occurred at 12:00 p.m.

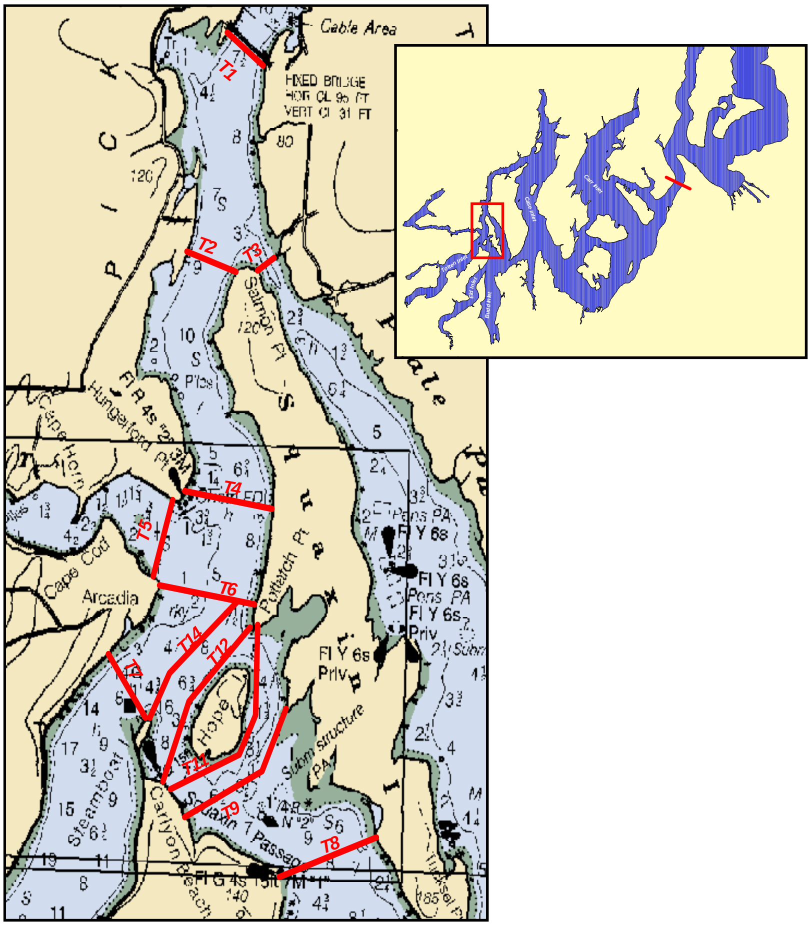


Figure 9. September 2007 ADCP transect locations planned for both ebbing and flooding tide conditions. Inset provides the location of the detailed transects.

Deployments

Paired bottom-mounted ADCPs were deployed in three inlets between August and October 2007. They were deployed in Carr Inlet between August 14 and September 7, in Case Inlet between September 7 and 21, and in Budd Inlet from September 21 and October 17. Specific locations were selected based on information collected in July to avoid complex cross-channel flow patterns. Figure 10 presents the station locations.

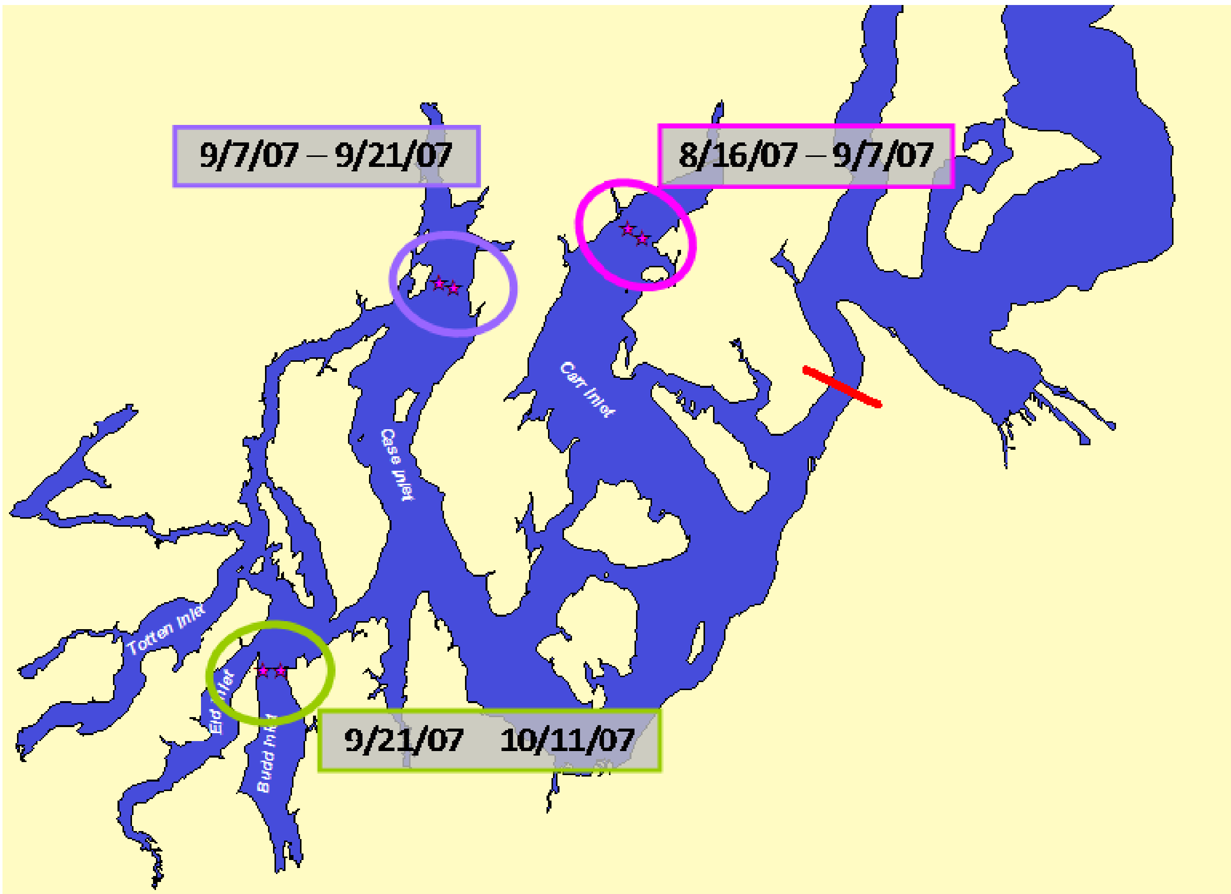


Figure 10. Bottom-mounted ADCP deployments for August through October 2007.

Additional bottom-mounted ADCP deployments were conducted from October 18 through December 24, 2007 to understand the complex flow patterns around Hope Island (Figure 11). In October, bottom-mounted ADCPs were deployed on the North Squaxin (T2) transect in Pickering Passage in a depth of about 20 m (47º 13' 36.3" N and -122º 55' 54.8" W) and along the South Squaxin (T8) transect east of Hope Island at about 15 m depth (47º 10' 29.7" N and -122º 54' 56.1" W). A third ADCP was bottom-mounted along the Totten Inlet (T7) transect in about 30 m of water (47º 11' 21.0" N and -122º 56' 42.0" W) and moved on November 21 to the Hammersley Inlet (T6) transect near Potlatch Point (47º 11' 55.2" and -122º 55' 37.8" W). All but the South Squaxin ADCP were retrieved; the final ADCP has not yet been recovered.

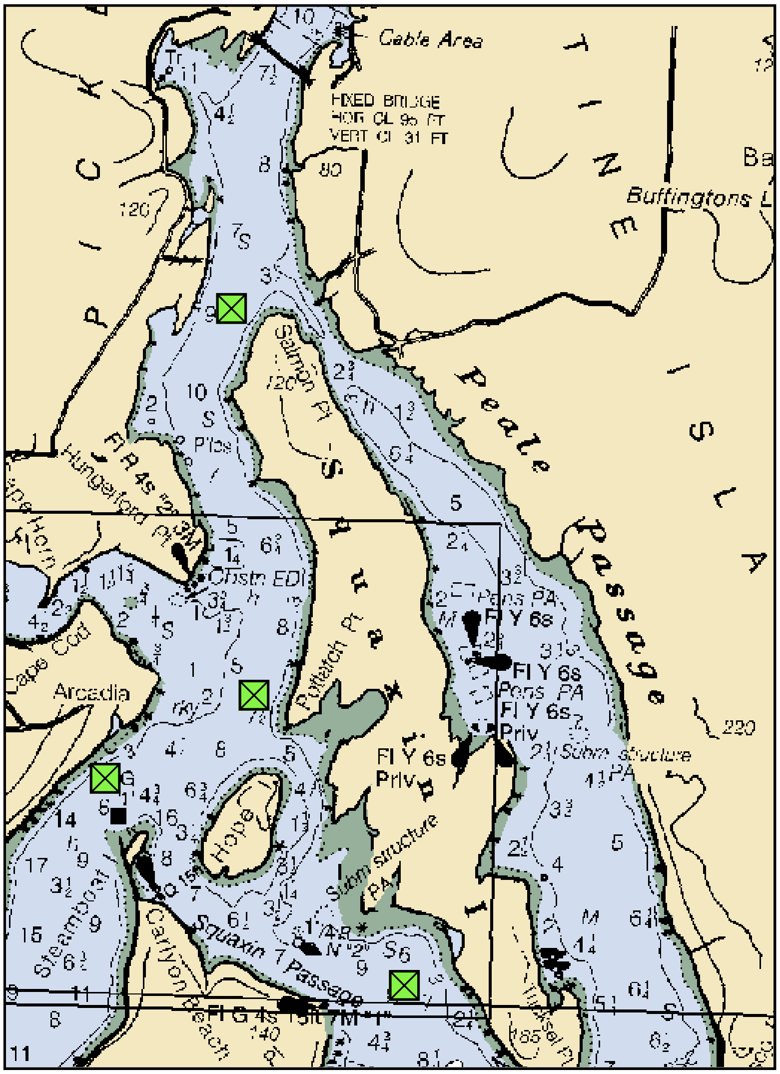


Figure 11. Bottom-mounted ADCP deployments for October through December 2007. The southernmost deployment has not been located.

Benthic Flux

Benthic flux of oxygen and nutrients between the sediment and the water column likely influence DO levels in South Puget Sound. Addendum #2 to the QA Project Plan (Roberts and Coomes, 2007) presented the experimental design for the benthic flux study, which was designed to quantify sediment and water column fluxes. Three benthic flux chambers were deployed in each of four inlets (Budd, Carr, Case, and Eld), with stations corresponding to nominal depths of 5, 15, and 25 m. A total of six chambers were deployed over two inlets and retrieved the following day. The chambers were then shifted to the remaining six locations over two inlets and retrieved on the fourth day of the program. Three rounds of benthic flux sample deployments were conducted in September and October 2007. Construction and operation of the benthic flux chambers followed standard operating procedures (Roberts, 2007).

Each chamber was equipped with a calibrated Hydrolab Data Sonde 3 multi-probe that recorded temperature, DO, salinity, and pH continuously (30-min intervals) during deployment. Hydrolabs were pre-calibrated and post-checked according to standard operating procedures (Swanson, 2007).

Once the units were deployed, samples were collected immediately following deployment then up to four times prior to retrieval using a peristaltic pump. Table 4 summarizes sample parameters and logistics for benthic flux chambers, while Figure 12 summarizes the deployment locations. The original plan anticipated the same locations would be reoccupied in subsequent sampling rounds; however, the actual deployment locations varied somewhat.

Table 4. Benthic flux chamber sample information. See the *Glossary* for laboratory codes and the notes to Table 3 for method codes.

Parameter	Laboratory	Method	Bottle	Preservative	Hold time
Dissolved oxygen	ML	3	A	Cool to 4ºC; dark	3-5 days
Ammonium	SFSU	6	B	Filter; freeze	1-3 months
Nitrate	SFSU	1	B	Filter; freeze	1-3 months
Nitrite	SFSU	1	B	Filter; freeze	1-3 months
Total nitrogen	UW MCL	8	C	Cool to 4ºC	1-3 months
Soluble reactive phosphorus	SFSU	2	B	Filter; freeze	1-3 months
Total phosphorus	UW MCL	8	C	Cool to 4ºC	1-3 months

Bottle codes:

A. 125-mL glass iodine titration flask
B. 175-mL acid-washed and rinsed HDPE
C. 60-mL wide-mouth HDPE

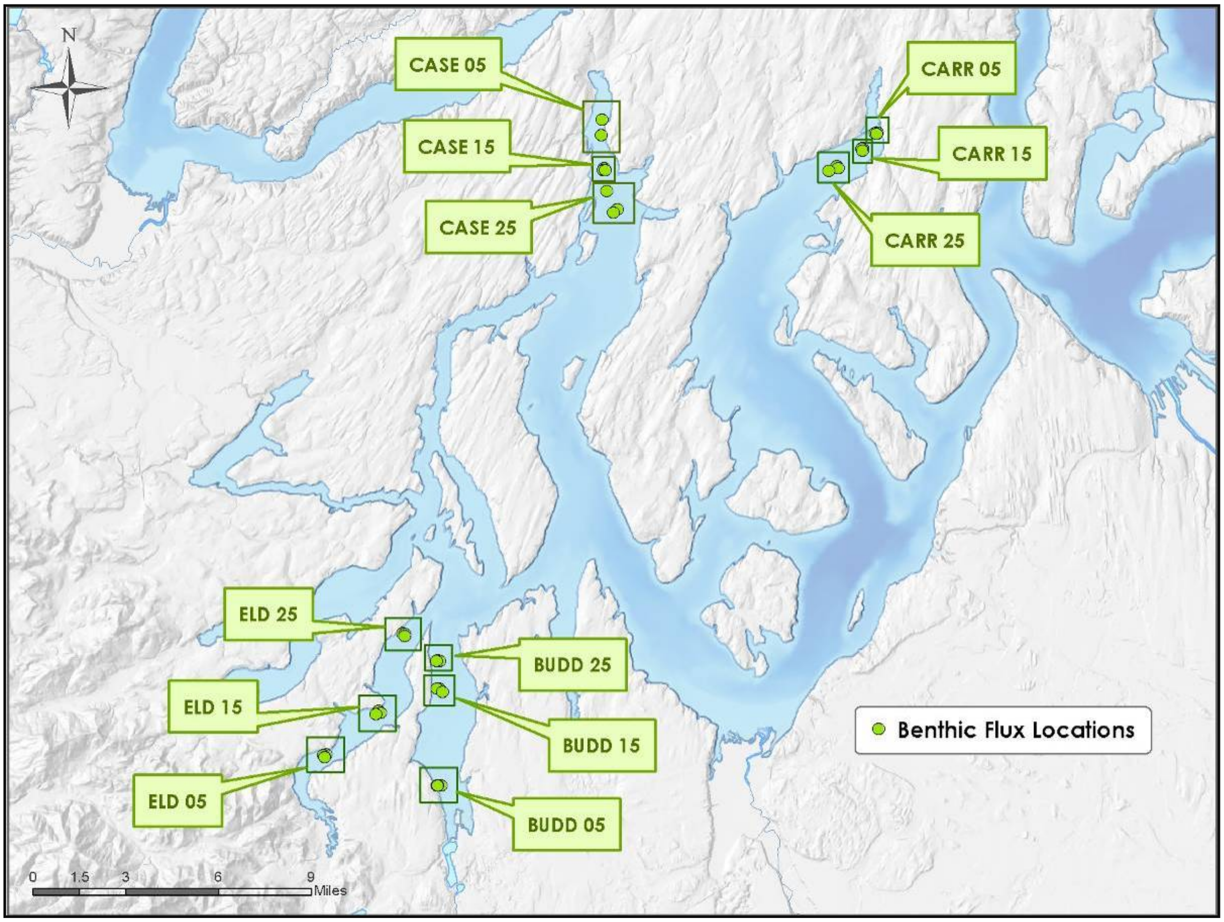


Figure 12. Benthic flux chamber deployment locations for September and October 2007.

Sediment Traps

Addendum #3 to the QA Project Plan (Roberts and Pelletier, 2007) described the experimental design for the sediment trap study. The survey continued through May 2008, and the results will be summarized in a future addendum to this data report.

Quality Assurance Assessment

All environmental studies conducted by Ecology must have an approved Quality Assurance (QA) Project Plan that documents study objectives and procedures for achieving those objectives (Lombard and Kirchmer, 2004). In addition to describing the sampling design and protocols, the plan also establishes data quality objectives.

This section summarizes the quality control procedures for the data collection described in Albertson et al. (2007) and specifically reports the measurement quality objectives (MQOs). MQOs include field meter pre- and post-calibration results, laboratory blanks, laboratory spikes, laboratory replicates, and field replicates.

Freshwater Data

Freshwater data include field meter-collected data and laboratory results for tributary and wastewater treatment plant (WWTP) effluent characterization.

Field Meter Pre- and Post-calibration

Table 13 of the QA Project Plan established MQOs for field measurements. All field meters were calibrated according to the manufacturer's recommendations. Hydrolab measurements followed standard operating procedures (Swanson, 2007), while streamflow measurements followed protocols in Ecology (1993). All Hydrolabs passed pre- and post-deployment checks. No field replicates were recorded for temperature, conductivity, pH, or streamflow.

Winkler DO samples were collected as a field check on the meter readings. For tributaries, 23 Winkler DO samples were collected to check 277 measurements (8.3% of samples), including six sites where multiple replicate Winkler DO samples were collected. At these six sites, Winkler DO results showed very low variability (0.3% RSD). The Hydrolab measurements showed low overall variability when compared with the Winkler results (2.7% mean RSD for 23 replicates) and all comparisons were <10% RSD. No supplemental samples were collected for Winkler titration from WWTPs.

Laboratory Blanks, Spikes, and Replicates

All samples were analyzed by Manchester Environmental Laboratory (MEL) using standard protocols (MEL, 2005). MQOs were presented in Table 13 of the QA Project Plan (Albertson et al., 2007). All samples were received and processed by MEL within established hold times, within the proper temperature range, properly preserved where applicable, and in good condition.

MEL qualifies any data that did not meet calibration checks or that may have parameters that could affect results. For WWTP samples that included chlorine, a neutralizer (sodium sulfite) was added that could affect the results; all BOD results were qualified as estimates. In addition, some laboratory calibration checks were not within acceptance limits, and these results are reported as estimates. For WWTP samples, matrix spikes may not have been high enough to provide an adequate check on the nutrient-enriched results.

Table 5 summarizes the QA results for both tributary and WWTP monitoring. MQOs were met for the project for laboratory quality control samples.

Laboratory blanks were generally below the reporting limit throughout the 2006-07 monitoring period. Levels slightly above the reporting limit were found in a few samples on occasion, such as for dissolved and total phosphorus and ammonium, but values were well below concentrations of interest in either tributaries or WWTPs.

Mean laboratory control samples (spikes) were within the acceptance criteria for the datasets for both tributaries and WWTPs. Individual sample pairs fell outside the acceptance criteria for a few samples, but these did not occur on the same date for all parameters. Carbon samples had the highest incidence of individual pairs falling outside of the acceptance criteria, and the results were qualified as estimates. For the tributary results, 2 values out of 19 total fell beyond the acceptance range for dissolved organic carbon (DOC), and 1 out of 13 for total organic carbon (TOC). For WWTP samples, 2 values out of 16 total fell beyond the acceptance range for DOC, and 3 out of 11 for TOC. In addition, 2 values out of 13 for WWTP ammonium samples and 1 out of 13 for WWTP orthophosphate samples fell beyond the acceptance criteria and were qualified as estimates.

Laboratory replicates met the target mean relative standard deviation (RSD) for the entire dataset. Carbon results for tributaries showed the greatest variability, with 3 out of 22 DOC pairs and 1 out of 22 TOC pairs with individual results above the target RSD. However, the dataset overall met the objectives, and these individual results were qualified as estimates. Similarly for WWTP samples, 1 out of 61 sample pairs for inhibited BOD (BODINH), 2 out of 18 sample pairs for DOC, and 1 out of 23 sample pairs for dissolved total persulfate nitrogen (DTPN) fell beyond the target and were qualified as estimates.

Table 5. Quality assurance assessment for freshwater data. See *Glossary* for abbreviations.

Parameter	Laboratory blanks (mg/L)				Laboratory spikes (%)				Laboratory replicates (%)			
	Count	Mean Value	Reporting Limit	Range	Count	Mean Value	Acceptance Criteria	Range	Count	Mean RSD	Target	Range
Tributary Results												
ALK	29	5	5	5 – 5			75 – 125				10%	
BOD5INH	NC				NC				24	0.4%		0.0 – 2.1%
DOC	42	1	1	1 – 1	19	95.0	75 – 125	72 – 128	22	5.8%	10%	0.0 – 32.1%
DTP	31	0.0013	0.001	0.001 – 0.010	31	98.8	75 – 125	91 – 115	5	1.9%	10%	0.5 – 3.4%
DTPN	26	0.025	0.025	0.025 – 0.025	16	97.6	75 – 125	83 – 107	21	2.3%	10%	0.0 – 14.4%
NH4N	24	0.010	0.010	0.010 – 0.010	16	93.6	75 – 125	83 – 103	20	1.0%	10%	0.0 – 6.7%
NO23N	29	0.010	0.010	0.010 – 0.010	16	95.2	75 – 125	86 – 105	23	0.3%	10%	0.0 – 1.3%
OP	34	0.003	0.003	0.003 – 0.003	21	99.6	75 – 125	94 – 110	26	0.7%	10%	0.0 – 3.4%
TOC	44	1	1	1 – 1	13	94.5	75 – 125	42[1] – 118	22	5.0%	10%	0.0 – 33.3%[2]
TP	37	0.001	0.001	0.001 – 0.001	32	99.7	75 – 125	83 – 117	9	1.0%	10%	0.0 – 2.7%
TPN	26	0.025	0.025	0.025 – 0.025	16	98.1	75 – 125	86 – 113	24	2.2%	10%	0.0 – 8.2%
Wastewater Treatment Plant Results												
ALK	40	5	5	5 – 5			75 – 125		28	0.3%	10%	0.0 – 0.6%
BOD5INH	51	0.026	4	-0.29 – 0.18					61	3.8%	25%	0.0 – 37.2%[3]
DOC	59	1	1	1 – 1	16	91.6	75 – 125	68 – 129	18	2.7%	10%	0.0 – 12.3%
DTP	47	0.0018	0.001	0.001 – 0.010	27	99.5	75 – 125	82 – 118	6	0.7%	10%	0.0 – 1.7%
DTPN	42	0.025	0.025	0.025 – 0.025	20	89.7	75 – 125	82 – 99	23	3.0%	10%	0.0 – 47.5%[4]
NH4N	43	0.012	0.010	0.010 – 0.100	13	95.3	75 – 125	56 – 241[5]	15	1.4%	10%	0.0 – 9.8%
NO23N	42	0.010	0.010	0.010 – 0.010	12	93.3	75 – 125	81 – 108	12	0.9%	10%	0.0 – 7.3%
OP	62	0.003	0.003	0.003 – 0.0054	13	107.4	75 – 125	93 – 148	17	1.5%	10%	0.0 – 5.5%
TOC	57	1	1	1 – 1	11	82.7	75 – 125	46[6] – 105	19	2.6%	10%	0.0 – 9.1%
TP	45	0.0016	0.001	0.001 – 0.010	26	103.4	75 – 125	88 – 125	5	1.0%	10%	0.2 – 1.2%
TPN	44	0.025	0.025	0.025 – 0.025	18	93.3	75 – 125	83 – 112	23	0.9%	10%	0.0 – 3.9%

[1] Corollary laboratory spike sample for DOC had 97% recovery. Without the single 42% recovery, the dataset mean matrix spike recovery is 98.8%.
[2] Both TOC and DOC laboratory replicates in October 2006 had anomalously high values. All other individual TOC lab splits were <7% RSD. A second anomalously high laboratory replicate for DOC occurred in September 2006.
[3] Anomalously high lab replicate for BOD5INH occurred August 2006. Next highest value was 20.2%.
[4] Anomalously high lab replicate for DTPN occurred March 2007. Corresponding TPN had lab replicate value of 2.1% RSD. Next highest value was 2.2% RSD.
[5] Anomalously high lab replicate for NH3 occurred April 2007. Next highest value was 110%.
[6] Corollary laboratory spike sample for DOC had 85% recovery. Without the single 46% recovery, the dataset mean matrix spike recovery is 86.4%.

Field Replicates

Field replicates were collected from one tributary or WWTP location per sampling event, or at a nominal rate of 4.9% for tributary samples and 5.2% for WWTP samples for laboratory analytes. Field replicates met the project target RSD for all tributary and WWTP samples. Individual field replicate pairs fell outside the target, but these instances did not occur on the same date or from the same location to suggest a bias in the results. For the data analyses presented in the remainder of this document, the original sample value was used; the field replicates were used for QA assessment only. Table 6 summarizes results for field replicates by parameter.

Table 6. Field replicates (%) for tributary and wastewater treatment plant samples. See *Glossary* for abbreviations.

Parameter	Count	Mean RSD	Target Mean Dataset RSD	Range
Tributary Results				
ALK	15	2.1%	10%	0.0 – 22.4%
BOD5INH	NC		NC	
DOC	15	4.3%	10%	0.0 – 10.1%
DTP	15	2.5%	10%	0.6 – 6.6%
DTPN	15	5.6%	10%	0.0 – 12.1%
NH4N	15	1.7%	10%	0.0 – 12.9%
NO23N	15	1.4%	10%	0.0 – 8.0%
OP	15	7.5%	10%	0.0 – 80.1%[1]
TOC	15	6.0%	10%	0.0 – 18.4%
TP	15	3.4%	10%	0.0 – 14.5%
TPN	15	6.5%	10%	0.0 – 26.7%
Wastewater Treatment Plant Results				
ALK	14	5.3%	10%	0.0 – 71.2%[2]
BOD5INH	14	14.0%	25%	0.0 – 47.1%[3]
DOC	14	6.7%	10%	0.0 – 23.4%
DTP	14	1.0%	10%	0.0 – 3.0%
DTPN	14	2.4%	10%	0.0 – 9.8%
NH4N	14	5.8%	10%	0.0 – 18.5%
NO23N	14	9.2%	10%	0.2 – 70.2%[4]
OP	14	3.1%	10%	0.3 – 16.3%
TOC	13	4.3%	10%	0.0 – 13.4%
TP	14	2.1%	10%	0.1 – 7.7%
TPN	14	4.7%	10%	0.4 – 11.4%

[1] Anomalously high field replicate for OP occurred May 2007. Next highest value was 5.2%. Without value, dataset field replicate mean was 2.3% RSD.
[2] Anomalously high field replicate for alkalinity occurred July 2007. Next highest value was 0.7%. Without value, dataset field replicate mean was 0.2% RSD.
[3] Anomalously high field replicate for BOD5INH occurred April 2007. Next highest value was 38.6%. Without value, dataset field replicate mean was 11.4% RSD.
[4] Anomalously high field replicate for NO23N occurred August 2006. Next highest value was 14.7%. Without value, dataset field replicate mean was 4.5% RSD.

Marine Water Data

Marine water column data collection was carried out with conductivity, temperature, and depth (CTD) Sea-Bird Electronics instrument packages (in-situ vertical profiles of select parameters) and discrete laboratory sample analyses. This was done to characterize chemical and biological characteristics of select stations. See the *Experimental Design* section and Table 4 of the QA Project Plan (Albertson et al., 2007) for description of marine surveys and station locations, respectively. See Appendix B for the instrument details. Parameters measured by each type of sampling were listed in Table A-1 of the QA Project Plan.

CTD Calibration

Table 12 of the QA Project Plan established MQOs for CTD measurements. CTD sensors were calibrated according to manufacturer's recommendations (Sea-Bird Electronics, 2007), and CTD deployments were carried out according to recommended protocols. Replicate casts were taken at selected stations on *Barnes* and *Skookum* cruises to determine reasonableness and reliability of CTD performance. Appendix B lists calibration dates and includes calibration certificates for all CTD sensors used.

Dissolved Oxygen (DO) Sensor Calibration

CTD DO sensor measurements from each cruise were calibrated using discrete Winkler DO samples according to the Winkler-to-CTD DO ratio method described in Sea-Bird Electronics (2008).

CTD DO voltage was first calibrated using current sensor calibration coefficients provided by the manufacturer (Step 1). These initial estimates of CTD DO were used to calculate an average DO ratio between Winkler-titration data and CTD DO readings. The original sensor calibration slope term (SOC1) was multiplied by this ratio to generate a refined slope term (SOC2, Step 2). Data from individual cruises were grouped together in order to calculate cruise-specific Winkler-to-CTD DO ratios and SOC2 values. New SOC2 values were used in combination with original calibration voltage offsets (Voffset1) and Phi values (estimated per Sea-Bird Electronics protocols) to calculate final CTD DO results for a particular cruise (Step 3). The following equations are used in this method:

- Step 1- Initial Calibration: CTD DO = SOC1*(CTD DO Voltage + Voffset1)*Phi
- Step 2- Sensor Calibration: SOC2 = SOC1 * (mean Winkler-to-CTD DO)
- Step 3- Refined/Final Calibration: CTD DO = SOC2*(CTD DO Voltage + Voffset1)*Phi

Corrections are applied to data averaged over 0.5-m bins. This method has been reviewed and approved by Sea-Bird Electronics (Appendix D).

The number of Winkler DO samples collected to correct the CTD DO data varied by cruise. For *Liberty* cruises, approximately 40 Winkler DO samples were collected on each cruise to calibrate approximately 1700 depth-averaged (in 0.5-m bins) data records, or approximately 2.5% of all samples. For *Barnes* cruises, approximately 200 Winkler DO samples were collected to calibrate

7500 depth-averaged data records, or 2.7% of samples. For *Skookum* cruises, 28 Winkler DO samples were collected on average to calibrate 3,000 depth-averaged data records, or 1% of samples.

The root-mean-squared-error (RMSE) of calibrated data relative to Winkler results was calculated for each voyage and is shown in Table 7. Applying the procedure described above decreased the mean overall RMSE from 0.74 to 0.36 mg/L.

Table 7. Root-mean-squared-error between Winkler DO values and CTD results prior to and following calibration using the method described above.

Cruise	CTD Dissolved Oxygen	
	Before calibration	After calibration
R/V Barnes		
B1 - Jul06	0.700	0.682
B2 - Sep06	1.038	0.652
B3 - Dec06	0.528	0.474
B4 - Apr07	0.625	0.600
B5 - Jun07	4.536	0.673
B6 - Sep07	0.752	0.555
R/V Skookum		
S1 - Aug06	0.346	0.321
S2 - Oct06	0.533	0.144
S3 - Nov06	0.150	0.155
S4 - Feb07	0.541	0.431
S5 - Mar07	0.529	0.522
S6 - Apr07	0.562	0.506
S7 - May07	1.168	0.369
S8 - Jul07	0.969	0.604
S9 - Oct07	0.908	0.550
R/V Liberty		
L1 - Jul06	0.695	0.497
L2 - Aug06	0.416	0.262
L3 - Sep06	0.546	0.360
L4 - Oct06	0.381	0.102
L5 - Nov06	0.706	0.307
L6 - Dec06	0.511	0.265
L7 - Jan07	0.644	0.454
L8 - Feb07	0.480	0.194
L9 - Mar07	0.428	0.106
L10 - Apr07	0.442	0.146
L11 - May07	0.679	0.252
L12 - Jun07	0.699	0.315
L13 - Jul07	0.595	0.381
L14 - Aug07	0.563	0.140
L15 - Sep07	0.572	0.091
L16 - Oct07	0.650	0.117

Replicate Winkler DO samples were collected at a selected station on each cruise. At these stations, Winkler DO results showed very low variability (1.9% RSD). All individual results were <10% RSD.

pH Sensor Calibration

A pH sensor was added to CTD packages on each cruise, starting in September 2006. Due to the highly sensitive nature of the pH sensor, measurements drifted significantly or failed on several sampling events, despite bimonthly calibration and strict adherence to prescribed maintenance protocols. All pH data were inspected and put through rigorous QA tests. Any questionable pH data were removed from the dataset.

Laboratory Instrument Calibration

The Ecology Marine Lab (ML) is accredited by Washington State's Environmental Laboratory Accreditation Program. The ML is accredited for analyses of two parameters: dissolved oxygen and chlorophyll-a. Methods for these analyses are listed in Table 3. To maintain accreditation, the lab analyzes blanks and standards during every sample run (10-40 samples). In addition, replicate samples are collected to test precision in the lab.

Lab fluorometers (Turner Designs model 10AU) used for chlorophyll-a determination are calibrated with a primary standard annually to test performance and set calibration coefficients. A secondary standard is analyzed at least twice during daily sample runs to test for instrument control. By means of analyses of the secondary standard, an instrument drift was detected in late 2006. This drift resulted in an underestimation of chlorophyll-a by ~1 ug/L. In winter, when levels are already very low, this underestimated final chlorophyll values by about 50%. In the spring/summer/fall, when chlorophyll values were higher, this effect underestimated final chlorophyll levels by 5-10%.

In addition, a primary standard was not readily available from the scientific supplier, so calibration of the instrument was delayed. A second calibrated fluorometer (Turner Designs model 10) was used to analyze samples. Once the primary standard was available, the instrument was "post-calibrated" and coefficients were calculated. These post-calibration coefficients were applied to data collected from July – December 2006. An applications scientist at Turner Designs, the instrument manufacturer, validated the appropriateness of this correction method.

Laboratory Blanks, Spikes, Replicates

Ecology Marine Lab

Dissolved oxygen (DO) and chlorophyll-a samples were analyzed by Ecology's Marine Lab (ML) using standard protocols (Stutes and Bos, 2007). Measurement quality objectives were presented in Table 12 of the QA Project Plan. All samples were received and processed by ML within established hold times, within the proper temperature range, properly preserved where applicable, and in good condition. Table 8 summarizes the QA results for DO and chlorophyll-a analyses. Measurement quality objectives were met for the project for laboratory quality control samples.

Overall, laboratory blanks were generally at or below the reporting limit throughout the monitoring period, with one exception. Method blank determination revealed a low amount of contamination in a sub-set of chlorophyll-a samples collected in September 2007. Although the potential effect on the final values was determined to be <0.06 ug/L (less than the reporting limit), samples analyzed during this time period were qualified as estimates.

Mean laboratory control samples (standards) were within the acceptance criteria for marine water column data. Laboratory replicates met the target mean relative standard deviation (RSD) for the entire dataset. Chlorophyll-a replicates had the greatest variability. Several pairs fell outside of the acceptance criteria, but these did not all occur on the same date or cruise so no bias was detected. Whether this variability was due to sampling technique, filtration technique, or actual laboratory analyses was not readily discernible. These samples were qualified as estimates in the final dataset. Additionally, replicate Winkler DO samples were collected at a selected station on each cruise. At these stations, Winkler DO results showed very low variability (1.9% RSD). All individual results were <10% RSD and met the overall objectives.

Manchester Environmental Lab

Alkalinity samples were analyzed by Manchester Environmental Laboratory (MEL) using standard seawater protocols. Measurement quality objectives (MQOs) were presented in Table 12 of the QA project Plan. All samples were received and processed by MEL within established holding times, within the proper temperature range, properly preserved where applicable, and in good condition. All results fell within calibration criteria, and all blanks were well below the reporting limit.

Table 9 summarizes the QA results for alkalinity analyses. MQOs were met for the project for laboratory quality control samples.

Mean laboratory control samples (standards) were within the acceptance criteria for marine alkalinity data. Several batches of a certified standard were obtained from Scripps Institute of Oceanography. These standards were formulated with natural seawater and had different concentrations of alkalinity, thus standard recovery is presented as a percentile. Laboratory control sample analysis was excellent with an overall mean for the dataset of 101%, based on acceptance criteria of 95% - 105%.

Laboratory replication was excellent, with a mean RSD for the entire dataset of 0.6%, well below the target mean of 10%.

UW Marine Chemistry Lab

Samples were analyzed by the UW Marine Chemistry Lab (MCL) for the following parameters: dissolved inorganic nutrients (nitrate, nitrite, ammonium, orthophosphate, and silicate), total persulfate nitrogen, total dissolved persulfate nitrogen, total phosphorus, total dissolved phosphorus, and salinity. MQOs were presented in Table 12 of the QA Project Plan. All samples were received and processed by MCL within the proper temperature range, properly preserved where applicable, and in good condition. In a few instances, holding times were exceeded for dissolved inorganic nutrient analyses. Parameters primarily affected by these extended hold times were ammonium and silicate. Samples held past established storage times were qualified as estimates.

Ecology qualified any data that did not meet calibration checks or that may have constituents that could affect results. One of the primary challenges of seawater nutrient analyses (dissolved and total) is the lack of available seawater nutrient blanks that have the same salinity matrix and concentration as that of Puget Sound samples. Standard procedures call for the use of low nutrient seawater (LNSW) collected from specific ocean sites for the preparation of standards and blanks. UW MCL uses natural low nutrient seawater for preparation of standards and blanks, referred to as seawater checks. Samples contained detectable concentrations of parameters such as nitrate and silicate and slightly elevated levels of others like orthophosphate and nitrite. Although used as blanks, these concentrations are often above the reporting limits and consequently are factored into the calculation of the standard concentrations.

For total nitrogen and phosphorus analyses, standard procedures prescribe the inclusion of method (reagent) blanks in the persulfate digestion step. By nature of its preparation, persulfate will have detectable concentrations of nitrogen and phosphate contamination. Thus, blank analyses reveal the levels of nitrogen and phosphate present in the digestion reagent. Method blank results are used to generate a factor to account for reagent contributions.

Table 9 summarizes the QA results for nutrient and total nitrogen and total phosphorus analyses. MQOs were met for the project for laboratory quality control samples.

Laboratory blanks were analyzed from several different batches of LNSW throughout the monitoring period. Analyses of nutrient blanks revealed that values were relatively low when compared to the sample dataset, and any contribution effects to final results were factored out.

Mean laboratory control samples (standards) were within the acceptance criteria established by lab for marine nutrient and total nitrogen and phosphorus results. A few individual NH_4 standards fell outside the acceptance criteria, but these did not occur on the same date, so no analytical bias was detected. Results associated with standards that exceeded acceptance criteria were qualified as estimates.

Laboratory replicates met the target mean RSD for the entire dataset. Individual sample pairs fell outside the acceptance criteria for a few samples, but these did not occur on the same date for all parameters, so no bias was detected. NH_4 and NO_3 results showed the greatest variability, with more individual results above the target RSD. Several individual pairs fell below the reporting limit, and due to the low concentrations, variability as low as 0.01 uM results in very high RSDs. Thus all replicate results below reporting limit were removed from the dataset analyses and qualified as estimates. Overall the dataset met the objectives.

Dissolved organic carbon (DOC) samples and particulate organic carbon and nitrogen (PCN) samples were collected and sent to UW MCL for analyses. Starting in the fall of 2006, the lab experienced a failure of the instrument used to analyze DOC samples (Postel, personal communication), and results did not differentiate between the organic and inorganic fraction. Analysis of carbon standards failed to reveal contamination by the inorganic fraction, as standards are formulated from organic carbon only. Supplemental analyses and QA tests are necessary to determine if any results are viable. In addition, PCN data will be presented concurrently with the DOC results.

Field Replicates

Field replicates were collected on each research cruise at a nominal rate of 5% for laboratory analytes. Field replicates met the project target RSD for all marine water samples. The highest variability of field replication was seen in chlorophyll-a and dissolved nutrient results. Individual field replicate pairs fell outside the mean target RSD, but these instances did not occur on the same date or come from the same location to suggest a bias in the results. As in laboratory replicate analyses, any replicate results that fell below reporting limits were removed from the dataset and qualified as estimates.

Analyses revealed that in some instances, "replicate" samples were collected from different Niskin (CTD) bottles that had closed at depths further than 0.5 m apart in space. Ideally, field replicates are taken from two different Niskin bottles that close at the same depth (<0.5 m apart). Individual pairs were removed from the dataset if they did not meet the definition of replicate. Due to natural variability in the water column, chlorophyll-a and dissolved nutrients would be most affected by this condition so these datasets were closely analyzed for depth effects on replication. Also, variability in sampling procedures or between field personnel would have the greatest effect on chlorophyll samples and ammonium samples. The slightly higher %RSD for these two parameters is thought to indicate field sampling effects. However the variability occurs randomly throughout the project so no systematic bias was detected.

For the data analyses presented in the remainder of this document, the original sample value was used. The field replicates were used for QA assessment only. Table 11, Table 12, and Table 13 summarize results for field replicates by lab and by parameter.

Table 8. Quality assurance results for marine dissolved oxygen and chlorophyll samples analyzed by the Ecology Marine Laboratory.

Parameter	Laboratory blanks				Laboratory standards (% recovery)				Laboratory replicates (%)			
	Count (No.)	Mean Value	Reporting Limit	Range	Count (No.)	Mean Value	Acceptance Criteria	Range	Count (No.)	Mean RSD	Target Mean RSD	Range
DO (mg/L)	126	0.05	0.05	0.047 - 0.054	106	0.502	0.475 – 0.525	0.510 – 0.528	170	1.9%	10%	0 – 20%
Chl a (ug/L)	96	0.05[11]	0.01	0.00 - 0.80					189	9.2%	10%	0 – 47 %

Table 9. Quality assurance results for marine alkalinity samples analyzed by Manchester Environmental Laboratory.

Parameter	Laboratory blanks (uM/kg)				Laboratory standards (% recovery)				Laboratory replicates (%)			
	Count (No.)	Mean Value	Reporting Limit	Range	Count	Mean Value	Acceptance Criteria	Range	Count (No.)	Mean RSD	Target Mean RSD	Range
Alkalinity	74	0.840	1	0.840 - 0.840	66[12]	100.75	95 – 105%	97 – 104%	168	0.6%	10%	0.0 – 3.2%

[11] Six laboratory blanks collected on the September 2007 *Barnes* cruise showed elevated levels of chlorophyll a, probably due to reagent contamination. Final amounts of chlorophyll-a contribution to samples were less than 1 ug/L. However, all affected data have been qualified as estimates. Without these six blanks, the mean blank value of the entire dataset is 0.01 ug/L, with a range of 0.00 – 0.11 ug/L.

[12] Certified reference materials based on natural seawater were obtained from Andrew Dickson, Scripps Institute of Oceanography, University of California, San Diego. Several standards from different batches were used, so results are reported as % recovery.

Table 10. Quality assurance results for marine dissolved and total nutrients samples analyzed by the University of Washington Marine Chemistry Laboratory.

Parameter	Laboratory blanks (µM)				Laboratory standards (% recovery)				Laboratory replicates (%)			
	Count (No.)	Mean Value	Reporting Limit	Range	Count (No.)	Mean Value	Acceptance Criteria	Range	Count (No.)	Mean RSD	Target Mean RSD	Range
Nitrite	51	0.05[13]	0.03[14]	0.00 - 0.14	49	100%[16]	95 – 105%	98 - 104%	160	1.6%	10%	0.0 – 19.30%
Total Nitrogen	49	7.0; 16.2[15]	0.38	7.00; 16.00±0.50	45	100%	95 – 105%	97 – 103	265	3.6%	10%	0.0 – 47.1%
Nitrate	50	2.38[13]	0.15	0.00 – 5.14	47	100%	95 – 105%	99 –101%	160	0.8%	10%	0.0 – 20.3%
Total Phosphorus	58	0.06[15]	0.02	0.06 – 0.12	43	100%	95 – 105%	96 – 104	265	2.0%	10%	0.0 – 44.2%
Ortho-Phosphate	51	0.5[13]	0.03[14]	0.04 – 0.65	49	100%	95 – 105%	97 – 103%	160	0.9%	10%	0.0 – 11.7%
Silicate	51	3.56[13]	0.21	0.55 – 9.75	49	101%	95 – 105%	99 – 102%	160	1.8%	10%	0.0 – 22.0%
Ammonium	51	0.03[13]	0.05	0.00 – 0.13	49	100%	95 – 105%	95 – 105%	146	7.2%	10%	0.0 – 55.2%

[13] A uniform certified seawater nutrient blank is not available commercially, due to great variability between waterbodies in the seawater matrix, which can alter the analytical signal or interfere with chemical reactions. Standard methods recommend preparing blanks and standards from a natural low-nutrient seawater (LNSW), with salinity equal to sample salinities. In estuaries, salinity variability can be great; thus, a single standard cannot be used. UW MCL prepares standards and blanks from natural LNSW to match Puget Sound salinities, resulting in a large variability of actual nutrient concentrations between different batches. Results for these pseudo-blanks are often greater than the reporting limit. Consequently, blank results are factored into the calculation of standard concentrations.

[14] Table 12 of the QA Project Plan lists reporting limits for nitrite and orthophosphate as 0.02 uM; however, review of the UW MCL standard operating procedures revealed that the lab lists reporting limits for NO2 and PO4 as 0.03 uM as updated in this table.

[15] Due to the nature of the persulfate reagent, nitrogen and phosphate concentrations are often present. Inclusion of a method (reagent) blank in the digestion step reveals the concentrations of these species. UW MCL used a few different batches of the reagent, with variable concentrations of nitrogen and phosphorus. Levels detected in the reagent are presented here as a range for total phosphorus, distinct batches for total nitrogen. UW MCL calculates a factor for reagent contributions to the method.

[16] Standards were made from natural low nutrient seawater. Several standards from different batches were used, so results are reported as % recovery.

Table 11. Field replicate (%) summary for marine DO and chlorophyll samples analyzed by the Ecology Marine Laboratory.

Parameter	Count (No.)	Mean RSD	Target Mean RSD	Range
DO	169	1.2%	10%	0 – 17.3%
Chla	172	9.5%	10%	0 – 43%

Table 12. Field replicate (%) summary for marine alkalinity samples analyzed by Manchester Environmental Laboratory.

Parameter	Count (No.)	Mean RSD	Target Mean RSD	Range
Alkalinity	169	1.2%	10%	0.2 – 1.5%

Table 13. Field replicate (%) summary for marine dissolved and total nutrient samples analyzed by the University of Washington Marine Chemistry Laboratory.

Parameter	Count (No.)	Mean RSD	Target Mean RSD	Range
Nitrite	166	5.7%	10%	0.0 – 93.5%
Total Nitrogen	296	4.6%	10%	0.0 – 45.7%
Nitrate	166	2.3%	10%	0.0 – 45.7%
Total Phosphorus	300	2.3%	10%	0.0 – 26.2%
Orthophosphate	166	1.2%	10%	0.0 – 20.40%
Silicate	166	2.0%	10%	0.0 – 43.75%
Ammonium	148	6.5%	10%	0.0 – 33.2%

San Francisco State University

Replicate nutrient samples were collected from within the benthic flux chambers using the same sampling apparatus. A total of 30 pairs of dissolved and total nutrients were analyzed. Dissolved inorganic nutrients (NO_3, NO_2, NH_4, and PO_4) were analyzed by the San Francisco State University Romberg Tiburon Center marine laboratory (SFSU), under the direction of William P. Cochlan. Measurement quality objectives for all marine samples are presented in Table 12 of the QA Project Plan (Albertson et al., 2007). Addendum #2 to the QA Project Plan (Roberts and Coomes, 2007) states that these MQOs will be used for benthic flux nutrient samples as well. All samples were received and processed by SFSU within the proper temperature range and in good condition.

Field replicates were collected at the rate of 22% (30 of 166 samples). All parameters met the dataset targets. A single sample collected during the second round produced the highest RSD for all parameters. A second sample collected within the same inlet also had anomalously high RSD values. Table 14 summarizes field replicates analyzed by SFSU by parameter.

Table 14. Field replicates for benthic flux samples (%) analyzed by SFSU.

Parameter	Count (No.)	Mean RSD	Target Mean RSD	Range
Nitrate + Nitrite	30	2.7%	10%	0.0 – 40.5%*
Ammonium	30	5.2%	10%	0.3 – 22.6%*
Soluble reactive phosphorus	30	2.4%	10%	0.0 – 20.5%*

* Anomalously high field replicate collected 9/25/07 from Eld Inlet, 5-m depth. Without this sample and a second sample collected at 15-m depth in Eld Inlet, the highest paired sample RSD is 5.5, 13.2, and 8.6%, respectively, for nitrate + nitrite, ammonium, and soluble reactive phosphorus.

Field Replicates for Other Project Components

In addition to the field replicates analyzed by the laboratories described above, other field replicates were collected to quantify field variability and equipment replicability.

Benthic Flux Chambers

No replicate benthic flux chambers fitted with Hydrolab instruments were deployed. However, multiple dissolved oxygen (DO) grab samples were collected for Winkler titration at the same time as nutrient samples. A total of 120 Winkler DO samples were used to correct the continuous DO time series recorded with the Hydrolab instruments. The mean of all DO corrections was -0.01 mg/L, although this does not include three DO corrections where the difference between the Hydrolab reading and Winkler DO value was >2 mg/L. The difference remained fairly constant over the deployment in six inlets total. Hydrolab #16 had mean offsets of -2.1 to -3.4 mg/L on two occasions, but the initial deployment had offsets of -0.5 and -0.7 mg/L. Hydrolab #33 had mean offsets of -2.3 and -2.9 mg/L during the final deployment but -0.3 and -0.5 mg/L during the first deployment; the meter was not used for the second round of sampling.

While the absolute DO values for the three deployments across six stations cannot be guaranteed, the relative DO level was used to calculate sediment oxygen consumption and the meters functioned appropriately. Other than these six records, DO corrections varied from -0.68 to 1.21 mg/L by deployment.

Acoustic Doppler Current Profilers (ADCPs)

On June 26, 2007, two surface-mounted ADCP transects were conducted across Dana Passage, the first at 12:41 p.m. and the second at 12:55 p.m. during a flood tide. Low tide occurred at 10:07 a.m. and high tide at 5:43 p.m. in Budd Inlet. During the first pass, the total water flux was 16,030 m^3/s. During the second pass, total flux was 15,720 m^3/s. The RSD was 1.4%. While the replicate surveys were conducted for a slightly different purpose, the results function as a field replicate check of the equipment.

Other Relevant Data

In addition to the data specifically collected for the South Puget Sound study, data analysis and modeling will incorporate information from other monitoring efforts.

Moorings

The two moorings in South Puget Sound are a part of Ecology's marine ambient program and are not a direct component of the present project. Quality assessment protocols are described in the draft mooring QA Project Plan (Jaeger and Grantham, 2009) and accessed through the mooring web page, www.ecy.wa.gov/programs/eap/mar_wat/moorings.html.

National Atmospheric Deposition Program

The National Atmospheric Deposition Program is a cooperative research program involving multiple agencies. This program is independent of the present South Puget Sound study. Quality assurance information is available on the web site, nadp.sws.uiuc.edu/.

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Results

Data collection programs concluded in October 2007. Results are included in this report for all but the following programs:

- Sediment traps remained in place through May 2008. Results will be reported in an addendum to this document.
- Primary productivity analyses and interpretation has not been completed. Results will be reported in an addendum.
- Phytoplankton species identification and biovolume measurements have not been completed by UW MCL. Results will be reported in an addendum.
- One bottom-mounted ADCP has not been located to date. If the instrument is found, a supplemental report will summarize the results in context with the other bottom-mounted ADCP deployments.

Results in this report are presented separately for freshwater and marine data. Additional loading information has been compiled from other sources. The final section in this report also includes a compilation of loads to South and Central Puget Sound from all sources quantified to date.

Freshwater Data

Wastewater Treatment Plant (WWTP) Monitoring

Monthly 24-hour composite samples were collected from the WWTPs identified in Figure 4 from August 2006 through October 2007. A total of 17 plants were monitored for the entire time period, and an additional 12 plants were added for July through October 2007.

Streamflow

Plants report daily flows on paper copies of the Discharge Monitoring Reports (DMRs) submitted to Ecology or EPA as a condition of NPDES permits. Only monthly average flows are captured electronically by Ecology or EPA. Each plant provided daily flow data for the entire 2006-07 period of monitoring. Discharges on the day that the 24-hour composite samples were collected were pulled from the records and used to estimate instantaneous loads.

Figure 13 summarizes the daily plant flows by region for the day on which composite samples were collected. If for some reason no sample was collected from a plant, as when a sample was discarded inadvertently, that plant's daily flows are not reflected in the figure.

Apparently, higher regional WWTP discharge totals for July through October 2007 reflect the additional plants participating in the program. The added plants constituted <1.5% of the total WWTP inflows for South Sound, Sinclair Dyes, and North Central regions and 6% of the total WWTP inflows for South Central Puget Sound. Commencement Bay total inflows reflect the Simpson plant inflows for July through October 2007, which represent 51 to 54% of the total wastewater inflow. Therefore, with the exception of the Simpson plant discharge to Commencement Bay, the added plants for July through October 2007 do not add substantially to the wastewater inflows, and the monthly wastewater flow totals are comparable throughout the study period.

The high plant flows in November 2006 are indicative of a wet weather event at the time of monitoring that increased flows, even in plants with completely separate stormwater collection systems. Flows were 21 to 64% higher from November through April than from May through October, depending on the region. South Puget Sound, south of Tacoma Narrows, received a monthly average of 29.8 mgd of treated wastewater, as monitored in the present study. The region south of Alki Point received 144 mgd, and the area south of Edmonds received 258 mgd.

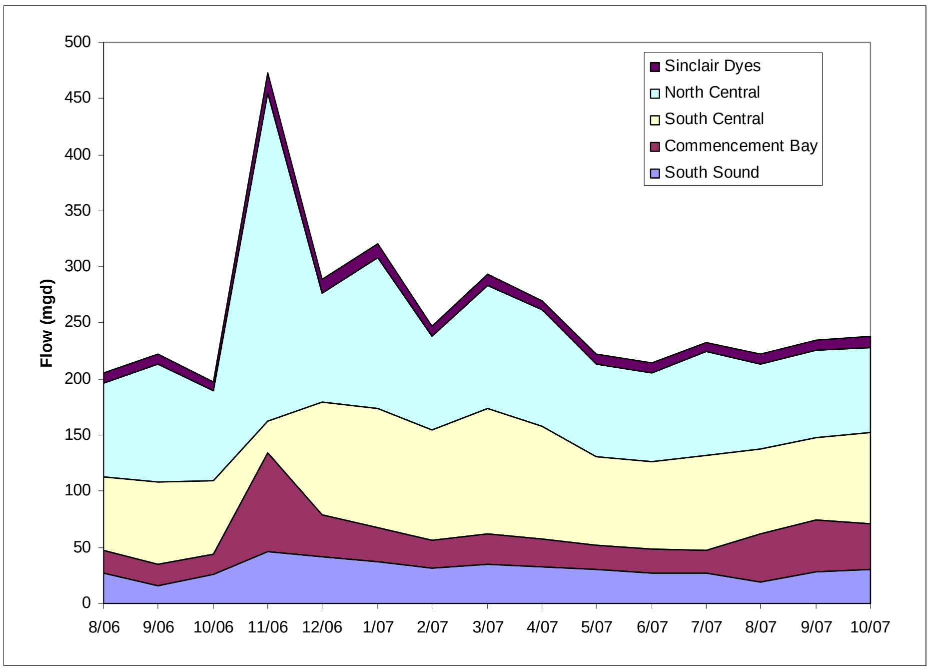


Figure 13. Monthly flow totals in the sampled wastewater treatment plants.

Concentrations

Composite sample data were compiled to evaluate seasonal variability in effluent concentrations and to quantify plant-to-plant variability across regions.

Figure 14 through Figure 17 present box and whisker plots of total (persulfate) nitrogen, dissolved inorganic nitrogen (DIN), nitrate + nitrite, and ammonium concentrations over the 15-month data collection period. Concentrations were consistent throughout the year, with median DIN concentrations varying from 13.3 to 27.6 mg/L across all plants and a grand median of 21.8 mg/L[16]. The November 2006 results illustrate the effect of storms on effluent concentrations, where the effluent is somewhat diluted by additional rainfall, even in separate sewer systems. Nearly all nitrogen is released as DIN, with very little particulate organic nitrogen. Ammonium concentrations were higher than nitrate + nitrite when averaged across all

[16] Statistics do not include the Simpson Tacoma Kraft plant, which had a median DIN concentration of 0.1 mg/L.

plants. Several plants released higher levels of nitrate + nitrite than ammonium due to differences in treatment processes.

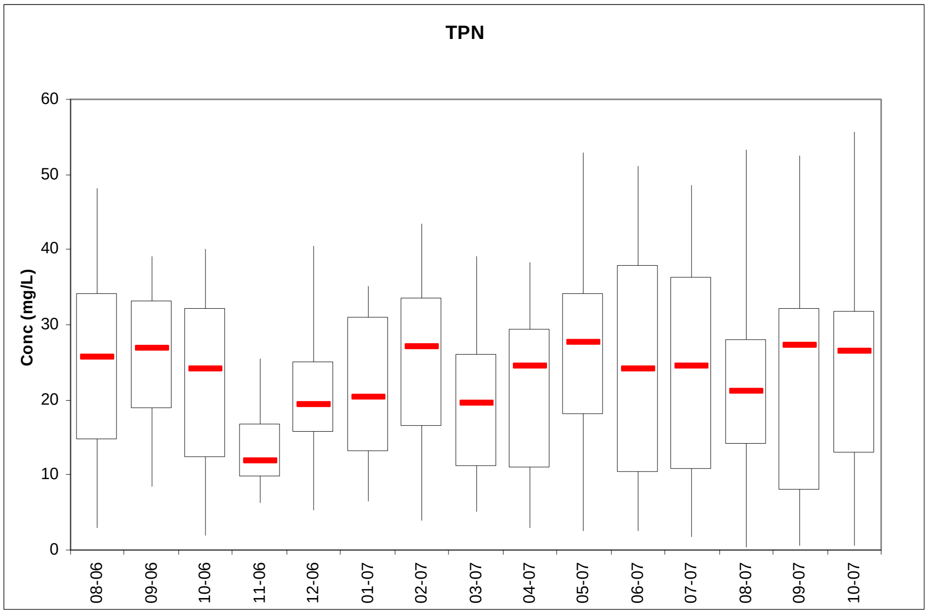


Figure 14. Temporal fluctuations of total (persulfate) nitrogen concentrations averaged across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

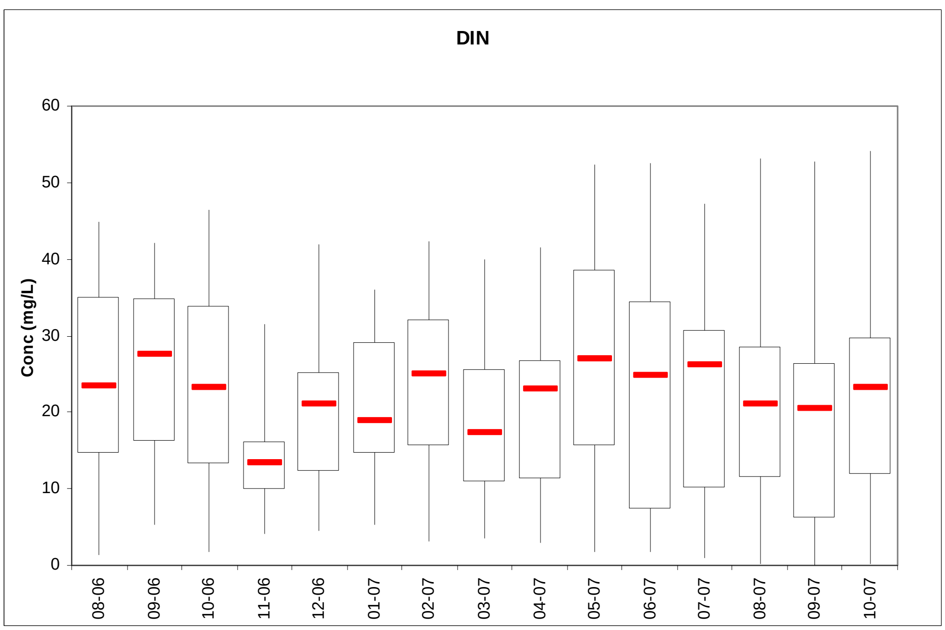


Figure 15. Temporal fluctuations of dissolved inorganic nitrogen (DIN) concentrations averaged across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

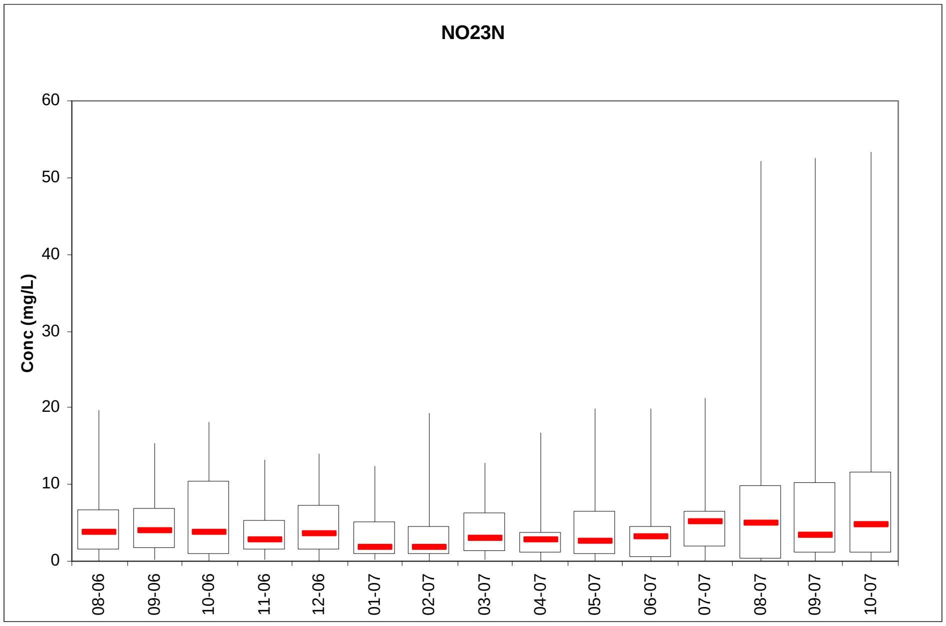


Figure 16. Temporal fluctuations of nitrate + nitrite concentrations averaged across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

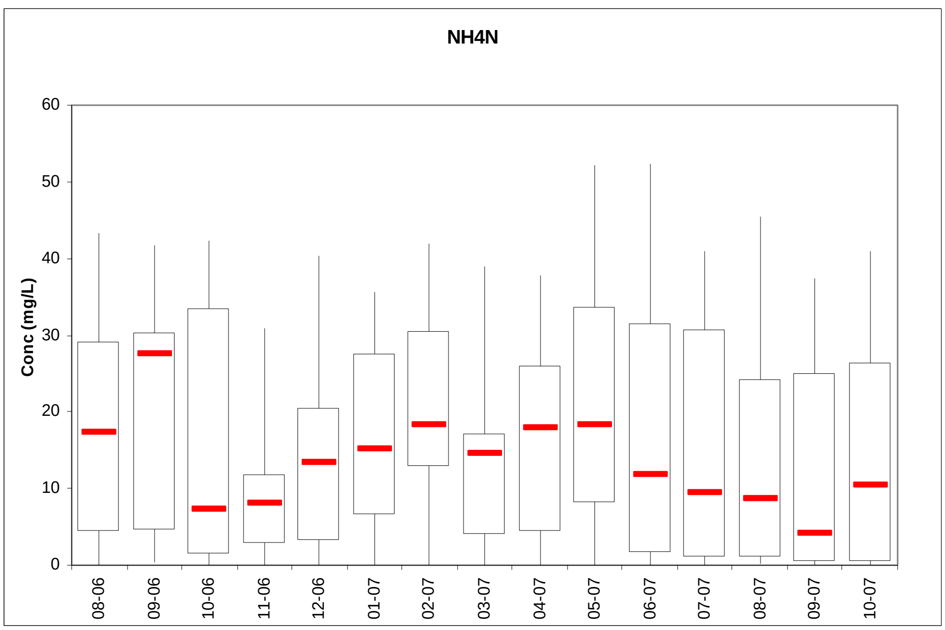


Figure 17. Temporal fluctuations of ammonium concentrations averaged across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Within any given month, effluent nitrogen levels varied from plant to plant, due in part to the range of treatment processes employed. Figure 18 through Figure 21 present the total persulfate nitrogen, DIN, nitrate + nitrite, and ammonium concentrations listed by individual plants. Comparing these figures to those above, more of the variability is attributed to plant-to-plant variability than to temporal variability within a particular plant. The mean difference between the 25th and 75th percentile monthly DIN concentrations averaged across all plants is 17.8 mg/L, while the average plant effluent varies 5.8 mg/L between the 25th and 75th percentile concentrations.

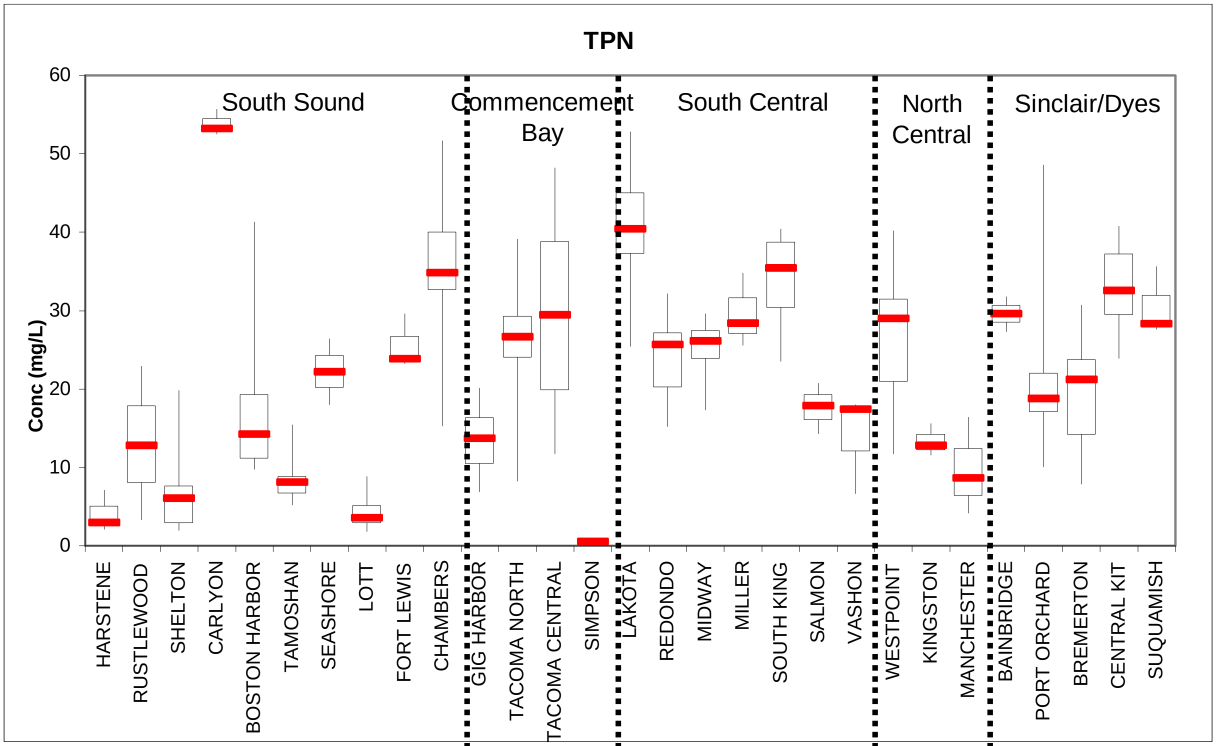


Figure 18. Total persulfate nitrogen concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values. Dashed lines distinguish different regions within the project domain. Low median DIN concentrations (<10 mg/L) were produced by Hartstene, Shelton, Tamoshan, LOTT, Simpson, and Manchester.

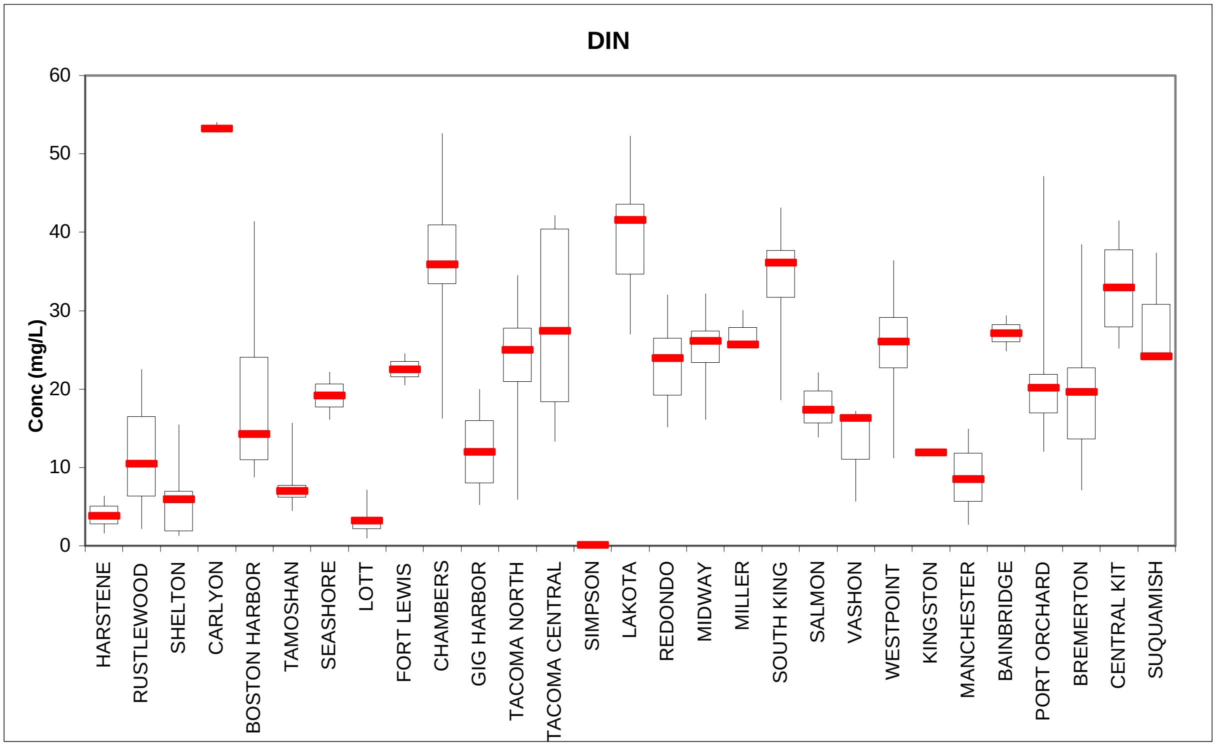


Figure 19. Dissolved inorganic nitrogen (DIN) concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Comparing Figure 20 and Figure 21, most plants produced higher concentrations of ammonium than nitrate + nitrite, but several have treatment processes that favor the delivery of nitrate + nitrite. Both forms of nitrogen are added for the primary parameter of interest, which is DIN. The average of the monthly across-plant median DIN concentrations for November through April (19.7 mg/L) is slightly lower than the drier months (24.1 mg/L).

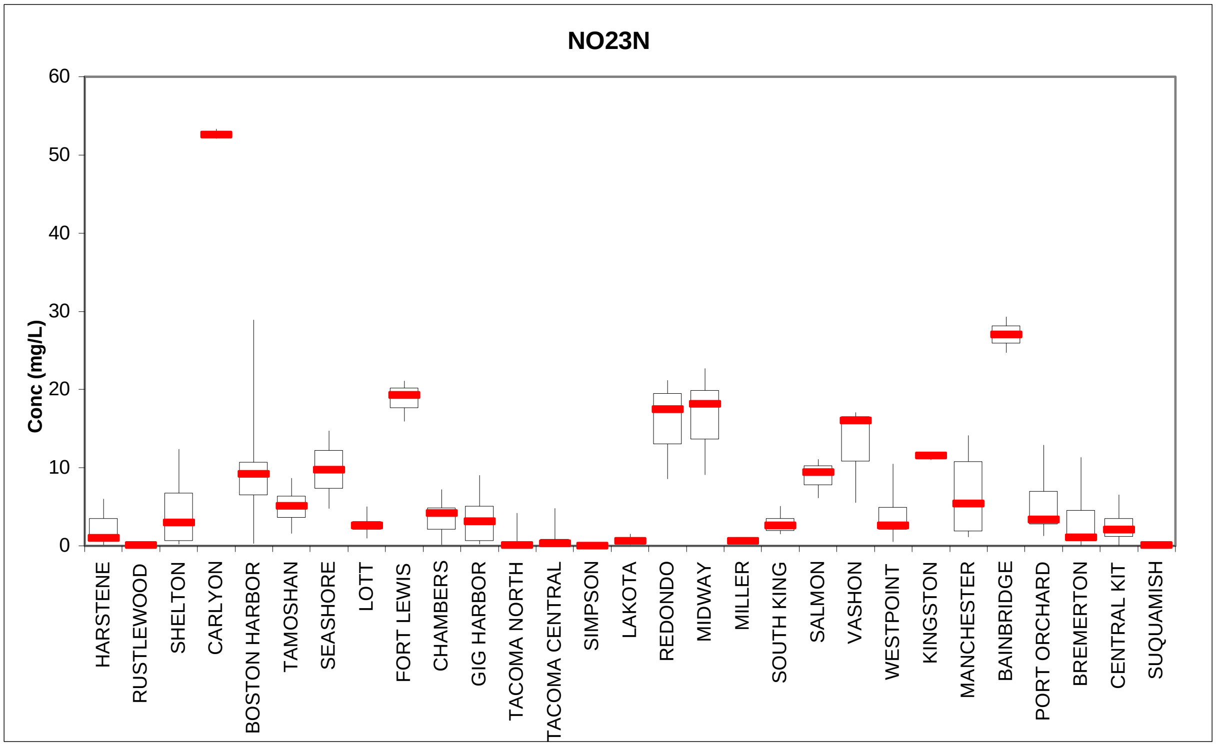


Figure 20. Nitrate + nitrite concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

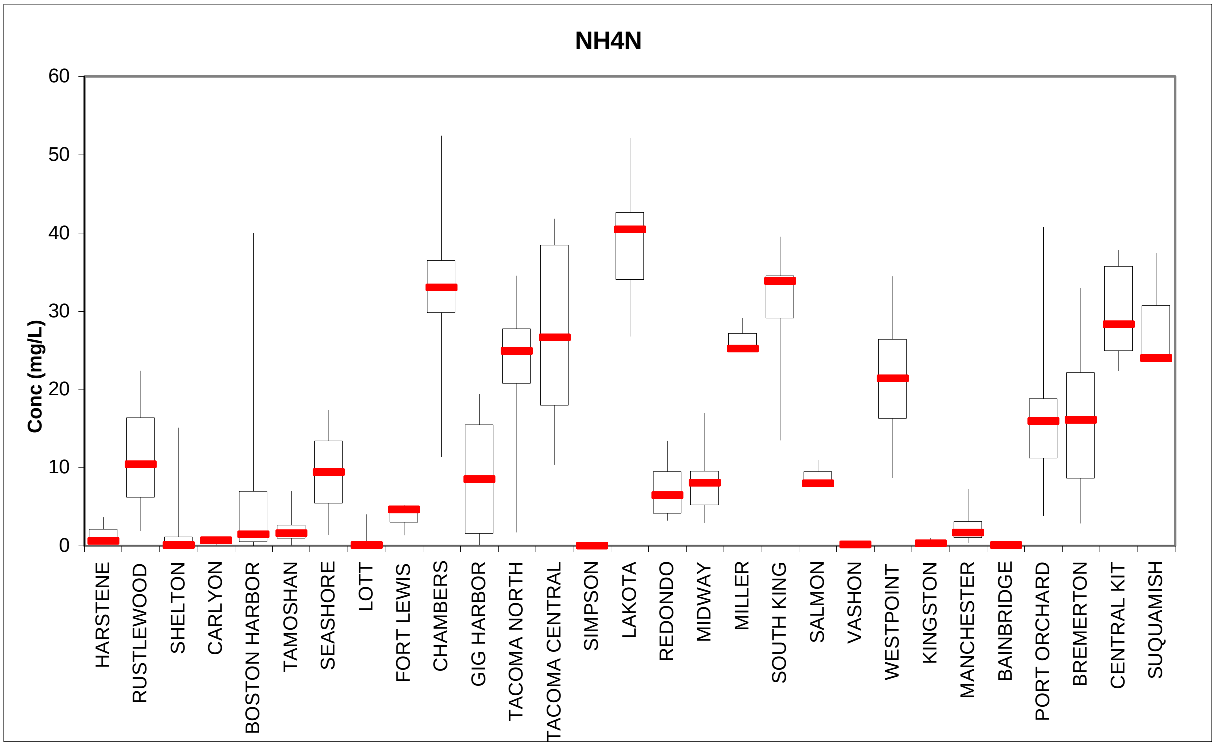


Figure 21. Ammonium concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Figure 22 through Figure 25 present the median plant nitrogen species concentrations geographically, where effluent concentrations differ due to wastewater process differences. Dissolved inorganic nitrogen (DIN) constitutes the dominant form of nitrogen, and Figure 22 and Figure 23 reflect similar patterns. The relative ratio of ammonium-to-nitrate + nitrite varies among plants, but most produce more ammonium than nitrate + nitrite. The patterns in nitrate + nitrite and ammonium are slightly different than for DIN and total nitrogen.

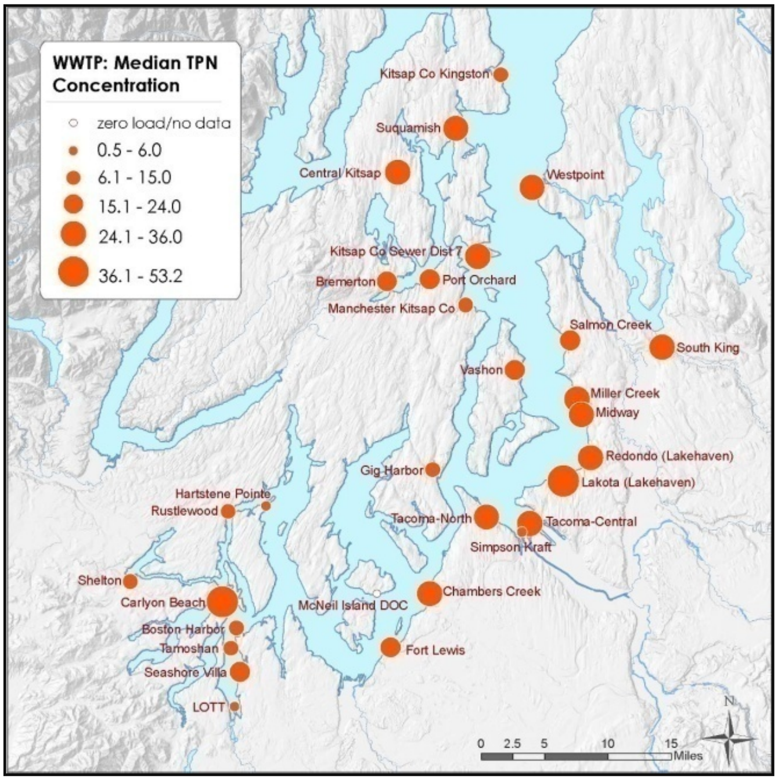


Figure 22. Median wastewater treatment plant concentrations of total persulfate nitrogen for August 2006 through October 2007.

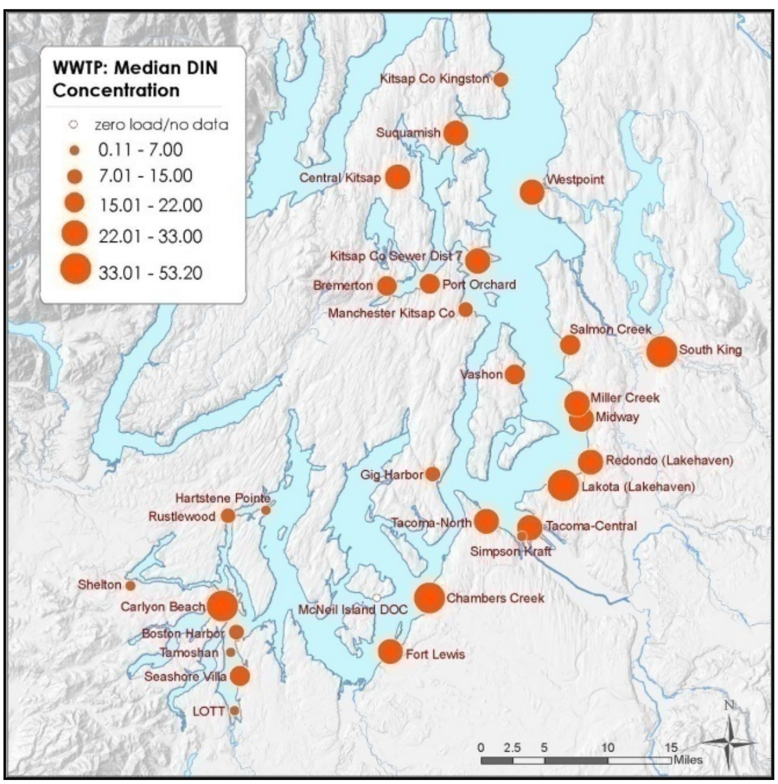


Figure 23. Median wastewater treatment plant concentrations of dissolved inorganic nitrogen for August 2006 through October 2007.

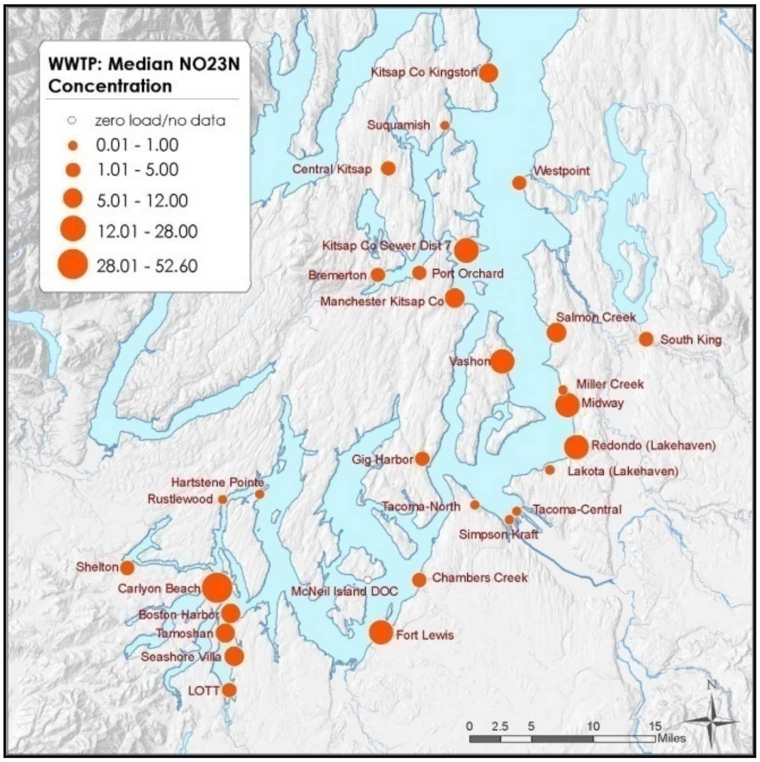


Figure 24. Median wastewater treatment plant concentrations of nitrate + nitrite for August 2006 through October 2007.

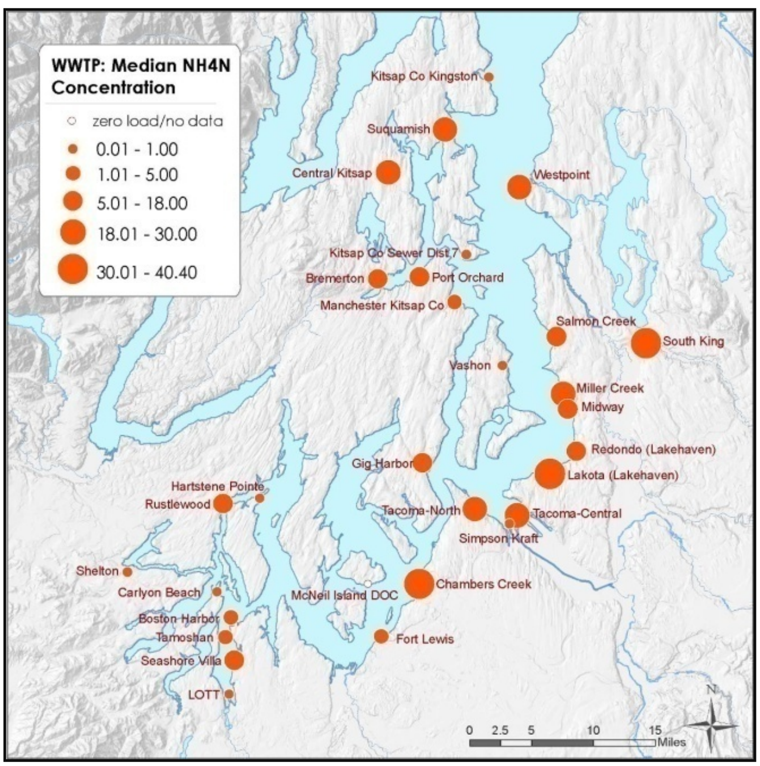


Figure 25. Median wastewater treatment plant concentrations of ammonium for August 2006 through October 2007.

Temporal variability of total phosphorus and orthophosphate among plants is presented in Figure 26 and Figure 27. As with nitrogen, very little organic phosphorus is discharged from the plants, and nearly all phosphorus is in the form of orthophosphate. Median orthophosphate concentrations varied from 2.3 to 4.5 mg/L with a grand median of 3.4 mg/L. The mean November through April orthophosphate concentration (2.7 mg/L) is lower than the May through October average concentration (4.0 mg/L).

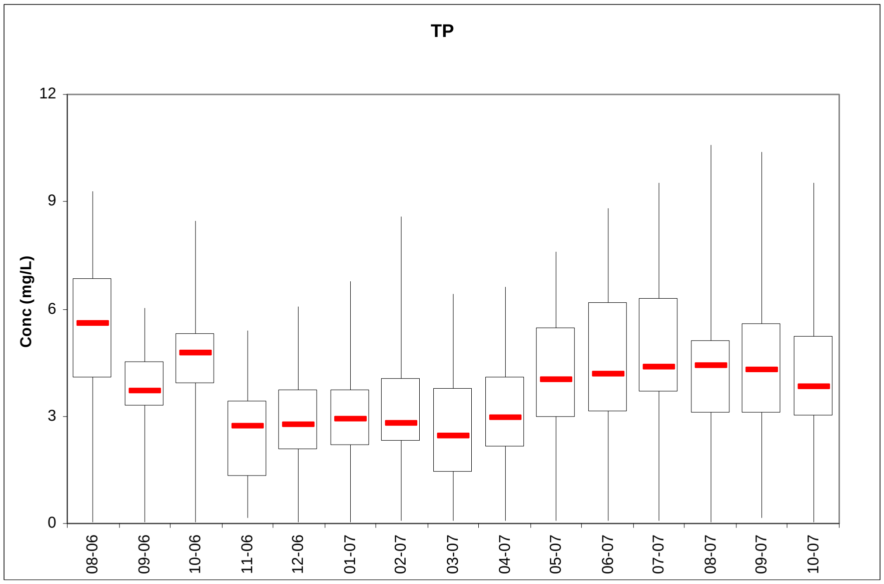


Figure 26. Total phosphorus concentrations over time across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

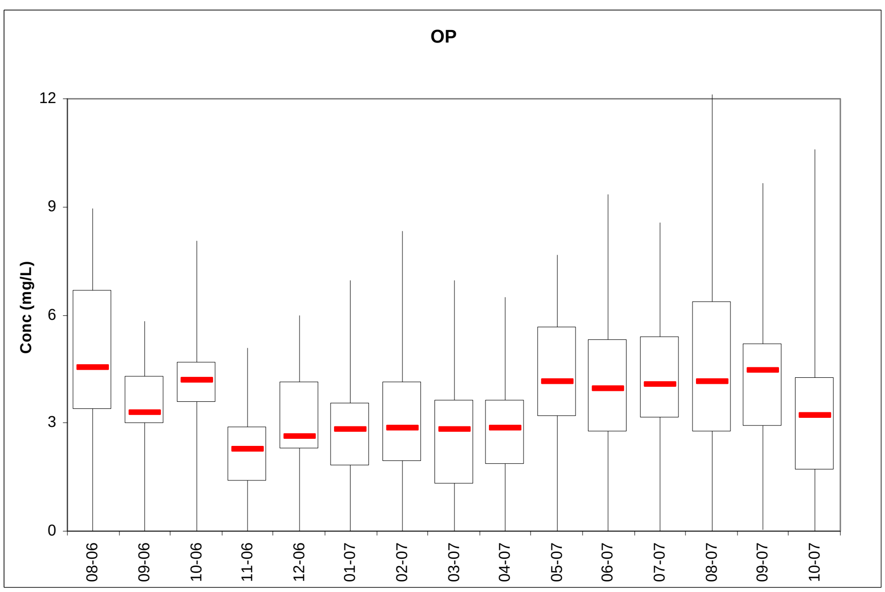


Figure 27. Orthophosphate concentrations over time across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

As with nitrogen, the greatest variability in effluent phosphorus concentrations resulted from plant-to-plant variation and the effect of the various treatment practices in place. Figure 28 and Figure 29 present total phosphorus and orthophosphate concentrations by plant. Mean values of the differences between monthly 25th and 75th percentile concentrations was 2.2 mg/L, while the mean within-plant range between the 25th and 75th percentile was 1.3 mg/L. Median effluent orthophosphate concentrations were < 1.5 mg/L at the Tacoma North, Chambers, Simpson, and Suquamish plants.

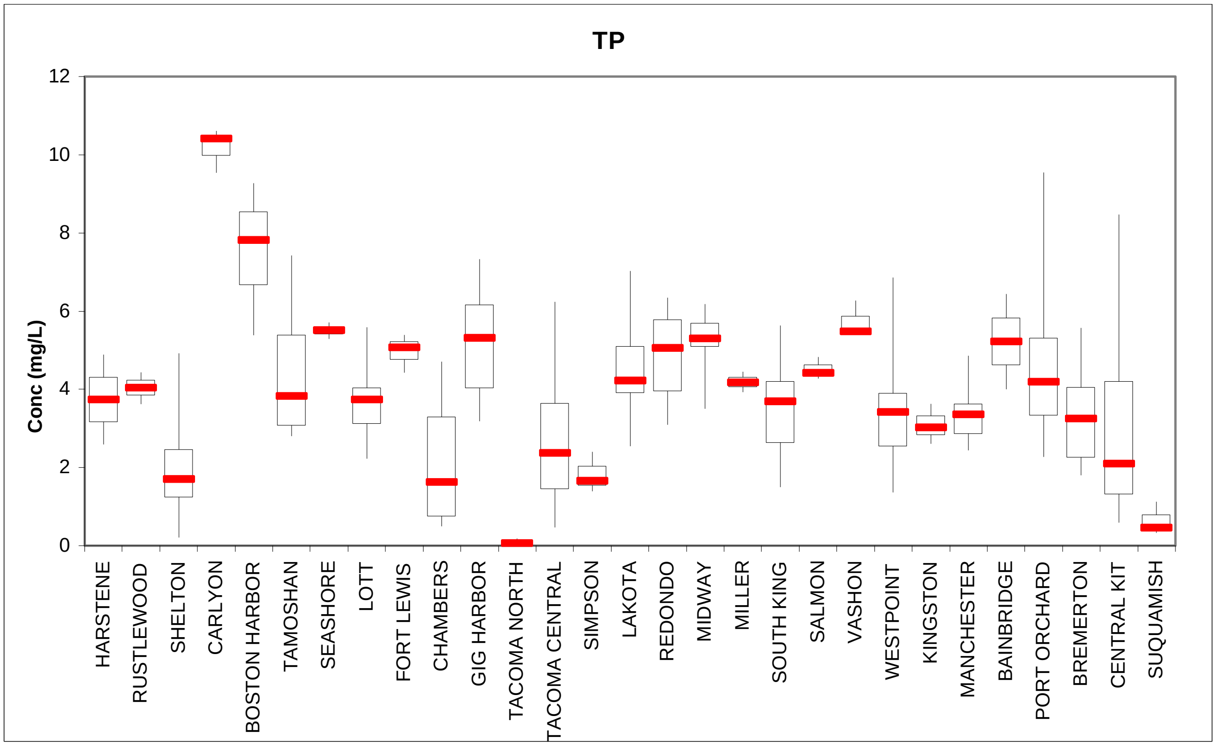


Figure 28. Total phosphorus concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

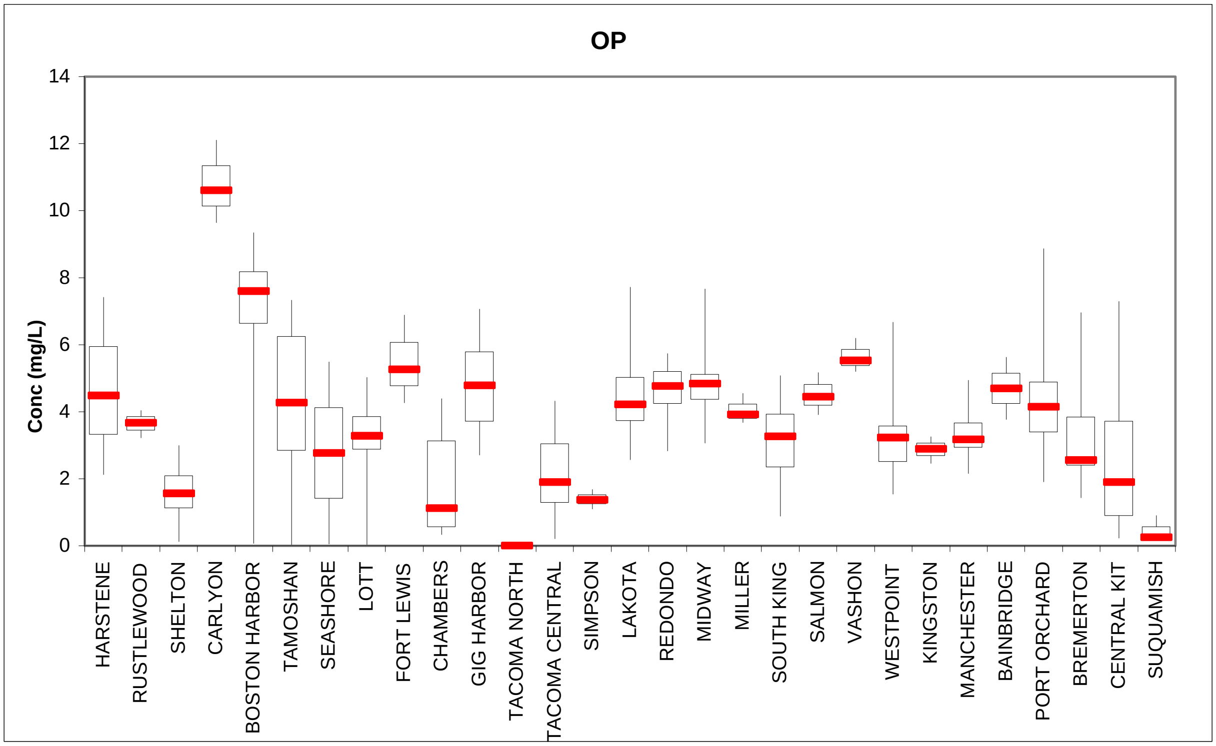


Figure 29. Orthophosphate concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Figure 30 and Figure 31 present the median plant phosphorus concentrations geographically. The Tacoma North plant produces the lowest phosphorus levels of all of the WWTPs in South and Central Puget Sound. Phosphorus concentrations in the Simpson industrial discharge are comparable to the lowest levels produced by domestic WWTPs.

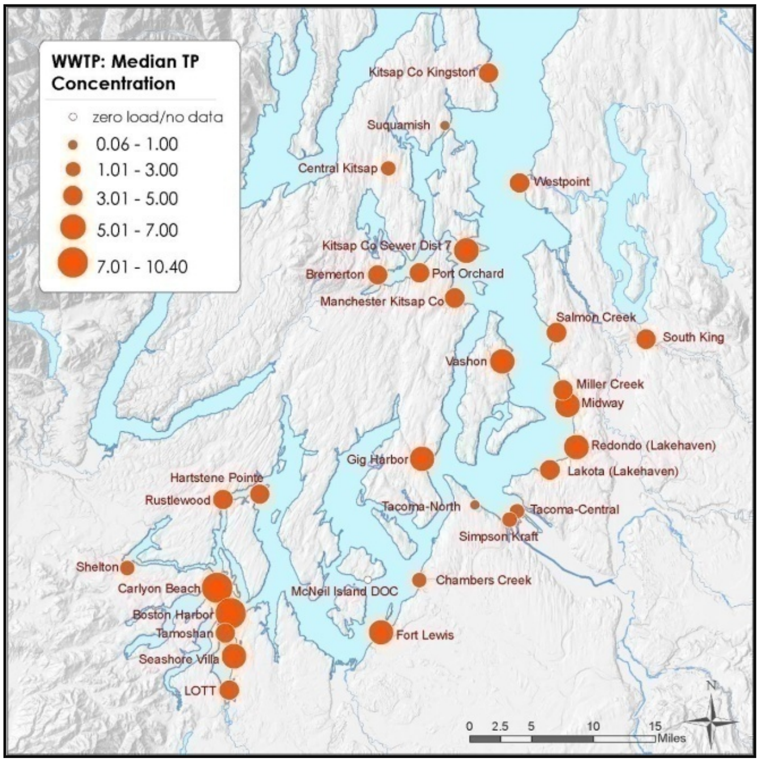


Figure 30. Median wastewater treatment plant concentrations of total phosphorus for August 2006 through October 2007.

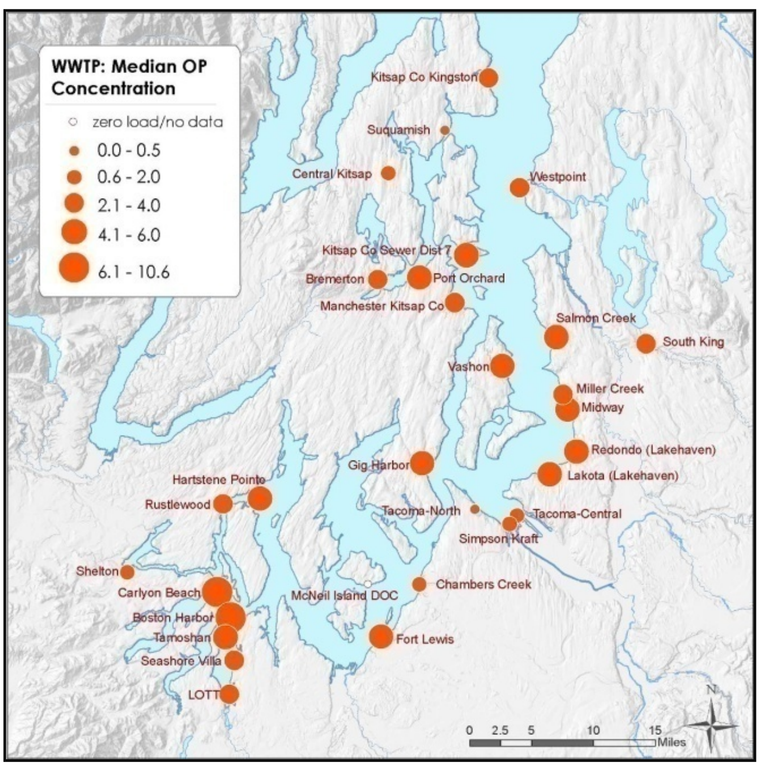


Figure 31. Median wastewater treatment plant concentrations of orthophosphate for August 2006 through October 2007.

Organic carbon results showed similar patterns of geographic and temporal variability. Figure 32 and Figure 33 present total and dissolved organic carbon (DOC) concentrations over time across all participating plants. Very low levels of particulate organic carbon were released, and nearly all organic carbon was in the dissolved form. Median DOC concentrations varied from 8.7 to 15.2 mg/L with a grand median of 11.5 mg/L. The higher values in August through October 2007 were influenced by the addition of the Simpson plant and other WWTPs monitored only in 2007.

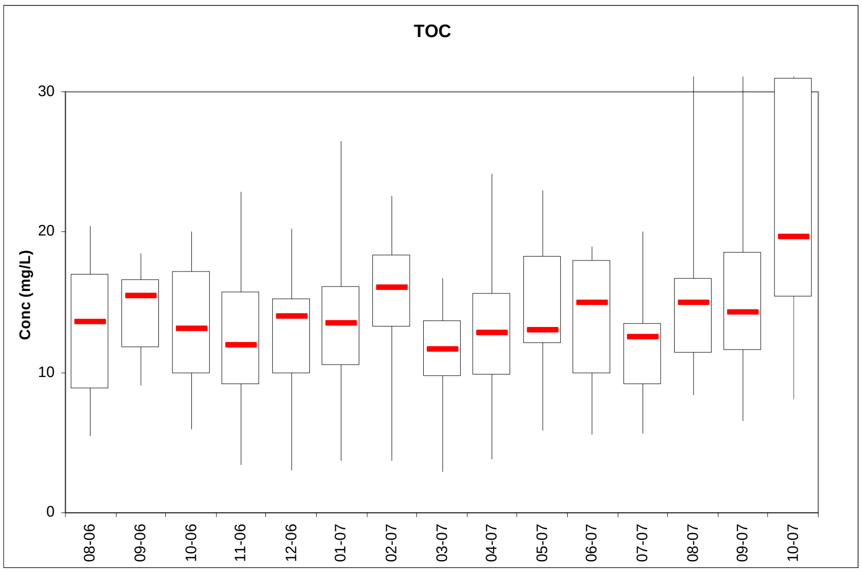


Figure 32. Total organic carbon concentrations over time across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

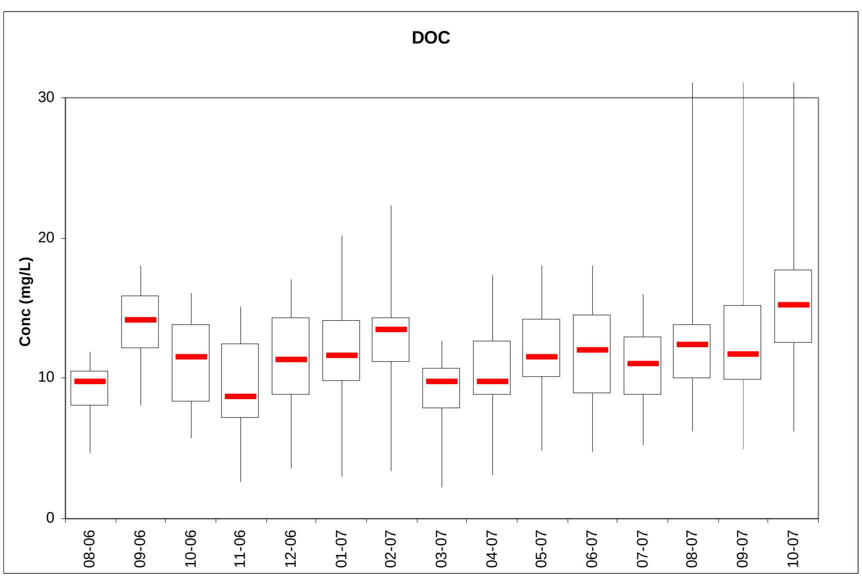


Figure 33. Dissolved organic carbon concentrations over time across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Figure 34 and Figure 35 present total and DOC concentrations listed by plant. Median effluent concentrations from domestic WWTPs generally ranged from 10 to 15 mg/L of either total or DOC. Concentrations are much higher in the effluent of the Simpson Tacoma Kraft mill due to the fundamental differences in pulp and paper treatment as compared with wastewater treatment. The difference was also evident in DIN and orthophosphate concentrations which were 0.0 and 1.4 mg/L, respectively.

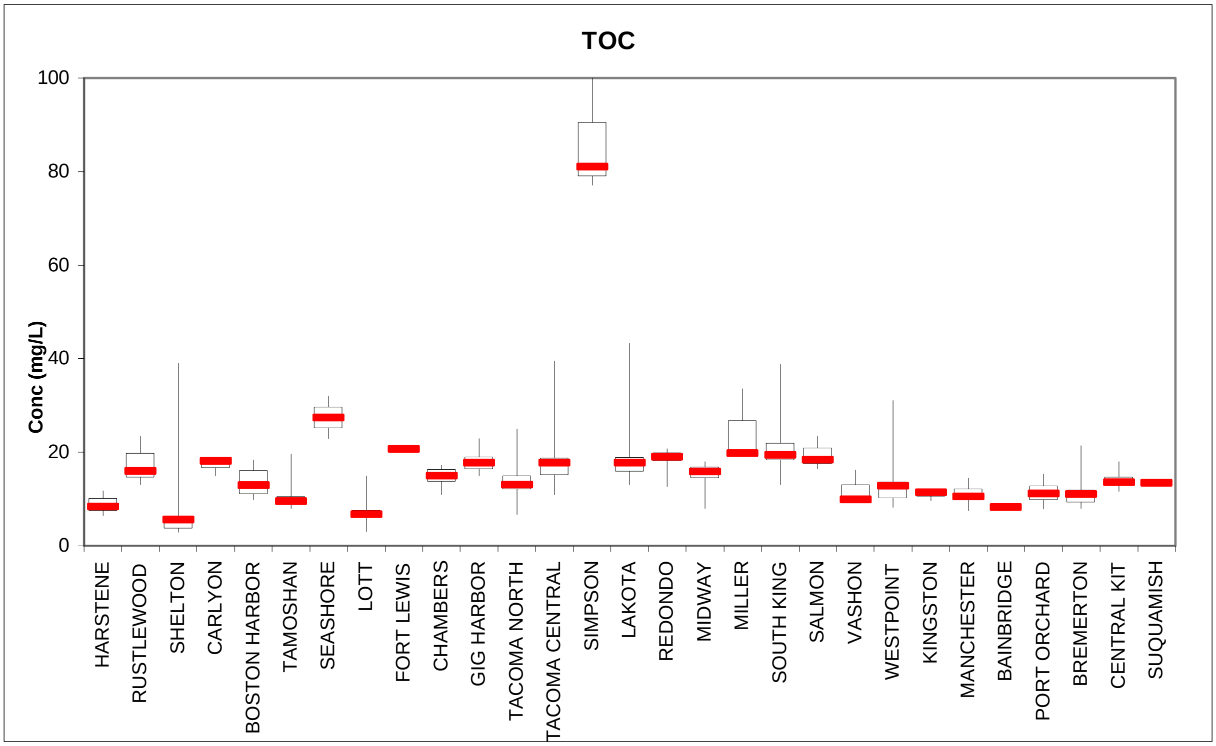


Figure 34. Total organic carbon concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

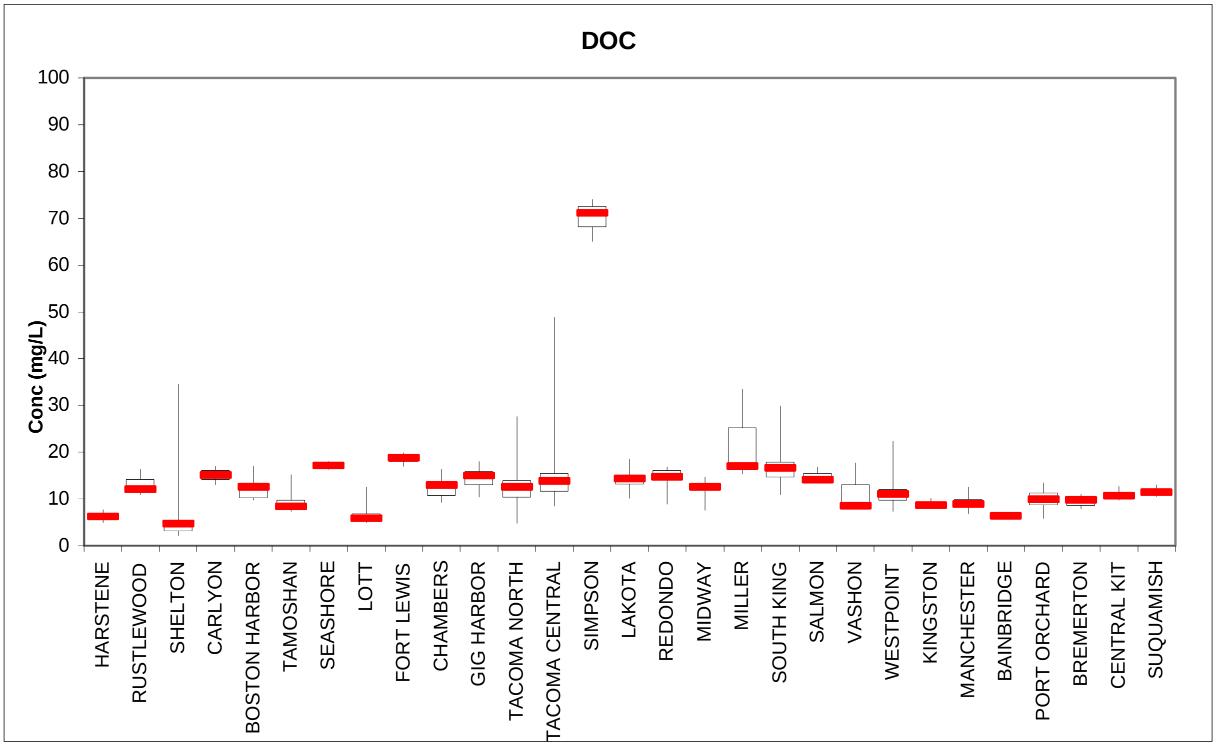


Figure 35. Dissolved organic carbon concentrations by wastewater treatment plant for July 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Figure 36 and Figure 37 present the median plant carbon concentrations spatially. The industrial discharge from the Simpson plant produces higher concentrations of organic carbon than the domestic WWTPs.

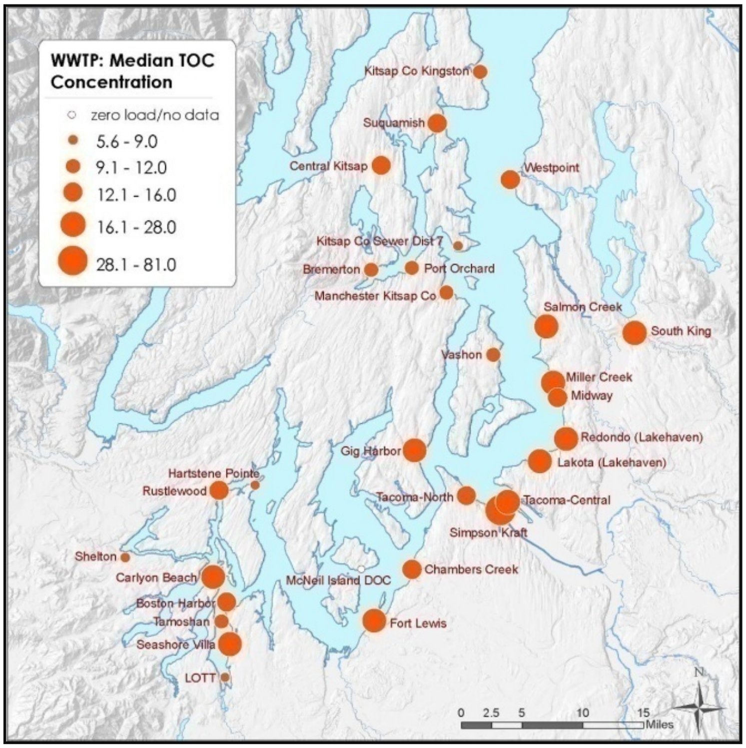


Figure 36. Median wastewater treatment plant concentrations of total organic carbon for August 2006 through October 2007.

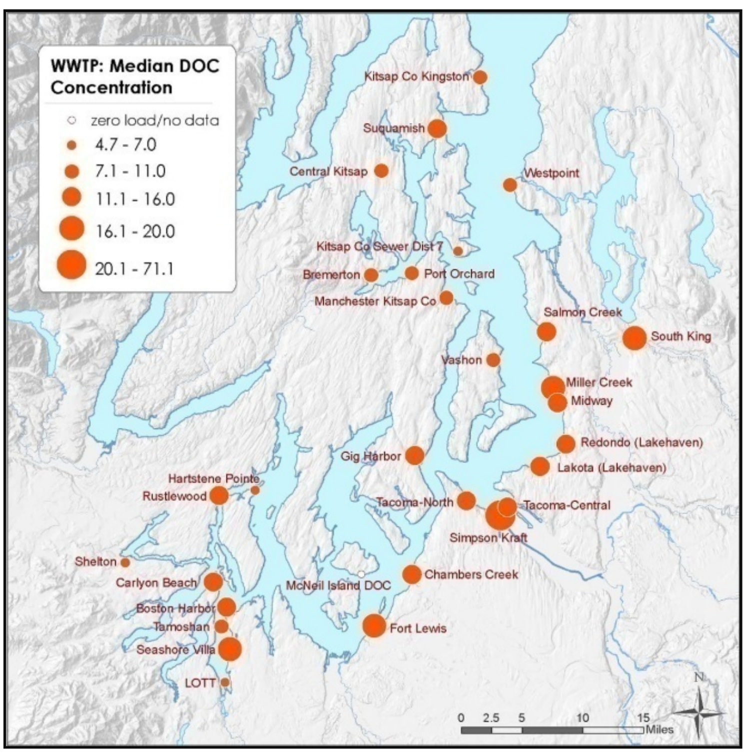


Figure 37. Median wastewater treatment plant concentrations of dissolved organic carbon for August 2006 through October 2007.

Inhibited biochemical oxygen demand (BOD) levels were somewhat constant over time, as evident in Figure 38. Median levels varied from 5.0 to 10.0 mg/L with a grand median of 6.0 mg/L. These levels were strongly influenced by the detection limit of 4.0 mg/L. Most of the variability was due to plant-to-plant differences from treatment practices, similar to observations made for nutrients. Figure 39 presents biochemical oxygen demand concentrations by plant. The average plant produced an effluent range of 2.7 mg/L between the 25th and 75th percentile while the difference in monthly median values averaged 4.9 mg/L. BOD concentrations in the Simpson discharge were similar to those from domestic wastewater discharges.

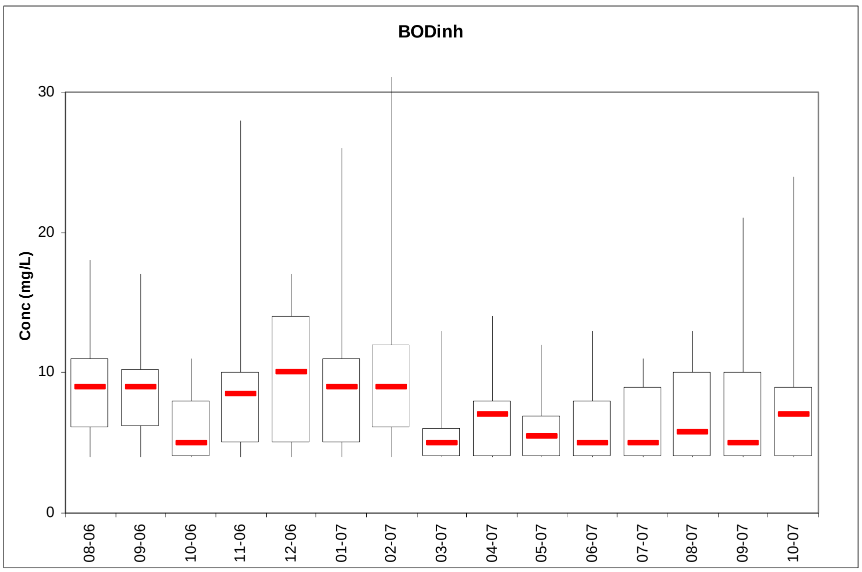


Figure 38. Inhibited biochemical oxygen demand concentrations over time across all wastewater treatment plants. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

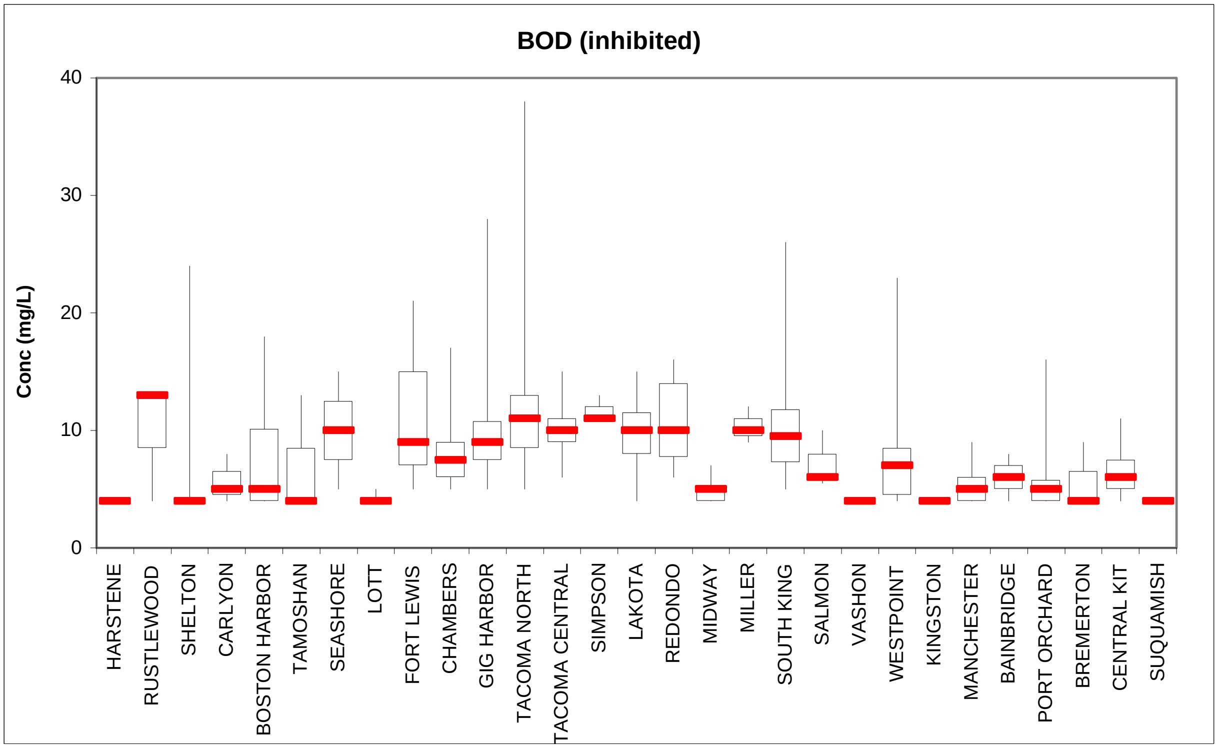


Figure 39. Inhibited biochemical oxygen demand concentrations by wastewater treatment plant. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Tributary Monitoring

Monthly grab samples were collected from the tributaries identified in Figure 5 from August 2006 through October 2007. The four largest rivers are part of Ecology's ambient monitoring networks. Supplemental samples were collected at those sites to complete the list of parameters required for the present study. A total of four rivers and 14 streams were monitored from July 2006 through October 2007 and an additional 20 streams were added for July through October 2007.

Only samples from the four largest ambient stations were collected in November 2006 when a storm event precluded the collection of grab samples from the remaining tributaries. In addition, Sequalitchew Creek was only sampled on one occasion. The stream is diverted away from its channel for most of the year.

Streamflow

In addition to grab samples from the smaller tributaries, field staff measured streamflow during most sampling events. Goldsborough and Chambers Creeks had the largest discharge rates during dry weather and wet weather. USGS maintains permanent gages on the streams, as well as on Huge Creek within the Minter Creek watershed.

Figure 40 presents the instantaneous streamflows measured by Ecology staff as well as the USGS continuous gaging record for Goldsborough. Sampling was conducted at representative flows during dry weather. The December 2006 sampling event captured a winter storm event. The sampling interval missed several spring storm events but was representative of higher baseflows during this time period. The median of the instantaneous Goldsborough Creek streamflow measurements (72 cfs) was close to the median flow of the USGS continuous streamflow measurements (69 cfs).

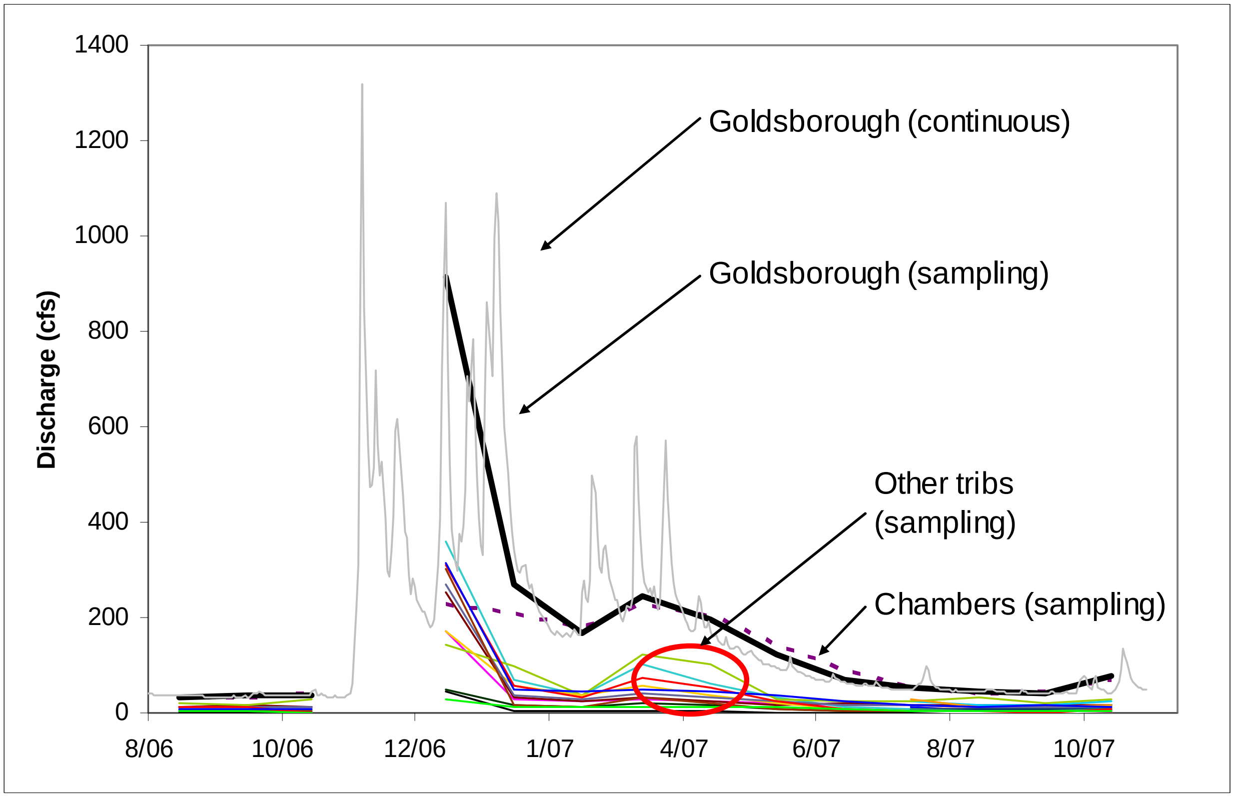


Figure 40. Instantaneous streamflow measurements for tributaries, including Chambers and Goldsborough Creeks, as well as the USGS continuous gaging results for Goldsborough Creek.

USGS gage data were used to calculate flows for the Deschutes, Nisqually, and Puyallup Rivers. USGS gage data from Goldsborough, Huge, and Chambers Creeks were used to fill in missing instantaneous flows from the sampling network using ratios of tributary areas and mean annual precipitation that were developed during the Phase 1 study (Albertson et al., 2002; Roberts and Pelletier, 2001).

Because the initial hydrodynamic model domain extends north to the Edmonds boundary, estimates of freshwater inflows were needed for the Cedar River, Lake Washington, and Lake Union basin; the Green/Duwamish River; and the greater Sinclair/Dyes Inlet watershed, including Vashon Island. Lincoln (1977) previously developed factors for estimating larger basin flows from a variety of USGS gage station data. However, several of these stations have been discontinued in the interim, and new flow factors were needed. Table 15 presents the equations for estimating flows in the basins based on specific USGS gage data. Figure 41 presents both the USGS gage data and daily estimates for large basins derived for those gages in Table 15.

Table 15. Source information for estimating streamflow from river basins beyond South Puget Sound.

Basin	Source Gages	Lincoln (1977)	Revised Estimate
Cedar River Lake Washington Lake Union	Cedar River at Renton Mercer Creek Juanita Creek Issaquah Creek Sammamish River	$Q_{Lk\ Wash} = 1.4721 * (Q_{Cedar} + Q_{Mercer} + Q_{Juanita} + Q_{Issaquah} + Q_{Sammamish} + Q_{Swamp})$	$Q_{Lk\ Wash} = 1.5538 * (Q_{Cedar} + Q_{Mercer} + Q_{Juanita} + Q_{Issaquah} + Q_{Sammamish})$
Green/Duwamish	Green River at Tukwila Green River at Auburn Sammamish River	$Q_{Green/Duwamish} = Q_{Green\ @\ Tukwila} + 0.4904 * Q_{Sammamish}$	$Q_{Green/Duwamish} = 1.1028\ Q_{Green\ @\ Auburn} + 0.4904 * Q_{Sammamish}$
Sinclair/Dyes + Vashon	Huge Creek	(not included)	$Q_{Sinclair/Dyes/Vashon} = 37.1\ Q_{Huge}$

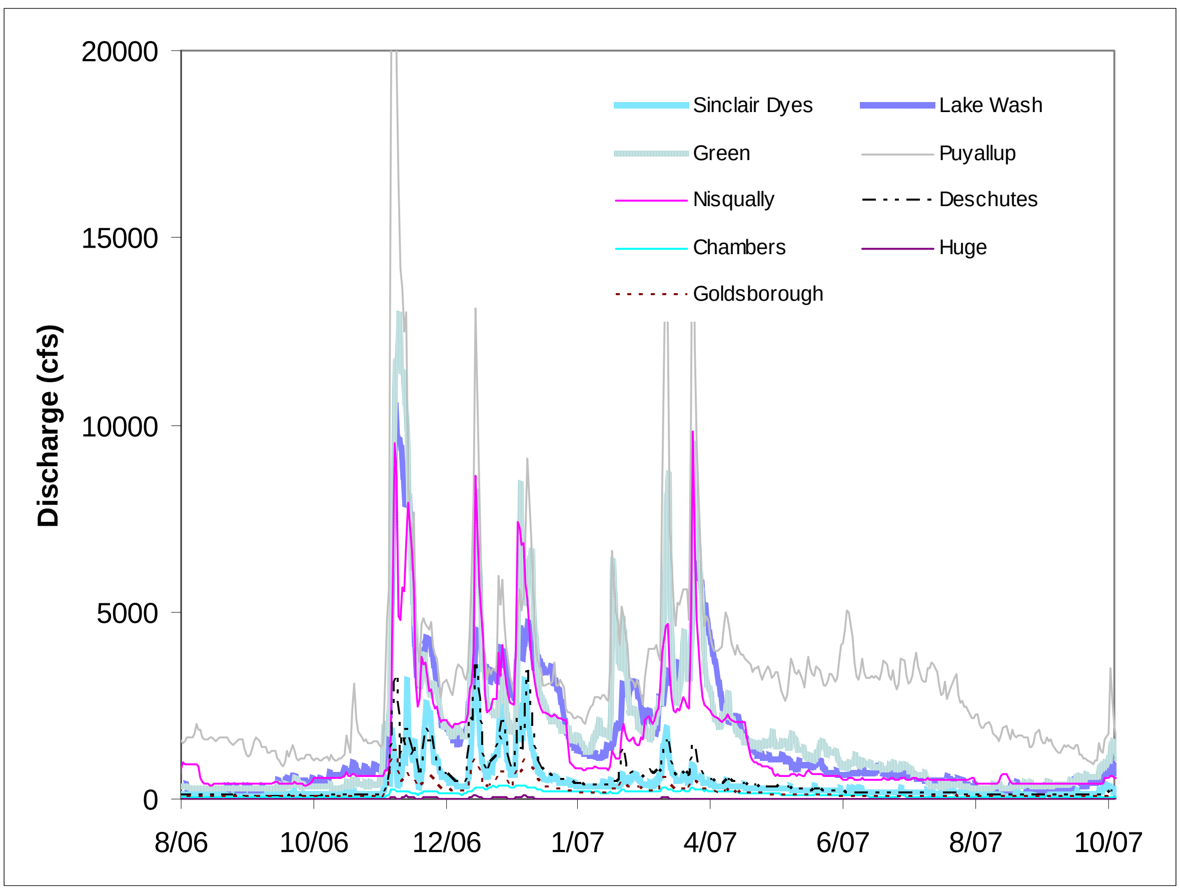


Figure 41. Streamflow measurements for USGS gage locations (thin lines) and estimates for other large basins (Sinclair/Dyes, Green/Duwamish, Lake Washington) without gaging near the mouths (thick lines).

Lincoln (1977) used the Green River at Tukwila and the Sammamish River to estimate flows from the greater Green/Duwamish River watershed. However, due to backwater effects at the gage, the USGS no longer reports streamflow for the Green River at Tukwila. The next upstream gage, the Green River at Auburn, was substituted and the drainage areas were used to scale up these flows to estimate the Green River at Tukwila (by a factor of 1.1028). The Sammamish River site has been transferred to King County's Hydrologic Information Center and is now operated as King County station 51T.

The Ballard Locks regulate streamflow from the Cedar River, Sammamish River, Lake Sammamish, Lake Washington, and Lake Union watersheds. While flows are estimated by the U.S. Army Corps of Engineers, the data are not released for many years (Nairn, personal communication), and no measurements are presented. Lincoln (1977) used the combined flows from the Cedar River, Mercer Creek, Juanita Creek, Issaquah Creek, Sammamish River, and Swamp Creek scaled up to represent the total tributary area. However, the Swamp Creek gage has been discontinued, and the flow factor was modified by the ratio of the gaged area with Swamp Creek to the area without Swamp Creek (by a factor of 1.0555).

The Sinclair/Dyes Inlet watershed, Vashon Island, and watershed area adjacent to Central Puget Sound do not have a single representative gage. Mean annual streamflow normalized by watershed area (cfsm = cfs/mi^2) was compared for all USGS gages near South and Central Puget Sound, and Table 16 summarizes the results for June 2006 through October 2007. The large rivers east of South and Central Puget Sound have their headwaters in the Cascade Mountains, with much higher precipitation that produces a high unit streamflow.

Table 16. USGS stream gage characteristics for sites near South and Central Puget Sound, June 2006 – October 2007.

Name	Gage No.	Area (mi^2)	Area (km^2)	Unit Streamflow (cfs/mi^2)
Cedar River at Renton	12119000	185	479	3.61
Chambers Creek	12091500	104	269	1.09
Deschutes River	12080010	162	420	2.38
Goldsborough Creek	12076800	54.9	142	2.83
Green River at Auburn	12113000	399	1033	3.26
Huge Creek	12073500	6.47	17	1.62
Nisqually River	12089500	517	1339	2.53
Puyallup River	12101500	948	2455	3.49
Sammamish River at Woodinville	12125200, KC51T	159	412	1.75
Lake Washington	(composite)	631	1634	2.31
Sinclair/Dyes/Vashon	(estimate)	240	621	1.62

In addition, the Chambers Creek watershed has a very complicated hydrogeology that is not necessarily representative of other areas. Goldsborough Creek also possesses a high unit streamflow. Because Huge Creek is physically the closest long-term gaging location to the greater Sinclair/Dyes Inlet watershed and because the unit streamflow of Huge Creek is lower than that of the rivers originating in the Cascade Mountains, Huge Creek was used to estimate flows for the larger watershed. Because the tributary area is small, estimated flows likely overestimate the high-flow pulses of the Sinclair/Dyes watershed, which would naturally attenuate peak flows. However, the approach is a reasonable estimate to include the Sinclair/Dyes freshwater inflows in the initial hydrodynamic model development.

Concentrations

Tributary grab samples were analyzed for the parameters listed in Table 2. In addition, several parameters were calculated from the laboratory data. Dissolved inorganic nitrogen (DIN) is the sum of nitrate + nitrite and ammonium. Organic nitrogen is the difference between total nitrogen and DIN. Organic phosphorus is the difference between total phosphorus and orthophosphate. Particulate organic carbon is the difference between total organic carbon and dissolved organic carbon.

Figure 42 through Figure 45 present box and whisker plots of total nitrogen and various species that illustrate where high concentrations occur. South of the Tacoma Narrows, several streams have median DIN concentrations above 1.0 mg/L: Goodnough, Woodland, Butler, Mission, McAllister, Miller, and Chambers Creeks. Others, notably tributaries to Case, Hammersley, and Totten Inlets, have median concentrations below 0.5 mg/L. All smaller tributaries to the east side of Central Sound have median concentrations >0.7 mg/L. Of the largest inflows, the Green/Duwamish system has the highest concentrations. Ammonium levels tend to be low in comparison with nitrate + nitrite, although several rivers and streams had some high levels. Hylebos and McAllister Creeks have the highest median nitrogen concentrations, due in part to the relative contribution of groundwater in those systems.

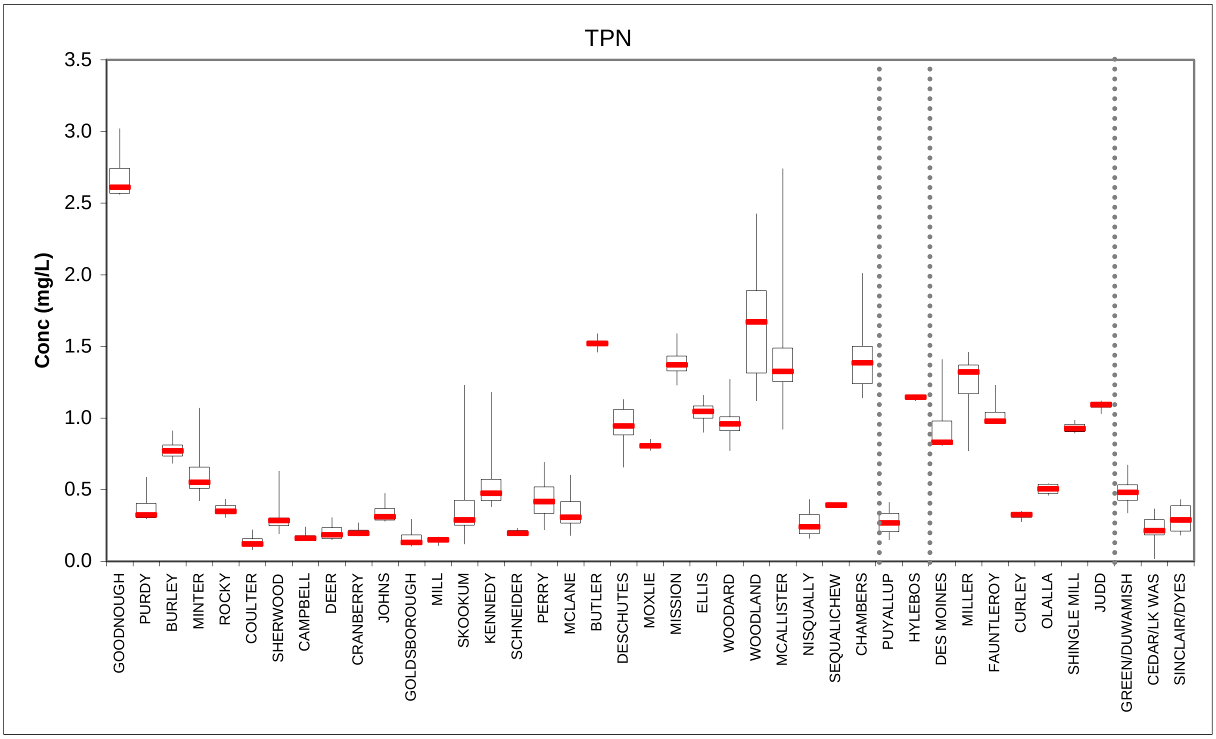


Figure 42. Total (persulfate) nitrogen concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values. Dashed gray lines distinguish South Puget Sound, Commencement Bay, South Central Puget Sound south of Alki Point, and the model domain north of Alki Point.

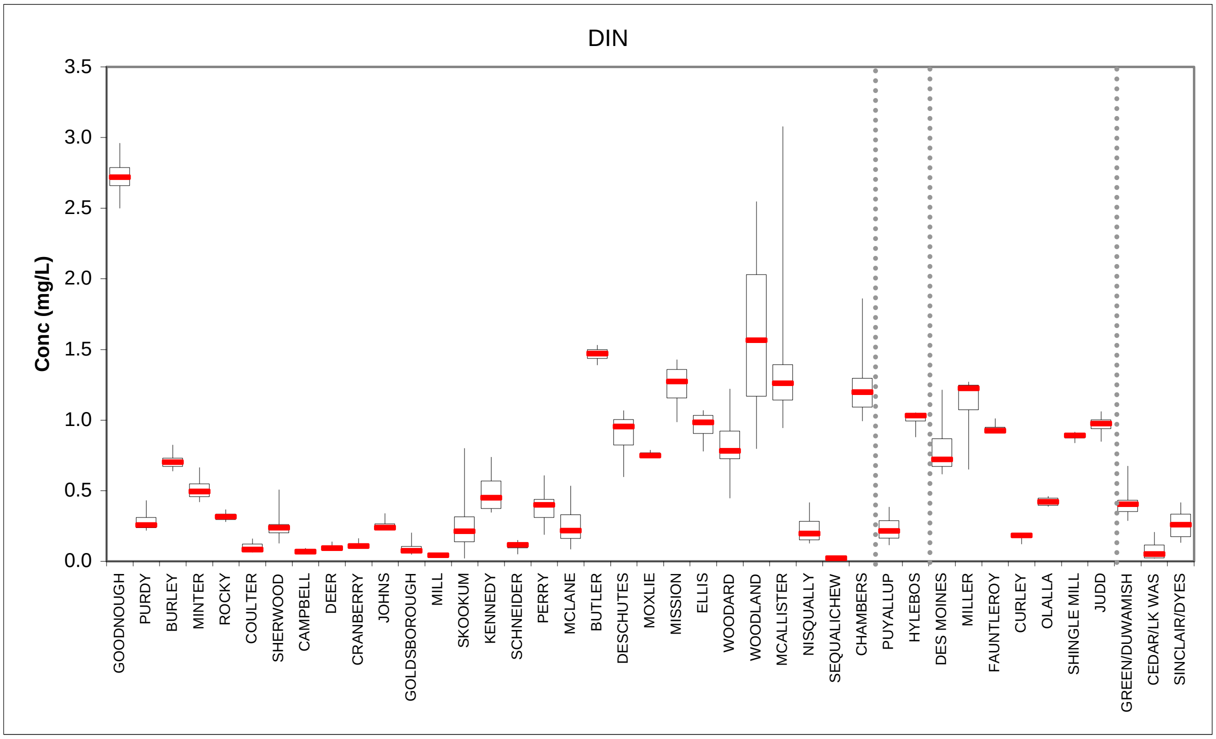


Figure 43. Dissolved inorganic nitrogen (DIN) concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

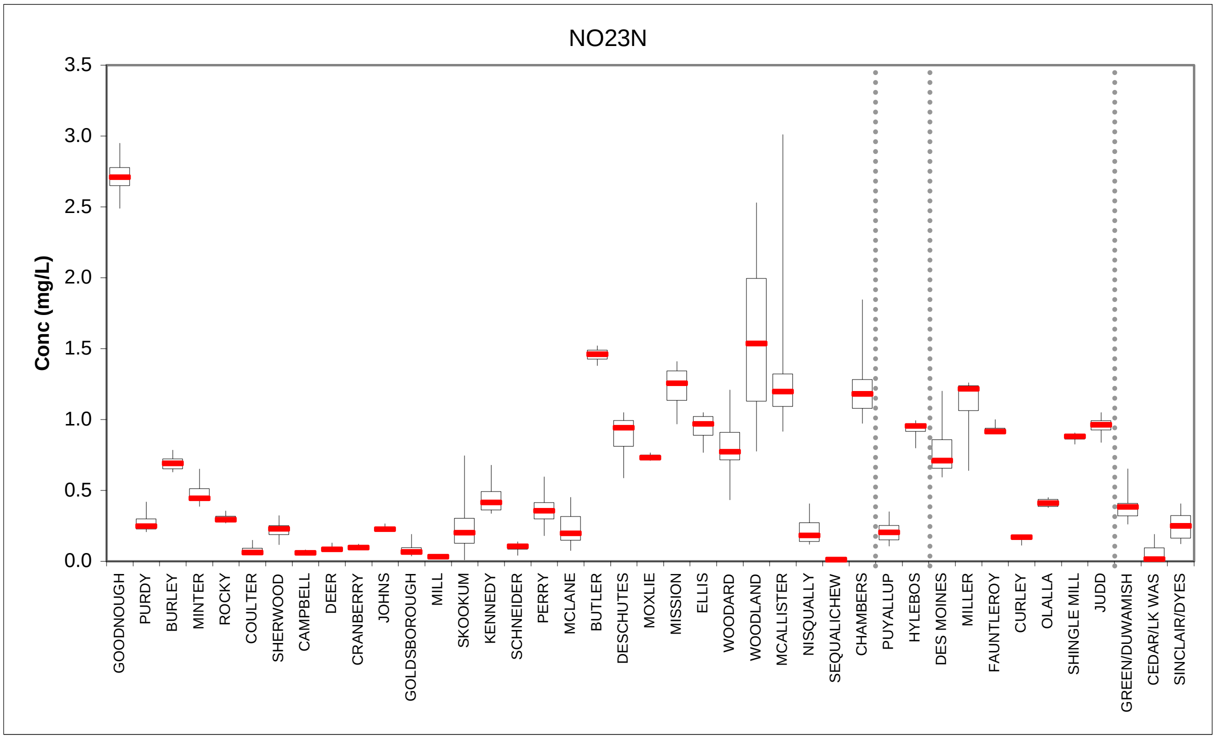


Figure 44. Nitrate + nitrite concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

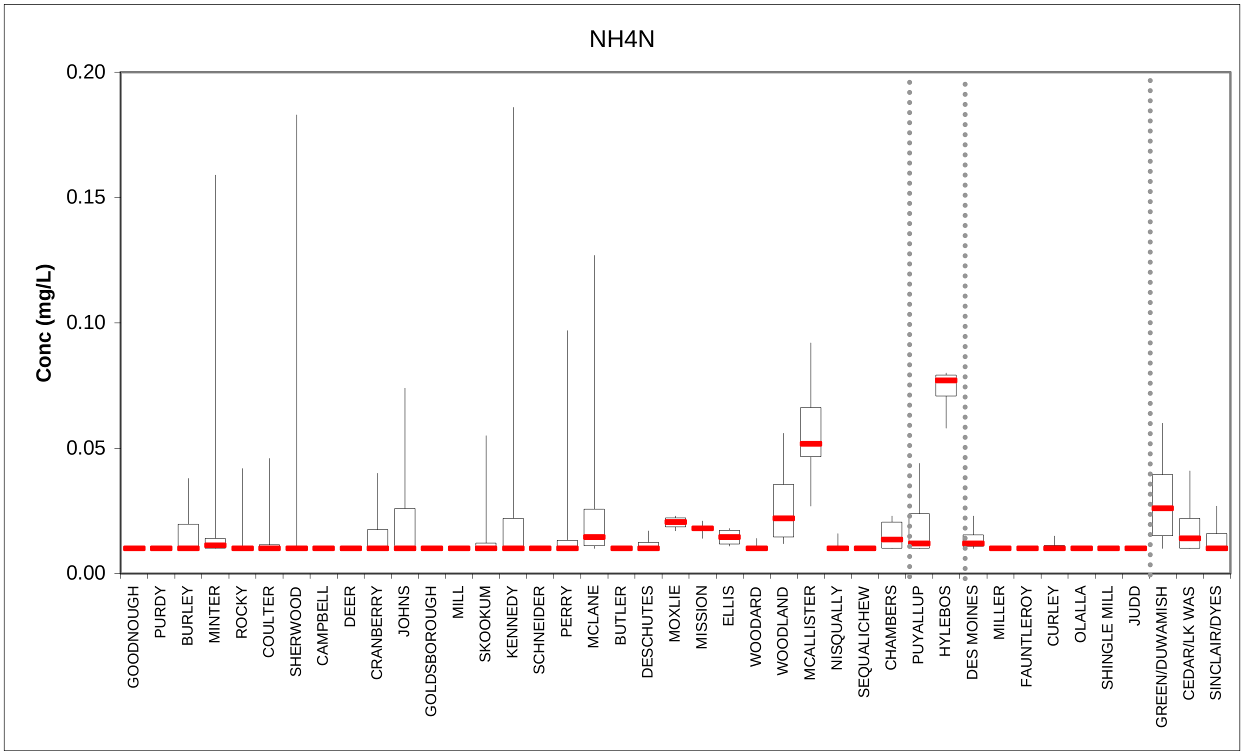


Figure 45. Ammonium concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Median concentrations of nitrogen are also presented geographically in Figure 46 through Figure 49. The highest concentrations of total nitrogen and DIN are found around Budd Inlet, Carr Inlet, and in areas tributary to Central Puget Sound, while the lowest levels are found in the tributaries to Case, Hammersley, and Totten Inlets. Highest levels of ammonium are found in McAllister Creek, Hylebos Creek, and the Green/Duwamish system.

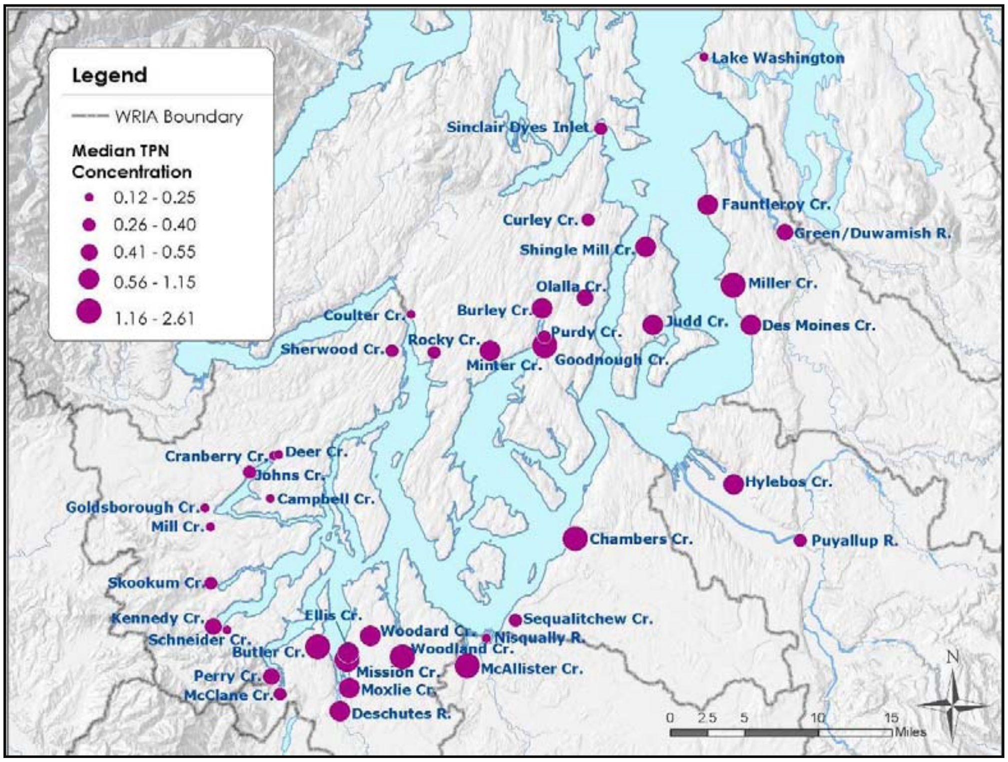


Figure 46. Median tributary concentrations of total persulfate nitrogen for August 2006 through October 2007.

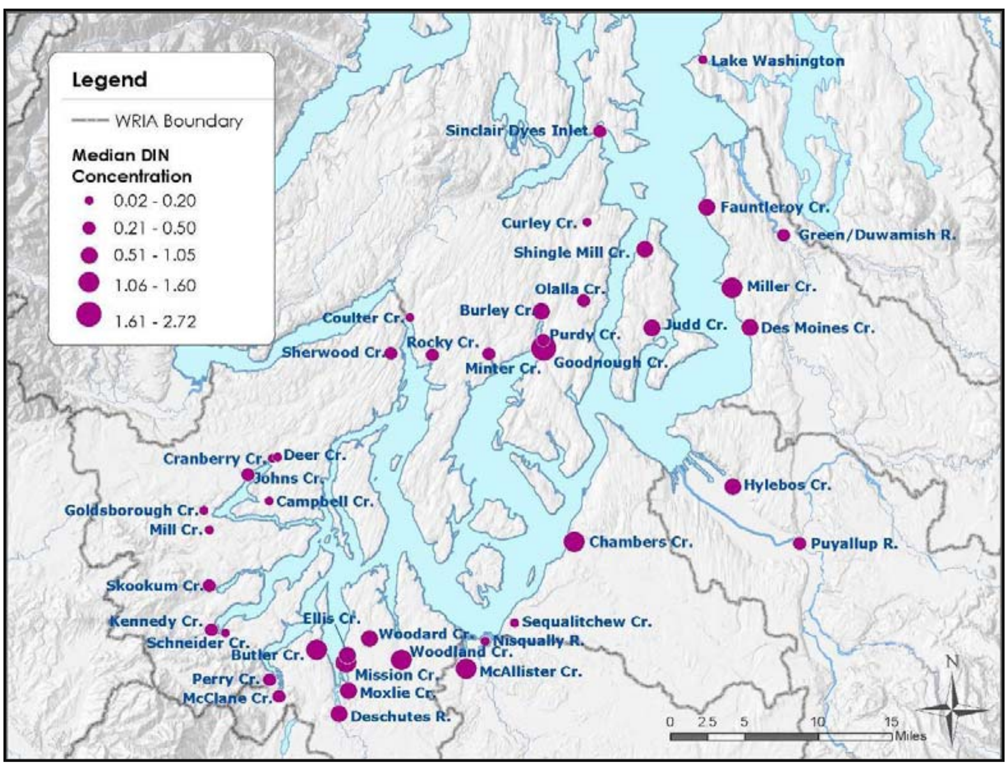


Figure 47. Median tributary concentrations of dissolved inorganic nitrogen for August 2006 through October 2007.

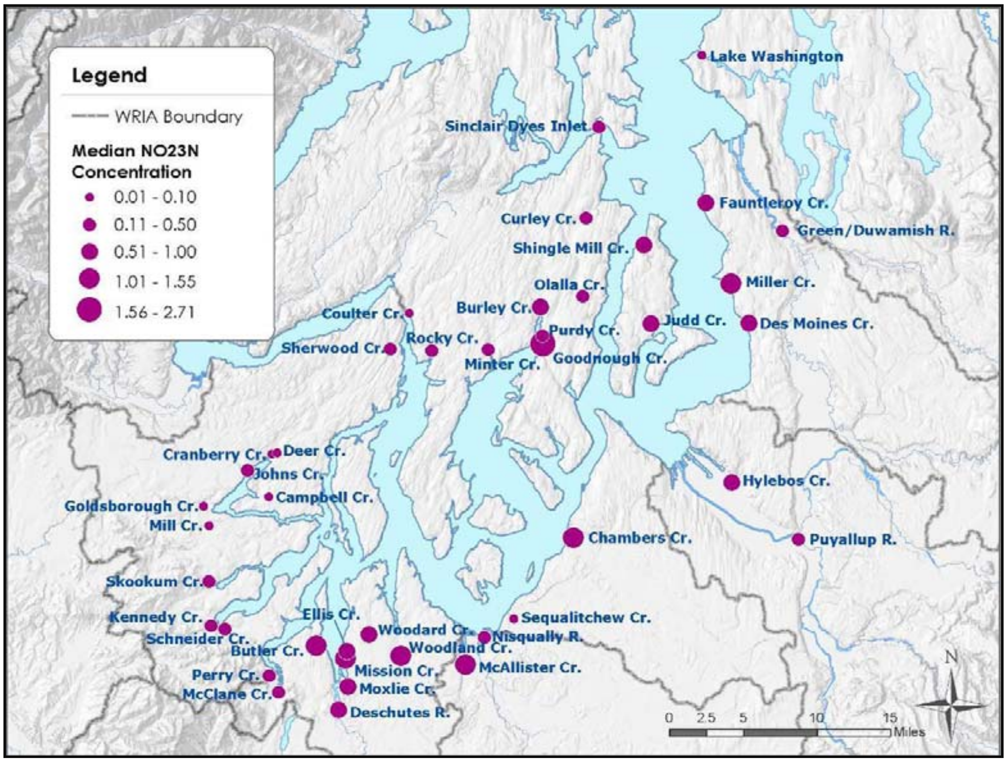


Figure 48. Median tributary concentrations of nitrate + nitrite for August 2006 through October 2007.

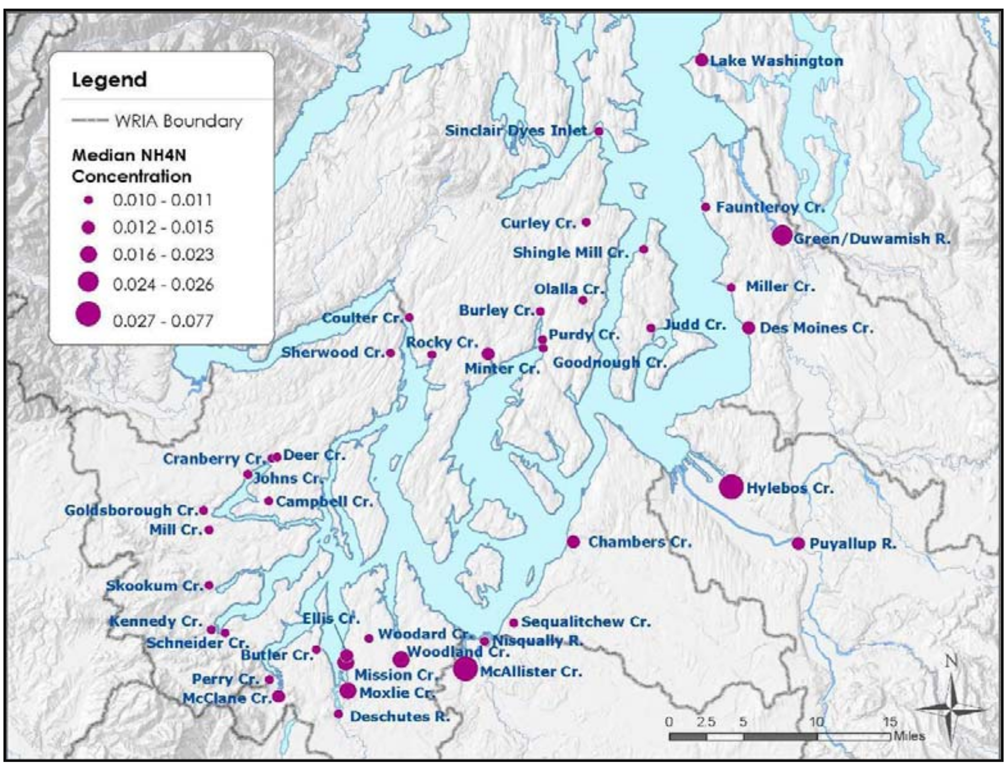


Figure 49. Median tributary concentrations of ammonium for August 2006 through October 2007.

Figure 50 and Figure 51 present box and whisker plots of total phosphorus and orthophosphate. The highest median concentrations occur in McAllister and Mission Creeks south of the Tacoma Narrows as well as tributaries to Commencement Bay and South Central Puget Sound. The small creeks tributary to Case Inlet, Hammersley Inlet, and Totten Inlet tend to have the lowest levels, as do most of the larger rivers. Of the large rivers, the Puyallup River has the highest total phosphorus concentrations, although orthophosphate levels tend to be similar to the other large rivers.

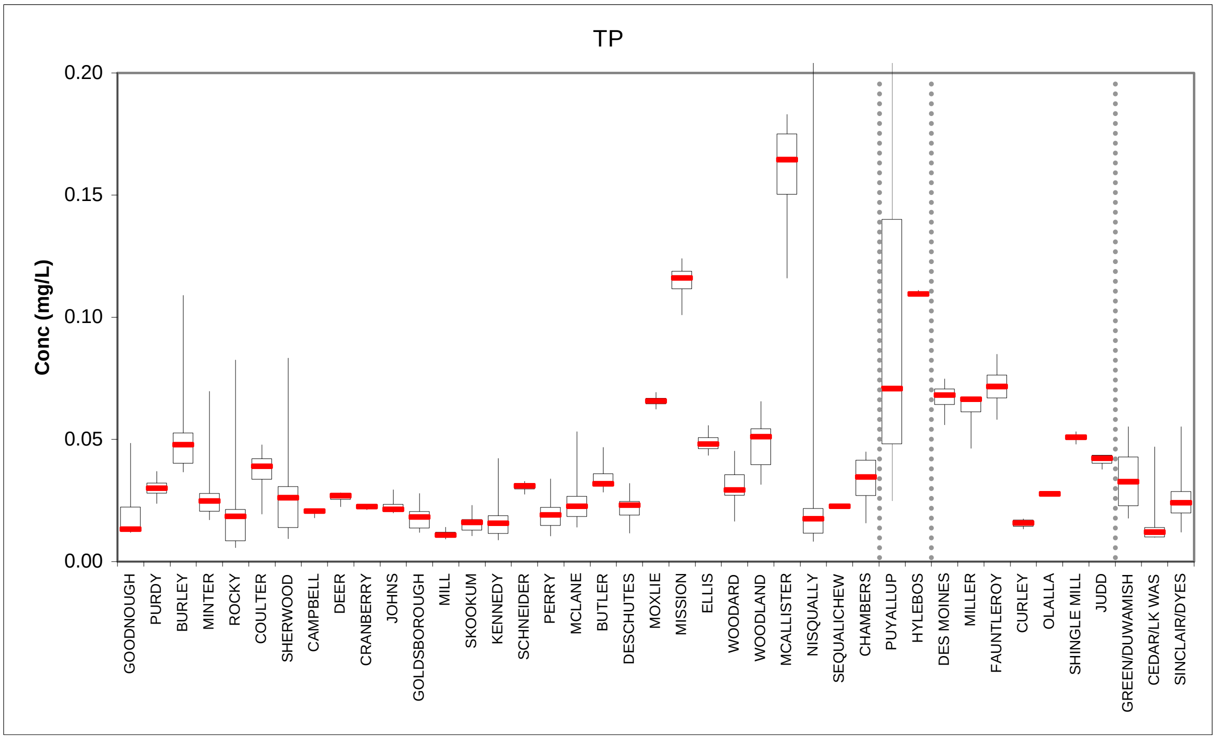


Figure 50. Total phosphorus concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

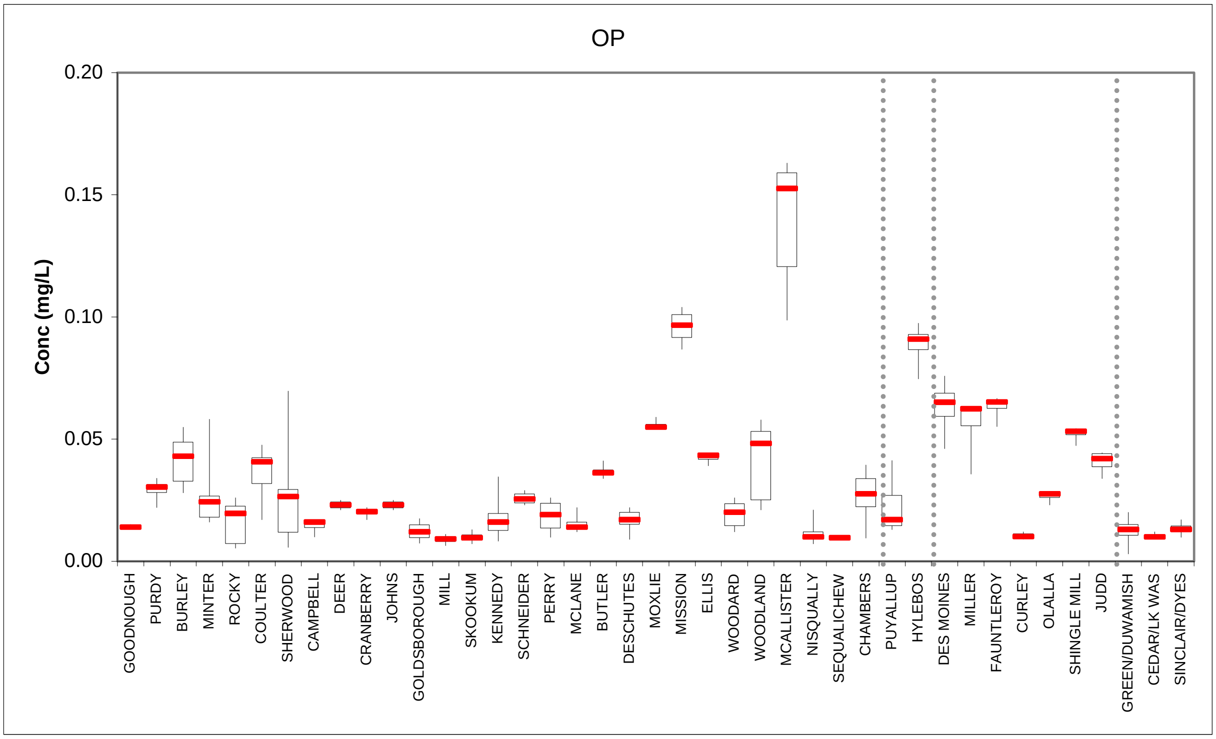


Figure 51. Orthophosphate concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Figure 52 and Figure 53 present the median concentrations spatially. The watersheds on the south and east sides of South and Central Sound exhibit the highest concentrations of total phosphorus and orthophosphate, while the watersheds tributary to Eld, Totten, Hammersley, and Case Inlets produce the lowest concentrations.

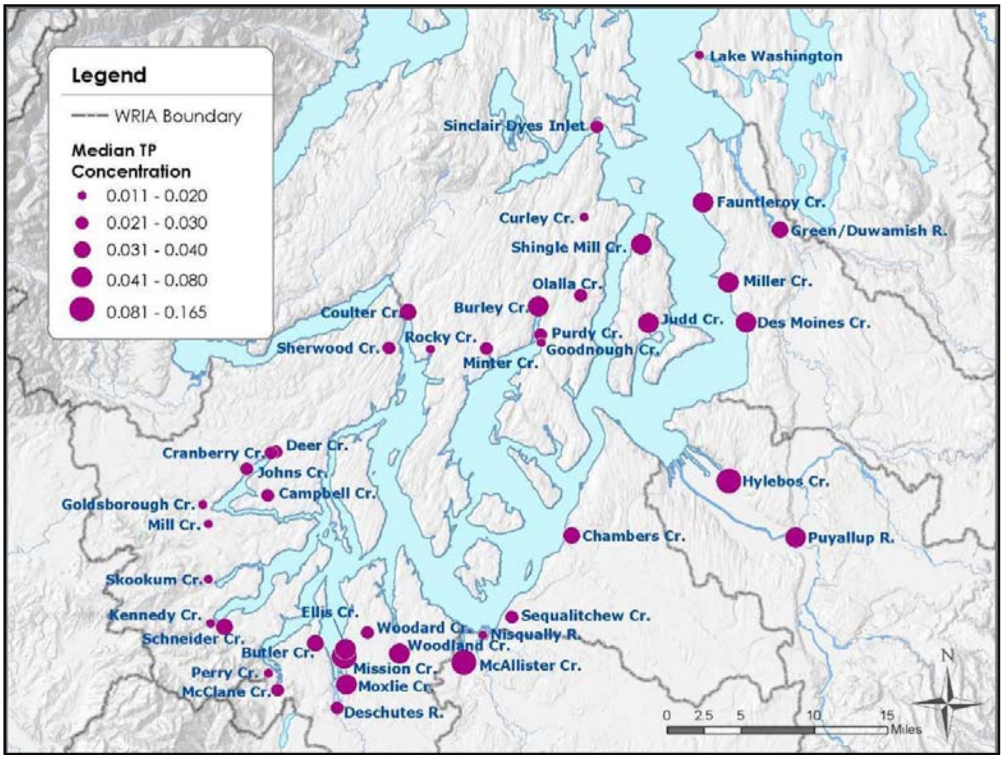


Figure 52. Median tributary concentrations of total phosphorus for August 2006 through October 2007.

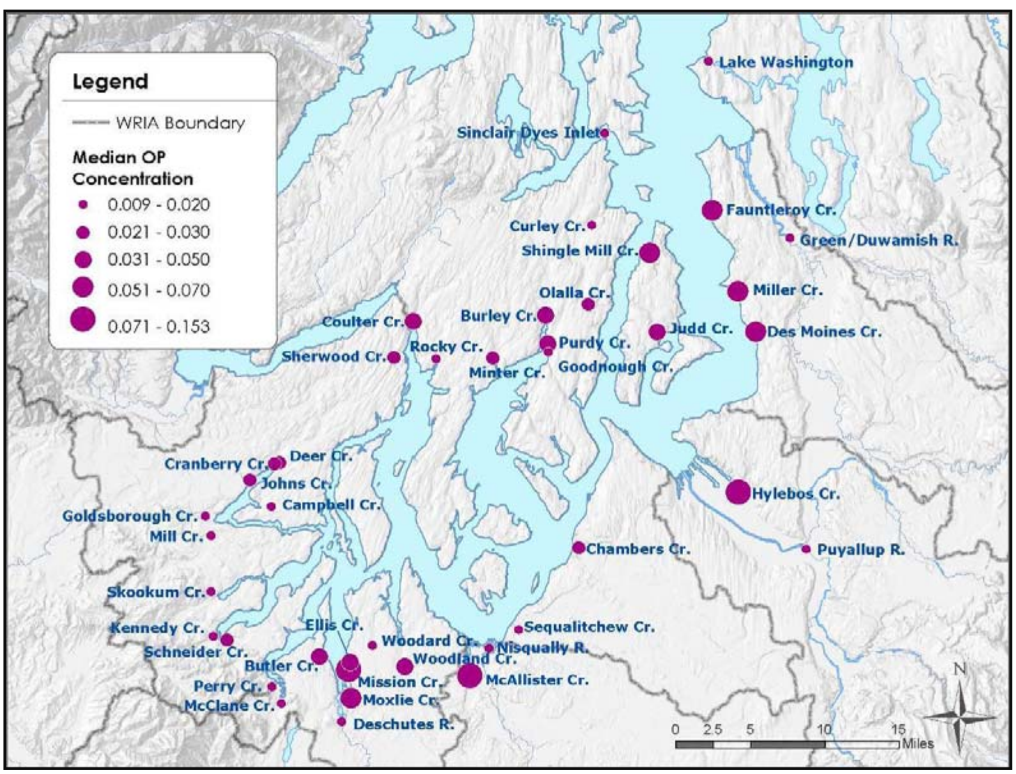


Figure 53. Median tributary concentrations of orthophosphate for August 2006 through October 2007.

Figure 54 and Figure 55 present total and dissolved organic carbon concentrations in freshwater inflows. Woodard Creek has the highest organic carbon concentrations south of Tacoma Narrows, but all rivers had median concentrations between 1 and 5 mg/L, and nearly all organic carbon is in dissolved form. Sequalitchew Creek was flowing and sampled only once during the project, and it is unclear what might have contributed to the very high organic carbon levels.

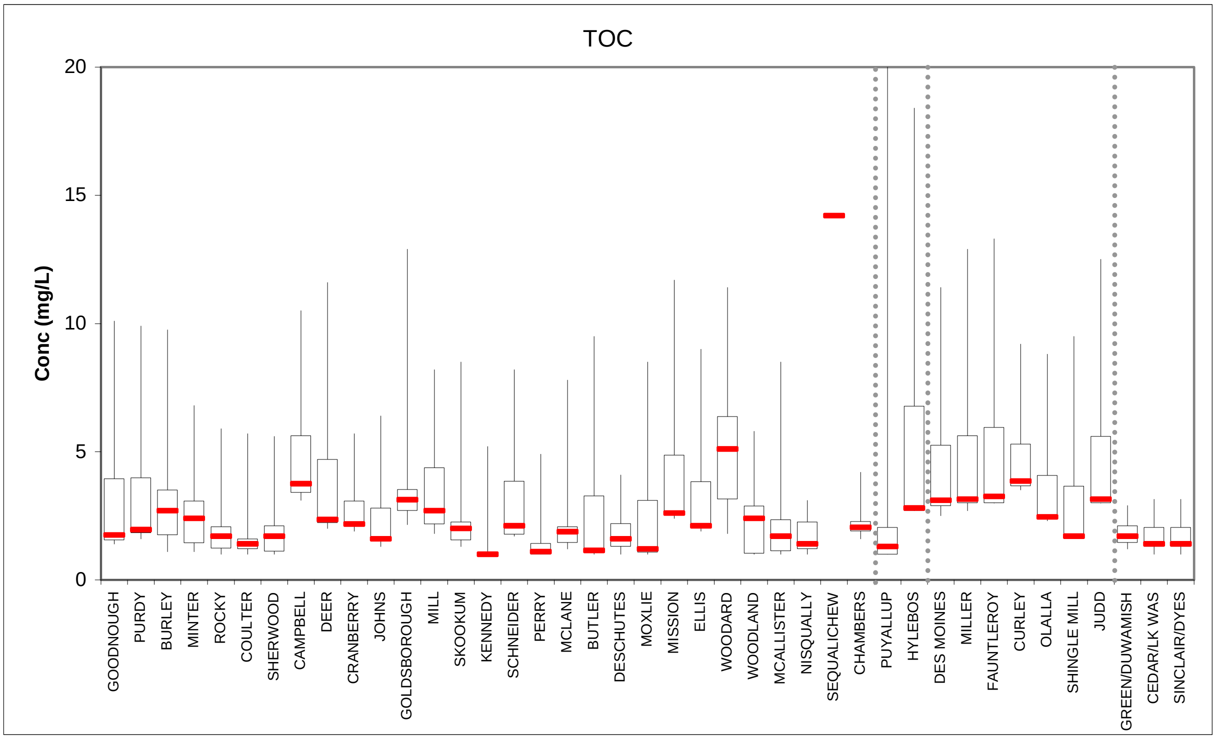


Figure 54. Total organic carbon concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

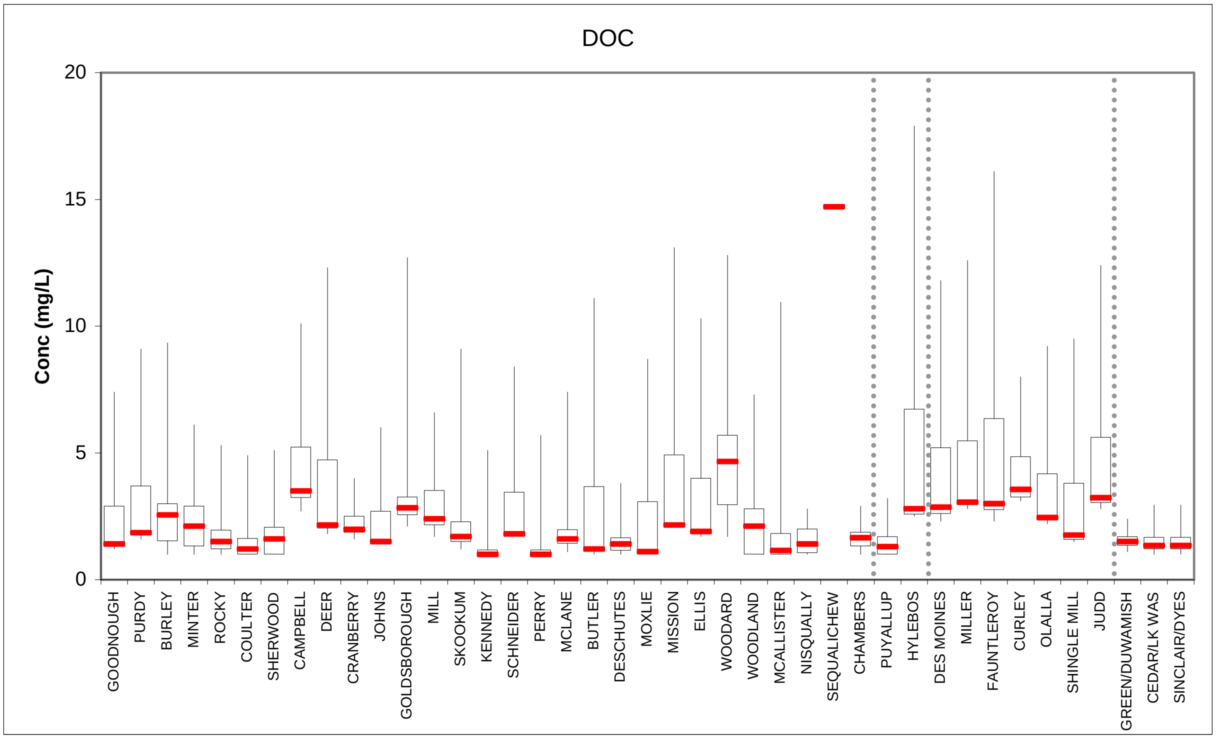


Figure 55. Dissolved organic carbon concentrations in rivers and tributaries for August 2006 through October 2007. Boxes represent the 25th and 75th percentile concentrations, thick red lines indicate the 50th percentile (median) concentrations, and lines extend to the minimum and maximum values.

Figure 56 and Figure 57 present the median organic carbon concentrations spatially. Because nearly all organic carbon is in dissolved form, the patterns are the same. The highest concentrations occur in south King County and around Henderson Inlet, but also in the low-development watersheds tributary to Hammersley Inlet. The lowest concentrations are found in tributaries to Totten, Eld, and Case Inlet, as well as the major rivers.

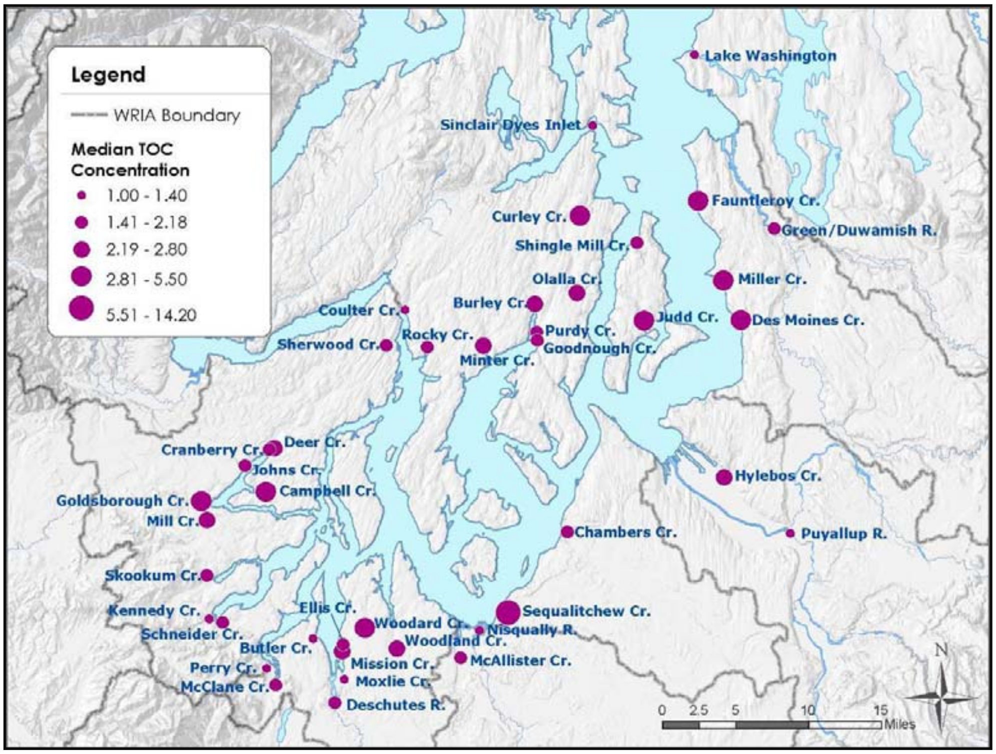


Figure 56. Median tributary concentrations of total organic carbon for August 2006 through October 2007.

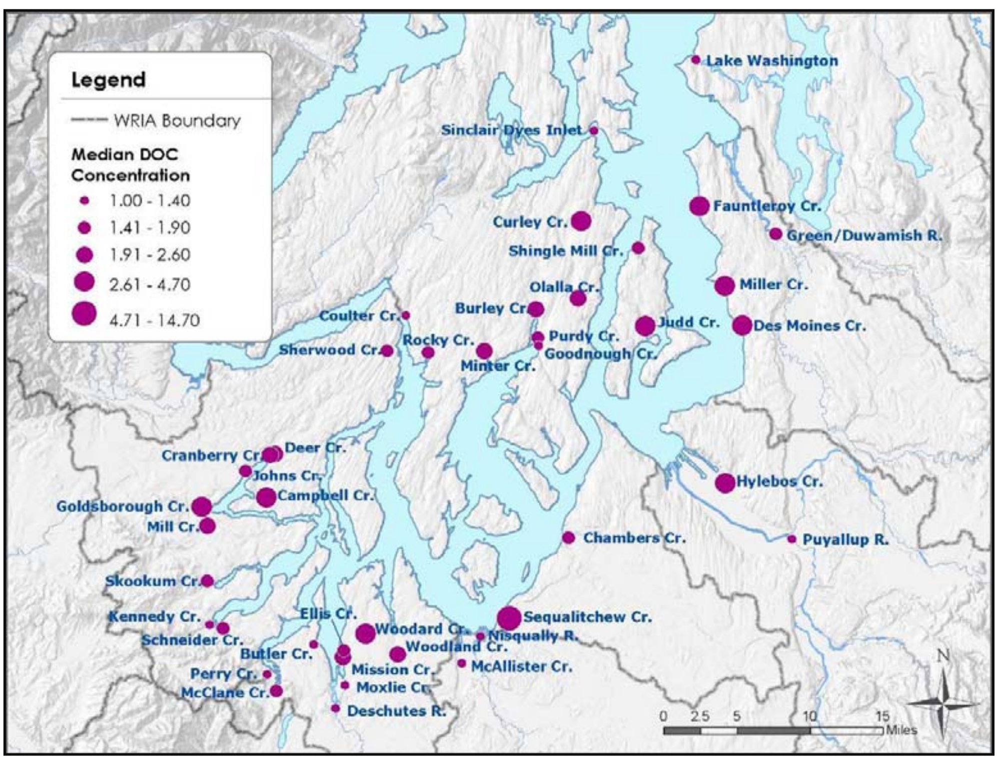


Figure 57. Median tributary concentrations of dissolved organic carbon for August 2006 through October 2007.

Load Estimates

Instantaneous load estimates for both tributaries and wastewater treatment plants (WWTPs) were estimated from monthly samples and flow measurements based on the time-weighted mean of individual sampling days. A future effort will use a statistical technique called *multiple linear regression* to develop daily time series for each inflow and water quality parameter to support water quality model development. While a variety of wet-weather events occurred on monitoring days, the simple time-weighted estimates represent a reasonable initial step toward understanding tributary loads.

If no samples were collected from a tributary or WWTP in a given month, the site was not included in the monthly summary. For example, no samples from small tributaries were collected due to high-flow conditions in November 2006; therefore, the tributary totals for that month reflect the large rivers only that are part of the ambient monitoring program (and are sampled from bridges).

Watershed loads from the area around Sinclair and Dyes Inlets, including Vashon Island, and the area between the Puyallup and Green/Duwamish Rivers were estimated from the flows described above and median water quality concentrations from the major rivers. If the area south of the Tacoma Narrows is sensitive to these inputs, these load estimates will be refined. The estimates were included to complete the watershed contributions south of Edmonds.

In addition, loads from the Lake Washington basin, including the Cedar River, were based on monitoring conducted from October 1993 through September 1994. This was because that was the only year that Ecology monitored the Ship Canal as part of its ambient monitoring program and no other recent monitoring data are available. During this period, nitrogen and phosphorus concentrations were lower in the Ship Canal than in either the Cedar River or Sammamish River, and neither river adequately represented the combined effects of the large lakes. Therefore, the monthly results from 1993-1994 were assigned to the corresponding month in 2006-2007 as a first estimate of loads from the Lake Washington basin. If the area south of the Tacoma Narrows is sensitive to these inputs, these load estimates will be refined.

From May through October, South Sound river inflows contributed an average of 890 kg/d of DIN, but they contributed five times as much from November through April (4,800 kg/d; Figure 58). The seasonal pattern holds for all regions in the project area. South of Edmonds, rivers and streams contributed 2,400 kg/d in the dry months, but 13,700 kg/d in the wet months. Most of the total nitrogen was in the form of DIN, which is primarily nitrate + nitrite. Ammonium levels were above detection limit concentrations in the winter, but the loads were small compared to nitrate + nitrite.

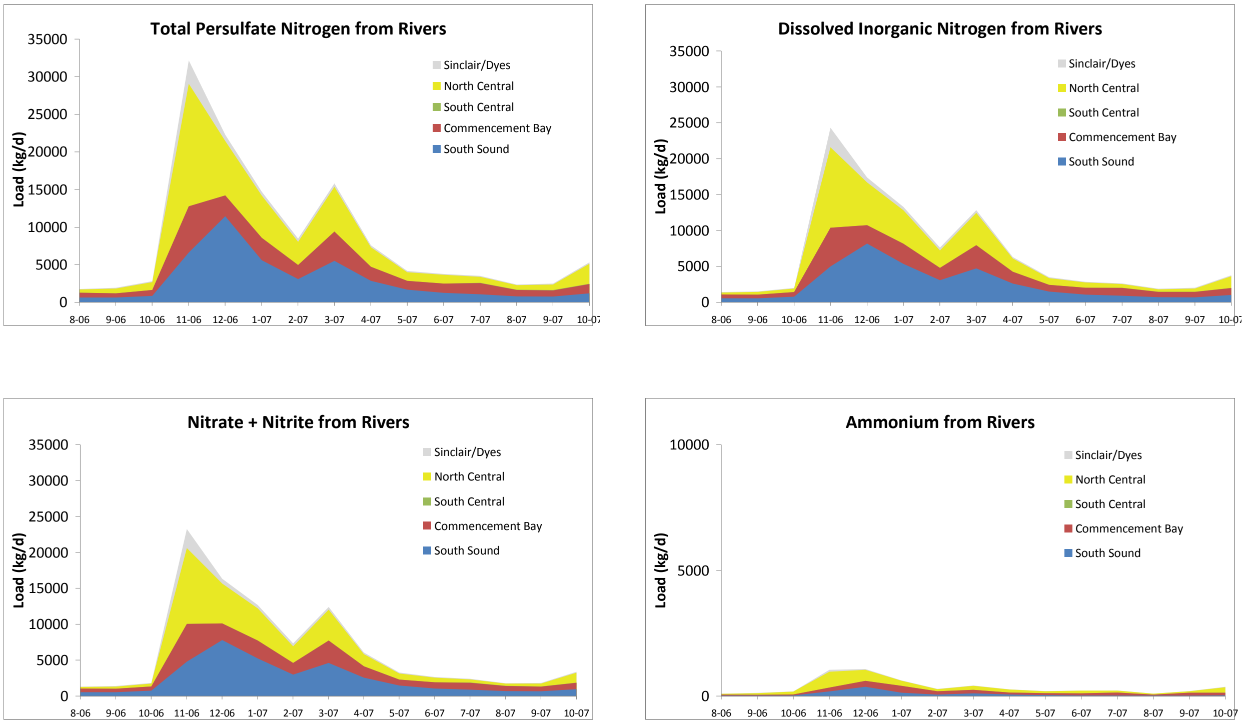


Figure 58. Nitrogen loads from rivers and streams totaled by regions.

The phosphorus loads (Figure 59) also reflect the seasonal variation in the flows, and winter loads are far greater than summer loads. Most of the phosphorus load is in the form of organic phosphorus, since orthophosphate loads are relatively low throughout the project area. Total phosphorus loads are highest for Commencement Bay from the Puyallup River.

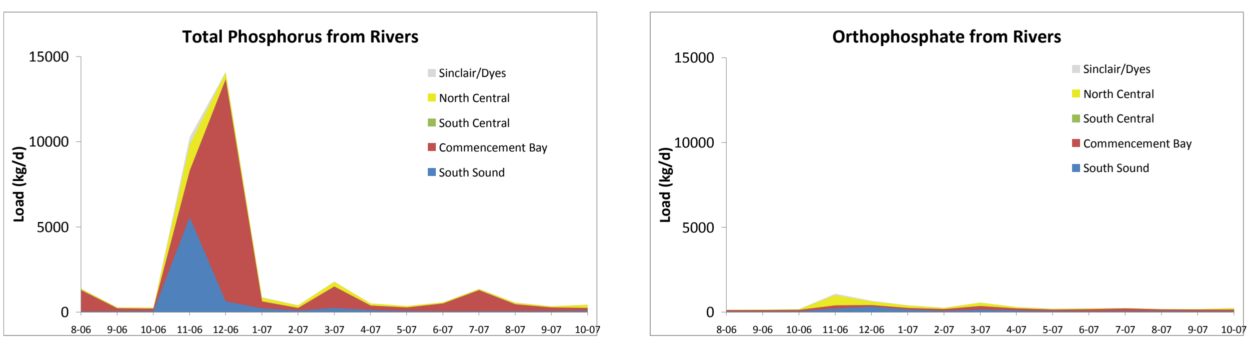


Figure 59. Phosphorus loads from rivers and streams totaled by regions.

Higher total and dissolved organic carbon loads from rivers and streams occurred in the winter, due to both the higher flows and higher concentrations (Figure 60). A second peak occurred in March 2007 in association with a higher flow event as well as higher concentrations of carbon.

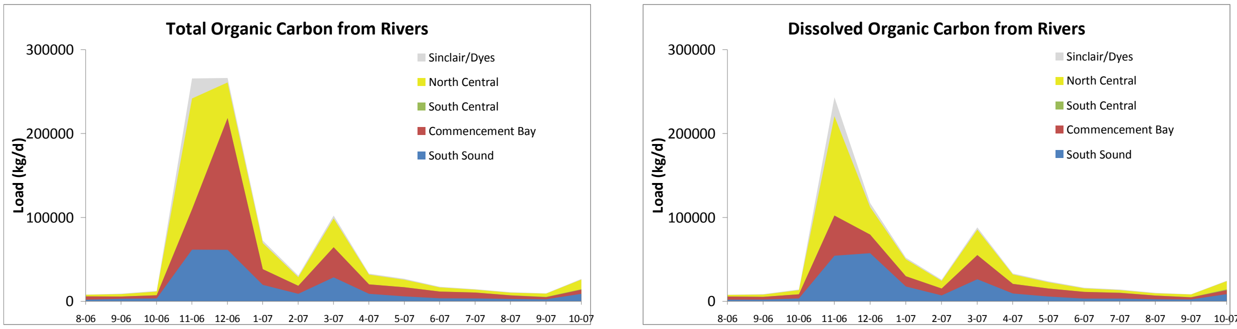


Figure 60. Organic carbon loads from rivers and streams totaled by regions.

South Sound WWTPs produced an average of 2,780 kg/d of DIN, while the Commencement Bay and South Sound together produced an average of 5,380 kg/d (Figure 61). The entire area south of Edmonds produced an average of 26,100 kg/d, mostly from South Central and North Central Puget Sound. The November 2006 and July 2007 decreases in DIN from South Central WWTPs are artifacts of missed sampling events at two separate plants, and no attempt was made to fill in results for these two dates. South Sound and Commencement Bay together produce 21% of the DIN load from WWTPs discharged south of Edmonds.

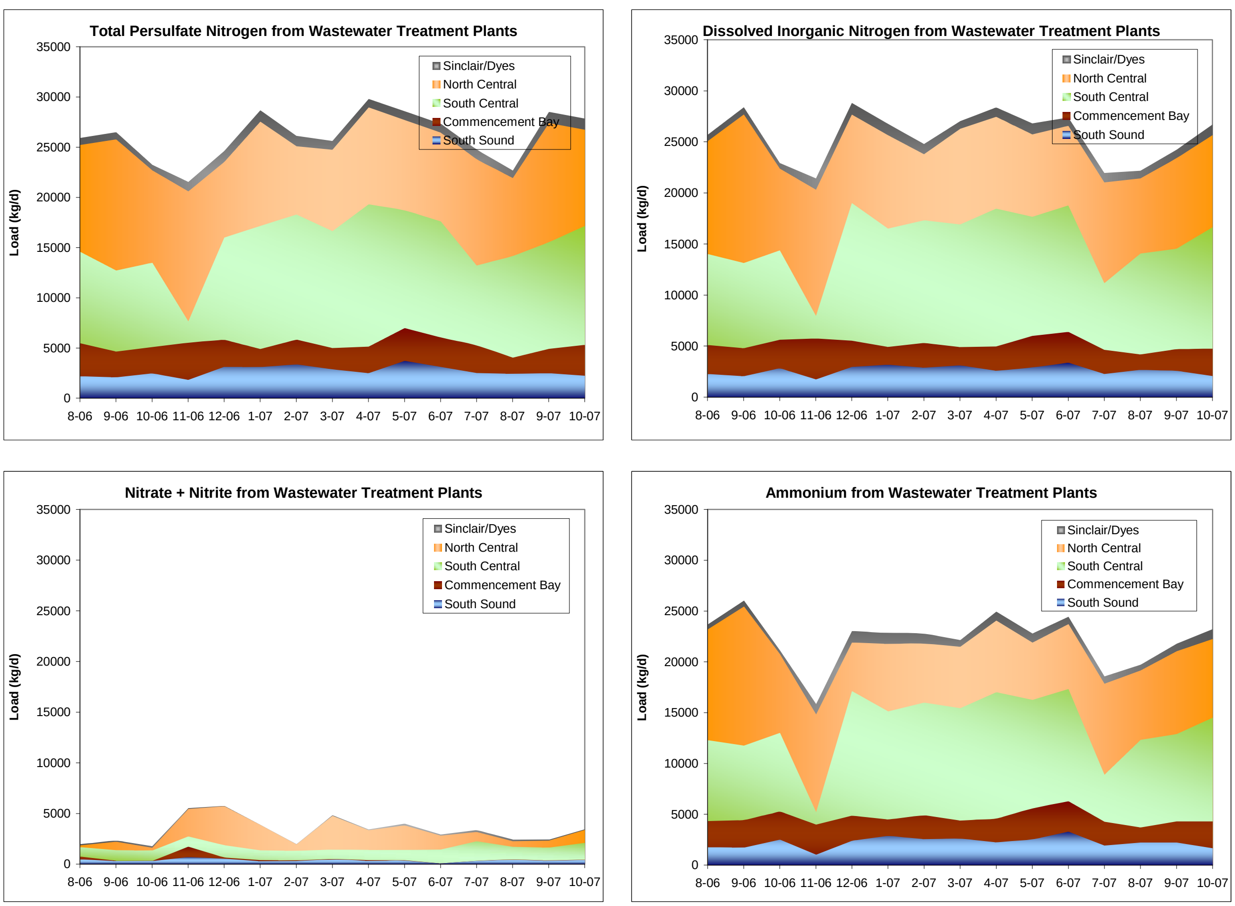


Figure 61. Nitrogen loads from wastewater treatment plants totaled by region.

South Puget Sound WWTPs produced an average of 283 kg/d of phosphorus (Figure 62). Commencement Bay and South Sound produce an average of 493 kg/d, accounting for 17% of the total 2,900 kg/d of total phosphorus discharged from WWTPs south of Edmonds.

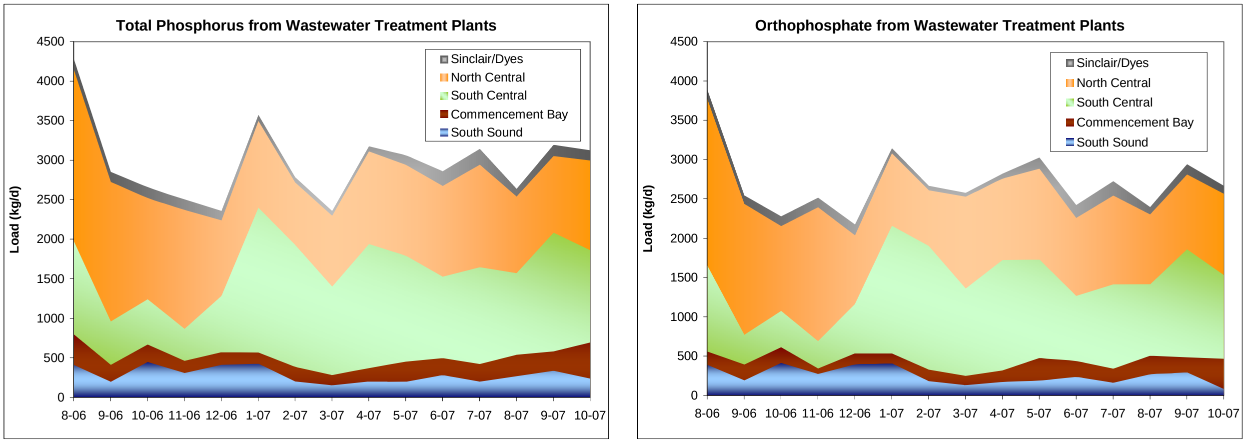


Figure 62. Phosphorus loads from wastewater treatment plants totaled by region.

The apparent increase in carbon loads from WWTPs in late summer 2007 resulted from the addition of the Simpson industrial discharge (Figure 63).

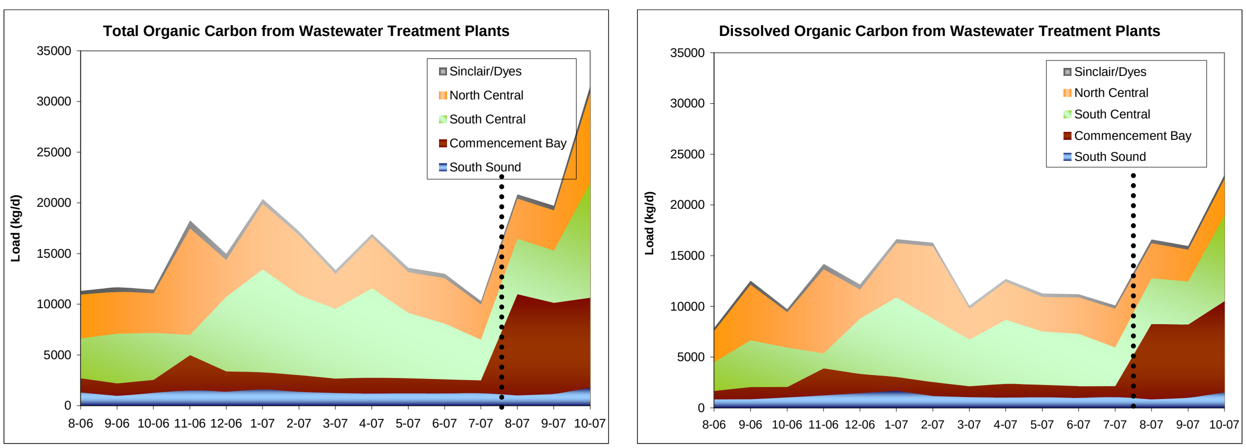


Figure 63. Organic carbon loads from wastewater treatment plants totaled by region. The dashed line indicates when monitoring commenced at the Simpson plant, which contributed high levels of carbon.

The combined contributions of tributaries and WWTPs are presented in Figure 64 for average daily loads over a one-year period. In Budd Inlet, Chambers Creek, and Commencement Bay, tributaries and WWTPs discharge comparable levels of DIN. Rivers and streams dominate in other areas such as Totten Inlet, Eld Inlet, Henderson Inlet, northern Case Inlet, northern Carr Inlet, and the Nisqually Reach, while WWTPs dominate in South Central Puget Sound.

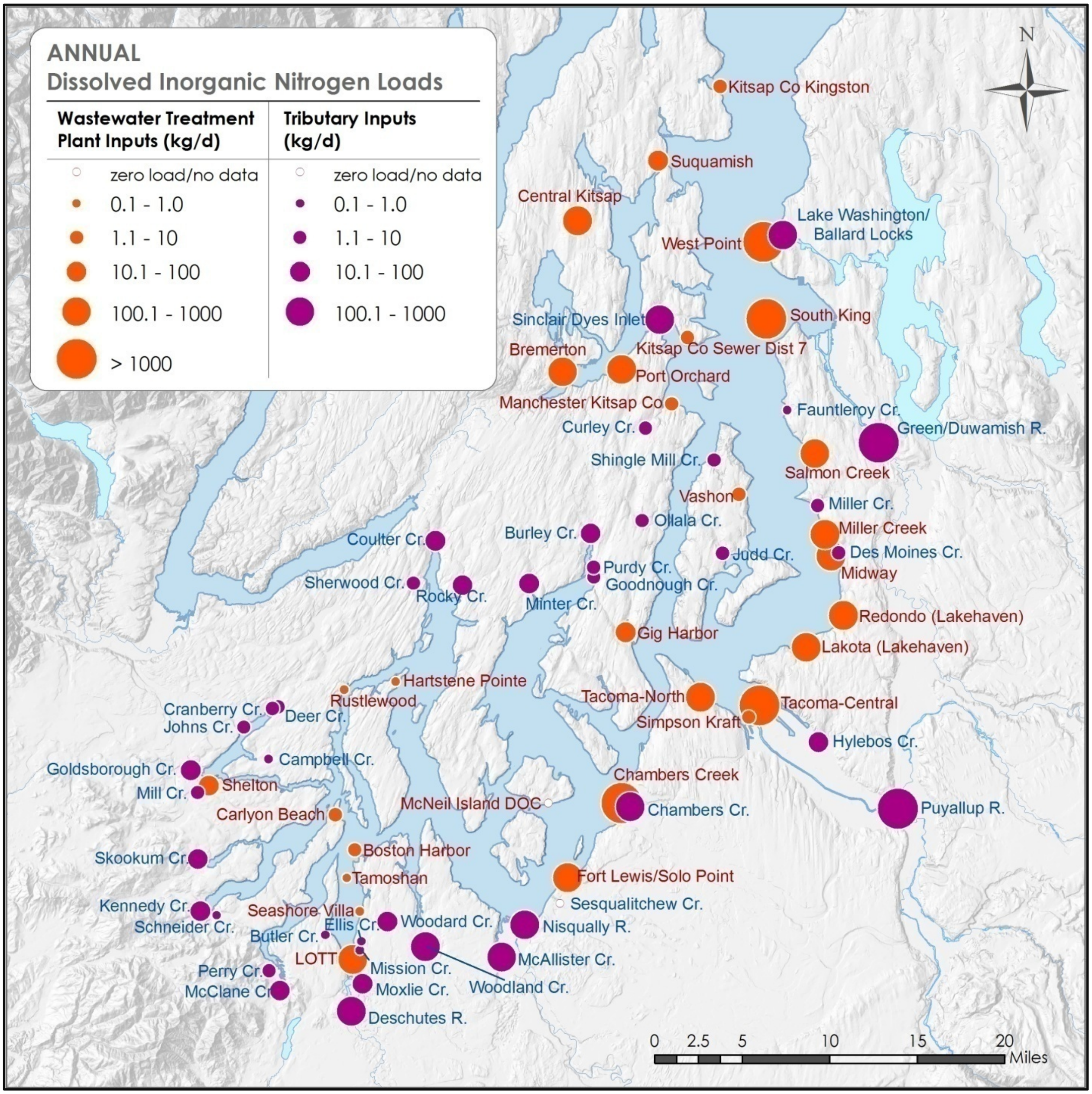


Figure 64. Annual dissolved inorganic nitrogen (DIN) loads from rivers and wastewater treatment plants in South and Central Puget Sound.

All tributaries and WWTPs were monitored in September 2007, generally associated with the lowest near-bottom DO levels. At this time, the largest sources of DIN in South Puget Sound are the Chambers Creek and LOTT WWTPs, Chambers Creek, the Nisqually River, the Deschutes River, and several smaller tributaries, as shown in Figure 65. WWTP loads are comparable to their annual mean values, while the river and stream contribution decrease due to the lower streamflows in the late summer.

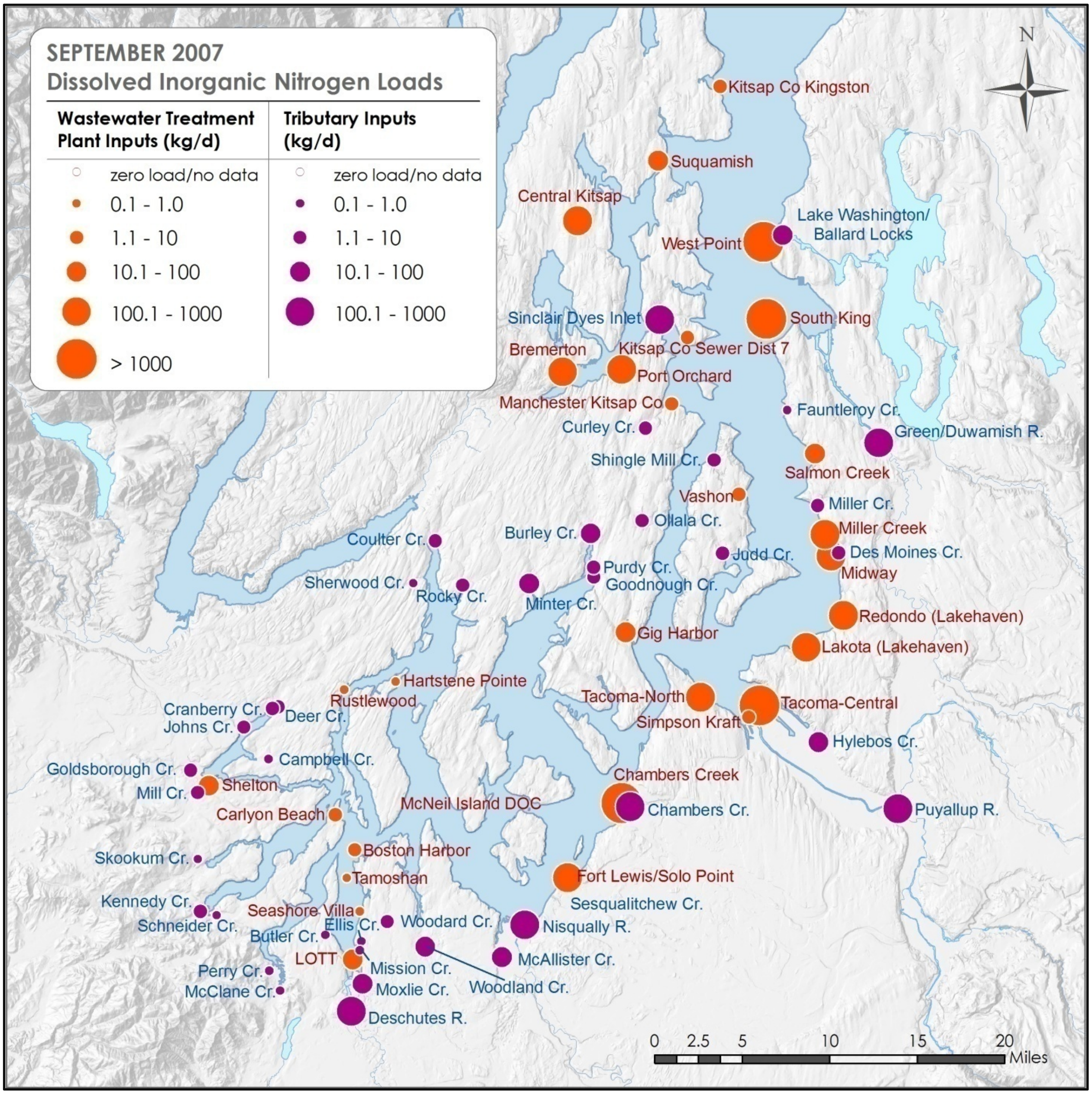


Figure 65. September 2007 dissolved inorganic nitrogen (DIN) loads from rivers and wastewater treatment plants in South and Central Puget Sound.

In addition, Figure 66 summarizes DIN loads from tributaries and WWTPs for South Puget Sound and for Commencement Bay and south. In the dry weather months, particularly from August through October, DIN loads from tributaries are lower than those from WWTPs, but the loads may be comparable or higher in the wet weather months. In South Puget Sound between November and April, WWTPs produced an average of 2,750 kg/d of DIN while rivers and streams produced 4,840 kg/d. However, between May and October, WWTPs still produced 2,560 kg/d of DIN, but rivers and streams produced decreased loads of 890 kg/d, primarily due to the lower flows during this time period. During the low-flow summer season, rivers and streams produced 26% of the DIN load to South Puget Sound and 25% to Commencement Bay and south. WWTPs produced 74% and 75%, respectively.

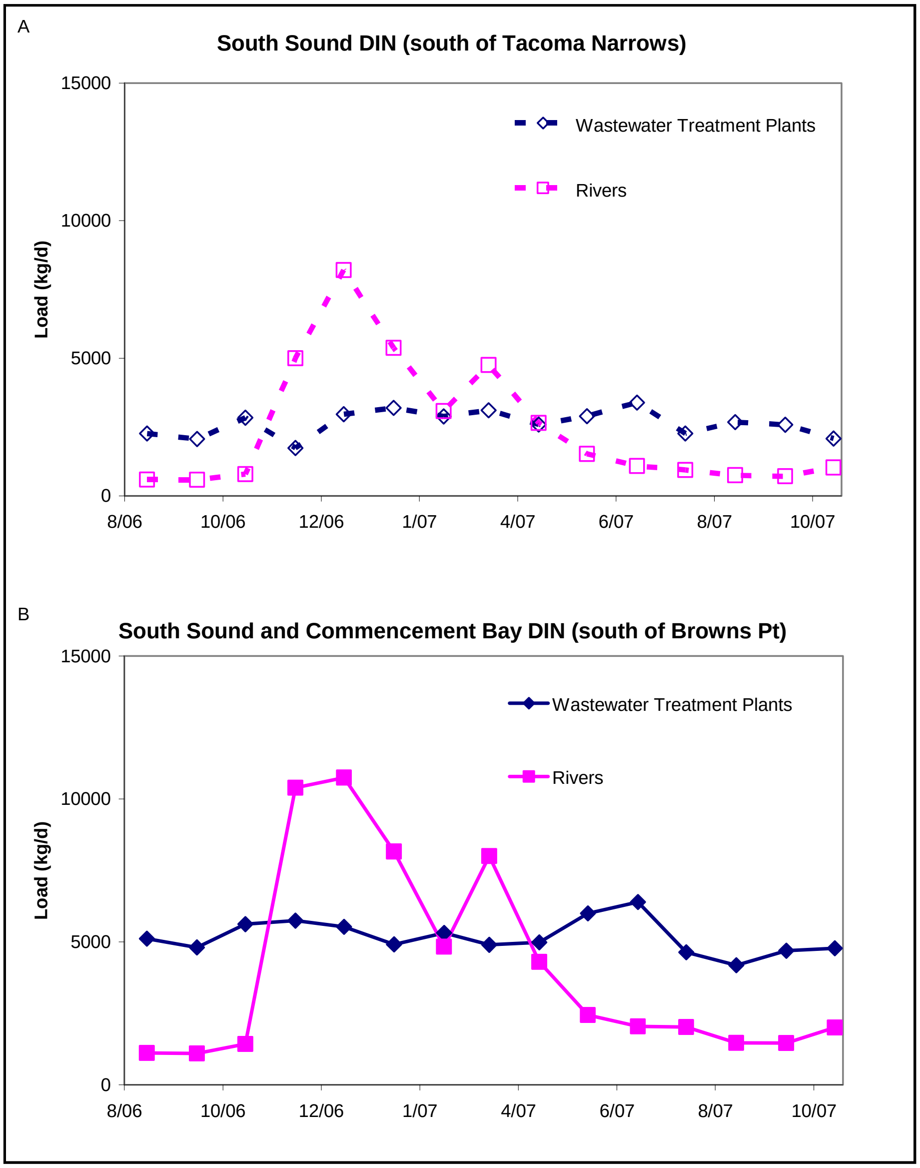


Figure 66. Dissolved inorganic nitrogen (DIN) loads from tributaries and wastewater treatment plants in (A) South Sound (south of Tacoma Narrows) and in (B) Commencement Bay and South Sound (south of Browns Point).

Table 17 summarizes the mean annual and September contributions from WWTPs, and Table 18 summarizes river mouth contributions for both South and Central Puget Sound. These interim estimates are based on the discrete monthly monitoring data, and the data have not been extrapolated to daily values to date. Daily loads will be developed as input to the water quality model, and the values presented in Tables 17 and 18 will be updated.

Table 17. Loads from monitored point sources directly tributary to South and Central Puget Sound estimated from monthly samples.

Point Source	Mean DIN load (kg/d)	
	Annual	Sept 2007
South Sound (south of Tacoma Narrows)		
Boston Harbor	2.4	1.2
Carlyon Beach	3.6	3.3
Chambers Creek	2481	2491
Fort Lewis	247	208
Hartstene Pointe	0.8	0.3
LOTT	158	76.0
Rustlewood	0.7	0.1
Seashore Villa	0.9	0.7
Shelton	55.5	13.2
Tamoshan	0.7	0.6
South Sound subtotal	2,950	2,790
Central Sound (Edmonds to Tacoma Narrows)		
Kitsap Co Sewer District No. 7 (Bainbridge/Fort Ward)	7.7	5.9
Bremerton	331	203
Central Kitsap	469	507
Gig Harbor	41.2	19.0
Kitsap Co Kingston	5.3	4.6
Lakota (Lakehaven)	799	578
Manchester Kitsap Co	6.4	2.9
Midway	447	356
Miller Creek	261	241
Port Orchard	132	108
Redondo (Lakehaven)	252	202
Salmon Creek	119	92.9
Simpson Kraft	9.9	1.9
South King	9592	8376
Suquamish	16.1	17.5
Tacoma Central	2130	1704
Tacoma North	383	380
Vashon	3.1	0.1
West Point	9185	8847
Central Sound subtotal	24,200	21,600
South and Central Puget Sound Total	27,100	24,400

Table 18. Loads from monitored rivers and streams tributary to South and Central Puget Sound.

Stream/River	Mean DIN Load (kg/d)	
	Annual	Sept 2007
South Sound (south of Tacoma Narrows)		
Deschutes River	653	198
Butler Creek	0.2	0.1
Ellis Creek	0.8	1.0
Mission Creek	0.9	0.8
Moxlie Creek	16.3	15.3
Nisqually River	872	199
Burley Creek	55.0	23.7
Campbell Creek	0.4	0.2
Chambers Creek	391	112
Coulter Creek	12.8	2.6
Cranberry Creek	3.5	2.1
Deer Creek	5.3	3.3
Goldsborough Creek	68.3	4.9
Goodnough Creek	1.6	2.4
Johns Creek	7.2	4.4
Kennedy Creek	89.8	3.5
McAllister Creek	191	51.2
McLane Creek	36.2	0.8
Mill Creek	1.7	1.0
Minter Creek	57.8	13.3
Perry Creek	9.4	0.6
Purdy Creek	1.4	1.0
Rocky Creek	25.7	3.2
Schneider Creek	0.3	0.2
Sequalitchew Creek		
Sherwood Creek	3.0	0.4
Skookum Creek	70.1	0.4
Woodard Creek	16.6	6.5
Woodland Creek	133	56.6
South Sound subtotal	2,720	710
Central Sound (Edmonds to Tacoma Narrows)		
Hylebos Creek	20.5	17.7
Puyallup River	1622	734
Green/Duwamish Watershed	1900	427
Lake Washington/Cedar River Watershed	517	35.8
Sinclair/Dyes Watershed	346	107
Curley Creek	4.1	4.1
Des Moines Creek	3.0	2.2
Fauntleroy Creek	0.7	0.7
Judd Creek	4.1	3.7
Miller Creek	6.7	6.4
Olalla Creek	6.0	5.1
Shingle Mill Creek	4.5	4.1
Central Sound subtotal	4,440	1,350
South and Central Puget Sound	7,160	2,060

NA Not available. Sequalitchew Creek diverted upstream of the mouth, and no outlet was located.

Figure 67 presents the sum of all measured river and WWTP monthly loads for both South Sound (south of Tacoma Narrows) and the combined South and Central Puget Sound (south of Edmonds). On an annual basis, shown in Figure 68, WWTPs and rivers produced comparable loads of DIN to South Puget Sound. However, in September 2007 when river loads declined with flows, WWTPs contributed 80% of the inputs to South Puget Sound. Because of the larger population centers in Central Puget Sound, the ratio of tributary-to-WWTP contributions shifts. On an annual basis, WWTPs contribute 79% and rivers 21% of the DIN load to the combined South and Central Puget Sound. In September 2007, WWTPs contributed over 90% of the DIN load to South and Central Puget Sound.

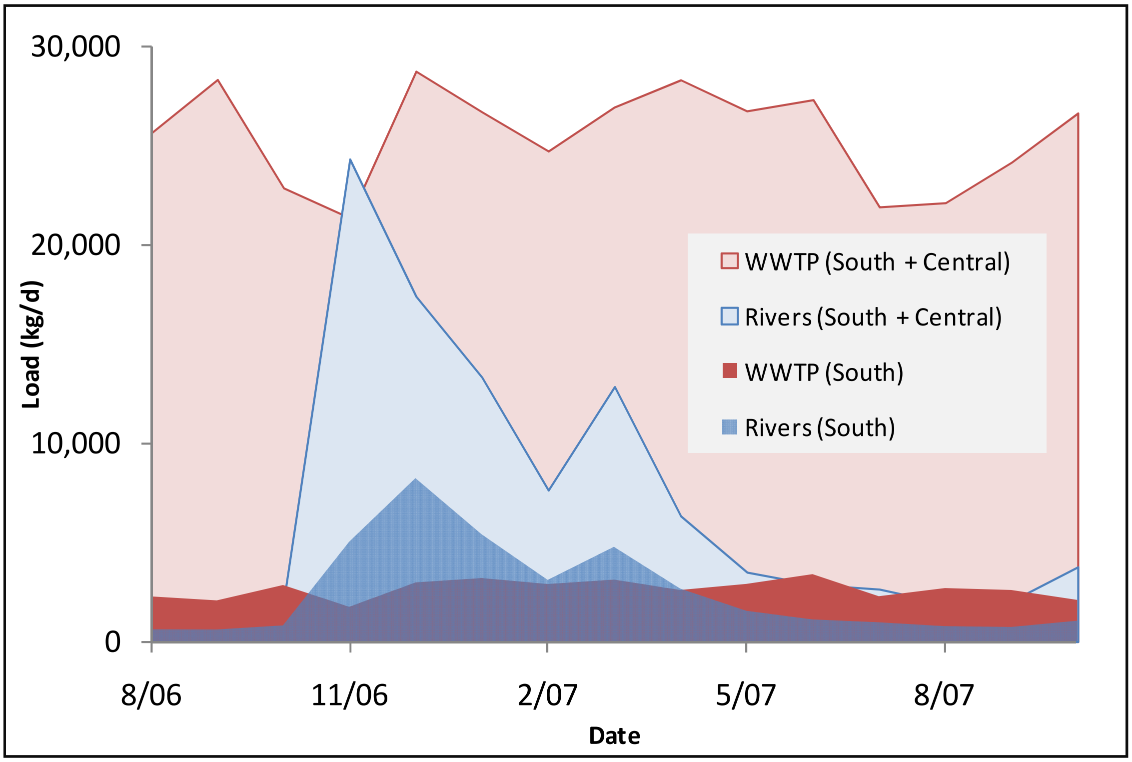


Figure 67. Monthly DIN loads for rivers and wastewater treatment plants tributary to South Sound and the combined South and Central Puget Sound.

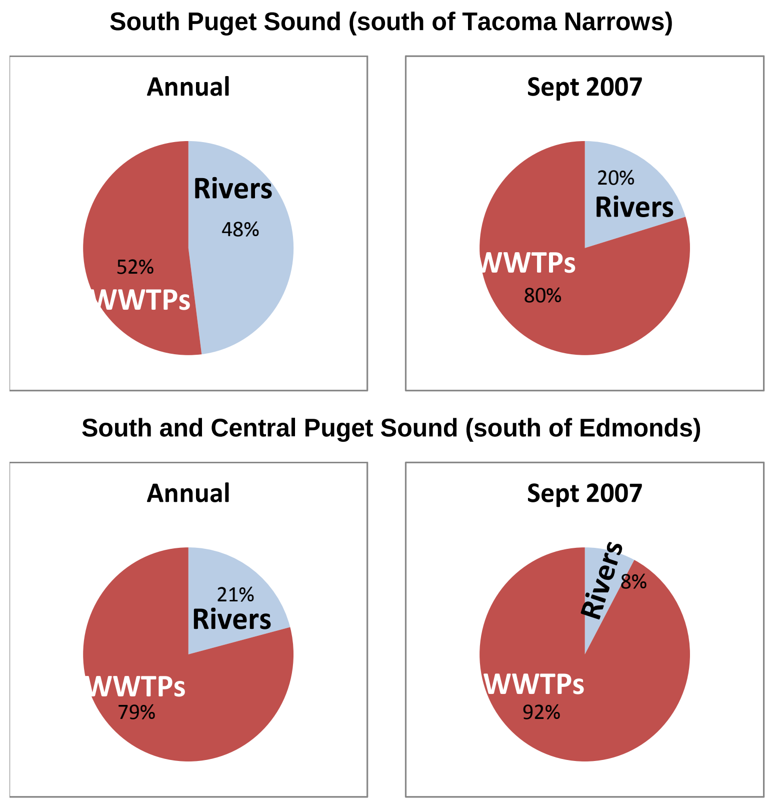


Figure 68. Annual and late summer (September 2007) contributions of DIN load from rivers and wastewater treatment plants that discharge directly to Puget Sound.

Marine Water Data

Data and analysis for marine data in South and Central Puget Sound are compiled from three components of the study:

1. Cruises (research voyages) consisting of instrument (conductivity temperature depth, CTD) profiles of the water column and discrete samples for chemical and biological variables and parameters.
2. Circulation (current) studies made with moored and towed acoustic Doppler current profilers (ADCPs).
3. Benthic flux studies.

Other marine data will be published in addenda to this QA Project Plan. These will include data for sediment traps; phytoplankton species identification and biovolume measurements; and primary productivity.

Cruises

Cruises included sites within both South and Central Puget Sound (Figure 7). Results are presented below for profiles of in-situ variables, laboratory analyses, and spatial and temporal patterns.

Conductivity, Temperature, Depth (CTD) Profiles

A complete set of individual profiles collected during this project are available in Appendix C or by data request (see *Introduction*).

Example vertical profiles are presented in Figure 69 for the potential open model boundaries at Rich Passage, Alki Point, and Edmonds. Results indicate expected seasonal patterns, with warmer waters of higher salinity in the late summer coinciding with lower DO levels. The data show similar water mass properties on the west and east sides of the Edmonds and Alki cross-sections. The slightly cooler, saltier, and less-oxygenated water entering on the west side of Edmonds and Alki at depth noted earlier by Cannon and Ebbesmeyer (1991) was not evident in these data.

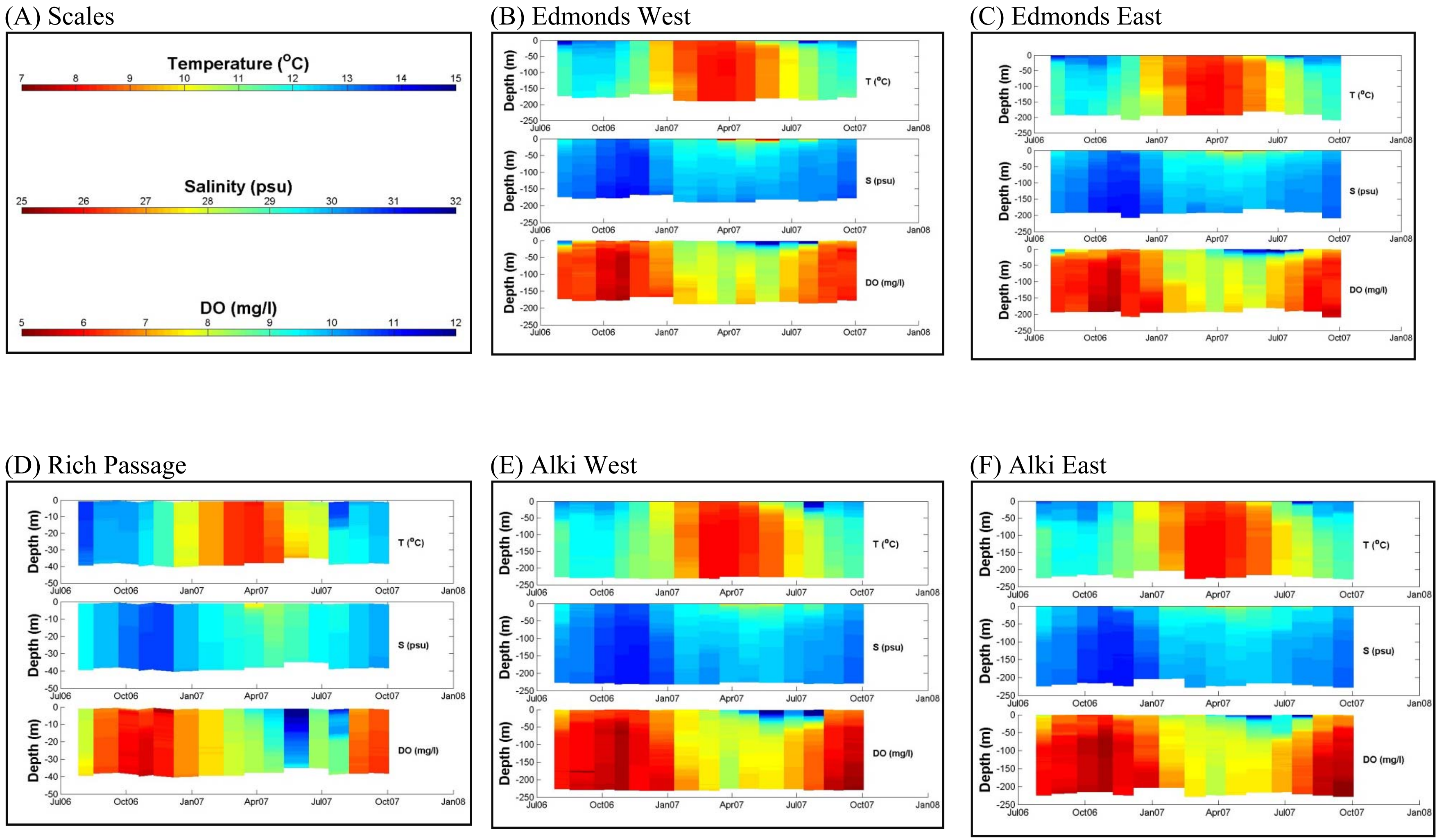


Figure 69. Temporal changes in vertical profiles of temperature, salinity, and dissolved oxygen across open model boundaries using the scales shown in (A). Open model boundaries include (B) Edmonds west, (C) Edmonds east, (D) Rich Passage, (E) Alki west, and (F) Alki east.

Secchi Depths

A comparison of euphotic zone depth and station depth (MLLW) was made to determine locations where the euphotic zone included the entire water column. In these areas, light penetration to the benthos could support benthic primary production that may be important to the overall biogeochemistry of these locations. Stations where the euphotic zone reaches the benthos have been plotted in Figures 70 and 71. For these figures, the sampling period was divided into summer (March 21 – September 21 and winter (September 21 – March 21. Numbers in each figure indicate the percentage of observations during each 6-month period that showed the euphotic zone included the entire water column.

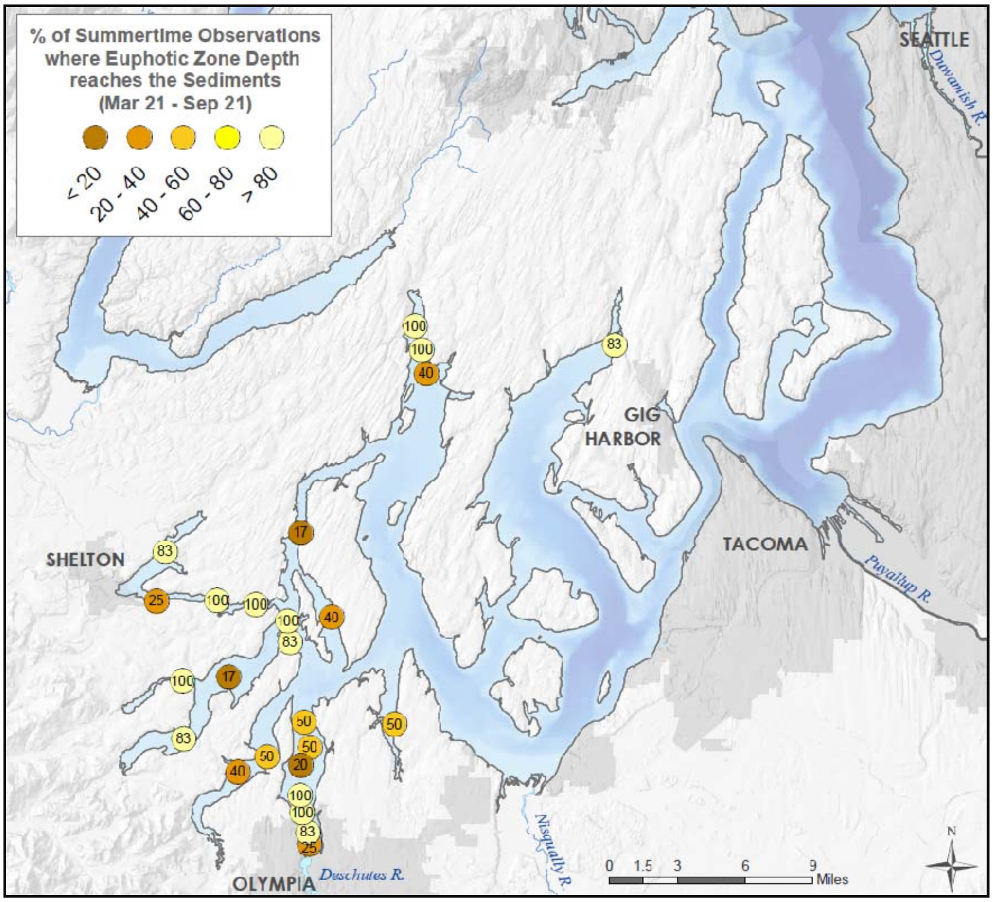


Figure 70. Percent time that the euphotic zone extends to the bottom sediments, based on Secchi depth measurements, for summer observations.

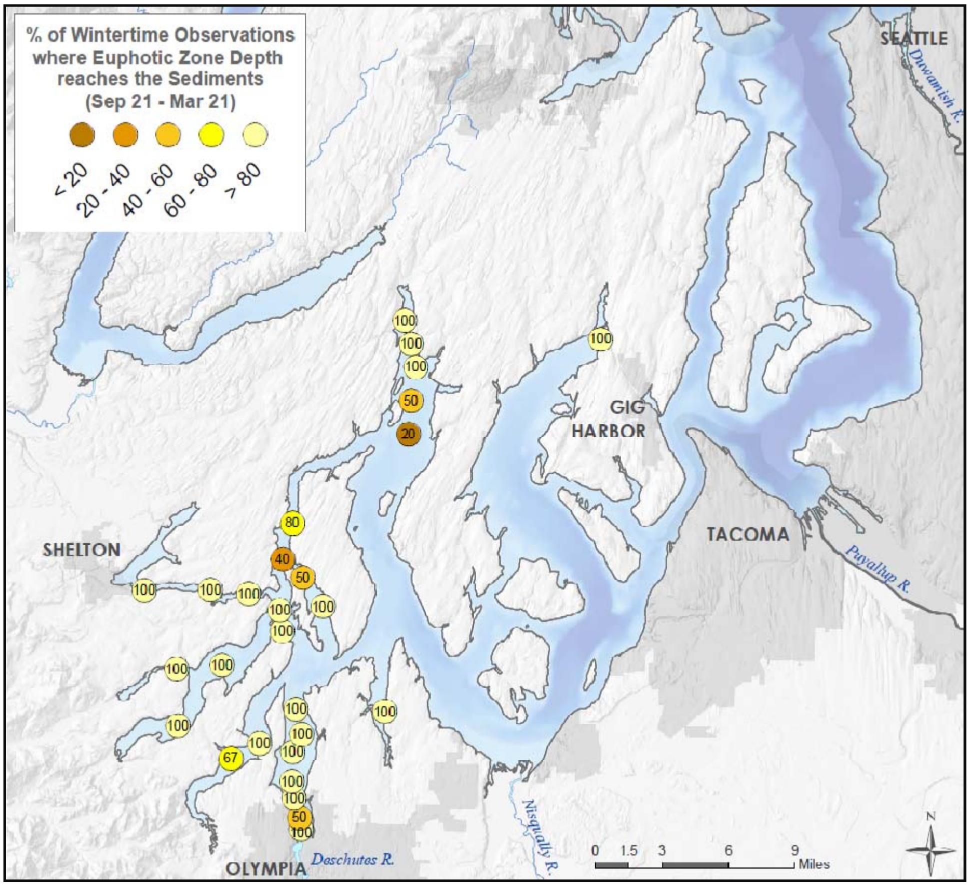


Figure 71. Percent time that the euphotic zone extends to the bottom sediments, based on Secchi depth measurements, for winter observations.

Laboratory Analyses

A complete set of time-series plots and spatial plots for all parameters described below are presented in Appendix C – Marine Data. For discussion purposes and to illustrate patterns, example graphics are presented for a boundary station (Edmonds east) and an interior station (Case Inlet station SS52).

Alkalinity

Alkalinity results for the Central Sound stations and a station in central Case Inlet are presented in Figure 72. The highest alkalinity levels occurred in late September and early October 2006, consistent with decreasing river flows. Values were in the range of 2150 to 2250 uM/kg for Central Sound and near Tacoma Narrows but were lower for most South Sound stations. Alkalinity levels then decreased during winter 2006 and early spring 2007 at all stations, mainly due to increased freshwater inputs with lower alkalinity levels. Fall 2007 alkalinity levels were generally lower than 2006 levels.

The lowest concentrations for the Central Sound stations occurred in December 2006, with the exception of an event between early April and early May 2007. During this event, surface levels of alkalinity decreased considerably at the Edmonds stations and throughout the entire water column at Rich Passage and Alki west. This decrease was probably caused by increased freshwater inputs, seen in CTD salinity profiles taken at the same time. The effect was highly localized and was not captured at other Central Sound or South Sound stations.

At South Sound stations, alkalinity levels were typically 100 uM/kg less than the values seen at Central Sound stations. Temporally, the lowest levels were seen in December 2006. Totten Inlet and Oakland Bay showed the lowest winter levels, with values less than 1900 uM/kg. Levels remained fairly low at these two inlets during 2007.

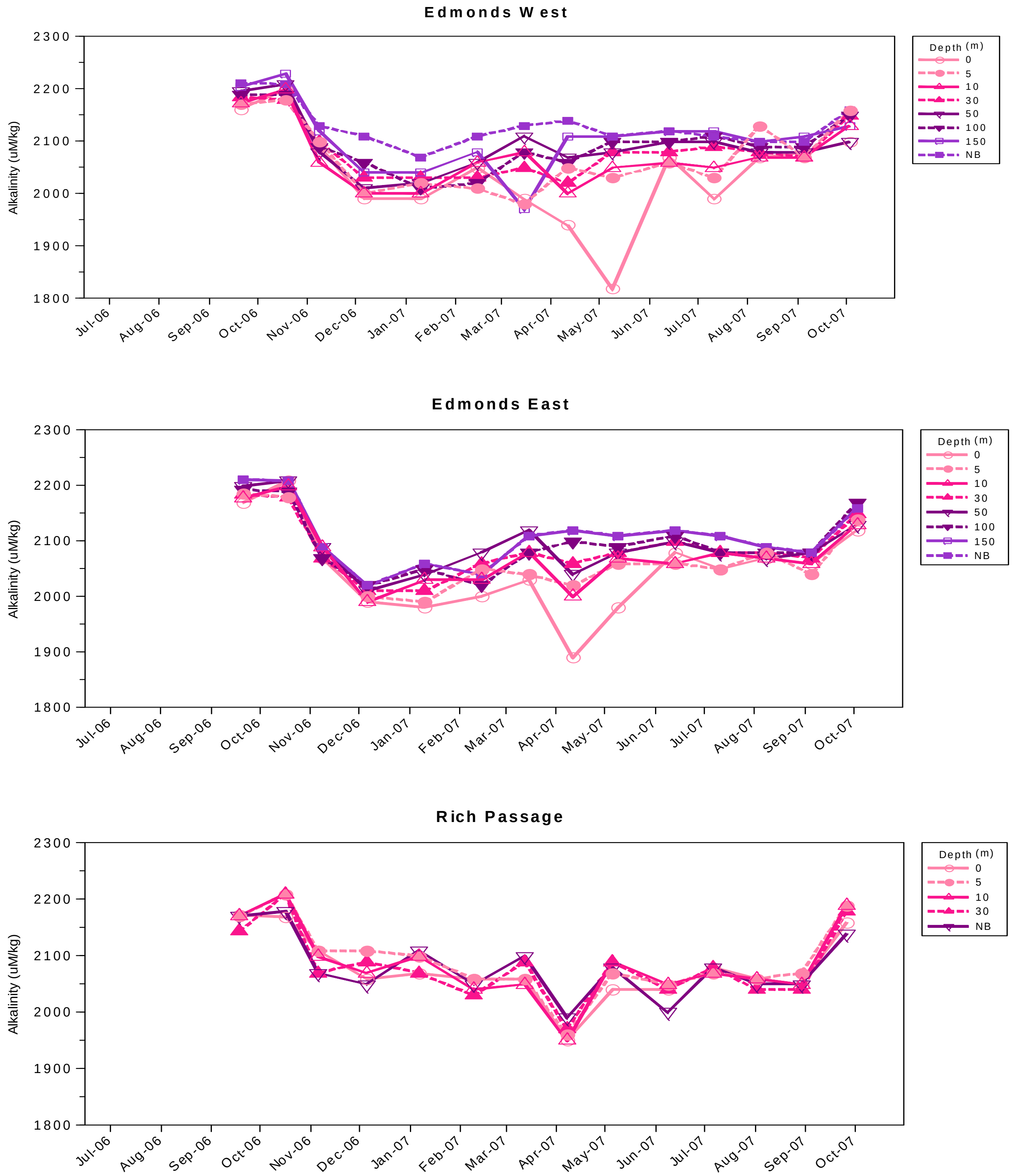


Figure 72a. Monthly alkalinity results from Central Sound and central Case Inlet (SS52) from July 2006 – October 2007.

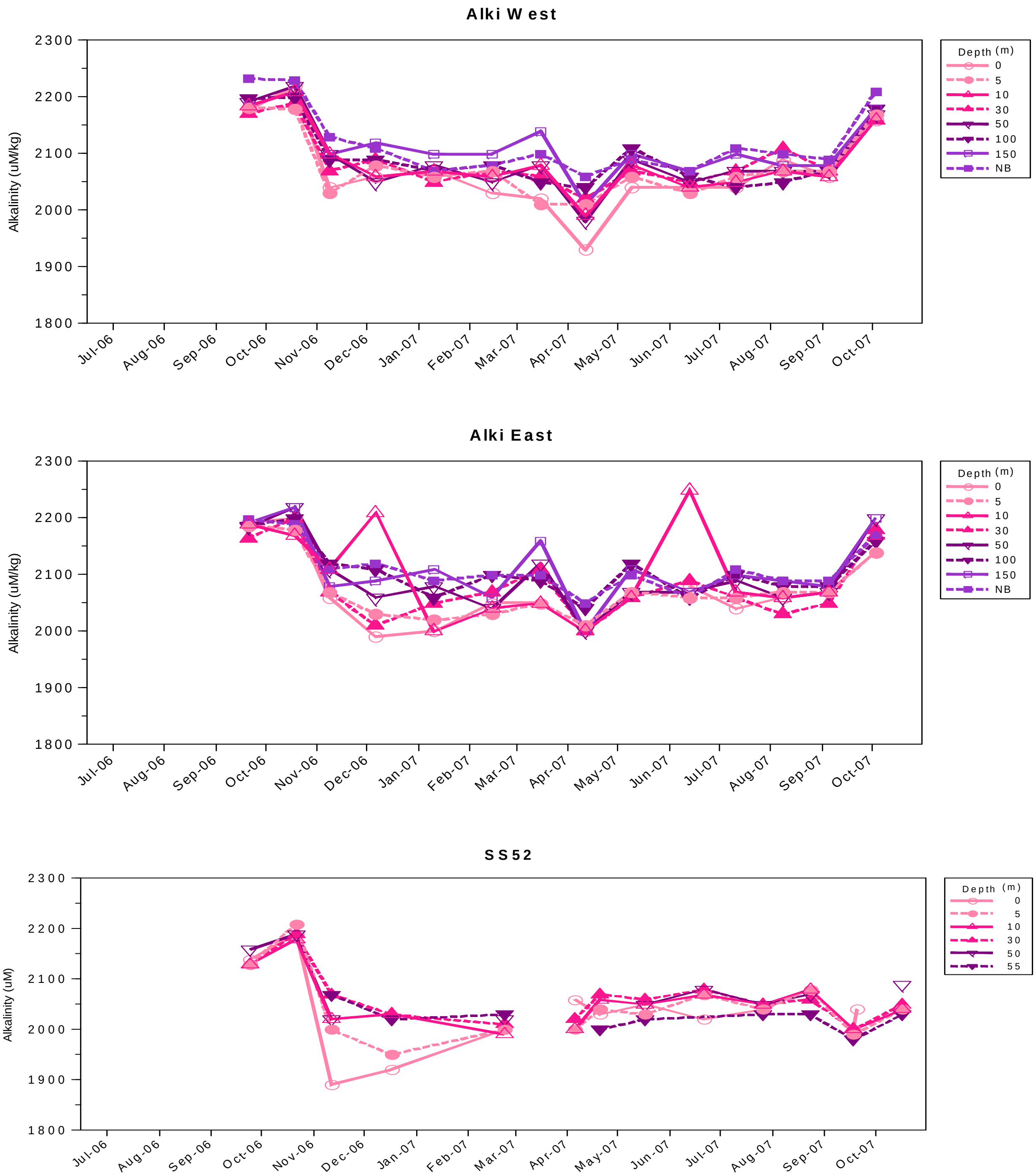


Figure 72b. Monthly alkalinity results from Central Sound and central Case Inlet (SS52) from July 2006 – October 2007.

Chlorophyll-a

Chlorophyll-a concentrations from different depths are presented for July 2006 through October 2007 at two representative stations in Figure 73. Chlorophyll-a patterns vary both temporally and spatially. Higher concentrations of chlorophyll-a were seen in summer and fall 2007 than in 2006. Highest chlorophyll-a levels in Case Inlet were observed during the spring and summer. From the complete set of results in Appendix C, high chlorophyll-a levels occurred in spring and late summer 2007 at stations throughout Carr, Case, and Budd Inlets. Blooms typically occurred one month earlier and at higher levels in South Sound than in Central Sound.

The spring bloom commenced in mid-April 2007 at the Central Sound stations. Peak concentrations varied both temporally and spatially. At several South Sound stations, the spring bloom commenced a few weeks earlier, in late March. Highest levels of chlorophyll were seen in mid-April at most South Sound stations, except for central Carr and Budd Inlet, where very large blooms occurred in late September 2007. Highest chlorophyll levels were seen in May at the Alki stations and in June at the Edmonds stations.

The highest chlorophyll-a concentrations (>30 ug/L) were observed during spring and summer 2007 in Budd, Totten, Eld, Henderson, Carr (central and north) and Case Inlets, as well as north Pickering Passage and Oakland Bay. The lowest levels relative to other stations were found at the Nisqually Reach and Tacoma Narrows stations and generally during the winter at all stations.

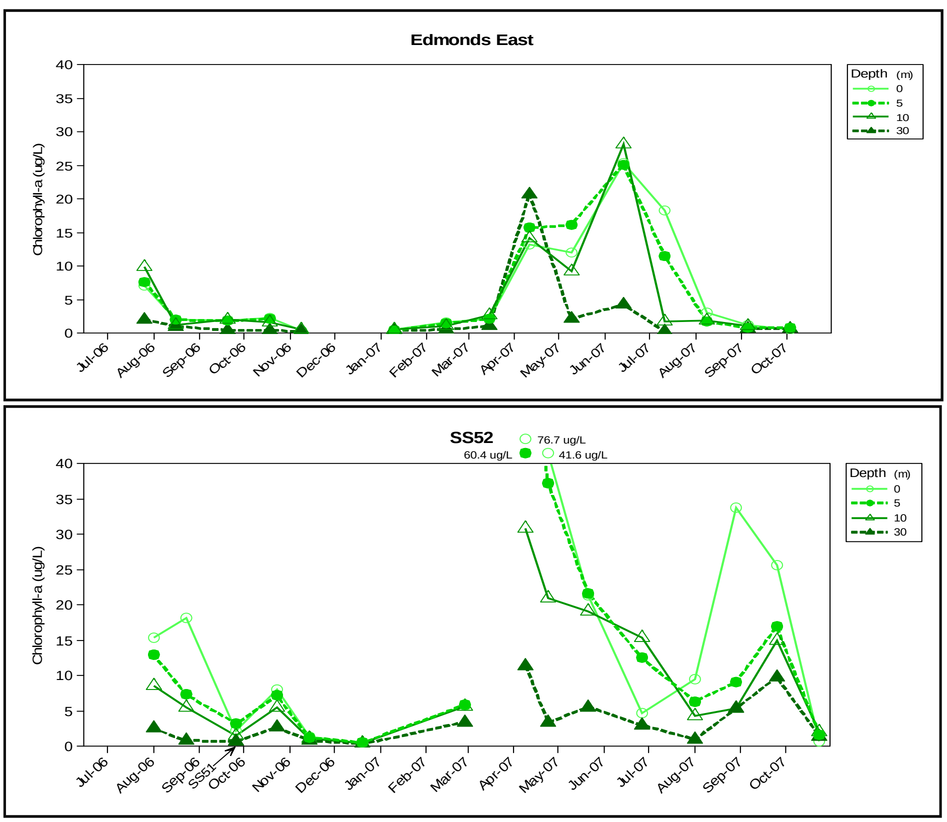
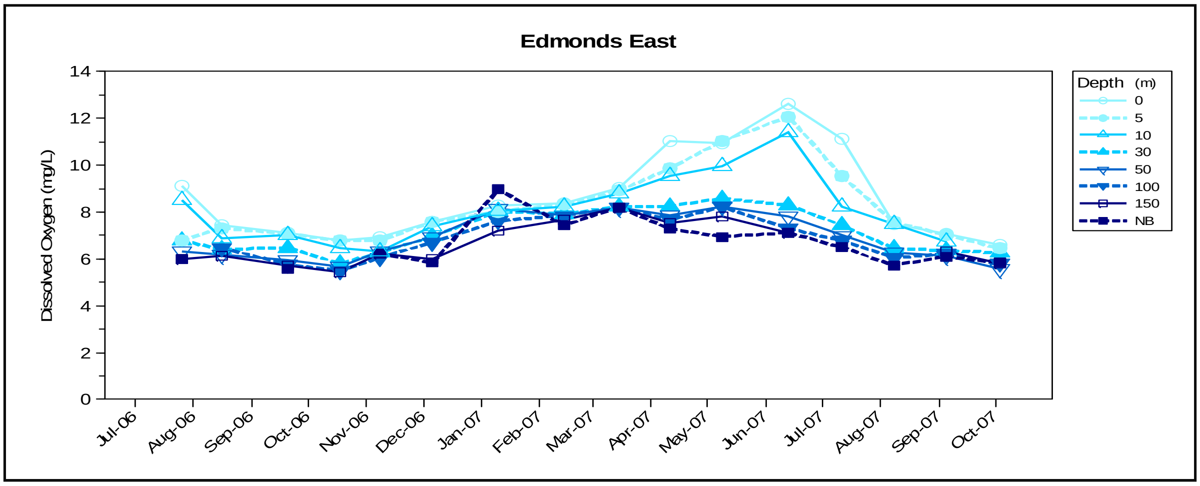


Figure 73. Monthly chlorophyll-a concentrations from Edmonds East and central Case Inlet (SS52) from July 2006 – October 2007.

Dissolved Oxygen

Dissolved oxygen (DO) concentrations using Winkler analyses are presented for July 2006 through October 2007 for Edmonds east and central Case Inlet in Figure 74.

Concentrations generally ranged from 6 – 12 mg/L throughout the study area. Higher concentrations of DO (>10 mg/L) were only found in the upper water column. These concentrations coincided with higher chlorophyll-a levels and photosynthetic processes during spring and summer of 2007. The greatest difference in DO concentration between surface and near-bottom depths occurred in 2007. The lowest near-bottom DO concentrations occurred in late summer, both in 2006 and 2007. The highest DO concentrations occurred during large spring and late summer bloom events at South Sound stations in Budd, Totten, Carr, and Case Inlets. Lowest individual concentrations were seen at the heads of Budd, Case, and Carr Inlets. Concentrations <7 mg/L occurred at both the northern boundary (Edmonds east) and within South Puget Sound (central Case Inlet).



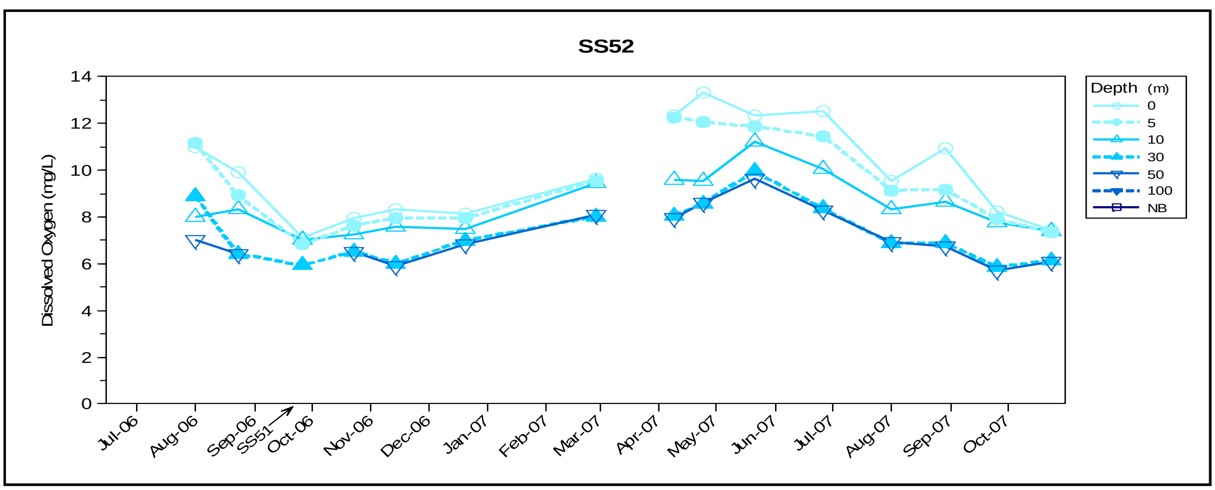
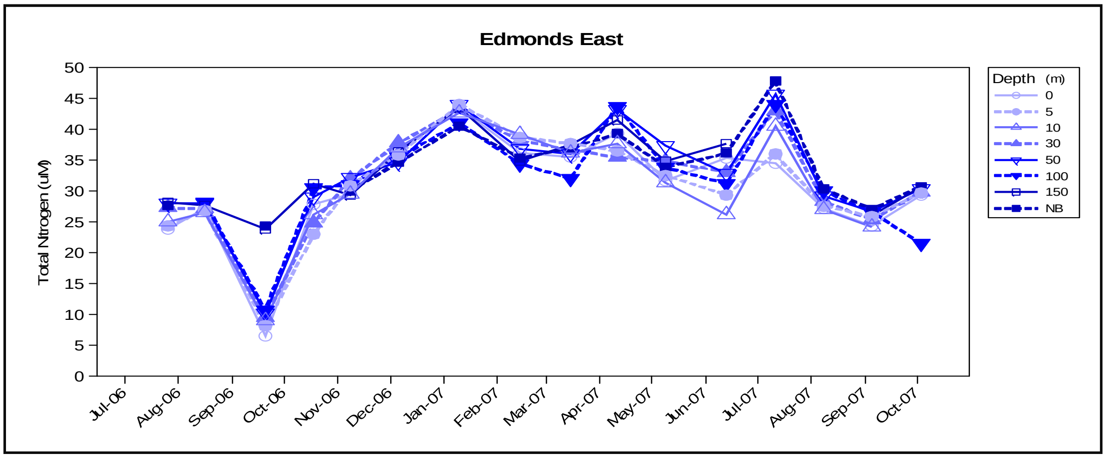


Figure 74. Monthly dissolved oxygen concentrations from Winkler samples collected at Edmonds east and in central Case Inlet (SS52) from July 2006 – October 2007.

Total Nitrogen

Total nitrogen concentrations are presented for July 2006 through October 2007 at Edmonds east and central Case Inlet in Figure 75. Total nitrogen concentrations generally varied between 20 and 50 uM, with higher levels in the winter and spring than in summer and fall. The lowest total nitrogen concentrations (15-25 uM, or 0.21-0.35 mg/L) occurred in Central Puget Sound, through the Tacoma Narrows, and within Dana Passage. Temporally, the lowest levels occurred in late summer/fall of 2006. In contrast, the lowest South Sound total nitrogen concentrations (15-30 uM) occurred in late summer/fall of 2007 for most stations.

In Central Puget Sound, high total nitrogen levels occurred in July 2007 for all but the surface layer. This event could be related to a large *Heterosigma* bloom that occurred throughout most of the Central Sound, Strait of Juan de Fuca, and Strait of Georgia during this time (Kim Stark, King County, personal communication). High levels in July 2007 did not reach South Sound stations, and levels were somewhat lower relative to other months.



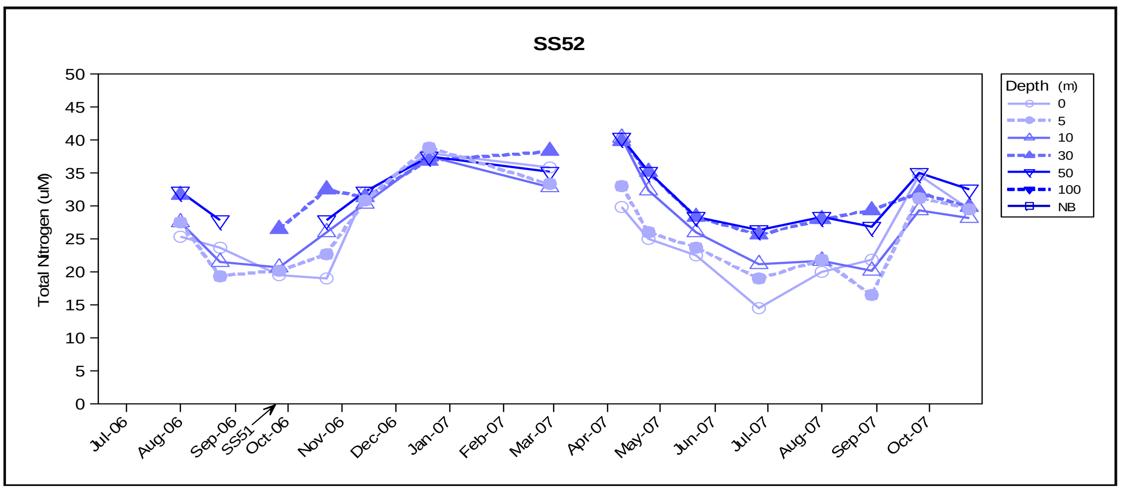


Figure 75. Monthly total nitrogen concentrations for Edmonds east and central Case Inlet (SS52) from July 2006 – October 2007. September 2006 data are from an adjacent station (SS51), which was inadvertently sampled in place of SS52.

Dissolved inorganic nitrogen

Dissolved inorganic nitrogen (DIN) concentrations are presented for July 2006 through October 2007 for Edmonds east and central Case Inlet in Figure 76. Concentrations generally ranged between 20-30 uM (0.28 – 0.42 mg/L) for most depths, except during the algae growing season when levels in the upper euphotic layers decreased due to increased algae consumption. Near-bottom DIN varied seasonally, with higher levels in the winter and spring than summer and fall.

Seasonally lowest DIN concentrations in the upper 10 meters occurred from April - August 2007, but less DIN depletion occurred in 2006. On the contrary, from the complete figures in Appendix C, central Carr Inlet showed surface DIN draw down only in late summer (September 2007). Surface DIN depletion occurred somewhat earlier in the western inlets. Low DIN levels were not recorded at Tacoma Narrows, Nisqually Reach, or Dana Passage stations. However, these passages did show variability in DIN concentrations throughout the water column in June – July 2007.

Seasonally, the highest DIN levels (around 30 uM) and the most uniform concentrations throughout the water column occurred throughout Central and South Puget Sound in the winter and spring months (November 2006 – March 2007). Local nitrogen sources may have produced locally higher levels, as occurred at the head of Carr Inlet during late April 2007 in the bottom layer.

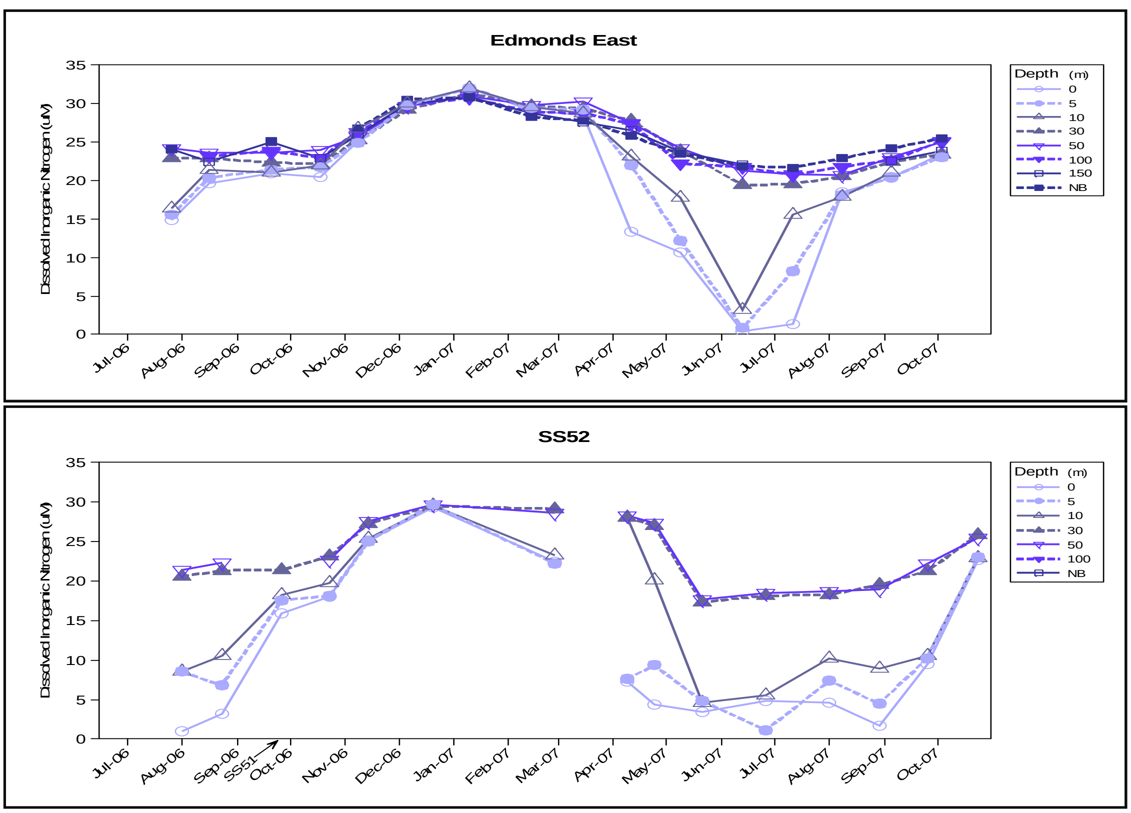


Figure 76. Monthly dissolved inorganic nitrogen (DIN) concentrations for Edmonds east and central Case Inlet (SS52) from July 2006 – October 2007.

Ammonium

Ammonium concentrations, a constituent of DIN, are presented for July 2006 through October 2007 at Edmonds east and central Case Inlet in Figure 77. Ammonium concentration patterns differed from those of DIN at Central Sound stations, with lower concentrations observed during the winter/late spring and higher levels during the summer/fall. Temporal ammonium patterns were much more variable for South Sound. Very low (<0.5 uM, or 0.007 mg/L) ammonium levels occurred in December 2006 throughout Central Puget Sound, through the Tacoma Narrows and Nisqually Reach, and into portions of Case and Carr Inlets. Slightly higher December concentrations (>1 uM) were observed in Budd, Eld, Totten, north Case, and north Carr Inlets and Oakland Bay.

Near-bottom ammonium levels were enriched compared with surface values in summer and fall, with generally higher enrichment in 2007 than 2006. Higher near-bottom levels and greater enrichment were observed in South Sound compared with Central Puget Sound.

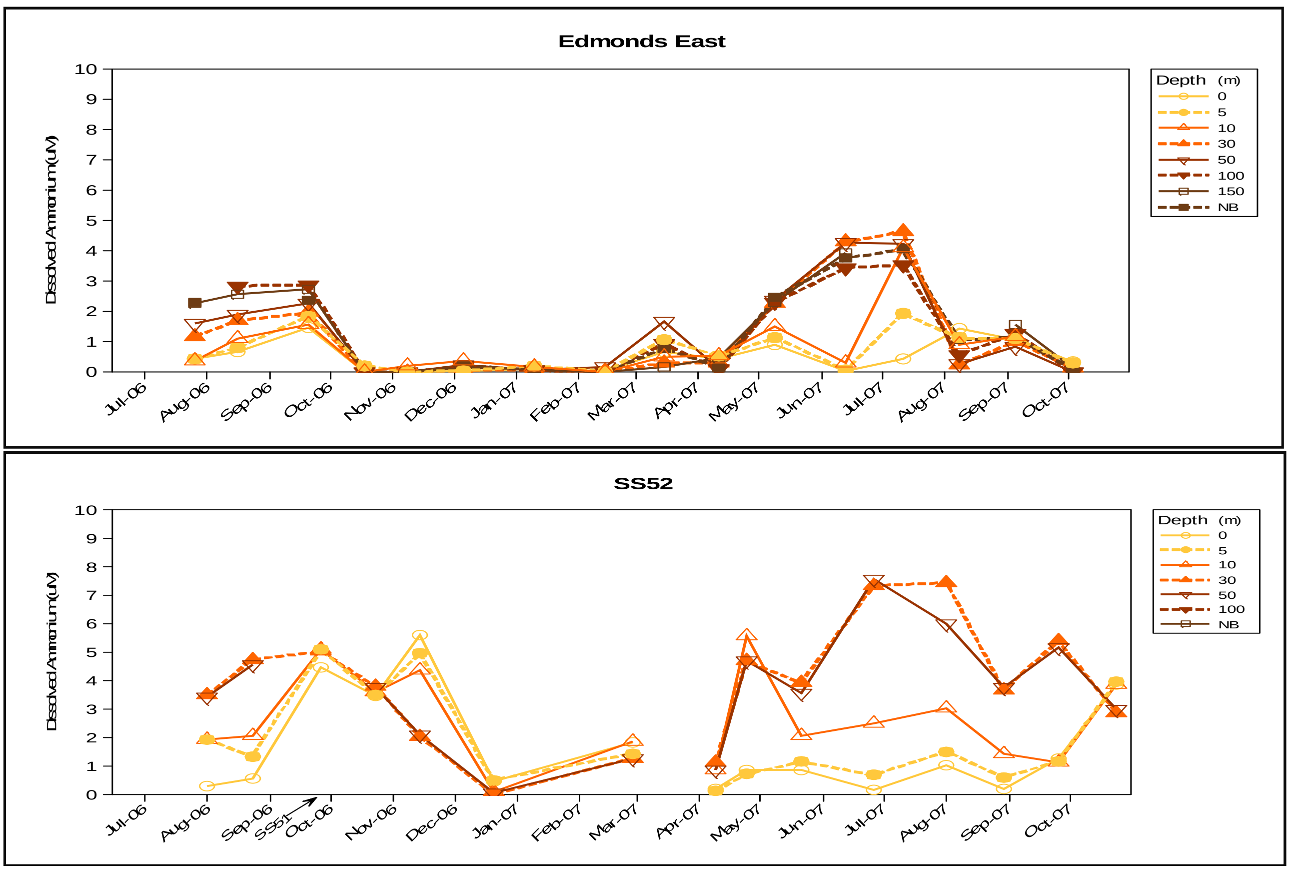


Figure 77. Monthly ammonium concentrations for Edmonds east and central Case Inlet (SS52) from July 2006 – October 2007.

Seasonal ammonium contribution to DIN

Figure 78 illustrates the seasonal contributions of ammonium to DIN at the depth where maximum ammonium was observed using the same data presented in Figure 76 and Figure 77. The maximum concentration of NH4 was determined and then plotted in proportion to nitrate+ nitrite observed for the same depth. For most stations, maximum ammonium concentrations occurred deeper in the water column during the spring, summer, and fall. In the winter, maximum ammonium concentrations were observed more frequently in the surface or upper 5 m at most stations. In the western finger inlets (shown on the right side of the figures), ammonium is a much larger component of DIN than in other areas. This is likely related to biological cycling indicated by high chlorophyll-a levels in those areas. An exception to this spatial pattern occurred in September 2007, when DIN was >15 uM at most stations.

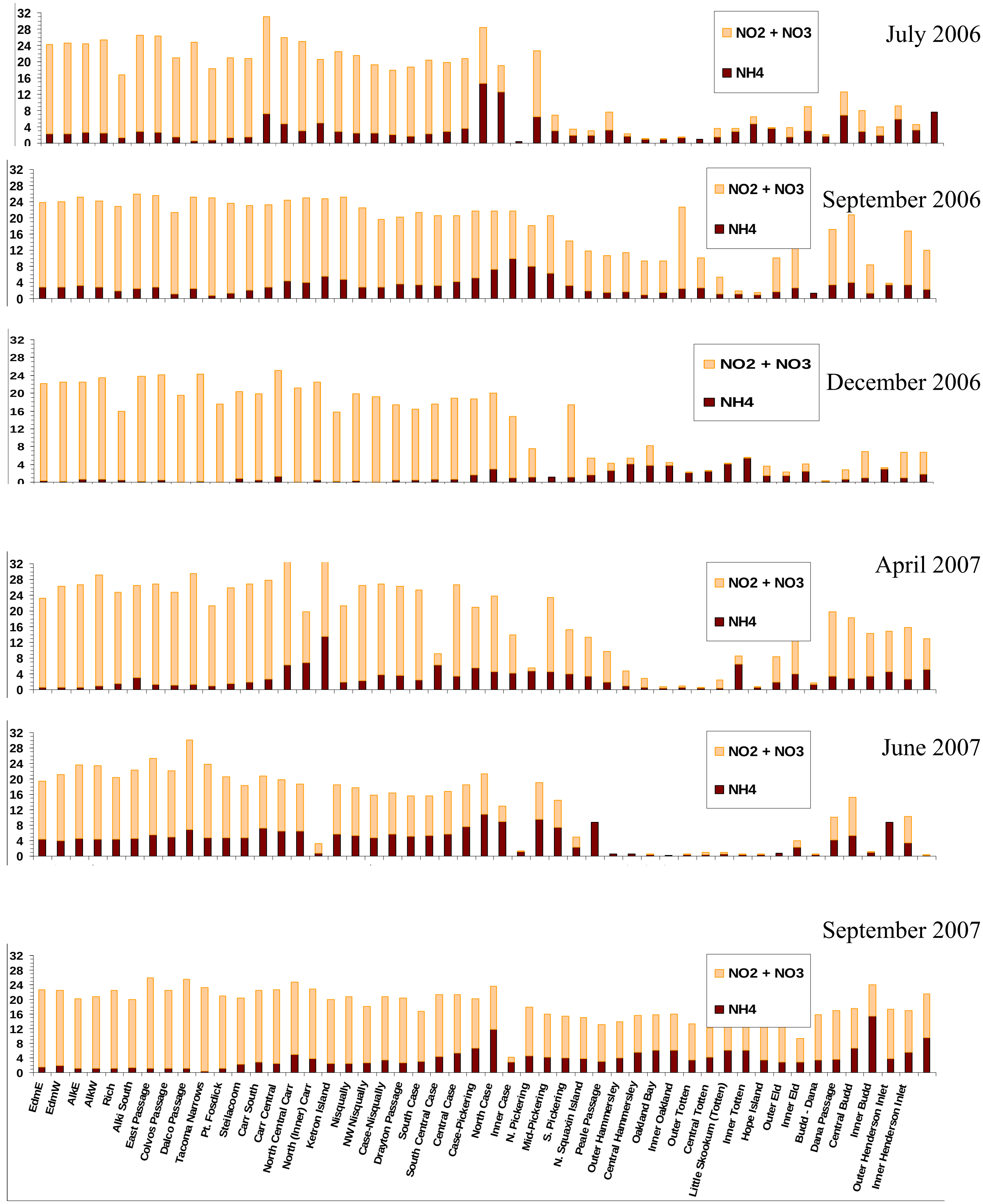
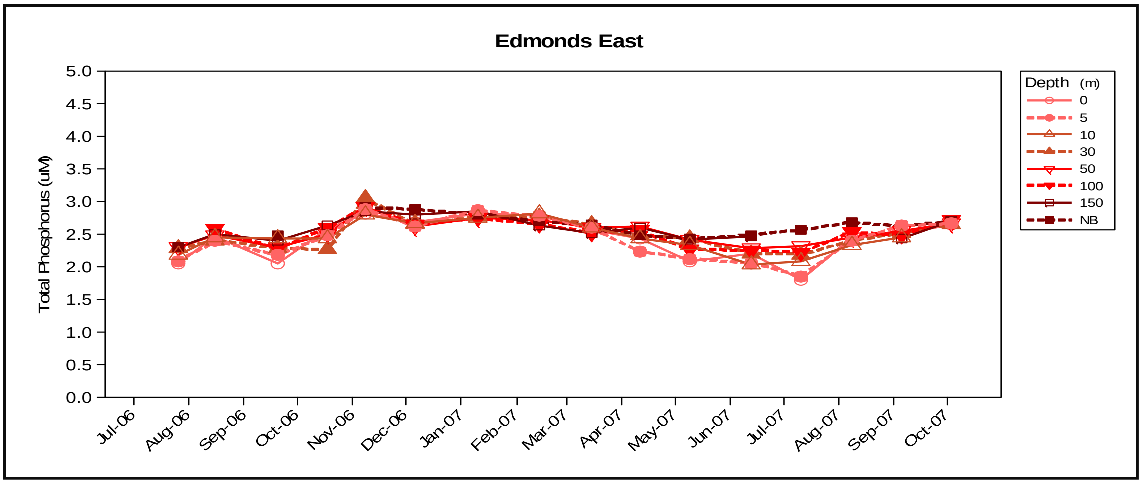


Figure 78. Relative contributions of nitrite and nitrate (NO2 + NO3) and ammonium (NH4) as uM by station an inlet from north to south clockwise around the shoreline.

Total Phosphorus

Total phosphorus concentrations are presented for July 2006 through October 2007 for Edmonds east and central Case Inlet in Figure 79. Total phosphorus concentrations were higher in magnitude but with less variability with depth in the winter than the summer and generally ranged from 2 to 3 uM (0.06 to 0.09 mg/l). Budd and Eld Inlets, shown in Appendix C, were the exceptions. In Eld Inlet, surface values greater than 4 uM occurred in September 2006 and September 2007. The highest concentrations were recorded in central and inner Budd Inlet, where values above 3 to 4 uM were evident in September, both in 2006 and 2007. The lowest concentrations of total phosphorus occurred between April and June 2007, within Eld, Totten and Case Inlets and north Pickering Passage.



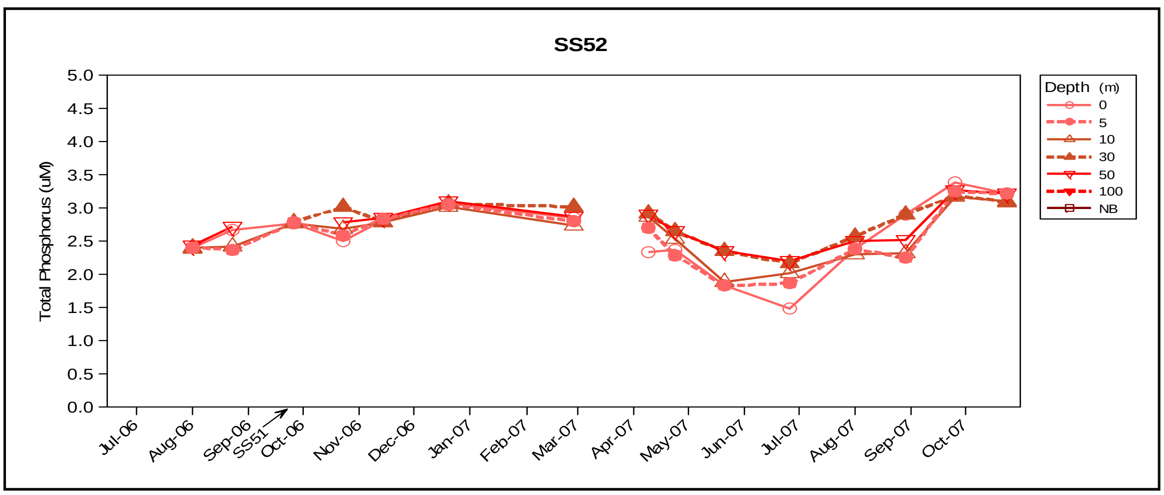


Figure 79. Monthly total phosphorus concentrations for Edmonds east and central Case Inlet (SS52) from July 2006 – October 2007.

Orthophosphate

Results for orthophosphate, also called soluble-reactive phosphate, are presented for July 2006 through October 2007 at Edmonds east and central Case Inlet in Figure 80. Seasonally, concentrations are higher and more uniform from October to March. Orthophosphate patterns follow those of DIN, with surface depletion evident in the summer in both Central and South Puget Sound, and stronger depletion in 2007 than 2006. The lowest concentrations occurred in Budd, Totten, and Eld Inlets in April 2007 and in both Central Sound and the head of Carr Inlet in June and July 2007.

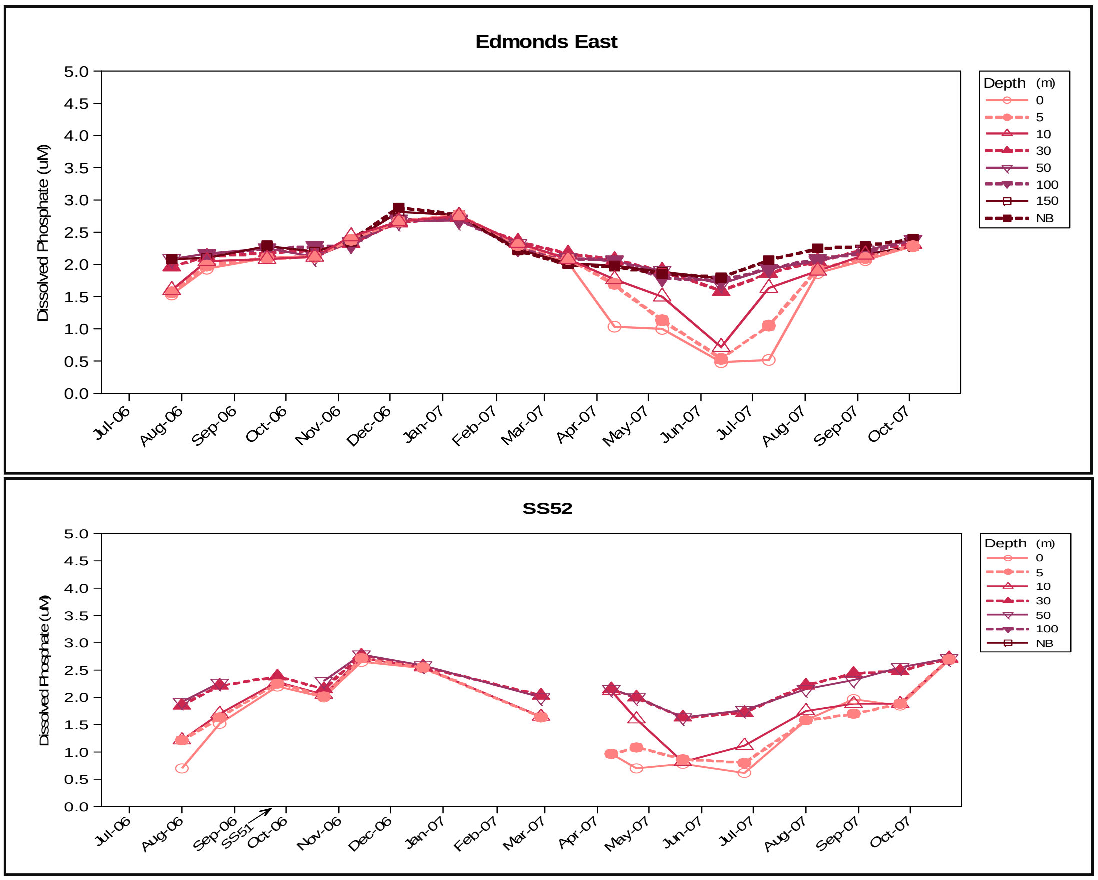


Figure 80. Monthly orthophosphate concentrations for Edmonds east and central Case Inlet (SS52) from July 2006 – October 2007.

Dissolved organic carbon and particulate carbon and nitrogen

Dissolved organic carbon and particulate organic carbon and nitrogen samples were collected from a subset of stations on all cruises from June 2006 through October 2007. However, the laboratory experienced a failed valve in the analytical instrument, which resulted in incomplete removal of the dissolved inorganic carbon fraction from samples for at least some months. Further investigation will determine the usability of these data. An addendum will present the final organic carbon and nitrogen data.

Spatial and Temporal Patterns

Ammonium

Figure 81 and Figure 82 show surface and near-bottom concentrations of ammonium from discrete samples collected during quarterly intensive cruises.

Surface ammonium concentrations were low (<2 uM) throughout Central Puget Sound, Tacoma Narrows, eastern Nisqually Reach, and central Carr Inlet. Moderate (2 to 5 uM) to high (5 to 10 uM) ammonium concentrations occurred within South Sound. The lowest levels occurred in the winter months. Concentrations often were higher in the western inlets and at the head of Budd and Case Inlets than in other areas (see Appendix C). Surface ammonium concentrations were highest in September 2007 throughout South Puget Sound and were much higher than in late summer 2006.

Similarly, bottom ammonium concentrations generally were lower in Central Puget Sound through Tacoma Narrows and east of Nisqually Reach, although high levels occurred throughout the area in June 2007. Very high concentrations (>10 uM) occurred in September 2007 and were highest at the heads of the inlets. Lowest levels were found in December 2006, but even in winter, near-bottom concentrations were highest near the heads of the inlets.

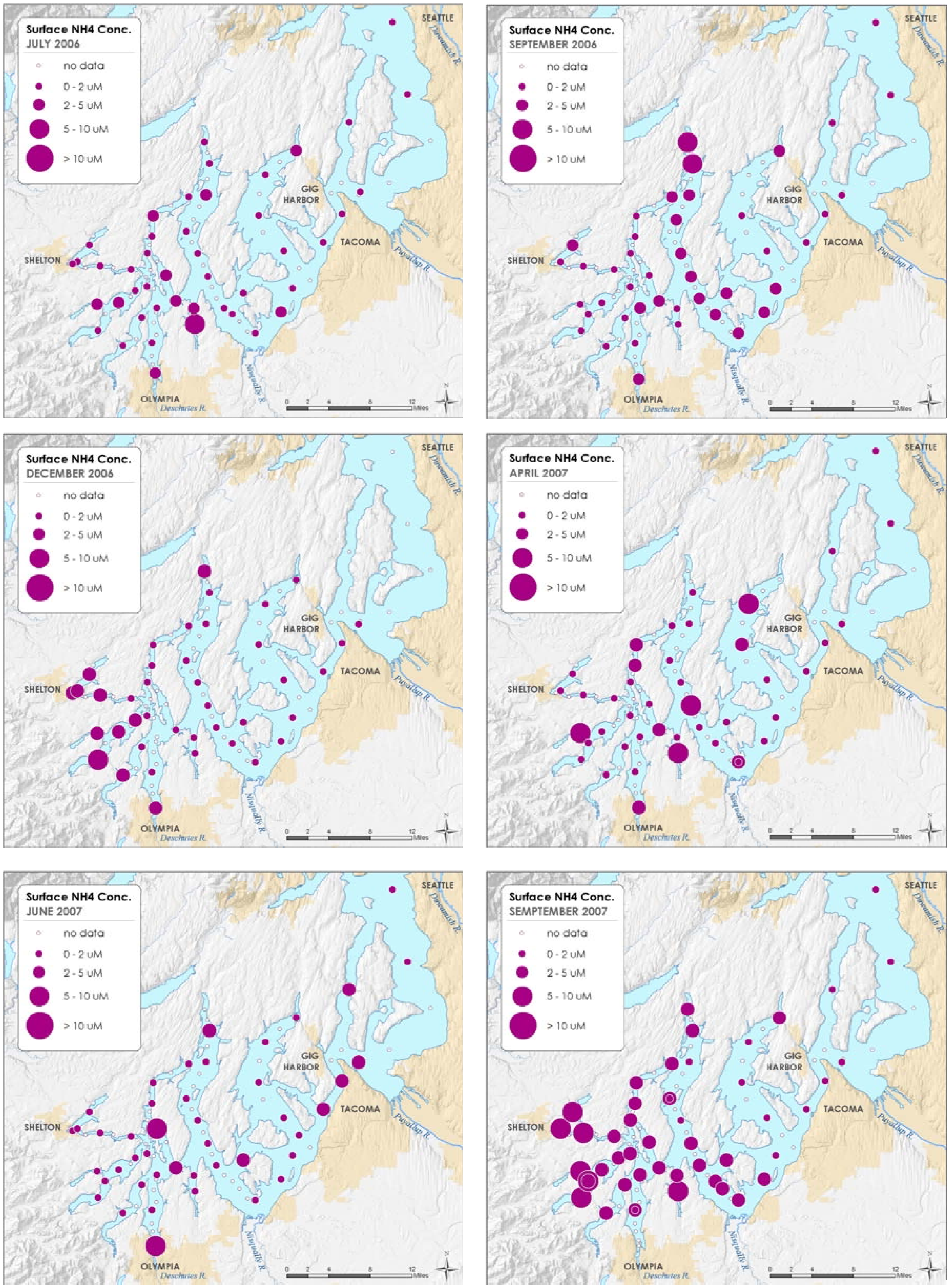


Figure 81. Surface ammonium concentrations from quarterly cruises between July 2006 and September 2007. Categorical definitions (<2 uM low, 2-5 uM moderate, 5-10 uM high, and >10 uM very high) are based on Newton et al. (2002).

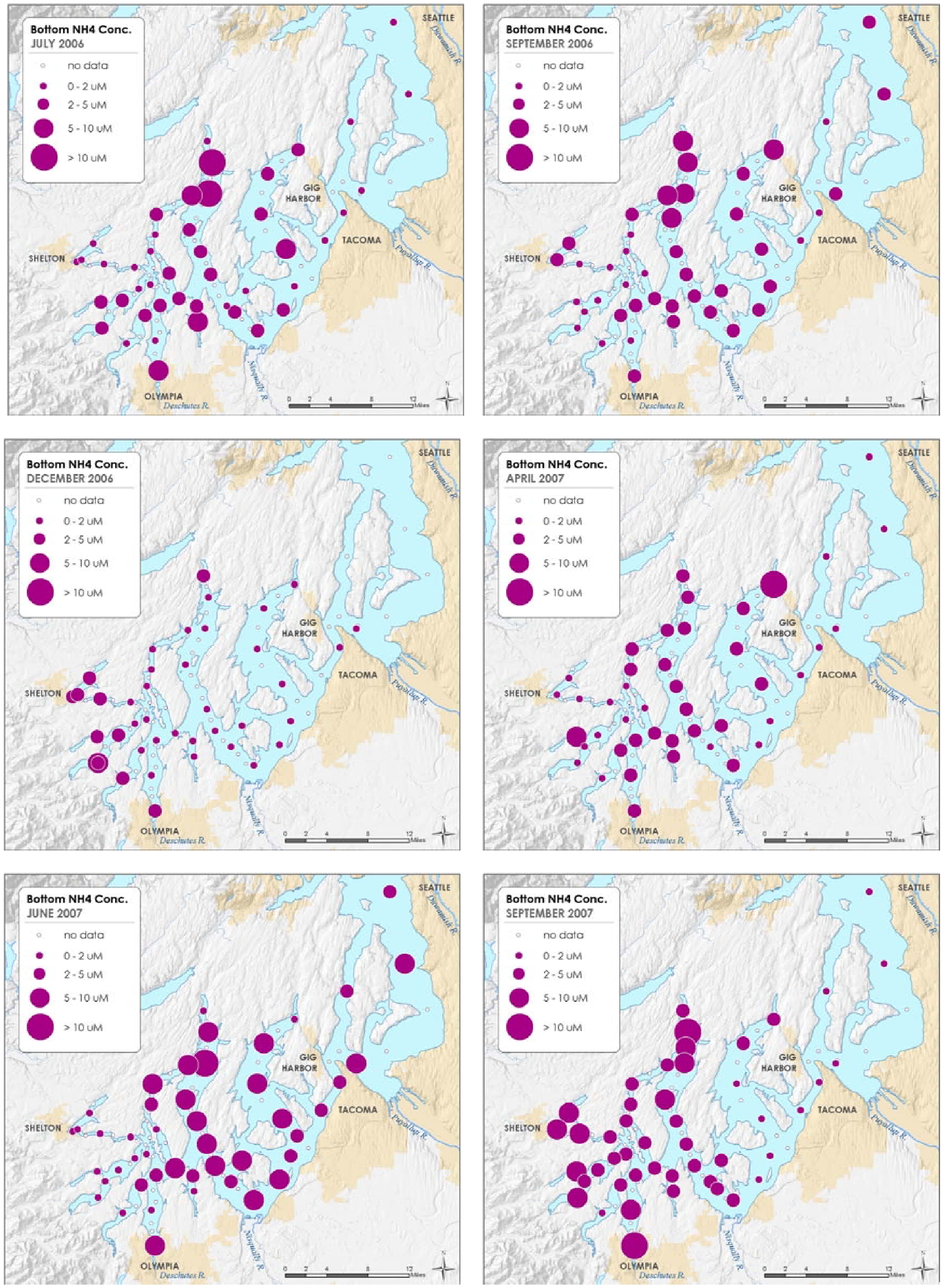


Figure 82. Bottom ammonium concentrations from quarterly cruises between July 2006 and September 2007. Categorical definitions (<2 uM low, 2-5 uM moderate, 5-10 uM high, and >10 uM very high) are based on Newton et al. (2002).

Near-bottom results

Figures 83 through 88 present near-bottom calibrated dissolved oxygen (DO) (mg/L), DO saturation (%), temperature (°C), and stratification from CTD profiles recorded during quarterly intensive cruises. (*Stratification* is the difference between surface and near-bottom density as delta sigma-t.)

Near-bottom DO concentrations reflect complex, temperature-dependent productivity processes and the influence of oceanic conditions. DO concentrations varied considerably throughout the year, with the lowest concentrations in the summer and the highest in spring. During the summer, inner Budd Inlet had the lowest concentrations, but the heads of Carr, Case, and Henderson Inlets also had low concentrations. Hammersley, Totten, and Eld Inlets had higher concentrations than the other western inlets. The region from Tacoma Narrows to Dana Passage tends to be uniform, although June 2007 results indicate a pocket of low DO around the Nisqually Reach.

Dissolved oxygen saturation is temperature-dependent, and cold water can hold more oxygen than warmer water. Thus, percent DO saturation is a better indicator of overall primary productivity than DO concentration because saturation accounts for this temperature dependence. Supersaturation (>100%) may result from algae blooms, while low saturation may indicate benthic oxygen demand. During quarterly cruises, the highest supersaturation was observed in July 2006 and April 2007 in the shallow inlets in the western side of the basin and around Harstine Island and the head of Case Inlet, likely resulting from very high productivity. Lowest percent saturation was observed at Tacoma Narrows, inner Budd and northern Case and Carr Inlets in September 2006, June 2007, and September 2007, as well as uniformly throughout the basin in December 2006.

Near-bottom temperatures exhibited an east-west gradient, with warmer summer temperatures in the western inlets and at the heads of inlets, coincident with shallow water depths. The warmest near-bottom temperatures were recorded July 31 through August 3, 2006, with east-to-west temperature differences approaching 8°C. Temperatures were coolest in the winter. Results indicate the shallow inlets were colder than the rest of South Puget Sound in December 2006. September 2006 temperatures were slightly warmer than September 2007 temperatures.

Stratification, calculated as the simple difference between near-surface and near-bottom density, indicates mixing in the water column. Higher differences suggest stronger stratification either from freshwater inputs as occurs in the winter and spring or from thermal processes in the summer. Strong summer stratification frequently occurred at stations in shallow inlets such as Budd Inlet, Oakland Bay, and the head of Case and Carr Inlets. Freshwater-induced stratification occurred in December 2006 and April 2007 in the Nisqually Reach and the heads of inlets, as well as during an unusually wet June 2007.

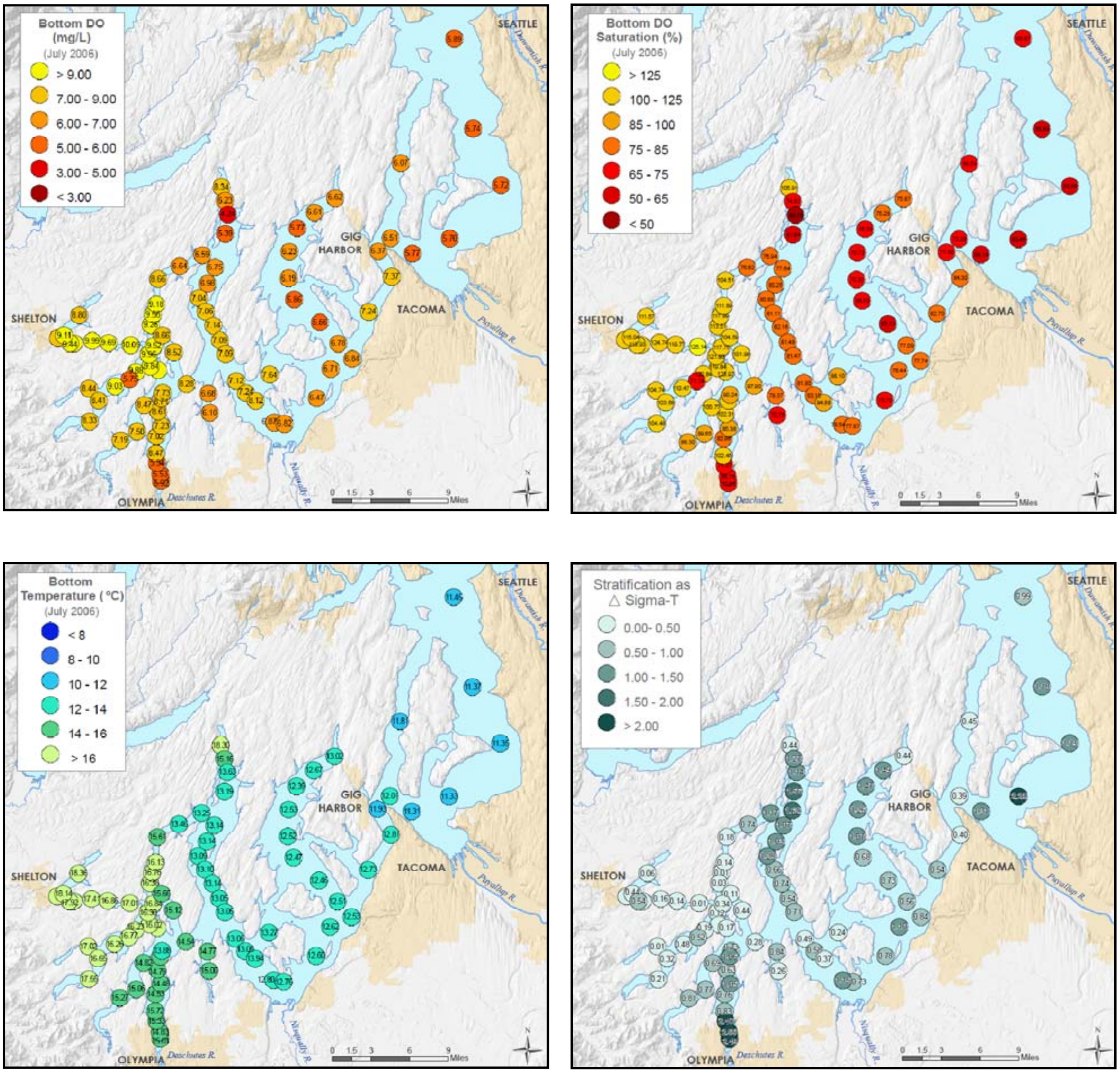


Figure 83. Spatial patterns of near-bottom concentrations from the July 31 – August 3, 2006 cruise. (A) Calibrated DO (mg/L), (B) calibrated DO saturation (%), (C) temperature (ºC), and (D) proxy for stratification (delta sigma-t).

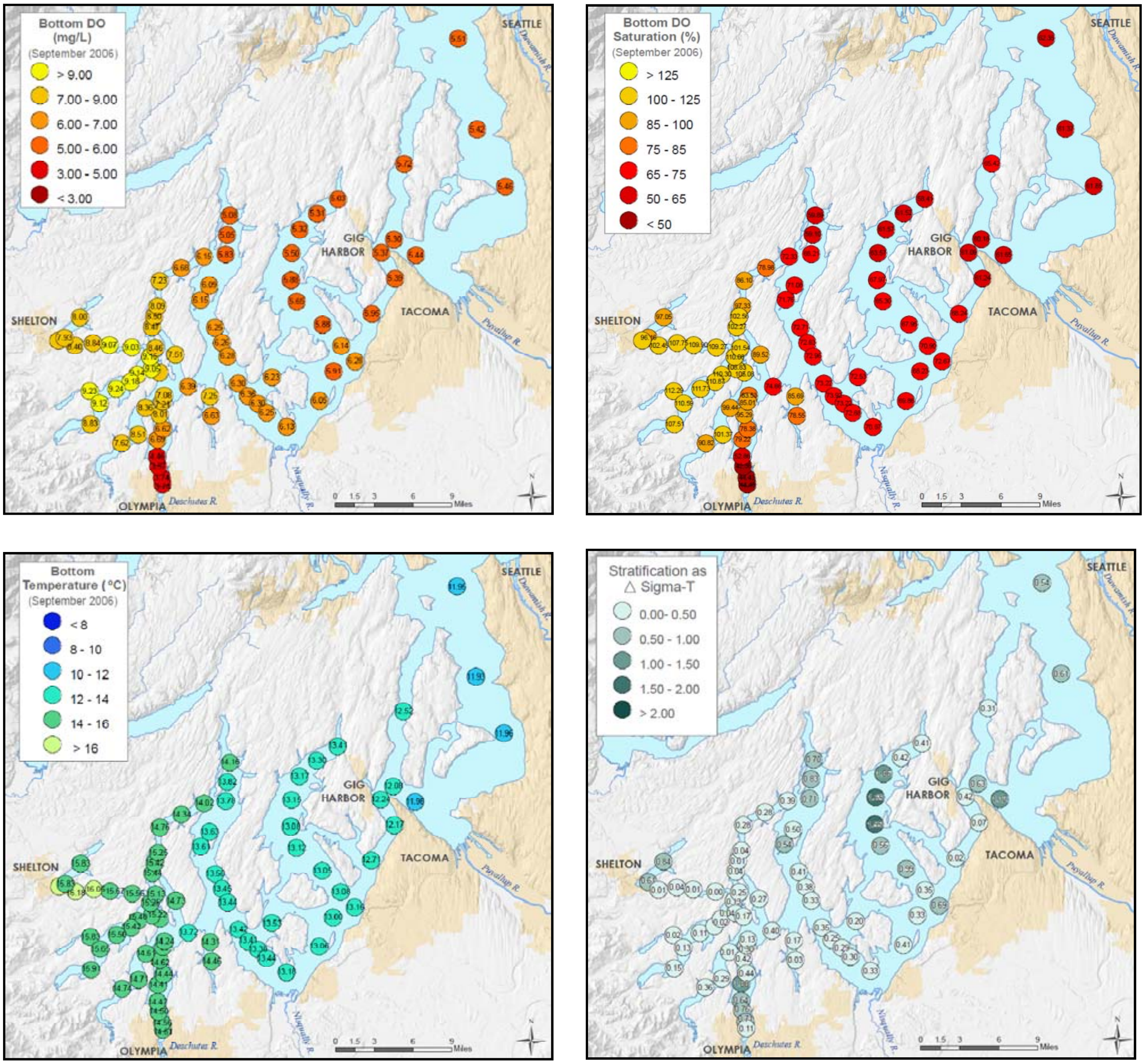


Figure 84. Spatial patterns of near-bottom concentrations from the September 25-27, 2006 cruise. (A) Calibrated DO (mg/L), (B) calibrated DO saturation (%), (C) temperature (^{o}C), and (D) proxy for stratification (delta sigma-t).

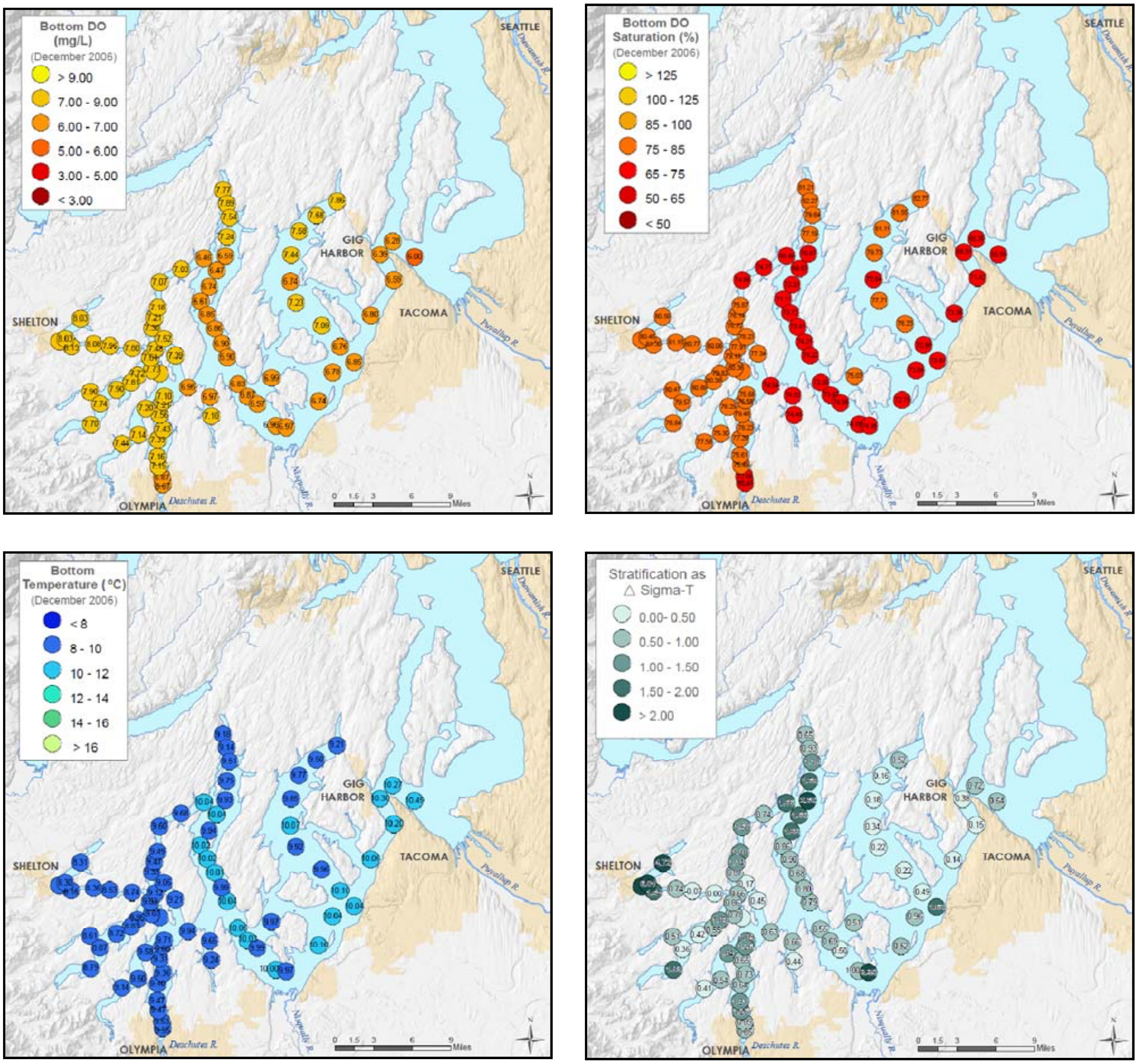


Figure 85. Spatial patterns of near-bottom concentrations from the December 18-21, 2006 cruise. (A) Calibrated DO (mg/L), (B) calibrated DO saturation (%), (C) temperature (ºC), and (D) proxy for stratification (delta sigma-t).

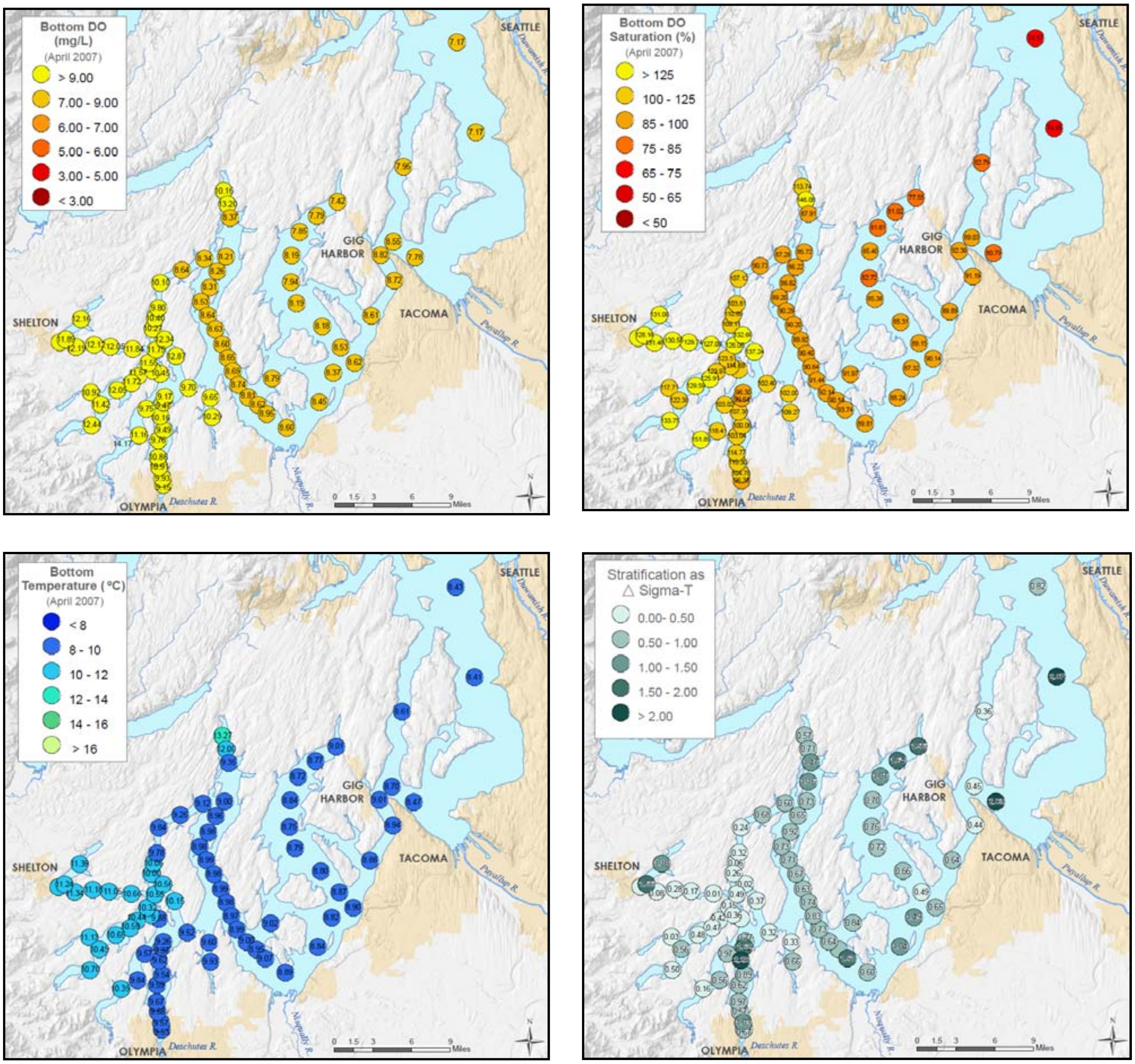


Figure 86. Spatial patterns of near-bottom concentrations from the April 23-26, 2007 cruise. (A) Calibrated DO (mg/L), (B) calibrated DO saturation (%), (C) temperature (°C), and (D) proxy for stratification (delta sigma-t).

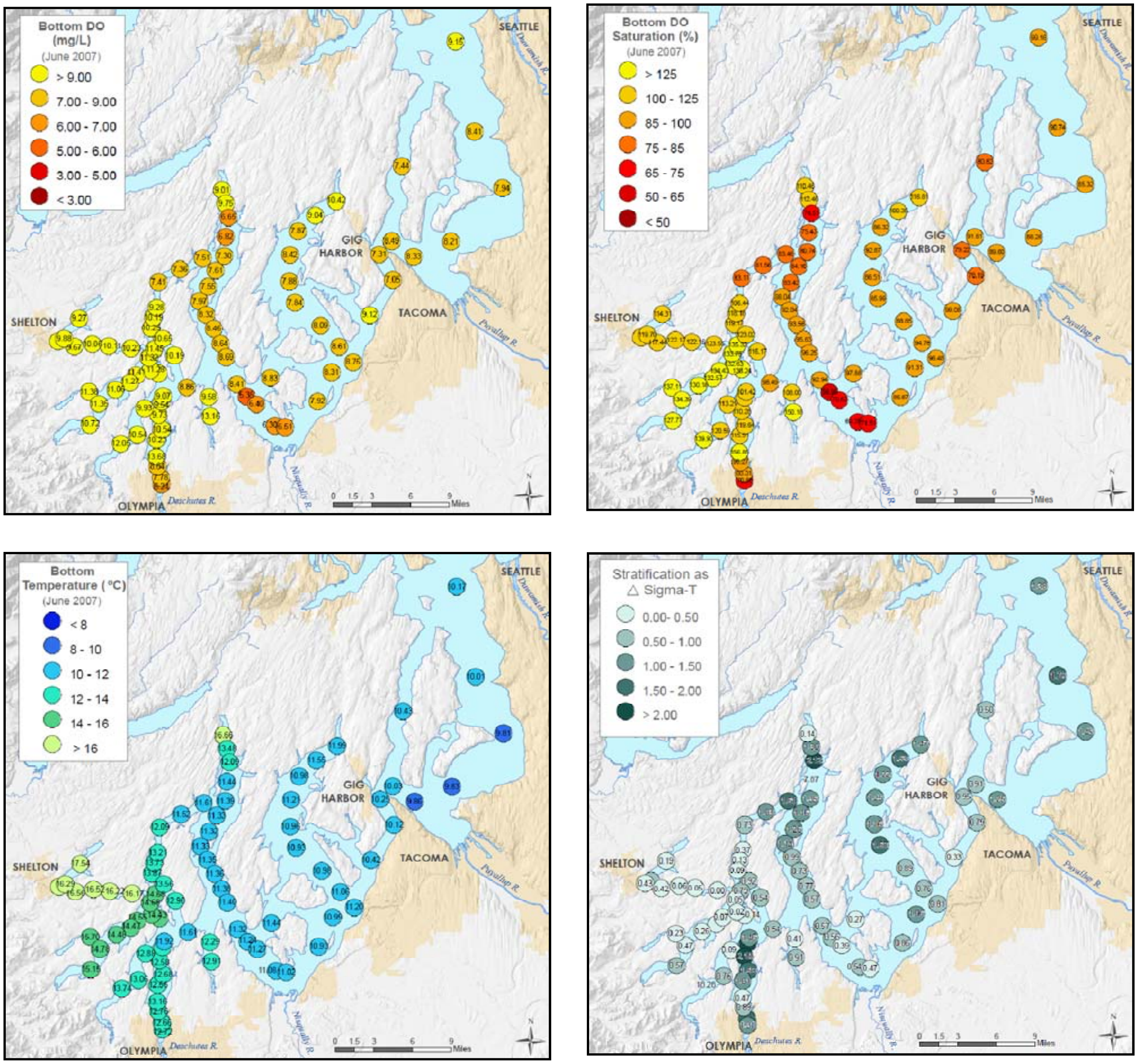


Figure 87. Spatial patterns of near-bottom concentrations from the June 25-29, 2007 cruise. (A) Calibrated DO (mg/L), (B) calibrated DO saturation (%), (C) temperature (°C), and (D) proxy for stratification (delta sigma-t).

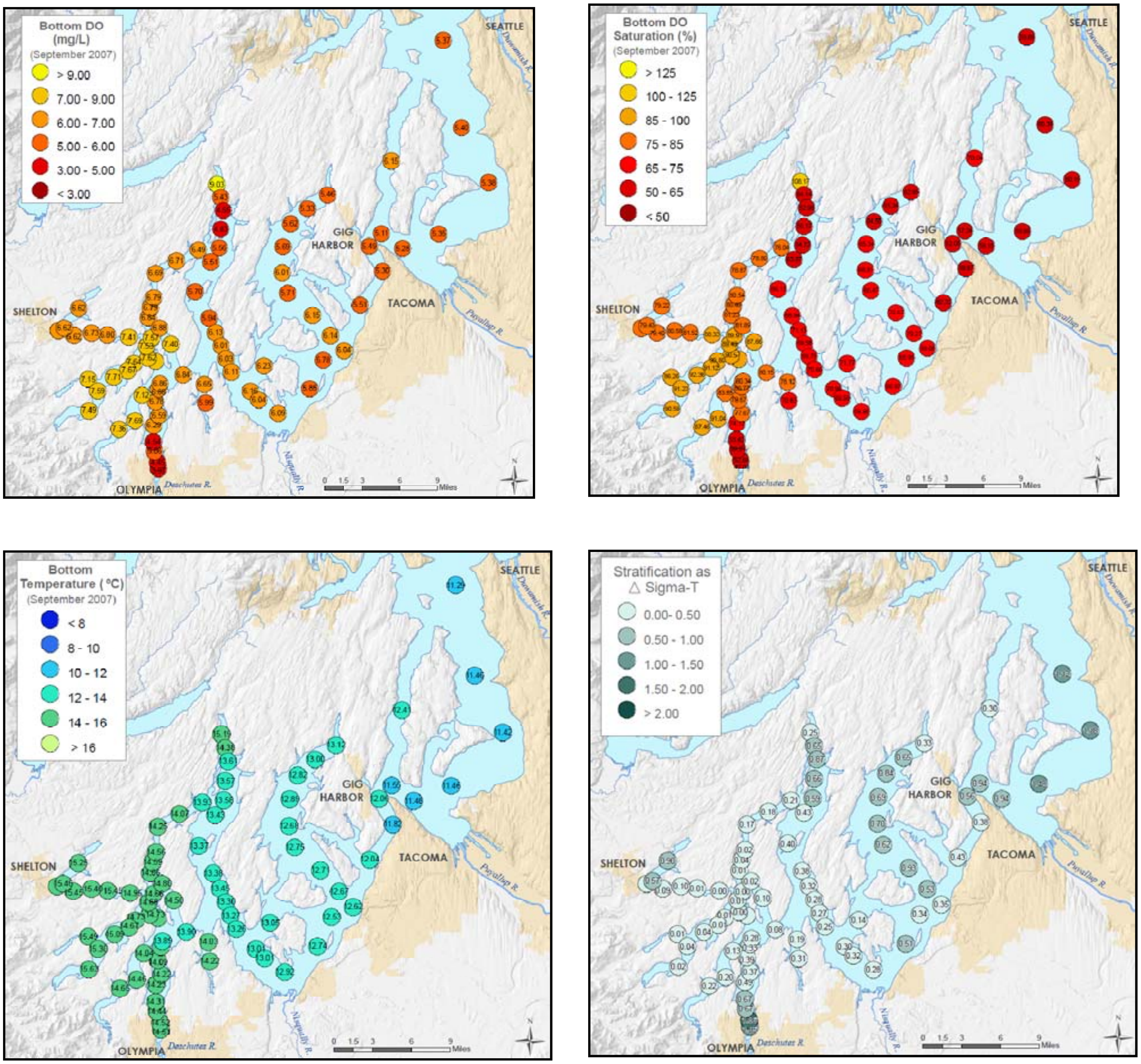


Figure 88. Spatial patterns of near-bottom concentrations from the September 24-27, 2007 cruise. (A) Calibrated DO (mg/L), (B) calibrated DO saturation (%), (C) temperature (^{o}C), and (D) proxy for stratification (delta sigma-t).

Acoustic Doppler Current Profilers

A combination of surface transects and bottom-mounted ADCPs were used to describe the spatial and temporal variability in current velocity vectors at key locations in South Puget Sound. Surface transects, recorded as a shore-to-shore slice perpendicular across inlets or passages, provided instantaneous flow rates. Total water mass flux was calculated by integrating the velocity over the cross-sectional area. Bottom-mounted ADCP results provide details on the temporal variability, and results are presented as depth-averaged velocity. Comparing patterns between paired deployments also provides information on cross-channel variability to distinguish rotational patterns in currents that affect gross exchanges within inlets.

July Transects

Transects were conducted on these dates: Budd, Totten, and Eld Inlets, and Hope Island - July 10; Carr Inlet - July 11; and Case Inlet - July 12 (Appendix E). All transects were conducted during flooding tide conditions. Detailed cross-sectional results are presented in Appendix E. While the cross-inlet flow patterns were fairly uniform at many transects (e.g., the mouths of Budd, Totten, and Eld Inlets at transects BTE1, BTE4, and BTE5), complex cross-channel flow patterns occur around Hope Island (BTE2 and BTE3).

Figure 89 and Figure 90 summarize the water fluxes spatially for the Budd/Totten/Eld transects and Carr/Case transects, respectively. The Budd Inlet transects indicate a strong decrease in the mass flux in southern Budd Inlet as compared with Central Budd Inlet, although there were 40 minutes between the two transects. Near Hope Island, more water passed to the south than the north, and the north flux was affected by an eddy that formed on the west side of the island. Of the water that passed Hope Island, 25% of the water flowed into Totten Inlet and the rest flowed north. The tidal node, then, was north of Hope Island.

In Case Inlet, a strong decrease in mass flux occurred from south to north. Of the water that passed Herron Island, most of the water flowed west through Pickering Passage around Harstine Island, and only 35% flowed into northern Case Inlet past Stretch Island. Exchanges were also diminished into the northernmost reaches of Case Inlet past Rocky Point. In Carr Inlet, the mass fluxes north of Fox Island and the northern inlet were comparable.

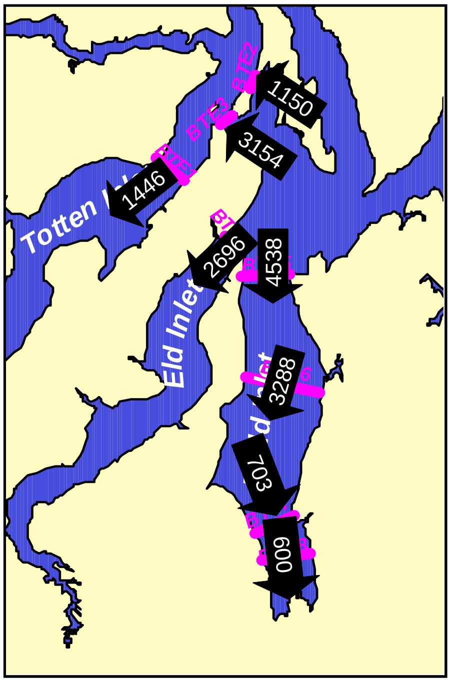


Figure 89. Budd, Totten, and Eld Inlet instantaneous mass flux (m^3/s) for July 10, 2007, recorded over a 4-hour period between 9:30 and 13:30. Low tide occurred at 9:05 a.m. and high tide at 4:34 p.m.

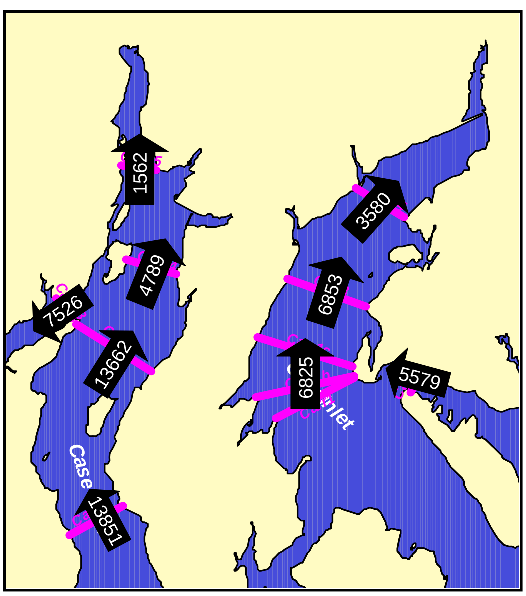


Figure 90. Carr and Case Inlet instantaneous mass flux (m^3/s) for July 11 and 12, 2007, recorded during a flooding tide over a 4-hour period. The CASE1 transect was recorded July 11 while the remaining Case Inlet transects were recorded July 12. See Figure 89 for the tide stage.

September Transects

Additional surface transects were conducted on September 26, 2007, under ebb conditions in the morning and flood conditions in the afternoon (see Appendix E). As with the July transects, several indicated more uniform conditions, such as within Pickering Passage, and far more complex structures occurred near Hope Island.

The flux estimates are presented in Figure 91 and Figure 92 spatially. The transects were recorded sequentially and do not represent synoptic (simultaneous results) conditions. However, adjacent transects were recorded with minimal lag time. Therefore, the large differences in fluxes between the mouth of Hammersley Inlet and Arcadia Point are due to spatial changes primarily and not due to large changes in tidal velocity. The results indicate large-scale flow patterns. On the ebbing tide, the water leaving Hammersley Inlet ebbs north through Pickering Passage, as does some of the water leaving Totten Inlet. In fact, the flow splits from Totten Inlet, with roughly half flowing past Hope Island and the rest flowing north through Pickering, due to the plug-like effect of Hope Island. Very little water ebbs or floods through Peale Passage; it is likely limited by the shallow northern water depths.

On a flooding tide, water entering Hammersley Inlet floods through Pickering Passage, whereas Totten Inlet likely floods with water traveling through Pickering Passage as well as around Hope Island. Under the conditions monitored, the tidal node occurs immediately west of Hope Island.

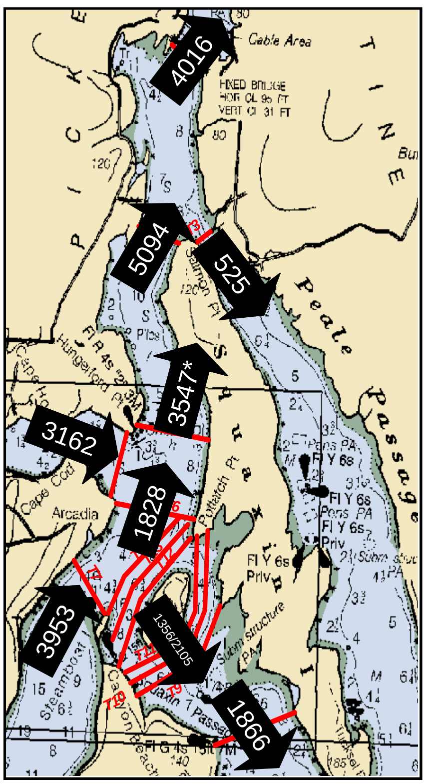


Figure 91. Instantaneous mass flux around Hope Island for September 2007 (ebbing tide) recorded over 3.5-hour period. Asterisk indicates flux likely influenced by very complex cross section. Low tide occurred at 11:59 a.m. and high tide at 6:02 p.m. Two values around Hope Island represent two adjacent transects within the complex flow zone.

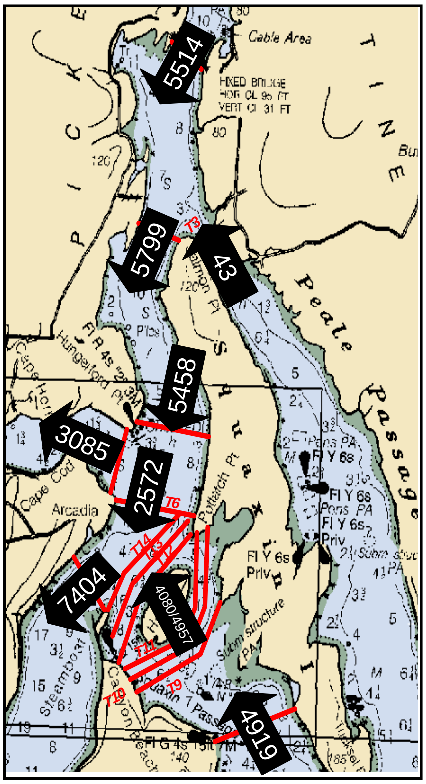


Figure 92. Instantaneous mass flux around Hope Island for September 2007 (flooding tide) recorded over 3.5-hour period. See Figure 91 for the tide stage. Two values around Hope Island represent two adjacent transects within the complex flow zone.

Bottom Mounts in Carr, Case, and Budd Inlets

Results from the bottom-mounted ADCP deployments will be used for multiple purposes, including hydrodynamic model confirmation. These data will be revisited in the upcoming hydrodynamic model report. However, the data also offer insights into fundamental processes in key locations within Carr, Case, and Budd Inlets.

Figure 93 presents both the depth-averaged velocity of each ADCP in three inlets as well as the mean and difference between the east and west results. The vertically averaged results for each ADCP represent the tidal signal or barotropic contribution to water velocity. When the east and west data are averaged, the mean current speed describes the overall water flux across the section. The difference between the east and west records suggests a rotational component to the velocity structure, where under certain tidal or wind conditions more water enters the inlets on the east or west side.

In Carr Inlet, the east and west ADCP results are similar but not identical. Both ADCPs indicate high-frequency variations in the records, indicative of wind events. By contrast, the two Case Inlet ADCPs illustrate lower-frequency variations, and the western ADCP showed slightly higher peak velocity than the eastern ADCP. Budd Inlet ADCP results illustrate high-magnitude current speeds associated with tidal forcing as well as high-frequency oscillations associated with wind.

(A) Vertically-averaged speed (cm/s) for west and east ADCPs	(B) Mean west and east (planar) and difference in west and east (rotational) speed (cm/s)

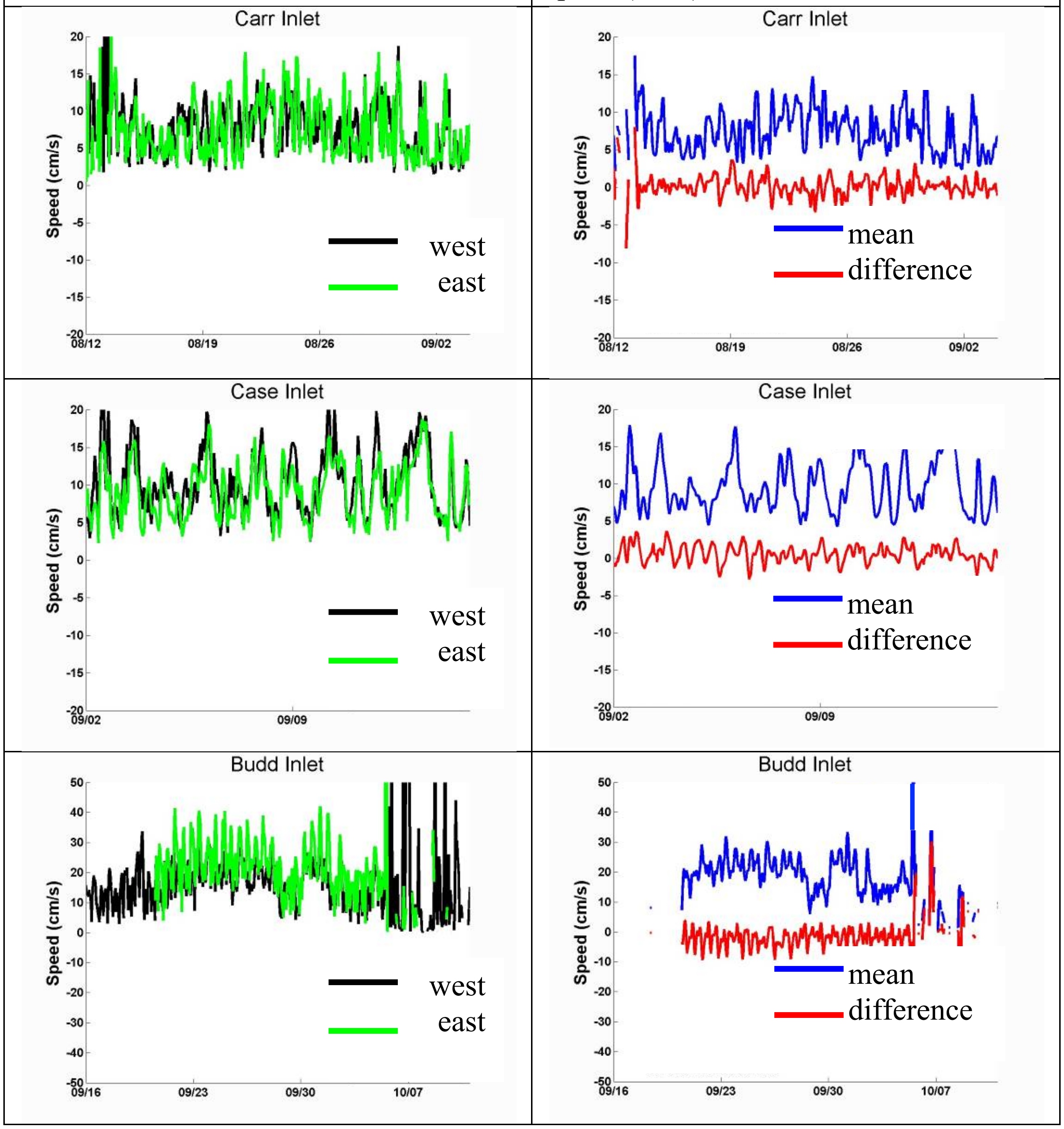


Figure 93. Velocity data collected from bottom-mounted ADCPs deployed in Carr, Case, and Budd Inlets in August 2007. The mean of the two records indicates the average current speed across the section. The rotational component results from the differences in speed in the two records, giving rise to more water entering on one side of the inlet than the other.

The patterns show that water current is not purely the result of tidal forces, which would show as a smooth oscillation between flood and ebb tides. Instead, the patterns also are affected by differences in circulation across the inlets as well as by wind to varying degrees depending on location. Accounting for changes in the vertical and horizontal axis among plots, the higher-frequency signal in the Carr Inlet record reflects the stronger influence of wind than the tides in determining velocity patterns. On the other hand, speed variations in Case Inlet follow tidal patterns and are less influenced by wind. The Budd Inlet record shows both influences. A more detailed analysis of these data will be included in the upcoming hydrodynamic model report.

Bottom Mounts near Hope Island

Data from the long-term deployment around Hope Island have not been compiled because the southernmost ADCP has not been located. More information will be presented in the hydrodynamic model report.

Benthic Flux

Benthic fluxes were measured for oxygen and nutrients within four inlets, at three nominal depths, and three times in September and October 2007. Sediment DO consumption rates were calculated based on the complete Hydrolab dataset. Winkler data were used when primary productivity influenced results, by the chamber lifting off the bottom during sampling, or if the water oxygen was depleted during the deployment. Linear consumption rates were calculated as the initial values minus the final values, based on either Hydrolab or Winkler data. Where the final value was affected by one of the interferences listed above, the previous DO reading was used in the calculation.

Figure 94 presents the sediment oxygen demand (SOD; decreased oxygen concentration in the water column) data, normalized by the chamber volume and the cross-sectional sediment surface area. Instantaneous rates range from 0.0 to 1.7 g-O_2/m^2-d with a grand mean of 0.7 g-O_2/m^2-d. SOD rates vary by inlet (ANOVA, p=0.006). The highest values were found in Eld Inlet.

Sediment oxygen demand may be offset by productivity (photosynthesis results in a day/night cycle) if the chamber admits light. While all chambers were to be painted black to eliminate productivity effects, some were inadvertently deployed in the euphotic zone with a light chamber. These records reflected not just a steady drawdown in oxygen concentrations but the cyclic effect of photosynthesis. The net effect is to underestimate the actual SOD rates. Therefore, the results may be biased low.

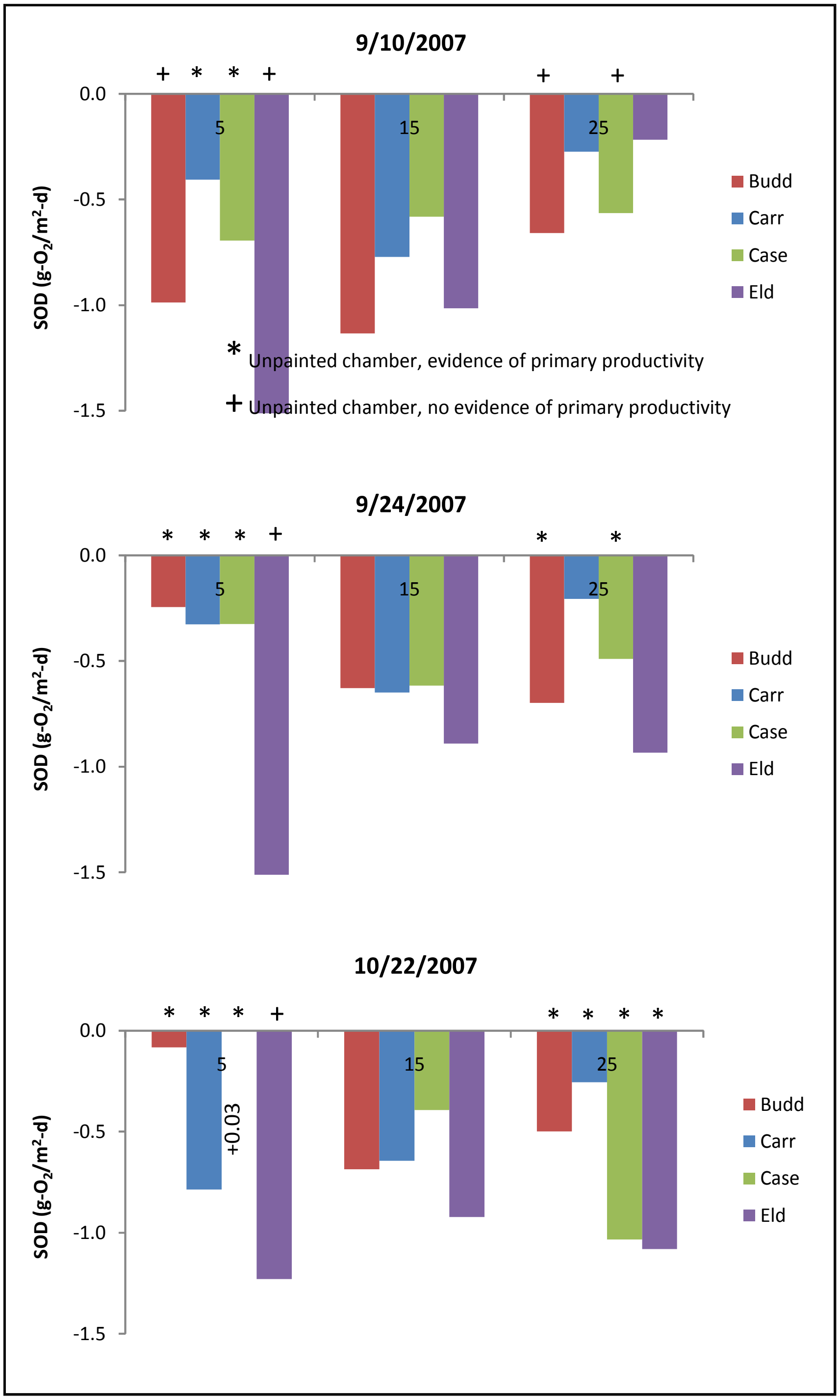


Figure 94. Sediment oxygen demand (SOD) rates based on linear estimates from late summer 2007 benthic flux chambers. Data are grouped by nominal depth (5, 15, and 25 m). Light chambers influenced rates for some results, indicated with an asterisk. Clear chambers with no evidence of primary productivity are indicated with +.

Benthic processes also release ammonium and a net positive flux of dissolved inorganic nitrogen (DIN) to the surface waters results. Figure 95 compares DIN rates based on initial and final nutrient concentrations by inlet, depth, and sampling round. Individual rates vary from 0 to 0.13 g-N/m^2-d with an overall grand mean of 0.052 g-N/m^2-d. Eld Inlet had the highest DIN loads from the sediment to the overlying water column at several stations and monitoring rounds.

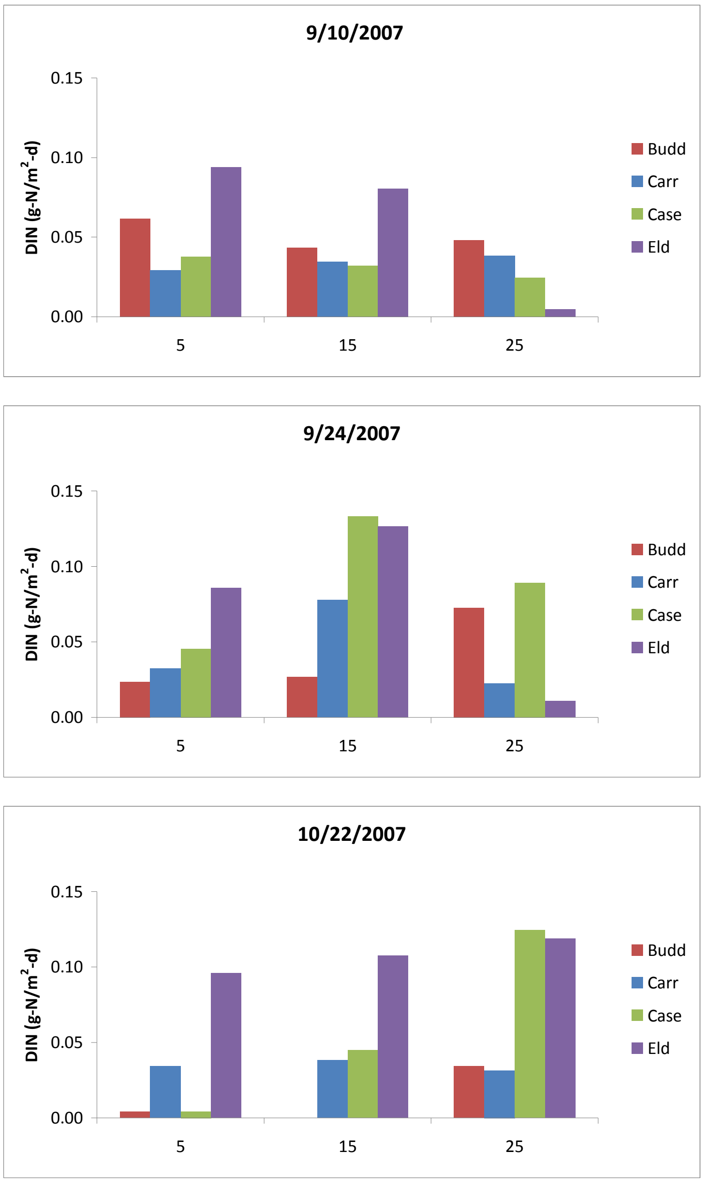


Figure 95. DIN loads from sediment to water rates based on 24-hour deployments from late summer 2007 benthic flux chambers.

Organic nitrogen fluxes across the sediment-water interface varied in direction (Appendix F). Over the 36 measurements, the mean organic nitrogen flux was 0.038 g-N/m^2-d (range -0.10 to 0.34 g-N/m^2-d). However, the direction of the flux and the magnitude were highly variable, with most of the September 10, 2007 5-m and 25-m results, and nearly all of the October 22, 2007 (all depths) results, showing a net flux of organic nitrogen into the sediments.

The net effect of DIN and organic nitrogen fluxes is a net source of total nitrogen from the sediments to the water column, although the direction and magnitude vary among locations and sampling rounds. The highest total nitrogen fluxes (Appendix F) occurred in Eld and Budd Inlets. The October 22, 2007 fluxes are markedly lower in general than the September 2007 results.

Total phosphorus fluxes averaged 0.025 g-P/m^2-d across all stations and monitoring periods and ranged from -0.008 to 0.115 g-P/m^2-d (Appendix F). The highest-magnitude fluxes occurred in Eld Inlet. Nearly all the phosphorus was in orthophosphate form, which averaged 0.024 g-P/ m^2-d across all stations and times (Figure 96). Organic phosphorus fluxes averaged 0.001 g-P/ m^2-d.

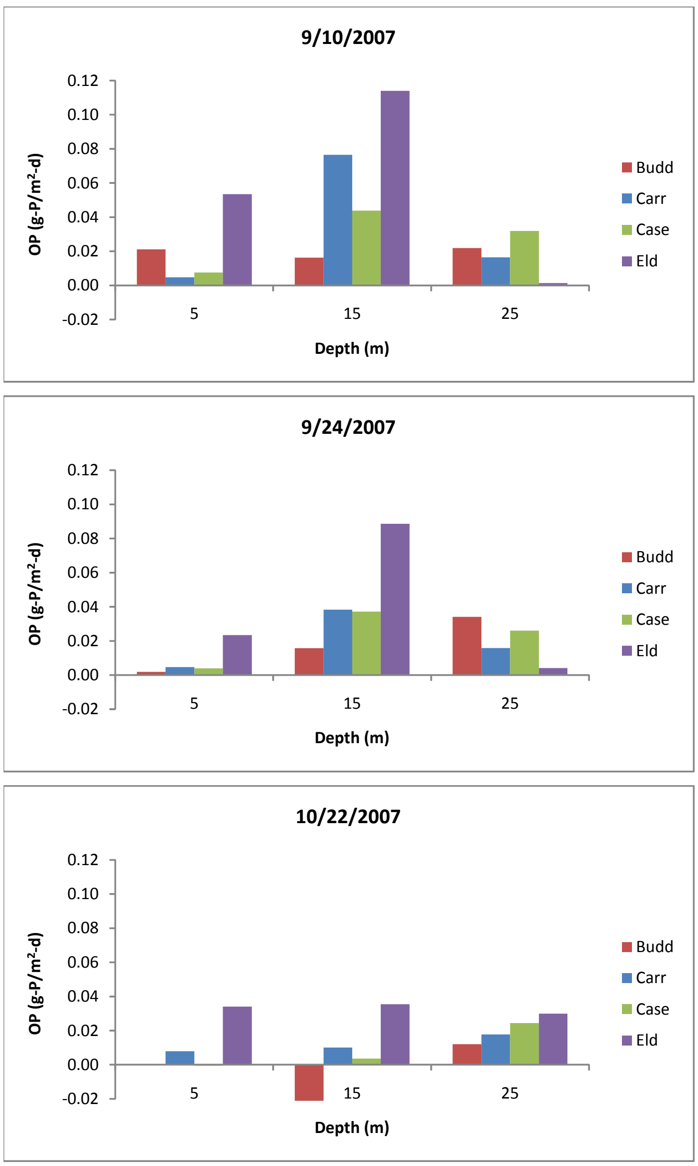


Figure 96. Orthophosphate loads from sediment to water. Rates based on 24-hour deployments from late summer 2007 benthic flux chambers.

The World Flux Database is a compilation of both U.S. and international flux measurements compiled by the Chesapeake Biological Laboratory (Bailey and Boynton, 2007). Based on over 7000 measurements, mean sediment oxygen consumption is approximately 1.0 g-O_2/m^2-d in Chesapeake Bay and 0.8 g-O_2/m^2-d worldwide. Mean ammonium flux rates are approximately 0.074 g-N/m^2-d in Chesapeake Bay and 0.040 g-N/m^2-d worldwide. DIN fluxes averaged 0.064 g-N/m^2-d in Chesapeake Bay, including the net loss of nitrate + nitrite. No worldwide values for nitrate + nitrite fluxes were presented, but DIN fluxes were available.

The mean oxygen and DIN fluxes from the present study are lower than the reported mean value of the Chesapeake Bay fluxes but higher than the worldwide mean from Bailey and Boynton (2007).

Mean dissolved inorganic phosphorus fluxes in the World Flux Database (Bailey and Boynton, 2007) are similar worldwide and for Chesapeake Bay at 0.015 g-P/m^2-d. Mean phosphorus fluxes for the present study were higher than for Chesapeake Bay.

Extrapolating benthic fluxes to inlet load estimates

Benthic fluxes of nutrients result from biochemical activity within the sediments. The original source of the nutrients includes organic matter loads from the watershed and water surface as well as the internal processing that occurs mediated by the biota in the water column. Benthic fluxes often are described as internal loads, in that the sediments act as temporary storage reservoirs of nutrients from external sources and internal water column and sediment processing. This internal cycling of nutrients is important to quantify because the reservoir may buffer waterbody conditions to changes in external loads.

Table 19 estimates inlet-wide nutrient internal loads for key portions of the study area. Budd Inlet sediments seasonally produce up to 1100 kg/d of DIN. No winter benthic fluxes were measured but are expected to be low due to lower overall biological activity. These late-summer seasonal estimates are expected to be higher than the annual average sediment fluxes. Also, benthic fluxes may not be uniform across depths, particularly the very deep areas of Carr Inlet, and these values are presented for comparison purposes only.

Table 19. Benthic nutrient fluxes extrapolated to various inlets based on the grand mean fluxes.

Waterbody	Area (km^2)	DIN (kg/d)	OP (kg/d)	TN (kg/d)	TP (kg/d)
Grand mean fluxes (g/m^2-d)		*0.052*	*0.024*	*0.085*	*0.025*
Budd Inlet	21.4	1121	508	1809	535
Carr Inlet north	44.0	2310	1047	3727	1103
Carr Inlet south	48.5	2546	1153	4107	1216
Case Inlet	60.2	3160	1432	5099	1509
Other South Sound	239.8	12,586	5703	20,309	6011
South Sound (subtotal)	413.9	21,723	9843	35,053	10,374

See *Glossary* for abbreviations.

Previous benthic flux studies in Budd Inlet (Aura Nova Consultants et al., 1998) found an ammonium flux of 395 metric tons per year (from the sediment to the water column) and a nitrate flux of -69 metric tons per year (from the water column to the sediment) summed over the entire Budd Inlet (2.0×10^7 m^2). The calculations were based on benthic flux chamber measurements from four stations: West Bay (BI-5), southern Budd Inlet near Priest Point Park (BA-1), central Budd Inlet (LOON-1 or BUD005), and northern Budd Inlet near Gull Harbor (BD-2). The mean annual DIN flux found in the *Budd Inlet Scientific Study* was equivalent to 326 metric tons of nitrogen per year or 890 kg-N/d.

The *Budd Inlet Scientific Study* annual mean loads, based on benthic fluxes measured up to 20 times between September 1996 and October 1997, were comparable to the values found in the current study. Both nutrient release and oxygen consumption peaked in the late summer and approached zero during winter. Across the four stations, peak seasonal ammonium fluxes were around 8 mmol-N/m^2-d, equivalent to 0.11 g-N/ m^2-d or 2400 kg-N/d for all of Budd Inlet. Winter ammonium fluxes were approximately 600 kg-N/d. Similarly, orthophosphate fluxes were approximately 1300 kg-N/d in the summer and 170 kg-P/d in the winter.

Overall, the present study found peak late-summer nutrient flux rates approximately half the values found in the Budd Inlet Scientific Study. The difference could be due to methodological variations between the two studies or reductions in sediment cycling over time.

Other Relevant Data

In addition, relevant data collected by Ecology and others under independent projects are compiled where available.

South Sound Mooring Results

Ecology has maintained continuous monitoring near-bottom sensors in two nearshore locations within South Puget Sound since October 2006. The Budd Inlet mooring (BUD01) is located at the Port of Olympia. It records water pressure, water temperature, salinity, and DO levels at 15-minute intervals at a fixed depth of 1.1 meters above the sediment surface. The Squaxin Passage mooring (SQX01) records similar information near Carlyon Beach. Station depths are 7.7 and 6.7 m at mean lower low water for BUD01 and SQX01, respectively.

Figure 97 presents interim data from the two moorings (Jaeger et al., 2008). Daily mean DO levels were 8 mg/L or higher through May 2007, but declined to below 5 mg/L from July through September in Budd Inlet. The Squaxin Passage daily mean DO levels remained near 8 mg/L throughout the year (limited data available for the summer). Final data will be distributed through the Ecology marine ambient monitoring web page.

The DO values for the Budd Inlet mooring are consistent with data collected during cruises. Concentrations below the water quality standards were recorded in July, August, and September 2007. Cruises captured these conditions.

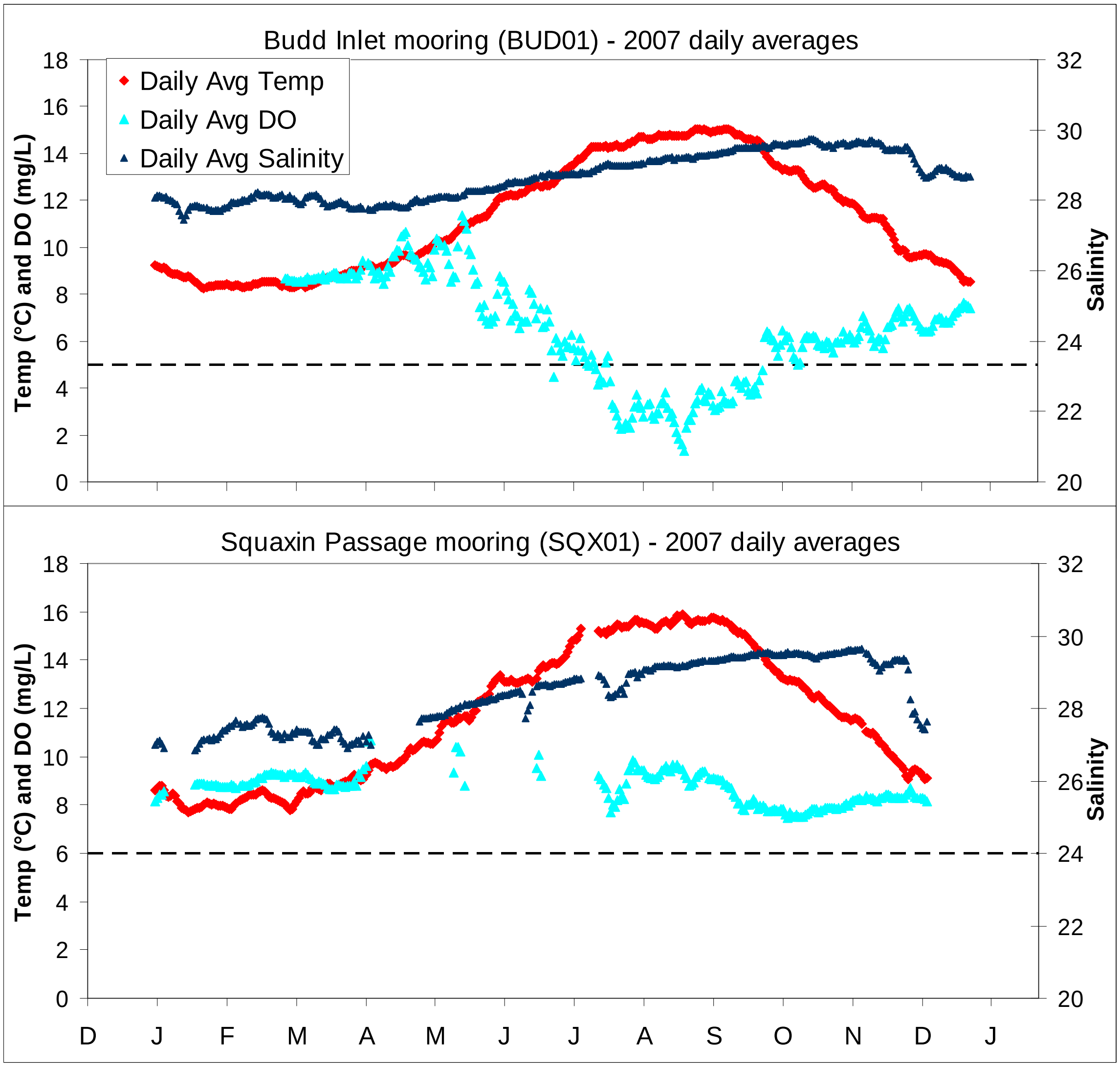


Figure 97. Continuous mooring data (preliminary) for stations located 1.1 meters above the sediment surface. Data gaps indicate that data did not meet minimum QA/QC requirements until further investigation. Source: Jaeger et al. (2008). The dashed lines indicate the water quality standard for each location.

Combined Sewer Overflows

South of the Tacoma Narrows, only a portion of downtown Olympia is served by a combined sewer system, where storm drainage is intentionally routed to the wastewater treatment plant. However, no combined sewer overflows (CSOs) have occurred for many years (Dougherty, personal communication), and the facility operates under a CSO abatement program.

Episodic sanitary sewer overflows (SSOs) occur in Shelton and infrequently in Olympia. SSOs are caused by obstructions in sewer lines that cause the wastewater to backup through manholes. There are no estimates for SSO volumes or nutrient loads, and these are believed to be negligible in comparison to other nutrient sources (Dougherty, personal communication).

National Atmospheric Deposition Program

The National Atmospheric Deposition Program maintains a monitoring network to measure a variety of water quality parameters in wet deposition. Western Washington includes three stations; however, none are located near Puget Sound. For 2006, the last year for which data have been summarized, wet deposition of nitrate and ammonium varied from 0.9 to 2.2 kg-N/ha-yr, with a mean of 1.43 kg-N/ha-yr for the three stations. Applying this rate to the water surface area of South Puget Sound, south of Tacoma Narrows, atmospheric deposition produces an additional 170 kg-N/d. Including the land and water surface area, wet deposition produces 1700 kg-N/d. However, the nitrogen that falls on the land surface is accounted for within the tributary load estimates. For the water surface area between Edmonds and the Tacoma Narrows, atmospheric deposition produces an additional 210 kg-N/d.

Comparing the atmospheric deposition unit loads to the land surface to the total loads exported to Puget Sound, atmospheric deposition could be responsible for up to 60% of the watershed inputs. However, this value does not account for attenuation within the watershed.

Onsite Septic System Inputs

The Washington State Department of Health (DOH) estimates the wastewater produced by residents served by onsite septic systems is 175 mgd throughout the Puget Sound region (Woolrich, personal communication). No estimates for the South Sound watershed are available. Because rivers and streams were monitored at the mouths, concentrations and loads will include any upstream onsite system loads and attenuation in groundwater. Measured loads will be applied to unmeasured areas to account for shoreline regions not tributary to large rivers or streams, and the effect of onsite septic systems will be implicit in the loading rates.

Summary of Other Sources

Nutrient sources other than the rivers and WWTPs contribute additional loads to South and Central Puget Sound. Septic systems are included with measured river inputs. Atmospheric deposition to the water surface increases DIN loads to Puget Sound by 5%. Nutrient fluxes into and out of the northern model boundary will be quantified using the water quality model later in the project. Internal sources from sediments are locally important, particularly during the late summer. In shallow inlets, sediment releases of DIN are comparable to external watershed loads. Figures 98 and 99 summarize DIN loads to South and Central Puget Sound as annual averages and late summer (September 2007) conditions, respectively.

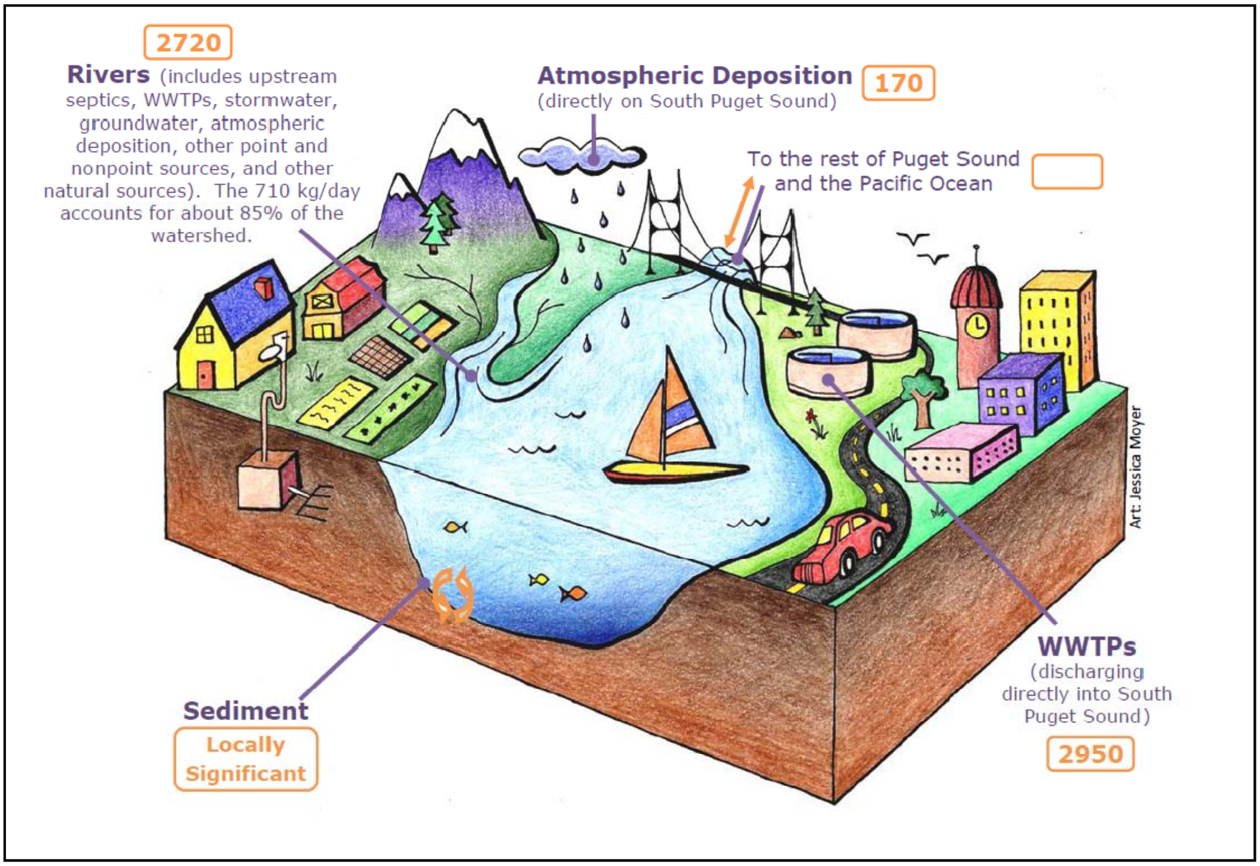


Figure 98. Annual average dissolved inorganic nitrogen (DIN) loading to South Puget Sound (kg/d). Nutrient fluxes with the rest of Puget Sound will be determined using the model.

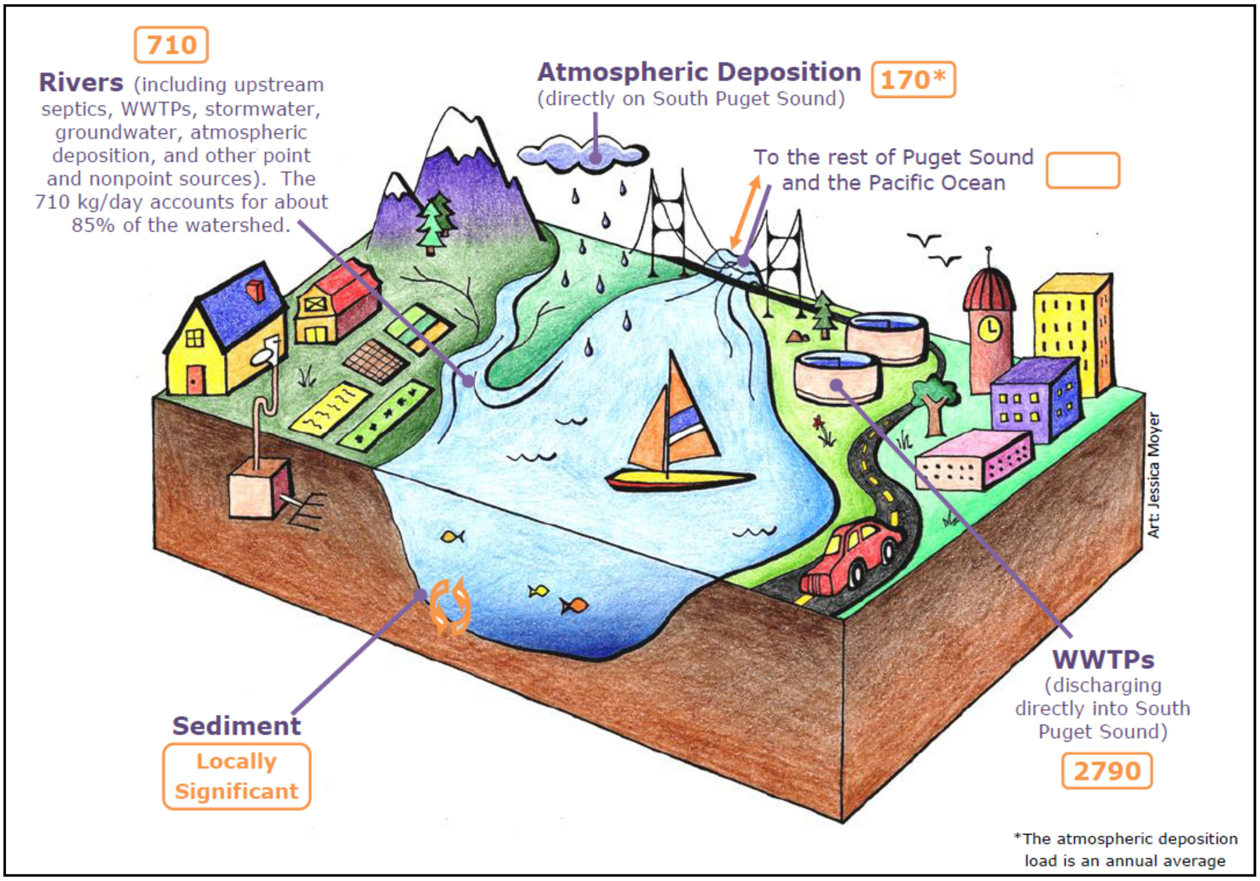


Figure 99. September 2007 dissolved inorganic nitrogen (DIN) loading to South Puget Sound (kg/d). Nutrient fluxes with the rest of Puget Sound will be determined using the model.

Conclusions

The Washington State Department of Ecology began this study to determine how nitrogen from a variety of sources affects dissolved oxygen in South Puget Sound. Portions of South Puget Sound do not meet Washington State water quality standards for dissolved oxygen. The study includes collecting and analyzing data, developing hydrodynamic and water quality models, and assessing alternative management scenarios. This report summarizes nitrogen (nutrient) and related data collected from July 2006 through October 2007.

The data were collected from 90 marine stations within South and Central Puget Sound, 29 wastewater treatment plants (WWTPs) discharging directly to Puget Sound, and 39 rivers and streams. Of the nutrient loads from the land surface, rivers and WWTPs are significant sources of dissolved inorganic nitrogen (DIN; the sum of ammonium and nitrate plus nitrite). Nutrients recycled from sediments are an important influence and during late summer may release loads comparable to those from WWTPs and rivers. Other sources of nitrogen include atmospheric inputs which are small in comparison to watershed sources, and septic systems which are included in the watershed loads within the sites monitored.

Water circulation and velocity patterns are complex. Stratification was most intense in Budd, Carr, and Case Inlets, and Oakland Bay. Low near-bottom dissolved oxygen occurred in many parts of South Sound, including but not limited to Budd, Carr, and Case Inlets. DIN levels varied seasonally and spatially, and also reflected surface oxygen depletion associated with productivity. Chlorophyll levels were highest in shallow inlets as well as in north Pickering Passage and Oakland Bay.

Freshwater Results

Rivers and tributaries produced an annual mean of 2,720 kg/d of DIN, primarily in the form of nitrate + nitrite, to South Puget Sound. The entire Puget Sound watershed area south of the Edmonds boundary produced a total of 7,160 kg/d of DIN, including estimates for watersheds tributary to Sinclair and Dyes Inlets and to Lake Washington. Seasonally, higher DIN loads occur in the wet winter months, when loads could be twice the annual mean.

Annual mean DIN estimates were based on time-weighted loads derived from individual sampling days. A future effort will use a statistical technique called *multiple linear regression* to extrapolate monitoring data to develop a daily time series of inflows for the water quality model. However, because the sampling days coincided with a variety of wet-weather and baseflow events, the simple estimates are a reasonable step toward understanding nitrogen loads to South and Central Puget Sound.

River and tributary estimates include upstream onsite septic systems and some WWTPs that discharge to freshwater upstream of Puget Sound, and these have not been quantified to date.

Rivers and streams with high concentrations of DIN include those in southern King County; Goodnough Creek in northern Carr Inlet; Hylebos, Chambers, and McAllister Creeks, all strongly influenced by groundwater; and tributaries to Henderson and Budd Inlets.

Wastewater treatment plants produced an annual mean of 2,950 kg/d of DIN, primarily in the form of ammonium, to South Puget Sound. The entire area south of the Edmonds boundary produced a total of 27,100 kg/d of DIN. Loads remained fairly constant and did not exhibit an obvious seasonal pattern. Monthly variations resulted mostly from lack of sampling from WWTPs on occasion, when the composite sample was not retained for this project.

Annual mean estimates of WWTP loads were based on time-weighted values derived from individual sampling days, and no attempt was made to fill missing information for this report. At most WWTPs, monthly variation was relatively low, indicating that the effect of sludge dewatering on effluent quality was not as variable as anticipated. Only the Tacoma Central plant showed a wide range between the 25^{th} and 75^{th} percentile DIN concentrations that may reflect sludge dewatering patterns. A future effort will develop daily flows and loads for each WWTP to provide water quality model input.

On an annual basis, tributaries and WWTPs produced comparable amounts of DIN south of the Tacoma Narrows. However, in September when river loads declined, WWTPs contributed 80% of the DIN load to South Puget Sound. Because of the larger population centers in Central Puget Sound, the ratio of tributary-to-WWTP contribution shifts. On an annual basis, rivers contributed 21% and WWTPs contributed 79% of the DIN load south of Edmonds. But in September as river loads declined, WWTPs contribute over 90% of the DIN load to Central and South Puget Sound.

Marine Water Results

Low levels of dissolved oxygen (DO) occurred throughout South Puget Sound in near-bottom waters. Concentrations below the Washington State water quality standards were recorded in Budd, Carr, Case, and Henderson Inlets; Pickering Passage; Dana Passage; and the Nisqually Reach. Central Puget Sound and the Tacoma Narrows also exhibited low near-bottom DO in summer 2007. Lowest levels occurred in southern Budd Inlet, but levels near or below 5 mg/L occurred in Case and Carr Inlets as well as through the Tacoma Narrows in September 2006. Low levels persisted to December 2006 and returned again in June 2007. The unusually cool and wet summer in 2007 likely contributed to the less DO depletion in September 2007 compared with September 2006. Winkler DO values confirmed the patterns observed with oxygen sensors, and the highest values occurred in the upper water column in the summer months associated with algal productivity.

Stations at Edmonds, Alki, and Rich Passage reflected complex spatial and temporal patterns. Further comparisons will be made in the upcoming hydrodynamic model report as a basis for the model boundary determination. Some cross-channel variability occurred and will be evaluated further.

Biochemical characteristics, such as DIN, ammonium, and chlorophyll-a levels, in addition to hydrodynamics (stratification, circulation, residence time), often differed between the Central Basin, Tacoma Narrows, the deeper eastern South Sound Inlets (Carr and Central Case Inlets), and the shallow western inlets (Budd, Totten, Eld, Oakland Bay, and the head of Carr Inlet). Differences in levels of ammonium, plankton growth, and the long residence times make the western inlets and the heads of Case and Carr Inlets much more prone to degraded water quality conditions, including occurrences of low DO.

DIN values indicated surface water depletion in the summer months. Ammonium peaked in Budd Inlet in September 2007. Ammonium levels were much higher in the western inlets and heads of Case and Carr Inlets than the rest of South and Central Puget Sound, and contributed more to overall DIN. This has many implications for productivity and excessive plankton growth and will be explored further with primary productivity results.

Chlorophyll levels were generally higher in 2007 than 2006. Blooms of chlorophyll occurred about one month earlier in South Puget Sound compared with Central Puget Sound. Spring blooms occurred, but the highest levels were recorded in September 2007. The areas with the highest chlorophyll levels included Budd, Totten, Eld, Henderson, Carr, and Case Inlets; north Pickering Passage; and Oakland Bay. The lowest levels occurred within the Nisqually Reach and at the Tacoma Narrows.

Stratification was most intense in the shallow waters of Budd, Case, and Carr Inlets, and Oakland Bay.

Water column velocity profiles were used to quantify cross-channel complexity and variation with depth, and the results were integrated across a section to develop instantaneous mass flux estimates. Cross-sections reflected structures such as gyres and particularly complex patterns around Hope Island. Budd, Carr, and Case Inlets showed highly decreased water exchanges near the heads of each inlet, even with the temporal offsets of the cross sections.

The northern end of Case Inlet is isolated by circulation patterns where most of the water flux travels north around Harstine Island. In addition, high water exchanges north around Fox Island isolate northern Carr Inlet as well as a zone west of Fox Island. Based on the September transects, Totten Inlet outflows split on the ebbing tide and flowed both north through Pickering Passage and east past Hope Island. On a flood tide, Totten received inflows from both Pickering Passage and around Hope Island. Therefore, a tidal node existed west of Hope Island, and the increased friction caused by Hope Island forced water to travel around Pickering Passage. Bottom-mounted velocity profile results indicated that Carr Inlet circulation was highly influenced by wind, whereas Case and Budd Inlet patterns reflected more of the smooth tidal forcing.

Benthic flux chambers installed in Budd, Carr, Case, and Eld Inlets provided local information on sediment fluxes of oxygen, nitrogen, and phosphorus. Sediment oxygen demand (SOD) was highest in Eld Inlet, which also produced the highest rates of phosphorus, ammonium, and DIN. Although SOD rates were fairly constant over the three fall sampling events, nitrogen releases were lower in late October than in September. Rates indicate that sediment flux is a seasonally important process.

Extrapolating rates to Budd Inlet, sediments produced approximately 1100 kg/d of DIN. Extensive sediment fluxes monitored during the *Budd Inlet Scientific Study* (Aura Nova Consultants et al., 1998) found an annual mean of 890 kg/d and a summer peak of 2400 kg/d of DIN. Because the historical flux rates used a different methodology, direct comparisons cannot be quantitative. However, historical results corroborate the order of magnitude estimates found in the present study and the overall importance of sediment processes in South Puget Sound. Sediment fluxes alone are not responsible for the low levels of DO found in Budd Inlet, since higher SOD and DIN rates were found in neighboring Eld Inlet, which does not have extensive DO depletion.

Two continuous mooring stations have been installed in South Puget Sound as part of a separate ambient monitoring program. Results from 2007 indicated that while DO concentrations 1.1 meter above the bottom remained near 8 mg/L throughout the year at Squaxin Passage, levels fell below 5 mg/L from July through September in Budd Inlet.

Remaining Data

Data collection for the *South Puget Sound Dissolved Oxygen Study* is nearly complete. The present report includes summaries of all but the following data:

- Sediment traps remained deployed through May 2008. Data will be summarized in an addendum to this report.
- Phytoplankton samples have not been analyzed by the University of Washington Marine Chemistry Lab (UW MCL). Results will be presented in an addendum to this report.
- Productivity data have not been compiled. Results will be presented in an addendum to this report.
- Dissolved organic carbon data from UW MCL have not been accepted or rejected; however, ongoing quality control procedures will clarify the utility of the data. An addendum to this report will summarize any usable data or clarify the status.
- The final acoustic Doppler current profiler (ADCP) has not been located, and the corollary ADCP data around Hope Island will not been summarized until the final ADCP is either located or considered lost. The status will be clarified in an addendum to this report or in the hydrodynamic model report.

Recommendations

Data were collected as described in the Quality Assurance Project Plan. The data described in this document should be used to refine loads to the South and Central Puget Sound and to provide in-situ data to compare with model output in subsequent phases of the project. The data meet the study objectives. Specific recommendations are listed below for any future monitoring conducted in the region and for limitations on a few data included in this document.

The following recommendations are provided to (1) guide how the information included in this document is used, and (2) suggest future data collection activities.

Data Gaps and Recommendations for Future Data Collection

Freshwater Results

Flow and load estimates were developed for the Lake Washington and Lake Union basins because very few data are available. The U.S. Army Corps of Engineers tracks flows through the Ballard Locks, a large volume of water flowing into Puget Sound, but these data were not available. The Washington State Department of Ecology (Ecology) historically collected water quality data from the Ballard Locks, but neither Ecology nor King County included this location in recent ambient monitoring programs. King County does monitor Lake Union near the Ballard Locks. Because the typical total nitrogen concentration was somewhat higher than the historical Ballard Locks data, the Lake Washington basin load estimates may be somewhat underestimated. Future flow and nutrient monitoring within the Locks would improve load estimates.

As in-situ continuous monitors become available for nitrogen components such as nitrate, deploying these monitors within key rivers and streams would provide better information on temporal changes in concentrations.

Marine Results

Future addenda will describe additional marine data collected during the study that were not available for this report. Topics include phytoplankton species identification and biovolume measurements; marine primary productivity; marine carbon data; sediment traps; and acoustic Doppler current profiler (ADCP) current data.

Continuous marine monitoring data were not included in the study due to resource limitations and environmental factors. Ideally, continuous profiling moorings located in mid channel or at multiple locations across the channel at Edmonds or Alki would provide detailed temporal and spatial patterns of water column parameters. However, mooring instruments within active shipping channels is unlikely. Future technologies that allow mooring deployment in these areas should be evaluated. Alternatively, if continuous profiling moorings are available to characterize conditions at key locations within South and Central Puget Sound, the potential sites should be evaluated with hydrodynamic models. This would ensure that the sites are representative of a broad area and not unduly influenced by a nearshore process.

Characterization of nutrient sources could be further investigated through stable isotope studies at key locations. Additionally, as technology improves, moored nutrient sensors could be deployed to provide better information on marine nutrient processes at key locations with regard to appropriate representativeness.

ADCP results offered important insights to spatial and temporal velocity patterns in South Puget Sound, and additional current velocity data would improve understanding of circulation in key areas. The model could be used to identify potential locations for either surface- or bottom-mounted surveys. Quantifying velocity characteristics in the Tacoma Narrows, potentially including ADCPs on the Tacoma Narrows bridges, would be helpful to future model comparisons.

Additional benthic flux measurements should be made to confirm the high sediment-water exchanges found in 2007, possibly adding other locations or characterizing other seasons.

Recommended Data Collection Changes

Freshwater Results

Given the low variability within a given wastewater treatment plant (WWTP), future effluent monitoring could be conducted quarterly for the smallest WWTPs. Monthly monitoring is recommended for the largest WWTPs.

Monthly monitoring sufficiently captured seasonal variability in streams, but future monitoring also should consider focusing on storm conditions.

Marine Results

Logistical constraints prevented collection of monthly water column samples at many of the interior South Sound basin stations. Therefore, discrete (point) samples were collected at only four stations in Carr and Case inlet. Given spatial variability in several water column properties between the shallow western inlets and deeper eastern inlets and Central Basin boundary stations, future monitoring should include discrete sample collection at a larger set of stations.

Limitations on Using the Data

Freshwater Results

Freshwater data collected from rivers, streams, and WWTPs are available in Ecology's EIM database. Where appropriate field or laboratory procedures varied from standard protocols, results are flagged with an indicator of data quality. These data should be used with caution.

The annual estimates of nutrient loads from rivers, streams, and WWTPs were based on time-weighted means of the monthly data. These initial values will be refined to daily inputs in upcoming tasks to support the water quality modeling. A statistical tool called *multiple linear regression* will be used to extrapolate using factors that influence daily and seasonal variations, including streamflow and time of the year. While the actual numbers may change from the initial estimates, the overall patterns are not expected to change significantly. This is because the WWTPs produced little variation over time, and the rivers and streams were sampled during high-flow conditions.

One exception was the Tacoma Central WWTP, which had the greatest variability between the 25th and 75th percentile concentrations of dissolved inorganic nitrogen (DIN) that may have been due to sludge dewatering patterns. Patterns will be evaluated more closely when developing the daily time series, and the overall annual loads may vary from the initial estimates.

Future efforts also will extrapolate to unmonitored locations. Nearly 90% of the watershed area was included in the monitoring program, but loads from the remaining watershed areas will be estimated for completeness. In addition, two small WWTPs were not monitored, but loads will be estimated from facility effluent flows and the characteristics of the monitored WWTPs.

Marine Results

Marine conductivity, temperature, and depth (CTD) and lab data collected from cruises are available on the web, by data request, and through Ecology's EIM database. Where appropriate field or laboratory procedures varied from standard protocols, results are flagged with an indicator of data quality. These data should be used with caution. Any data that did not meet quality control standards were removed from the dataset and were not considered further in analyses or modeling products.

CTD profiles of pH data should be used as an estimate and a measure of relative pH patterns throughout the water column. Despite adherence to standard protocols for deployment of the pH sensor, logistical constraints prevented calibration of the sensor prior to each cast, and data accuracy is not of high quality.

ADCP transect results represent a snapshot in time and are not synoptic.

Benthic flux results indicate the magnitudes of sediment-water exchanges of dissolved oxygen (DO) and nutrients. Primary productivity influenced some measurements, which are identified in the figures. These measurements should be used with caution.

Upcoming Schedule

The data reported in this report are part of the larger *South Puget Sound Water Quality Study*, which includes hydrodynamic and water quality model development as well as alternative future scenarios representing a variety of potential management actions. Remaining work includes the following:

- **Technical Advisory Group**: Continues to meet approximately quarterly to review and discuss project findings at key milestones.
- **Data Report Addenda**: As described in the *Conclusions*, several outstanding data products will be summarized as addenda to the current data report. These addenda will be developed as the data are available in 2009.
- **Hydrodynamic Model Report**: Hydrodynamic model development, calibration, and confirmation continues. The draft hydrodynamic model report will be released for comment, and the report will be finalized in 2009. The report will include a recommendation on the northern boundary location depending on the results of tracer dispersion from major river and WWTP flows within Central Puget Sound.
- **Water Quality Modeling**: Water quality model development builds from the hydrodynamic model development. Model calibration and confirmation will continue through 2009. Depending on the findings of the hydrodynamic model report, the model domain will be adjusted as the area south of Edmonds or south of Alki Point. Interim results will be provided to the Technical Advisory Group, and the Water Quality Model Report will document the findings; the report will be released for comment in 2009.
- **Potential Future Scenarios**: Future scenarios will be developed in conjunction with the Technical Advisory Group in 2009 and simulated using the hydrodynamic and water quality models.
- **Technical Report**: The project technical report will summarize the findings of the potential future scenarios. The schedule is highly contingent on the progress made on water quality model calibrations and will vary with the number of scenarios to be simulated. The current plan is to finalize the technical report by summer 2010.

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Appendices

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Appendix A. Glossary, Acronyms, and Abbreviations

Glossary

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

Ambient: Background or away from point sources of contamination

Baseflow: Groundwater discharge.

Benthic: Bottom

Benthos: Sediment-dwelling invertebrates

Central Puget Sound: Puget Sound south of Edmonds and north of Tacoma Narrows.

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.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Ebb tide: Transition from high to low tide.

Euphotic: Nutrient-rich and high in productivity resulting from human activities such as fertilizer runoff and leaky septic systems.

Fecal coliform: That portion of the coliform group of bacteria which is present in intestinal tracts and feces of warm-blooded animals as detected by the product of acid or gas from lactose in a suitable culture medium within 24 hours at 44.5 plus or minus 0.2 degrees Celsius. Fecal coliform bacteria are "indicator" organisms that suggest the possible presence of disease-causing organisms. Concentrations are measured in colony forming units per 100 milliliters of water (cfu/100 mL).

Flood tide: Transition from low to high tide.

Marine water: Salt water

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

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the 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.

Nutrient: Substance used by organisms to live and grow. Marine plant (algae or phytoplankton) growth often is limited by the nutrient, nitrogen.

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 5 acres of land.

Sediment oxygen demand: Decreased oxygen concentration in the water column.

South Puget Sound: Puget Sound south of Tacoma Narrows.

Stratification: Difference between surface and near-bottom density as delta sigma-t.

Synoptic: Simultaneous.

Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
ALK	Alkalinity
BOD5	5-day biochemical oxygen demand
BOD5INH	Inhibited BOD5
CBOD5	5-day biochemical oxygen demand
cfs	Cubic feet per second
CFSM	Cubic feet per second per square mile
CMS	Cubic meters per second
Cl	Chlorine
COD	Chemical oxygen demand
CTD	Conductivity temperature and depth profiler
DIN	Dissolved inorganic nitrogen (nitrate, nitrite, ammonium)
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DTP	Dissolved total phosphorus
DTPN	Dissolved total (persulfate) nitrogen
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database (Ecology)
EPA	U.S. Environmental Protection Agency
FC	Fecal coliform
HCl	Hydrochloric acid
kg/d	Kilograms per day

LNSW	Low-nutrient seawater
LOTT	Lacey, Olympia, Tumwater, and Thurston County Alliance
MCL	Marine Chemistry Laboratory (UW)
MEL	Manchester Environmental Laboratory (Ecology)
mgd	Million gallons per day
ML	Marine Laboratory (Ecology)
MLLW	Mean lower low water
mmol	Millimole, or one-thousandth of a mole. A mole is an SI unit of matter.
MQO	Measurement quality objective
NA	Not applicable
NC	Not collected
NH3	Ammonia
NH4N	Ammonium
NO23N	Nitrate plus nitrite
OP	Orthophosphate (also called soluble reactive phosphorus)
PAR	Photosynthetically active radiation
PCN	Particulate organic carbon and nitrogen
PRISM	Puget Sound Regional Synthesis Model
Q	Streamflow
QA	Quality assurance
QC	Quality control
Q_{maxmo}	Maximum month discharge
RSD	Relative standard deviation
R/V	Research vessel
SFSU	San Francisco State University
SM	Standard Methods
SOD	Sediment oxygen demand
SRP	Soluble reactive phosphorus
TAC	Technical Advisory Committee
TDN	Total dissolved nitrogen
TDP	Total dissolved phosphorus
TEMP	Temperature
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TPN	Total (persulfate) nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TSS	Total suspended solids
uM	Micromolar (a chemistry unit)
USGS	U.S. Geological Survey
UW	University of Washington
WAC	Washington Administrative Code
WPLCS	Water Quality Life Cycle System Database
WRIA	Water Resource Inventory Area
WWTP	Wastewater treatment plant

Appendix B. CTD Calibration Certificates

Notes:

King County and the University of Washington both maintain current sensor calibration by exchanging sensors due for calibration with newly calibrated sensors. Sensors are sent to manufacturers for calibration on a regular basis.

The Washington State Department of Ecology maintains current sensor calibration by sending in designated sensors to manufacturers for calibration on (approximately) an annual schedule, based on the frequency of instrument use.

Table B1. CTD sensors used for South Sound marine water column sampling, by agency, including serial numbers and calibration dates.

Owner/ Agency	Sensor	Serial Number	Calibration Date(s)			
King Co	SBE3 - Temperature	2825	Dec-05			Feb-08
King Co	SBE3 - Temperature	2782		Oct-06		
King Co	SBE3 - Temperature	2586			Oct-07	
King Co	SBE4 - Conductivity	2417		Oct-06		
King Co	SBE4 - Conductivity	2440	Dec-05			Feb-08
King Co	SBE4 - Conductivity	2586			Oct-07	
King Co	SBE29 - Pressure	362	Dec-04[1]			
King Co	SBE29 - Pressure	421		Oct-06		
King Co	SBE29 - Pressure	419			Oct-07	
King Co	C-Star Transmissometer	852PR	Oct-05		Dec-07	
King Co	C-Star Transmissometer	1000PR		Oct-06		
King Co	Wet Star Fluorometer	624P	Jan-05		Nov-07	
King Co	Wet Star Fluorometer	422P		Dec-06		
King Co	Licor (surface)	Q25276	Dec-05			
King Co	Licor (surface)	Q25960			Oct-07	
King Co	Licor (spherical)	SPQA 2496	Dec-05			
King Co	Licor (spherical)	SPQA 2806			Oct-07	
King Co	SBE43 - DO	677	May-05		Oct-07	
King Co	SBE43 - DO	737		Nov-06		Feb-08
UW	SBE3 - Temperature	2060	Dec-04[1]	Nov-06		Jan-08
UW	SBE4 - Conductivity	1824	Dec-04[1]	Nov-06		Feb-08
UW	SBE9+ - Pressure	57657	Jan-04	Nov-06	Jun-07	
UW	SBE43 - DO	537	Jun-05	Nov-06	Jul-07	Feb-08
UW	SBE43 - DO	518	May-05	Feb-06	Aug-07	
UW	SBE18 - pH	601	new[2]		Jun-07	
UW	C-Star Transmissometer	CST-400DR	Mar-05		Jul-07	
UW	C-Star Transmissometer	CST-539PR			Jan-07	
UW	Wet Star Fluorometer	FLRTD-199	Aug-04[1]	Nov-06		Mar-08
UW	Wet Star Fluorometer	FLRTD-230	Sep-04[1]		Oct-07	
UW	Biospherical PAR (underwater)	4173	Jun-04[1]	Nov-06		
UW	Biospherical PAR (surface)	QSR2200 - 20269	new[2]		Jan-07	
Ecology	SBE3 - Temperature	1329	Jun-05	Dec-06	Dec-07	Jan-08
Ecology	SBE4 - Conductivity	1068	Jun-05	Dec-06	Dec-07	Jan-08
Ecology	SBE29 - Pressure	153	Jun-05	Dec-06	Dec-07	Jan-08
Ecology	SBE43 - DO	445	Jun-05	Dec-06	Dec-07	Jan-08
Ecology	SBE18 - pH	577	new[2]	Aug-06	Sep-07	Jan-08
Ecology	C-Star Transmissometer	CST-645PR	Jul-05	Dec-06	Dec-07	Feb-08
Ecology	Wet Star Fluorometer	WS3S-941P	Jun-05	Dec-06	Dec-07	Feb-08
Ecology	LICOR (spherical)	1415	May-04[1]			May-08

[1]Sensor calibration performed >18 months before the start of the project (June 2006); no discernible drift effect on data.
[2]Sensor purchased after commencement of the project; not used prior to the initial calibration date. S/N – serial number

Appendix C. Marine Data

This appendix is available only electronically on the web, linked to the report at
www.ecy.wa.gov/biblio/0803037.html

Appendix D. Seabird Confirmation of Dissolved Oxygen Correction

From: David Murphy [mailto:dmurphy@seabird.com]
Sent: Friday, December 07, 2007 4:25 PM
To: Albertson, S. (Skip) (ECY); cjanzen@seabird.com
Cc: alberts@ocean.washington.edu; Pelletier, Greg (ECY); Maloy, Carol (ECY); Roberts, Mindy (ECY)
Subject: RE: Follow up on adjusting SBE43 DO sensors with Winkler data (fwd)

Hi Skip,

I recall that you got good results with this method when we corresponded about it previously. I think this is a good defensible approach to improving the quality of your data.

Since you have calculated oxygen before you bin the data you might incur a small error since there is no guarantee that average oxygen concentration will equal oxygen concentration calculated from the averages of sensor voltage, temperature, salinity and pressure. This would be a random error rather than a bias.

I would expect this error to be less than the uncertainties caused by sampling and titrating. Since you are using a regression to estimate new coefficients to correct oxygen the best measure will be the correlation coefficient. If you are getting a good "r" you will get a good correction.

I don't think it is advisable to do this on a cast by cast basis, where you would calculate an Soc and Voffset for each cast. If would be better to combine multiple casts taken over a reasonably short time. This will give you better statistics.

Another suggestion for validating this work is to chart your derived correction factors versus time. We do this for the reference sensors in our calibration lab. We expect Soc and Voffset to change slowly and in one direction.

Dave

David Murphy
R & D Manager, Seabird Electronics
Voice: 425 643 9866 ext 226
Fax: 425 643 9954

-----Original Message-----
From: Albertson, S. (Skip) (ECY) [mailto:salb461@ECY.WA.GOV]
Sent: Tuesday, December 04, 2007 6:50 PM
To: dmurphy@seabird.com; cjanzen@seabird.com
Cc: alberts@ocean.washington.edu; Pelletier, Greg (ECY); Maloy, Carol (ECY); Roberts, Mindy (ECY)
Subject: RE: Follow up on adjusting SBE43 DO sensors with Winkler data (fwd)

Hi Dave/Carol,

How are you? (Drying out from yesterday I hope).

I spoke with Mindy Roberts regarding her contact with you both at the recent ERF meeting in Providence concerning the pairing of Winkler DO results with bin-averaged data to make a regression (see method outlined below). We are very interested in doing this with our current project because of the massive number of (vertical) casts made with multiple CTDs from at least four different vessels (i.e., R/V Thompson (UW), R/V Barnes (UW), R/V Skookum (Ecology), and R/V Liberty (KCDNR)). Strictly following your Application Note 64-2 would mean re-processing a lot of data with new coefficients, while using the bin-average shortcut (if you deem it worthy) would mean that we could correct the data with update queries within our database. We understand the need to field-calibrate DO over a range of values, which is hard to achieve in a lab without special equipment, but feel this method is capable of achieving just that. The question really comes down to when it's acceptable to average the data, before or after working with it. Incidentally, we routinely use vertical bins of 0.5 m in Puget Sound. Do you think this would be acceptable?

Very best regards,

- Skip

-----Original Message-----
From: Albertson, S. (Skip) (ECY)
Sent: Monday, July 03, 2006 1:02 PM
To: 'dmurphy@seabird.com'
Cc: 'alberts@ocean.washington.edu'
Subject: RE: Follow up on adjusting SBE43 DO sensors with Winkler data (fwd)

Hi Dave,

I actually got better results applying your Application Note 64-2 to bin-averaged data (i.e., not reprocessing individual scans) than by using linear statistics methods (Eqn 3, below). I think that whatever nonlinearities are inherent in normalizing Winkler results by phi, that they offer an improvement that is worth taking.

You might want to amend your application note so that other users realize there is this option for improving bin-averaged DO data without reprocessing it.

Since the original determination of DO, DO1 is:

DO1 = Soc1 (V + Voff1) * phi Eqn 1

and the final determination of DO, DO2 is:

DO2 = Soc2 (V + Voff2) * phi Eqn 2

Where Soc2 and Voff2 are derived from graphs of Winkler/phi against SBE 43 raw voltage as described in Appendix A (Fig. 3). Since the voltage, V, remains the same both before and after the correction is determined, these equations can be combined and the improved estimate of DO (DO2) can be expressed in terms of only known variables:

DO2 = (Soc2 / Soc1) * DO1 + (Voff2 - Voff1) * phi Eqn 3

Where:
V = SBE 43 output voltage signal (volts)
T = CTD temperature (°C)
S = CTD salinity (psu)
P = CTD pressure (dbars)
Oxsat (T, S) = oxygen saturation (Ecology uses mg/l)

Best regards,

Skip Albertson

---------- Forwarded message ----------
Date: Fri, 2 Jun 2006 11:49:45 -0700
From: David Murphy <dmurphy@seabird.com>
To: 'Skip Albertson' <alberts@ocean.washington.edu>
Subject: RE: Follow up on adjusting SBE43 DO sensors with Winkler data

Hi Skip,

Sorry for the tardy reply. I have read your SOP and it looks fine to me. I suspect that if you compare option 1 with option 2 you will see very little difference in the results. The main difference in the 2 approaches is that number 2 moves the temperature and pressure correction terms to the independent side of the equation (the Winkler side). Considering that you are correcting a large CTD oxygen data set with a sparse Winkler data set I'll bet that the difference between the two methods will be negligible so I think you should do what ever is most convenient.

Regarding the bin average question, the oxygen calculation equation requires temperature, salinity, and sensor output voltage. The best calculation is made from data scans that contain these, rather than the average over an interval.

Dave

-----Original Message-----
From: Skip Albertson [mailto:alberts@ocean.washington.edu]
Sent: Thursday, June 01, 2006 10:33 AM
To: dmurphy@seabird.com
Subject: Follow up on adjusting SBE43 DO sensors with Winkler data

Hi Dave,

We'd be happy to try the new algorithm you offer on your website to re-calibrate our SBE43 DO sensor with Winkler titation data. That method, I believe, still requires re-processing the raw data once you have calculated the new coefficients, does it not?

I wondered if you had any more thoughts on our hope to adjust several years' worth of processed bin-averaged oxygen results with Winkler titration data? Hereafter we plan to use the method outlined in SeaBird Application Note 64-2 (based on Owens and Millard), but that (also) requires reprocessing the data with a new Soc and Voffset. What to do with the old data if we want to avoid reprocessing it?

There are three options:

1) Use standard stat methods (see our attached SOP; please feel free to review it!) to come up with a linear regression.

2) Use the bin-averaged data and solve for a new-improved DO (i.e., DO2) in terms of the slope and Voffset derived from the Winkler/phi vs SBE43 voltage curve (Soc2 and Voff2, respectively) and the variables we already know from the annual calibration (Soc1 and Voff1); DO1 and phi are either in the database (bin-averaged, of course) or can be calculated from the bin-averaged values of T & S):

DO2 = Soc2 [(DO1 / (phi * Soc1) - Voff1) + Voff2) * phi

This equation is a combination of:

DO1 = Soc1 (V + Voff1) * phi
DO2 = Soc2 (V + Voff2) * phi

The real question is what do we lose by using the bin-averaged data!

3) Do nothing.

I would rather do something!

Best regards,

Skip (Ecology)

Appendix E. Acoustic Doppler Current Profiler (ADCP) Results

This appendix is available only electronically on the web, linked to the report at www.ecy.wa.gov/biblio/0803037.html

Appendix F. Benthic Flux Results

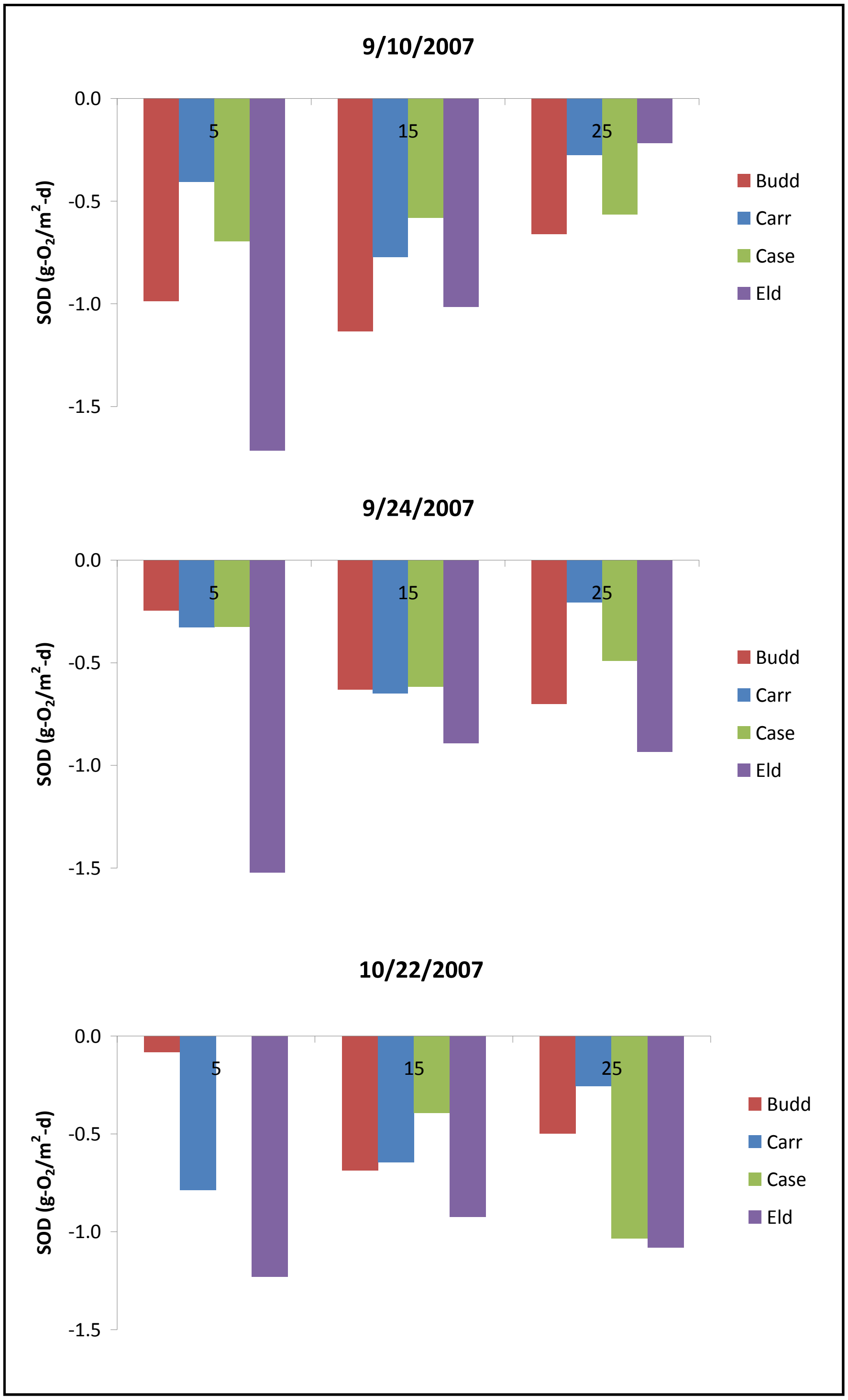

Figure F-1. Sediment oxygen demand (SOD) by inlet and depth (5, 15, 25 meters) for late summer 2007 benthic flux chambers.

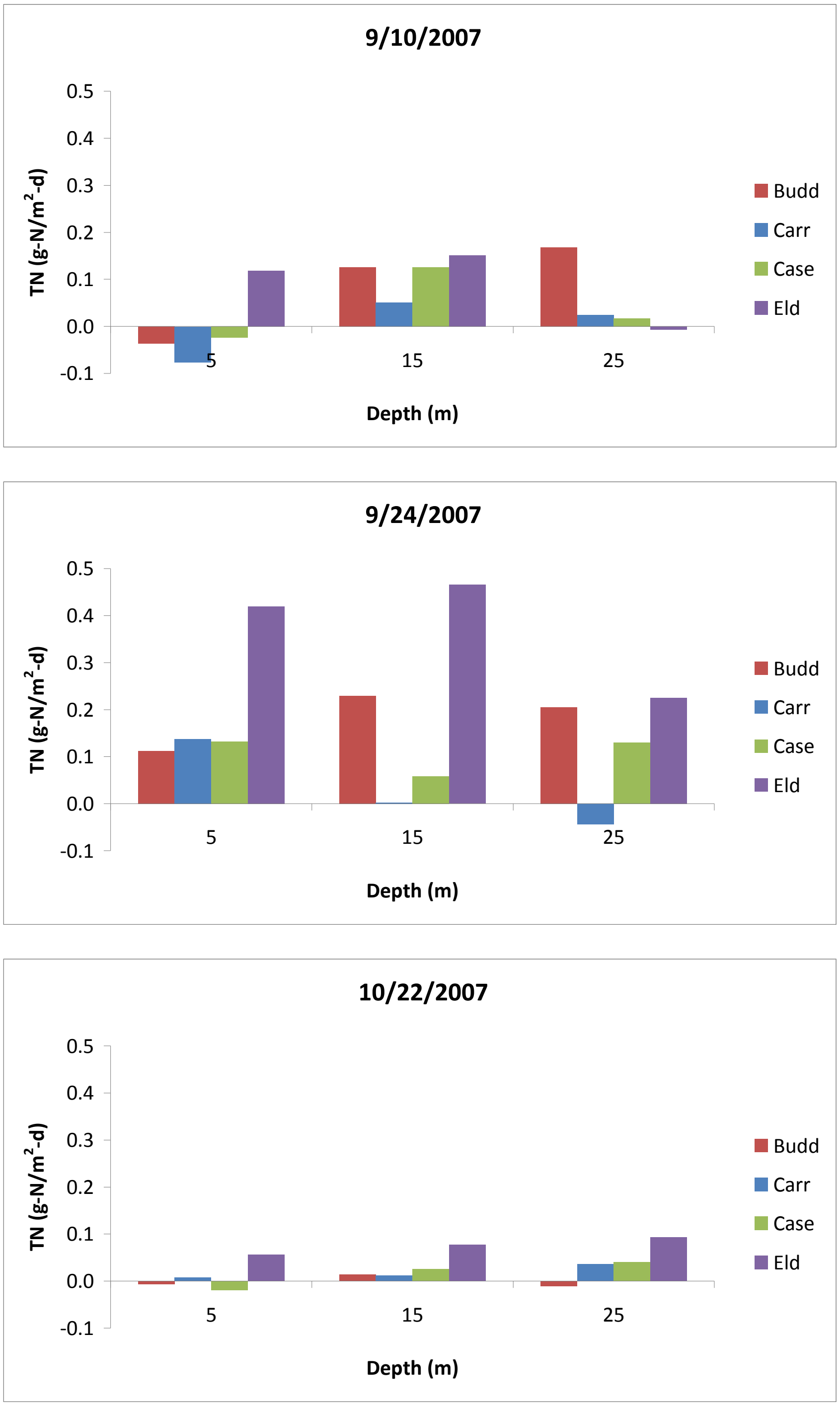

Figure F-2. Total nitrogen (TN) loads from sediments by inlet and depth for late summer 2007 benthic flux chambers.

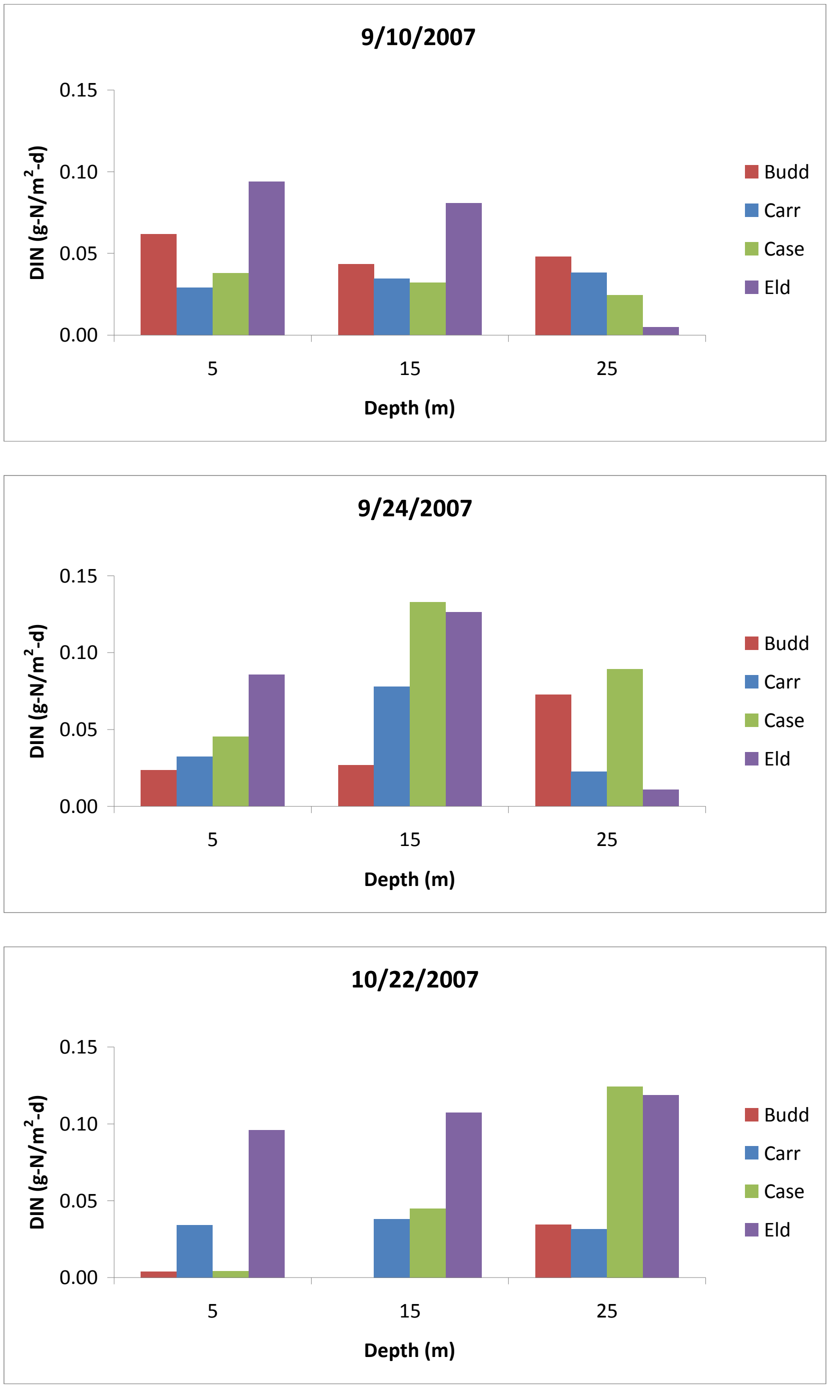

Figure F-3. Dissolved inorganic nitrogen (DIN) nitrogen loads from sediments by inlet and depth for late summer 2007 benthic flux chambers.

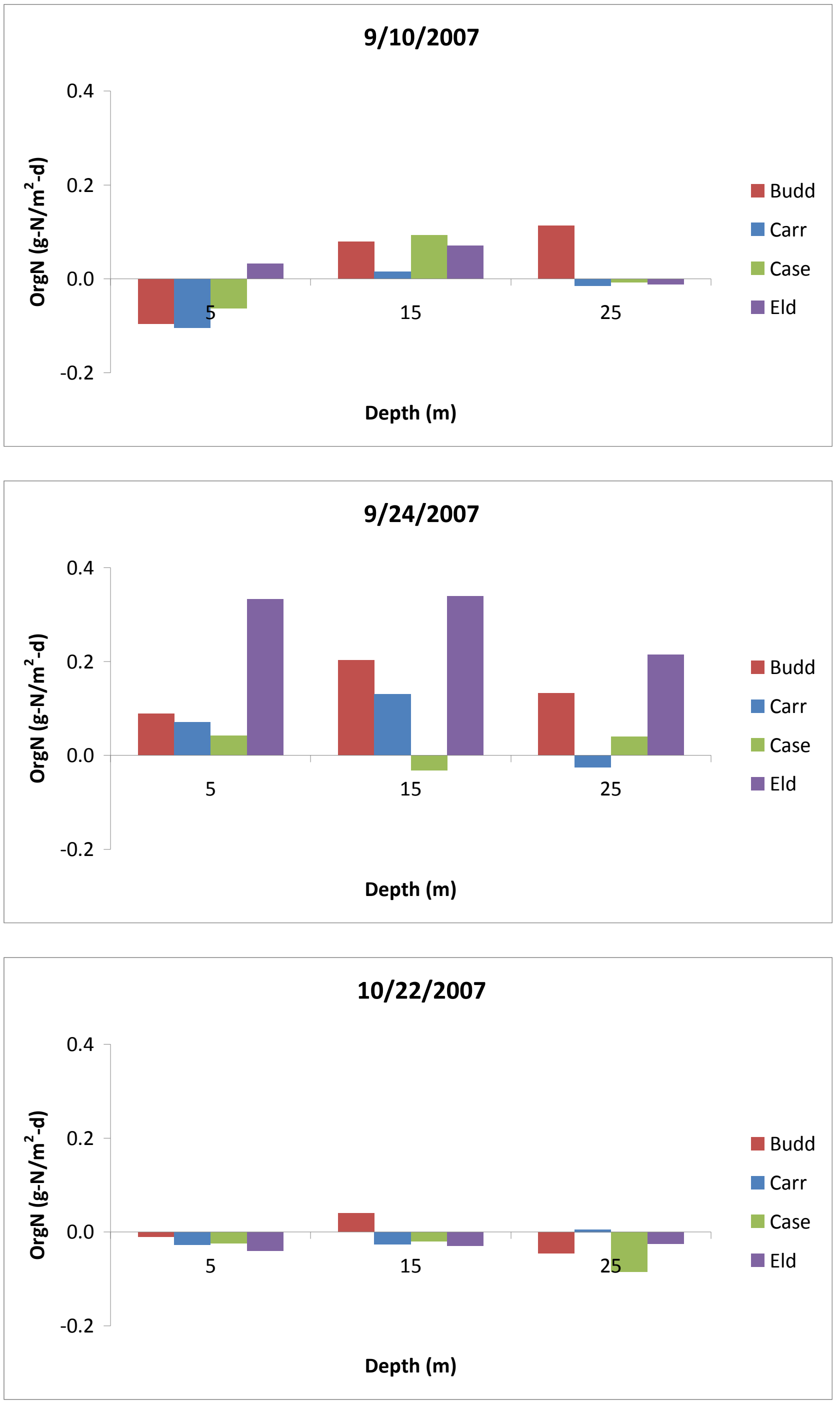

Figure F-4. Organic nitrogen (OrgN) nitrogen loads from sediments by inlet and depth for late summer 2007 benthic flux chambers.

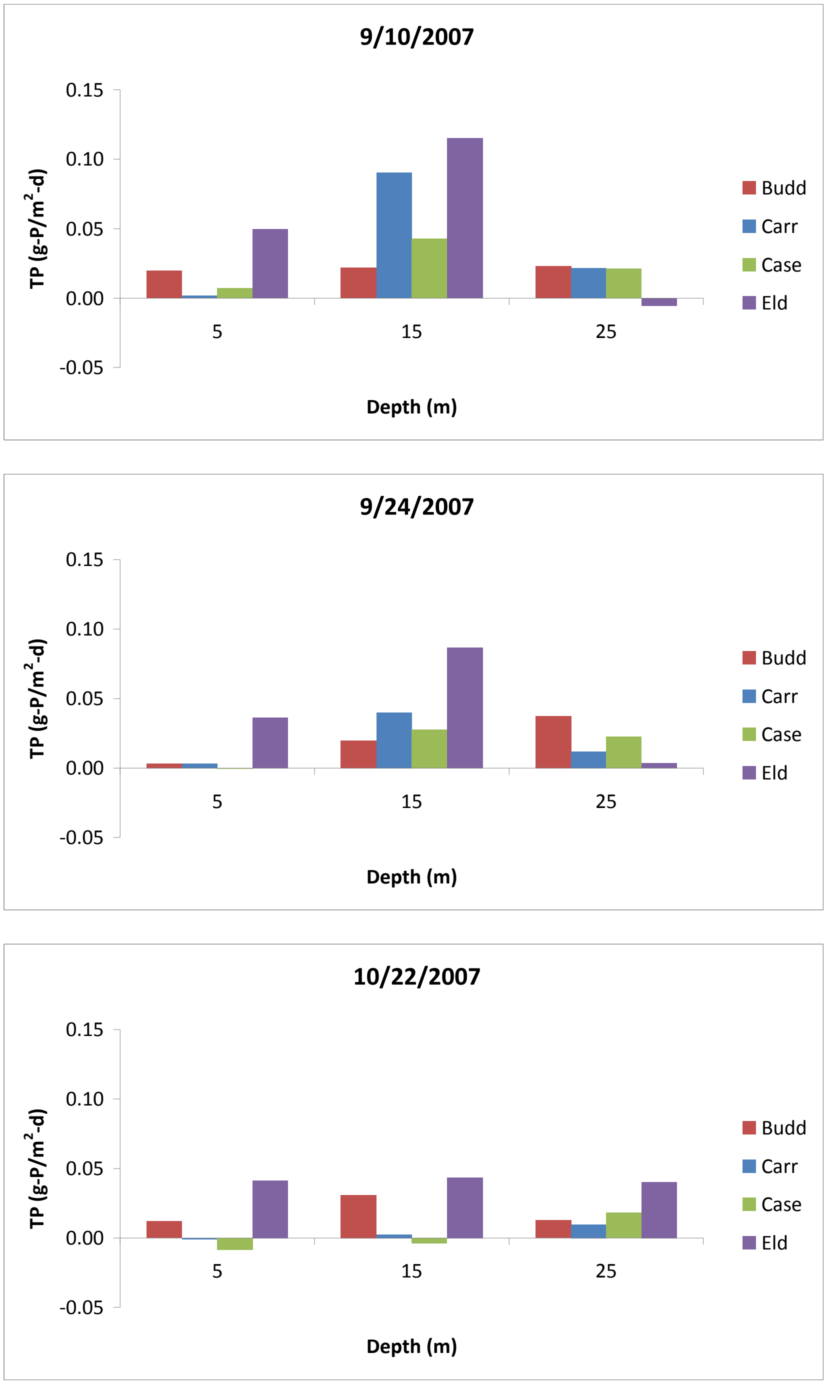

Figure F-5. Total phosphorus (TP) loads from sediments by inlet and depth for late summer 2007 benthic flux chambers.

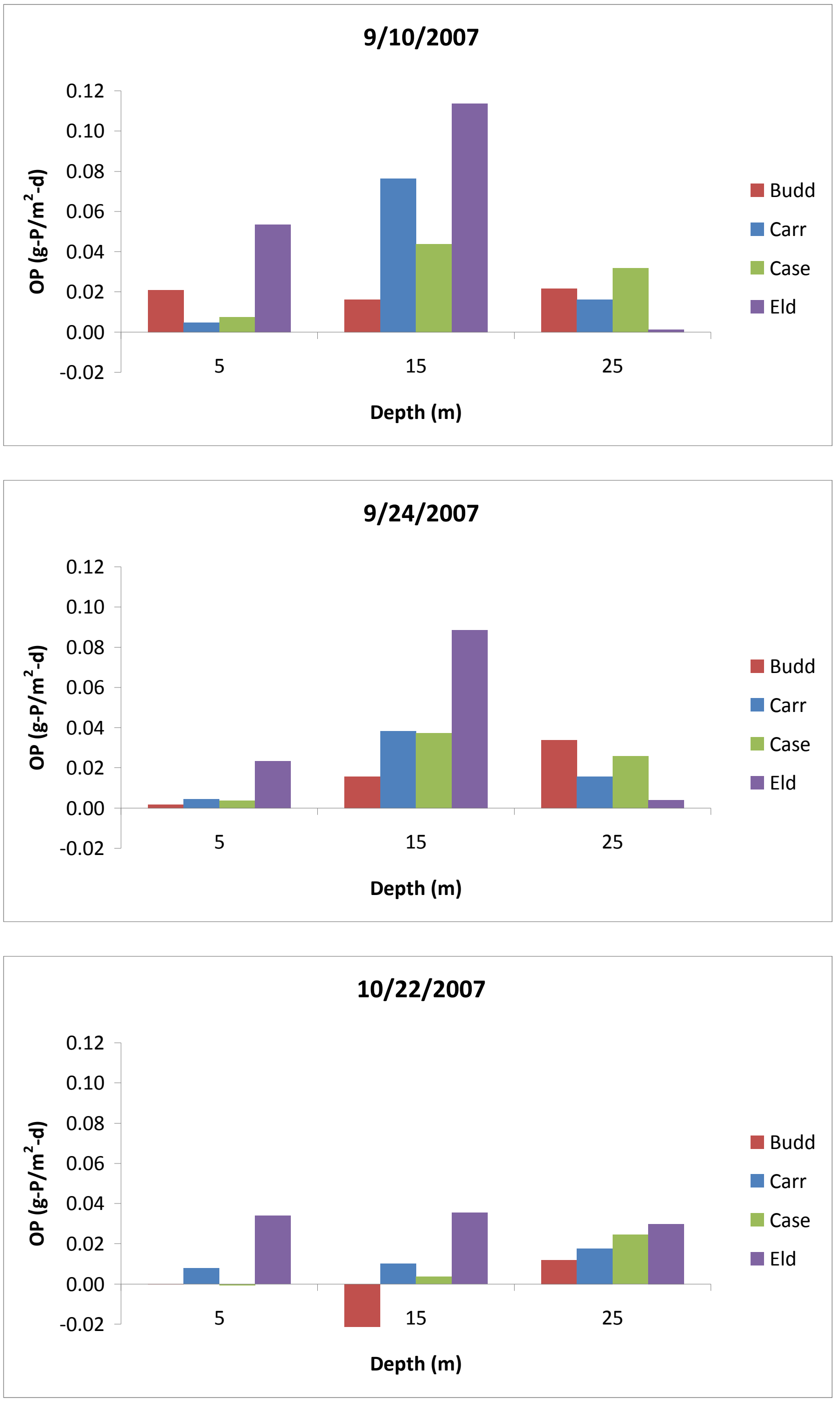

Figure F-6. Orthophosphate (OP) loads from sediments by inlet and depth for late summer 2007 benthic flux chambers.