Puget Sound Dissolved Oxygen Model

Interim Nutrient Load Summary for 1999-2008

DRAFT: June 23, 2011

Publication No. 10-03-0xx

DEPARTMENT OF
ECOLOGY
State of Washington

Publication and Contact Information

This report is available on the Department of Ecology's website at www.ecy.wa.gov/biblio/1103xxx.html

Data for this project are available at Ecology's Environmental Information Management (EIM) website www.ecy.wa.gov/eim/index.htm. Search User Study ID, MROB0004.

The Activity Tracker Code for this study is 06-509-01.

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

Cover graphic:
Map showing Puget Sound and the Straits of Georgia and Juan de Fuca, which make up the study area for this study.

Puget Sound Dissolved Oxygen Model

Interim Nutrient Load Summary for 1999-2008

by

Teizeen Mohamedali, Mindy Roberts, and Brandon Sackmann
Environmental Assessment Program

and

Andrew Kolosseus
Water Quality Program

Washington State Department of Ecology
Olympia, Washington 98504-7710

This page is purposely left blank

Table of Contents

List of Figures

List of Tables

This page is purposely left blank

Abstract

Nutrient loads, particularly nitrogen, have been identified as a potential stressor to the Puget Sound ecosystem. One consequence of excessive nutrient loads may be low dissolved oxygen (DO) concentrations. Field data have shown that portions of Puget Sound fall below Washington State water quality standards for DO. In order to understand the underlying dynamics that result in low DO concentrations, the Washington State Department of Ecology has initiated a study to identify nutrient loads as a first step to determine whether human sources of nitrogen contribute to low levels of dissolved oxygen.

The study also involves the development of a hydrodynamic and water quality model of the entire Puget Sound estuary system to further our understanding of processes that affect DO. The main goals of this project are to (1) understand the behavior of Puget Sound under current and future conditions based on hydrodynamic and water quality modeling of Puget Sound and (2) determine the influence of human nutrient inputs on low DO levels relative to natural contributors (Sackmann, 2009). If humans are contributing significantly to low levels of DO in Puget Sound, then subsequent phases would evaluate the level of nutrient reductions necessary to improve DO concentrations in Puget Sound.

This report presents the results of an effort to quantify the magnitudes and sources of nitrogen loading into Puget Sound. Rivers and WWTPs are both significant sources of nitrogen, particularly dissolved inorganic nitrogen (DIN; sum of ammonium and nitrate + nitrite). DIN concentrations in WWTP effluent are generally higher than concentrations in rivers; however, river flow volumes are generally higher than WWTP discharge volumes. The ratio of WWTP and river DIN loads varies in different regions of Puget Sound and at different times of the year. Overall, river DIN loads are slightly greater than WWTP DIN loads on an average annual basis, while WWTP loads are slightly greater in the summer when streamflows are much lower. When natural loads are subtracted from total current loads, point sources of DIN within the U.S. are almost three times greater than human non-point sources.

On-going modeling efforts will take into account other variables that influence this dynamic ecosystem, allowing us to assess whether human sources of nutrients impact water quality.

Acknowledgements

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

- Many staff members of the wastewater treatment plants (WWTPs) discharging to South and Central Puget Sound provided assistance in collecting samples as part of the South Puget Sound Dissolved Oxygen Study, as well as reviewed and provided us with data for their plants. This information provided the basis for wastewater treatment plant load estimates throughout Puget Sound and the U.S. waters of the Salish Sea.

- Washington State Department of Ecology staff collected information under the separate South Puget Sound Dissolved Oxygen Study that was used as a basis for load analyses in this report:
  - Karen Burgess (Northwest Regional Office) and Greg Zentner (Southwest Regional Office) managed communications with the WWTPs through the permit writers (Mahbub Alam, Mike Dawda, Dave Dougherty, Alison Evans, Bernard Jones, Tonya Lane), and Marc Heffner provided input regarding the Simpson industrial discharge.
  - Chuck Hoffman analyzed and performed WWTP regressions.
  - Ryan McEliece, Chris Moore, and Brandon Slone conducted all freshwater monitoring, including coordinating with WWTP staff for composite sample collection.
  - Steve Golding helped develop the South and Central Puget Sound WWTP monitoring program.
  - Dave Hallock and Bill Ward performed supplemental freshwater monitoring

Executive Summary

Introduction

Portions of Puget Sound have low dissolved oxygen (DO) levels that fall below Washington State water quality numeric criteria. Low DO levels impair the ability of marine life to survive or thrive, and can affect the healthy functioning of the Puget Sound ecosystem. DO levels decrease when significant quantities of nitrogen enter Puget Sound and stimulate extensive algae growth. When these algae bloom and die, the decomposition process uses up DO in the bottom waters, decreasing DO levels.

To help us understand the processes that affect DO levels, the Washington State Department of Ecology is developing an intermediate-scale mathematical model for the entire Puget Sound estuary system including the Straits of Georgia (SOG) and Juan de Fuca (SJF). The study focuses on Puget Sound and its tributary watersheds south of Deception Pass, including Admiralty Inlet, Whidbey Basin, Hood Canal, and Central and South Puget Sound. The model boundary also extends into Canada past the Fraser River since these regions define important boundary conditions and nutrient loading into Canadian waters may influence Puget Sound water quality (Figure ES-1).

In order to simulate water quality in Puget Sound, the model requires information about nutrient loading into Puget Sound from a variety of sources. This report specifically focuses on nutrient loading estimates from rivers and wastewater treatment plants discharging into Puget Sound during the ten-year period from 1999 to 2008.

The main goals of this project are to (1) understand the behavior of Puget Sound under current and future conditions based on hydrodynamic and water quality modeling of Puget Sound and (2) determine the influence of human nutrient inputs on low dissolved oxygen (DO) levels relative to natural contributors (Sackmann, 2009). Ongoing modeling efforts will show if human-related sources of nitrogen need to be reduced to protect water quality. The modeling will also be used to assess alternative management scenarios.

In this report, ―Puget Sound” refers the marine waters of the study area south of Deception Pass, while the ―Straits” refers to marine waters of the study area north and west of Deception Pass predominantly covered by the Strait of Georgia (SOG) and the Strait of Juan de Fuca (SJF). The Straits extend into both U.S. and Canadian waterways, and in some cases, specific references will be made in figures and plots to either the U.S. or Canadian portions of the Straits as Straits (U.S.) and Straits (Canada), respectively.

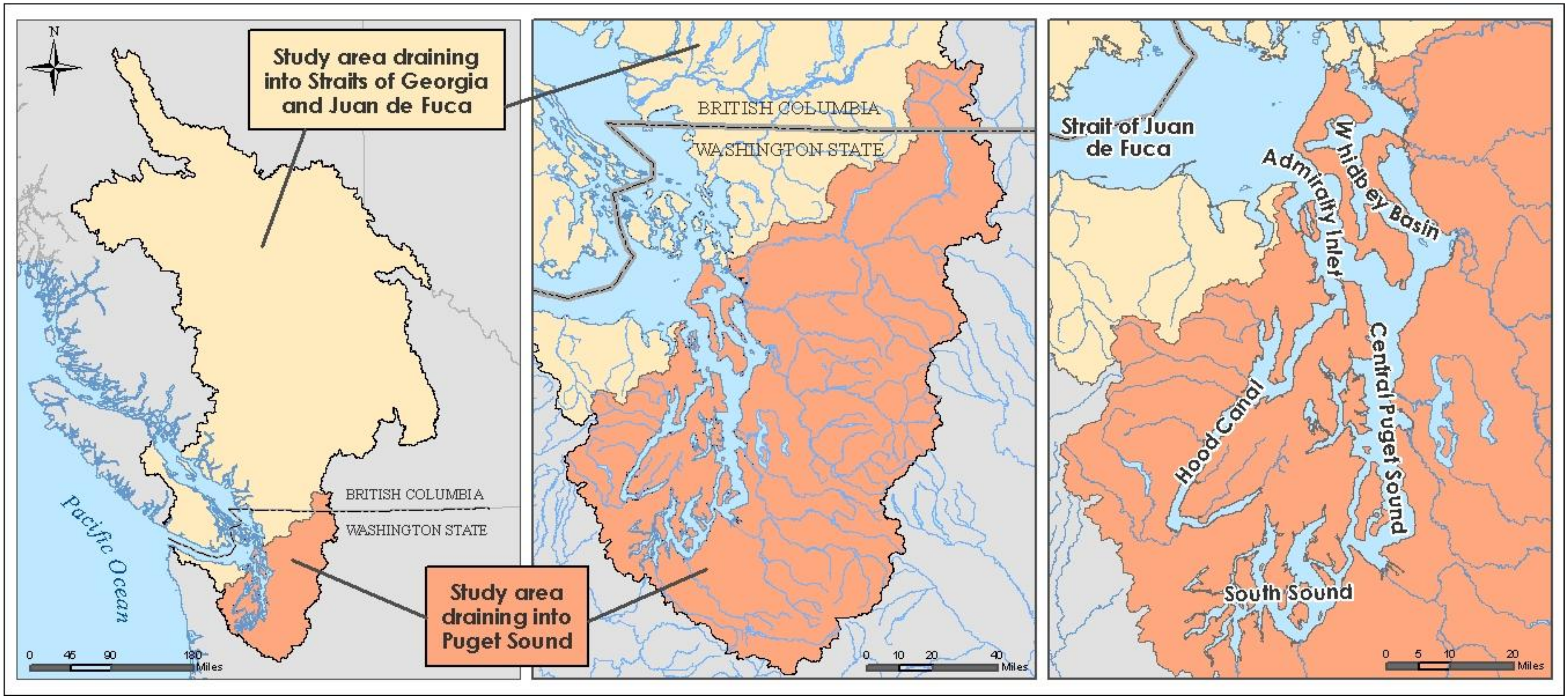

Figure ES-1. Study area for the Puget Sound Dissolved Oxygen Model Study. The primary area of interest includes the watersheds that drain into Puget Sound, but watersheds that drain into the Straits are also included.

Methods

We estimated nutrient loads to Puget Sound and the Straits from both watersheds as well as WWTPs from 1999-2008. Nutrient loads were estimated from monitoring data, where available. However, available data did not span the entire time period of interest, and did not provide us with the temporal resolution needed by the model to simulate seasonal and sub-seasonal variations in Puget Sound.

This report specifically describes the development of daily nutrient loading estimates from the monthly field monitoring data, and presents these loading estimates. A multiple linear regression method was applied to the field data to develop continuous daily concentrations and loads of nutrients for calendar years 1998 through 2008. This method relates concentrations to flow and time of year using a best fit to monitoring data, but may not capture trends in concentration unrelated to trends in flow. The resulting daily loads provide a better fit to monitoring data than simply using monthly or annual averages. The same method was used by Mohamedali et. al. (2011), where we found that regression-derived estimates compared relatively well with field data.

Continuous daily nutrient load data are not only needed for the calibration and validation of the hydrodynamic and water quality model, but these data also provide us with a more comprehensive understanding of nutrient loads. The development of daily nutrient data allows us to quantify the relative magnitude of nutrient loads from rivers and WWTPs, describe the seasonal nature of these loads, and compare loads going into different regions of Puget Sound and the Straits.

This report primarily focuses on, and presents nitrogen load summaries from WWTPs and rivers, and also explores the relative contribution of loads from groundwater, on-site septic systems and the atmosphere. However, in addition to these sources of nitrogen, the water quality model will also include nitrogen loading from the ocean and internal sediment fluxes. This will allow us to analyze the effect of all these sources on DO levels.

In addition to estimating nutrient concentrations and loads for 1998-2008, we also calculated natural (i.e., no human influence) nutrient concentrations and loads for inflows into Puget Sound and the Straits. Natural conditions in this study refer to the concentrations of nutrients in rivers and streams without significant human influences/sources of nutrients. By definition, there would be no WWTP or septic system inputs into Puget Sound and the Straits under natural conditions. Once these concentrations are established, they can be used as inputs into the water quality model so that we can evaluate the water quality of Puget Sound under natural conditions.

Natural conditions were established from the results of a meta-analysis where we considered concentration data from various sources: ambient monitoring data, rainfall data, and data from other studies. Monthly 10^{th} percentiles of ambient data were used to represent natural nutrient concentrations for different regions in Puget Sound and the Straits.

Results and Discussion

Of all the forms of nitrogen, dissolved inorganic nitrogen (DIN; sum of nitrate+ nitrite and ammonium) is of greatest interest since this form of nitrogen is required by marine algae. Figure ES-2 compares median DIN concentrations in rivers and WWTPs discharging directly into Puget Sound and the Straits between 1999 and 2008. River DIN concentrations reflect all upstream point (discrete) and nonpoint (diffuse) sources that discharge into these rivers.

The highest DIN concentrations are found in watersheds that drain into South and Central Puget Sound as well as watersheds that drain into the waters north of Whidbey Basin. Low DIN concentrations are found in watersheds which drain the Olympic Peninsula to either the Strait of Juan de Fuca or Hood Canal. DIN concentrations in WWTP effluent are one to two magnitudes higher than concentrations in rivers, with the highest concentrations found in the effluent of the Carlyon, Lakota, Central Kitsap and South King WWTPs.

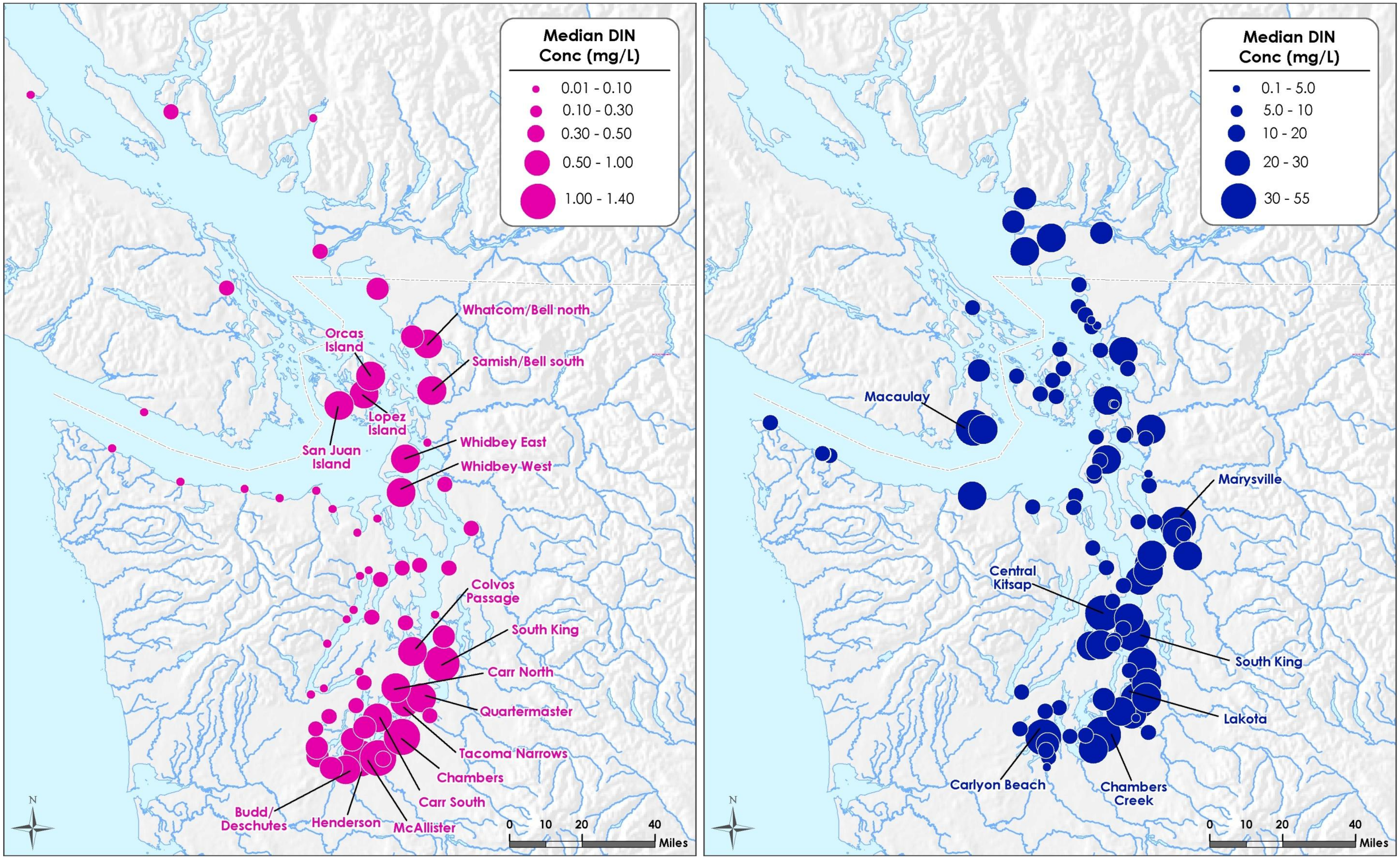

Figure ES-2. Median river (left) and WWTP (right) dissolved inorganic nitrogen (DIN) concentrations for 1999 to 2008. Different scales illustrate relative concentrations by source.

Even though DIN concentrations, as shown in Figure ES-2, are useful in identifying nutrient hotspots, high and low DIN concentrations do not always translate into high and low DIN loads. For example, a river with low DIN *concentration* might still have a high DIN *load* (where load = concentration x streamflow) if that particular river is large and subsequently has very high streamflows. Therefore, rivers and WWTP effluents with the highest DIN concentrations do not necessarily have the highest DIN loads. To facilitate comparison, we also calculated loads for all rivers and WWTPs.

DIN loads from rivers and streams are comparable to loads from WWTPs on an annual average basis (Figure ES-3). Wastewater in Canadian WWTPs generally undergoes a lower level of treatment than those in the U.S. Figure ES-3 shows that loads from Canadian facilities are relatively large, but comparable to the West Point and South King WWTPs, the two plants that have the largest DIN loads of all U.S. WWTPs.

The Fraser River contributes, by far, the largest river load in the whole study area since it drains a significant portion of western Canada, and has considerably higher streamflows than other rivers in the study area. However, if we only look at the rivers in the U.S., the five rivers with the largest loads are, in order, the Snohomish, Skagit, Nooksack, Stillaguamish and Puyallup, which together contribute 18,890 kg/d of DIN, which is 65% of the average annual DIN load from all U.S. rivers in the study area.

In the main basin of Puget Sound (between Edmonds and Tacoma Narrows), WWTP loads dominate. This is because there are a larger number of WWTPs serving large populations in the main basin. West Point and South King WWTPs are the two largest point-sources of DIN, together contributing 56% of the average annual DIN load from all U.S. WWTPs in the study area. The load from these two WWTPs totals 19,320 kg/d, which is comparable to the total DIN load from the five U.S. rivers with the highest DIN loads.

DIN loads from WWTPs dominate in the summer (average of July, August and September), which is a critical time for DO conditions (Figure ES-4). During this time, river loads are lower because of lower flows.

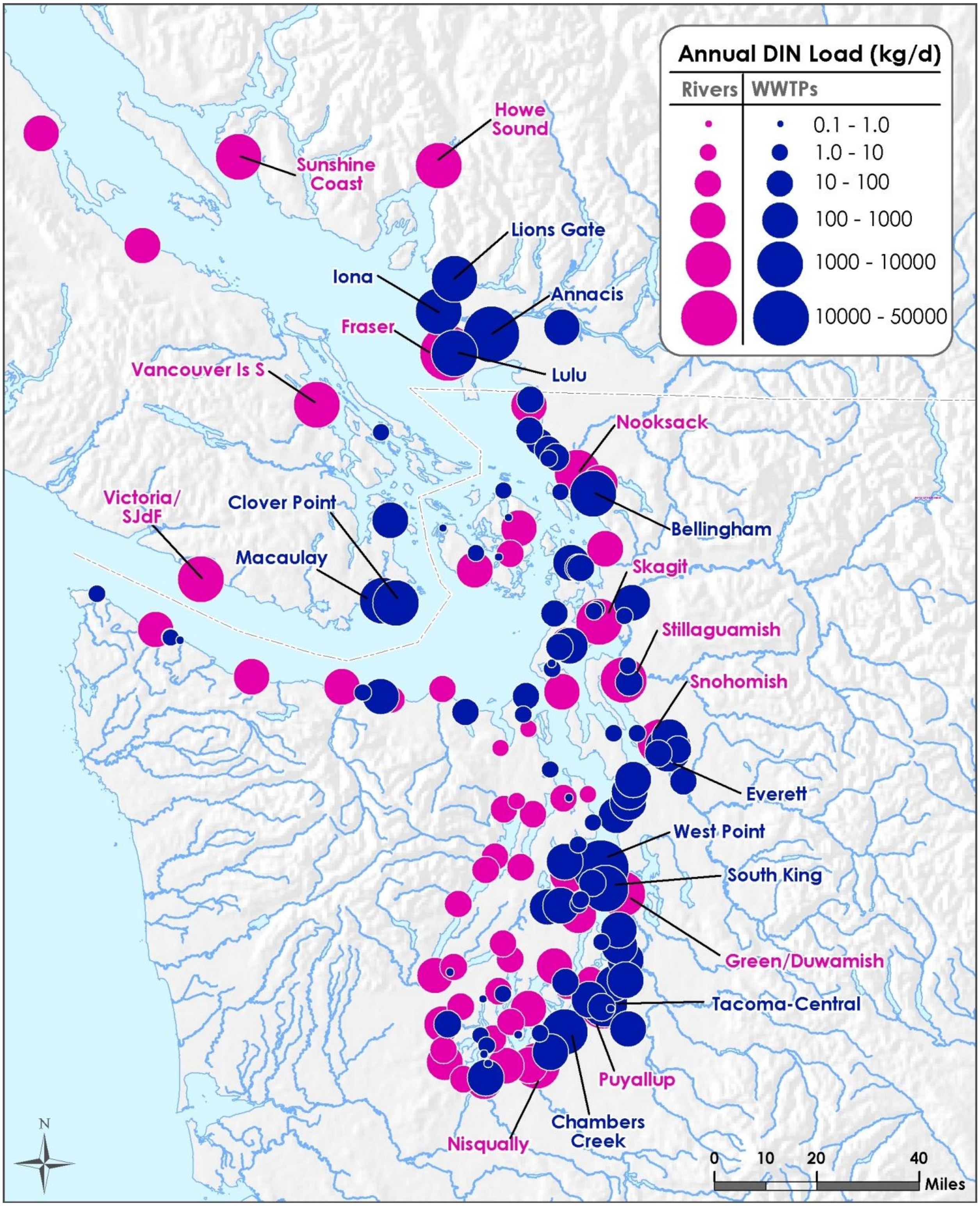

Figure ES-3. Mean annual dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs for 1999 to 2008.

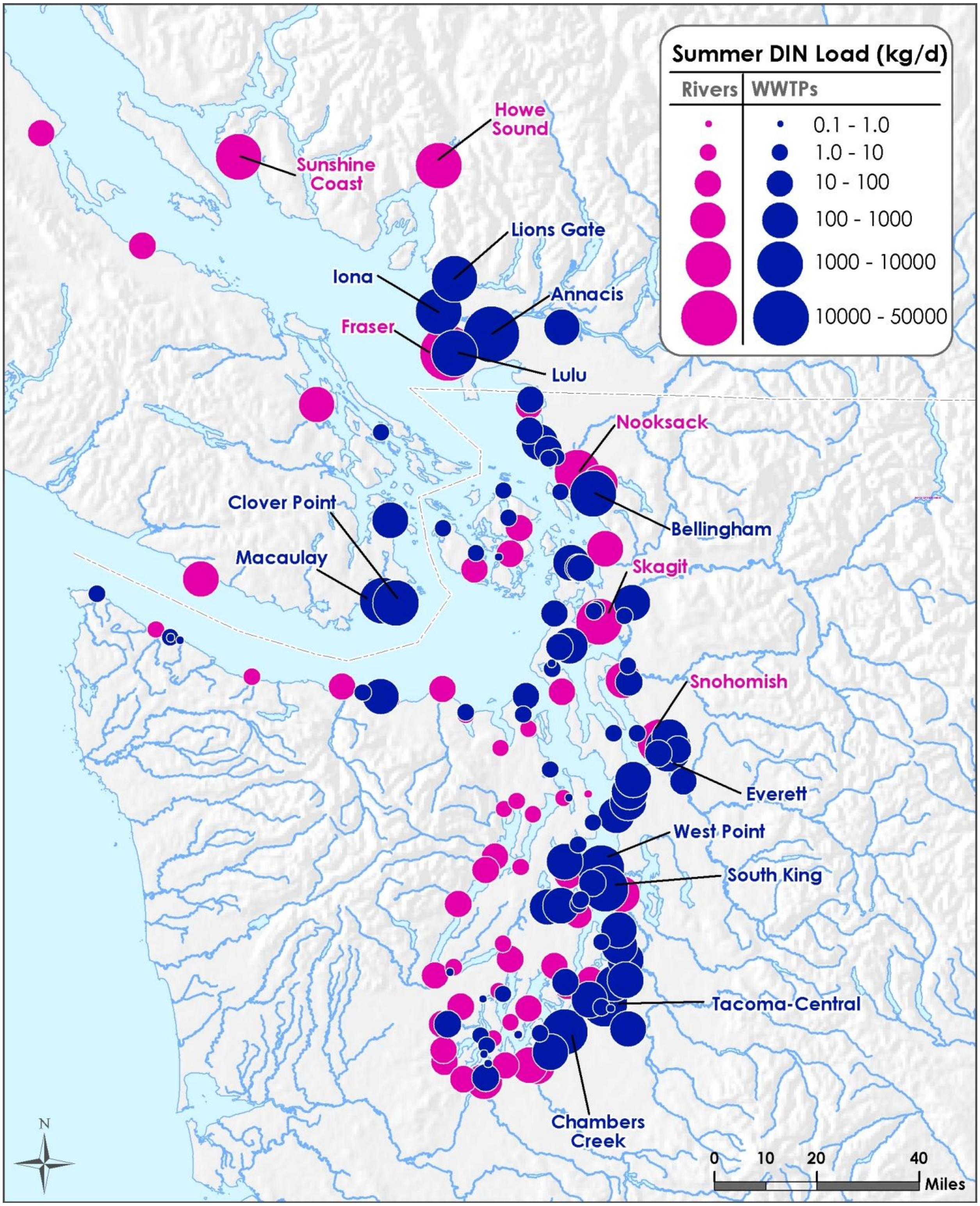

Figure ES-4. Mean summer dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs for 1999 to 2008.

Over the 10-year period from 1998-2008, there is no noticeable increasing or decreasing trend in overall DIN loads, though trends in individual rivers and WWTPs may exist (Figure ES-5). Monthly river DIN loads are more variable than monthly WWTP DIN loads since river loads reflect variability in river flows, which change with seasons. The seasonal patterns in river DIN loads are different for rivers in Puget Sound and rivers in Canada. Rivers in Puget Sound experience high flows during the wetter months of November through April. In Canada, rivers show higher loads between May and July predominantly because of the Fraser River‘s snowmelt and flow-control pattern during the summer months.

Monthly average DIN loads (rivers plus WWTPs) into Puget Sound waters and the Straits range from approximately 80 – 180 metric tons/day. On average, rivers draining directly into Puget Sound waters contribute 32% of the total river loads into Puget Sound and the Straits, while WWTPs discharging directly into Puget Sound contribute 52% of the total WWTP loads into Puget Sound and the Straits.

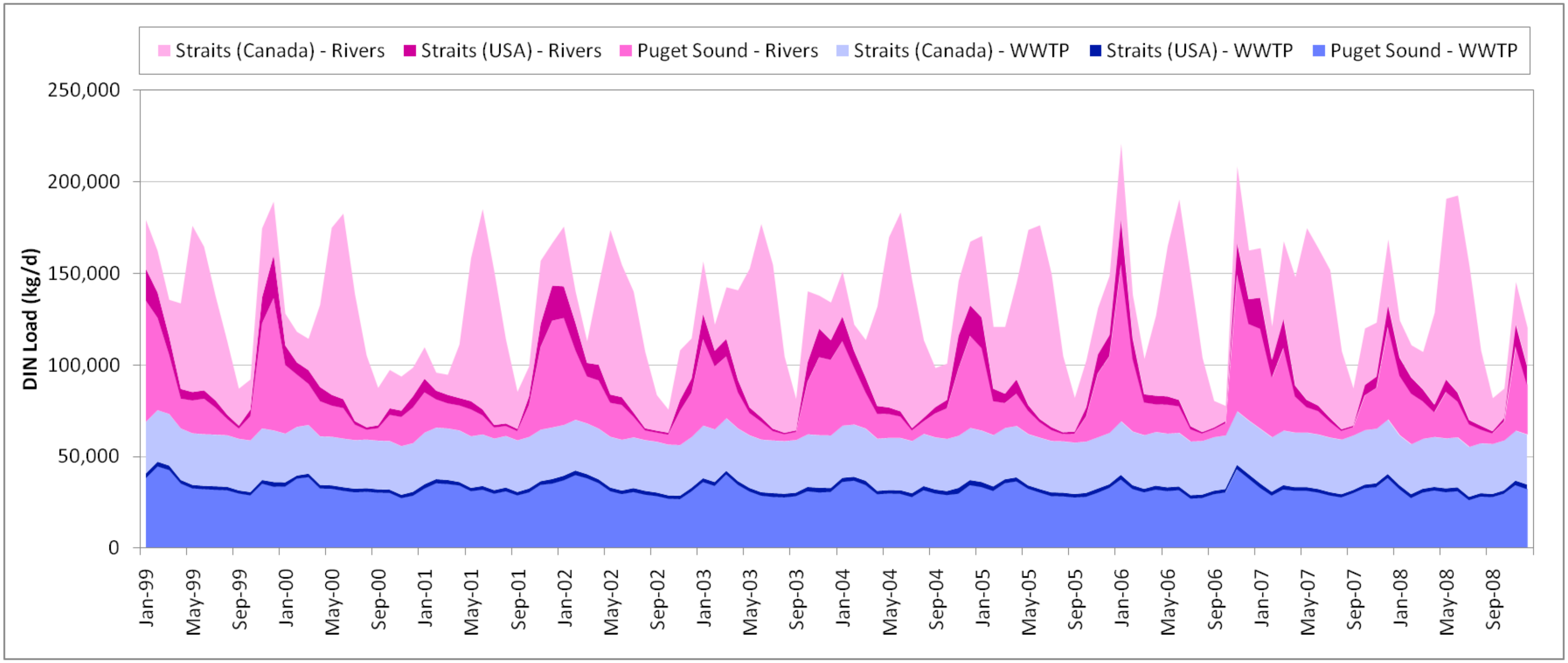

Figure ES-5. Monthly dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into Puget Sound and the Straits during 1999-2008.

In Puget Sound, rivers contribute slightly lower DIN loads (41%) than WWTPs (59%) on an annual bases (Figure E-6, top). However, WWTP loads dominate (81%) during the summer months when rivers loads are low due to lower flows. In the Straits, river DIN loads contribute 62% of the DIN load on an annual basis and 61% during the summer (Figure E-6, middle).

When loads from all sources into both Puget Sound and the Straits are combined, river DIN load contributions (54%) are slightly greater than those from WWTPs (46%) on an annual basis. The ratio of river to WWTP load flips during the summer, when rivers contribute 48% of the load and WWTPs contribute 52% of the load (Figure E-6, bottom).

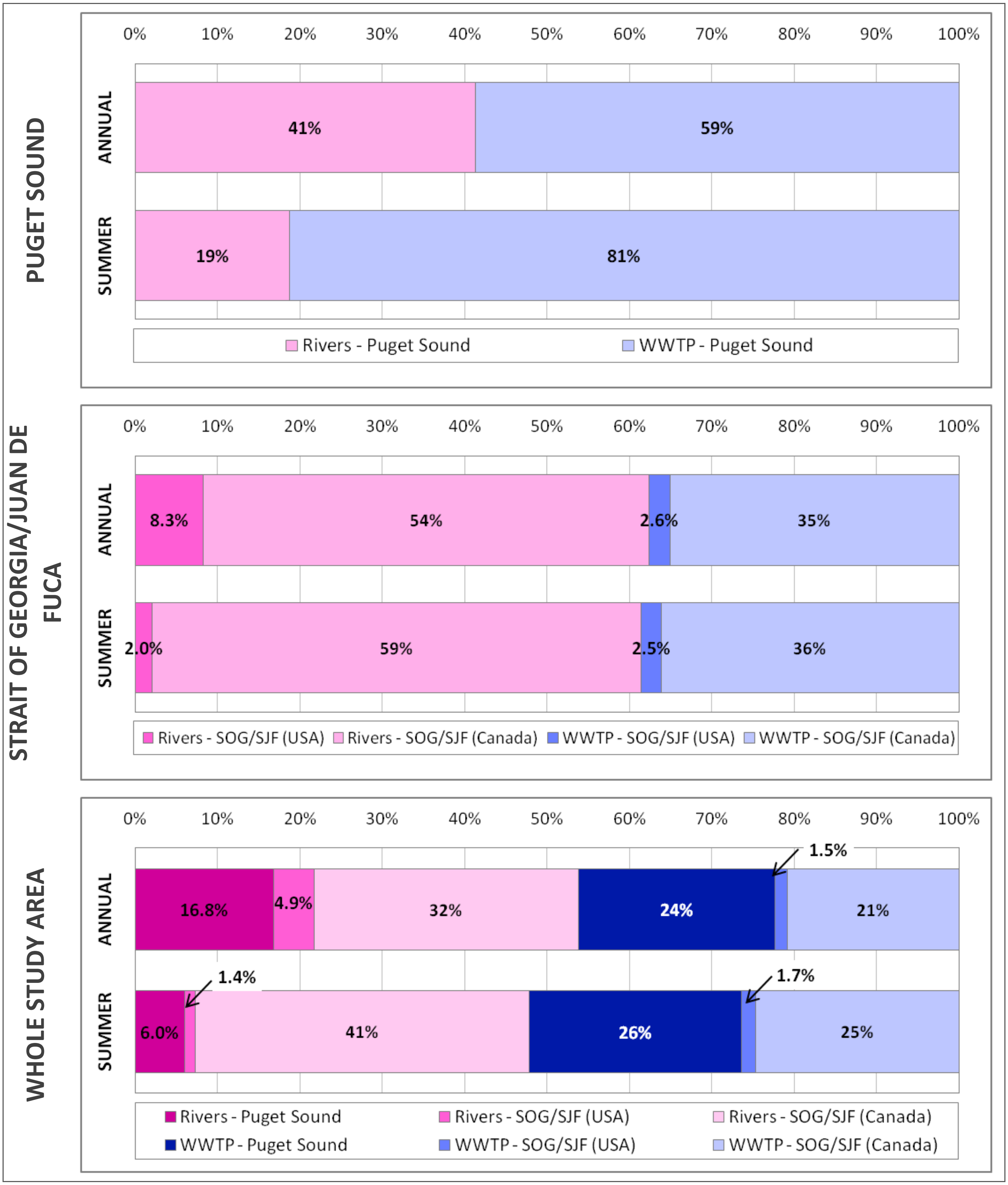

Figure E-6. Bar charts comparing the relative contributions of dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into Puget Sound and the Straits on an annual basis and during the summers of 1999-2008.

Overall, DIN loads from rivers and WWTPs in Canada are 12% greater than DIN loads from U.S. rivers and WWTPs, contributing to 53% of the total DIN load into Puget Sound and the Straits (Figure E-7).

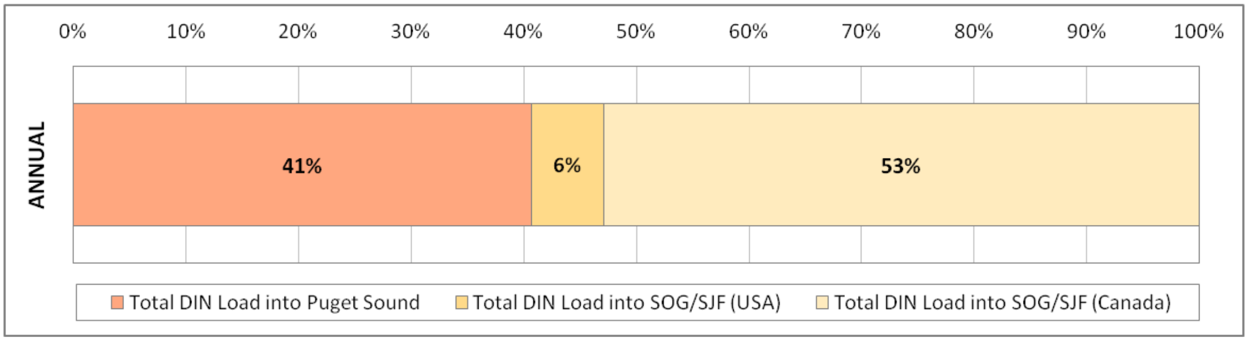

Figure E-7. Annual dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into Puget Sound and the U.S. and Canadian portions of the Strait of Georgia/Juan de Fuca (SOG/SJF).

When we include the DIN load from atmospheric deposition onto the surface waters of Puget Sound and the Straits, we see that this constitutes only 4% of the total DIN load (Figure ES-8)[1].

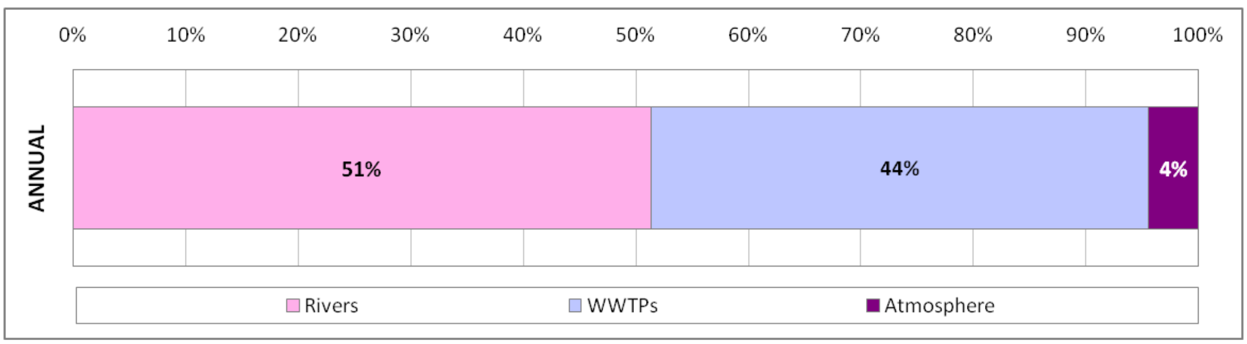

Figure ES-8. Annual dissolved inorganic nitrogen (DIN) loads from rivers, WWTPs, and the atmosphere into Puget Sound and the U.S. and Canadian portions of the Strait of Georgia/Juan de Fuca (SOG/SJF).

Loads from on-site septic systems and groundwater are included in the 'Rivers' share of the bar chart.

Oceanic loads will be calculated as part of the modeling effort and are not specified using the same method as that used for wastewater treatment plant or river loads. The loads in and out of the model at the Strait of Juan de Fuca boundary, as well as the net effect, will be calculated once the model is calibrated and applied to a series of scenarios.

[1] This atmospheric load refers to nitrogen loading from the atmosphere deposited directly onto the marine surface water. It is distinct from the atmospheric load received by terrestrial portions of the study area, which we include in the watershed loads.

The Impact of Nitrogen Loading

Though the magnitude of sources of nitrogen is important, several other factors also play a role in determining the effect of these loads on DO concentrations in the marine water. The time, location, and depth of the discharge are all important due to seasonal and circulation patterns in Puget Sound and the Straits. Other important factors that determine DO concentrations are temperature, sunlight, incoming oceanic water, and other environmental variables.

The water quality model will account for these different variables in evaluating the impact of nutrient loads on DO concentrations in Puget Sound. The modeling will also allow us to assess, for example, what fraction of loads entering the Straits eventually circulate south into Puget Sound, and whether these loads affect DO levels. The loading results presented here provide valuable information, but prior to modeling cannot be used to calculate the impact of the different sources of nitrogen on DO concentrations.

Natural Conditions

We also calculated natural nutrient concentrations, which includes the concentrations and loads of nutrients in rivers and streams that drain into Puget Sound and the Straits in the absence of human sources of nitrogen. Since historic water quality data are not available from pre-development times, we had to use more current ambient data as well as atmospheric (rainfall) data to calculate natural conditions. We did not calculate natural conditions for Canadian sources because of limited data.

Concentration patterns varied spatially across rivers different regions of Puget Sound. Seasonal variations were also noticeable, with lower river concentration in the summer when productivity is high, and higher concentrations in the wetter winter months. To reflect both spatial variations and seasonal variations in in-stream nutrient processes, we calculated the natural condition concentration as the minimum of either (1) the monthly 10^{th} percentile of recent ambient data from large rivers or (2) the monthly median from nearby atmospheric data collected at stations managed by the National Atmospheric Deposition Program (NADP).

Table ES-1 compares natural condition DIN load contributions to both human non-point and point sources into different regions of Puget Sound and the Straits. The difference between human and natural loads reflects the influence of anthropogenic sources of nutrients, including changes in land use and development, increases in population, and loads from WWTPs.

The difference between 1999-2008 loads and natural loads reflects the influence of anthropogenic sources of nutrients, including changes in land use and development, increases in population, and loads from upstream WWTPs discharging to rivers.

Total point sources (WWTPs) into Puget Sound and the Straits (34,200 kg/d) contribute almost three times as much as human non-point sources (11,800 kg/d). In Puget Sound, human sources of DIN (both point and non-point) are 180% higher than natural loads, while in the Straits, they are 100% higher. The magnitude of human DIN loads entering Puget Sound waters varies spatially, with the largest human contributions entering the main basin of Puget Sound (Puget Main). This human DIN load to Puget Sound is almost entirely from WWTPs.

Table ES-1. Comparison of natural and 1998-2008 average annual DIN loads from rivers and WWTPs into the Puget Sound and the Straits.

	Average Annual DIN Load (kg/d)			
	Natural Conditions	**Human Non-Point Sources (in rivers)[1]**	**Human Point Sources (WWTPs)[2]**	**Total Human**
South Sound	2,000	2,120	2,540	4,660
Commencement Bay	1,190	920	2,440	3,360
Elliott Bay	840	800	0	800
Puget Main	810	30	22,700	22,730
Sinclair Dyes Inlet	130	100	1,010	1,110
Whidbey	9,090	3,660	3,470	7,130
Admiralty	20	110	40	150
Hood Canal	440	370	1	371
Strait of Juan de Fuca	280	200	310	510
Strait of Georgia	2,630	3,510	1,760	5,270
Puget Sound Subtotal[3]	**14,500**	**8,100**	**32,200**	**40,300**
Straits (US) Subtotal[3]	**2,900**	**3,700**	**2,100**	**5,800**
Total[3]	**17,400**	**11,800**	**34,300**	**46,100**

[1] Human non-point sources = (1999-2008 annual average river loads) – (natural condition loads)

[2] Human point sources = 1999-2008 annual average WWTP loads

[3] These totals have been rounded to the nearest 100 kg/d

The proportion of current loads that are from human point and non-point sources is 73% in Puget Sound and 67% in the Straits. Human activity, such as changes in land use and development and growing population, has increased DIN loads (Figure ES-8).

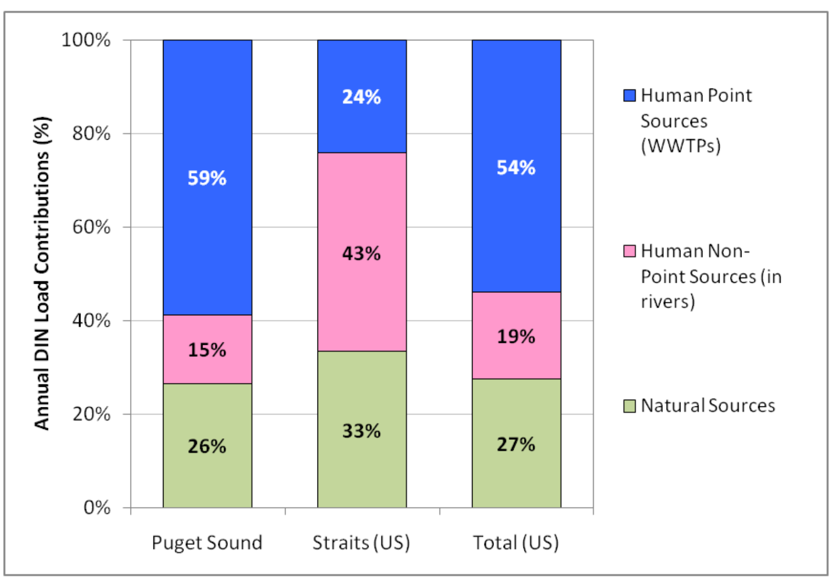

Figure ES-8. Relative contributions of annual dissolved inorganic load to Puget Sound and the Straits (U.S.) from human point sources (WWTPs), human non-point sources (in rivers), and natural sources.

Comparison to Previous Studies

Nutrient load estimates from this study were compared to those developed by five other studies, including Embrey and Inkpen (1998), Mackas and Harrison (1997), Hallock (2009), Mohamedali et. al (2011) and Paulson et. al (2006). Overall results were comparable, but loads from specific watersheds were sometimes higher and sometimes lower than those predicted by the other studies. Differences between studies could be a result a few factors, including different time periods of analysis, different water quality data sources, and different methods used to estimate nutrient loads.

Conclusions

As a result of this assessment of nitrogen loads, we now have comprehensive estimates of nutrient loads into Puget Sound as well as their relative magnitudes and sources. We are now able to describe how the relative contributions of DIN loads change over the course of the year, and compare loading into different regions of Puget Sound.

The water quality modeling effort will be key in identifying how sensitive DO levels in Puget Sound are to these different sources of nitrogen and whether DIN loading into the Straits affects the water quality of Puget Sound further south. These nutrient loading data will be used as part of the water quality modeling effort.

Using these nutrient loading estimates from 1999-2008, the water quality model will also allow us to (1) assess alternative management scenarios by reducing/changing DIN loads from particular sources and (2) evaluate how effective these changes might be in improving DO levels in Puget Sound.

Introduction

This report is part of a larger multi-year study investigating the water quality of Puget Sound. The Washington State Department of Ecology (Ecology) initiated this study because portions of Puget Sound fall below Washington State Water Quality Standards (Figure 1) for dissolved oxygen (DO).

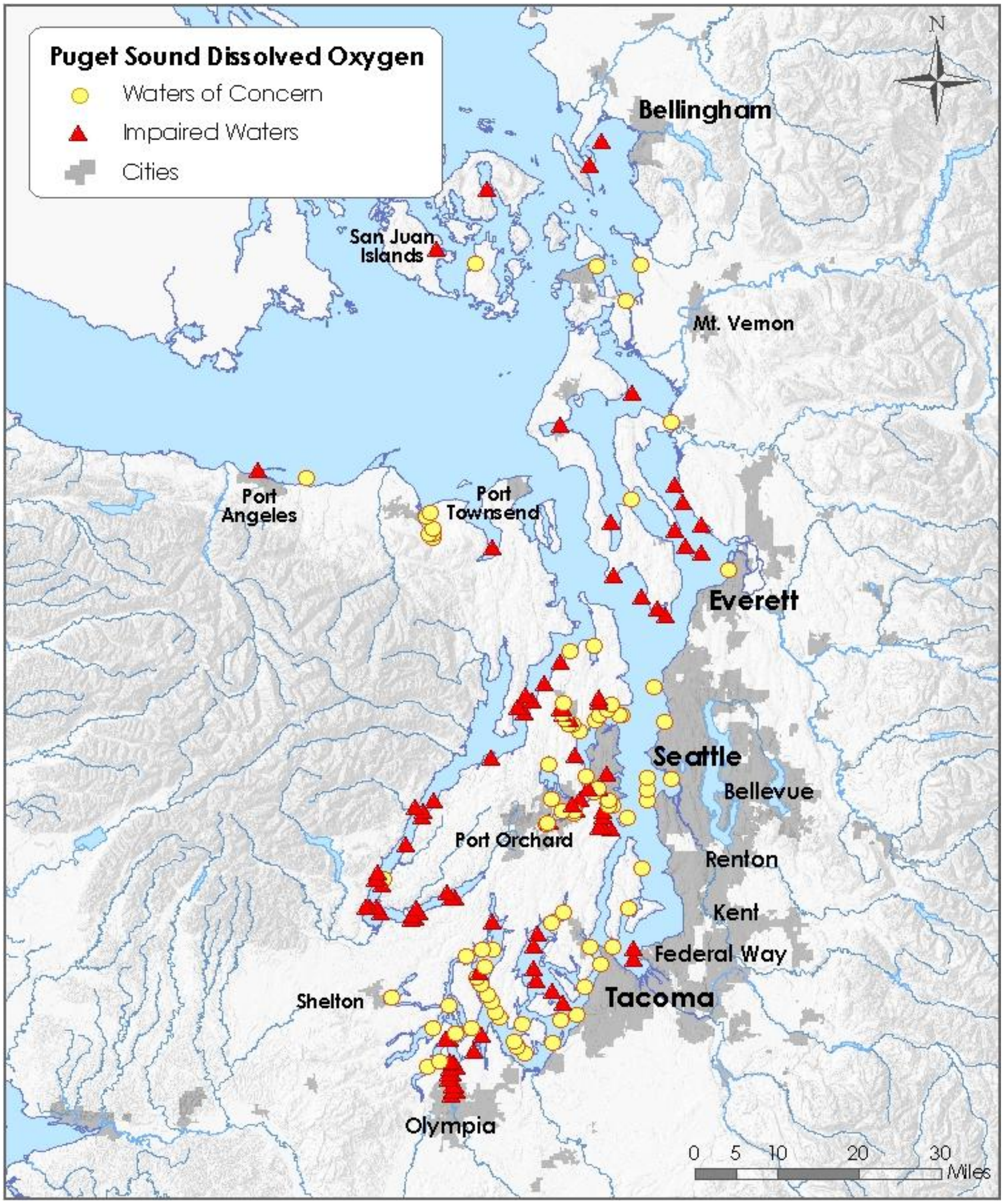

Figure 1. Results from the 2008 Water Quality Assessment for dissolved oxygen in Puget Sound.

Physical, chemical, and biological factors govern DO levels. Sluggish water circulation and warm temperatures, which can occur at the heads of shallow inlets, create favorable growth conditions for algae. Nutrient loading into these waters can further stimulate algae growth. When the algae die, organic matter decomposition consumes DO. Therefore, DO concentrations decrease when nutrients, particularly nitrogen, enter Puget Sound and stimulate algae growth. Likewise, coastal upwelling can bring low DO waters onto the continental shelf which may also influence Puget Sound oxygen levels (Landry and Hickey, 1989). Low DO levels can be harmful to fish and other marine life, raising concerns about the health of the Puget Sound ecosystem.

The study involves the development of an intermediate-scale computer model of the entire Puget Sound estuary system to further our understanding of processes that affect DO. The main goals of this project are to (1) understand the behavior of Puget Sound under current and future conditions based on hydrodynamic and water quality modeling of Puget Sound and (2) determine the influence of human nutrient inputs on low DO levels relative to natural contributors (Sackmann, 2009). If humans are contributing significantly to low levels of DO in Puget Sound, then subsequent phases would evaluate the level of nutrient reductions necessary to improve DO concentrations in Puget Sound.

This study is a joint collaboration between Ecology, the Environmental Protection Agency (EPA), Pacific Northwest National Laboratories (PNNL), and the University of Washington Climate Impacts Group (UW-CIG). PNNL, under contract to Ecology, is developing a circulation and water quality model of Puget Sound and the rest of the Salish Sea. This model is called the Puget Sound Dissolved Oxygen Model (PSDOM).

The model domain includes all of Puget Sound, plus the Strait of Georgia (SOG) and the Strait of Juan de Fuca (SJF) (Figure 2). The northern boundary of the PSDOM is located north of Vancouver, Canada so that the potential influence of the Fraser River and Canadian wastewater discharges can be evaluated. The model will therefore require information on nutrient loading from watersheds located in British Columbia (B.C.), which drain into SOG/ SJF. However, the main area of interest is Puget Sound and its tributary watersheds and the relative contribution of U.S. human sources on Puget Sound water quality.

In this report, ―Puget Sound” refers the marine waters of the study area south of Deception Pass, including Admiralty Inlet, Whidbey basin, Hood Canal, and South and Central Puget Sound. ―Straits” refers to marine waters of the study area north and west of Deception Pass predominantly covered by the SOG and SJF. The Straits extend into both U.S. and Canadian waterways, and in some cases, specific references will be made to either the U.S. or Canadian portions of the Straits.

The PSDOM requires time series of flows and nutrient loads from discrete inflow points to simulate seasonal and sub-seasonal variations in Puget Sound. The purpose of this report is to document and present the nutrient loading estimates developed by Ecology (which will be used by PNNL as the input time series into the model), and evaluate relative contributions to the various basins that comprise the study area. Subsequent reports will describe the model applications.

We used several sources of data to develop nutrient loading estimates for the PSDOM. Most of the data were collected as part of another Ecology study, called the *South Puget Sound Dissolved Oxygen Study* (Albertson et al., 2007). This study is also ongoing, and involves the development of finer-scale circulation and water quality models that cover a smaller geographic domain than the PSDOM.

The South Puget Sound Dissolved Oxygen Study (SPSDO study) included data collection between July 2006 and October 2007 over an area that includes marine areas and watersheds south of Edmonds. The field effort included marine water quality measurements within South and Central Puget Sound, and those data will be used for PSDOM model calibration. The South Sound effort also included monthly grab samples from rivers and streams as well as monthly 24-hour composite samples from wastewater treatment plants (WWTPs). The experimental design is described in detail in the Quality Assurance (QA) Project Plan (Albertson et al., 2007), and the results from this field data collection effort were subsequently published in an Interim Data Report (Roberts et al., 2008) and load summary (Mohamedali et al., 2011). These data and methods were adapted for use at the larger Puget Sound scale for use in the PSDOM.

Since the PSDOM‘s domain extends further north than the SPSDO study, additional data were needed for areas north of Edmonds to develop comprehensive nutrient loading estimates for the full model domain. We therefore supplemented data from the SPSDO study with additional data from (1) Ecology‘s ambient river monitoring stations, which are sampled monthly and (2) Environment Canada‘s water quality monitoring network for a few large rivers in British Columbia. Nutrient loading estimates for U.S. WWTPs outside of the SPSDO study area were based on plant characteristics from the SPSDO study, supplemented by available self-monitoring data. Canadian WWTP contributions were based on self-monitoring data as well.

Water quality parameters required by the PSDOM include various forms of nitrogen, phosphorus, and carbon. Data for most parameters of interest were available within Puget Sound watersheds, but limited information was available for these parameters in other areas, particularly those watersheds draining into the Straits. In these cases, typical values from available information were used instead.

This report specifically describes (1) the development of 1999-2008 monthly nutrient loading estimates for rivers from monthly ambient monitoring data supplemented by monthly grab samples taken within South and Central Puget Sound, (2) the development of 1999-2008 monthly nutrient load estimates for WWTPs from available permit compliance data and extrapolations from the 2006-2007 SPSDO study, and (3) the results of these in the context of nutrient loading to Puget Sound and the larger Salish Sea. A statistical method called *multiple linear regression* was applied to the field data to develop continuous daily loads of nutrients for the years 1999 through 2008.

We also calculated the natural nutrient conditions, which includes the concentrations and loads of nutrients in rivers and streams that drain into Puget Sound in the absence of human sources of nitrogen. To calculate natural conditions, we performed a meta-analysis of various methods based on ambient monitoring data, rainfall data, and data from other studies. Monthly 10^{th} percentiles of ambient data were eventually used to represent natural nutrient concentrations for different regions in Puget Sound and the Straits.

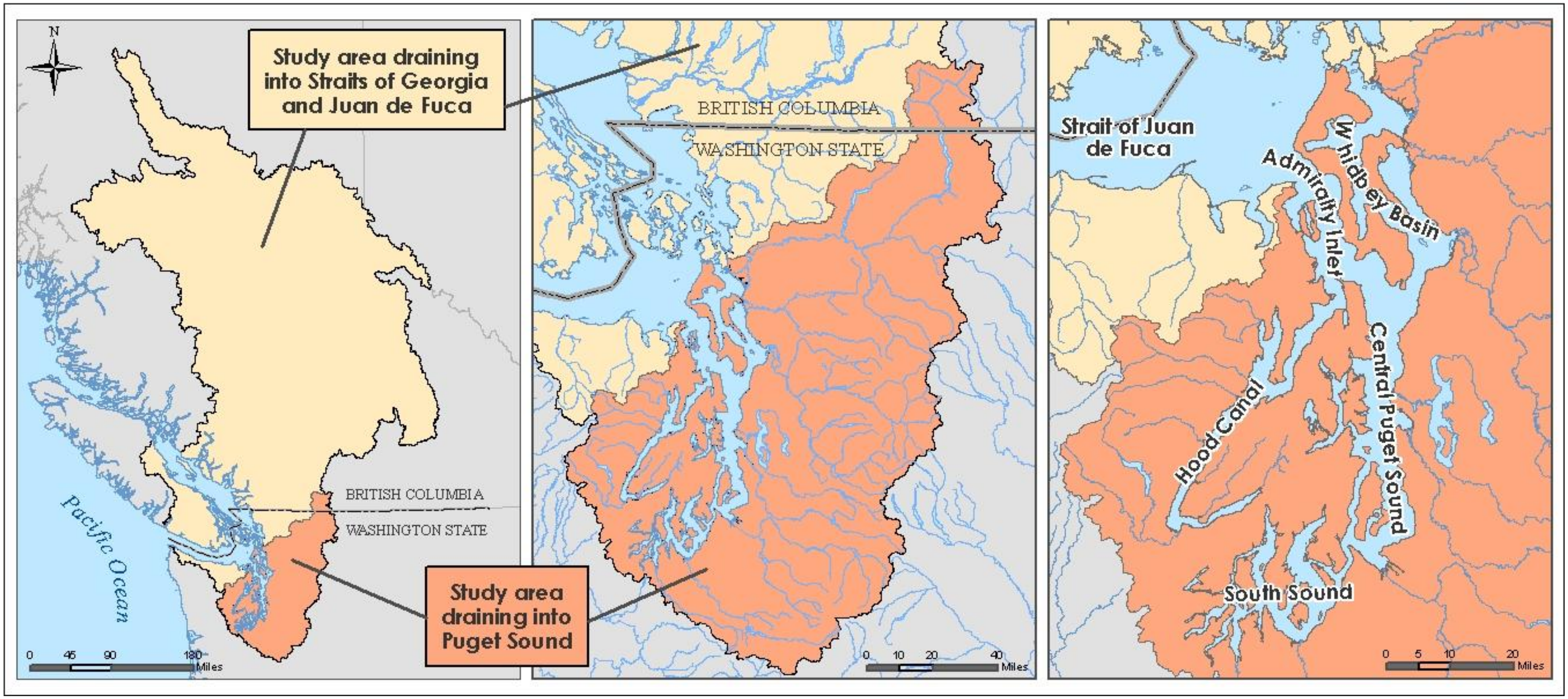

Figure 2. Study area for the Puget Sound Dissolved Oxygen Model Study. The primary areas of interest are the watersheds that drain into Puget Sound, but watersheds that drain into the Straits are also included.

Methods

We estimated nutrient loads to U.S. and Canadian waters from watersheds (which include a variety of upstream human sources) as well as WWTPs that discharge directly to marine waters. These loads will be used in the model, but the information itself provides insight to relative contributions between watersheds and WWTPs, relative contributions from different regions in Puget Sound, and temporal variations over the period 1999 through 2008. ―Watersheds" refers to all surface water inputs to marine waters, and ―WWTPs" refers to both municipal and industrial effluents. This section describes the information sources and the analytical methods used to derive time series of nutrient loads to the PSDOM from watersheds and WWTPs. The section also summarizes information sources for onsite sewage systems and groundwater contributions and describes the methods used to assess natural conditions.

Watershed Loads

Monitoring Data Availability

We used field water quality data from a variety of sources to develop watershed nutrient loading estimates for a total of 64 watersheds for the period 1999 through 2008. The primary source of the data was collected as part of the SPSDO study, which monitored 33 rivers monitored between 2006 and 2007 (Figure 3).

The SPSDO study included 14 stations sampled monthly between July 2006 through October 2007 in South and Central Puget Sound. All samples were collected using standard operating procedures and processed at Ecology‘s Manchester Environmental Laboratory (MEL) using standard procedures. All lab replicates met the target mean relative standard deviation (RSD) for the entire dataset (Roberts et al., 2008). Further details of the experimental design can be found in the QA Project Plan (Albertson et al., 2007).

Ecology‘s ambient freshwater monitoring program includes 13 stations near the mouths of the larger rivers tributary to Puget Sound and the Straits. We used monthly water quality data collected during 2006 and 2007 to coincide with the data collection period of the SPSDO study. All samples are collected using standard operating procedures and processed at Ecology‘s MEL using standard procedures. Data quality for the ambient monitoring program is evaluated annually against requirements specified in the program‘s Quality Assurance Monitoring Plan (Hallock and Ehinger, 2003). Data are available online and also published in annual reports for each water year.

Even though no actual monitoring took place at Sinclair Dyes Inlet and Lake Washington/Ship Canal during the field effort, flow and concentration data for these two locations were estimated using data and information from the watersheds that they drain or from adjacent watersheds. These methods are described in more detail by Roberts et al. (2008).

Environment Canada‘s Water Quality and Monitoring Surveillance Division, in partnership with provincial and territorial organizations, operate a water quality network that includes six stations of interest to this study. Their program includes the collection of in-situ water quality samples that are then analyzed in the laboratory (Environment Canada, 2010). We obtained water quality data through a formal data request, and primarily used data from the years 2006 and 2007 for rivers in Canada that drain into the Straits.

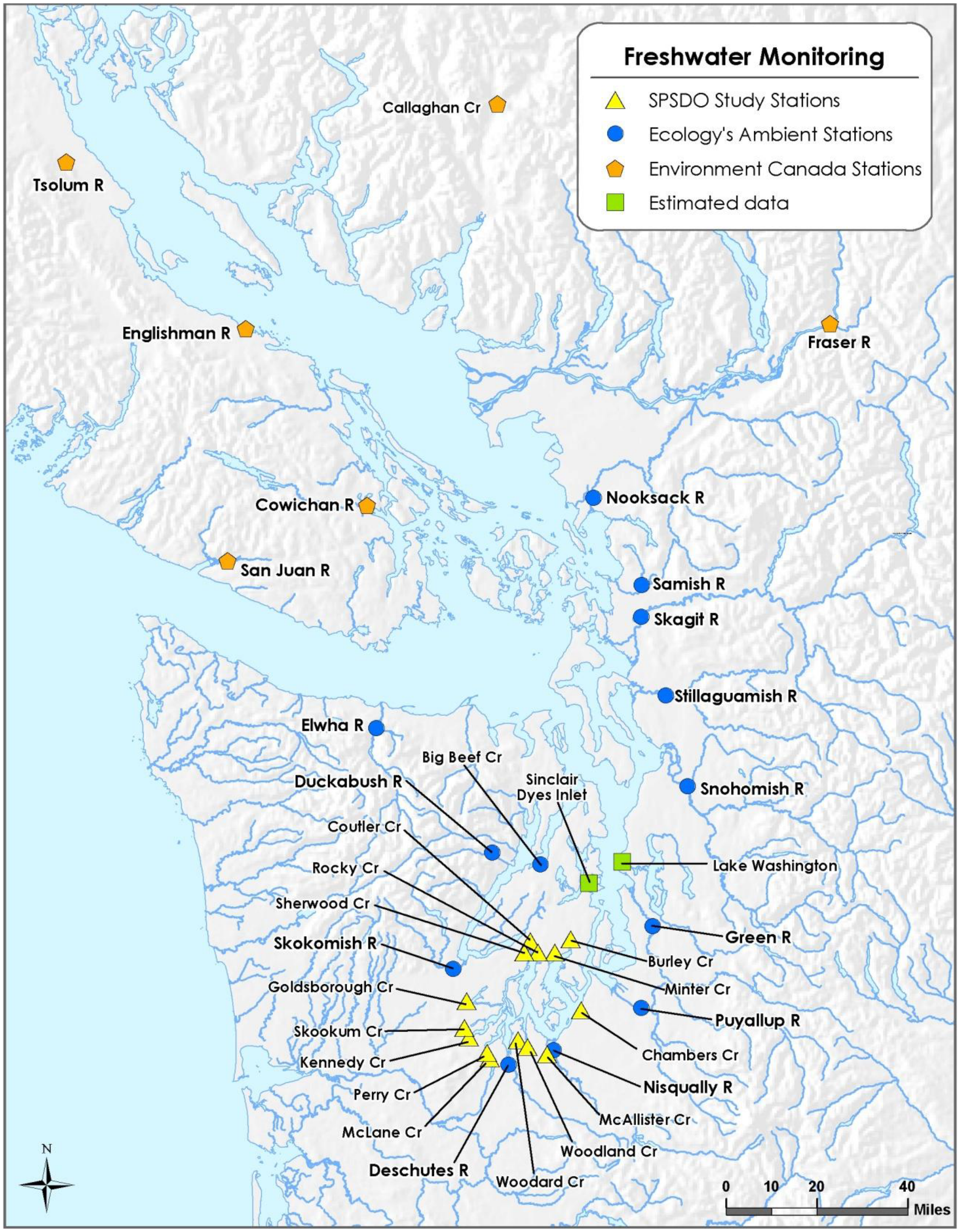

Figure 3. Location of water quality monitoring stations where data were collected by different entities and used to develop nutrient loading estimates for this study.

Different data sources provide different water quality parameters. The SPSDO study sampled the most comprehensive set of water quality parameters. This included physical instantaneous measurements of temperature, conductivity, and pH, as well as grab samples for laboratory analysis (Table 1). Included in Table 1 are a few additional parameters that were calculated from these measured parameters. Ecology's ambient monitoring program includes most, but not all the parameters in Table 1. In these cases, parameters were calculated as indicated by the footnotes in Table 1. These parameters are needed by the model to adequately characterize the water quality of inflows in Puget Sound and the Straits.

Table 1. Nutrient parameters included in Ecology's South Sound and ambient monitoring programs.

Parameter Name	Parameter Abbreviation	Calculation Method
Measured Parameters		
Nitrate + Nitrite	NO23N	--
Ammonium	NH4N	--
Total Persulfate Nitrogen	TPN	--
Dissolved Total Persulfate Nitrogen	DTPN	--
Ortho-Phosphate	OP	--
Total Phosphorus	TP	--
Dissolved Total Phosphorus	DTP	--
Total Organic Carbon	TOC[1]	--
Dissolved Organic Carbon	DOC[1]	--
Calculated Parameters		
Dissolved Inorganic Nitrogen	DIN	NO23N + NH4N
Particulate Organic Nitrogen	PON	TPN – DTPN[2]
Dissolved Organic Nitrogen	DON	DTPN – (NO23N + NH4N)[3]
Particulate Organic Phosphorus	POP	TP – DTP[2]
Dissolved Organic Phosphorus	DOP	DTP – OP[2]
Particulate Organic Carbon	POC	TOC - DOC

[1] For Ecology's ambient stations where there were no carbon data: Historical data were used to develop regression coefficients. When historical data were not available representative values of 1.6 mg/L and 1.5 mg/L were used for TOC and DOC, respectively.
[2] For Ecology's ambient stations where there were no DTPN data: PON = DON = 0.5*[TPN – (NO23N + NH4N)]
[3] For Ecology's ambient stations where there were no DTP data: POP = DOP = 0.5*(TP – OP).

Environment Canada's water quality sampling program did not collect data for each of the parameters listed in Table 1, and the data available for Canadian rivers was generally less frequent. However, the PSDOM requires only estimates of Canadian contributions given that this is not the primary area of interest in the modeling domain. We included enough information to represent these sources relatively roughly; if we determine that these sources strongly influence Puget Sound water quality conditions, then we will revise these time series using the best information available in subsequent project phases. The following parameters were generally available across all stations: NO23N, DTPN, TP, OP, DTP and DOC. Table 2 presents the concentration values used to represent parameters for Canadian rivers if no measured data for that parameter were available but were required by the PSDOM. In most cases, the value of detection limit for a particular parameter was used if concentration data were not available.

Table 2. Estimates of missing parameters in water quality data from Canadian rivers.

Parameter Name	Parameter Abbreviation	Method
Nitrate + Nitrite	NO23N	Assumed a constant concentration of 0.10 mg/L
Ammonium	NH4N	Assumed a constant concentration of 0.001 mg/L
Ortho-Phosphate	OP	If DTP data were present, assumed OP = DTP. Otherwise, assumed a constant concentration of 0.001 mg/L
Particulate Organic Nitrogen	PON	Assumed a constant concentration of 0.001 mg/L
Dissolved Organic Nitrogen	DON	Assumed a constant concentration of 0.001 mg/L
Particulate Organic Phosphorus	POP	Assumed a constant concentration of 0.001 mg/L
Dissolved Organic Phosphorus	DOP	Assumed a constant concentration of 0.001 mg/L
Dissolved Organic Carbon	DOC	Assumed a constant concentration of 0.0 mg/L

Estimating Daily Streamflow

Since the PSDOM requires daily time series for streamflows, we developed continuous daily streamflows at the *mouth* of each gaged and ungaged watershed within the study area for the years 1999-2008. The United States Geological Survey (USGS) maintains continuous stream gages on several streams and on most of the large rivers within the Puget Sound area. Permanent USGS gaging stations capture approximately 69% of the watershed tributary to the main study area, which includes all watersheds tributary to Puget Sound (south of Deception Pass).

For rivers and streams that had a USGS gaging station located within their watershed, data from the USGS were retrieved and extrapolated to the mouth of the watershed by scaling the streamflow record by the larger watershed area and average annual rainfall.

While the ungaged areas are relatively small, we also estimated streamflow for these watersheds so that all surface water inputs were included. First, we identified the nearest continuously gaged stations in watersheds of similar size, land use, and proximity. Next, we normalized this continuous streamflow record by drainage area and average annual rainfall. Finally, we scaled the normalized streamflow by the area and average annual rainfall of the target watershed. The same approach was applied to watersheds with no primary stream inflow point.

Ecology field staff also recorded instantaneous discharge measurements at several streams sampled under the SPSDO study that do not have continuous flow gages. Estimated flows were compared to discrete measurements where available. Mohamedali et al. (2011) presented plots of predicted and observed flows at all stations which did not have a USGS gage station and where instantaneous flow measurements were made. Observed and predicted flows were comparable across all sites. Figure 4 presents representative sites from Appendix B of Mohamedali et al. (2011).

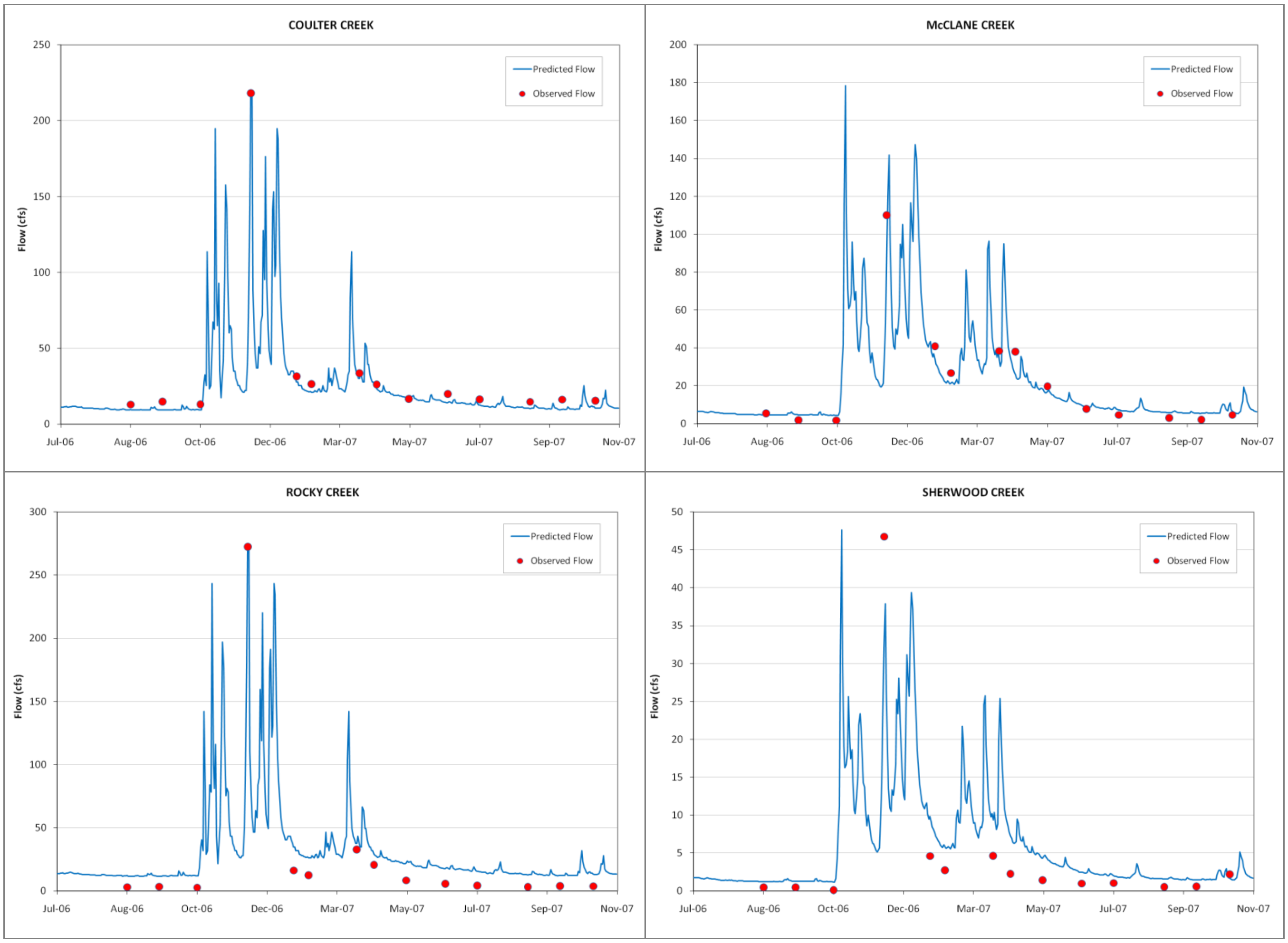

Figure 4. Predicted and observed flows at representative creeks with 15 months of instantaneous flow data.

Flow formulations for a few rivers/watersheds used a slightly more complex equation using data from more than one USGS gage. Table 3 presents these flow equations, which were adapted from Lincoln (1977) using updated gages and watershed areas.

Table 3. Source information for estimating streamflow from watersheds that used multiple USGS flow gages.

Watershed	USGS Source Gages	Equation to Estimate Flow
Lake Washington	Cedar River Mercer Creek Juanita Creek Sammamish River	$Q_{Lk\ Wash} = 1.7080 * (Q_{Cedar} + Q_{Mercer} + Q_{Juanita} + Q_{Sammamish})$
Sinclair/Dyes	Huge Creek	$Q_{Sinclair} = 26.98 * (Q_{Huge})$
Green River	Green River @ Auburn Sammamish River	$Q_{Green} = 1.1028 * (Q_{Auburn}) + 0.3701 * (Q_{Sammamish})$
Nisqually River	Nisqually River @ McKenna Centralia Power Canal	$Q_{Nisqually} = 1.2230 * (Q_{McKenna} + Q_{Centralia\ Power})$

Streamflow data for the rivers in British Columbia, Canada were available through the Water Survey of Canada (WSC). WSC is the national authority responsible for the collection, interpretation and dissemination of standardized water resources data and information in Canada (Environment Canada, 2010). WSC collects water level and streamflow data from a number of stations located throughout British Columbia.

Since WSC streamflow stations were not located at the mouths of rivers, these data were normalized by the drainage area at the point of measurement and then the normalized streamflows were scaled by the complete watershed area. Canadian watershed inflows were not normalized or scaled by the average annual rainfall; however, not as much detail was needed for the Canadian watersheds given they are outside of our primary area of interest.

Watershed Delineations

River and stream monitoring did not always occur at the mouth of each watershed. To capture the nutrient loading from all the watershed areas draining into Puget Sound, we extrapolated nutrient loads from the monitoring station to the mouth of each watershed, as well as to all unmonitored locations. A total of 64 watersheds are included in the PSDOM to represent watershed loads (Figure 5). These delineations were based on a 30-meter digital elevation model (DEM) and performed using available tools in ArcGIS. ArcGIS uses the information derived from the DEM to assess how water flows across the landscape and then determines watershed boundaries. Figure 6 further identifies and labels the location of the mouth of each of these 64 watersheds, specified as freshwater inflows in the PSDOM.

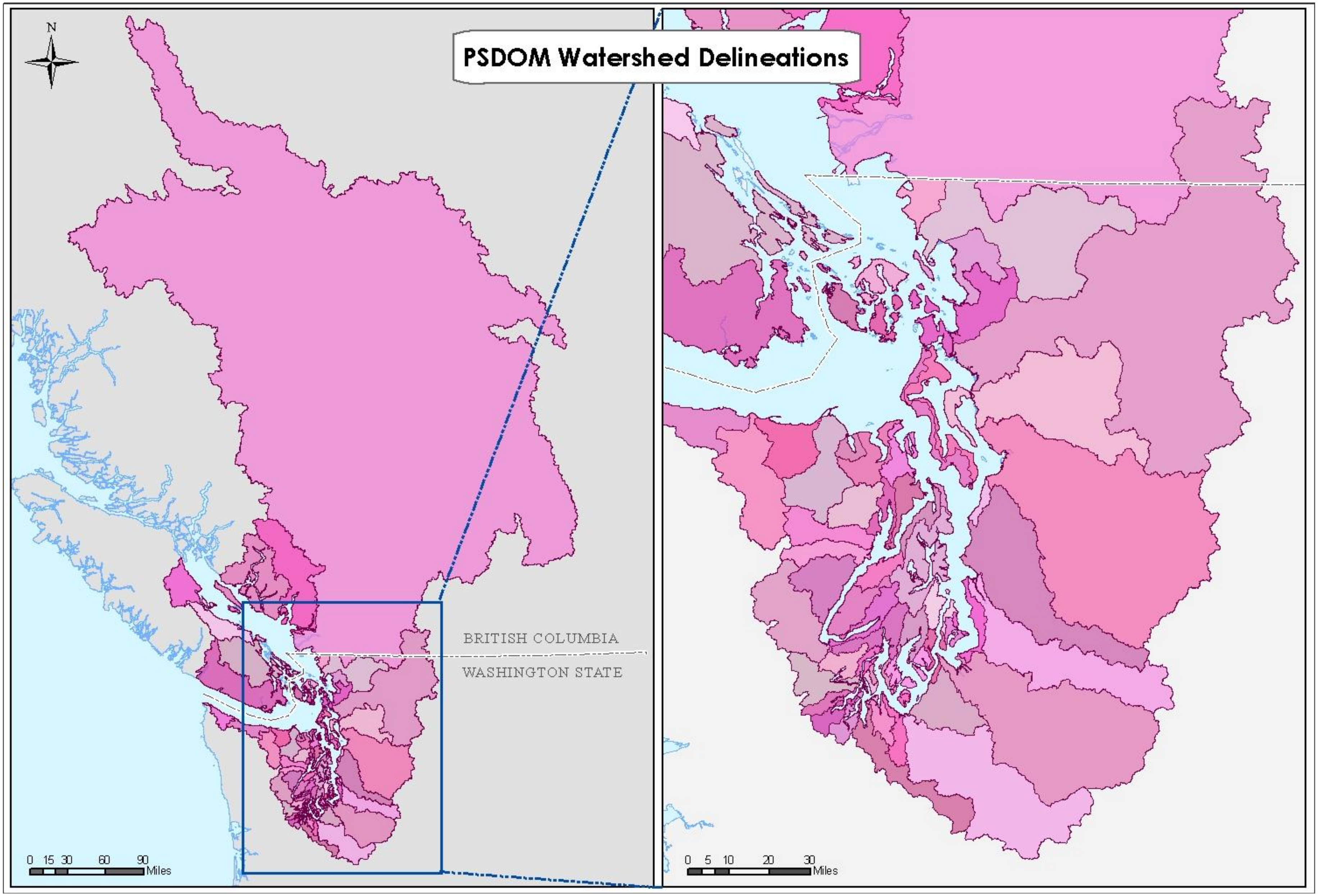

Figure 5. Delineation of the 64 watersheds which are included within the PSDOM.

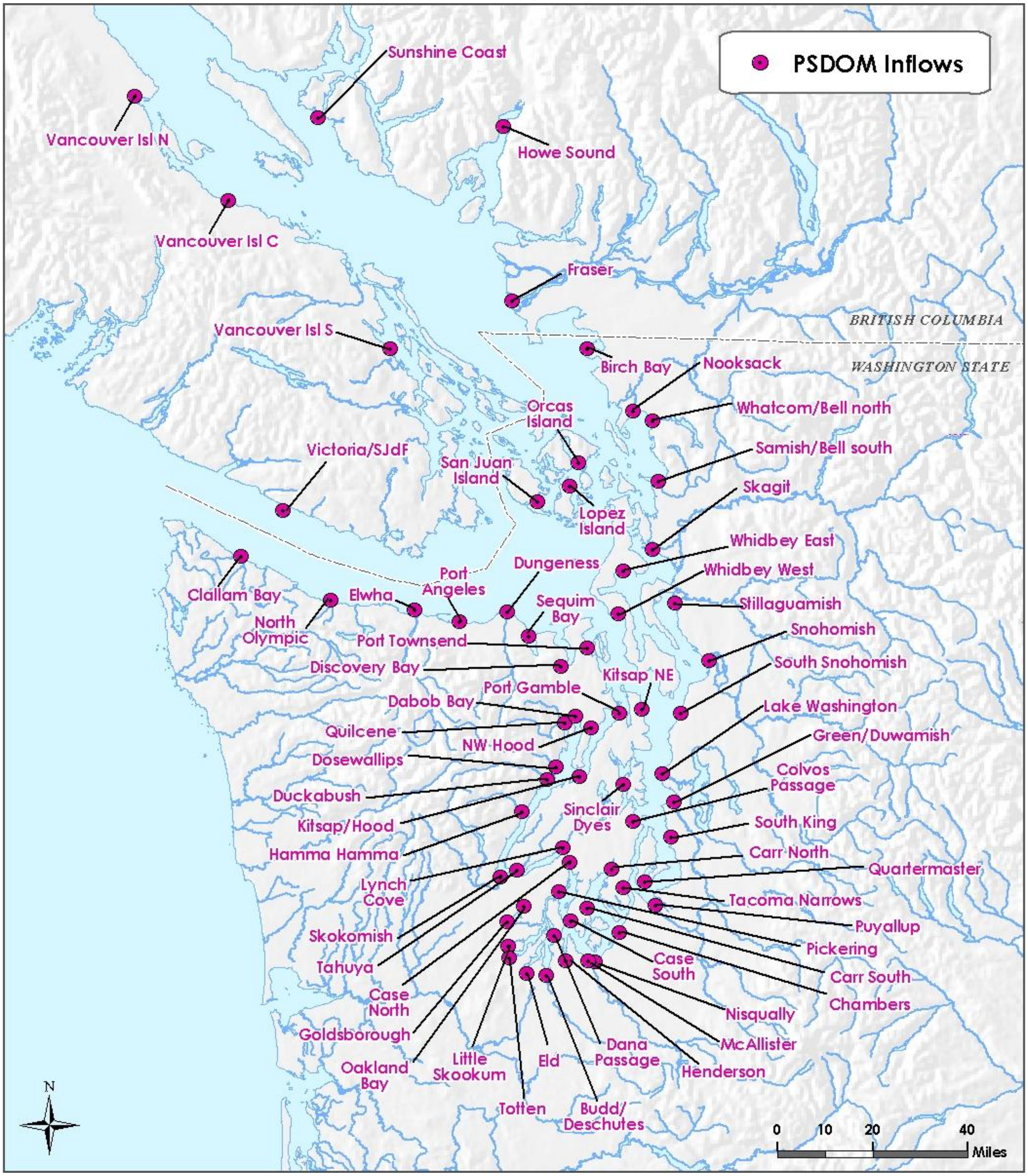

Figure 6. Location and names of the 64 freshwater inflows included in the PSDOM for which daily nutrient concentrations and loads were developed for the period 1999 through 2008.

Predicting Daily Concentrations

Data from the various monitoring efforts were used to estimate daily nutrient concentrations for all 64 watersheds/tributaries that drain into Puget Sound and the Straits, as identified in Figure 5. A statistical method called *multiple linear regression* was used to predict daily nutrient concentrations for the rivers and streams draining these watersheds. This statistical approach relates concentrations to flow patterns, time of year, and season using a best-fit to monitoring data. However, the approach may not capture trends in concentration unrelated to trends in flow. The same method was used by Roberts and Pelletier (2001) and Mohamedali et al. (2011) to estimate daily concentration time series of nutrients.

The multiple linear regression equation used in this analysis is given by:

Equation 1

$$\log(C) = b_0 + b_1 \log(Q/A) + b_2 [log\ (Q/A)]^2 + b_3 \sin(2\pi f_y) + b_4 \cos(2\pi f_y) + b_5 \sin(4\pi f_y) + b_6 \cos(4\pi f_y)$$

where

C is the observed parameter concentration (mg/L).
Q is streamflow (cms).
A is the area drained by the monitored location (km^2).
f_y is the year fraction (dimensionless, varies from 0 to 1).
b_i are the best-fit regression coefficients.

Logarithms of concentration and flow were used given the order of magnitude variability in the source data between different watersheds. To extrapolate results between basins of different areas, normalized flows (flows per unit area) were used in the regression.

Of the 64 watersheds within the study domain, 35 stations had sufficient water quality monitoring data available to calculate regression coefficients. For these 35 locations, all six variables in Equation 1 are known values (from available concentration data, streamflow data, watershed area, and time of year) except for the coefficients (b_i). The multiple linear regression model solves Equation 1 and determines the optimum combination of b_i coefficients that will yield the best fit between predicted and observed concentrations for each parameter of interest. The regression coefficients, b_i, were determined for each measured parameters[2] listed in Table 2.

Regressions were performed using the *Regression* tool within the *Analysis ToolPak* add-in for Microsoft Excel. In addition to the best-fit coefficients, the Excel output included an F value indicating the significance of the relationship, an R^2 and adjusted R^2, as well as a table of residuals. Model fit was evaluated based on the significance of the regression relationship (F value and p value), the adjusted R^2 value, the R^2 value generated by fitting a linear trend line to a plot of predicted vs. observed concentrations, and an evaluation of residual plots.

Outliers in the observed data were identified and removed from the dataset since the regression model would bias the relationship by trying to fit one extreme data point. The reported value was considered

[2] Regressions were also developed for temperature, dissolved oxygen and pH, but are not included in this report.

an outlier if it was more than three standard deviations away from the mean of the observed dataset for each parameter and stream. In several cases, however, the outlier was an unusually high concentration that occurred only during a single event such as the November 2006 storm event that caused widespread flooding. In this case, the observed value was not considered an outlier but representative of the natural response of the river or stream to the high-flow event. Outliers associated with high-flow events were therefore retained in the regression analysis.

If the regression relationship was not significant ($p > 0.05$), the least significant variable (the one with the largest p value) was removed from the equation. The regression was run a second time to generate a new set of regression coefficients. This was done iteratively by removing up to two variables for each parameter. If the regression was still not significant after removing two of the least significant variables, the original coefficients determined by including all six original variables were used.

Watershed-specific multiple regression model coefficients (b_i) were developed for each parameter at each of the 35 watersheds where we had sufficient water quality data. The watershed-specific regression coefficients were first used to predict daily concentrations using daily streamflow data.

Daily concentrations were compared to observed concentrations to see how well the model performed. Figure 7 presents a subset of the plots that were presented in Appendix D of Mohamedali et al. (2011). Since monitoring did not always occur during the largest flow event, the regression model tends to extrapolate patterns to higher flows, potentially producing a source of error. To minimize the error due to this extrapolation, the maximum concentrations recorded in the monitoring data were used to cap predicted concentrations for all parameters. In addition, predicted concentrations below the detection limit were replaced with a value equal to the detection limit for the specific parameter. A smearing adjustment was then applied to correct for bias due to retransformation from log space (Cohn, et al., 1992).

The watershed-specific regression coefficients were then used to predict daily concentrations at the mouth of each of PSDOM inflow points in Figure 6 for the calendar years 1999-2008 using the daily flow data. For the 29 watersheds that did not have a primary source of water quality data, we applied regression coefficients developed for the most appropriate nearby 35 watersheds. Equation 1 was then used to predict daily concentrations of parameters for these target watersheds using the target watershed's streamflow and area for the Q and the A in Equation 1.

The result was continuous daily streamflow and concentration data for all parameters of interest and for all 64 watersheds included in the PSDOM.

Figure 7. Predicted and observed concentrations (left column) and loads (right column) of nitrogen for the Deschutes River.

Calculating Daily Loads

Continuous daily loads from rivers and streams were calculated from the predicted daily concentrations and daily flows for the years 1999 through 2008 as follows:

Daily load = (predicted daily concentration) x *(daily streamflow)*

Predicted loads were then compared with observed loads for those locations where we had data, as shown in Figure 7.

Septic System Contributions

On-site septic systems represent a potential source of nutrient loads into marine waters within the study area. On-site septic system nutrient loads *upstream* of the monitoring location are included in our estimates of watershed loads. The extrapolation to the mouth of each watershed (and to unmonitored watersheds) should therefore reflect septic systems near the marine shoreline. However, if on-site septic systems in the unmonitored regions adjacent to Puget Sound are more numerous or if effluents are less attenuated, this extrapolation could underestimate DIN load contributions from septic systems.

As part of the SPSDO study‘s interim nutrient loading report, we evaluated the extent to which these watershed extrapolations captured the septic contributions in the shoreline fringe area. Whiley (2010) estimated DIN loads from on-site septic systems from regions outside of the SPSDO study‘s monitored watersheds and outside of municipal wastewater service areas. Using Whiley‘s (2010) results, we found that septic system loads from this area are *smaller* than the difference in loads from extrapolated and monitored regions. In Mohamedali et al. (2011), we concluded that our extrapolated loads adequately capture nutrient loads from on-site septic systems and no load subsidies are needed. Given this analysis, we assumed that extrapolated watershed loads for the PSDOM are also sufficient to account for on-site septic system loads located in outside of monitored regions.

Groundwater Contributions

Though groundwater DIN load estimates were estimated, these loads are also included in our estimate of watershed loads and were not considered a separate source of loading. Watershed loads include base flow (which is predominantly groundwater), and the extrapolation of watershed loads from the monitoring location to the mouth of each watershed also includes groundwater loads into Puget Sound from shallow near-shore areas. Because marine discharges of groundwater likely occur in shallow marine waters and represent sources near the shoreline, the nutrient sources in these regions are likely captured within the surface water pathway even though a small proportion may be delivered via a groundwater pathway.

Vaccaro et al. (1998) provides the best available estimates of groundwater discharge for the Puget Sound region at 100-1,000 ft^3/s (2.8 to 28 m^3/s). However, surface water inputs, including baseflow that represents groundwater contributions to rivers, total over 50,000 ft^3/s. Therefore, groundwater flow contributions are just a small proportion of all freshwater inflow. A recent study in the Hood Canal watershed found that nitrogen concentrations in groundwater seeps were similar to surface water contributions (Paulson et al., 2006). As a consequence, groundwater DIN loads will also be small relative to surface water loads. Even though we expected the DIN loads from groundwater to be small, we still did estimate groundwater DIN load contributions.

Using the groundwater discharge estimates from Veccaro et al. (1998), we then estimated loads using concentrations estimated by Pitz (1999). Pitz (1999) estimated concentrations of nitrate in groundwater discharging into South Puget Sound using water quality data from wells monitored by the Washington State Department of Health (WDOH). The geometric mean of concentrations from WDOH well data ranged from 0.25 to 0.65 mg/L in different regions of South Puget Sound. Pitz (1999) explains how these concentrations generally under-predict nitrogen concentrations in groundwater and can be biased low. The main reason for this bias is that WDOH wells are production wells which are used for water supply; these wells are deep and therefore capture water from aquifers which generally have higher water quality and therefore less nitrogen. However, these concentrations are comparable to those reported in Paulson et al. (2006).

To develop a conservative estimate of DIN loads, we selected a groundwater DIN concentration of 0.65 mg/L, which is the high end of WDOH data (assuming most of DIN in groundwater is in the form of nitrate) and close to the 0.6 mg/L value used by Paulson et al. (2006) to estimate groundwater contributions to Hood Canal. Multiplying this concentration by our range of groundwater flows, we calculated a range of groundwater DIN load estimates.

Wastewater Treatment Plant Loads

Ninety-nine municipal WWTP or industrial facilities discharge to the PSDOM study domain (Figure 8). This includes 78 U.S. municipal WWTPs[3], nine Canadian municipal WWTPs, five oil refineries, four active pulp/paper mills, and one aluminum facility within the Puget Sound study area. Each of these facilities discharges effluent directly into the marine waters of Puget Sound or into rivers downstream of the monitoring location. For example, the Puyallup WWTP has its outfall in the Puyallup River, but is included in this report since it is located downstream of ambient monitoring station on the Puyallup River.

Abitibi in Steilacoom and Georgia Pacific in Bellingham both have inactive National Pollutant Discharge Elimination System (NPDES) permits, and are therefore not included in this study. In addition, the Tenaska Cogeneration Plant only discharges non-contact cooling water, and we assumed zero concentration of nutrients in their effluent.

Starting in 2004, the three discharges located in the Everett area (Everett WWTP, Kimberly Clark, and Marysville WWTP) combined a portion of their discharges into a single outfall called OF100, which was located further off-shore. However, in order to present separate nutrient loading estimates for each of these plants, they will be represented as geographically distinct discharges. When these nutrient loads are used in the PSDOM, the portion of the effluent that flows out of OF100 will be represented in the correct location for 2004 and later.

[3] This does not include the Messenger House Care Center, which we considered small enough to be negligible or the Intalco sanitary contribution which was not included with the process water discharge.

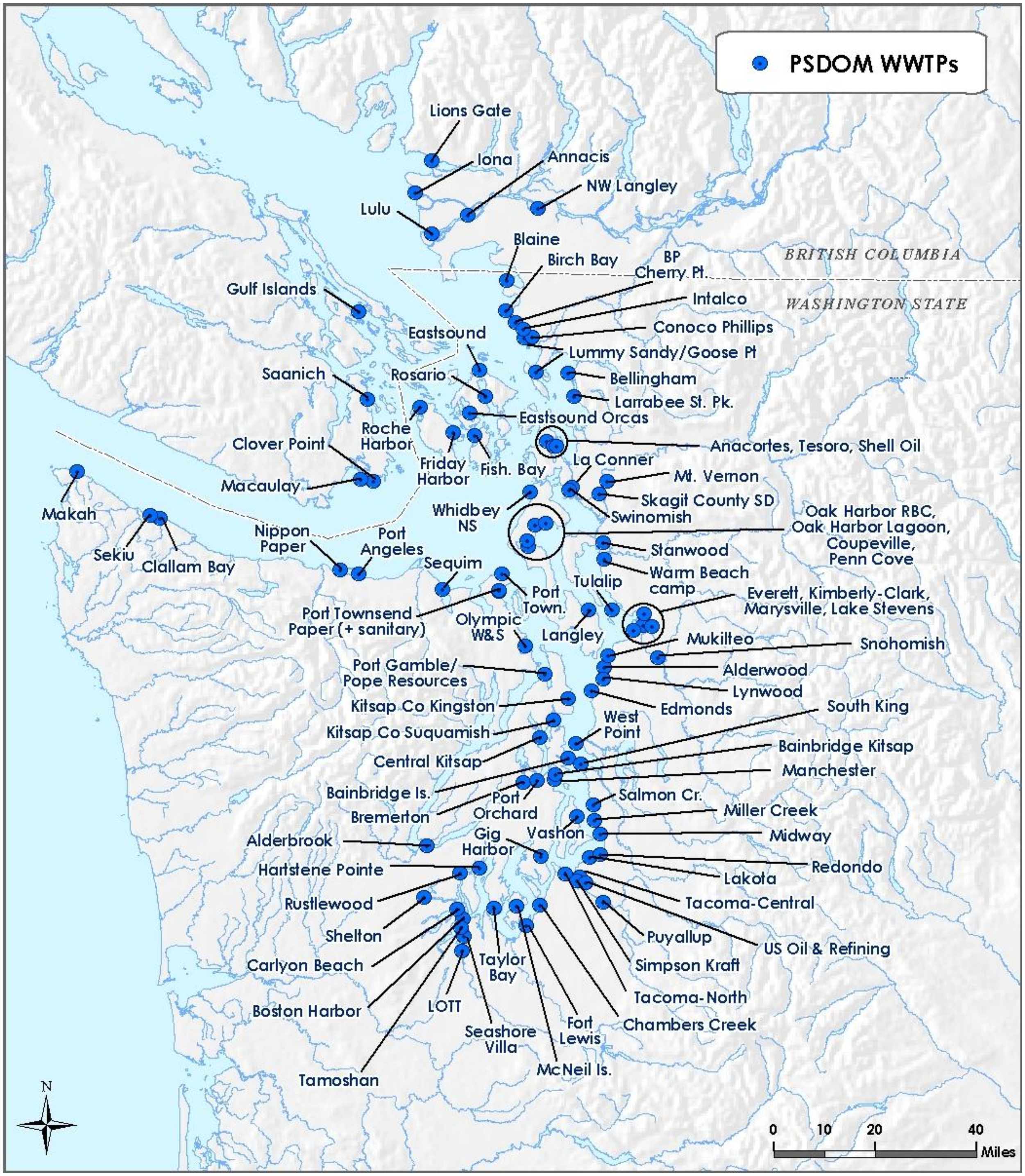

Figure 8. Location of municipal WWTPs and industrial discharges included in the PSDOM.

The Gulf Island WWTPs that discharge from Vancouver Island, B.C., are represented in this report as a single location, even though wastewater actually gets discharged through five different outfalls in close proximity to each other. Nutrient loads for Gulf Island WWTP are therefore the sum of loads from all five outfalls.

From this point forward, unless otherwise specified, reference to ‗WWTPs' includes all WWTPs as well as industrial discharges (oil refineries, pulp mills or aluminum facility) in the study area.

Effluent Monitoring Data

Each of the U.S. WWTPs operates under an individual National Pollutant Discharge Elimination System (NPDES) permit, which requires facilities to monitor effluent quality on a daily to weekly basis depending on the parameter. Non-federal facilities report concentrations of these parameters to Ecology as paper copies of Discharge Monitoring Reports (DMRs). Monthly average data are captured in an online database[4] administered by Ecology. Biochemical oxygen demand (BOD) and total suspended solids are reported, but most permits do not require monitoring for nutrients, including nitrogen, phosphorus, or carbon. A few facilities report ammonia concentrations. U.S. Environmental Protection Agency (EPA) manages federal facility permits, and permittees are required to submit data to the Permit Compliance System (PCS). As with non-federal systems, few of the parameters needed by the PSDOM are reported. Therefore, other information sources were needed to characterize nutrient content in treated municipal and industrial wastewater effluent.

The primary source of WWTP water quality data for the PSDOM was the SPSDO study (Roberts et al., 2008 and Mohamedali et al., 2011). Since the study area for the SPSDO study only included South and Central Puget Sound, only WWTPs located south of Edmonds were monitored. Seventeen WWTPs in South and Central Puget Sound were monitored over 15 months between August 2006 and October 2007. In addition, 12 WWTPs were monitored monthly for three months. These plants include the Simpson Kraft plant in Tacoma, which is one of the two industrial effluents in the SPSDO study. The WWTPs included in the SPSDO study are shown in Figure 9.

Samples were 24-hour composites collected by each plant‘s sampling equipment (as required by their permit) and reserved for Ecology staff to collect each month[5]. The location where the water quality sample was collected varied from plant to plant, but was within the plant and as close to the outfall as possible. For smaller plants without 24-hour composite sampling equipment, Ecology staff collected grab samples. Samples were analyzed for each measured parameter listed in Table 2 (same as for freshwater monitoring stations), plus one additional parameter: carbonaceous biochemical oxygen demand (CBOD)[6]. All samples were collected using standard operating procedures and processed at Ecology‘s MEL using standard procedures. All lab replicates met the target mean RSD for the entire dataset (Roberts et al., 2008). Further details of the experiment design can be found in the QA Project Plan (Albertson et al., 2007).

For plants north of Edmonds, we used any available data reported in DMRs. Generally CBOD data were available, but because most plants are not required to monitor nutrients, little supplemental data were available. We primarily used data reported in DMRs for the years 2006 and 2007 to be consistent with the SPSDO study time period.

[4] Until 2011, data were maintained in the Water Quality Permit Life Cycle System (WPLCS). In 2011 new data will be submitted electronically to the new PARIS system. At the time of publication, the old permit compliance data would not be migrated to the new system and WPLCS will remain the repository of this information for the foreseeable future.
[5] Occasionally, WWTPs failed to reserve a sample for Ecology staff, so fewer months of data are available.
[6] CBOD was not analyzed in rivers and streams where concentrations are nearly always below the reporting limit of 4 mg/L. Instead, CBOD is estimated from dissolved organic carbon (DOC) for rivers and streams.

Plant-specific flows were used to generate loads. However, only monthly average flows are captured electronically by Ecology or EPA. All large (> 10 mgd) and most of the medium (4-10 mgd) WWTPs participated in the SPSDO study by providing electronic daily effluent flow data to Ecology during the monitoring period (July 2006 – October 2007). For the rest of the medium WWTPs and a few small ones (< 4 mgd), daily effluent flow data reported in paper-copy DMRs were entered by Ecology staff for this same time period. For all other small WWTPs as well as WWTPs located outside of the SPSDO study area, monthly average flows were retrieved electronically and used to represent daily flows. For the years in the 1999-2008 study period for this study but outside of 2006-2007, flow data also came from DMRs.

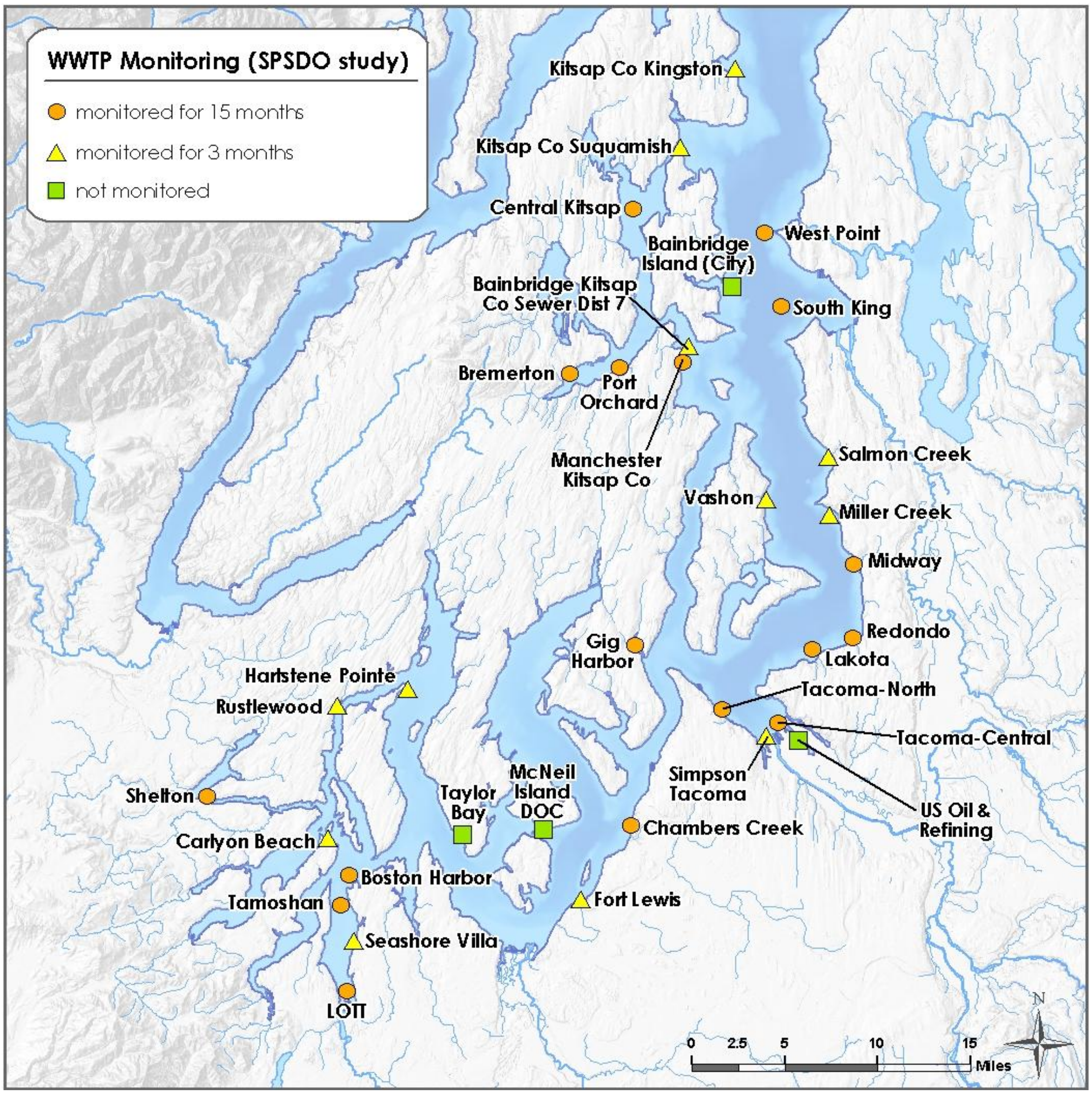

Figure 9. Locations of monitored and unmonitored WWTP discharges within the South Puget Sound Dissolved Oxygen study area.

All U.S. plants have secondary treatment technology. However, the Lacey Olympia Tumwater and Thurston County (LOTT) Alliance plant in Olympia has nutrient removal technology (tertiary or advanced treatment).

Canada Wastewater Treatment Plant Data

WWTPs in Canada are not subject to U.S. NPDES permits. However, limited effluent flow and water quality data were available from these WWTPs from the following two primary sources; these data were used to develop nutrient loading estimates.

1. Metro Vancouver reports on the five WWTPs located in and around Vancouver, B.C. They are required to report monthly effluent quality data under Operational Certificates issued by the Ministry of Water, Lands and Air Protection. The latest monthly reports include water quality data for various forms of nitrogen, phosphorus, carbon as well as CBOD (Metro Vancouver, 2010).

2. Capital Regional District (CRD) is the regional government for municipalities located on the southern tip of Vancouver Island. CRD (2010) monitors these WWTPs as part of their Wastewater and Marine Environment Program, and data are presented in annual reports (Marine Programs, 2009a and 2009b).

Of the five major outfalls in the Vancouver area, NW Langley, Annacis, and Lulu receive secondary treatment. Wastewater discharged at Iona and Lions Gate receives primary treatment only. In the Victoria area, the Gulf Islands and Saanich plants have secondary treatment, but the Clover Point and Macauley discharges receive preliminary screening only.

Predicting Daily Concentrations

Monthly concentrations of nutrients were predicted for all 96 WWTPs within the study area for the years 1999 through 2008. Since the PSDOM required continuous daily data, these monthly data were used to represent each day within a month by maintaining constant effluent flows and concentrations for each month). Unlike rivers and streams, WWTP flows and concentrations do not vary greatly from day-to-day and constant monthly values are appropriate to represent WWTP variability.

Monthly data from the SPSDO study‘s field monitoring effort were used to estimate monthly nutrient concentrations from 1999-2008 for the 17 WWTPs where 15 months of data were collected. To do this, we used a statistical method called *multiple linear regression*, which is the same method we used to predict watershed concentrations. This statistical approach relates concentrations to flow patterns, time of year, and season using a best-fit to monitoring data. The multiple linear regression equation used for WWTPs is given by:

Equation 2

$$\log(C) = b_0 + b_1 Q + b_2 Q^2 + b_3 \sin(2\pi f_y) + b_4 \cos(2\pi f_y) + b_5 \sin(4\pi f_y) + b_6 \cos(4\pi f_y)$$

where

C is the observed parameter concentration (mg/L).
Q is effluent flow (cms).
f_y is the year fraction (dimensionless, varies from 0 to 1).
b_i are the best-fit regression coefficients.

Note that unlike Equation 1 used for watersheds, Equation 2 does not normalize the flows by the area since drainage area is irrelevant to WWTPs, and the effluent flow is not transformed into log space since there is much less flow variability in WWTPs than in rivers.

The 17 WWTPs monitored under the SPSDO study account for 67% of the total mean annual discharge of all WWTPs that discharge into Puget Sound marine waters. For these 17 more intensely monitored WWTPs, all six variables in Equation 1 are known values (from available concentration data, effluent flow data, and time of year) except for the coefficients (b_i). The multiple linear regression model solves Equation 2 to determine the optimum combination of b_i coefficients that will yield the best fit between predicted and observed concentrations for each parameter of interest. The regression coefficients, b_i, were determined for each measured parameter listed in Table 2 (as well as for CBOD) using the same Excel tool as we did for estimating watershed concentrations. In addition, concentrations of additional parameters were calculated from these predicted concentrations, as listed in the bottom half of Table 2.

We developed WWTP-specific multiple regression model coefficients (b_i) for each parameter at the 17 WWTPs where we had 15 months of data from the SPSDO study. We also developed WWTP-specific coefficients for CBOD and ammonia (NH3) if sufficient data were available from DMRs for several WWTPs north of Edmonds. The WWTP-specific regression coefficients were first used to predict monthly concentrations using monthly effluent data at these WWTPs for the calendar years 1999-2008. Equation 2 requires a calendar date to represent the *year fraction* term, and we used the 15th day of each month to represent the whole month.

Monthly concentrations were compared to measured concentrations to see how well the model performed. Since monitoring did not always occur during the largest or smallest effluent flow, the regression model tends to extrapolate patterns to higher and lower flows, potentially producing a source of error. To minimize the error due to this extrapolation, predicted concentrations were capped by the maximum and minimum observed concentrations in the monitoring data for each specific plant.

As described in Mohamedali et al. (2011), a different approach was used for the WWTPs that had limited or no data where plant-specific regression coefficients could not be developed. The effluent flow rates influenced nitrogen levels in the effluent of the 15 intensively monitored plants, with the lowest concentrations in the smallest plants and the highest concentrations in the largest plants. To extrapolate to unmonitored plants, we accounted for plant size:

1. We divided all plants into three size groups according to the magnitude of their effluent flow: large (> 10 mgd), medium (4-10 mgd), and small (< 4 mgd) based on design flows in the permits.
2. Daily concentration templates were developed for each size group. These concentrations were the average of each nutrient parameter averaged across all plants that fell within each size group. In other words, for the ‗medium' template, the NO23N concentration was the average NO23N concentrations of all monitored medium plants. We developed concentration templates representative of all large, medium, and small WWTPs in the study using data from the 17 WWTPs for which regressions were developed.
3. These templates were applied to all other unmonitored WWTPs according to which size group they fell in. The medium concentration template was therefore applied to all unmonitored medium plants to represent their daily nutrient concentrations.

The WWTPs where we collected three months of data served as spot checks to see how well the template concentrations matched observed data. For example, Fort Lewis, Miller Creek, and Salmon Creek WWTPs are all medium plants that were monitored for only three months. As presented in Appendix E of Mohamedali et al. (2011), the extrapolation approach provided a reasonable fit to the plants monitored less intensely. The method introduced no overall bias, although some plant data showed concentrations that were above or below the template values.

As detailed below, the extrapolation method using size-based templates was not appropriate for one municipal plant because of the fundamentally different effluent quality. The method also was not appropriate for representing industrial effluent quality for the four pulp/paper mills, five oil refineries, and aluminum plant. Finally, because treatment technologies are different for eight of the nine Canadian WWTPs, the extrapolation templates were not appropriate. The method used to estimate concentrations from 1999-2008 for these exceptions are described in more detail below.

Carlyon Beach WWTP
Nitrogen concentrations at Carlyon Beach (53 mg/L median for TPN and NO23N) are much higher than the typical small WWTPs in the SPSDO study area (9.81 mg/L annual average TPN for small plants). The plant receives sewage tank pump outs and does not receive inflow and infiltration like most municipal treatment systems with transmission systems. Little variation occurred in the data collected at this plant over three months, but the values were uniformly higher than for typical small plants. Therefore, we calculated the average of these three months of data for all parameters and applied these averages for the full 1999-2008 time period.

Pulp/Paper Mills
As part of the SPSDO study, three months of data were also collected at Simpson Kraft in Tacoma. Effluent data showed some variability, although effluent nitrogen concentrations were much lower than typical municipal wastewater effluent and carbon content was much higher. We used these data to develop a *simple* linear regression relationship (not *multiple* linear regression) between flow and effluent concentration for all parameters except CBOD. These linear equations were then used to predict daily concentrations for these parameters using daily flows, with the minimum and maximum values capped by the monitoring data. Since sufficient CBOD data were available from the DMRs for Simpson Kraft, we were able to develop a specific multiple linear regression for CBOD.

The other three pulp/paper industries in the study area (Kimberly-Clark, Nippon Paper and Port Townsend Paper) did not have any plant-specific data except for effluent flow and CBOD data reported in DMRs. This CBOD data were used to develop plant-specific multiple linear regressions to predict CBOD concentrations for 1999-2008. For all other water quality parameters in Table 2, we assumed that the data collected at Simpson Kraft was representative of pulp/paper industries, and applied the mean of the Simpson Kraft data to these three pulp/paper industries for the years 1999-2008.

Oil Refineries
We did not collect any data at any of the five oil refineries: U.S. Oil & Refining, BP Cherry Point, Conoco Phillips, Shell Oil, and Tesoro Refining. Since these are not domestic wastewater or pulp/paper waste, the concentration templates developed using WWTP data and regressions could not be applied to their effluents. However, NH4N and CBOD data were available through WPLCS, and

site-specific multiple linear regression relationships were developed for these two parameters at all five facilities. These regression relationships were used to predict monthly NH4N and CBOD from 1999-2008.

For the rest of the parameters in Table 2, we used the following approach:

- Assume all effluent nitrogen is in the form of NH4N; therefore NO23N concentration = 0.0 mg/L)
- Assume constant OP concentration at 0.4 mg/L, based on an estimate by EPA for petroleum refineries (EPA, 1996). This is about 10 times lower than that typical of municipal wastewater effluent.
- Assume all organic carbon is in dissolved form. Therefore, TOC = DOC and POC = 0.0 mg/L. Assume constant DOC at 10 mg/L, based on monitoring data (9.5 mg/L) associated with U.S. Oil & Refining permit renewal and based on conversations with the industrial permit manager.

Intalco Aluminum Facility
We did not collect any data at the Intalco facility, and the discharge permit does not require monitoring for any of our parameters of interest except flow. However, BOD, TOC, ammonia, and nitrate are characterized in the effluent during permit renewals (Judy Schwieters, personal communication). We used these data as constant values in the Intalco effluent. Phosphorus is believed to be absent from the effluent stream according to the permit writer, and these plus other water quality constituents in Table 2 were set to 0.0 mg/L. All TOC was assumed to be in DOC form.

Canadian WWTPs
We used data from Metro Vancouver for the five WWTPs located in/around Vancouver and data from CRD for the WWTPs located on Vancouver Island to characterize municipal Canadian WWTP effluents. Since the PSDOM does not require fine-resolution data for these WWTPs, which are located in the model periphery, we applied a constant concentration (the average of 2008 values from reported data) for most parameters for the years 1999-2008.

Metro Vancouver, however, did not have any carbon data for any of their WWTPs. For carbon parameters, we applied the large-plant template concentrations of TOC, DOC and POC developed from U.S. plant data. Wastewater in two of the Canadian WWTPs generally undergoes a lower level of treatment than those in Washington State, so these template values are likely an underestimate of actual carbon concentrations at these plants. If we find that the PSDOM model is sensitive to these inputs, we will re-evaluate and refine these estimates.

The small template was applied for all parameters for the Gulf Islands WWTP since no annual report was found for this plant at the time we were gathering data. The other three WWTPs on Vancouver Island had 2008 data for all parameters so we simply applied a constant concentration (the average of 2008 values from reported data) for the years 1999 through 2008.

Calculating Daily Loads

Continuous monthly nutrient loads from WWTPs were calculated from the predicted monthly concentrations and monthly flows for the years 1999-2008 the same way as for watershed loads:

Monthly load = (predicted monthly concentration) x *(monthly effluent flow)*

Even though we capped WWTP concentrations by the maximum of observed instantaneous concentrations, many WWTPs had a few unusually high spikes in their loads due to a combination of regression parameters and coincident high plant flows. Though these spikes do not strongly influence seasonal inputs, we also capped all loads by the maximum instantaneous observed loads from the SPSDO study. Predicted loads were then compared with observed loads for those locations where we had data.

Natural Conditions

An important part of this study involves the development of natural conditions. Natural conditions in this study refer to the concentrations of nutrients in rivers and streams without significant human influences/sources of nutrients. By definition, there would be no WWTP, septic system inputs, or other human sources into Puget Sound under natural conditions. There are various natural sources and sinks of nitrogen in streams. These include rainfall, riparian and terrestrial vegetation, spawning salmon, various instream nitrogen biogeochemical cycling processes, and decomposition of organisms. Once natural watershed concentrations are established, they can be used as inputs into the water quality model so that we can evaluate the water quality of Puget Sound under natural conditions.

We did not develop natural conditions for Canadian watersheds because of limited information, and will develop these estimates once we have better scientific information directly from Canadian sources.

Since monitoring of rivers and streams has occurred post-human development, we do not have historic water quality data that go back far enough in time to reflect pristine, natural, or pre-development conditions in rivers and streams draining to Puget Sound. Therefore, recent data need to be used to determine natural concentrations of nutrients in rivers and streams.

We performed a meta-analysis to establish natural conditions for rivers and streams that drain into Puget Sound for the following parameters: TPN, NO23N, NH4N, TP, and OP. This meta-analysis primarily was based primarily on two sources of nutrient data: recent ambient data and atmospheric (rainfall) data. Natural nutrient concentrations were calculated for each month of the year to capture changes in concentration due to seasonality. The two sources of data that we used are described below, along with other sources of information which we consulted to check if our concentration estimates were within the right range.

Recent Ambient Water Quality Data at the Mouths of Rivers

Ecology maintains several ambient freshwater monitoring stations located throughout Washington. We used data collected between water years 2002-09 from monitoring stations located closest to the mouths of watersheds that drain into Puget Sound and the Straits. For TP, however, we only used data from water years 2008-09 since there was a change in MEL methods in 2003 and again in 2007. This change did not allow us to pool older data with newer data. Tenth percentiles represent the lower range of current observed concentrations and may therefore represent concentrations in the absence of human sources of nutrients. Table 4 lists the station locations selected within each region of study area.

Table 4. List of ambient monitoring stations grouped into different regions of Puget Sound that were used as part of the meta-analysis to establish natural conditions.

Region	Station Name(s)	Station ID	Percent Developed*
Puget Sound			
South Sound	Deschutes River at E St. Bridge Nisqually River at Nisqually	13A060 11A070	23%
Commencement Bay	Puyallup River at Meridian St.	10A070	19%
Puget Main	Cedar River at Logan St./Renton	08C070	48%
Elliott Bay	Green River at Tukwila	09A080	33%
Whidbey	Skagit River near Mt. Vernon Stillaguamish River near Silvana Snohomish River at Snohomish	03A060 05A070 07A090	8%
Hood Canal	Skokomish River near Potlatch Duckabush River near Brinnon	16A070 16C090	5%
Strait of Georgia/Juan de Fuca			
Strait of Georgia (USA)	Samish River near Burlington Nooksack River at Brennan	03B050 01A050	7%
Strait of Juan de Fuca (USA)	Elwha River near Port Angeles	18B070	24%

* Percent non-forested land cover based on the National Land Cover Dataset MRLC (Herrera, 2011).

After pooling concentration data from different ambient stations into the appropriate region of Puget Sound, we calculated the following concentration statistics for each region: 10^{th}, 25^{th} and 75^{th} percentiles, minimum, maximum and medians. We then analyzed concentration data in each region of Puget Sound, using monthly box-plots to identify differences between basins as well as seasonal patterns. The results of this analysis are presented in the Results section of this report.

Atmospheric (Rainfall) Data

The National Atmospheric and Deposition Program's (NADP) National Trends Network has stations that measure concentrations of nitrate and ammonia in rainfall throughout Washington State. Data from the following four stations in western Washington were retrieved for water years 2002-2009:

1. Olympic National Park – Hoh Ranger Station (WA14).
2. North Cascades National Park – Marblemount Ranger Station (WA19).
3. Mount Rainer National Park – Tahoma Woods (WA99).
4. La Grande (WA21).

We calculated monthly median concentrations of NO23N and NH4N for all stations.

Other Sources of Supporting Information

Puget Sound Toxics Runoff Project

Ecology‘s Puget Sound Toxics Loading Project estimated the concentrations of nutrients in surface runoff for both baseflow and stormwater events from watersheds with different land cover types (Herrera Environmental Consultants, 2011).

Field data for this project were collected and measured by Herrera Environmental Consultants. We used the median of the data collected from predominantly forested sub-basins within the Puyallup and Snohomish watersheds. These data were selected because under natural conditions, most of the watersheds that drain into Puget Sound were forested. A single annual median value was used to represent each month out of the year since these data were not collected at monthly intervals.

Hood Canal Dissolved Oxygen Program

The Hood Canal Dissolved Oxygen Program is a partnership of various organizations that conduct monitoring and analysis to address low DO levels in Hood Canal. As part of their analysis, they estimated natural background NO23N concentrations for rivers and streams entering Hood Canal (Steinberg et al., 2010).

EPA Ecoregional Criteria

The Environmental Protection Agency (EPA) has developed ecoregional nutrient criteria for rivers and streams throughout the nation. The Puget Sound region falls within ‗Nutrient Ecoregion II - Western Forested Mountains‘. Ecoregion II also includes most of the great mountain ranges located west of the Great Plains (EPA, 2000).

Results

Multiple Linear Regression

The *multiple linear regression* method used to estimate daily nutrient concentrations performed well in estimating the concentrations of most parameters when compared to observed data for both rivers and WWTPs. Overall, the method provides a better estimate of daily concentrations in rivers and WWTPs than using constant values or monthly averages. The method was also able to capture changes in concentration due to flow and seasonality.

For most parameters, predicted vs. observed nutrient *loads* compared better than predicted vs. observed nutrient *concentrations* across all streams and WWTPs. This was true even for those parameters that did not yield significant regression relationships or did not have high adjusted R^2 values. This is because the variability in flow exceeds the variability in concentration, resulting in predicted loads that match well to observed loads.

Table 5 presents a summary of the significance and adjusted R^2 values of the multiple linear regression relationships developed using concentration data in each of the watersheds that had sufficient data. The majority of parameters (9 out of 13) had significant regression relationships for the majority of watersheds. For these watersheds, the regression equation explains 50-81% of the variability (median R^2 values range from 0.50 to 0.81) in measured concentrations.

Table 5. Overall significance and median adjusted R^2 values of regression relationships developed for nutrient concentration parameters for the watersheds used to develop regressions.

Parameter	% significant relationships	Median Adjusted R^2
NO23N	94%	0.81
DTPN	89%	0.70
DOC	86%	0.69
TP	85%	0.75
TPN	84%	0.74
DTP	78%	0.68
OP	75%	0.67
POP	70%	0.62
NH4N	62%	0.50
DOP	52%	0.17
DON	48%	0.38
PON	30%	0.16
POC	18%	0.01

Regressions for all forms of nitrogen (except NH4N) performed very well. Concentrations of NH4N influenced by the analytical detection limit and are generally much lower than the other forms nitrogen, so even if NH4N predictions are less accurate, these concentrations will not significantly affect overall nitrogen loading estimates. The same applies to phosphorus and carbon. Inorganic forms of phosphorus and carbon generally had stronger regression relationships than the organic forms of phosphorus and carbon, which typically have lower concentrations.

Table 6 presents a summary of the significance and adjusted R^2 values of the multiple linear regressions relationships developed using concentration data at each of the 17 WWTPs from the SPSDO study that had sufficient data. Regression relationships developed for WWTPs were not as strong as those that were developed for rivers. However, the regression method still provided a better fit to monitoring data than simple averages, as indicated by the root mean square errors calculated using multiple methods for the Tacoma-Central WWTP. The Tacoma-Central plant was used for comparison because nitrogen levels in the effluent were more variable than at other plants.

Table 6. Overall significance and median adjusted R^2 values of regressions relationships developed for nutrient concentration parameters for the 17 WWTPs used to develop templates.

Parameter	% significant relationships	Median Adjusted R^2
DTP	47%	0.51
NO23N	41%	0.56
DTPN	35%	0.27
NH4N	35%	0.36
TPN	29%	0.20
TP	29%	0.41
OP	29%	0.32
TOC	24%	-0.03
CBOD	6%	0.10
DOC	0%	0.06

Mohamedali et al. (2011) presented plots of predicted and observed concentrations and loads for a few large rivers (Deschutes, Nisqually, Puyallup, and Green) in South Puget Sound, as well as for all large WWTPs (> 10 mgd) where we collected data. Appendix B of this report presents additional plots of predicted and observed nutrient concentrations for the four largest rivers in the U.S. north of Edmonds (Skagit, Snohomish, Stillaguamish and Nooksack), and Appendix C compares measured and predicted CBOD concentrations for a few of the largest pulp/paper mills and WWTPs in the U.S. for the area north of Edmonds not covered in the SPSDO study.

The rest of this report focuses primarily on DIN since (1) nitrogen is the nutrient of greatest concern in Puget Sound, (2) most total nitrogen is in the form of DIN for both rivers and WWTPs, and (3) of all the forms of nitrogen, DIN is the most bioavailable and therefore the most relevant in the context of low DO levels. Based on comparisons in South and Central Puget Sound, 86% of the total load from rivers is in the form of DIN while 90% of the total nitrogen from WWTPs is in the form of DIN (Mohamedali et al., 2011). Figures presenting our data for various other forms of nitrogen, phosphorus, and carbon are included in Appendix D and Appendix E. Each of these nutrient components is accounted for in the water quality model.

Watershed Loads

The total mean annual DIN loads into Puget Sound from all 64 watersheds varies from 60,000 to 80,000 kg/d from 1999-2008 (Figure 10). The totals include contributions from U.S. (22,000 to 40,000 kg/d) and Canadian watersheds (40,000 to 50,000 kg/d).

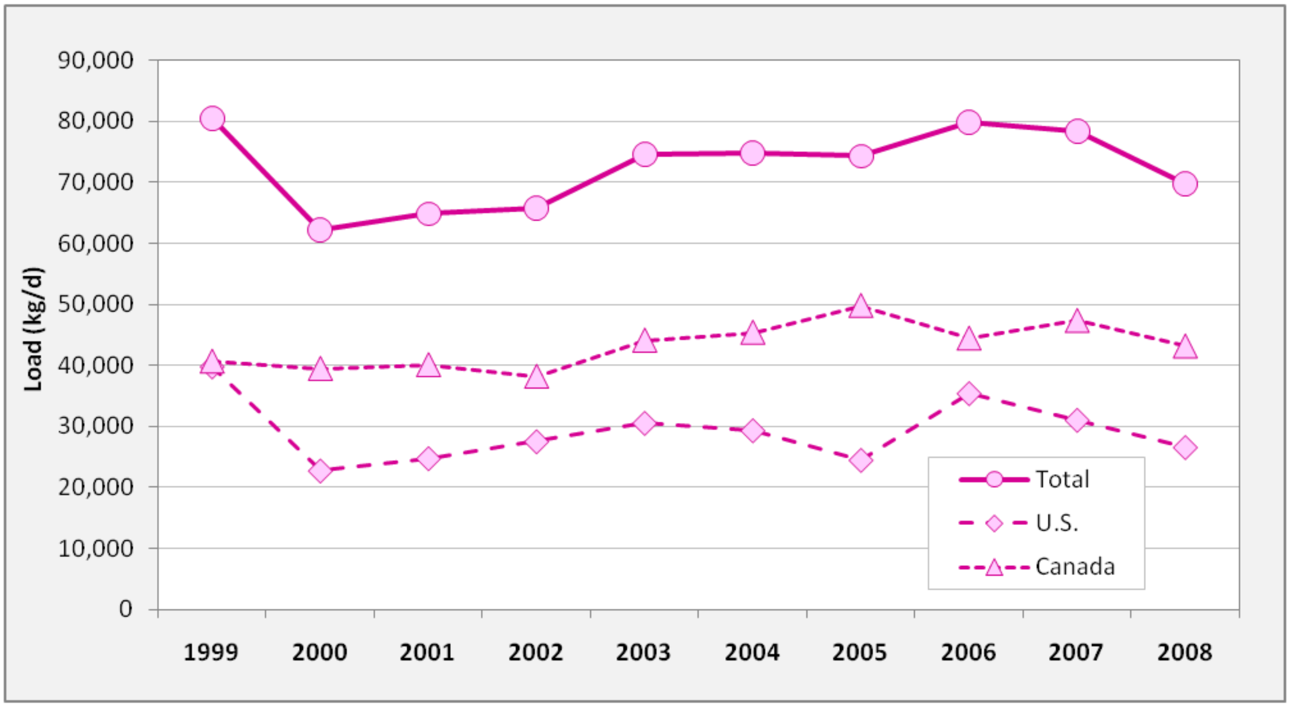

Figure 10. Sum of mean annual watershed DIN loads from all 64 watersheds from 1999-2008.

Figure 11 illustrates the geographic variation in annual median DIN concentrations for all watersheds in the study area for 1999-2008. In addition, Figure 12 presents box and whisker plots of annual median watershed DIN concentrations. The highest median concentrations of DIN (the form of nitrogen of greatest interest) are found watersheds in South Sound (Henderson, McAllister, Chambers, and Budd/Deschutes). These watersheds do not have headwaters in the Cascades and therefore do not benefit from dilution, they also have complicated hydrogeology and a larger concentration of septic systems. High median DIN concentrations are also found in the South King, Samish, Whatcom and Nooksack watersheds; the latter three have relatively high agricultural land uses.

The box and whisker plots show several watersheds with similar DIN concentration patterns. Identical concentration ranges indicate watersheds in close proximity where the same regression relationships were applied, resulting in similar predictions of DIN. The range of DIN concentrations found in rivers and streams draining into the southern basins of Puget Sound are greater than the rane of DIN concentrations found in rivers and streams draining the northern basins. Watersheds draining into Hood Canal have lower DIN concentrations than any of the other regions.

The watersheds that have high DIN concentrations are not necessarily the same ones that have high DIN loads since loads are generally higher for watersheds with higher flows and drainage areas. Figure 13 illustrates how all the larger rivers/watersheds in the study area have DIN loads that are at least an order of magnitude higher than the rest of the watersheds in the study area.

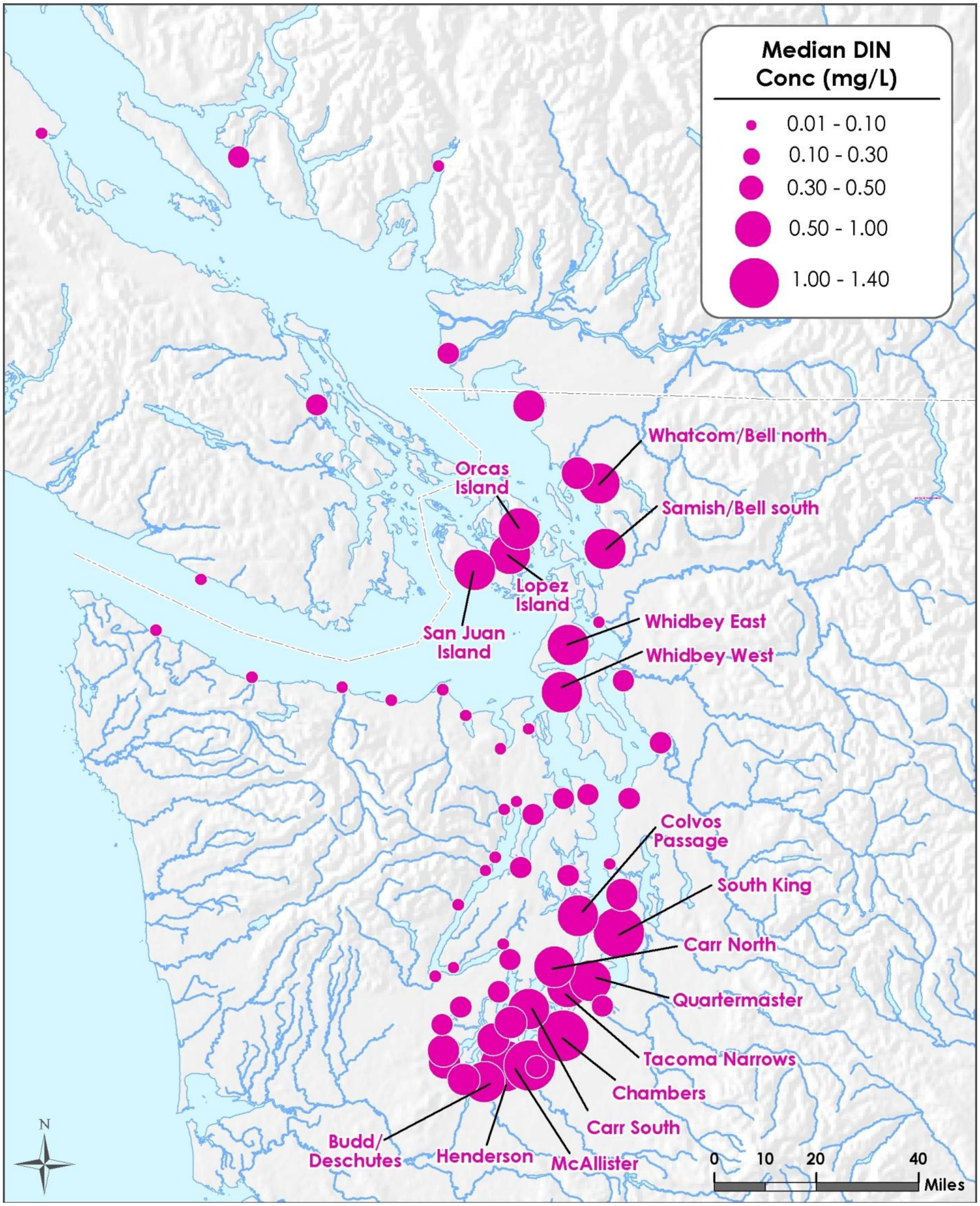

Figure 11. Annual median watershed dissolved inorganic nitrogen concentrations for 1999-2008.

Only watersheds that have median DIN concentrations greater than 0.50 mg/L are labeled.

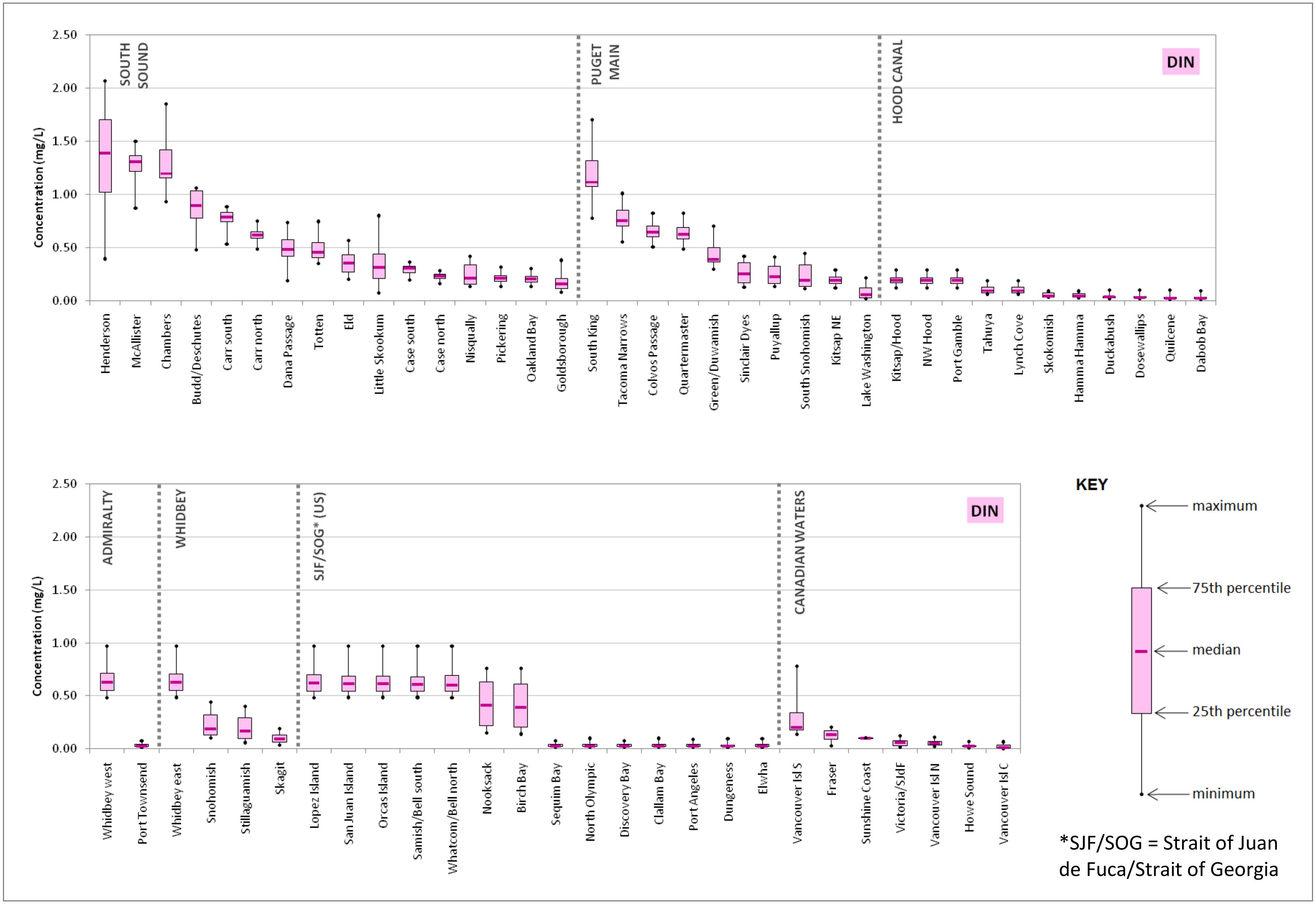

Figure 12. Box plots of dissolved inorganic nitrogen concentrations for watersheds draining into different regions of Puget Sound, 1999-2008.

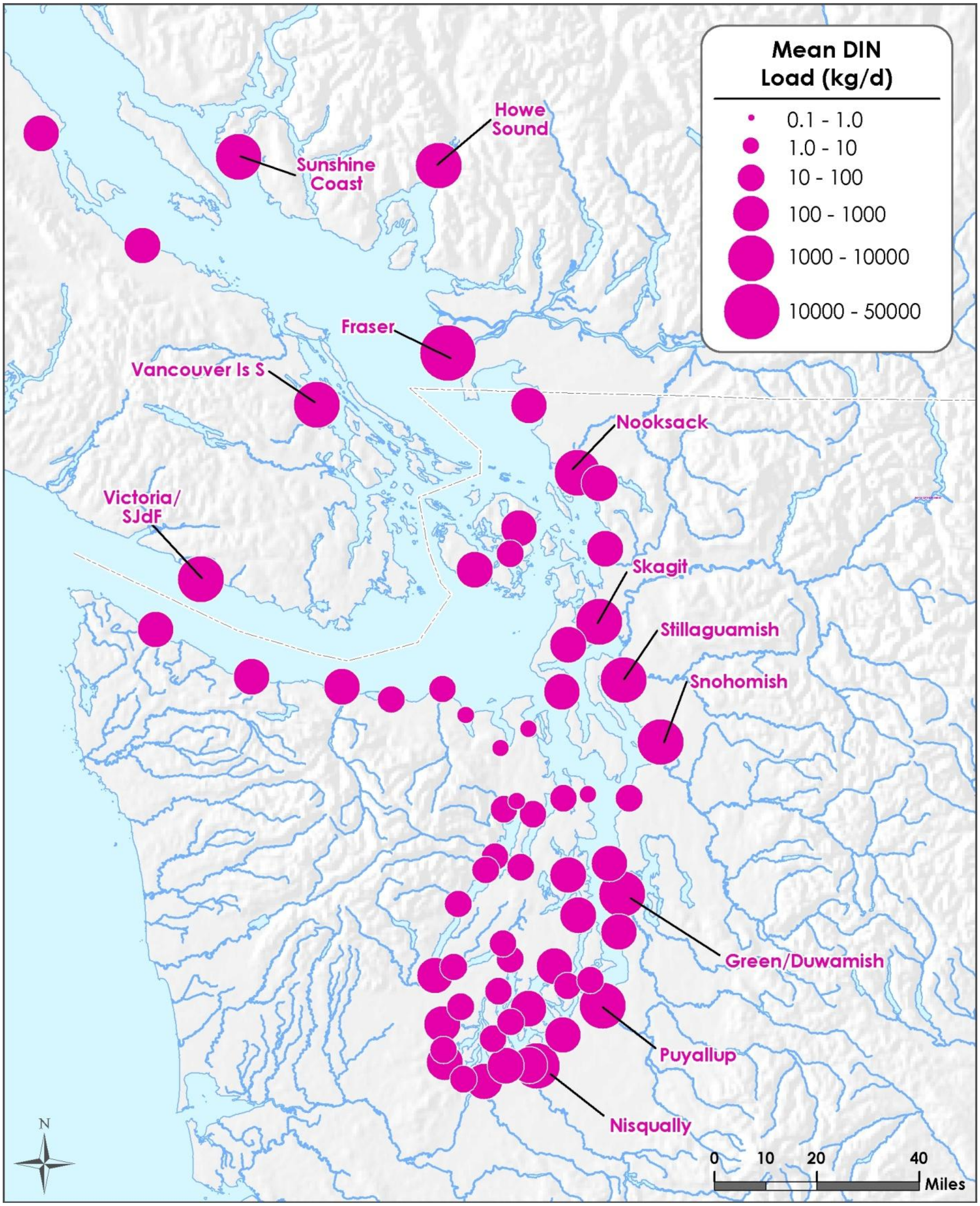

Figure 13. Mean annual watershed dissolved inorganic nitrogen loads for 1999-2008.
Only watersheds that have DIN loads greater than 1000 kg/d are labeled.

Table 7 presents the top 20 watershed DIN loads to the model domain. The Fraser River watershed is by far the largest watershed in the whole study area, draining a large portion of western Canada, and has a mean annual DIN load of 33,140 kg/d. This is followed, in order of DIN loads, by the Snohomish River (5,950 kg/d), Sunshine Coast (4,480 kg/d), Nooksack River (4,180 kg/d) and Skagit River (4,220 kg/d).

Table 7. Top 20 watershed contributions of DIN.

Rank	Watershed	Basin	Load (kg/d)
1	Fraser	Canada	33,136
2	Snohomish	Whidbey	5,945
3	Sunshine Coast	Canada	4,479
4	Nooksack	Canada	4,176
5	Skagit	Whidbey	4,224
6	Stillaguamish	Whidbey	2,441
7	Puyallup	Commencement Bay	2,105
8	Victoria/SJdF	Canada	2,039
9	Vancouver Isl S	Canada	1,777
10	Green/Duwamish	Elliott Bay	1,635
11	Nisqually	South Sound	1,427
12	Howe Sound	Canada	1,256
13	Budd/Deschutes	South Sound	842
14	Samish/Bell south	Canada	771
15	Whatcom/Bell north	Canada	609
16	Chambers	South Sound	488
17	Lake Washington	Puget Main	432
18	Vancouver Isl N	Canada	360
19	McAllister	South Sound	312
20	Sinclair Dyes	Sinclair Dyes	230

Though Figure 13 is useful for identifying the watersheds with the highest DIN loads, it does not account for difference in the size of each watershed relative to the others, which generally governs the total flow. We therefore normalized each watershed load by the watershed area to determine the ‗relative load', as follows:

$$Relative\ Load = \frac{load\ for\ watershed\ i/total\ load\ from\ all\ watersheds}{drainage\ area\ of\ watershed\ i/total\ area\ of\ all\ watersheds}$$

where *i* in the above equation represents a particular watershed in the study area. Relative loads greater than 1.0 are higher than average, while relative loads below 1.0 are less than average.

For example, the Fraser River watershed occupies 80.7% of the study area but accounts for 46.0% of the total DIN load. Its relative load is therefore 46.0 divided by 80.7, which is equal to

0.57 (i.e. below average). Figure 14 illustrates the relative loads for all the watersheds in the study area, where darker colors represent higher relative loads.

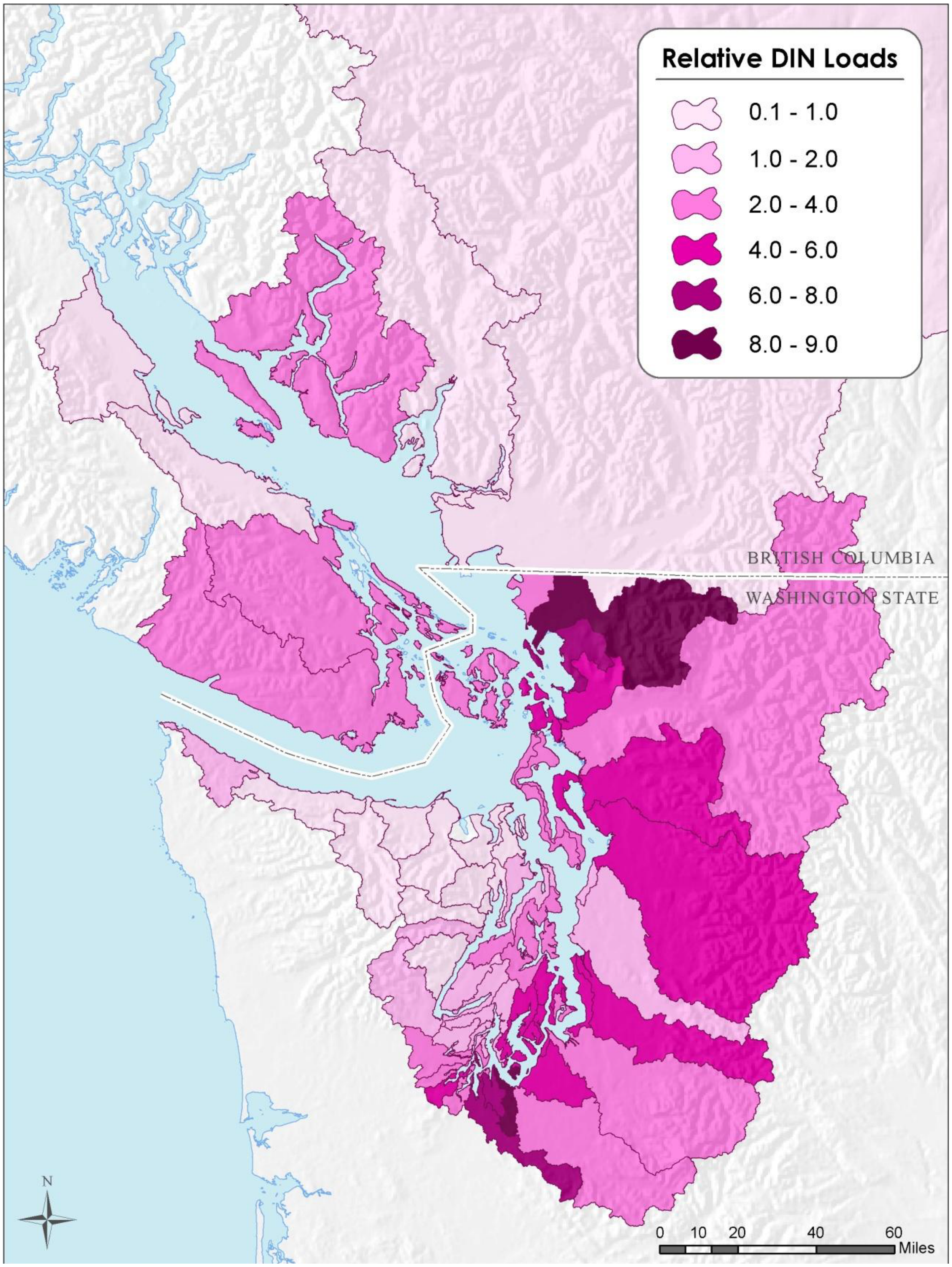

Figure 14. Annual relative dissolved inorganic nitrogen loads (ratio of fractional load to fractional area) from watersheds during 1999-2008.

Watersheds draining into Budd and Henderson Inlets in South Puget Sound as well as those draining into Bellingham Bay have some of the highest relative DIN loads. Some of these watersheds are more densely populated, or greater urban or agricultural land use in these watersheds compared to other watersheds (Embrey and Inkpen, 1998). In contrast, the loads from the Fraser River and those on the Olympic Peninsula draining to Hood Canal and the Strait of Juan de Fuca represent the lowest relative loads in the study domain.

Since the Deschutes River drains into Capitol Lake before entering Budd Inlet, we also estimated flows, nutrient concentrations, and loads at the outflow of Capital Lake. These concentrations and loads differ from those in the Deschutes River since some of the nutrients get assimilated within Capitol Lake before entering Budd Inlet. In this report, we are only presenting loads from the Deschutes River so that we can compare these with loads from other watersheds. However, the model will use the Capitol Lake data to represent the inflow into Budd Inlet.

The model will be used to determine what regions of Puget Sound or the Straits are more sensitive to nitrogen loading to others. The loading data by watersheds were summed based on these different regions of Puget Sound; the regional delineations are illustrated in Figure 15. These regions coincide with the regions in the Puget Sound Box Model, which is another model that is being developed and used by Ecology. However, the Puget Sound Box Model does not extend up north to B.C.; watersheds in B.C. are therefore subdivided into those draining mainland Vancouver and those draining Vancouver Island.

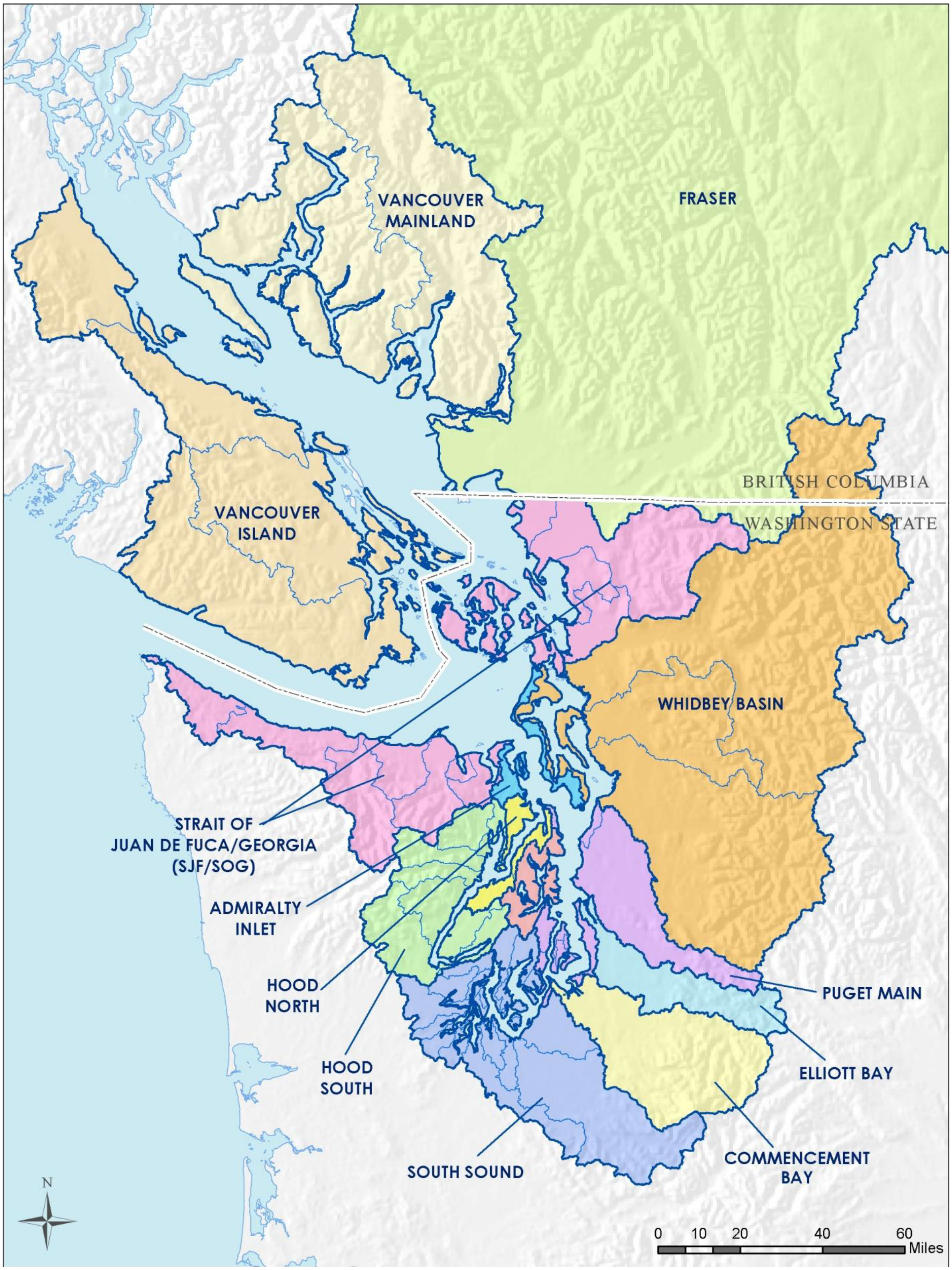

Figure 15. Watersheds in the study area color-coded and labeled according to the different regions in Puget Sound *into* which they drain (U.S. watersheds), or the areas *from which* they drain (Canadian watersheds).

Figure 16 presents monthly DIN for each region in Puget Sound identified in Figure 15. Except for the Fraser River, most other watersheds contribute peak loads in the winter, when streamflows are also at their peak. The Fraser River dominates summer loads due to a different seasonal pattern where its discharge is dominated by annual snowmelt in the summer months (Ferguson and Healey, 2009). Minimum loads occur in September throughout the basins, which coincides with annual low river flows.

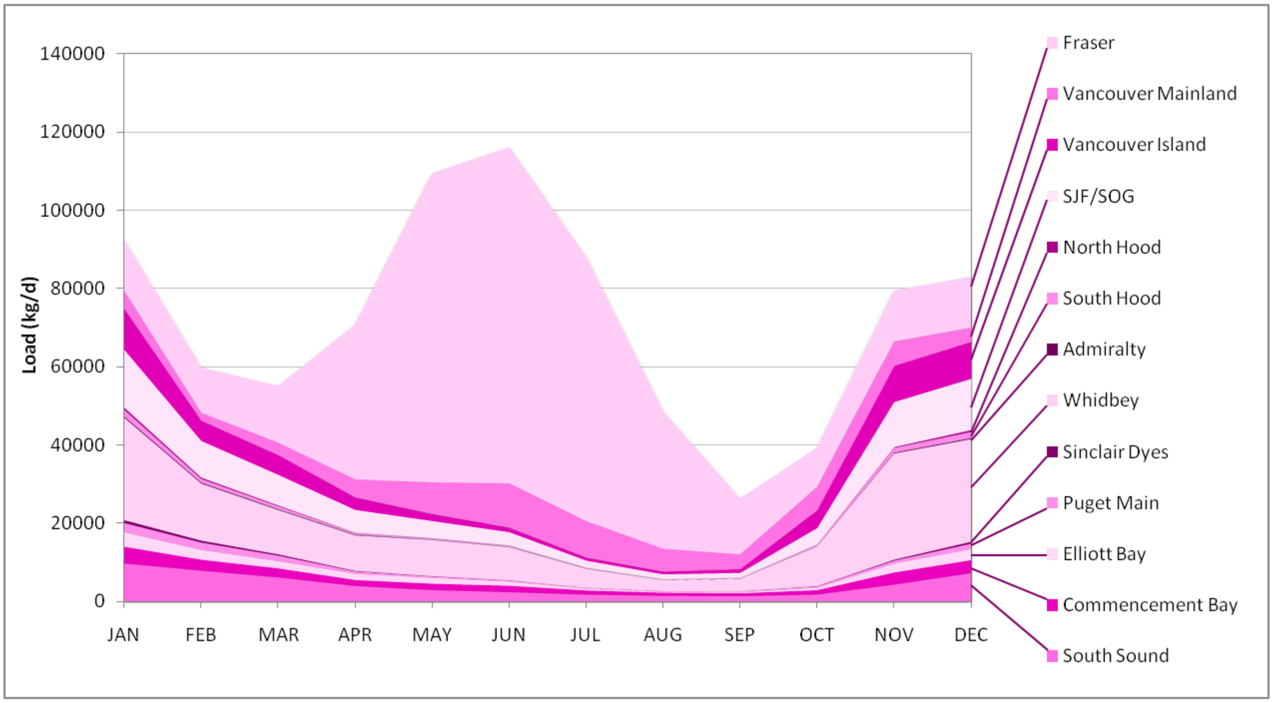

Figure 16. Monthly DIN loads from rivers by Puget Sound Action Area as well as Canadian sources.

Of the U.S. watersheds, those tributary to Whidbey Basin constitute 44% of the total U.S. contributions (Figure 17), followed by the Straits (23%) and South Puget Sound (14%). The three box model regions that comprise Central Puget Sound contribute 16% of the annual watershed load to U.S. waters. Hood Canal, Sinclair-Dyes, and Admiralty Inlet receive the remaining 3% of the annual DIN load from U.S. watersheds.

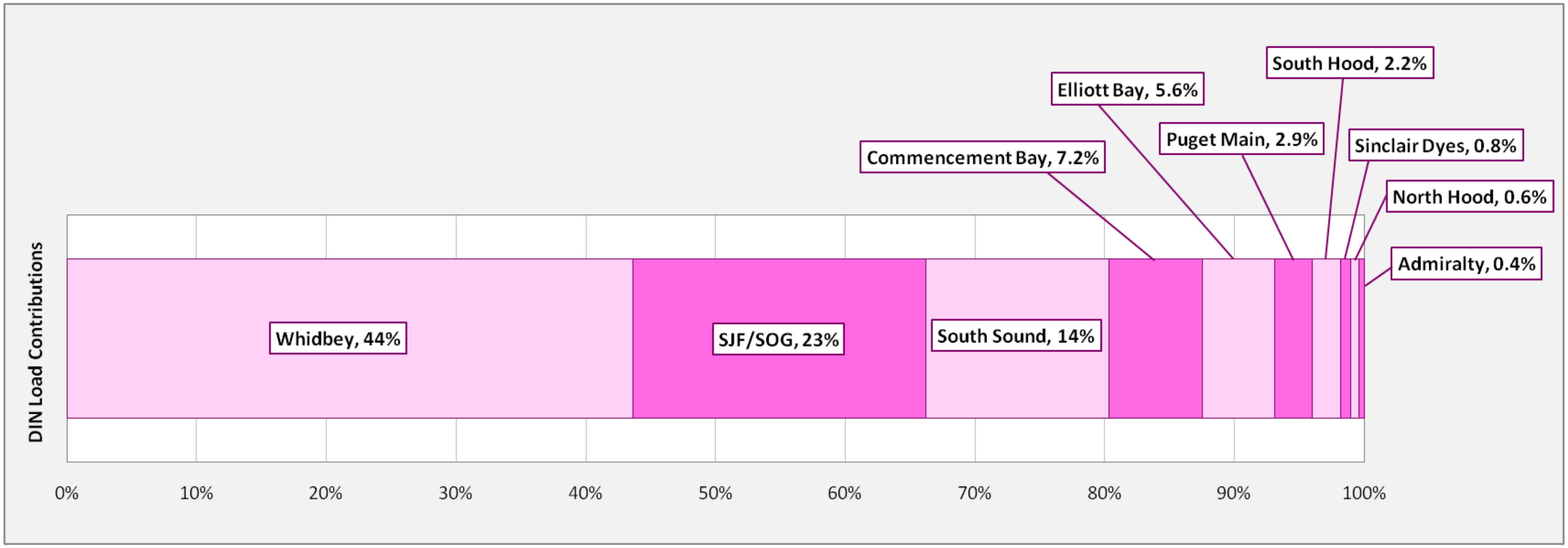

Figure 17. Annual U.S. watershed DIN loads by Box Model region.

Wastewater Treatment Plant Loads

The mean annual DIN loads into Puget Sound and the Straits from all WWTPs varied between 60,000 and 65,000 kg/d from 1999-2008 (Figure 18). U.S. contributions averaged 32,200 kg/d while Canadian WWTPs contributed an average load of 28,000 kg/d.

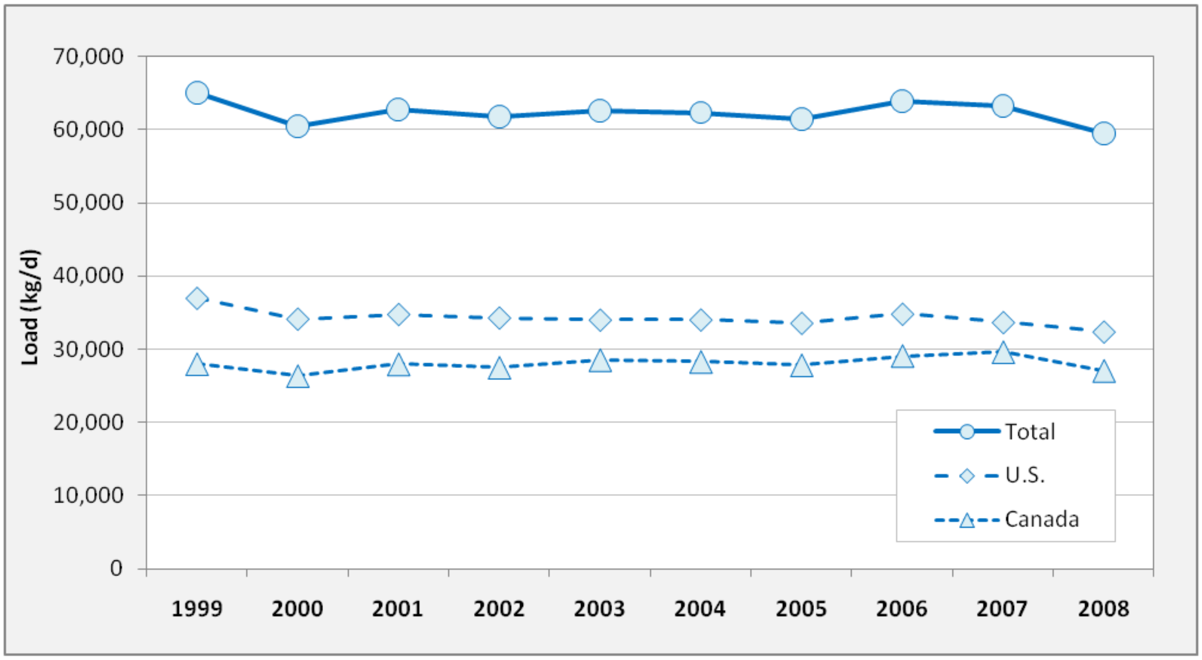

Figure 18. Sum of mean annual WWTP DIN loads from 1999-2008.

Figure 19 illustrates the geographic variation in annual median DIN concentrations for all WWTPs in the study area. From the SPSDO study, generally the highest concentrations were found in the largest plants. Figure 20 presents box and whisker plots of WWTP DIN concentrations. Plants estimated using the templates have identical ranges in the plots.

Effluent from the following WWTPs have the highest median DIN concentrations (in order): Carlyon Beach, Lakota, Central Kitsap, South King, Macaulay, Chambers Creek and Marysville.

Since some WWTPs are larger than others in terms of the magnitude of their effluent flow, the WWTPs that have the highest nitrogen concentrations are not necessarily the same ones that have the highest nitrogen loads. For example, even though Carlyon Beach has relatively high nitrogen concentrations compared to other WWTPs in the study area, the nitrogen loading from this WWTP is relatively low. Figure 21 illustrates annual DIN loads from all WWTPs in the study area. The largest loads coincide with the largest population centers.

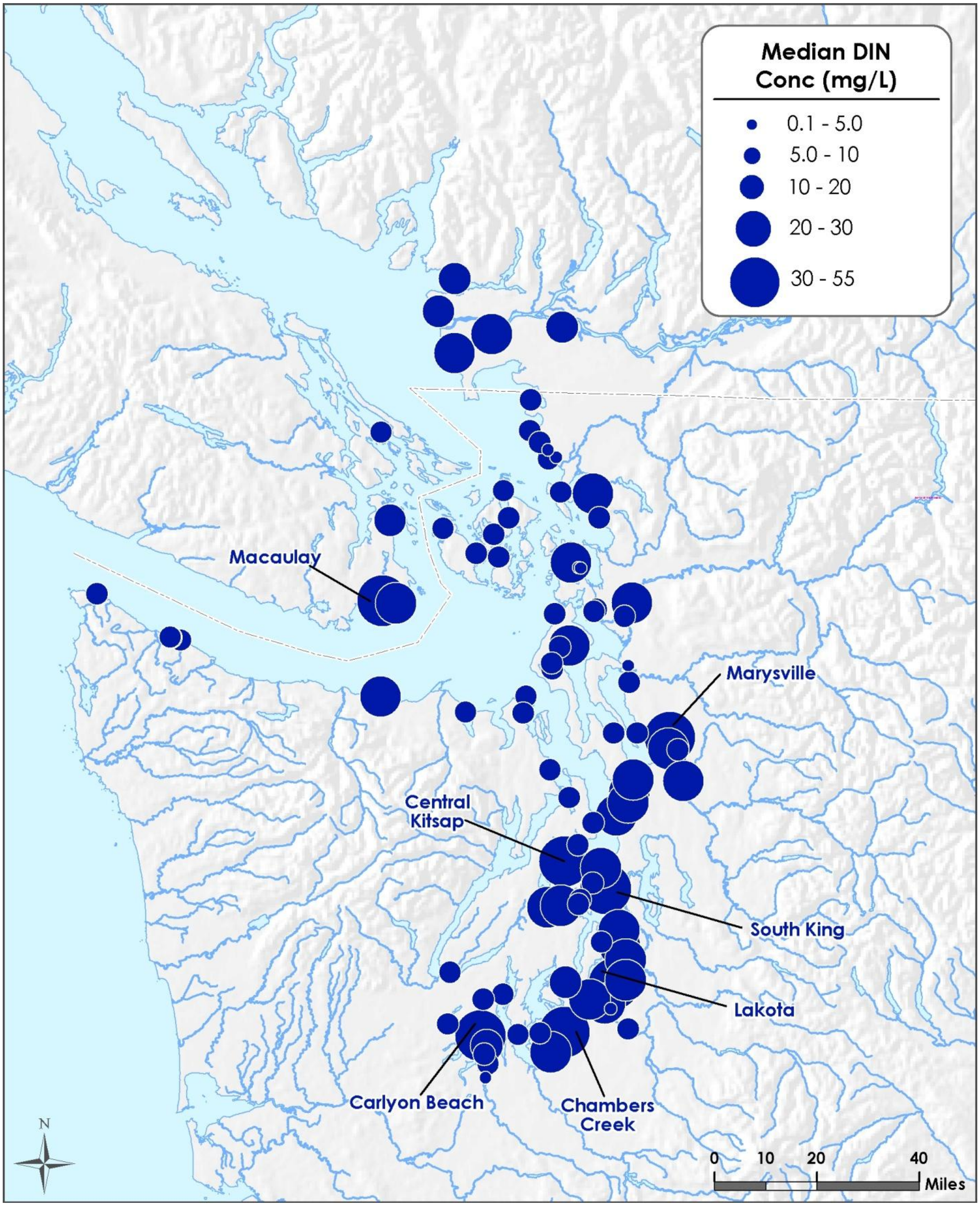

Figure 19. Median WWTP dissolved inorganic nitrogen concentrations for 1999-2008.
Only WWTPs that have DIN concentrations greater than 30 mg/L are labeled.

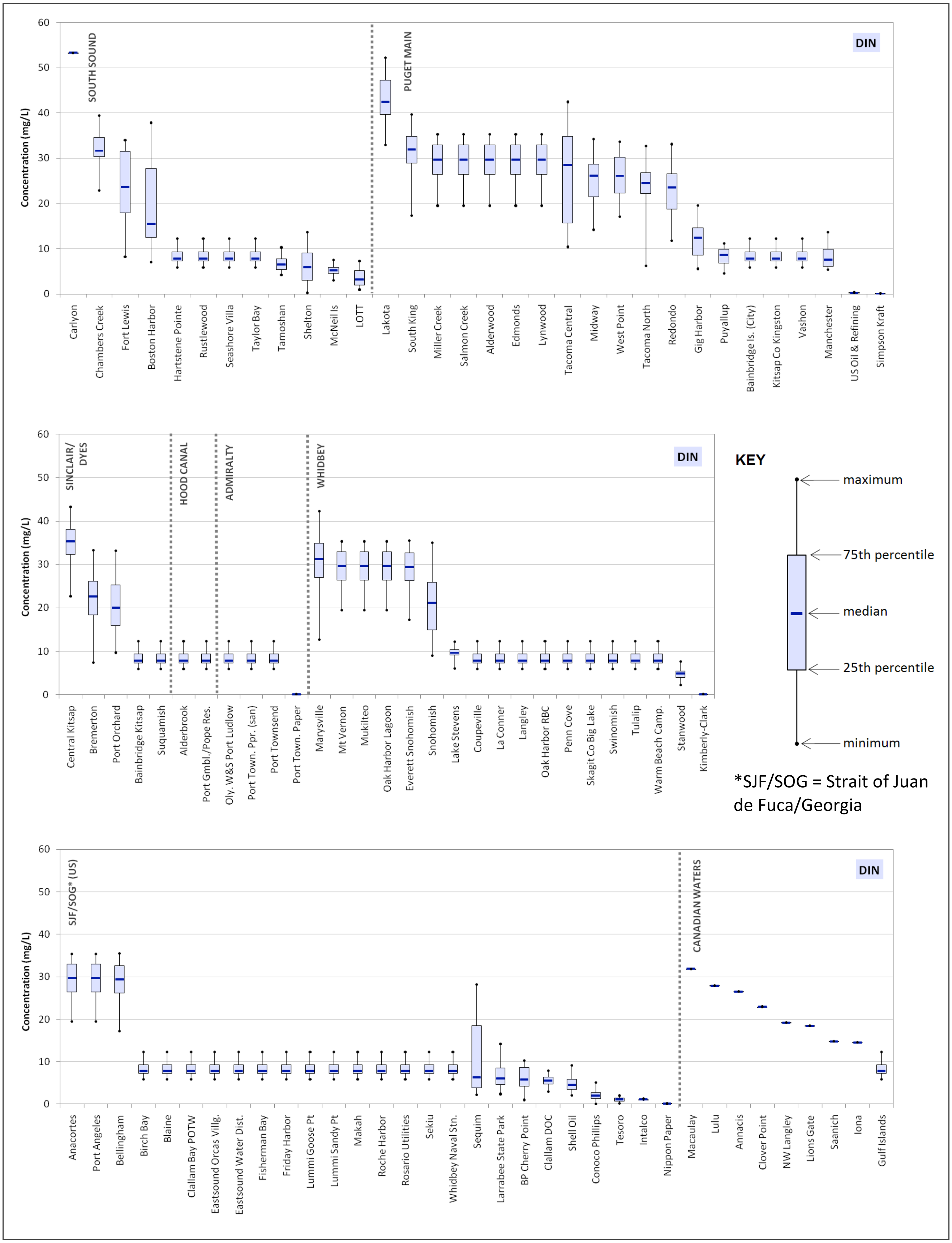

Figure 20. Box plots of dissolved inorganic nitrogen (DIN) concentrations for WWTPs discharging to Puget Sound and the Straits, 1999-2008.

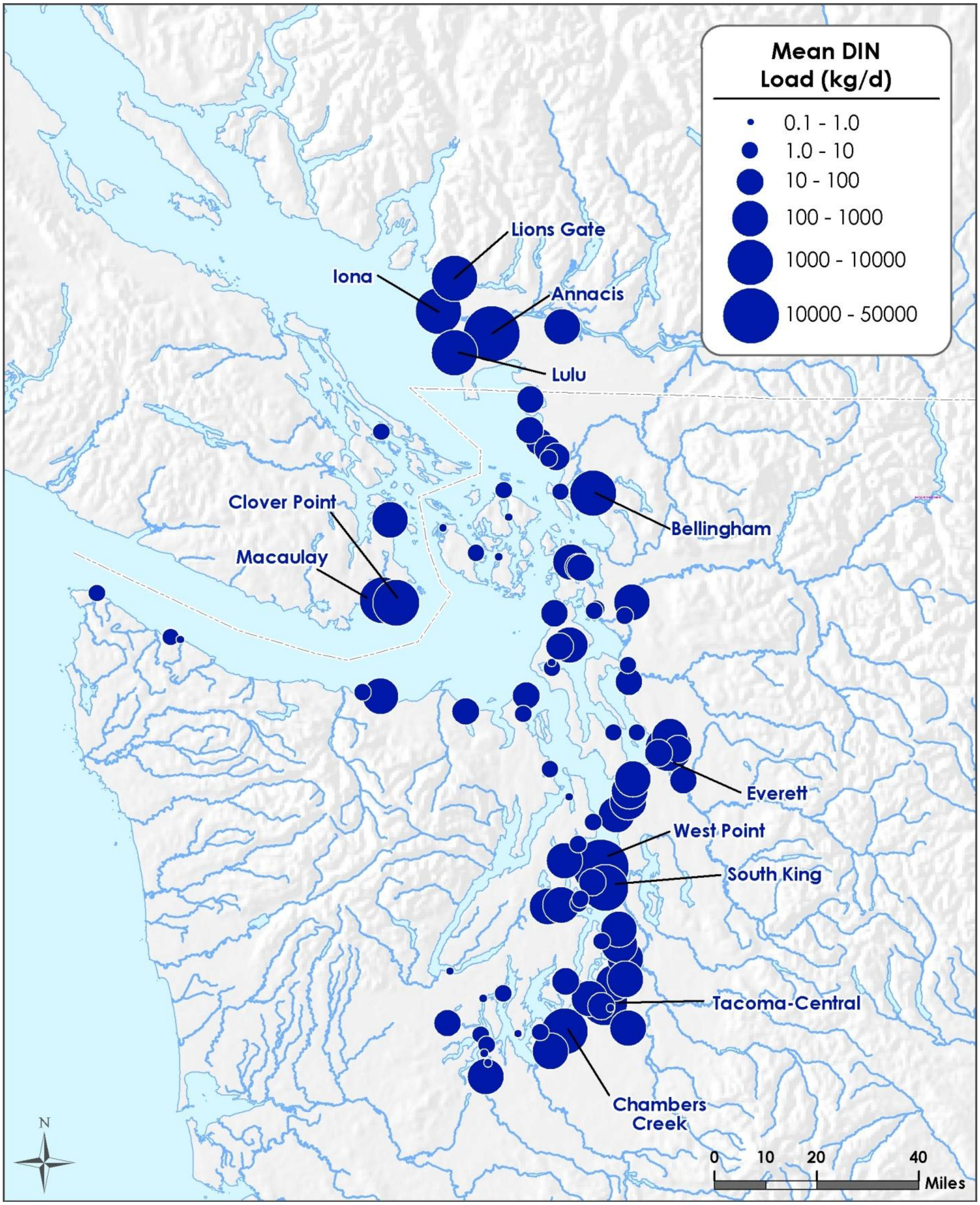

Figure 21. Mean DIN loads from WWTPs, 1999-2008.

Only WWTPs that have DIN loads greater than 1000 kg/d are labeled.

Table 8 presents the top 20 WWTP DIN loads to the model domain. The largest WWTP DIN loads serve the regional population centers in Vancouver (Annacis, Iona, Lulu, and Lions Gate) and Seattle (West Point and South King). These loads total 24,800 kg/d and 19,300 kg/d, respectively. The next largest loads serve the population centers of Victoria (2900 kg/d), Tacoma (2300 kg/d), Pierce County (Chambers Creek, 2000 kg/d), and Everett (2000 kg/d).

Table 8. Top 20 WWTP contributions of DIN.

Rank	Watershed	Basin	Load (kg/d)
1	Annacis	Vancouver Mainland	12,645
2	West Point	Puget Main	10,449
3	South King	Puget Main	8875
4	Iona	Vancouver Mainland	8359
5	Lulu	Vancouver Mainland	2121
6	Chambers Creek	South Sound	2028
7	Everett Snohomish	Whidbey	1989
8	Tacoma Central	Commencement Bay	1910
9	Lions Gate	Vancouver Mainland	1715
10	Macaulay	Vancouver Island	1431
11	Clover Point	Vancouver Island	1419
12	Bellingham	SJF/SOG	1281
13	Lakota	Puget Main	723
14	Edmonds	Puget Main	643
15	Marysville	Whidbey	507
16	Central Kitsap	Sinclair Dyes	461
17	Lynwood	Puget Main	450
18	Bremerton	Sinclair Dyes	418
19	Midway	Puget Main	415
20	Tacoma North	Commencement Bay	398

Monthly average nitrogen loads do not vary greatly over the course of the year (Figure 22). Canadian WWTPs contribute 45% of the average annual DIN load of all WWTPs in the study area. Within the U.S., the higher populations in Seattle (56%) and Tacoma (7%) contribute the largest mass loads from the higher population areas within Central Puget Sound.

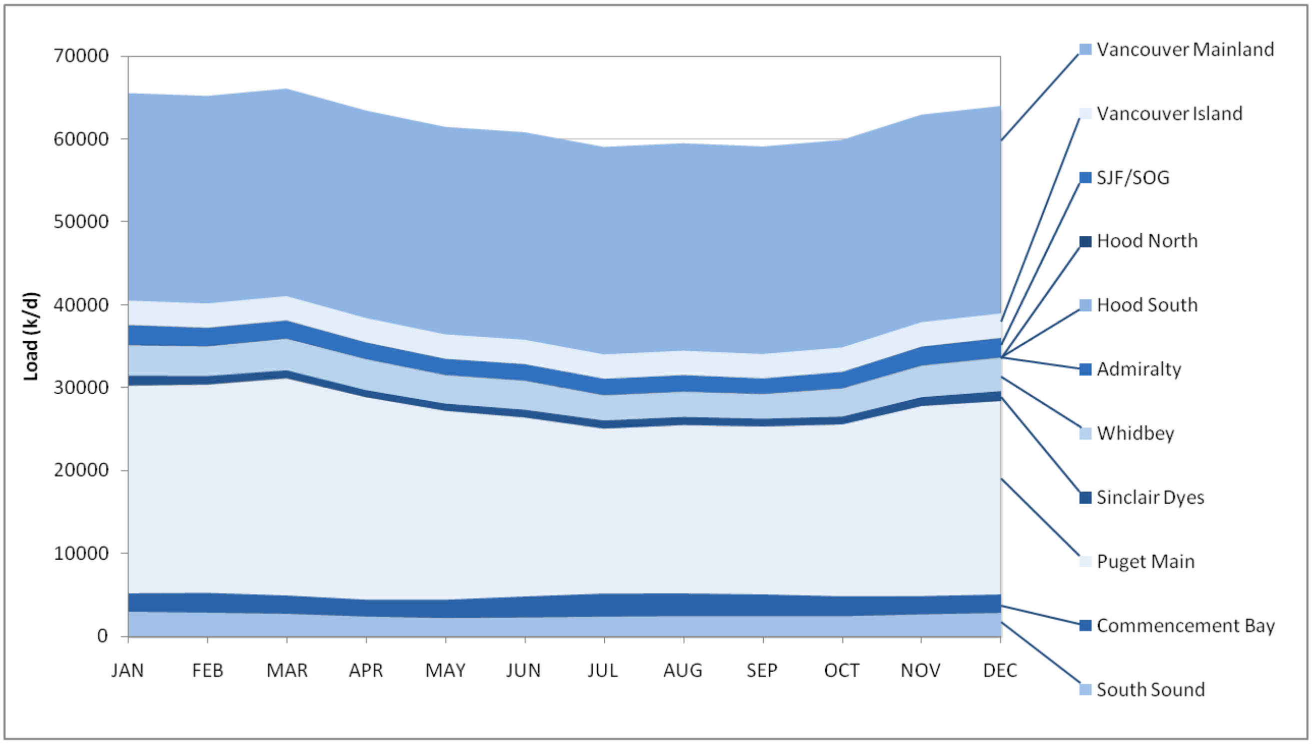

Figure 22. Monthly WWTP DIN loads by Box Model region, including Canadian sources.

Figure 23 compares average annual DIN loads for those WWTPs located in the U.S. The main basin of Puget Sound (Puget Main) receives 66% of total U.S. WWTP contributions, which is the highest relative to other basins in Puget Sound. Next is line is Whidbey basin (10%), South Sound (7.4%) , followed closely by Commencement Bay and SJF (7.1% and 6.0% respectively). Sinclair-Dyes Inlet, Admiralty Inlet, and Hood Canal receive the remaining 3.1% of the annual DIN load from U.S. WWTPs.

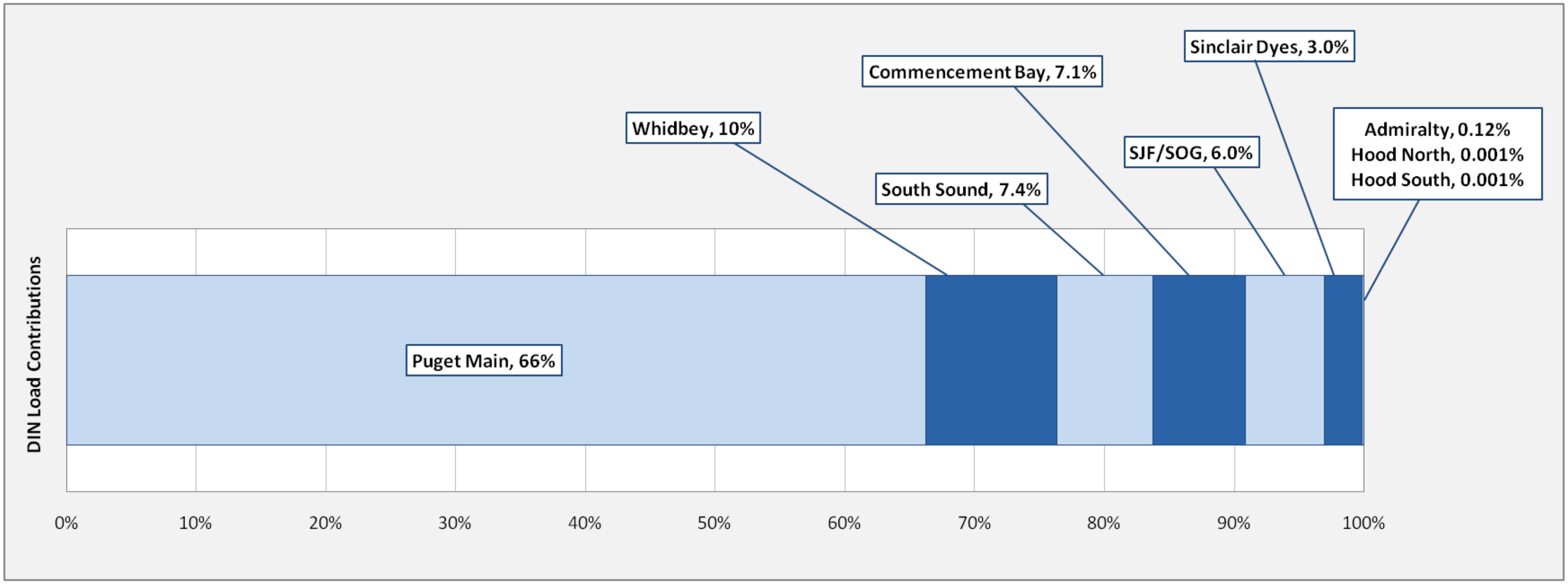

Figure 23. Annual U.S. WWTP DIN loads by Box Model region.

Combined Loads

In addition to nitrogen loads from rivers and WWTPs, the water quality model will include nitrogen loading from ocean exchanges, the atmosphere, and internal sediment fluxes. This will allow us to show the effect of all these sources on DO levels. Combined loads in this portion of the report, however, focus primarily on rivers and WWTPs.

Figure 24 compares and contrasts NH4N and NO23N concentrations for all rivers and WWTPs within the study area. These box plots were created by summarizing statistics on the *median* concentrations of NH4N and NO23N. For example, the minimum values in Figure 24 (lower bars with black dot) are the minimum of all median concentrations of NH4N and NO23N of all rivers/WWTPs.

WWTPs have NH4N concentrations that are two to three magnitudes higher than rivers, and NO23N concentrations that are about one magnitude higher than rivers. NO23N concentrations in rivers are generally higher than NH4N concentrations, while the opposite is true for WWTPs, which have higher NH4N concentrations than NO23N concentrations.

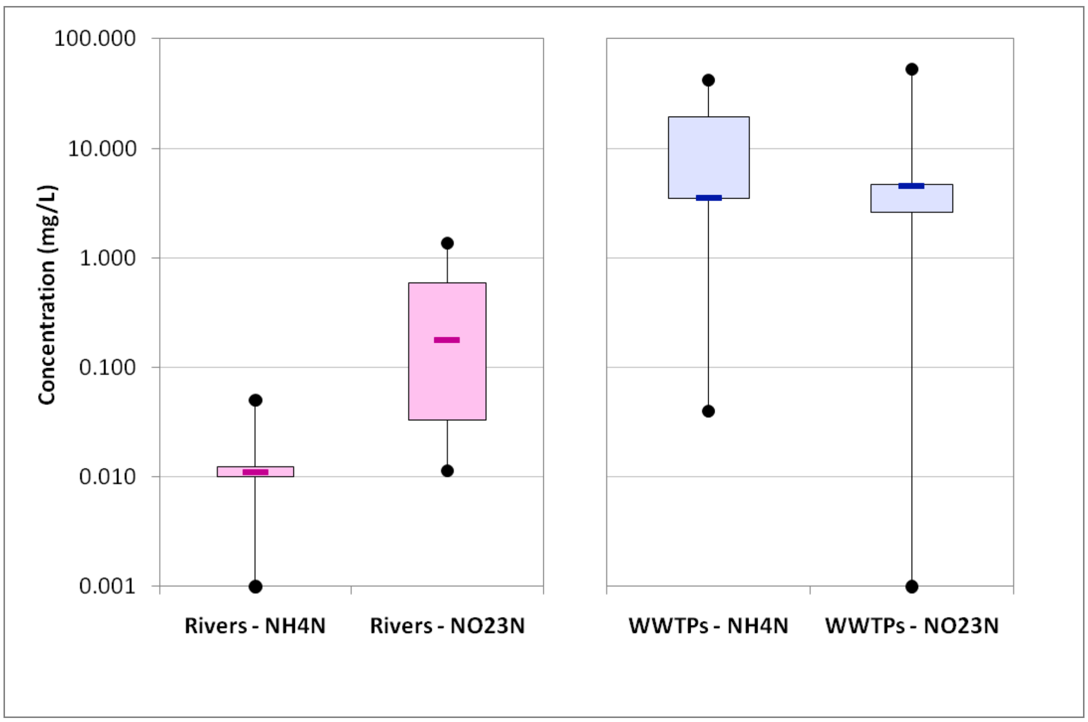

Figure 24. Box plots comparing the range of median concentrations of NH4N and NO23N across all rivers and WWTPs in the study area, 1999-2008.
The y-axis is on a logarithmic scale.

Combined average daily DIN loads for 1999-2008 from rivers and WWTPs are presented geographically in Figure 25. Watersheds draining mainland Vancouver dominate in terms of the magnitude of DIN load, but this is primarily because of high streamflows from the Fraser River, which has a DIN load of 33,140 kg/d. DIN loads from the Annacis and Iona WWTPs, located on mainland Vancouver contribute a total DIN load of 21,000 kg/d.

Within Puget Sound basins, WWTPs discharging into Puget Main dominate, discharging an average daily load that is 26 times greater than river loads into Puget Main. West Point and South King are the two largest WWTPs in the Puget Sound region, contributing a total DIN load of 19,320 kg/d on an annual average basis. The load from these two WWTPs is comparable to the total DIN load from the Snohomish, Skagit, Nooksack, Stillaguamish and Puyallup Rivers (18,890 kg/d).

River loads in both South and North Hood Canal are much larger than WWTP loads since there is only a single WWTP discharge directly into Hood Canal. On an annual basis, Commencement Bay receives comparable loads from rivers (2,100 kg/d) and WWTPs (2,440 kg/d).

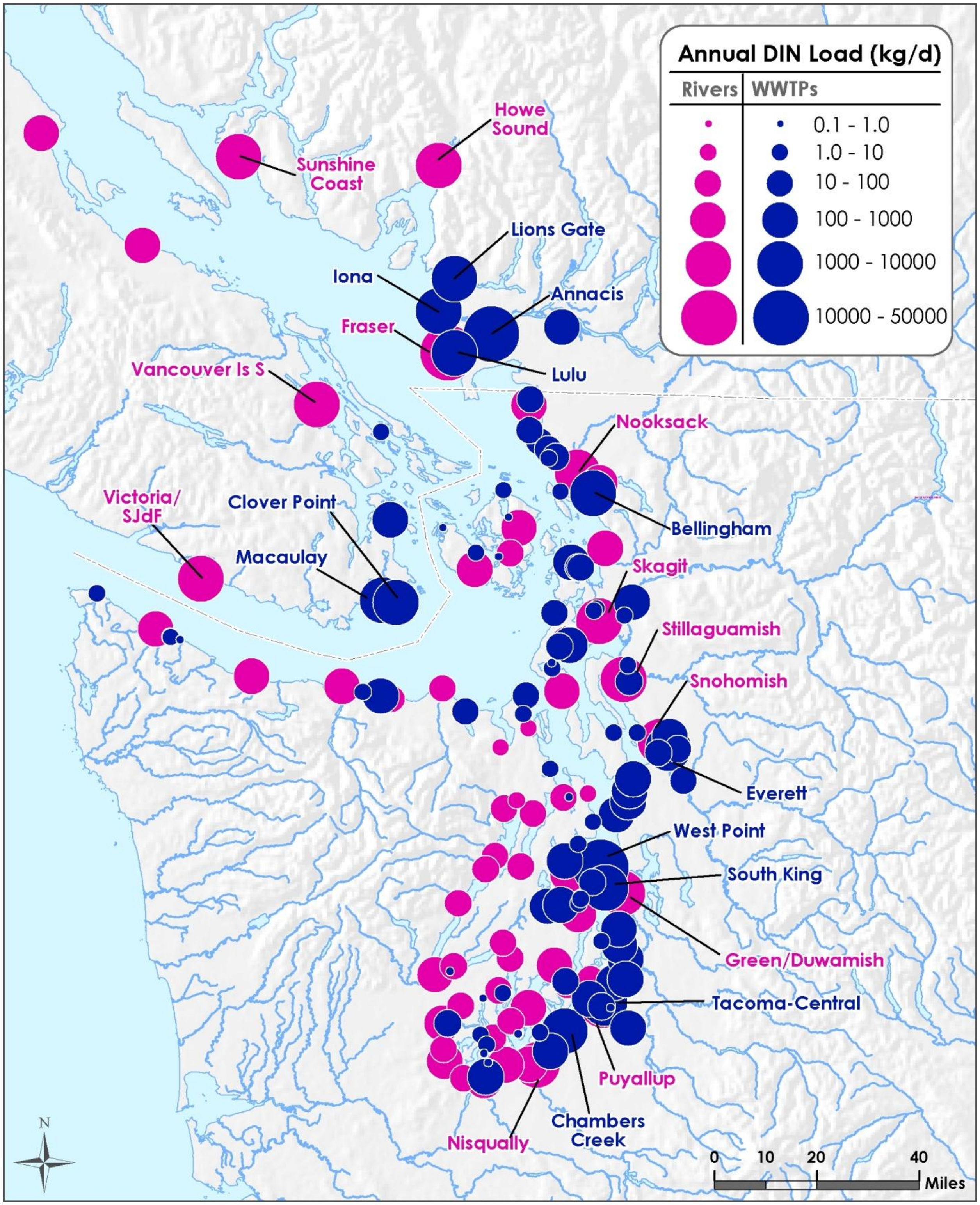

Figure 25. Annual dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs in Puget Sound during 1999-2008.

The relative magnitude of average daily DIN loads from rivers and WWTPs changes when evaluated only during the summer (average of July, August, and September). These summer months are critical since the lowest near-bottom DO levels are generally found in September

(Roberts, et al., 2008). The months preceding these low DO conditions are therefore an important time period.

As illustrated in Figure 26, DIN loads from rivers drop during the summer because of lower streamflows and less precipitation; this is true for all rivers except for the Fraser River which has peak streamflows in the summer (Ferguson and Healey, 2009). DIN loads from rivers in the U.S. during the summer are all below 1600 kg/d, which is the average summer load from the Snohomish River. This is much lower than the Snohomish River's annual daily load of 5950 kg/d.

During the summer, Annacis and Iona in Vancouver together contribute the largest summer load (21,000 kg/d) followed by West Point and South King (16,910 kg/d). During the summer, 99% of the loads into the Puget Main basin are from WWTPs.

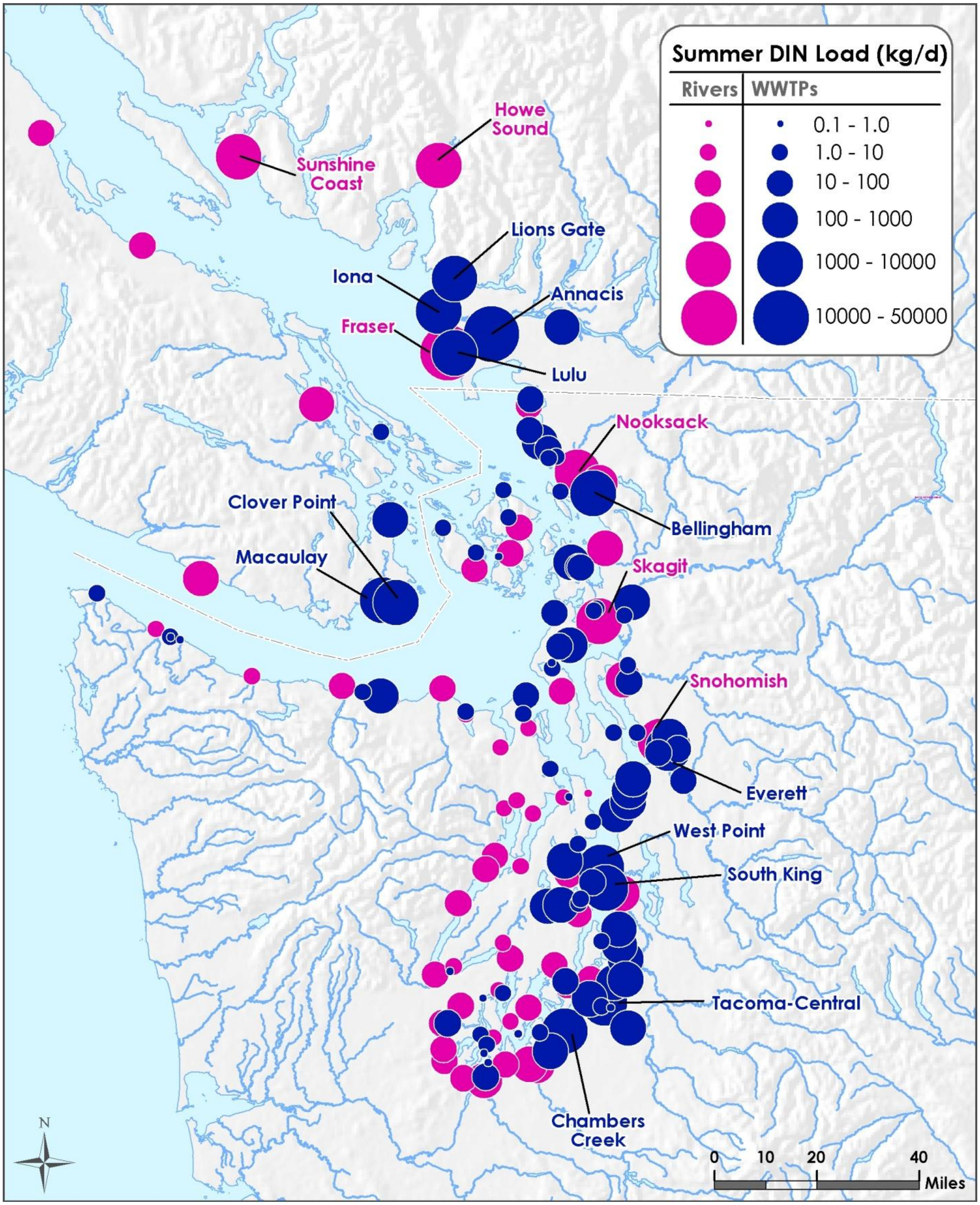

Figure 26. Summer (average of July, August, and September during 1999-2008) daily dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into Puget Sound.

Figure 27 presents the monthly average DIN loads from rivers and WWTPs in Puget Sound and the Straits for the full 10-year period between 1999-2008. There does not seem to be a noticeable trend or inter-annual variability in DIN loads during the 10-year period from 1999 to 2008. However, this might be a result of the limitation of the multiple linear regression method which does not identify trends in concentration which are unrelated to trends in flow.

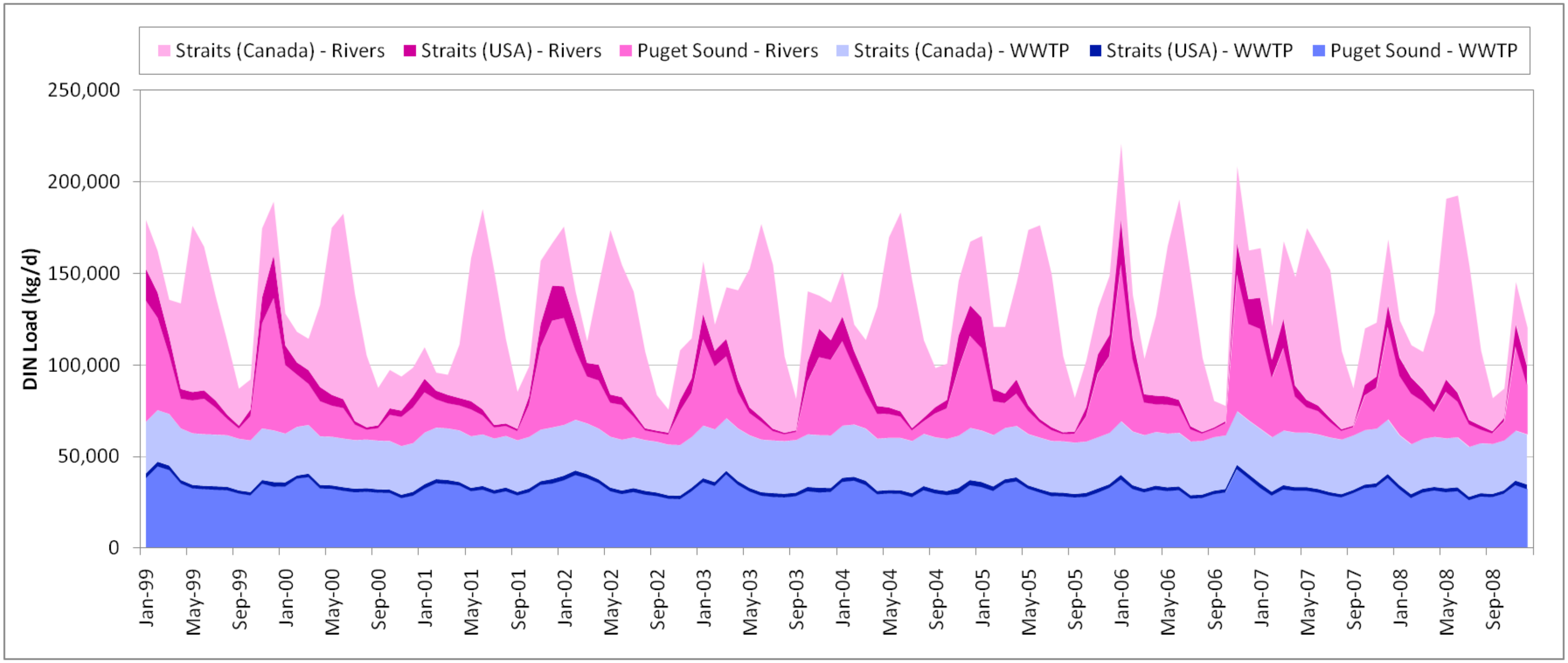

Figure 27. Monthly dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into Puget Sound and the Straits from 1999-2008.

Monthly river DIN loads are more variable than monthly WWTP DIN loads since river loads reflect variability in river flows, which change with seasons (Figure 27). The seasonal patterns in river DIN loads are different for rivers in Puget Sound and rivers in Canada; rivers in Puget Sound experience high flows during the wetter months of November through April, while Canadian rivers show higher loads between May and July predominantly because of the Fraser River's anomalous flow pattern during the summer months.

The monthly average DIN loads (rivers plus WWTPs) into Puget Sound and the Straits ranges from approximately 80 – 180 metric tons/day. On average, rivers in Puget Sound contribute 32% of the total river loads into Puget Sound and the Straits, while WWTPs in Puget Sound contribute 52% of the total WWTP loads into Puget Sound and the Straits.

In Puget Sound (south of Deception Pass), rivers (41%) have slightly lower DIN loads than WWTPs (59%) on annual bases (Figure 28, top). However, WWTP loads dominate (81%) during the summer months when rivers loads are low due to lower flows. In the Straits (both U.S. and Canadian portions), river DIN loads contribute 62% of the DIN load on an annual basis and 61% during the summer (Figure 28, middle). The higher summer DIN load form the Fraser River evens out differences between summer and annual river DIN load contributions in this region.

When loads from all sources are combined for the whole study area, river DIN load contributions (54%) are slightly greater than those from WWTPs (46%) on an annual basis. During the summer, river DIN loads (48%) are slightly lower than those from WWTPs (52%, Figure 28, bottom).

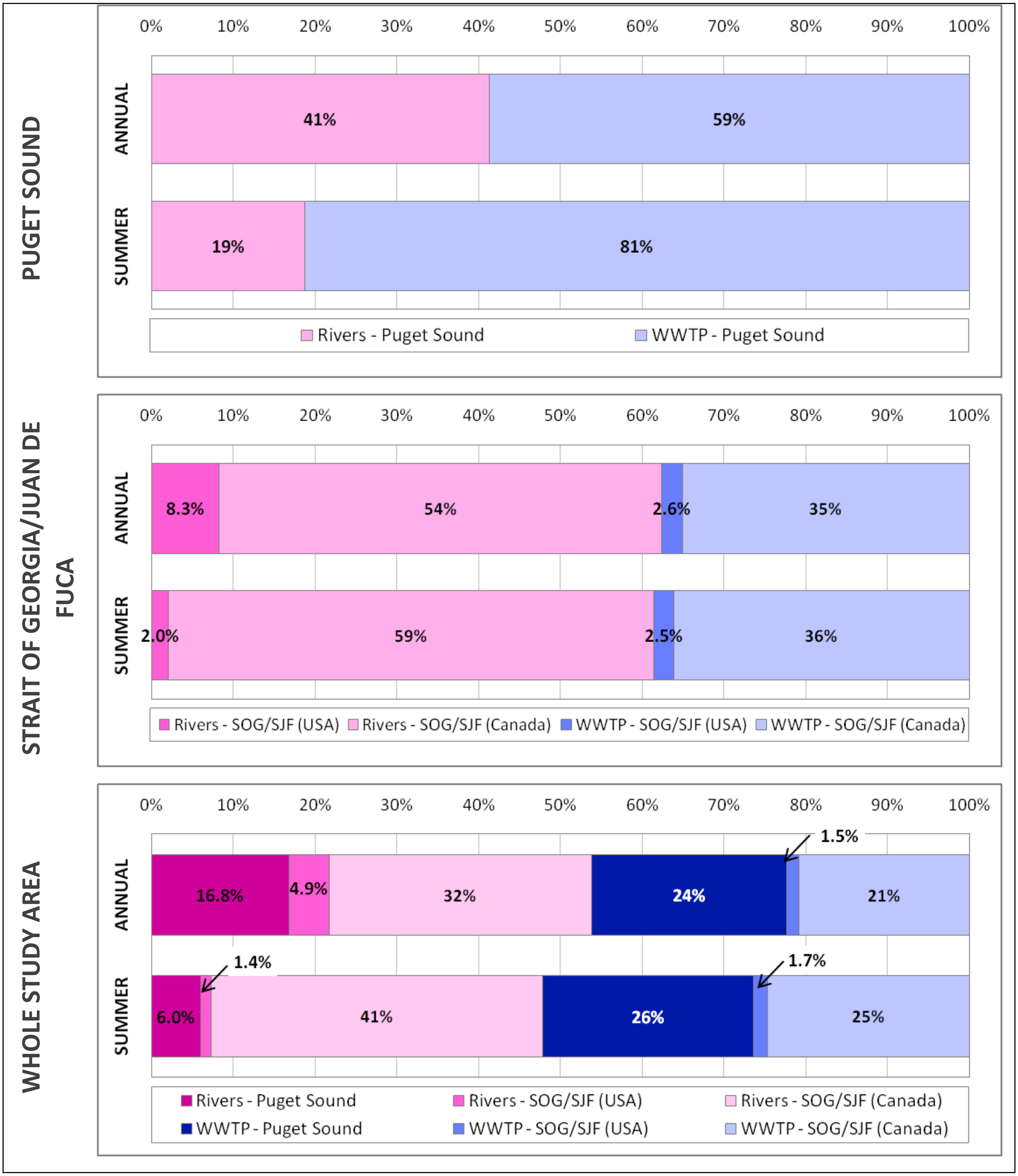

Figure 28. Bar charts comparing the relative contributions of dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into Puget Sound and the Straits on an annual basis and during the summers of 1999-2008.

Overall, DIN loads from rivers and WWTPs in Canada are 12% greater than DIN loads from U.S. rivers and WWTPs, contributing to 53% of the total DIN load into Puget Sound and the Straits (Figure 29).

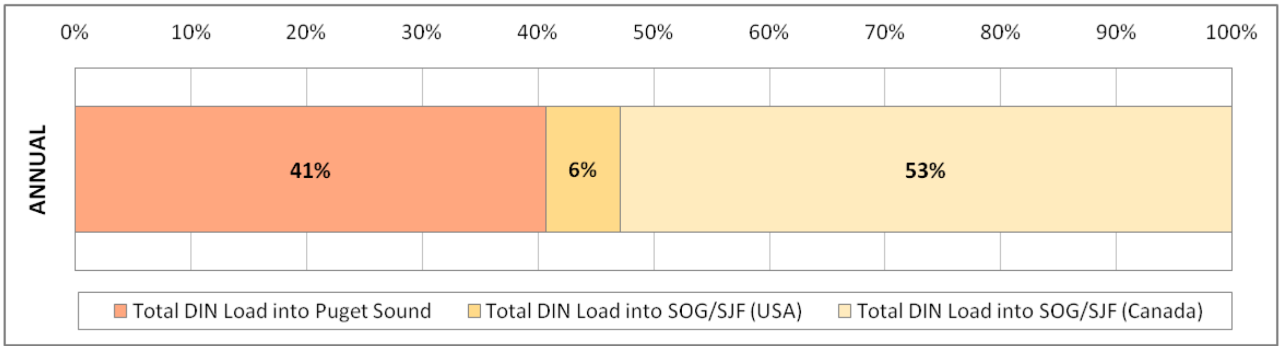

Figure 29. Annual dissolved inorganic nitrogen (DIN) loads from rivers and WWTPs into Puget Sound and the U.S. and Canadian portions of the Strait of Georgia/Juan de Fuca (SOG/SJF).

We can also normalize these loads by the total land area within our study to get load per unit area. For Puget Sound watersheds alone, (sum of all watersheds tributary to Puget Sound south of Deception Pass) the annual average river DIN loads per unit area from rivers is 280 kg/km^2-yr, while the combined load per unit area from rivers and WWTPs is 610 kg/km^2-yr.

Groundwater Loads

Vaccaro et al.'s (1998) estimate of 100 to 1000 ft^3/s of groundwater flow into Puget Sound makes up only 0.18 – 1.8% of the total freshwater inflow (rivers plus groundwater) into Puget Sound. After applying WDOH nitrate concentrations to this flow, groundwater DIN load constitutes 0.55 to 5.2 % of total freshwater DIN loads into Puget Sound.

The lower range of DIN loads (~ 0.5%) are within the noise of flow measurements. Even using the higher estimate of DIN loads (just over 5%), groundwater DIN loads from direct groundwater discharge are not likely to be a major determinant of marine nutrient levels in the Puget Sound region.

Table 9. Estimates of groundwater discharge and groundwater DIN loads into Puget Sound.

	Minimum estimate	Maximum estimate
PS Groundwater Discharge	100 cfs = 2.83 m^3/s	1000 cfs = 28.3 m^3/s
PS GW discharge as a % of freshwater inflows	0.18 %	1.8 %
PS GW DIN Load	159 kg/d	1590 kg/d
PS GW DIN Load as a % of freshwater inflows	0.54 %	5.2 %

As described in Mohamedali et al. (2011), even in South Sound where the long shoreline was used to apportion the groundwater inflows, groundwater constitutes <10% of the riverine inputs.

Therefore, groundwater contributions to Puget Sound and the Straits are represented solely as baseflow in rivers and streams. No additional subsidy was added to account for the direct-to-marine discharges because these are so small by comparison.

Atmospheric Loads

Atmospheric deposition of DIN to the surface waters of South and Central Puget Sound were estimated by Roberts et al. (2008) using data from the National Atmospheric Deposition Program. For this study, we used to the same methodology, but used the annual average of wet deposition of inorganic nitrogen data from 1999-2008 (1.14 kg-N/ha-yr). We then calculated atmospheric DIN loads by distributing this aerial loading rate over the total marine surface water area of Puget Sound and the Straits. The result was an annual average atmospheric DIN load of 5010 kg/d (Figure 30). These loads make up only 4% of the annual DIN loads in the study area[7].

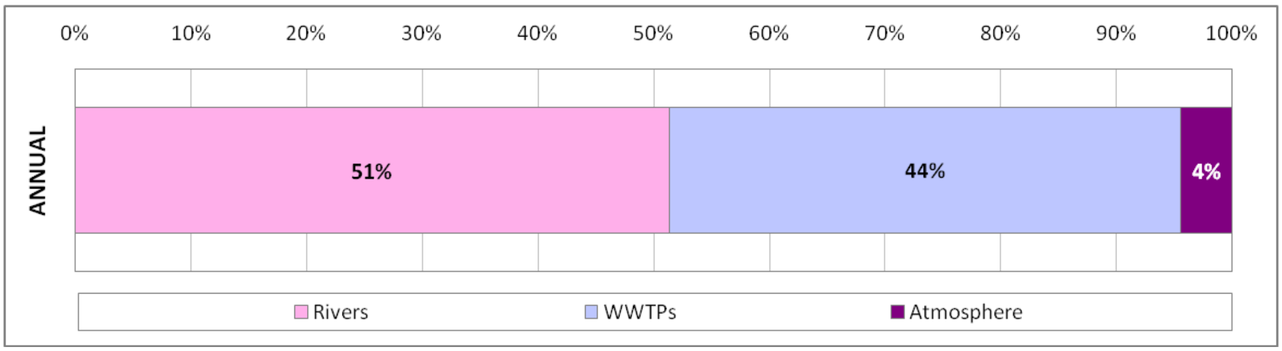

Figure 30. Annual dissolved inorganic nitrogen (DIN) loads from rivers, WWTPs, and the atmosphere into Puget Sound and the U.S. and Canadian portions of the Strait of Georgia/Juan de Fuca (SOG/SJF).

Loads from on-site septic systems and groundwater are included in the 'Rivers' share of the bar chart.

Oceanic Loads

Oceanic loads will be calculated as part of the modeling effort and are not specified using the same method as that used for wastewater treatment plant or river loads. Instead of a flow rate, tidally-varying water levels are specified at the northern model boundary. Differences in water levels induce flow back and forth throughout the model. Marine concentrations are specified for the incoming tide using observed data from the Strait of Juan de Fuca and the northern boundary of the Strait of Georgia. Concentrations for the outgoing tide reflect complex physical, chemical, and biological processes that are simulated within the modeling domain. The loads in and out of the model at the Strait of Juan de Fuca boundary, as well as the net effect, will be calculated once the model is calibrated and applied to a series of scenarios.

[7] This atmospheric load is refers to nitrogen loading from the atmosphere deposited directly onto the marine surface water. It is distinct from the atmospheric load received by terrestrial portions of the study area, which we assume to be included in the watershed loads.

A previous study used a salt balance approach to estimate the net ocean exchange at the Strait of Juan de Fuca. Mackas and Harrison (1997) calculated the net flux as 400,000 to 600,000 kg/d of total nitrogen. However the deep layer input brought in 2.6 to 2.9 million kg/d and the surface layer exported 2.1 to 2.4 kg/d, so these were derived as the difference between large numbers. Mackas and Harrison also cite an annual average net flux of 117,000 kg/d of nitrogen to Puget Sound at Admiralty Inlet.

Natural Conditions for Nutrient Loads

Table 10 summarizes results from the meta-analysis used to assess natural conditions for rivers and streams within the Puget Sound and the Straits watersheds.

Table 10. Nutrient result summary for rivers and streams in Puget Sound and nearby reference areas.

	Statistic	TPN (mg/L)	NO23N (mg/L)	NH4N (mg/L)	TP (mg/L)	OP (mg/L)	Notes*
Recent Ambient Data - Puget Sound							
South Sound	annual mean of monthly 10%iles	0.257	0.200	0.010	0.020	0.009	1
Commencement Bay	annual mean of monthly 10%iles	0.205	0.152	0.012	0.107	0.014	1
Puget Main	annual mean of monthly 10%iles	0.209	0.169	0.010	0.011	0.005	1
Elliott Bay	annual mean of monthly 10%iles	0.362	0.284	0.014	0.034	0.010	1
Whidbey	annual mean of monthly 10%iles	0.142	0.107	0.010	0.018	0.004	1
Hood Canal	annual mean of monthly 10%iles	0.044	0.027	0.010	0.009	0.005	1
Strait of Georgia (USA)	annual mean of monthly 10%iles	0.396	0.340	0.011	0.025	0.006	1
Strait of Juan de Fuca (USA)	annual mean of monthly 10%iles	0.027	0.014	0.010	0.014	0.003	1
	Mean of recent ambient data	**0.205**	**0.161**	**0.011**	**0.030**	**0.007**	
Atmospheric (rainfall) data							
Olympics	annual mean of monthly medians	--	0.117	0.012	--	--	2
North Cascades	annual mean of monthly medians	--	0.404	0.042	--	--	2
La Grande	annual mean of monthly medians	--	0.338	0.055	--	--	2
Mt. Rainier	annual mean of monthly medians	--	0.249	0.039	--	--	2
	Mean of atmospheric data	--	**0.277**	**0.037**	--	--	
Toxics in Surface Runoff							
Forested basins	median of data	0.270	0.210	0.010	0.015	0.005	3
Hood Canal Dissolved Oxygen Program							
Forested basins	Unclear	--	0.070	--	--	--	4
EPA Ecoregional Criteria							
Western forested mountains	25th percentile of data	0.12	--	--	0.01	--	5

***Notes:**

1. These are the mean of monthly 10%iles of recent data collected at several of Ecology's ambient monitoring stations, aggregated into different regions of Puget Sound. For all parameters except TP, these are the 10%tile of data collected between WY 2002 and WY 2009. For TP, data are from WY 2008 and WY 2009 since there was a change in lab methods in 2003 and in again 2007 which did not allow us to pool the older data with the newer data.
2. Atmospheric concentration data (i.e. rainfall) for WY 2002-2009 were downloaded from the National Atmospheric Deposition Program. There are four stations located in Western Washington: one in the Olympics, two near Mt. Rainier and one in the North Cascades.
3. Nutrient concentrations in surface runoff (baseflow and stormwater events) were measured by Herrera Environmental Consultants as part of the Puget Sound Toxics Loading project (www.ecy.wa.gov/biblio/0910052.html). The values here are the median of data collected from predominantly forested sub-basins in the Puyallup and Snohomish watersheds.
4. The Hood Canal Dissolved Oxygen Program has estimated this value as the natural background DIN concentrations for Hood Canal as part of their study (Steinberg, 2010). The value is intended to represent baseline streamwater DIN concentrations.
5. This is based on data from Legacy Storet, the National Stream Quality Accounting Network and the National Water-Quality Assessment collected between 1990 and 1998.

A number of methods are presented in Table 10 for context, but we did not use all of them to calculate natural conditions. There is considerable variation in 10^{th} percentile concentration data between different regions of Puget Sound, supporting regionally based natural conditions.

To further explore regional and seasonal variations in concentrations, we first analyzed box-plots of monthly DIN concentrations (DIN = NO23N + NH4N) concentrations for each region based on recent data from Ecology's ambient monitoring stations (Figure 31 and 32). Superimposed on these plots are the 10^{th} percentiles of these data as well as the monthly medians of atmospheric data from nearby NADP stations. Data from different atmospheric stations were applied to different regions of Puget Sound. For the Olympic region (Hood Canal and SJF), we used monthly atmospheric data from the Olympics atmospheric station. For the rest the Cascade region (all other regions), we applied the monthly averages of the other three atmospheric stations (North Cascades, La Grande and Mt. Rainer).

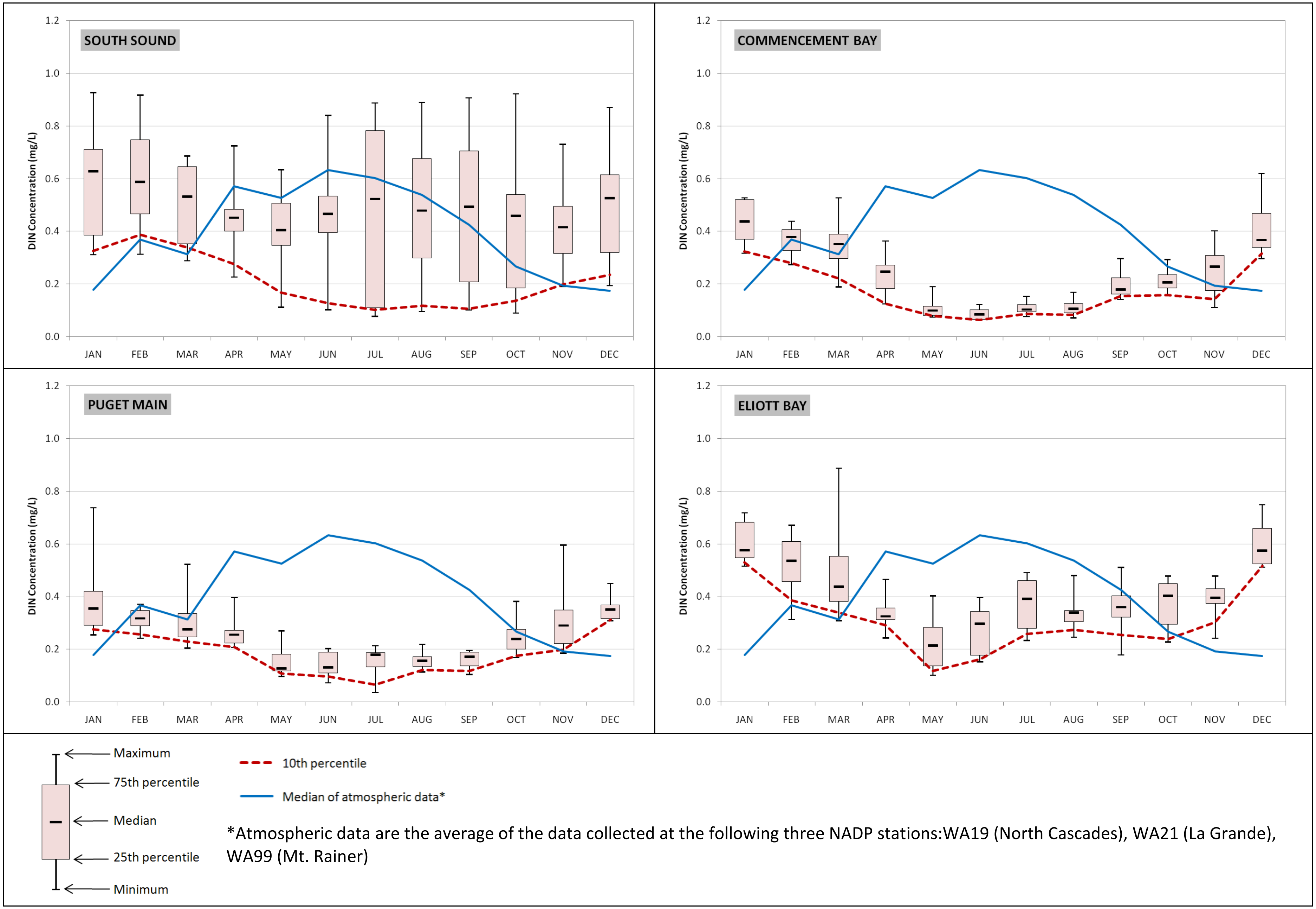

Figure 31. Monthly box-plots from ambient data collected in different regions of Puget Sound as well as monthly 10th percentiles and monthly median atmospheric concentrations of dissolved inorganic nitrogen.

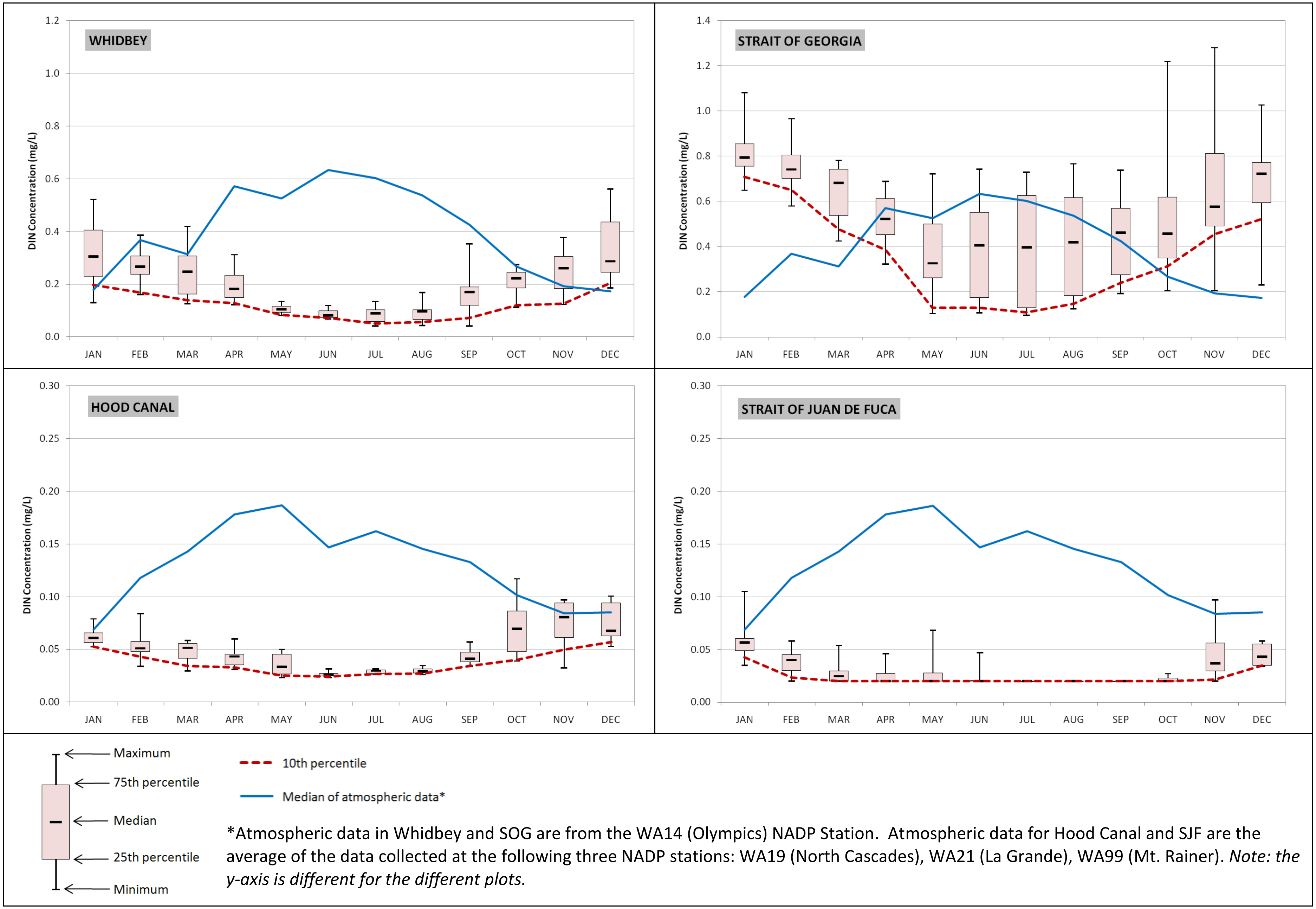

Figure 32. Monthly box-plots from ambient data collected in different regions of Puget Sound and the Straits as well as monthly 10th percentiles and monthly median atmospheric concentrations of dissolved inorganic nitrogen.

Patterns in Ambient River Data

The box-plots in Figure 31 and 32 illustrate interesting patterns in different regions of Puget Sound. Though there are noticeable seasonal variations in DIN concentrations in all regions, the seasonal strength of these patterns varies between regions. In particular, Commencement, Puget Main and Whidbey show low concentrations in the summer months (summer medians of approximately 0.1 mg/L compared to annual medians of almost 0.2 mg/L) suggesting significant uptake of nitrogen when productivity is high.

In contrast, SOG and South Sound have higher summer DIN concentrations (median of 0.4 and 0.5 mg/L) as well as a larger range of summer DIN concentrations. This suggests that DIN concentrations in these rivers may exceed their nutrient assimilative capacity, and the natural processes that facilitate the uptake of nitrogen may have broken down. Elliott appears to be in transition between these two patterns (i.e. high vs. low nutrient assimilation in the summer), with summer median concentrations of about 0.3 mg/L.

Hood Canal and SJF have much lower overall DIN concentrations (medians are < 0.05 mg/L) as well as dampened seasonal variation. The concentration of DIN in the atmosphere from the Olympics NADP station is higher than river DIN concentrations in both these regions. This suggests that rivers in the Olympic Peninsula are nitrogen limited and nitrogen additions to rivers and streams are quickly used up by biota rather than exported to Puget Sound.

In all regions, winter DIN concentrations are generally higher than summer concentrations. During this time, there is more rainfall and less productivity in streams. Rainfall events can also mobilize non-point sources of nitrogen in the watershed and transport this nitrogen into rivers through stormwater runoff.

Patterns in Atmospheric (Rainfall) Data

Monthly medians atmospheric nitrate concentrations also show seasonal variation. Concentrations are lower in the winter when rainfall is high (due to increased dilution), and higher in the drier summer months. Winter nitrate concentrations are comparable to concentrations measured in streams, while summer atmospheric nitrate concentrations are higher than those measured in streams.

Nitrogen concentrations from the atmospheric station in the Olympic Station are lower compared to the other three stations. The Olympic station does experience higher rainfall and, as a result, concentrations may be biased low if the atmosphere is source limited. The Olympic station is also upwind from Puget Sound watersheds and is therefore least influenced by local anthropogenic sources of nutrients.

Summary of Observations

The patterns described above suggest the following:

1. Different regions in Puget Sound and the Straits need to be represented by different natural conditions to reflect natural variations between regions such as in-stream processes, vegetation cover, extent of atmospheric deposition, geology, nutrient assimilation, etc.
2. During the summer, nutrient concentrations are a reflection of the nutrient assimilative capacity of streams. Monthly 10th percentiles are a reasonable estimation of natural concentrations during this time because these concentrations reflect nutrient uptake in streams which brings stream concentrations below concentrations measured in the atmosphere (rainfall).
3. During the winter and wetter months, stream concentrations higher because of high rainfall, low productivity and potential stormwater runoff contributions. Concentrations of nutrients in rainfall (rather than in-stream concentrations) are therefore more representative of natural conditions .

Based on the above lines of reasoning, we used a hybrid method to calculate natural nutrient concentrations. For each region and each month, we used the minimum value of either (1) the monthly 10th percentile of ambient data or (2) the monthly median of atmospheric data.

This approach takes into account both seasonal and spatial variations, and incorporates information from actual stream data as well as the atmosphere, which can be considered to be a _background' concentration.

The final set of natural DIN concentrations for each region is presented in Figure 33.

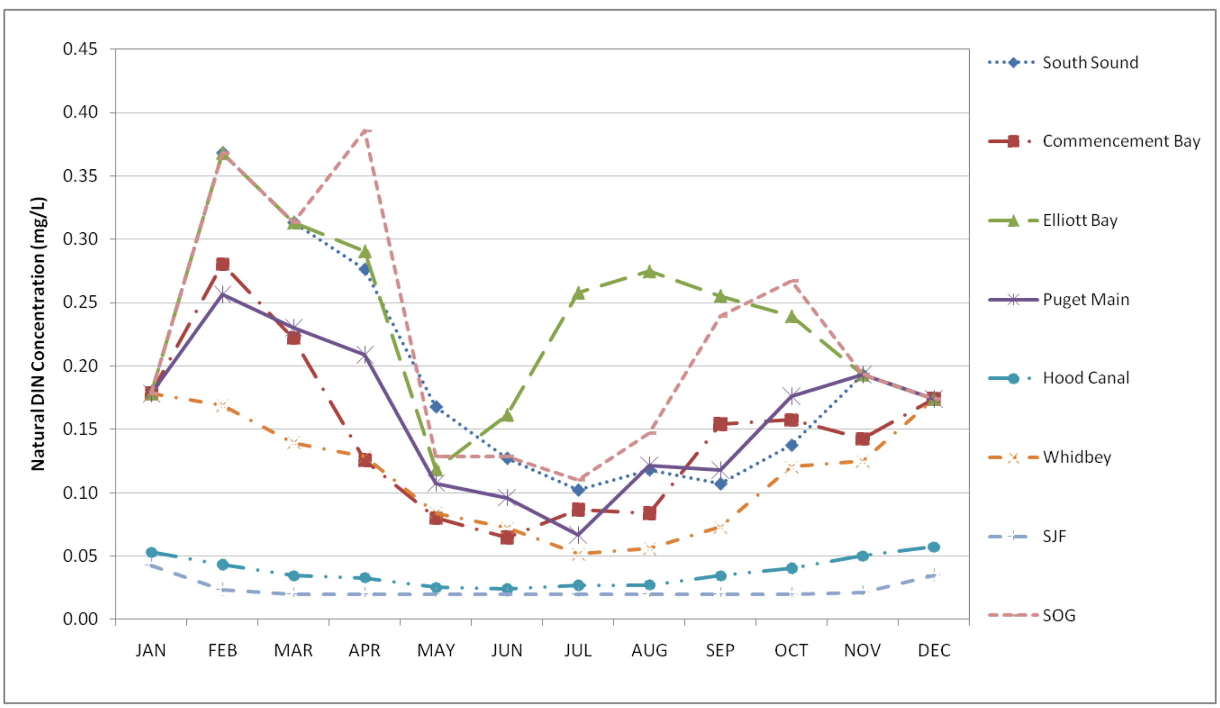

Figure 33. Natural dissolved inorganic nitrogen concentrations for different regions of Puget Sound and the Straits.

Since ambient data were only available for the larger rivers in the study area, the natural conditions we calculated from these data may not necessarily reflect natural conditions in smaller streams in the study area. However, these smaller streams have limited data, and their flow and load contributions are relatively minor compared to large rivers entering Puget Sound and the Straits. Also, ambient data were not available for watersheds draining into Admiralty and Sinclair-Dyes Inlet. We therefore applied SJF natural conditions to Admiralty Inlet, and Puget Main natural conditions to Sinclair-Dyes Inlet since these regions are in close proximity to each other.

The natural conditions we have calculated preserve the spatial trend that is present in atmospheric deposition with lowest values in the Olympics and highest values in the northeast and southeast basins. Natural conditions for the Olympic basins are below the values for forested basins from the surface runoff study (0.21 mg/L), which was conducted on the Cascade side of Puget Sound. Olympic natural conditions are comparable to but still below the HCDOP flow-weighted natural condition of 0.07 mg/L and EPA's ecoregional criteria of 0.12 mg/L. On the Cascade side, the natural conditions are similar to the values for forested basins from the surface runoff study for the Commencement, Puget Main, and Whidbey basins. However, natural conditions for South Sound and Strait of Georgia are higher.

Similar monthly natural conditions concentrations were calculated for phosphorus and other forms of nitrogen (Appendix F – to be added).

We then calculated the average daily DIN loads under natural conditions by multiplying the DIN concentrations in Figure 33 with the total daily streamflow (for each day in 1998-2008) of all rivers and streams within each region in Puget Sound and the Straits as follows:

$$DIN\ Load\ for\ Region\ i\ \left(\frac{kg}{day}\right) = \frac{\sum(DIN\ Concentration\ for\ Region\ i * Total\ Daily\ Streamflow\ of\ Region\ i)}{(365\ days/year\ x\ 10\ years)}$$

Under natural conditions, the total DIN load into Puget Sound was found to be 14,500 kg/d, and 2,900 kg/d into the U.S. portions of the Straits. These loads vary seasonally primarily due to seasonal flow fluctuations.

Discussion

Rivers and Wastewater Treatment Plants

Rivers and WWTPs that discharge into the Strait of Georgia from Vancouver Mainland have the largest DIN loads than any other region in the study area. The Fraser River is a large river draining a significant portion of western Canada (234,730 km^2/90,830 mi^2) – an area much larger than the sum of all watersheds draining directly into Puget Sound waters (29,220 km^2/11,280 mi^2). Therefore, simply because of the magnitude of its flow, the Fraser River dominates all other river DIN loads in the study area. The modeling phase of this study will investigate whether or not some of the Fraser River DIN loads circulate into Puget Sound, or if they simply get flushed out into the Pacific Ocean under typical estuarine circulation patterns.

WWTPs in Vancouver Mainland also dominate WWTP loads. The WWTPs in Canada generally undergo a lower level of treatment than those in Washington State and these facilities serve the largest populations (e.g. Vancouver B.C., with 2.2 million people). In addition, the Iona and Annacis WWTPs (both on Mainland Vancouver), are the two largest WWTPs in the study area in terms of flow, with an annual average discharge of 152 mgd and 126 mgd, respectively. However, the average plant median DIN effluent concentration of all large (>10 mgd) WWTPs in Canada is 24.7 mg/L. This is favorable in comparison to 25.7 mg/L, which is the average plant median DIN effluent concentration of all large WWTPs in the US (not including oil refineries and pulp/paper mills). Canadian contributions are included for completeness but are not subject to U.S. regulations. The rest of this discussion focuses primarily on rivers and WWTPs in the U.S. portions of the study area.

Rivers (except the Fraser River) exhibit a seasonal pattern in nitrogen loading over the course of the year because of variations in flow that are a response to variations in precipitation. Though the largest rivers do not necessarily have the highest nitrogen concentrations, they do tend to have larger nitrogen loads relative to the rest of the rivers and streams in the study area. Whidbey basin in northern Puget Sound receives the largest inputs of river DIN loads than all other regions of Puget Sound. These loads are primarily from three of the largest rivers in Puget Sound: the Skagit, Snohomish and Stillaguamish Rivers, which together contribute 56% of the total river DIN load into Puget Sound waters.

When we look at the relative DIN loads (where loads are normalized relative to the total load and by watershed area), a different pattern emerges. The rivers with the largest DIN loads do not necessarily have the highest relative loads. The highest relative DIN loads are found in watersheds that drain into South Sound (McAllister, Henderson, and Budd/Deschutes watersheds) and into the U.S. portions of the Strait of Georgia (the Nooksack and Whatcom watersheds). The Nooksack was also identified by Embrey and Inkpen (1998) for its high nitrogen yields which they attributed to animal manure and fertilizers.

Figure 34 illustrates how relative DIN loads vary with concentrations. Generally, watersheds with high DIN concentrations have higher relative DIN loads. However, Figure 34 also illustrates how watersheds with similar DIN concentrations in their rivers have a range of relative DIN loads and vice versa. This might be because different watersheds have different terrain, hydrology, geology as well as different natural and human sources of nutrients which can affect nutrient dynamics within the river/stream. Also, active management of non-point sources of nitrogen may reduce relative DIN loads in some watersheds relative to others that are similar in other ways.

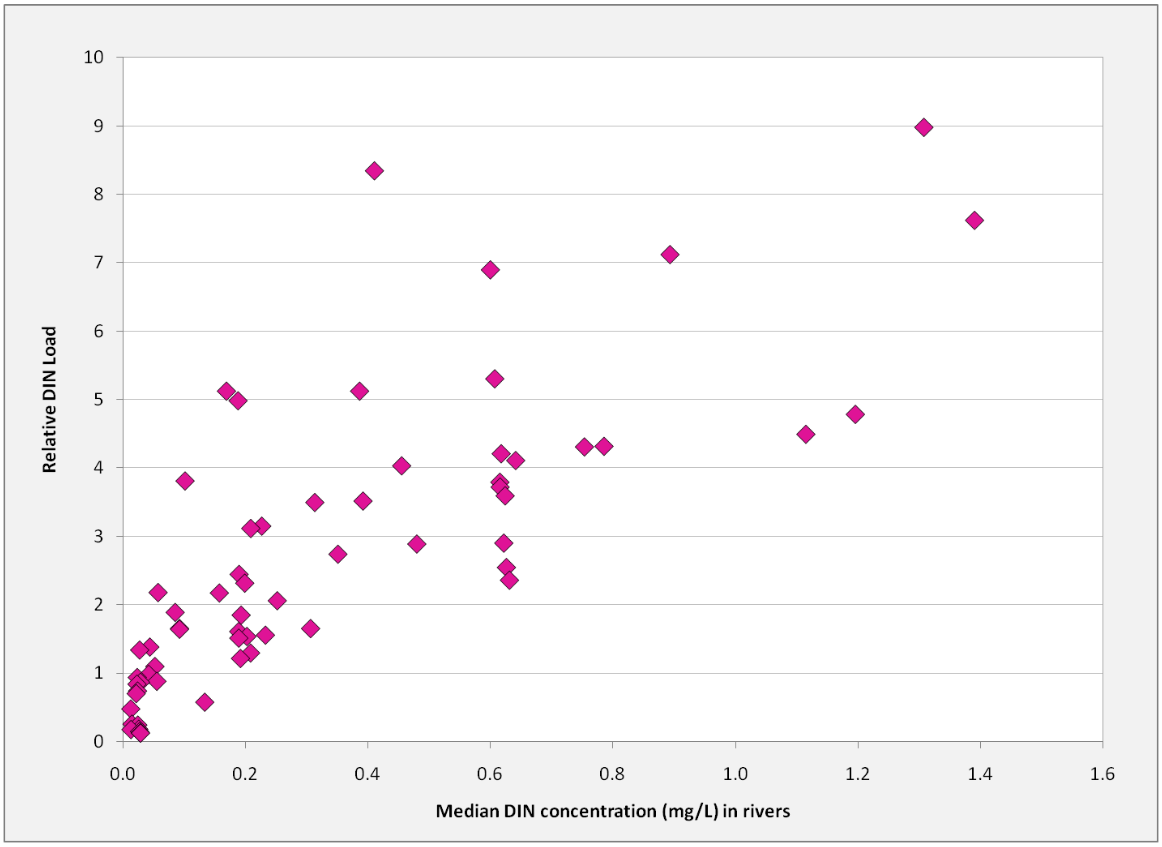

Figure 34. Relationship between median dissolved inorganic nitrogen (DIN) concentrations in rivers and average annual DIN watershed yields.

Relative DIN Load is a unit-less value; values greater than one are above average, values less than one are below average.

DIN contributions from watersheds also vary with land use. Though we did not specifically perform a quantitative analysis of land use or population and the effect on nitrogen loads, we found that watersheds in Puget Sound that drain into north Hood Canal and the U.S. side of the SJF have some of the lowest DIN concentrations, DIN loads and relative DIN loads. These watersheds drain the Olympic Peninsula, receive some of the highest precipitation rates in the headwaters, and are more forested than other watersheds in Puget Sound. In contrast, DIN loads are higher from watersheds in eastern Puget Sound; the lower portions of these watersheds are dominated by either agricultural or urban land uses (Embrey and Inkpen, 1998) and have higher populations. Land use and population in different watersheds may therefore play an important role in determining the magnitude of nonpoint nutrient sources into Puget Sound.

The main basin of Puget Sound (Puget Main, not including Commencement and Elliott Bays) receives the largest share of WWTP loads. These loads are primarily from the two largest

WWTPs in the U.S: West Point and South King, which together contribute 63% of the total WWTP DIN load into Puget Sound waters. These WWTP serve higher population centers and have larger service areas than others in Puget Sound, and therefore treat a large volume of wastewater. Even if treatment processes at these plants lower the *concentration* of nitrogen in the effluent, nitrogen *loads* are still high since effluent flows are high; higher flows result in higher loads.

Puget Main also receives the highest share of DIN loads overall (rivers plus WWTPs), which is a reflection of the high population in this region. The next highest share of DIN loads are received by Whidbey Basin, followed by the U.S. portions of the Straits and then South Sound.

The Impact of Nitrogen Loading

Though the magnitude of sources of nitrogen is important, several other factors also play a role in determining the effect of these loads on DO concentrations in the marine water. The time, location, and depth of the discharge are all important due to circulation patterns in Puget Sound. Other important factors that determine DO concentrations are temperature, sunlight, the incoming oceanic water, and other environmental variables.

The PSDOM will account for these different variables in evaluating the impact of nutrient loads on DO concentrations in Puget Sound. The modeling will also allow us to assess if the loads entering the Straits eventually circulate to Puget Sound, or if they primarily flow out into the Pacific Ocean. The loading results presented here provide valuable information but, prior to modeling, cannot be used to assess the impact of the different sources of nitrogen on DO concentrations.

Comparison to Previous Studies

Five previous studies have assessed nutrient contributions to Puget Sound and the Straits (Embrey and Inkpen, 1998; Hallock, 2009; Mackas and Harrison, 1997) or specific basins (Mohamedali et al., 2011; Paulson et al., 2006). Overall the current study loads are generally consistent with previous estimates.

In 1988, the USGS published a report by Embrey and Inkpen (1998) which presented estimates of nutrient sources to watersheds and yields from major watersheds in the Puget Sound basin (including the Straits). Figure 35 compares river DIN and TP yield (where yield is load per unit watershed area) estimates developed for this study with those estimated by in the Embrey and Inkpen‘s study for overlapping watersheds in Puget Sound.

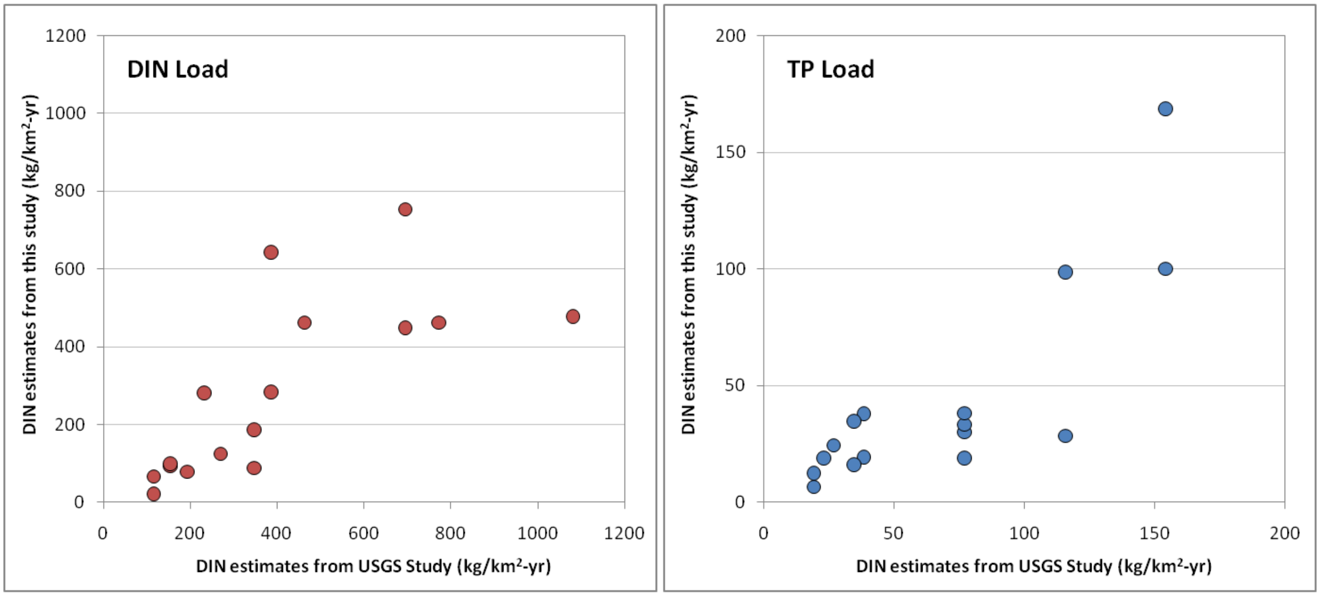

Figure 35. Comparison of USGS (Embrey and Inkpen, 1998) dissolved inorganic nitrogen and total phosphorus yields estimates with yields estimated for the PSDOM.

The two studies have comparable estimates of DIN yields for some rivers. In some cases, however, our study estimates are either higher or lower than those of the USGS study. TP yield estimates from our study are generally lower than those estimated by the USGS study.

There are a few reasons for differences between the estimates presented in this study and those presented by the USGS study. Embrey and Inkpen (1998) used data from 1980-1993, and in some cases, historic data from the 1970's, while our study used more recent water quality (primarily from 2006-2007) and streamflow data to develop estimates for 1999-2008. The two studies therefore cover different time periods which likely have different hydrographic patterns. Embrey and Inppen (1998) also had less comprehensive streamflow data sets, and in some cases estimated annual average loads based on average monthly loads rather than daily loads.

Between these two time periods, Hallock (2009) reported trends in NO23N concentrations. For example, ambient data from the Deschutes show an increasing trend in NO23N concentrations, while the Stillaguamish shows a decreasing trend. Our study predicted higher DIN yields than the USGS study in the Deschutes watershed, and lower DIN yields in the Stillaguamish watershed.

TP yield estimates from our study are lower than those from the USGS study for most watersheds. Embrey and Inkpen (1998) mention that their load estimates may be overestimated (or underestimated) because of bias due to sampling frequency. Some of the water quality sampling stations used by Embrey and Inkpen (1998) are also not coincident with the ones used in our study, and TP concentrations may be different along a stream gradient because of in-stream processes. The data they used was from the previous decade (from the 70's and 80's), when lab methodologies may have biased results. Also, phosphorus is generally easier to control than nitrogen and declining trends in TP during the 1990's may be a result of effective measures to reduce phosphorus inputs to streams. Results from a batch trend analysis of 24 ambient stations in Puget Sound rivers showed that nine of these stations had a significant declining trend in phosphorus.

Despite some difference in DIN and TP yields in individual watersheds, overall loads are relatively comparable between the two studies and within the same order of magnitude. The total river DIN load from U.S. rivers predicted by Embrey and Inkpen (1998) was 30,100 kg/d, while our study predicts 29,200 kg/d. Similarly, Embrey and Inkpen (1998) predict total TP load of 5,800 kg/d while our study predicts 4,600 kg/d.

Hallock (2009) evaluated trends in total nitrogen and nitrate concentrations and calculated both loads (kg/month) and yields (kg/mo-km^2) at Ecology‘s ambient monitoring stations throughout the Puget Sound basin and the Straits (U.S). Hallock‘s (2009) estimates are from data collected between WY 1995 and WY 2007, and compare relatively will with the estimates developed for this study (Figure 36).

Our study estimates are higher than estimates by Hallock (2009) for some watersheds and lower for other watersheds, but comparable overall. The largest differences in estimates are for the Deschutes, Samish, Cedar and Duckabush Rivers. Hallock did not total the load contributions or account for the unmonitored contributions in the Puget Sound watershed, and the sum (24,500 kg/d) is less than the total river contribution of 29,200 kg/d in this study.

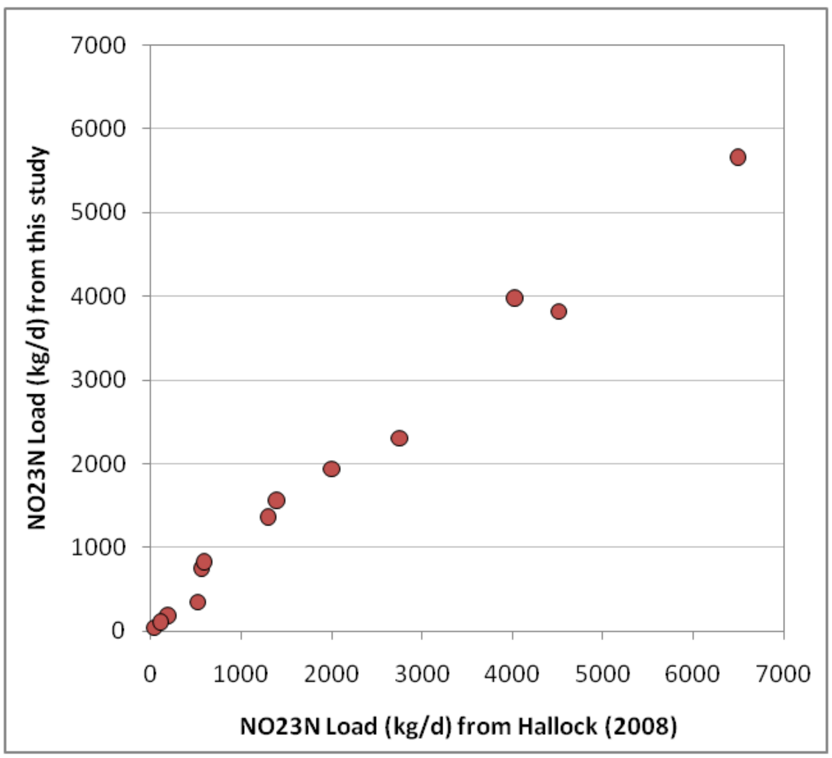

Figure 36. Comparison of Hallock (2008) nitrate + nitrite loads with those estimated for the PSDOM.

An earlier study compiled U.S. and Canadian nitrogen loads from rivers and wastewater treatment plants in the region, Mackas and Harrison (1997) estimated nitrogen loads to Puget Sound and the Straits to assess the potential for large-scale eutrophication. They compiled available information for the Fraser River and other U.S. and Canadian rivers as well as for wastewater sources for Victoria, Vancouver, and Seattle and the basin total.

Total wastewater contributions in the basin were estimated from population and a per capita nitrogen contribution (65,000-100,000 kg/d), but the current plant-based estimates are comparable to the low end of the range (Table 11). The Vancouver, Victoria, and Seattle wastewater contributions are also comparable. Fraser River loads derived from a previous study and extrapolated to account for the effect of population increases since the 1977 estimates are higher than those developed based on regressions of monitoring data but consistent given the two very different approaches. The total river loads for the entire basin are also comparable.

Table 11. Comparison of dissolved inorganic nitrogen load from different sources in Puget Sound and the Straits as estimated by this study and by Mackas and Harrison (1997).

Load Sources	**Our Study**	**Mackas and Harrison (1997)**	
	DIN (kg/d)	**lower/most probable** *DIN (kg/d)*	**upper limit** *DIN (kg/d)*
Wastewater			
Vancouver	23,125	20,000	22,000
Victoria	2,850	3,000	6,000
Seattle	19,324	15,000	16,000
Other[1]	18,001	27,000	56,000
Total Wastewater	**63,300**	**65,000**	**100,000**
River and Shoreline			
Fraser	33,135		50,000
Other rivers[2]	39,365	50,000	60,000
Shoreline groundwater[3]		5,000	15,000
Total River	**72,500**	**55,000**	**75,000**
Total River + Wastewater	**135,800**	**120,000**	**175,000**
Atmospheric Deposition			
Atmosphere - natural	--	2,500	--
Atmosphere - anthropogenic	--	6,000	--
Total Atmosphere	**5,000**	**8,500**	--
Net Ocean exchange			
Strait of Juan de Fuca	--	400,000	600,000
Admiralty Inlet (Puget Sound)	--	0	224,000

1. Other = [Total wastewater] – [Vancouver + Victoria + Seattle]

2. Total non-urban for this study = [Total Rivers (U.S + Canada)] – [Fraser]

3. Shoreline groundwater for our study is included in the 'Total non-urban' rivers

Mackas and Harrison (1997) also estimated nitrogen fluxes due to the net effect of ocean exchanges. For the sum of wastewater, river contributions, atmospheric deposition, and net ocean exchange with the Straits and Puget Sound, net ocean exchange represents 77% of the load through the Strait of Juan de Fuca. Wastewater and river contributions are comparable and represent 22 to 23%, with direct atmospheric deposition contributing <1% of the totals. That study concluded that while the loads are not likely to cause eutrophication at the larger system level, tributary inlets with low flushing adjoining more urban areas could be sensitive to nutrient inputs.

Mohamedali et al. (2011) used the same monitoring data to develop daily concentrations and loads for the rivers and streams of South and Central Puget Sound. Total loads for the area south of Edmonds were 10,900 kg/d from rivers and 26,700 kg/d from WWTPs for the period 2006-07. These were similar to but not identical to the 1999-2008 loads found in the present study (8,900 kg/d from rivers and 28,200 kg/d from WWTPs), which used a monthly prediction for WWTPs for the period 1999 through 2008. Differences in river loads are due to hydrology for the longer 10-year time period compared with just two years.

Paulson et al. (2006) estimated annual DIN loads to Hood Canal from local watershed sources. The centralized wastewater discharge was negligible (<3 kg/d) compared with other sources (1800 kg/d). Hood Canal load estimates in our study (810 kg/d from rivers, < 1 kg/d from WWTPs) are lower than those developed by Paulson et.al. (2006) and Steinberg et al. (2010). Both studies relied on extensive small-stream monitoring programs that collected data for several years and do not have long-term data available. Because the two long-term monitoring stations in the Hood Canal watershed are larger rivers with relatively low levels of development, extrapolations may not capture the influence of the shoreline contributions. This pattern is unique to Hood Canal, where the topography favors a shoreline fringe of development.

Natural Conditions

Using the monthly 10th percentiles of recent ambient data as well as monthly median of atmospheric (rainfall data), we identified natural condition concentrations for nitrogen and phosphorus within different regions of Puget Sound and the Straits. Natural concentrations are lower than current concentrations since they represent concentrations of nutrients in rivers and streams in the absence of human sources of nutrients. These lower concentrations translate into lower DIN loads under natural conditions.

Table 12 compares natural condition DIN load contributions to both human non-point and point sources. The difference between human and natural loads reflects the influence of anthropogenic sources of nutrients, including changes in land use and development, increases in population, and loads from WWTPs.

The largest human loads of DIN are generally found in more populated regions of Puget Sound. For example, Puget Main receives, by far, the largest total *human* load of nitrogen (22,730 kg/d) than any other region of Puget Sound; almost all of this load is from WWTPs in this region. After Puget Main, total human loads contributions are greatest into Whidbey Basin, SOG, South Sound and Commencement Bay. In Whidbey Basin and South Sound, human non-point and point sources contribute comparable loads. In contrast, the majority of human loads into SOG are from non-point sources, possibly reflecting the agricultural land-uses in the watersheds that drain into SOG.

Watersheds are less populated contribute lower human loads to Puget Sound, and these loads are generally dominated by human non-point sources that are transported to Puget Sound in rivers. The lowest human loads enter, in order, Admiralty Inlet, Hood Canal and the Strait of Juan de Fuca – all of which drain the Olympic Peninsula.

Table 12. Comparison of natural and 1998-2008 average annual DIN loads from rivers and WWTPs into the Puget Sound and the Straits.

	Average Annual DIN Load (kg/d)			
	Natural Conditions	**Human Non-Point Sources (in rivers)[1]**	**Human Point Sources (WWTPs)[2]**	**Total Human**
South Sound	2,000	2,120	2,540	4,660
Commencement Bay	1,190	920	2,440	3,360
Elliott Bay	840	800	0	800
Puget Main	810	30	22,700	22,730
Sinclair Dyes Inlet	130	100	1,010	1,110
Whidbey	9,090	3,660	3,470	7,130
Admiralty	20	110	40	150
Hood Canal	440	370	1	371
Strait of Juan de Fuca	280	200	310	510
Strait of Georgia	2,630	3,510	1,760	5,270
Puget Sound Subtotal[3]	**14,500**	**8,100**	**32,200**	**40,300**
Straits (US) Subtotal[3]	**2,900**	**3,700**	**2,100**	**5,800**
Total[3]	**17,400**	**11,800**	**34,300**	**46,100**

[1] Human non-point sources = (1999-2008 annual average river loads) – (natural condition loads)

[2] Human point sources = 1999-2008 annual average WWTP loads

[3] These totals have been rounded to the nearest 100 kg/d

Total point sources into Puget Sound and the Straits (34,200 kg/d) contribute almost three times as much as do human non-point sources (11,800 kg/d). In Puget Sound, human sources of DIN (both point and non-point) are 180% higher than natural loads, while in the Straits, they are 100% higher. The magnitude of human DIN loads entering Puget Sound waters varies spatially, with the largest human contributions entering the main basin of Puget Sound (Puget Main). This human DIN load to Puget Sound is almost entirely from WWTPs.

As an independent check on human nitrogen sources into Puget Sound and the Straits, we estimated human wastewater as the population times a per capita contribution. The current population is 4.1 million (Puget Sound Partnership, 2008). Using a per capita contribution of 4.5 kg-N/yr (Steinberg et al., 2010), this is equivalent to 50,500 kg/d of nitrogen. This estimate ignores animal manures and agricultural fertilizers, which Embrey and Inkpen identified as the two largest nutrient sources to the basin. However, the value is comparable to the total human contribution estimated above (46,100 kg/d).

A slightly different pattern emerges when we look at *percent* DIN load contributions (Figure 37). Again, the load from point sources into Puget Main is high at 97% of the total annual DIN load. However, the percent point source load contribution into Sinclair Dyes is also large (82%) even though absolute loads into Sinclair Dyes Inlet are relatively small. Percent point-source contributions are also larger than human non-point sources into Commencement Bay and SJF.

Relative contributions of loads from human point and non-point sources into South Sound and Whidbey Basin are comparable. Human non-point sources dominate in Elliott Bay, Admiralty Inlet, Hood Canal and SOG. There are virtually zero point source contributions into Elliott Bay and Hood Canal.

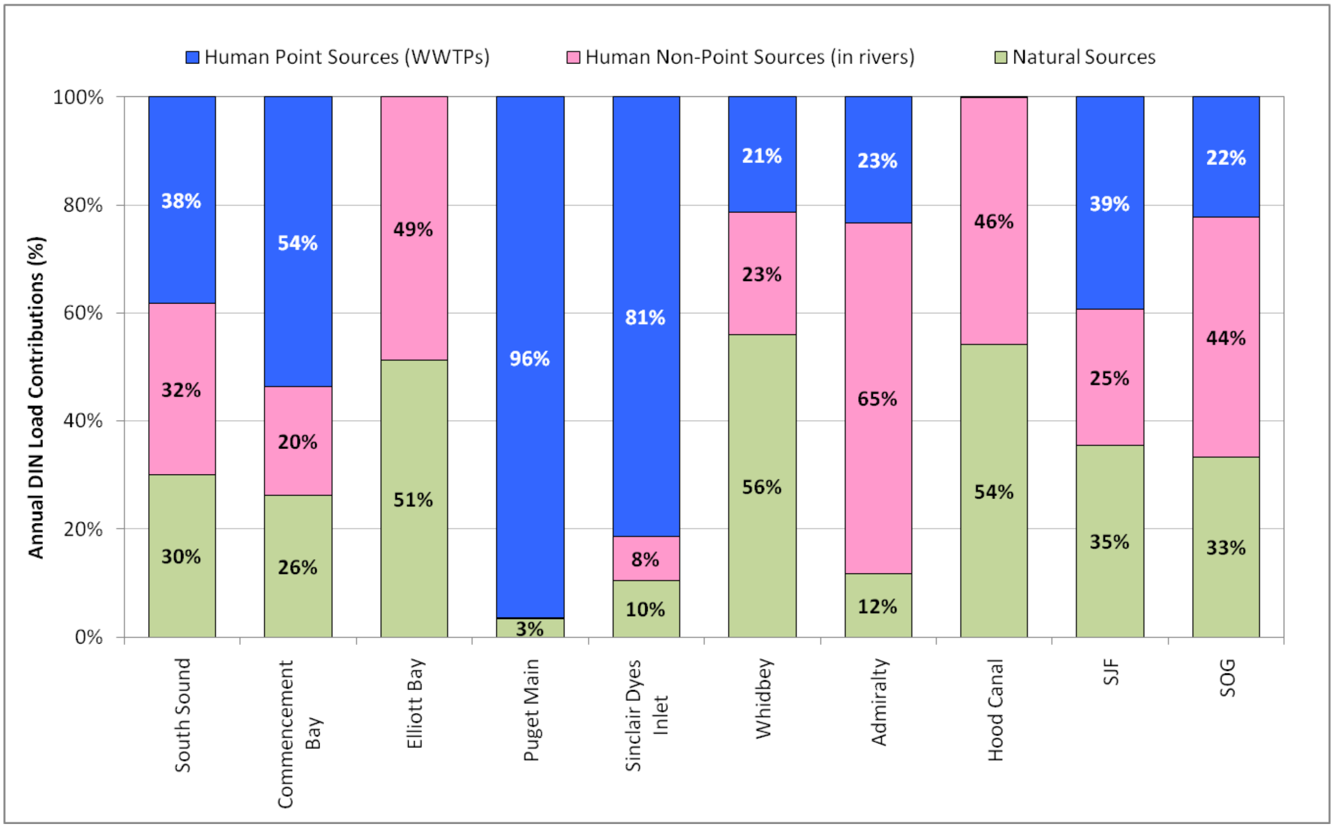

Figure 37. Relative contributions of annual dissolved inorganic load to different regions of Puget Sound from human point sources (WWTPs), human non-point sources (in rivers), and natural sources.

The proportion of current loads that are from human point and non-point sources is 73% in Puget Sound and 67% in the Straits. Human activity, such as changes in land use and development and growing population, has increased DIN loads (Figure 38).

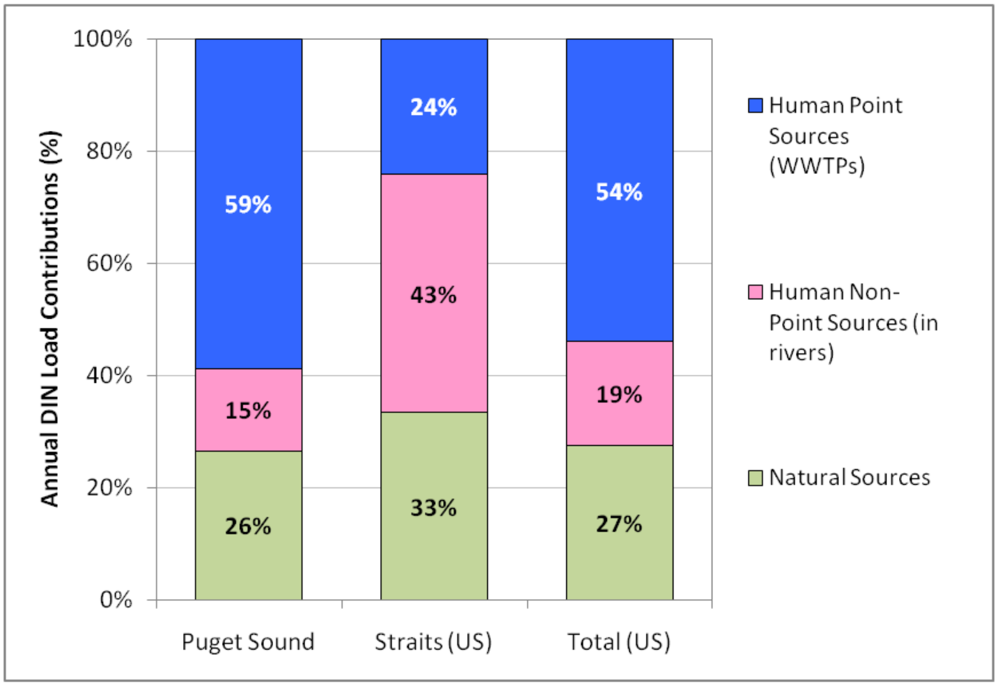

Figure 38. Relative contributions of annual dissolved inorganic load to Puget Sound and the Straits (U.S.) from human point sources (WWTPs), human non-point sources (in rivers), and natural sources.

Conclusions

The development of nutrient loading estimates presented in this report will be useful when applied to the PSDOM in evaluating the effects that these loads have on Puget Sound water quality. In addition, the *multiple linear regression* method used to develop these estimates are based mostly on site-specific monitoring data but also fill in information about rivers and WWTPs that were not monitored throughout the study period. These nutrient loading estimates are some of the most comprehensive estimates developed for the Puget Sound region to date. The compilation enables comparison of the relative magnitudes and sources of nutrients to Puget Sound.

Of these nutrients, dissolved inorganic nitrogen (DIN) is of greatest interest since this is the form of nitrogen most available to algae. DIN loads (rivers and WWTPs combined) from Canada are greater than those from the U.S; however, these loads may or may not affect Puget Sound water quality depending on the fate and transport of these nutrients once they enter the Straits.

Puget Main, the main basin of Puget Sound between Edmonds and Tacoma Narrows, receives 3.6 times the average DIN load than the overall average for all of Puget Sound (excluding loads into the Straits). WWTPs (34,300 kg/d) and rivers (29,200 kg/d) in the U.S. produce DIN loads of similar magnitude when summed across all regions of Puget Sound. However, when we look at specific regions of Puget Sound, the ratio of WWTP and river DIN loads is different. For example, in Puget Main, WWTPs discharges contribute 96% of the average annual DIN loads. In Sinclair-Dyes Inlet, WWTPs contributions are 82% of the total DIN load. In contrast, rivers contribute 79% of the total DIN loads into Whidbey Basin and 76% into the U.S. portions of the Straits.

Seasonality plays a noticeable role in the magnitude of river loads, but has a smaller effect on WWTP loads. The timing of nutrient loads into Puget Sound is important because DO also tends to have a seasonal pattern, and the lowest DO levels have been observed in late summer. Therefore, summer loading may have a larger influence on DO levels than annual average loads. WWTP loads during the summer dominate since river DIN loads are lower due to lower flows (this is true for all rivers except the Fraser River). When we look at loads into Puget Sound, WWTP DIN loads are 4.3 times greater than river loads during the summer, but only 1.4 times greater than river loads on an annual average basis.

The proportion of current loads that are from human point and non-point sources is 73% in Puget Sound and 67% in the Straits. Human activity, such as changes in land use and development and growing population, has increased DIN loads.

During the modeling phase of this study, natural condition loads will be used to evaluate what water quality conditions would be in Puget Sound in the absence of significant human influence on the ecosystem. In particular, the model will take into account other variables that influence this dynamic ecosystem, allowing us to assess whether human sources of nutrients impact water quality.

Recommendations

The estimates presented in this study focus primarily on the magnitude and timing of nutrient loading from rivers and WWTPs at the point at which these sources discharge directly into Puget Sound. River loads are influenced by a variety of factors upstream from the mouth of each watershed, such as land use, topography, atmospheric deposition, geology, and groundwater dynamics. If the model is able to identify which watersheds have a pronounced impact on Puget Sound water quality, it is important to investigate in more detail the specific sources of these nutrients further upstream.

For future analysis, refined estimates of DIN loads from on-site septic systems within monitored catchments would be helpful as an alternative means of estimating human contributions. This would allow us to determine the proportion of current watershed loads that are from on-site septic systems. Better estimates of attenuation of nitrogen in the soil would also improve our estimates of loading from septic systems. However, attenuation rates vary greatly, and the enormous heterogeneity of the subsurface environment complicates this estimate.

Since we used coarser data to develop loading estimates from Canadian watersheds and WWTPs, the PSDOM model should be used to assess how sensitive water quality in Puget Sound and the Straits is to loading from Canadian sources. If Canadian sources influence Puget Sound dissolved oxygen, then additional discussions with Canadian representatives is warranted to develop a joint understanding.

References

Albertson, Skip, Julia Bos, Karol Erickson, Carol Maloy, Greg Pelletier, and Mindy Roberts, 2007. South Puget Sound Water Quality Study, Phase 2: Dissolved Oxygen, Quality Assurance Project Plan. Washington State Department of Ecology, Olympia, WA. Publication No. 07-03-101. www.ecy.wa.gov/biblio/0703101.html.

Cohn, T.A., D.L. Caulder, E.J. Gilroy, L.D. Zynjuk, and R.M. Summers, 1992. The validity of a simple statistical model for estimating fluvial constituent loads—and empirical study involving nutrient loads entering Chesapeake Bay. Water Resources Research. 28(9):2353-2363.

Embrey, S.S. and E.L. Inkpen, 1998. Water-quality assessment of the Puget Sound basin, Washington, nutrient transport in rivers, 1980-93. U.S. Geological Servey, Branch of Information Services. WRI no. 97-4270.

EPA, 1996. Preliminary Data Summary for the Petroleum Refining Category. U.S. Environmental Protection Agency, Office of Water Engineering and Analysis Division, Washington D.C., NY. www.epa.gov/waterscience/guide/petroleum/files/prelim-data-study.pdf.

EPA. 2000. Ambient Water Quality Criteria Recommendations. Rivers and Streams in Nutrient Ecoregion II. Office of Water, Office of Science and Technology, Health and Ecological Criteria Division. Washington D.C. EPA – 822-B-00-015. http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/upload/2007_09_27_criteria_nutrient_ecoregions_rivers_rivers_2.pdf

Ferguson J.W. and M. Healey. 2009. Hydropower in the Fraser and Columbia Rivers: a contrast in approaches to fisheries protection. Catch and Culture, Fisheries Research and Development in the Mekong Region. 15 (1). http://www.mrcmekong.org/Catch-Culture/vol15_1May09/Hydropower-fraser.htm

Hallock, David. 2009. River and Stream Water Quality Monitoring Report, Water Year 2008. Washington State Department of Ecology, Olympia, WA. Publication No. 09-03-041. http://www.ecy.wa.gov/biblio/0903041.html

Herrera Environmental Consultants, Inc. 2011. Toxics in Surface Runoff to Puget Sound: Phase 3 Data and Load Estimates. Prepared for Washington State Department of Ecology, Olympia, WA. Publication No. 11-03-010. http://www.ecy.wa.gov/biblio/1103010.html

Landry, Michael R. and B. M. Hickey. 1989. Coastal Oceanography of Washington and Oregon. Elsevier Oceanography Series, 47. Elsevier Science Publishers, New York, NY.

Lincoln, John H. 1977. Derivation of freshwater inflow into Puget Sound. University of Washington, Department of Oceanography Special Report No. 72.

Mackas, David L. and Paul J. Harrison. 1997. Nitrogenous Nutrient Sources and Sinks in the Juan de Fuca Strait/Strait of Georgia/Puget Sound Estuarine System: Assessing the Potential for Eutrophication. Estuarine, Coastal and Shelf Science. 44:1-21.

Mohamedali, Teizeen, Mindy Roberts, Brandon Sackmann, Anthony Whiley and Andrew Kolosseus, 2011. South Puget Sound Dissolved Oxygen Study: Interim Nutrient Load Summary for 2006-2007. Washington State Department of Ecology, Olympia, WA. Publication No. 11-03-001. http://ww.ecy.wa.gov/biblio/1103001.html.

Paulson, A., Konrad, C., Frans, L., Noble, M., Kendall, C., Josberger, E., Huffman, R., and Olsen, T. 2006. Freshwater and Saline Loads of Inorganic Nitrogen to Hood Canal and Lynch Cove, Washington. USGS in cooperation with Hood Canal Dissolved Oxygen Program. Scientific Investigations Report 2006–5106. pubs.usgs.gov/sir/2006/5106/pdf/sir20065106.pdf.

Pitz, Charles. 1999. Estimated of Nitrate Loading to South Puget Sound by Groundwater Discharge. Washington State Department of Ecology, Olympia, WA. Report No. 99-348. http://www.ecy.wa.gov/biblio/99348.html.

Puget Sound Partnership. 2008. Puget Sound – Where land and sea meet. Olympia, WA. http://www.psparchives.com/puget_sound.htm (accessed June 22, 2011).

Roberts, Mindy, and Greg Pelletier, 2001. Estimating Loads of Nutrients, Bacteria, DO and TSS from 71 Watersheds Tributary to South Puget Sound. Proceedings of the Georgia Basin/Puget Sound Research Conference, Bellevue, WA. www.ecy.wa.gov/programs/eap/sps/psrc_2001_roberts_and_pelletier.pdf.

Roberts, Mindy, Julia Bos, and Skip Albertson, 2008. South Puget Sound Dissolved Oxygen Study: Interim Data Report. Washington State Department of Ecology, Olympia, WA. Publication No. 08-03-037. www.ecy.wa.gov/biblio/0803037.html.

Sackmann, Brandon, 2009. Deschutes River Continuous Nitrate Monitoring: Quality Assurance Project Plan. Washington State Department of Ecology, Olympia, WA. Publication No. 09-03-130. www.ecy.wa.gov/biblio/0903130.html.

Steinberg, P.D., M. T. Brett, J.S. Bechtold, J.E. Richey, L.M. Porensky and S.N. Smith. 2010. The Influence of Watershed Characteristics on Nitrogen Export to and Marine Fate in Hood Canal, Washington, USA. Biogeochemistry. *Online First*. www.springerlink.com/content/4737t5245l234715/. Accessed on 12/03/2010.

Vaccaro J.J., AJ. Hansen, Jr., and M.A. Jones. 1998. Hydrogeologic Framework of the Puget Sound Aquifer System, Washington and British Columbia. U.S. Geological Survey Professional Paper 1424-D, 77p + plate. http://pubs.er.usgs.gov/djvu/PP/pp_1424_d.djvu.

Appendices

This page is purposely left blank

Appendix A. Glossary, Acronyms, and Abbreviations

Glossary

Ambient monitoring: Background or away from point sources of contamination.

Anthropogenic: Human-caused.

Catchment: The area draining to a point (e.g. a storm drain).

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

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

Exclusive area: Area outside of monitored catchments/watersheds and outside of municipal wastewater service areas, but within the study area.

Extrapolated area: Area outside of monitored catchments/watersheds but within the study area.

Grab sample: A discrete sample from a single point in the water column or sediment surface.

Dissolved inorganic nitrogen (DIN): The sum of nitrate, nitrite and ammonium, which are all different inorganic forms of nitrogen. DIN is the most available form of nitrogen to algae.

Loading: The input of pollutants into a waterbody.

Marine water: Salt water.

Multiple linear regression method: A statistical technique used to determine the linear relationship between one dependent variable and two or more independent variables. In this study, the dependent variable is *concentration* and the independent variables are various terms that represent *streamflow* (or WWTP effluent flow) and *time of year*.

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

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

Nutrient: Substance such as carbon, nitrogen, and phosphorus used by organisms to live and grow. Too many nutrients in the water can promote algal blooms and rob the water of oxygen vital to aquatic organisms.

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

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.

Regression: A technique used to determine the mathematical relationship between a dependent variable and an independent variable(s) using a set of data points. The mathematical relationship can then be used to predict the dependent variable given a different values for the independent variable(s).

Sediment: Solid fragmented material (soil and organic matter) that is transported and deposited by water and covered with water (example, river bottom).

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

Study area: In this report, the study area includes the marine waters of Puget Sound and the Straits of Georgia and Juan de Fuca, as well as all the watersheds that drain into these marine waters.

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

Water year (WY): October 1 through September 30. For example, WY07 is October 1, 2006 through September 30, 2007.

10th percentile: A statistical number obtained from a distribution of a data set, above which 90% of the data exists and below which 10% of the data exists.

25th percentile: A statistical number obtained from a distribution of a data set, above which 70% of the data exists and below which 25% of the data exists.

75th percentile: A statistical number obtained from a distribution of a data set, above which 25% of the data exists and below which 75% of the data exists.

90th percentile: A statistical number obtained from a distribution of a data set, above which 10% of the data exists and below which 90% of the data exists.

Acronyms and Abbreviations

BP	British Petroleum
DMR	Discharge Monitoring Reports
DO	Dissolved Oxygen
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
HCDOP	Hood Canal Dissolved Oxygen Program
LOTT	Lacey, Olympia, Tumwater, and Thurston County Alliance
GEMSS	Generalized Environmental Modeling System for Surface Waters
MEL	Manchester Environmental Laboratory
NADP	National Atmospheric Deposition Program
NPDES	National Pollutant Discharge Elimination System
PNNL	Pacific Northwest National Laboratories
PSDOM	Puget Sound Dissolved Oxygen Model
QA	Quality assurance
RMSE	Root means square error
RSD	Relative standard deviation
SOP	Standard operating procedures
SPSDO	South Puget Sound Dissolved Oxygen
USGS	U.S. Geological Survey
UW-CIG	University of Washington Climate Impacts Group
WPLCS	Water Quality Permit Life Cycle System
WRIA	Water Resources Inventory Area
WSC	Water Survey of Canada
WWTP	Wastewater treatment plant
WY	Water year

Nutrient Parameters

BOD	Biological oxygen demand
CBOD	Carbonaceous biochemical oxygen demand
DIN	Dissolved inorganic nitrogen
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
DOP	Dissolved organic phosphorus
DTP	Dissolved total phosphorus
DTPN	Dissolved total persulfate nitrogen
NH4N	Ammonium
NO23N	Nitrate + nitrite
OP	Ortho-phosphate
PON	Particulate organic nitrogen
POP	Particulate organic phosphorus

TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TPN	Total persulfate nitrogen

Units of Measurement

cms	cubic meters per second, a unit of flow.
kg	kilograms, a unit of mass equal to 1,000 grams.
kg/d	kilograms per day
km	kilometer, a unit of length equal to 1,000 meters.
m	meter
mg	milligrams
mg/L	milligrams per liter, a unit of concentration; equivalent to mg-N/L, mg-P/L, or mg-C/L for nitrogen, phosphorus, and carbon compounds, respectively.
mgd	million gallons per day
mi	mile, a unit of length equal to 1,609 meters.

Appendix B. Rivers: Predicted and Observed Nutrient Concentrations and Loads

This appendix includes plots of observed and predicted concentrations and loads of various nutrient parameters for the four largest rivers in the U.S. north of Edmonds.

Figures B-1 and B-2 compare observed and predicted concentrations and loads of various parameters for the Skagit River.

Figure B-1. Predicted and observed concentrations (left column) and loads (right column) of nitrogen for the Skagit River (observed ammonium concentrations were at the detection limit and are therefore not presented).

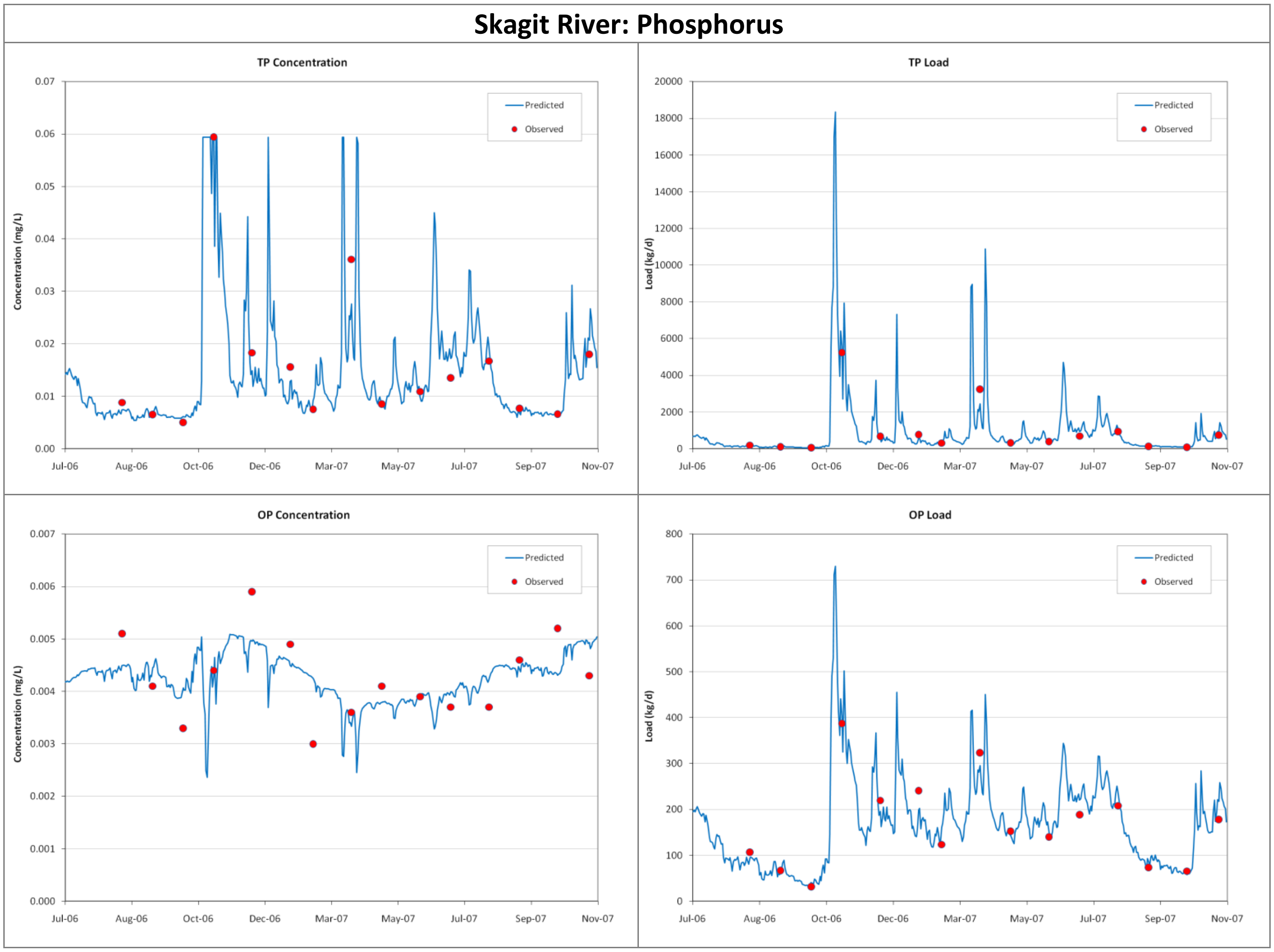

Figure B-4. Predicted and observed concentrations (left column) and loads (right column) of phosphorus for the Skagit River.

Figures B-3 and B-4 compare observed and predicted concentrations and loads of various parameters for the Snohomish River.

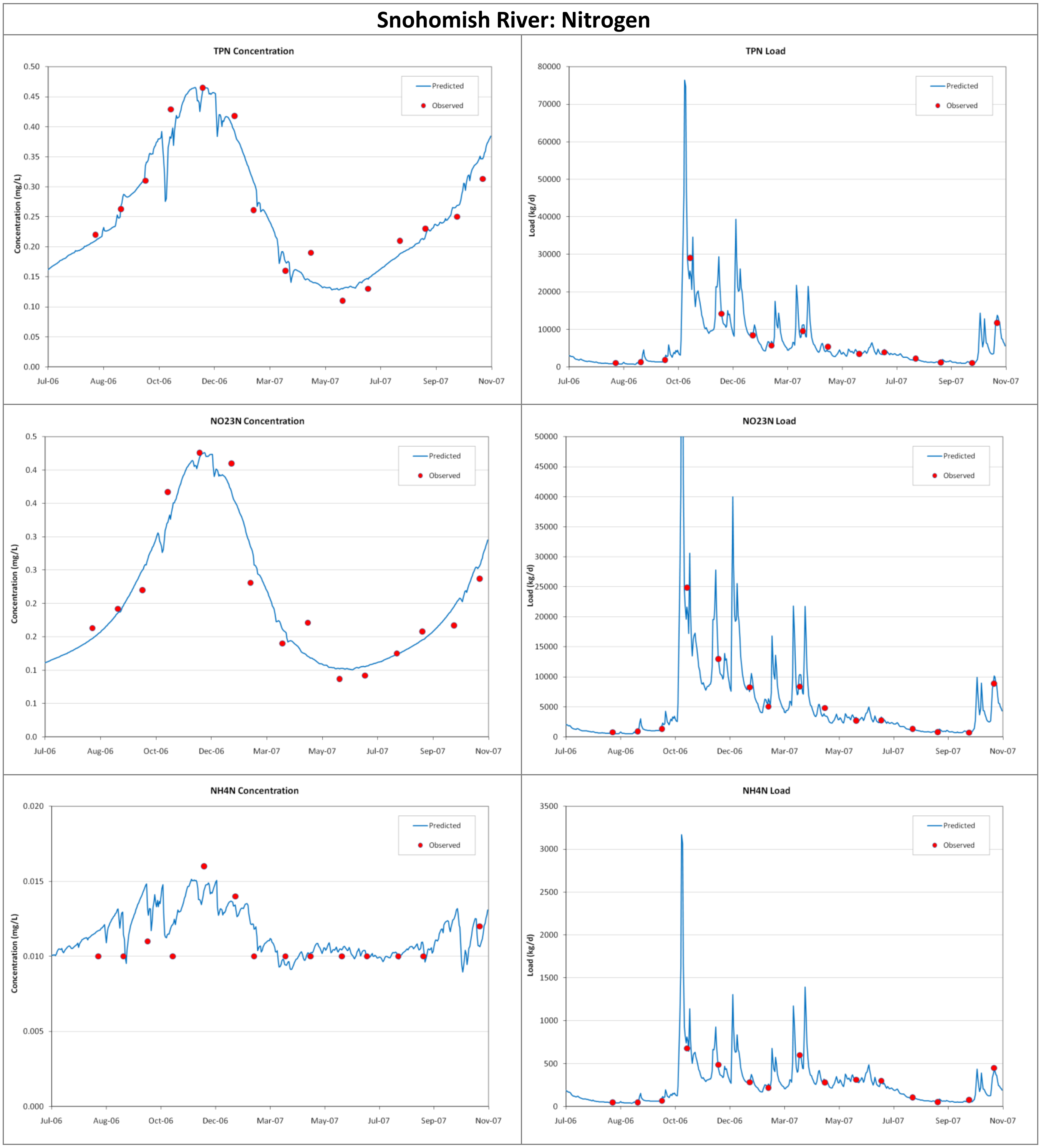

Figure B-3. Predicted and observed concentrations (left column) and loads (right column) of nitrogen for the Snohomish River.

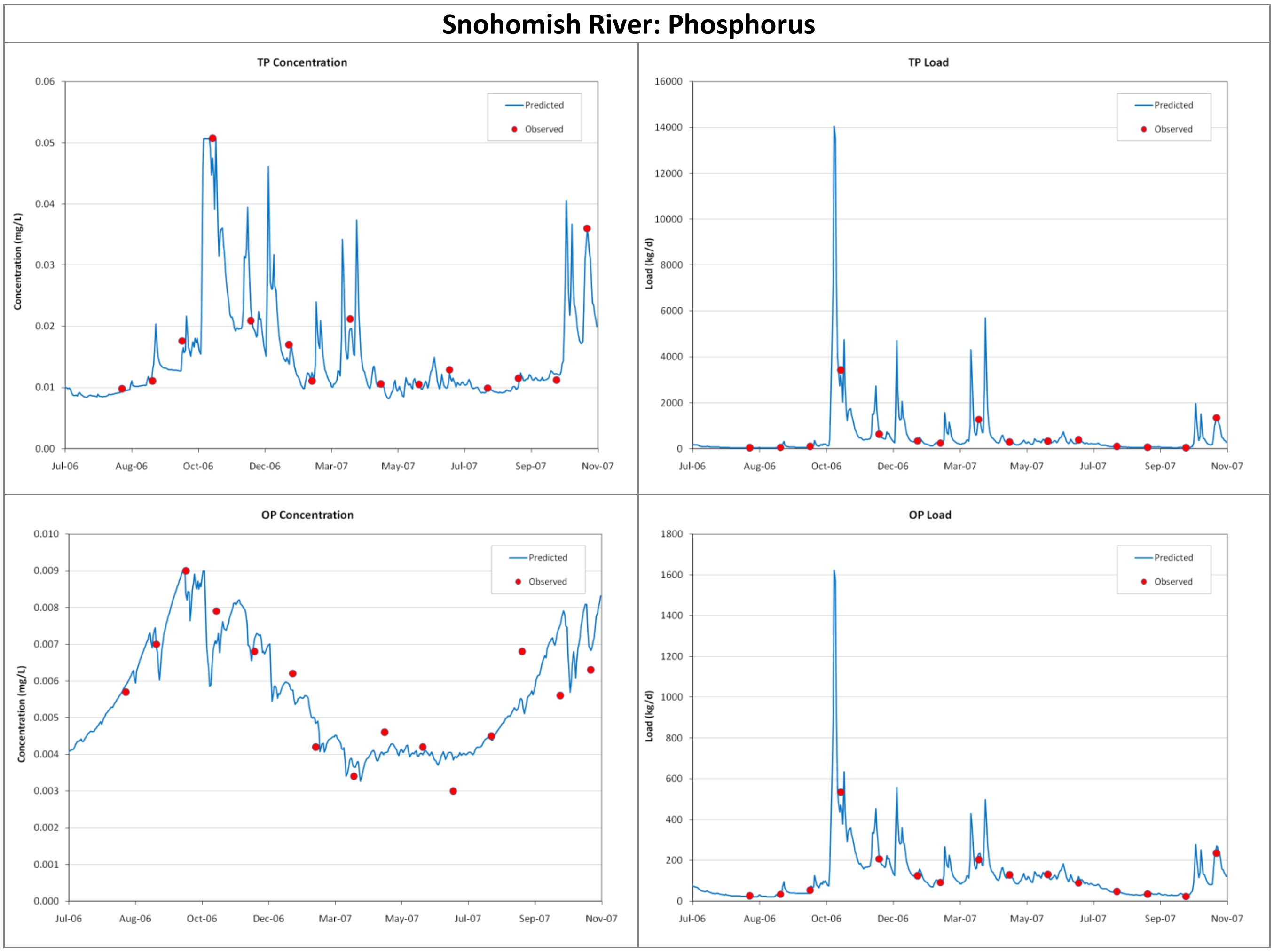

Figure B-4. Predicted and observed concentrations (left column) and loads (right column) of phosphorus for the Snohomish River.

Figures B-5 and B-6 compare observed and predicted concentrations and loads of various parameters for the Stillaguamish River.

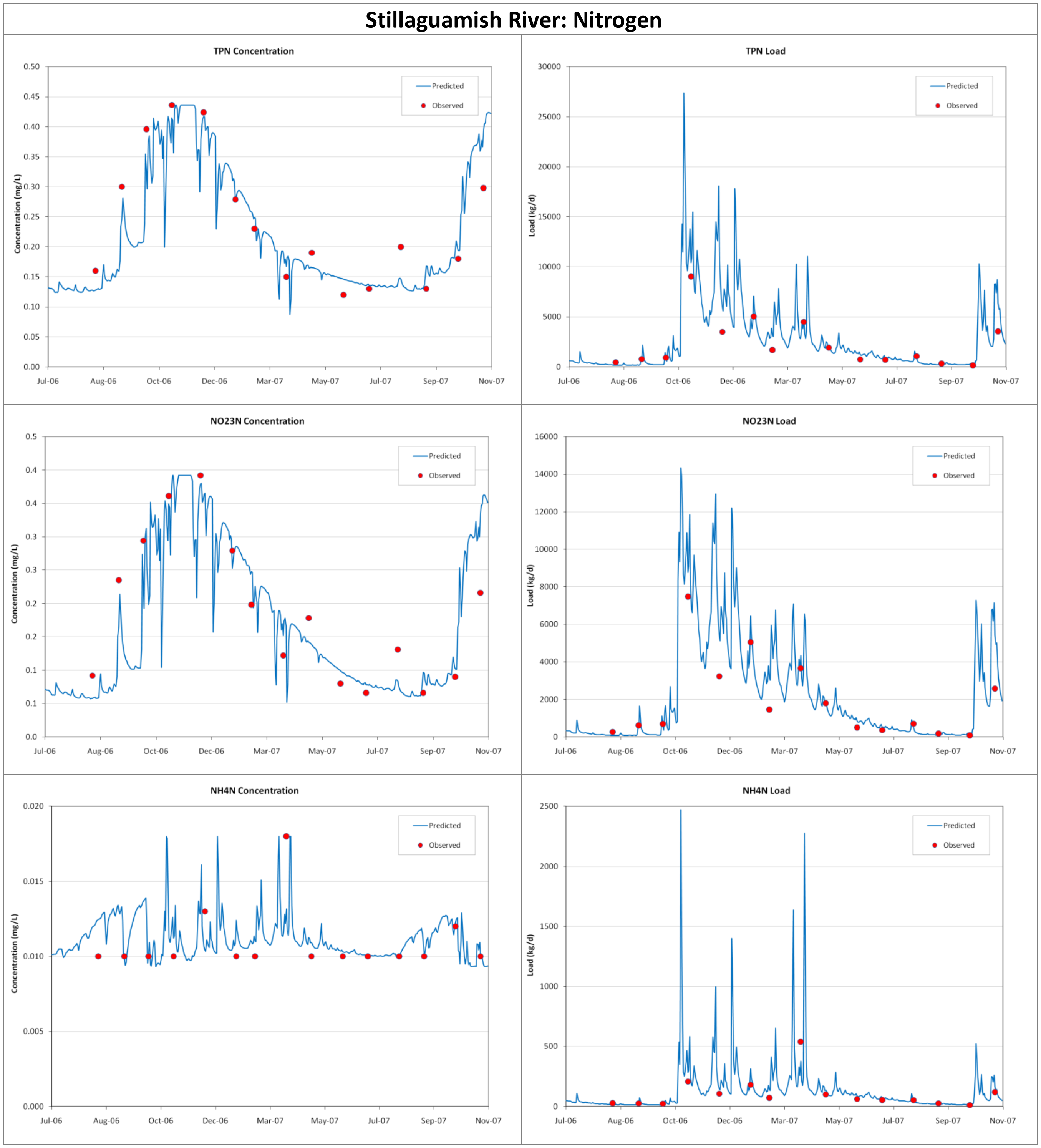

Figure B-5. Predicted and observed concentrations (left column) and loads (right column) of nitrogen for the Stillaguamish River.

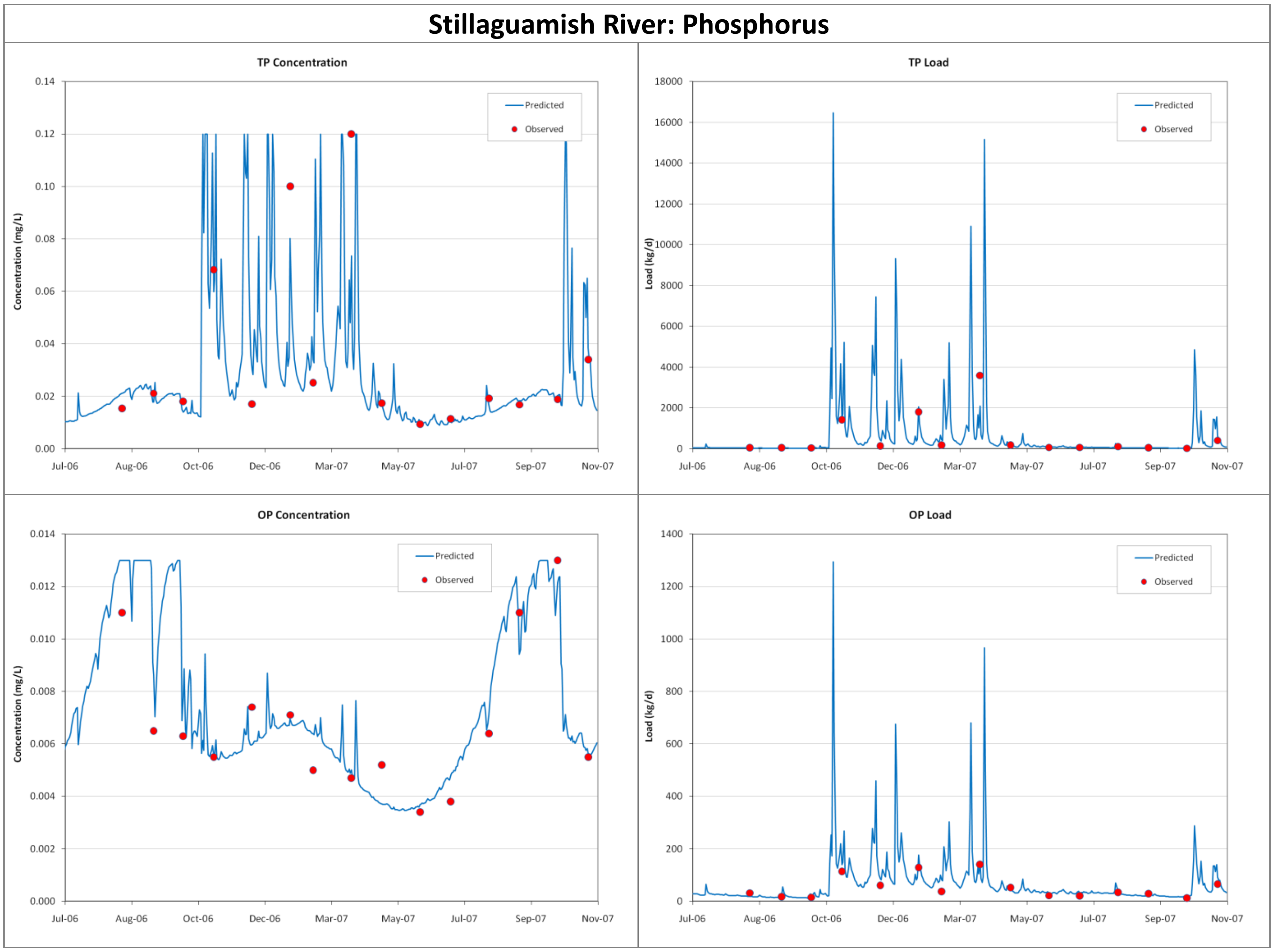

Figure B-6. Predicted and observed concentrations (left column) and loads (right column) of phosphorus for the Stillaguamish River.

Figures B-7 and B-8 compare observed and predicted concentrations and loads of various parameters for the Nooksack River.

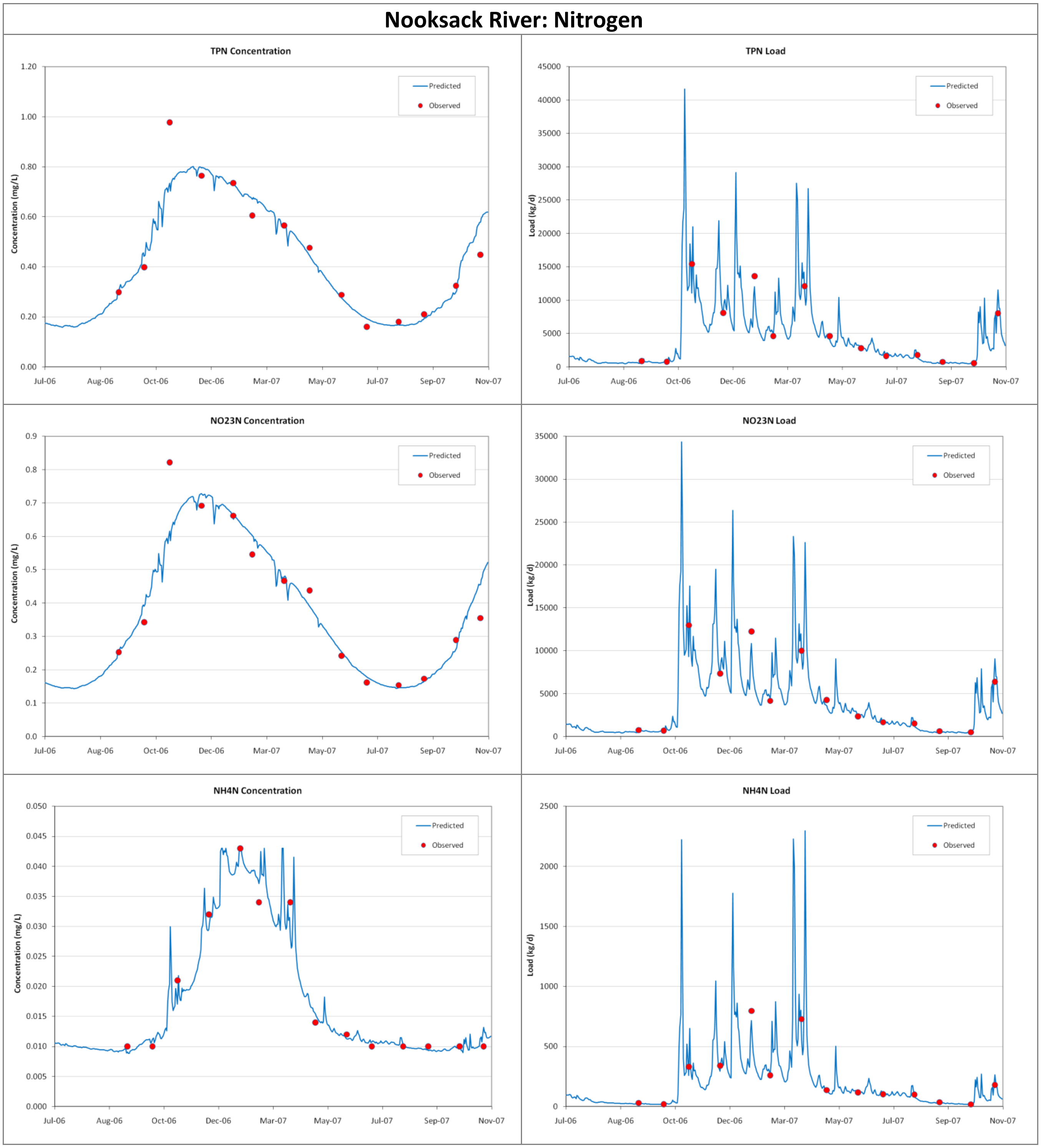

Figure B-7. Predicted and observed concentrations (left column) and loads (right column) of nitrogen for the Nooksack River.

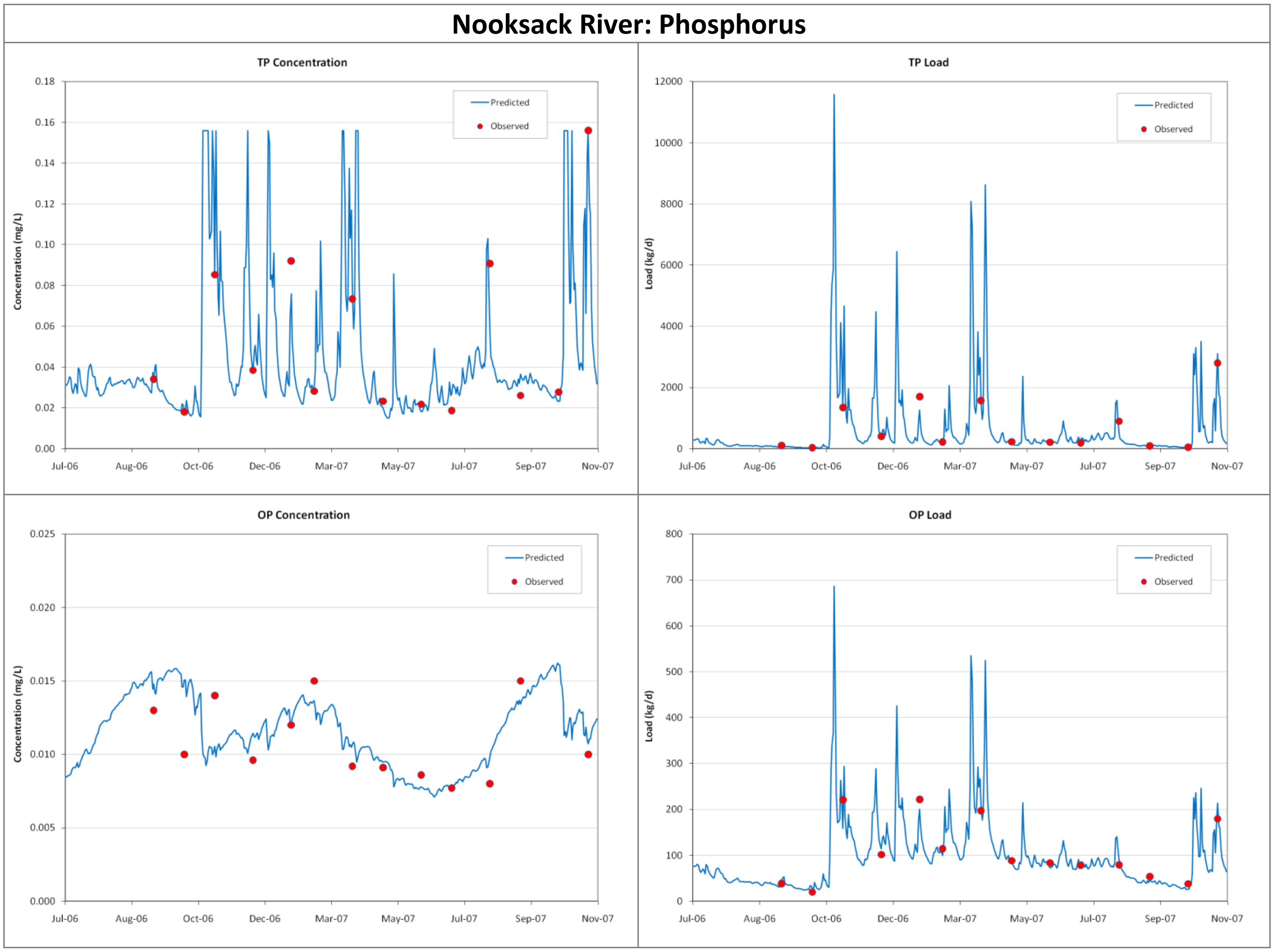

Figure B-8. Predicted and observed concentrations (left column) and loads (right column) of phosphorus for the Nooksack River.

Appendix C. Wastewater Treatment Plants: Predicted and Observed Carbonaceous Biological Oxygen Demand

Figures C-1 through C-3 compare observed and predicted concentrations and loads of carbonaceous biological oxygen demand (CBDO) for a three of the largest WWTPs north of Edmonds where site-specific regressions for CBOD were carried out.

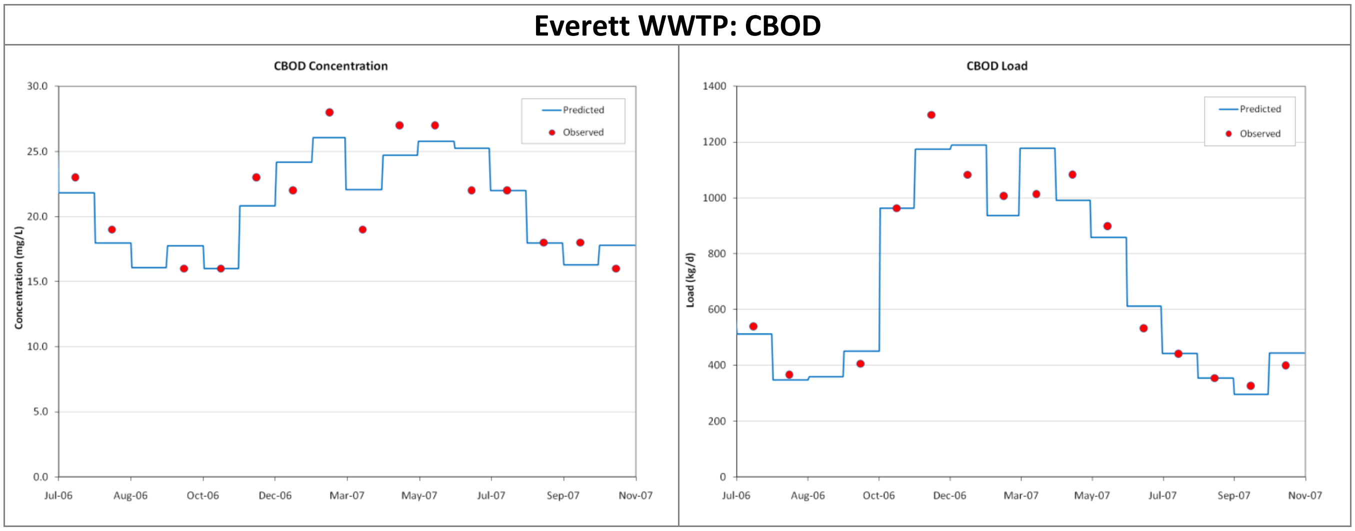

Figure C-1. Predicted and observed concentrations (left column) and loads (right column) of carbonaceous biological oxygen demand for Everett WWTP.

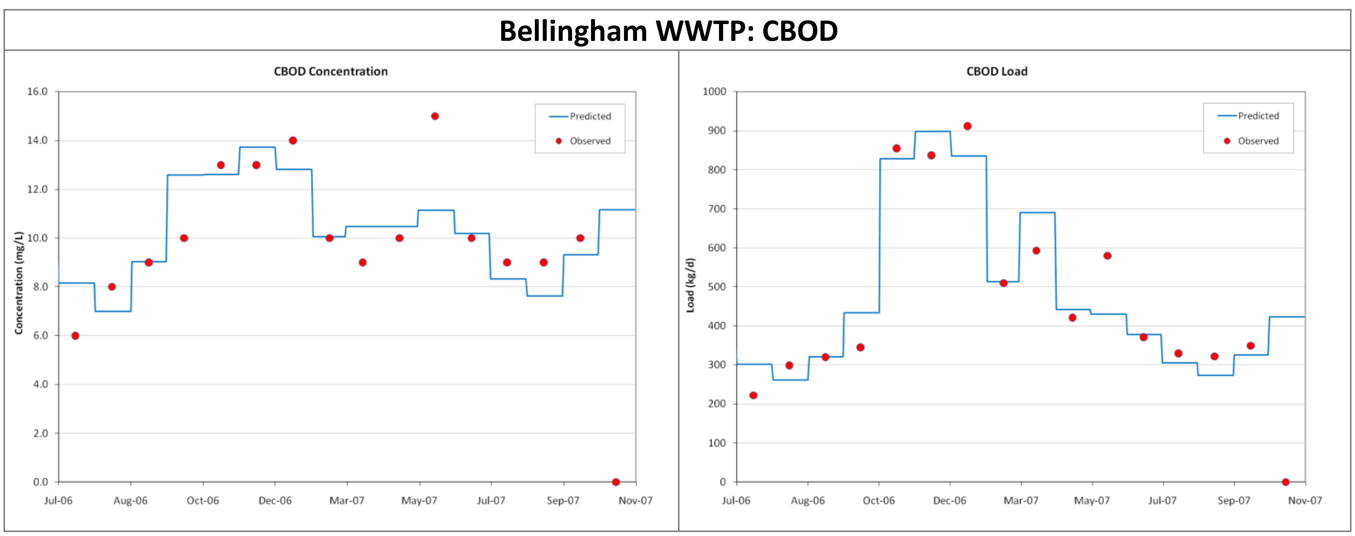

Figure C-2. Predicted and observed concentrations (left column) and loads (right column) of carbonaceous biological oxygen demand for Bellingham WWTP.

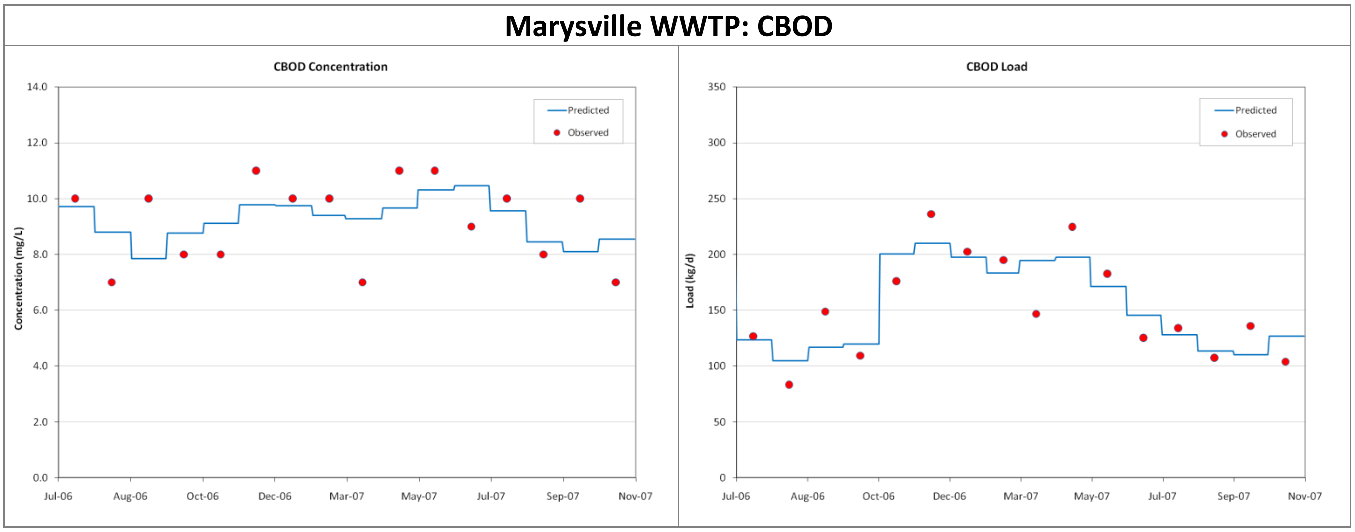

Figure C-3. Predicted and observed concentrations (left column) and loads (right column) of carbonaceous biological oxygen demand for Marysville WWTP.

Figures C-4 through C-7 compare observed and predicted concentrations and loads of carbonaceous biological oxygen demand (CBDO) for a four of the largest pulp/paper mills north of Edmonds where site-specific regressions for CBOD were carried out.

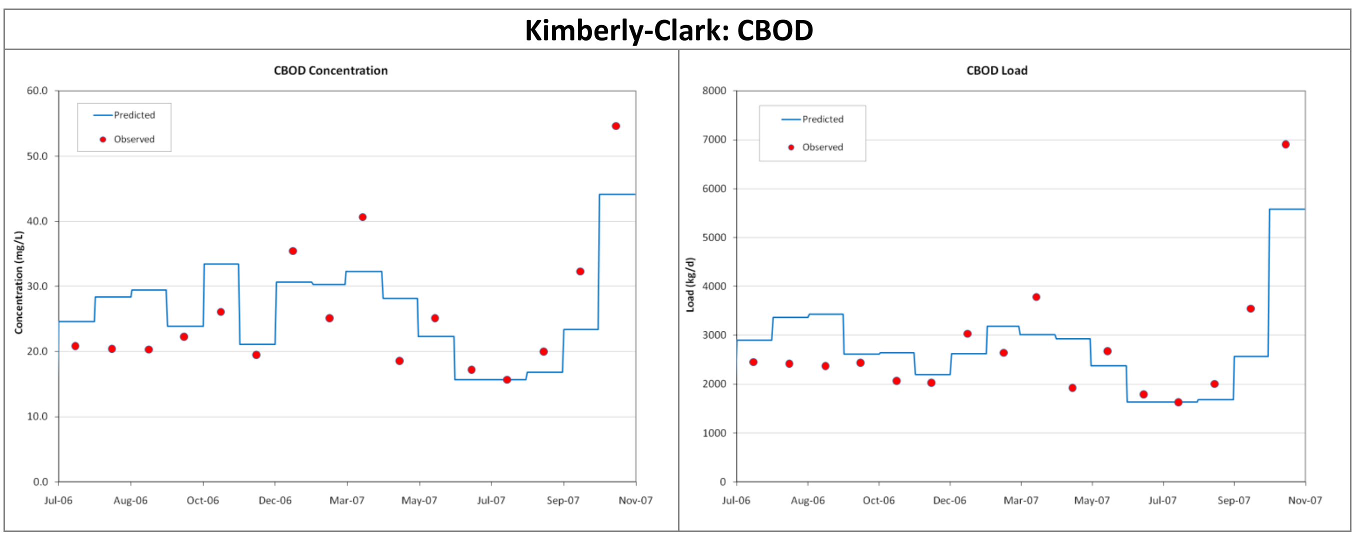

Figure C-4. Predicted and observed concentrations (left column) and loads (right column) of carbonaceous biological oxygen demand for Kimberly-Clark.

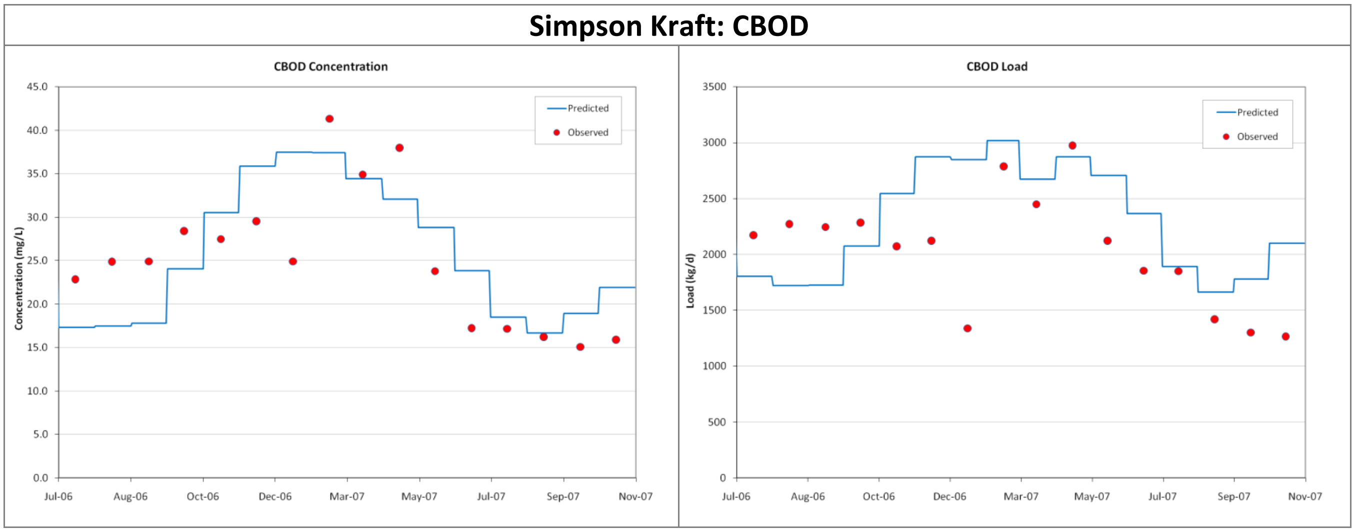

Figure C-5. Predicted and observed concentrations (left column) and loads (right column) of carbonaceous biological oxygen demand for Simpson Kraft.

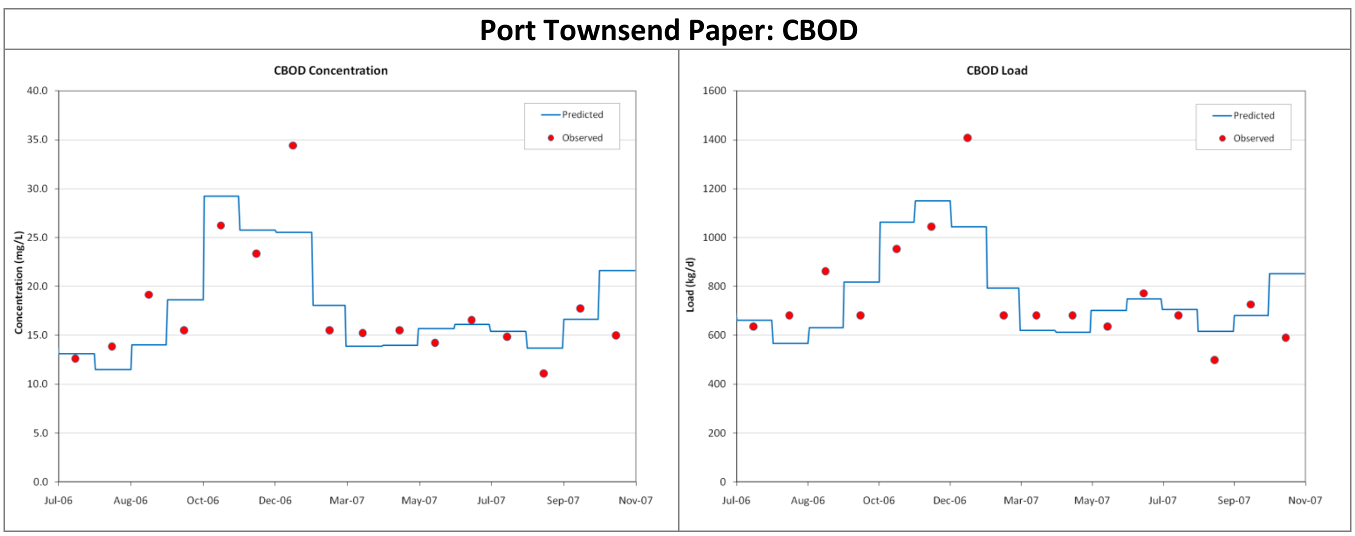

Figure C-6. Predicted and observed concentrations (left column) and loads (right column) of carbonaceous biological oxygen demand for Port Townsend Paper.

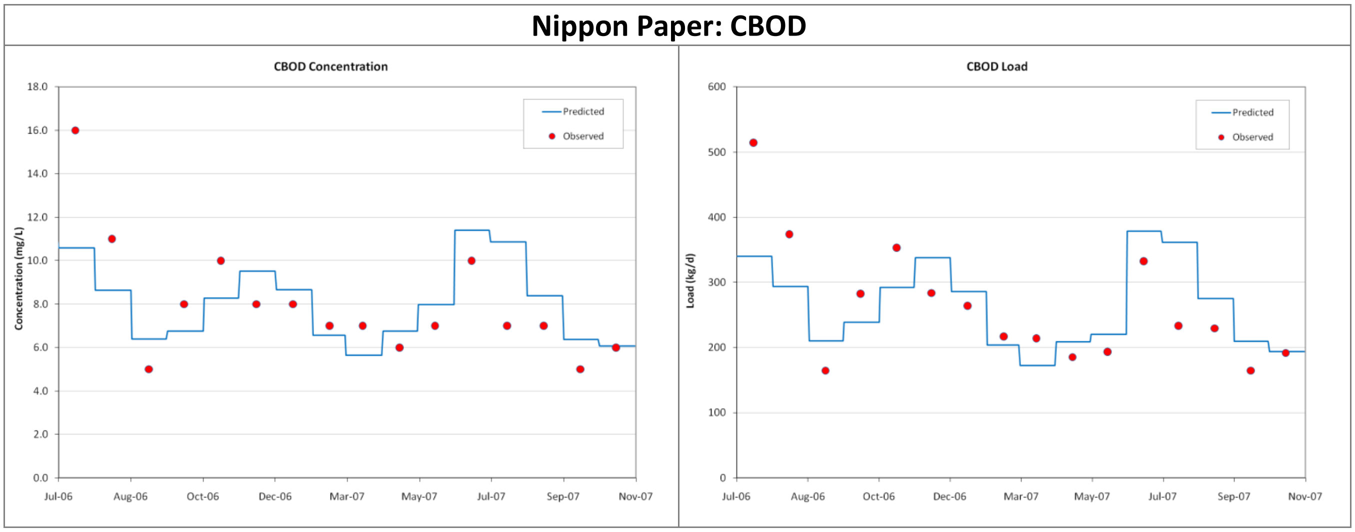

Figure C-7. Predicted and observed concentrations (left column) and loads (right column) of carbonaceous biological oxygen demand for Nippon Paper.

Appendix D. Rivers: Nutrient Loading

Table D-1 includes a summary of summer and annual dissolved inorganic nitrogen (DIN) loads from all watersheds tributary to Puget Sound and the Straits.

Figures D-1 through D-7 present concentration box plots of various nutrients (nitrogen, phosphorus, and carbon) for all rivers in the study area.

Table D-1. Mean summer (July-September) and annual DIN loads from all watersheds in the study area for 1999-2008

Watershed Name	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
South Sound		
Budd/Deschutes	266	842
Carr north	74.0	145
Carr south	56.1	125
Case north	31.8	83.6
Case south	6.99	16.4
Chambers	172	488
Dana Passage	8.75	22.1
Eld	16.2	65.4
Goldsborough	29.4	148
Henderson	95.7	205.4
Little Skookum	17.0	71.6
McAllister	156	312
Nisqually	438	1426
Oakland Bay	16.7	52.4
Pickering	4.90	15.1
Totten	18.9	102
Commencement Bay		
Puyallup	933	2105
Elliott Bay		
Green/Duwamish	424	1635
Puget Main		
Colvos Passage	46.0	128
Kitsap NE	0.83	7.58
Lake Washington	34.3	432
Quartermaster	13.0	37.1
South King	49.8	141
South Snohomish	6.78	25.4
Tacoma Narrows	26.1	73.2

Watershed Name	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
Sinclair Dyes Inlet		
Sinclair Dyes	48.9	229
Whidbey		
Skagit	1596	4224
Snohomish	1598	5945
Stillaguamish	407	2441
Whidbey east	32.8	144
Admiralty		
Port Townsend	2.77	4.94
Whidbey west	28.5	122
South Hood		
Dabob Bay	1.78	6.88
Dosewallips	16.09	66.2
Duckabush	13.30	55.0
Hamma Hamma	11.9	91.9
Lynch Cove	4.59	73.2
Quilcene	2.87	16.7
Skokomish	30.2	226
Tahuya	5.64	90.0
North Hood		
Kitsap/Hood	7.57	77.9
NW Hood	5.98	57.3
Port Gamble	4.59	44.5
Strait of Georgia/Juan de Fuca (U.S. waters)		
Birch Bay	48.0	196
Clallam Bay	8.58	141
Discovery Bay	4.75	8.59
Dungeness	17.9	33.8
Elwha	52.1	153

Watershed Name	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
Strait of Georgia/Juan de Fuca (U.S. waters)		
Lopez Island	16.2	74.1
Nooksack	1064	4175
North Olympic	8.38	121
Orcas Island	34.4	170
Port Angeles	9.22	16.9
Samish/Bell south	143	771
San Juan Island	29.5	145
Sequim Bay	1.21	2.16
Whatcom/Bell north	106	609
Vancouver Island		
Vancouver Isl C	11.6	186
Vancouver Isl N	69.7	360
Vancouver Isl S	466	1776
Victoria/SJdF	238	2038
Vancouver Mainland		
Howe Sound	1465	1256
Sunshine Coast	4846	4479
Fraser	38954	33136

	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
Puget Sound	6764	22627
Straits (U.S.)	1543	6618
SUBTOTAL (all U.S.)	**8306**	**29244**
Straits (Canada)	46051	43231
TOTAL	**54357**	**72475**

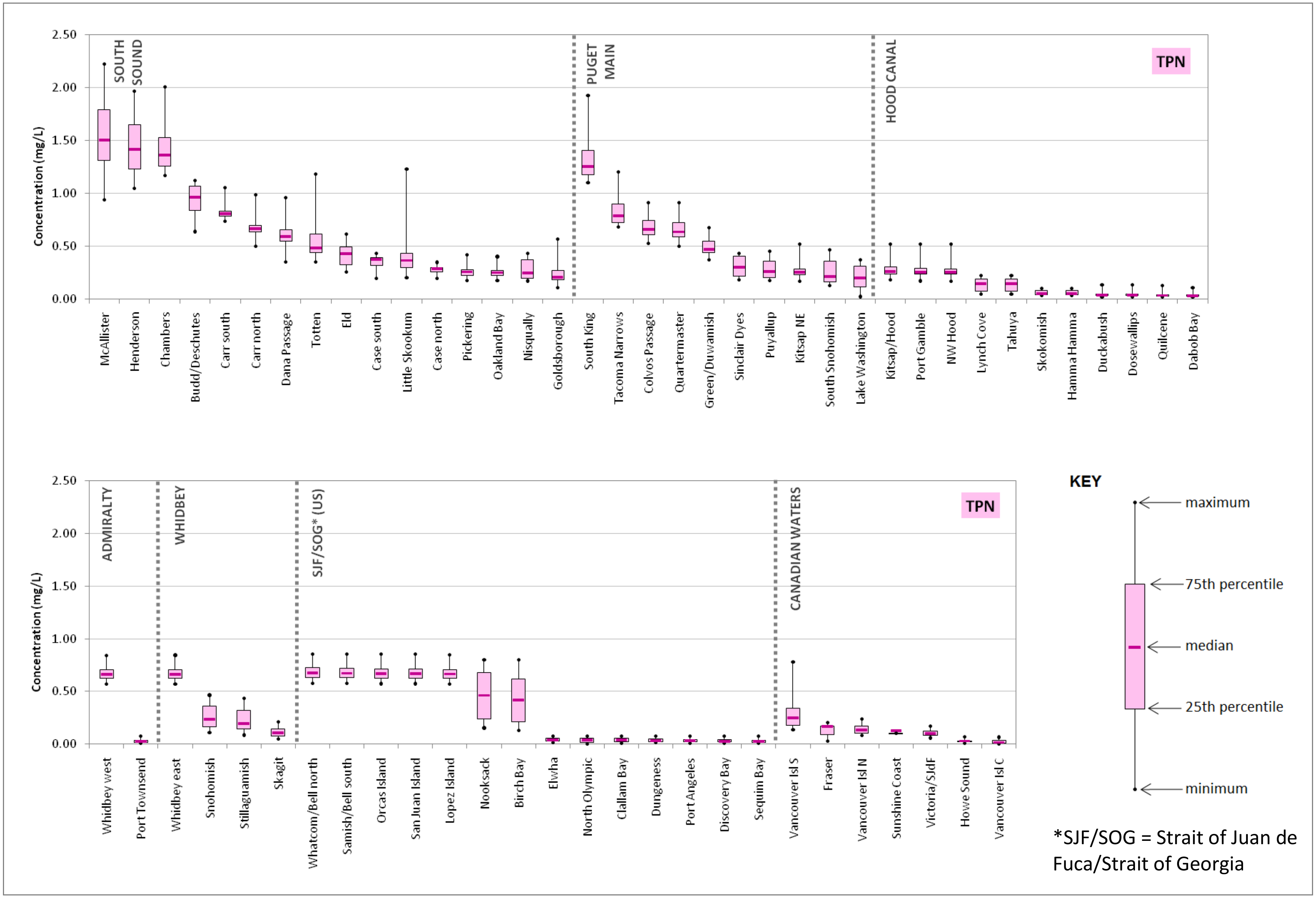

Figure D-1. Box plots of total persulfate nitrogen (TPN) concentrations for watersheds draining into different regions of Puget Sound, 1999-2008. *Since we did not have TPN data for Canada, we used TPN = DIN/0.80 for all watersheds draining into Canadian waters.*

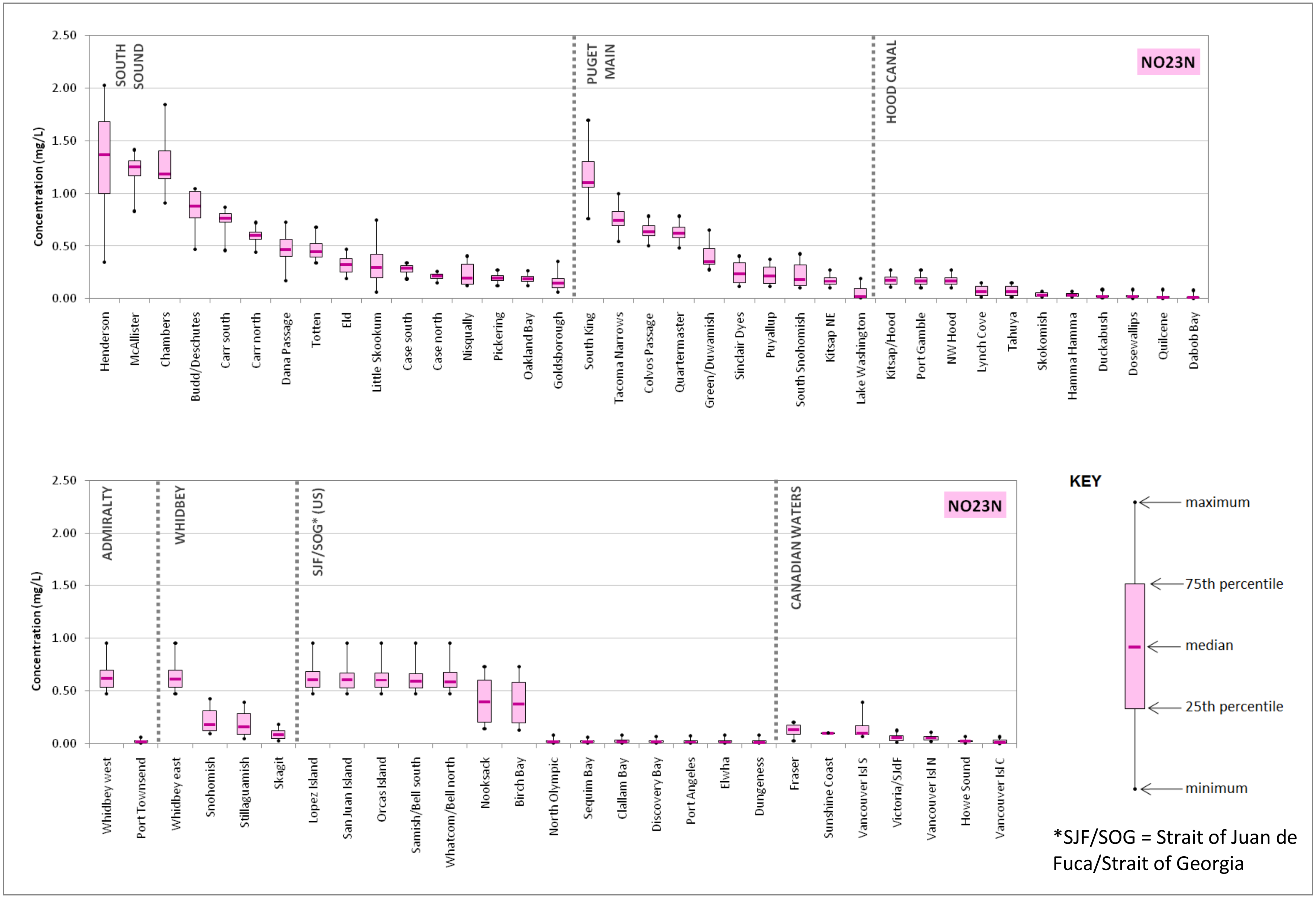

Figure D-2. Box plots of nitrate + nitrite (NO23N) concentrations for watersheds draining into different regions of Puget Sound, 1999-2008.

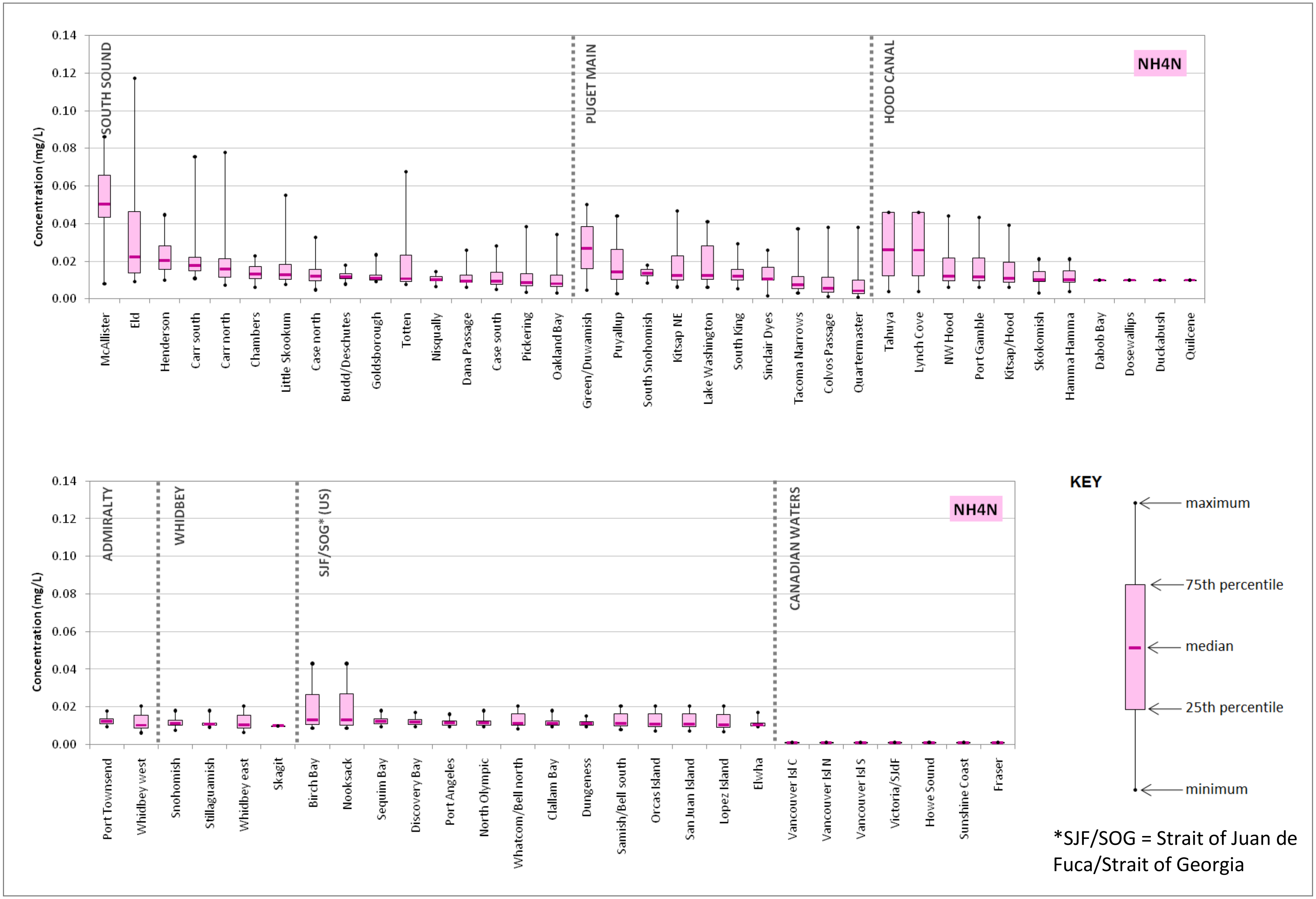

Figure D-3. Box plots of ammonium (NH4N) concentrations for watersheds draining into different regions of Puget Sound, 1999-2008.

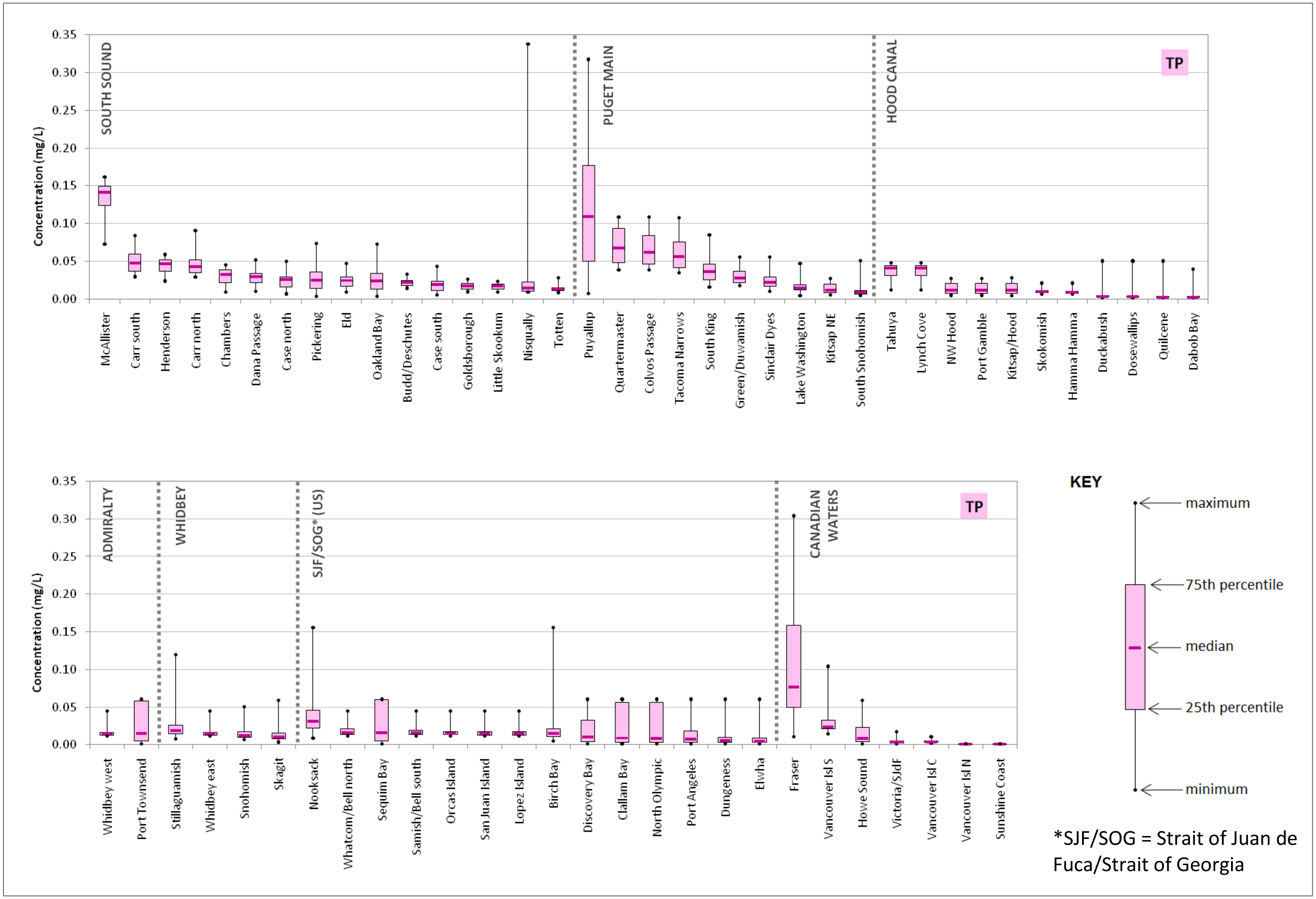

Figure D-4. Box plots of total phosphorus (TP) concentrations for watersheds draining into different regions of Puget Sound, 1999-2008.

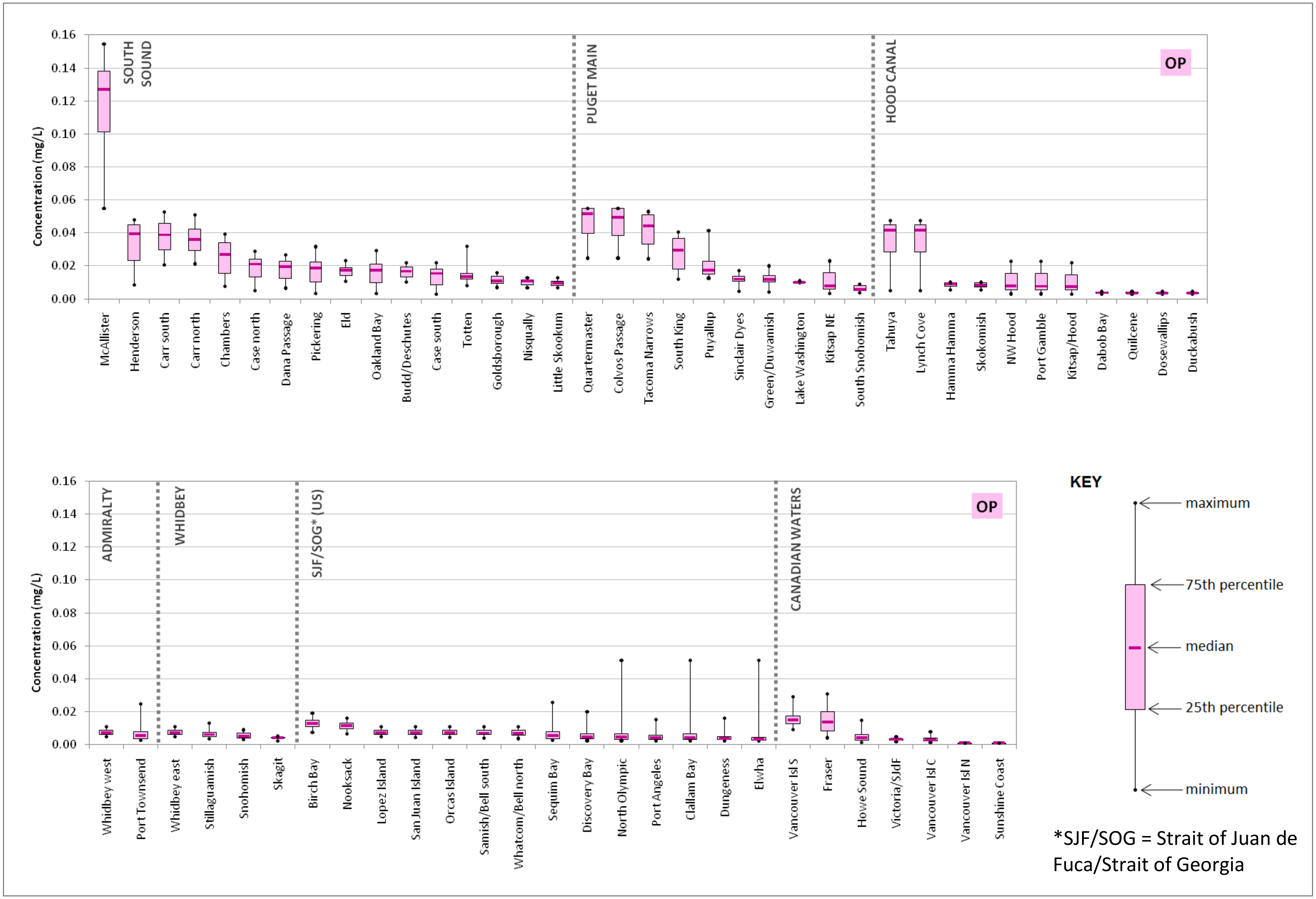

Figure D-5. Box plots of organic phosphorus (OP) concentrations for watersheds draining into different regions of Puget Sound, 1999-2008.

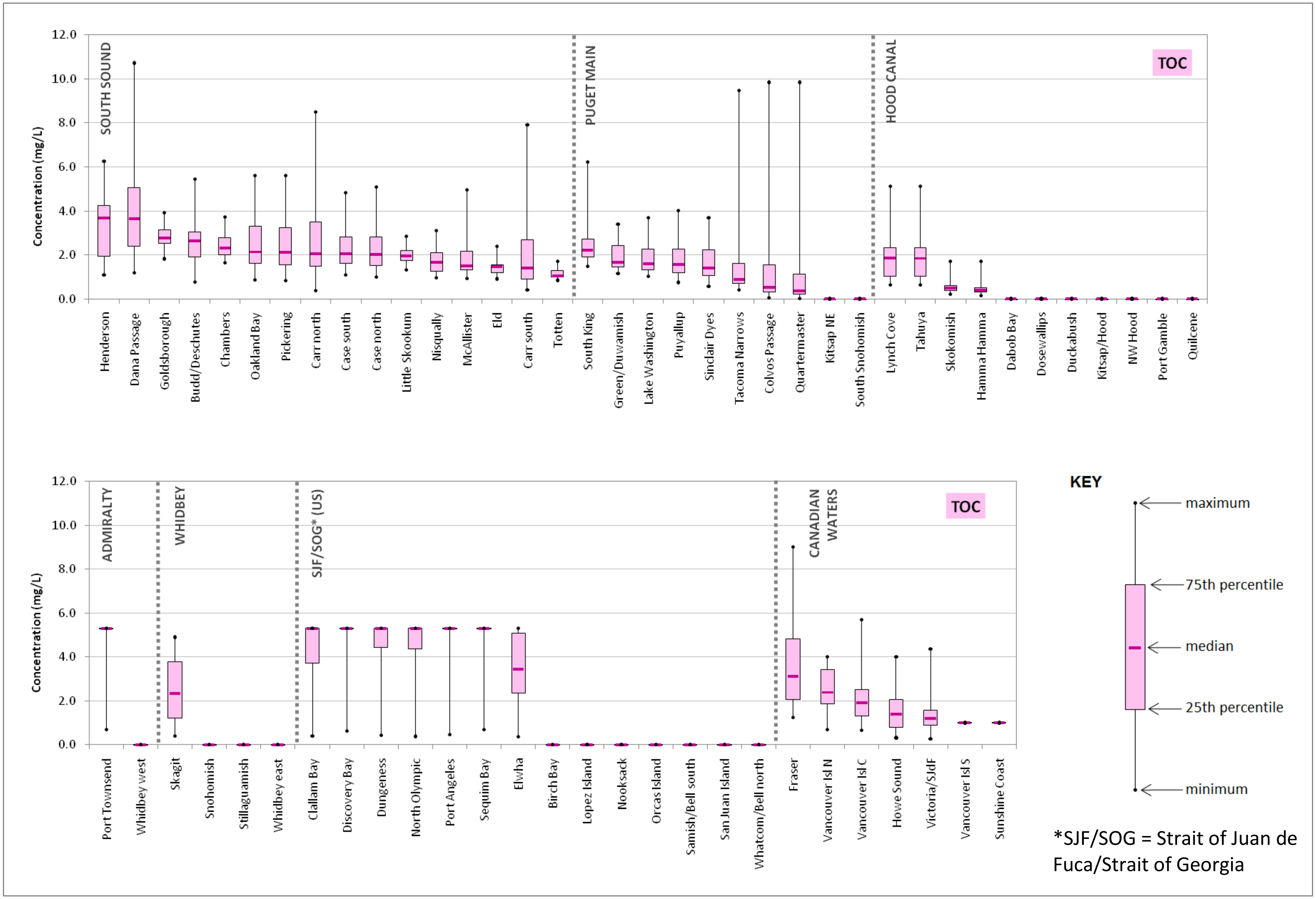

Figure D-6. Box plots of total organic carbon (TOC) concentrations for watersheds draining into different regions of Puget Sound, 1999-2008.

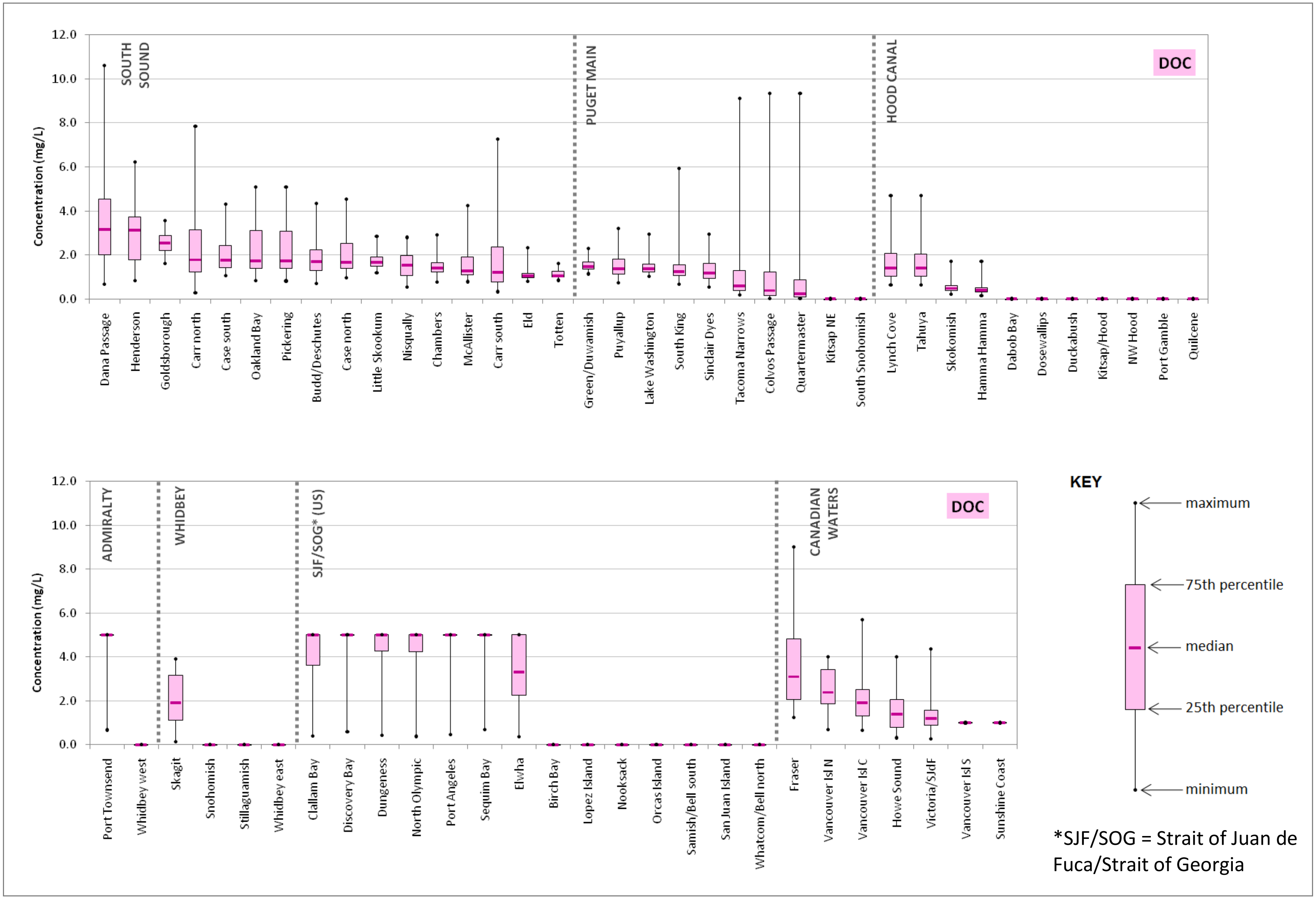

Figure D-7. Box plots of dissolved organic carbon (DOC) concentrations for watersheds draining into different regions of Puget Sound, 1999-2008.

Figures D-8 through D-14 present dot plots of nutrient loads for various parameters from all rivers in the study area.

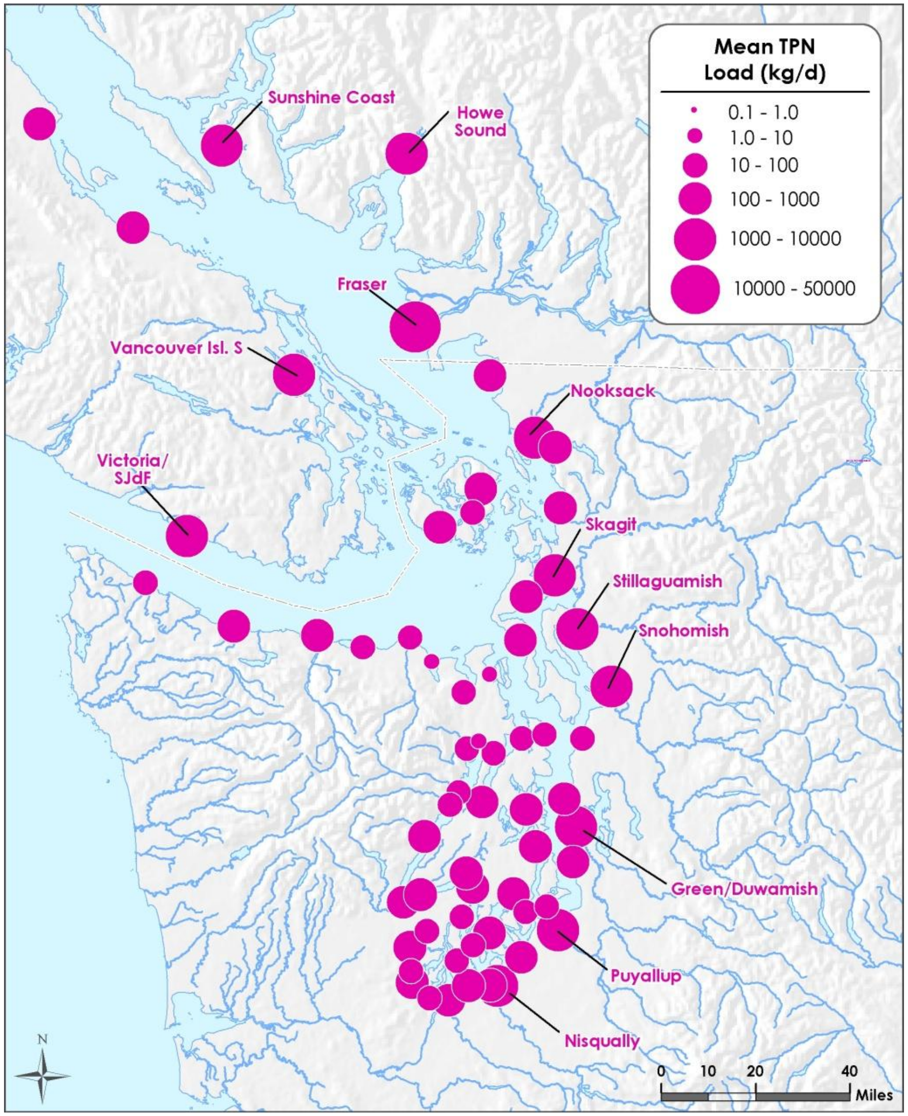

Figure D-8. Mean total persulfate nitrogen loads from watersheds during 1999-2008.

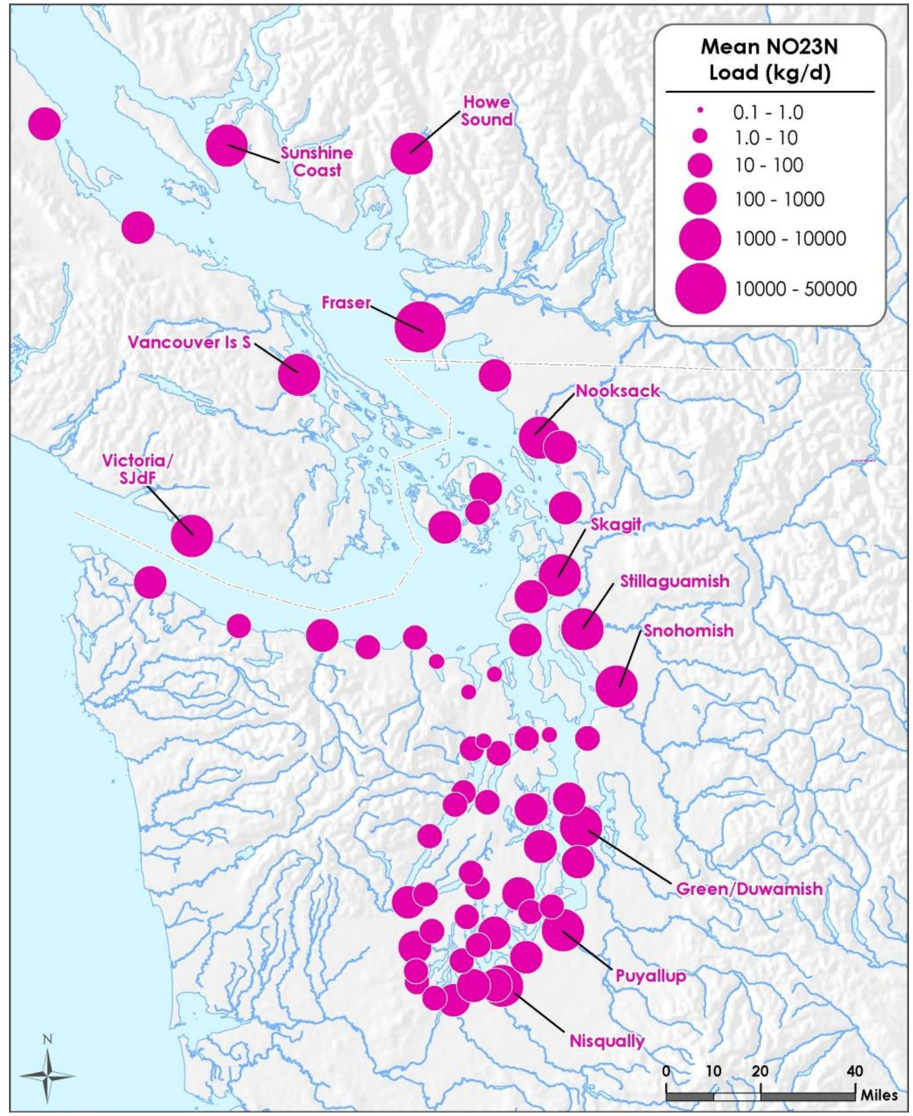

Figure D-9. Mean nitrate + nitrite loads from watersheds during 1999-2008.

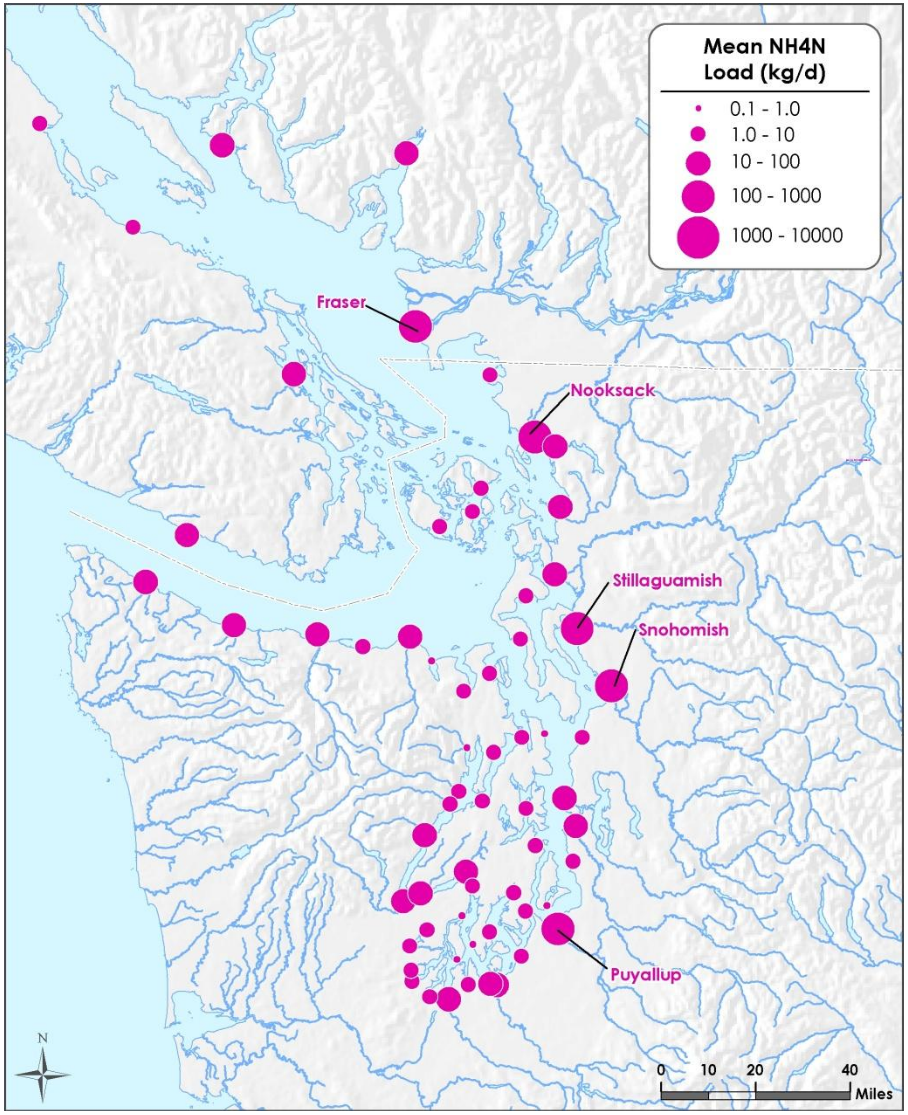

Figure D-10. Mean ammonium loads from watersheds during 1999-2008.

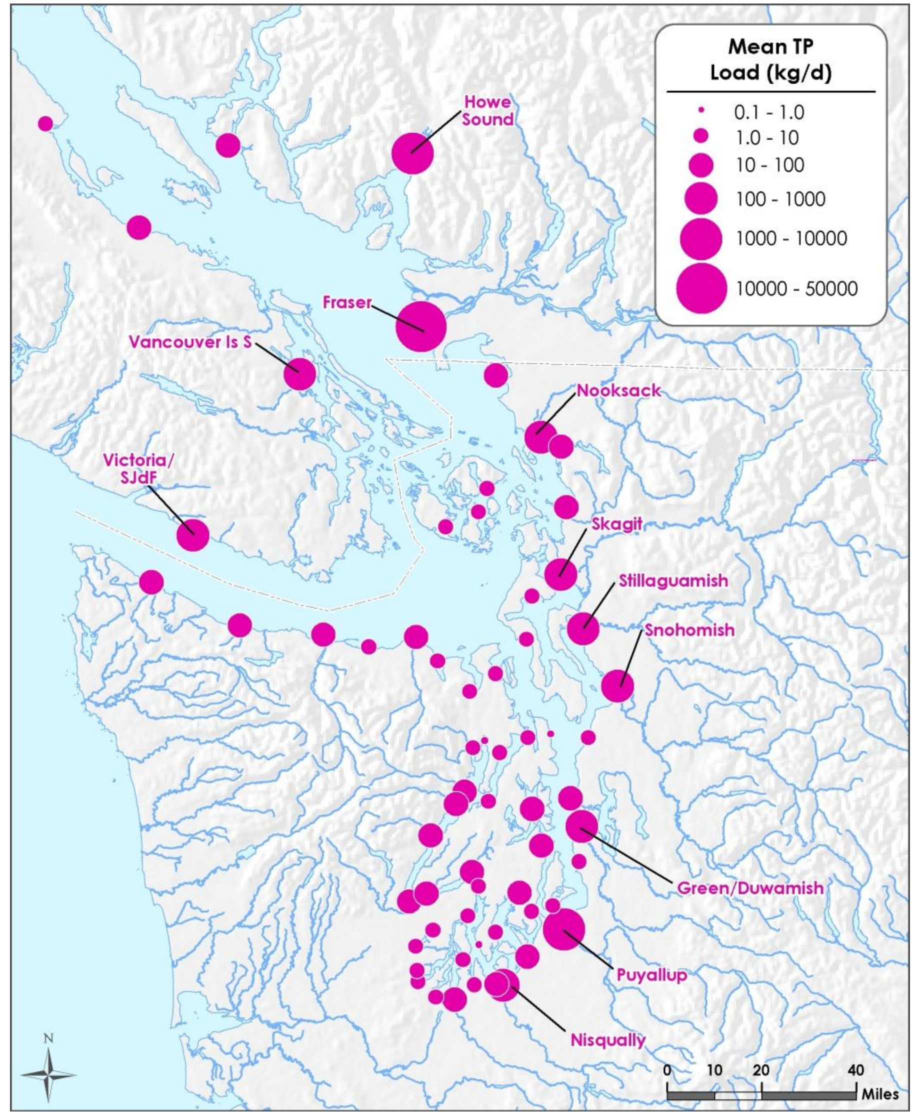

Figure D-11. Mean total phosphorus loads from watersheds during 1999-2008.

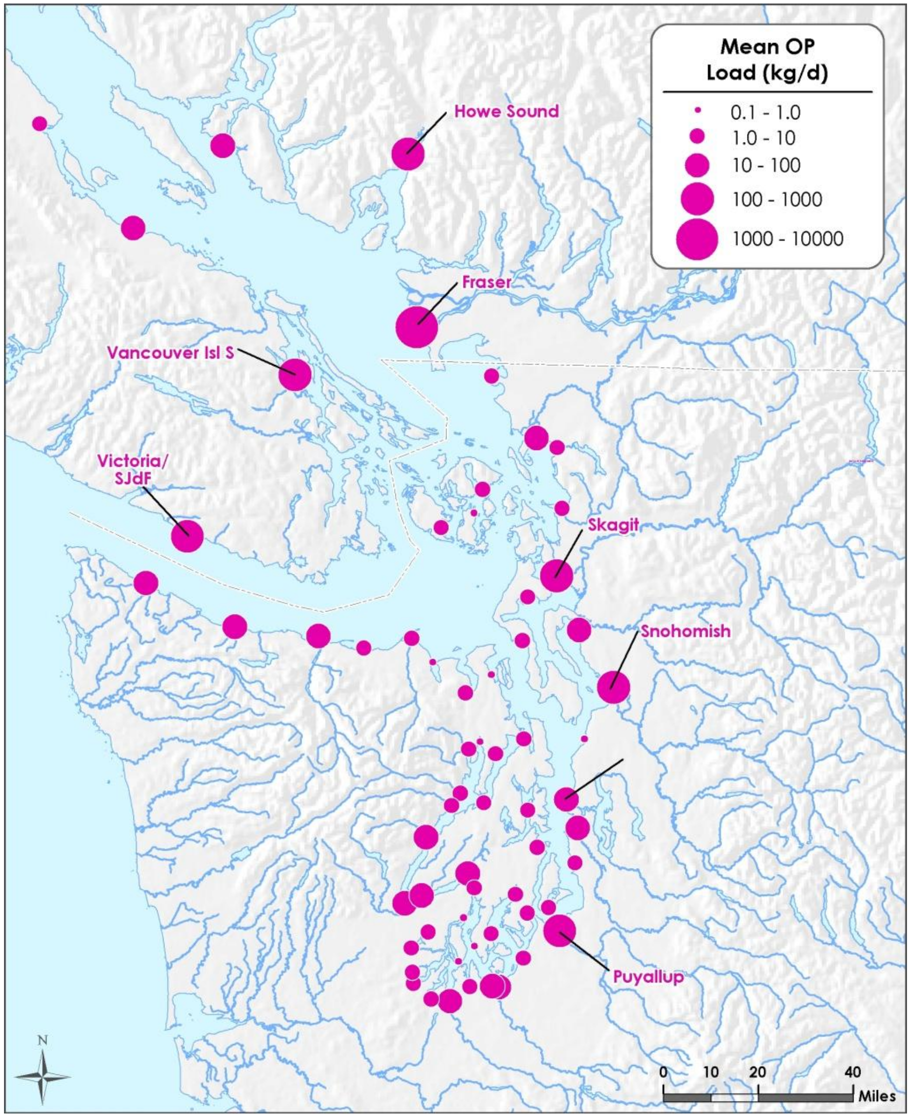

Figure D-12. Mean ortho-phosphate loads from watersheds during 1999-2008.

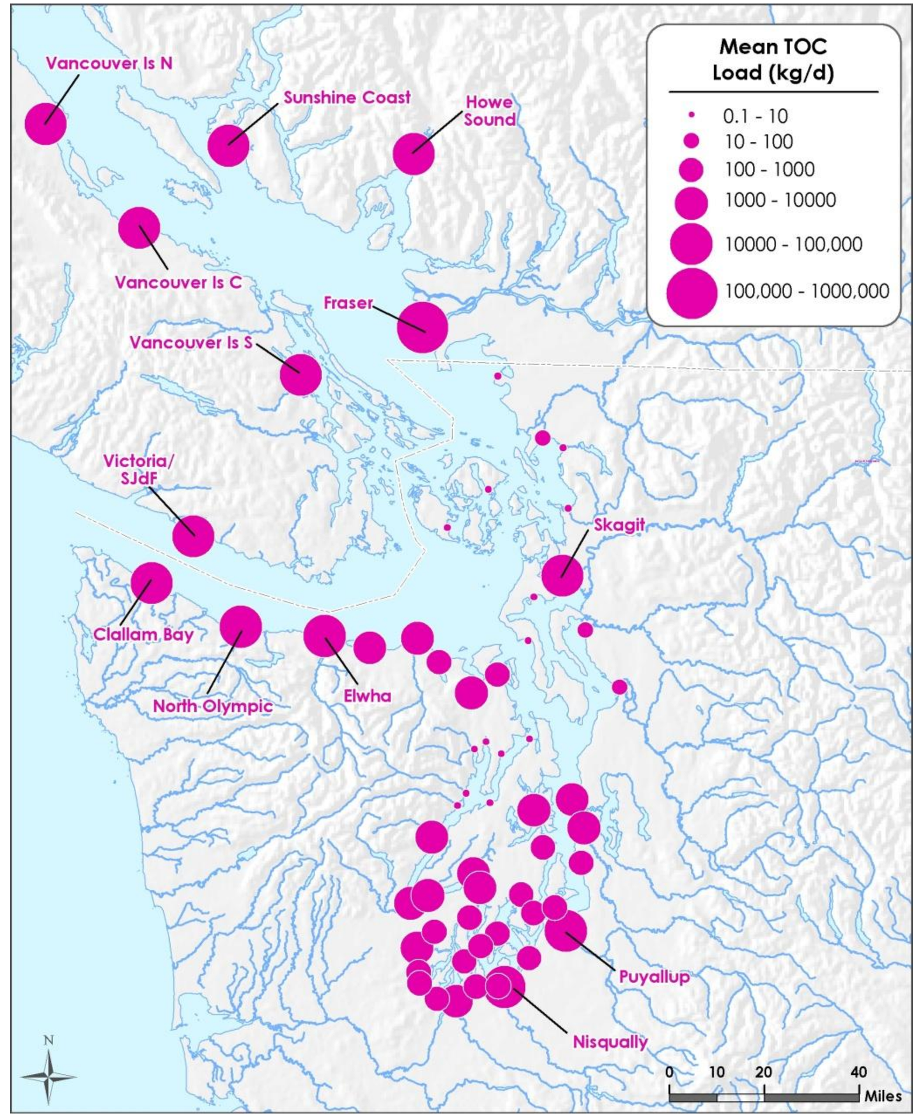

Figure D-13. Mean total organic carbon loads from watersheds during 1999-2008.

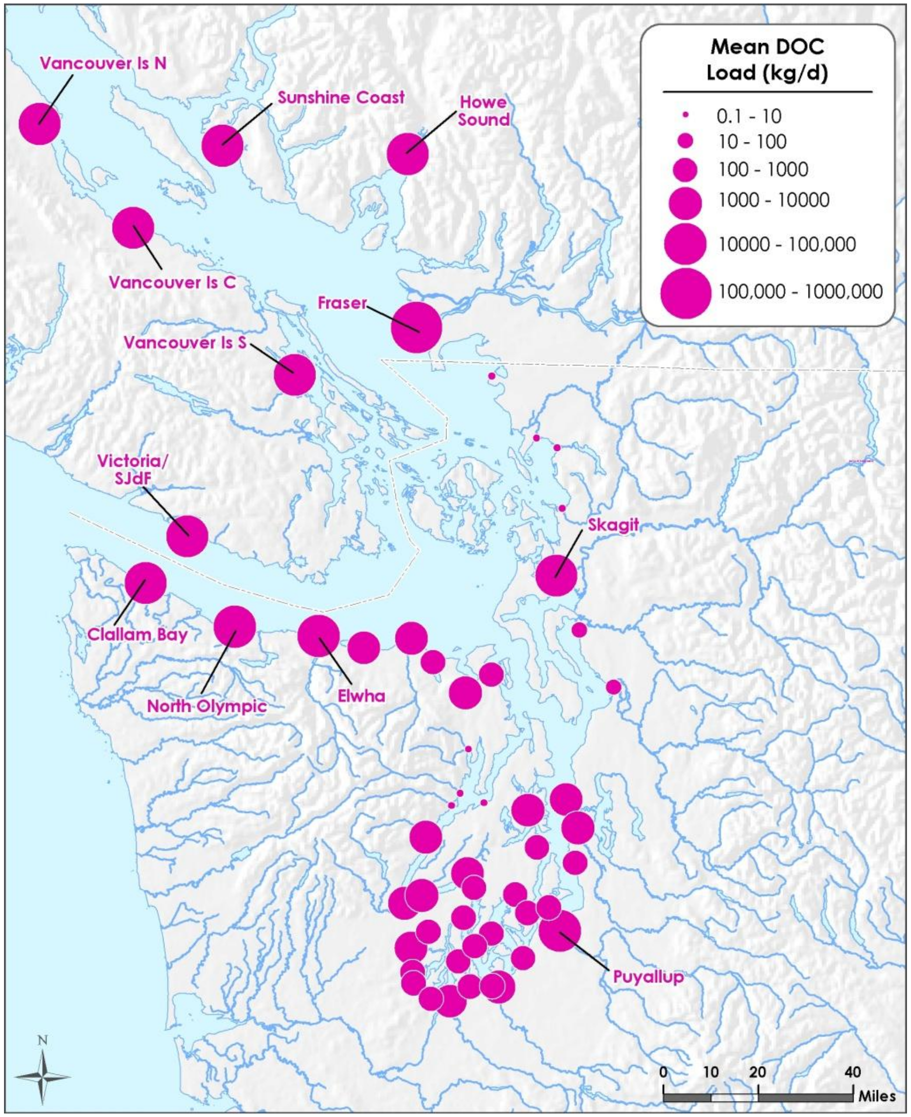

Figure D-14. Mean dissolved organic carbon loads from watersheds during 1999-2008.

Appendix E. Wastewater Treatment Plants: Nutrient Loading

Table E-1 includes a summary of summer and annual DIN loads from all WWTPs in the study area.

Table E-1. Mean summer (July-September) and annual DIN loads from all WWTPs discharging into Puget Sound waters (south of Deception Pass) for 2006-07.

WWTP Name	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
South Sound		
Boston Harbor	1.47	2.51
Carlyon	3.87	4.01
Chambers Creek	1984	2028
Fort Lewis	330	279
Hartstene Pointe	1.07	2.23
LOTT	58.8	164
McNeil Is	4.20	5.50
Rustlewood	0.45	0.70
Seashore Villa	0.33	0.41
Shelton	25.2	54.4
Tamoshan	0.56	0.68
Taylor Bay	0.31	0.32
Commencement Bay		
Puyallup	120	124
Simpson Kraft	7.93	10.0
Tacoma Central	2276	1910
Tacoma North	372	398
U.S. Oil & Refining	0.39	0.51
Puget Main		
Alderwood	227	226
Bainbridge Island (City)	13.9	16.1
Edmonds	523	643
Gig Harbor	33.3	34.6
Kitsap Co Kingston	2.74	3.28
Lakota	766	723
Lynwood	450	450
Manchester	4.10	6.26
Midway	421	415
Miller Creek	344	357
Redondo	211	229
Salmon Creek	237	266
South King	7892	8875
Vashon	1.89	3.47
West Point	9020	10449

WWTP Name	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
Sinclair Dyes Inlet		
Bainbridge Kitsap Co 7	1.27	1.74
Bremerton	372	418
Central Kitsap	459	461
Port Orchard	129	127
Suquamish	3.90	5.70
Whidbey		
Coupeville	4.32	5.43
Everett Snohomish	1778	1989
Kimberly-Clark	15.05	14.0
La Conner	6.39	7.46
Lake Stevens	64.3	71.7
Langley	2.33	2.50
Marysville	339	380
Mt Vernon	346	386
Mukilteo	195	189
Oak Harbor Lagoon	153	152
Oak Harbor RBC	14.6	16.1
Penn Cove	0.52	0.74
Skagit County 2 Big Lake	2.87	1.66
Snohomish	34.7	91.6
Stanwood	5.04	8.64
Swinomish	3.15	3.61
Tulalip	5.92	6.97
Warm Beach Campground	10.6	15.9
Admiralty		
Olympic W&S Port Ludlow	4.81	5.41
Port Townsend	25.8	28.6
Port Townsend Paper	5.56	5.52
Port Townsend Paper (sanitary)	0.15	0.16
Hood South		
Alderbrook	0.41	0.35
Hood North		
Port Gamble/Pope Resources	0.31	0.45

Table E-1. Mean summer (July-September) and annual DIN loads from all WWTPs discharging into the Straits (north of Deception Pass) for 2006-07.

WWTP Name	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
Strait of Georgia/Juan de Fuca (U.S. waters)		
Anacortes	167	194
Bellingham	1215	1281
Birch Bay	18.6	23.0
Blaine	11.8	17.4
BP Cherry Point	110	92.4
Clallam Bay POTW	0.38	0.73
Clallam DOC	1.72	2.64
Conoco Phillips	6.9	12.8
Eastsound Orcas Village	0.15	0.11
Eastsound Water District	2.39	2.44
Fisherman Bay	0.54	0.50
Friday Harbor	6.85	9.28
Intalco	15.1	15.0
Larrabee State Park	0.12	0.24
Lummi Goose Pt	5.48	8.51
Lummi Sandy Pt	2.38	3.41
Makah	5.15	6.37
Nippon Paper	3.86	3.80
Port Angeles	233	278
Roche Harbor	1.02	0.81
Rosario Utilities	1.11	0.88
Sekiu	0.99	1.73
Sequim	6.3	22.4
Shell Oil	84.6	67.9
Tesoro	12.3	12.1
Whidbey Naval Station	10.0	12.0

WWTP Name	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
Vancouver Island		
Clover Point	1419	1419
Gulf Islands	6.10	6.63
Macaulay	1431	1431
Saanich	144	144
Vancouver Mainland		
Annacis	12645	12645
Iona	8359	8359
Lions Gate	1715	1715
Lulu	2121	2121
NW Langley	182	182

	Summer DIN Load (kg/d)	Annual DIN Load (kg/d)
Puget Sound	29319	32207
Straits (U.S.)	1923	2069
SUBTOTAL (all U.S.)	**31242**	**34276**
Straits (Canada)	28023	28023
TOTAL	**90506**	**62299**

Figures E-1 through E-8 present concentration box plots of various nutrients (nitrogen, phosphorus, carbon, and biochemical oxygen demand) for all WWTPs in the study area.

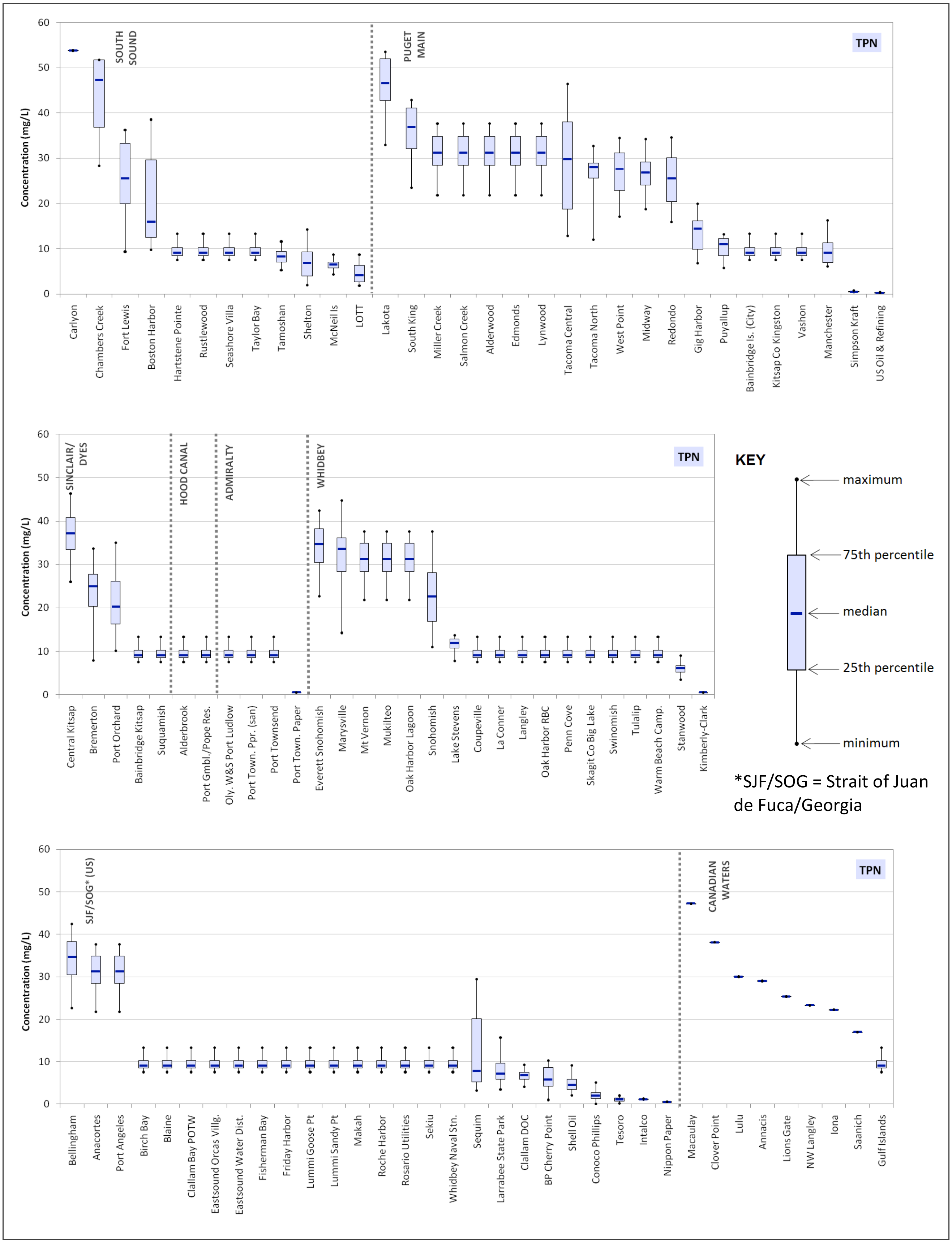

Figure E-1. Box plots of total persulfate nitrogen concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

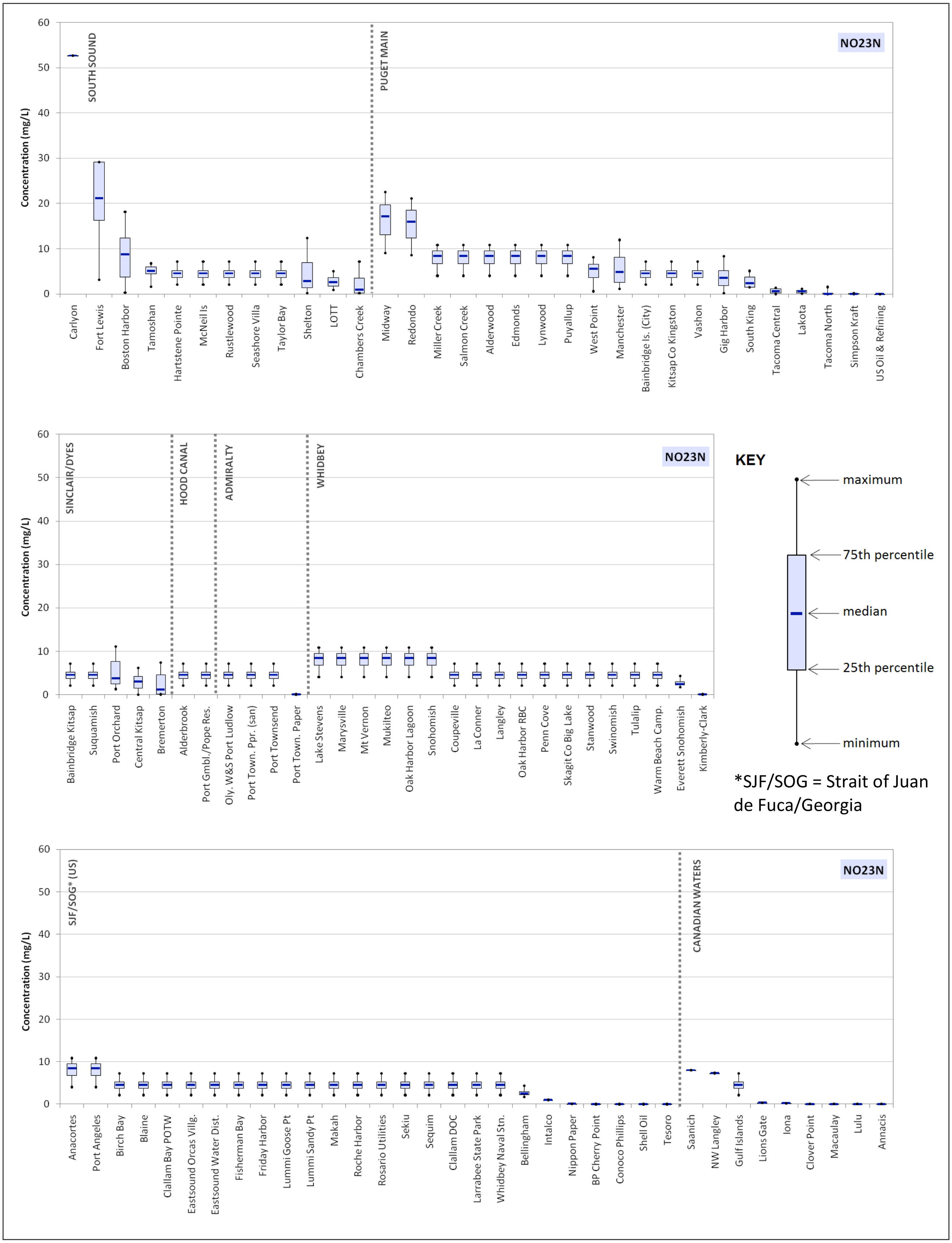

Figure E-2. Box plots of nitrate + nitrite concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

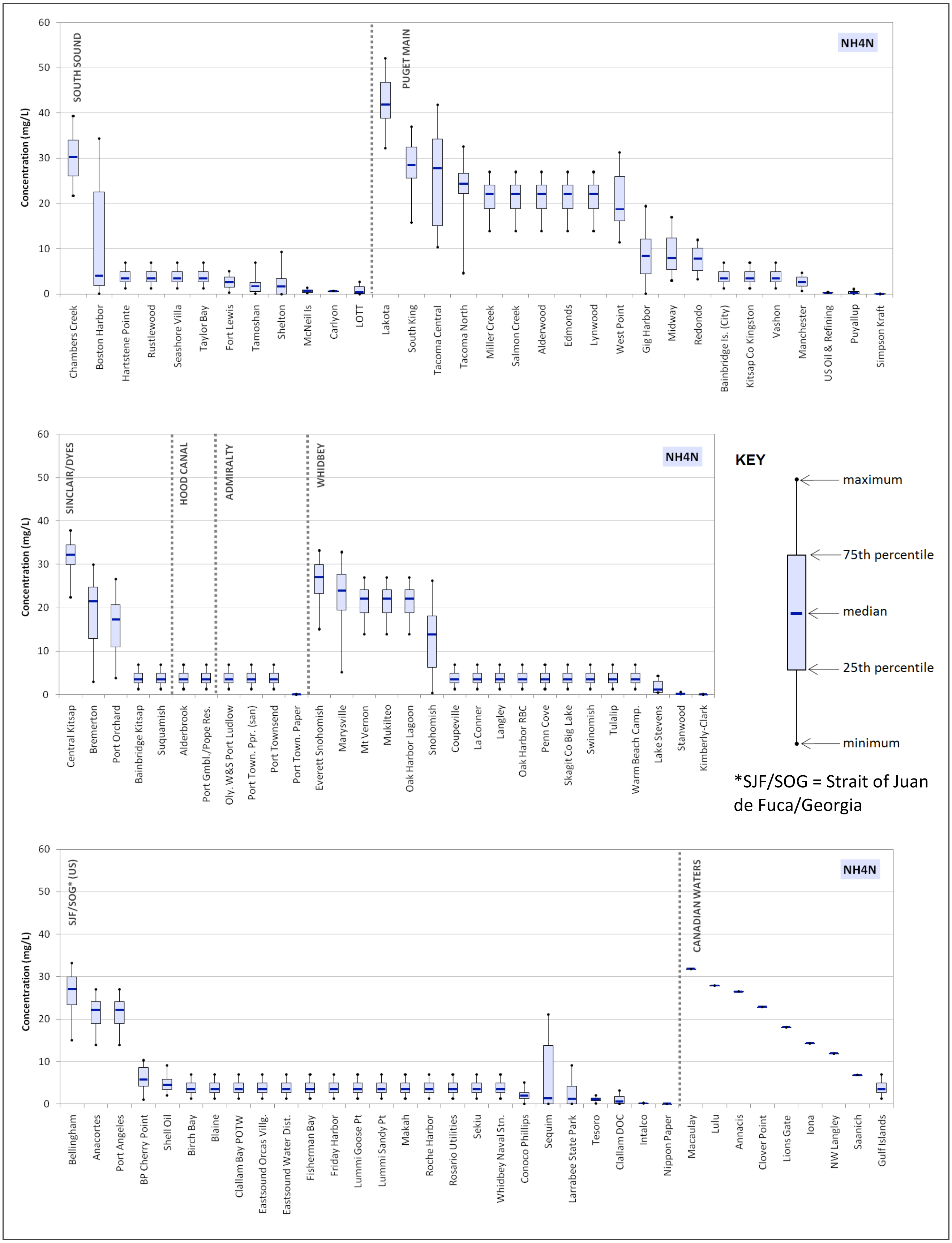

Figure E-3. Box plots of ammonium concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

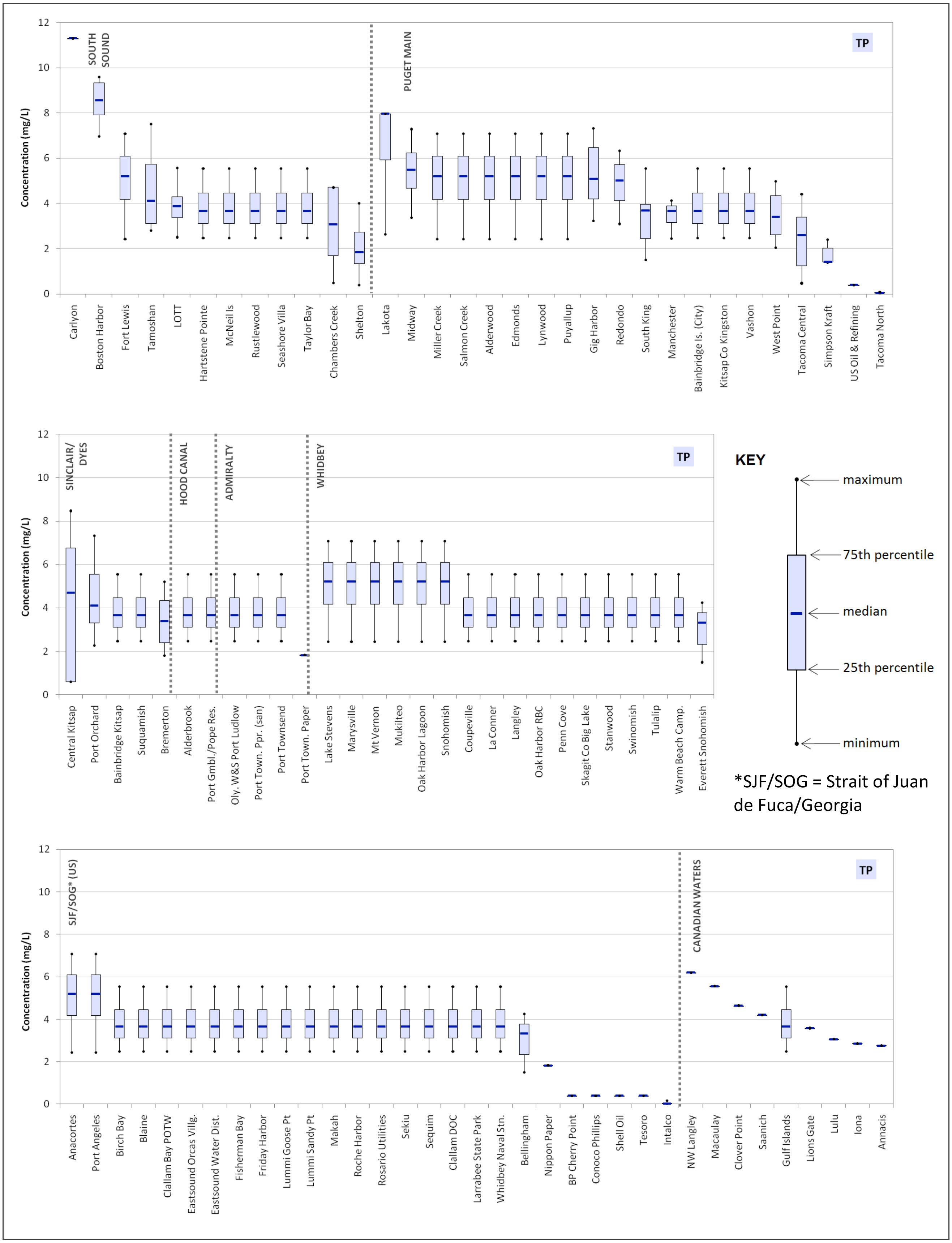

Figure E-4. Box plots of total phosphorus concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

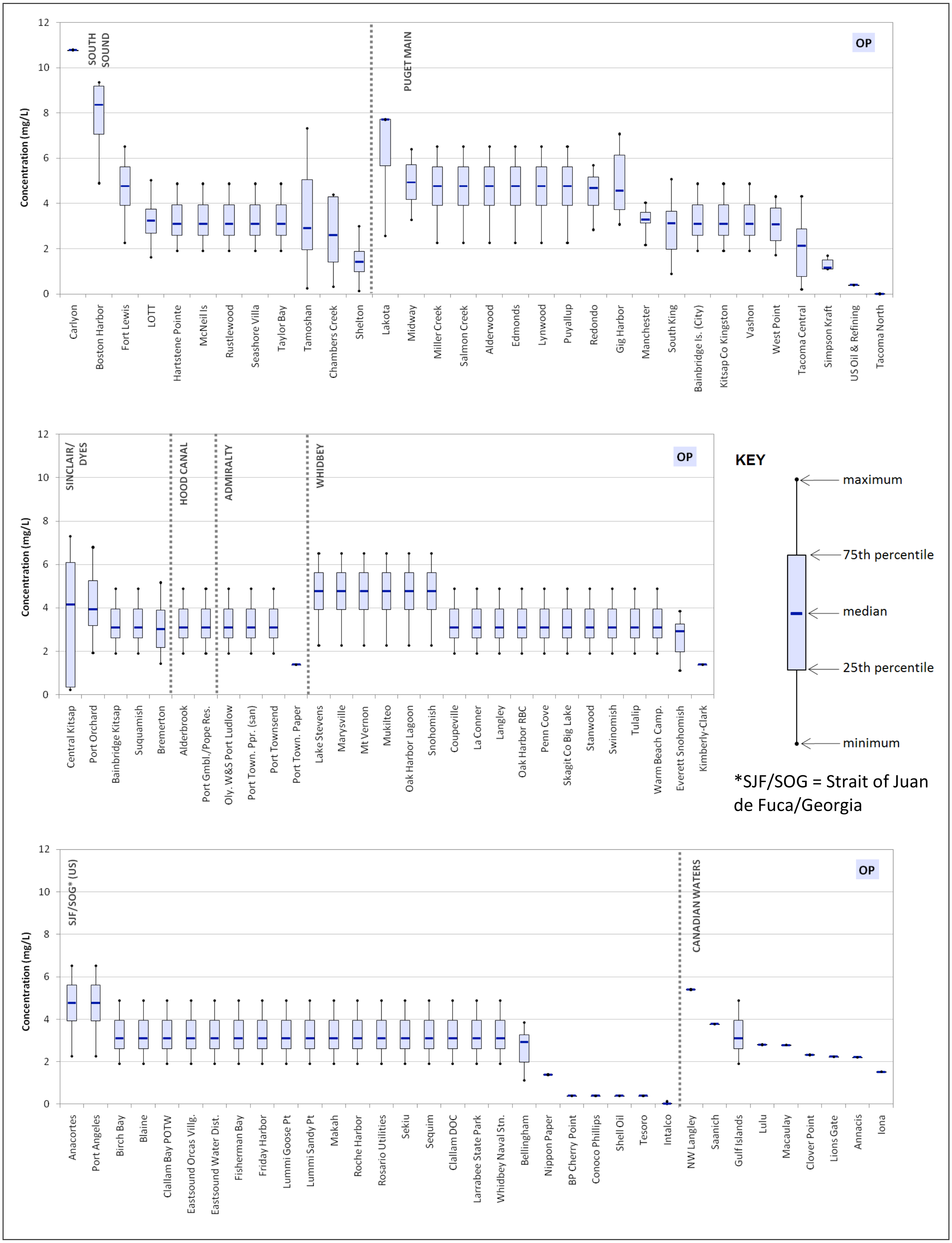

Figure E-5. Box plots of ortho-phosphate concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

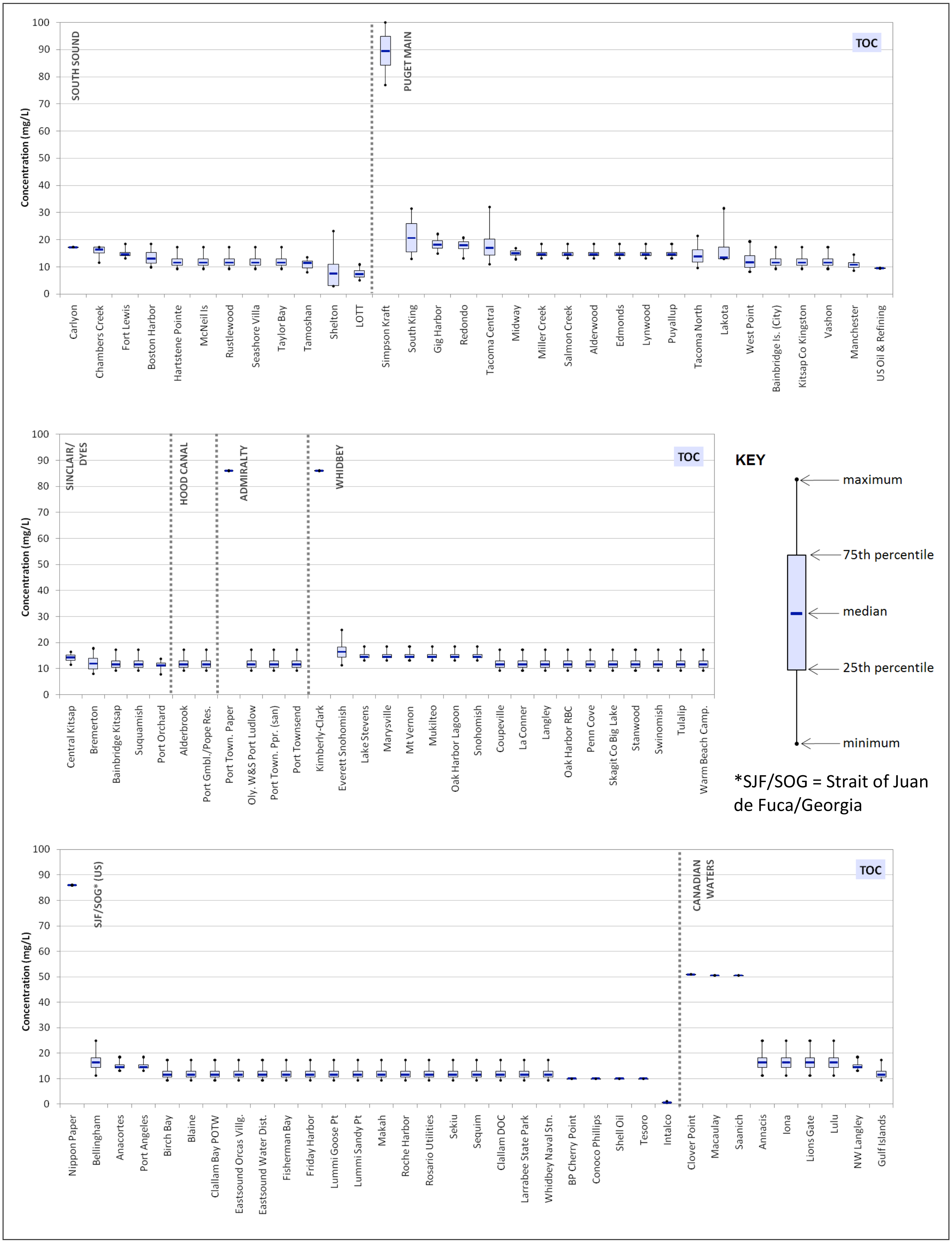

Figure E-6. Box plots of total organic carbon concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

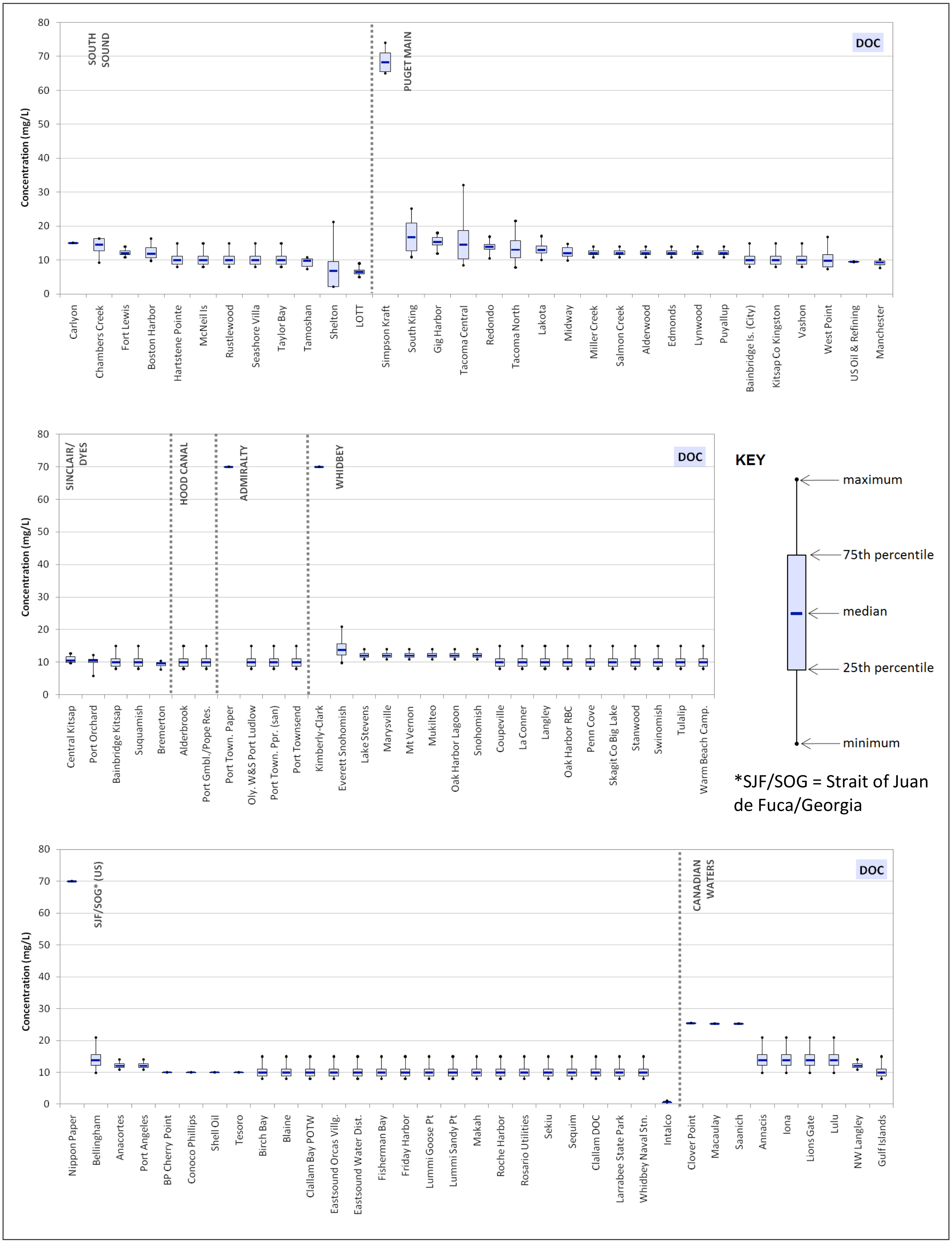

Figure E-7. Box plots of dissolved organic carbon concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

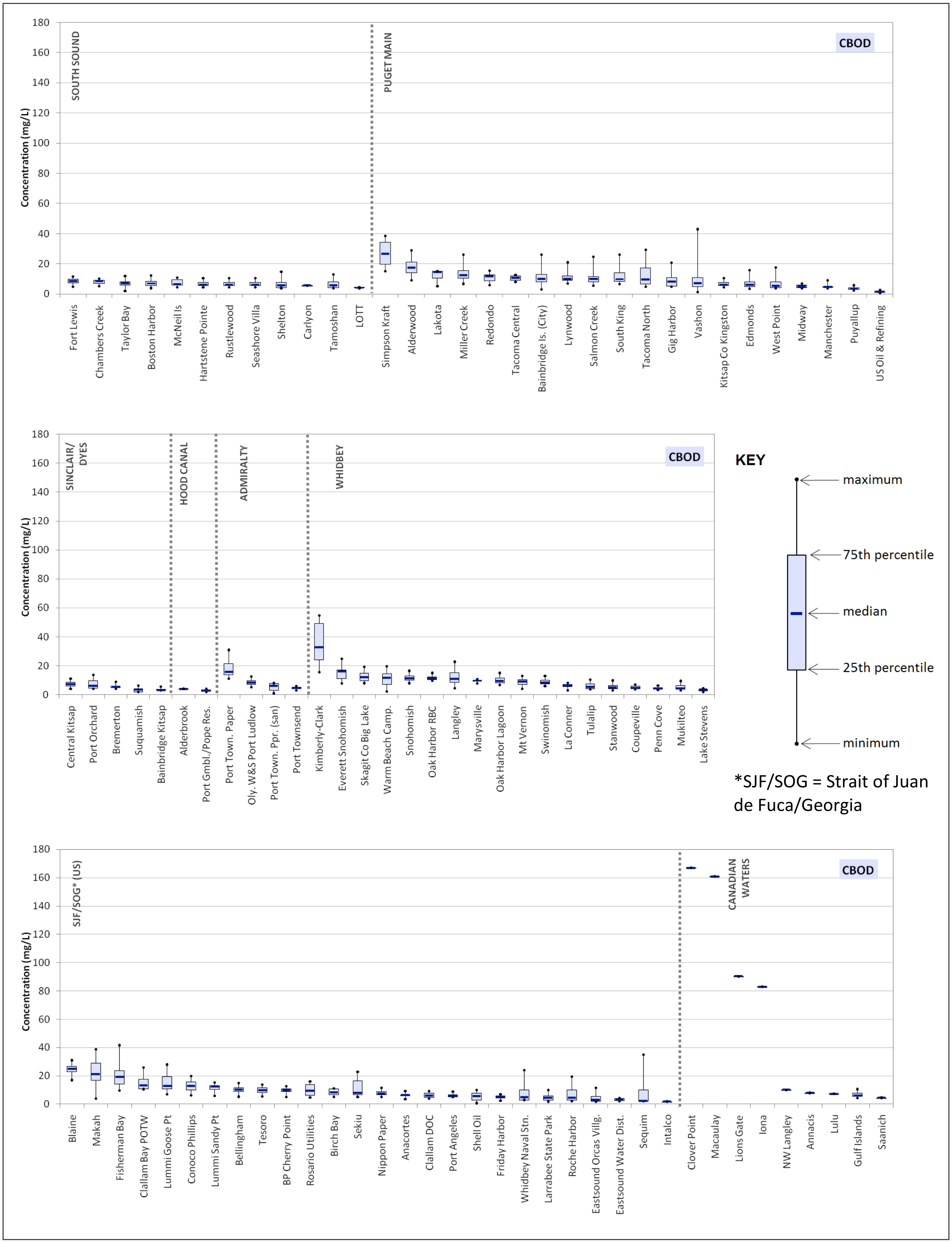

Figure E-8. Box plots of carbonaceous biochemical oxygen demand concentrations for WWTPs draining into different regions of Puget Sound, 1999-2008.

Figures E-9 through E-16 present dot plots of nutrient loads for various parameters from all WWTPs in the study area.

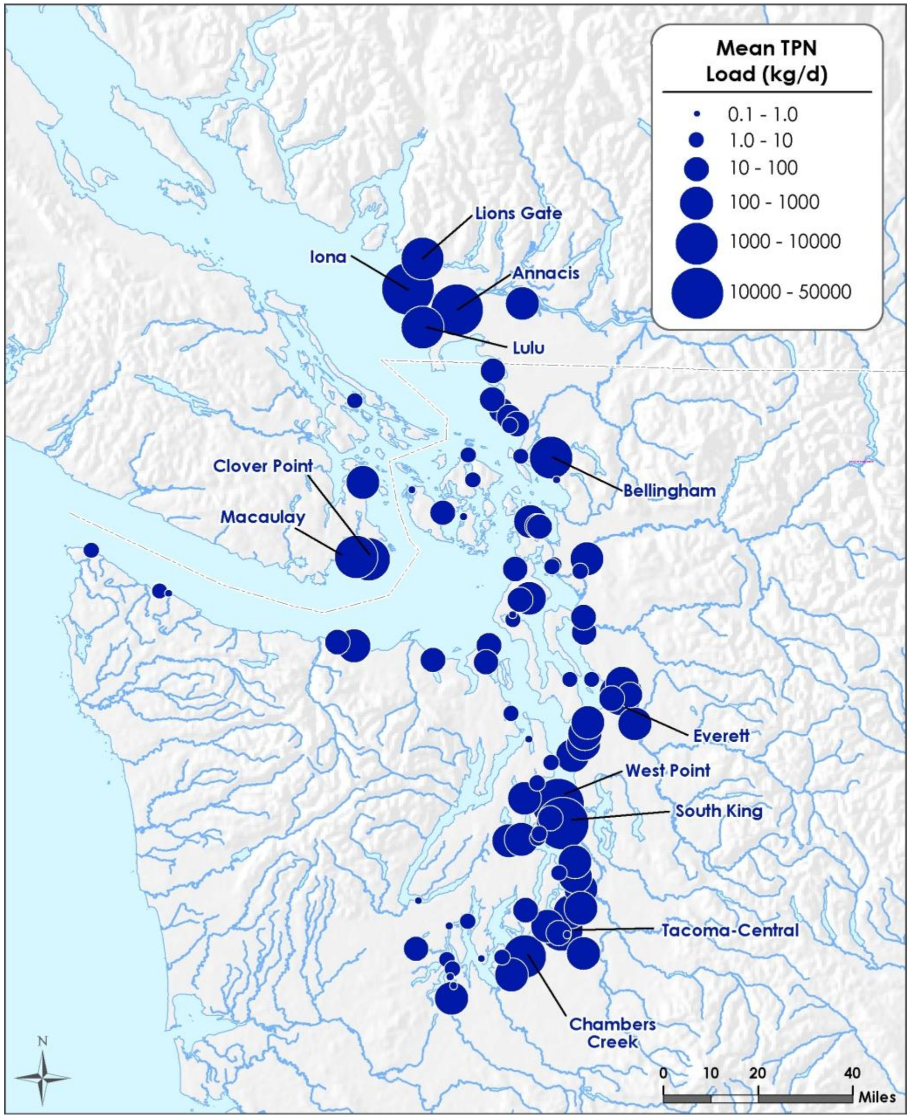

Figure E-9. Mean total persulfate nitrogen loads from WWTPs during 1999-2008.

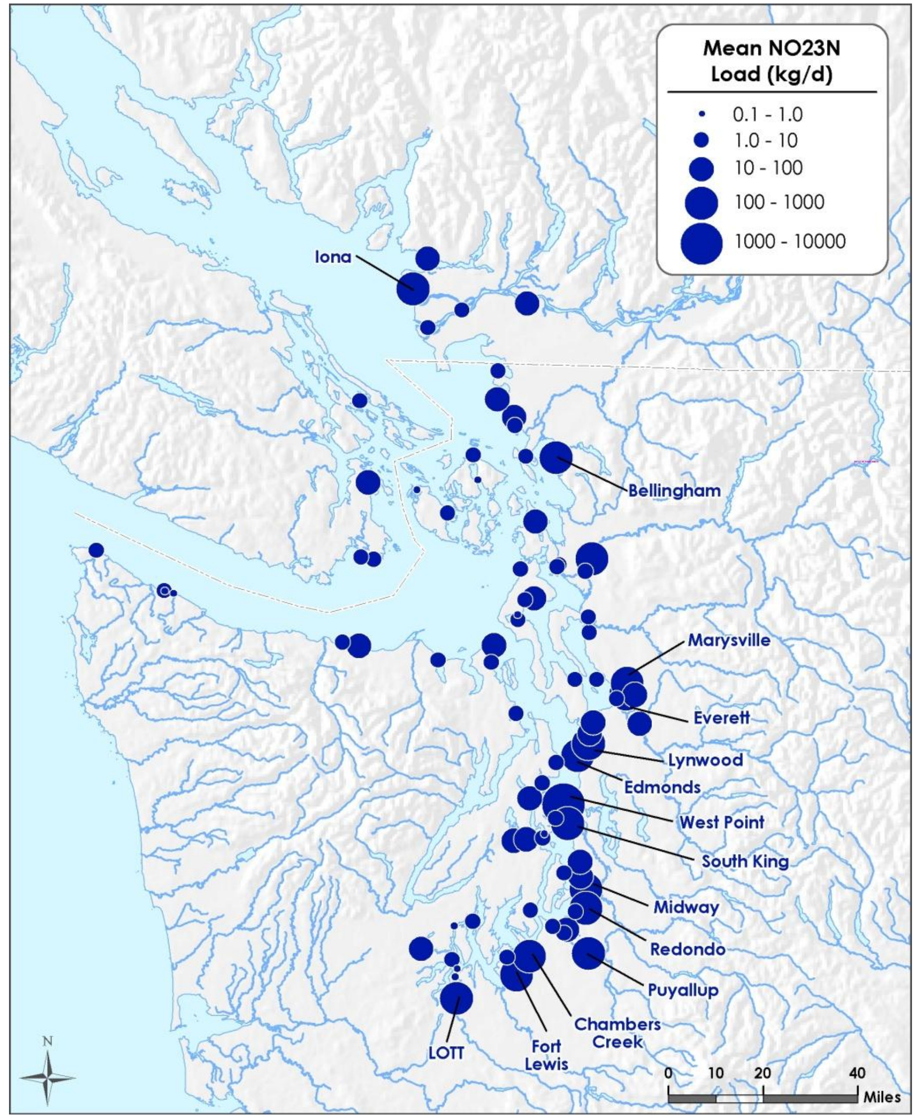

Figure E-10. Mean nitrate + nitrite loads from WWTPs during 1999-2008.

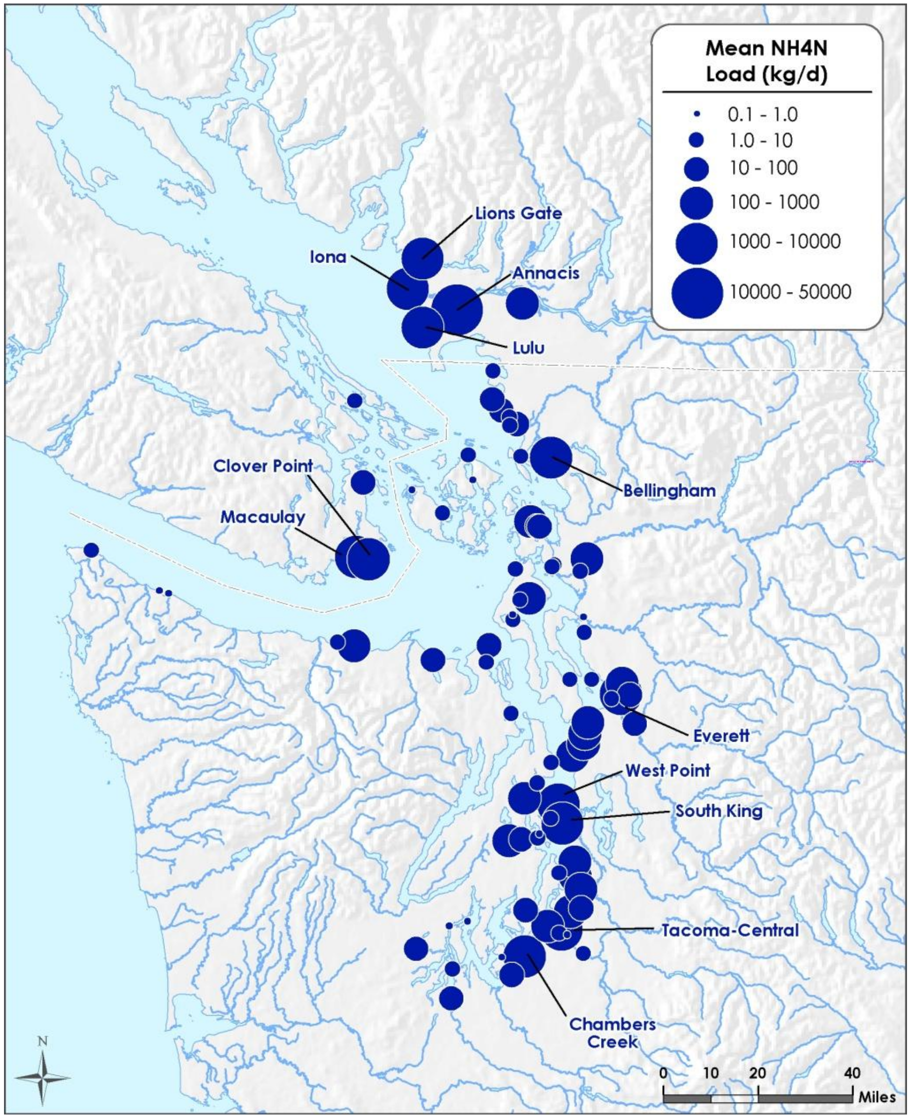

Figure E-11. Mean total ammonium loads from WWTPs during 1999-2008.

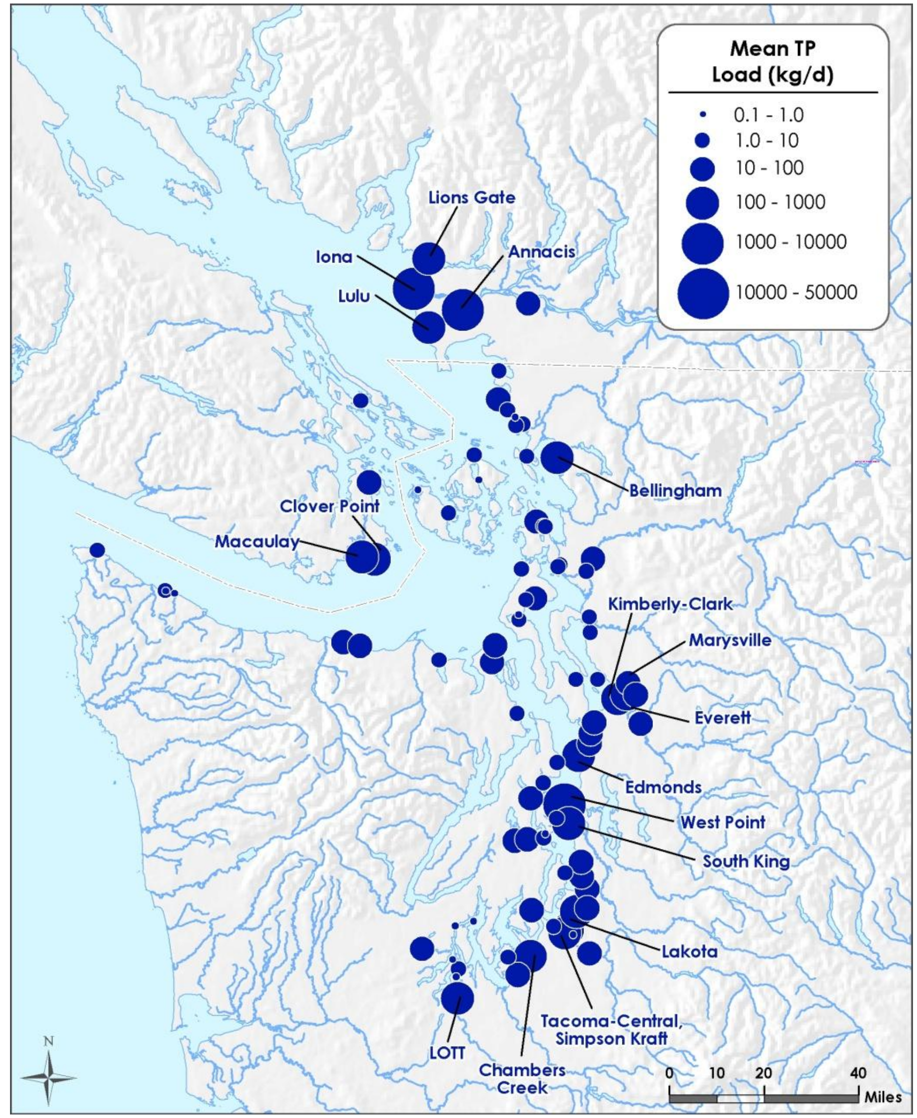

Figure E-12. Mean total phosphorus loads from WWTPs during 1999-2008.

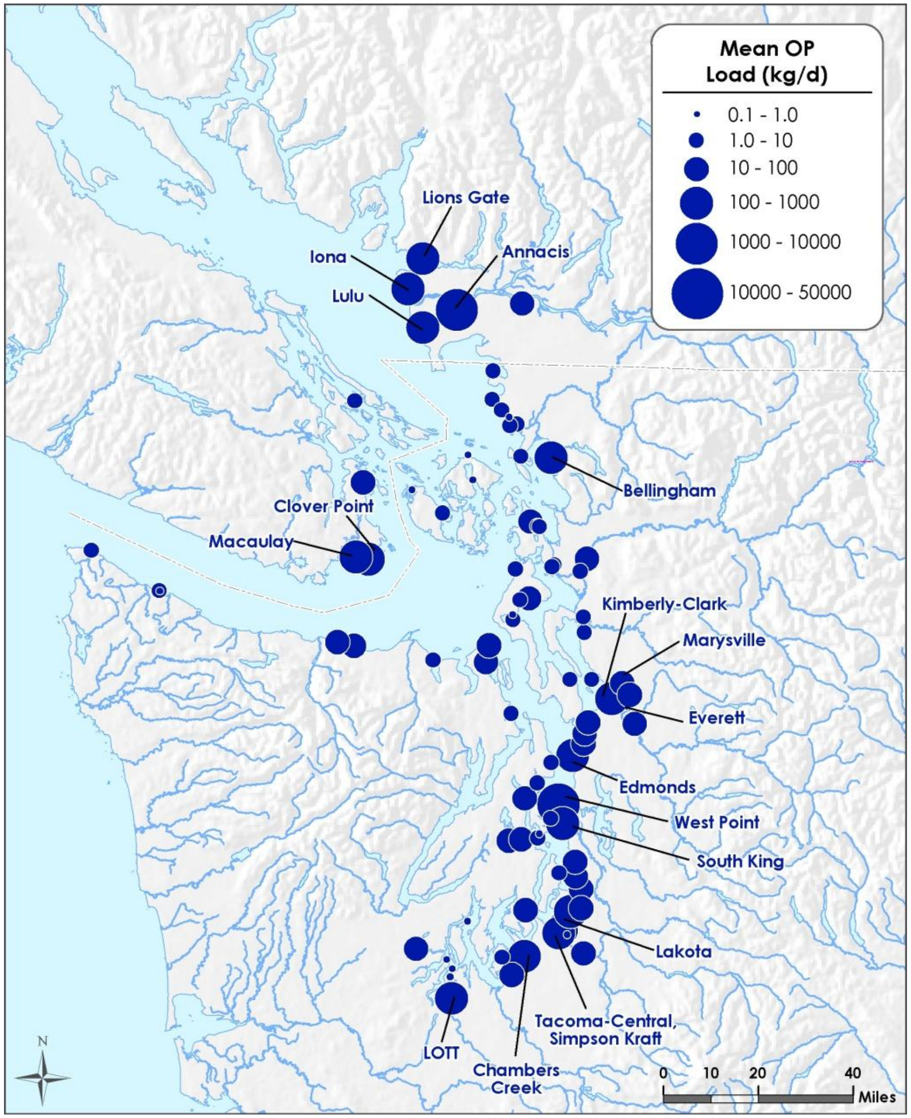

Figure E-13. Mean ortho-phosphate loads from WWTPs during 1999-2008.

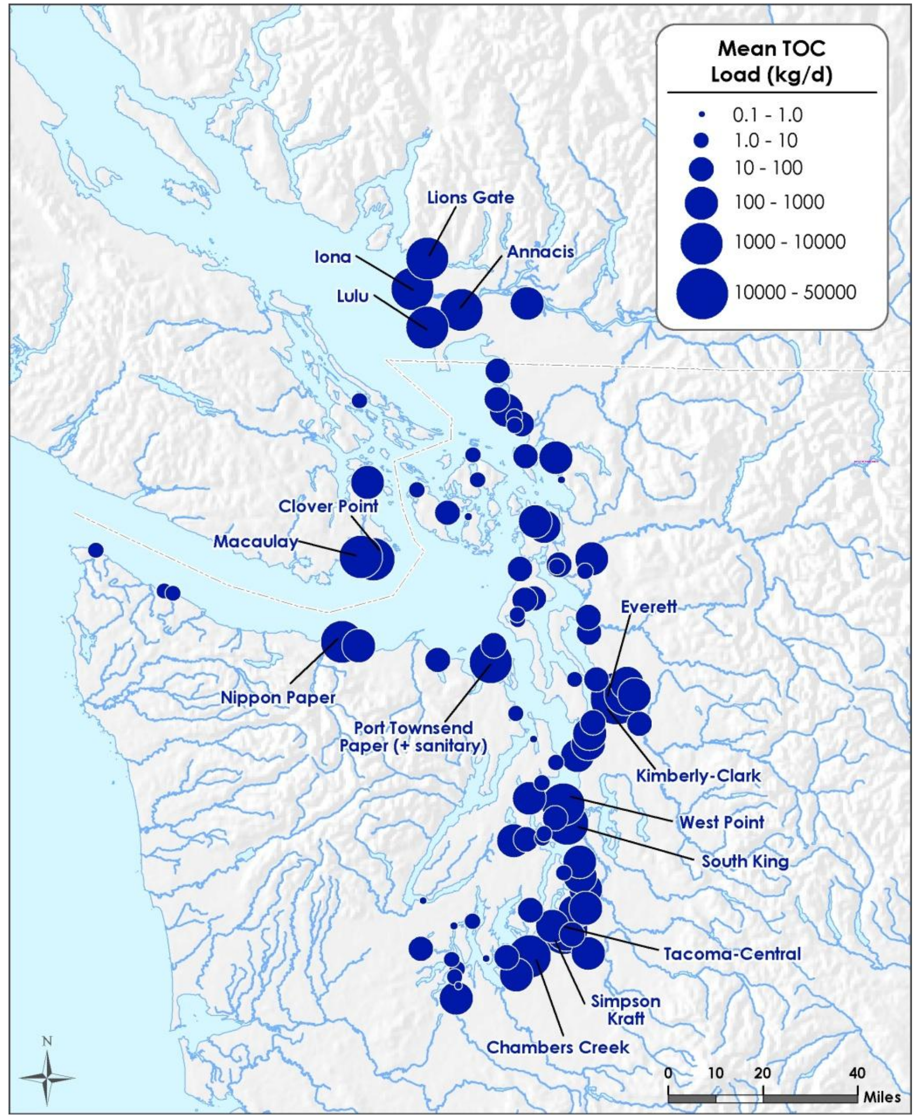

Figure E-14. Mean total organic carbon loads from WWTPs during 1999-2008.

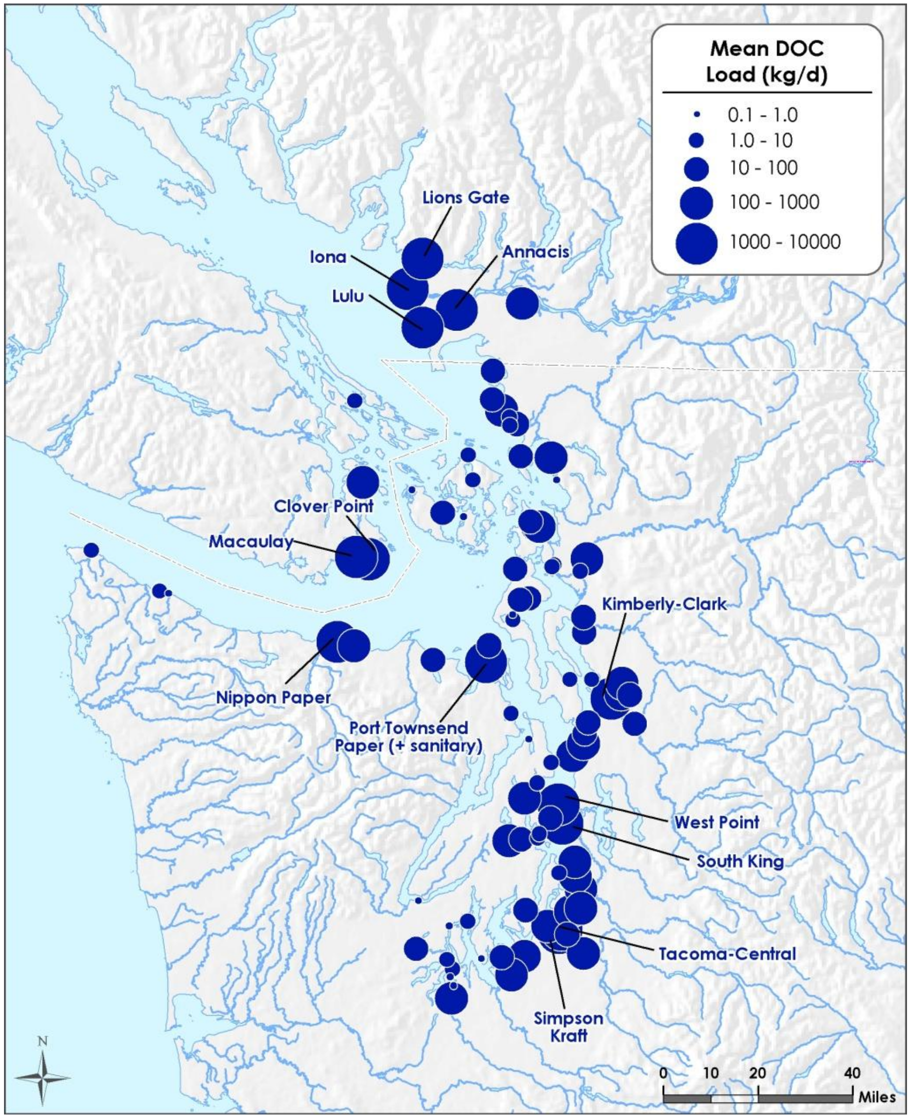

Figure E-15. Mean dissolved organic carbon loads from WWTPs during 1999-2008.

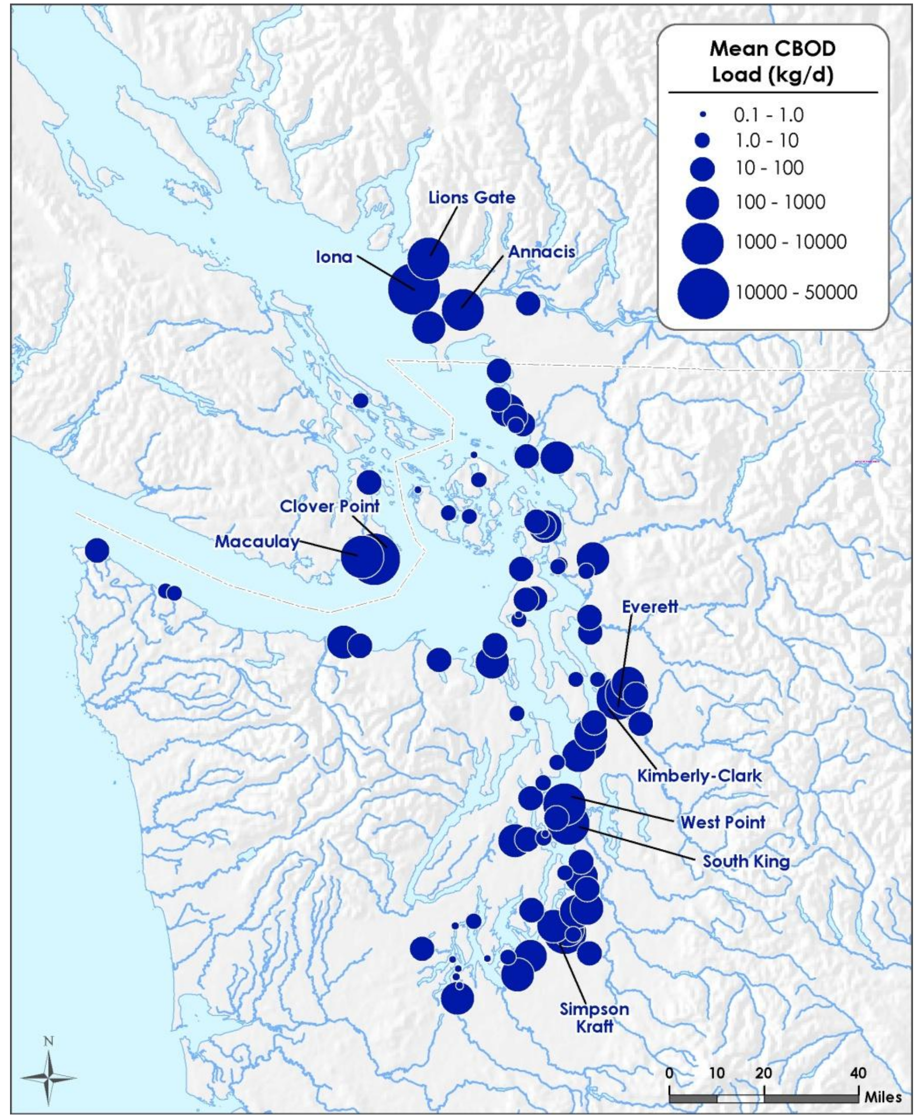

Figure E-16. Mean total carbonaceous oxygen demand loads from WWTPs during 1999-2008.

Appendix F. Natural Condition Concentrations

TO BE ADDED

Appendix G. Waterbody Numbers

Table F-1 lists the marine Waterbody Numbers (WBID) and names relevant to this study.

Table F-1. List of marine WBID names and numbers within the Puget Sound Dissolved Oxygen Model study area.

Waterbody ID	Waterbody Name
WA-01-0010	Strait Of Georgia
WA-01-0020	Drayton Harbor
WA-01-0050	Bellingham Bay (Inner)
WA-01-0070	Lummi Bay and Hale Passage
WA-01-0080	Bellingham Bay (Outer)
WA-02-0020	Boundary Pass, Haro Strait, and Middle Bank
WA-02-0030	San Juan Channel
WA-02-0040	Lopez Sound and West Sound
WA-02-0050	East Sound
WA-03-0020	Padilla Bay, Fidalgo Bay, and Guemes Channel
WA-03-3000	Joe Leary Slough
WA-06-0010	Saratoga Passage
WA-06-0020	Penn Cove
WA-06-0030	Holmes Harbor
WA-07-0010	Port Gardner And Inner Everett
WA-07-1005	Steamboat Slough
WA-09-0010	Elliott Bay
WA-10-0010	Commencement Bay (Outer)
WA-10-0020	Commencement Bay (Inner)
WA-10-0030	Thea Foss Waterway
WA-13-0010	Henderson Inlet
WA-13-0020	Budd Inlet (Outer)
WA-13-0030	Budd Inlet (Inner)
WA-14-0010	Squaxin, Peale, and Pickering Passages
WA-14-0020	Eld Inlet
WA-14-0050	Shelton Harbor (Inner)
WA-14-0100	Hammersley Inlet
WA-14-0110	Oakland Bay
WA-14-0120	Little Skookum Inlet
WA-14-0130	Totten Inlet
WA-15-0010	Port Madison
WA-15-0020	Eagle Harbor
WA-15-0030	Port Orchard, Agate Passage, and Rich Passage
WA-15-0040	Sinclair Inlet
WA-15-0050	Dyes Inlet and Port Washington
WA-15-0060	Carr Inlet
WA-15-0070	Henderson Bay
WA-15-0080	Port Gamble Bay

WA-15-0100	Liberty Bay
WA-15-0110	Colvos Passage
WA-15-0120	Quartermaster Harbor
WA-15-0130	Hale Passage
WA-17-0010	Dabob Bay and Quilcene Bay
WA-17-0020	Port Townsend (Outer) and Kilisut Harbor
WA-17-0030	Port Townsend (Inner)
WA-17-0040	Discovery Bay
WA-17-0050	Sequim Bay
WA-18-0010	Strait of Juan De Fuca (Central)
WA-18-0020	Port Angeles Harbor
WA-19-0010	Strait of Juan De Fuca (West)
WA-PS-0010	Skagit Bay and Similk Bay
WA-PS-0020	Port Susan
WA-PS-0030	Possession Sound (North)
WA-PS-0040	Possession Sound
WA-PS-0070	Tacoma Narrows
WA-PS-0090	Case Inlet and Dana Passage
WA-PS-0100	Hood Canal (North)
WA-PS-0130	Strait of Juan De Fuca (East)
WA-PS-0200	Rosario Strait
WA-PS-0210	Samish Bay
WA-PS-0220	Admiralty Inlet and Puget Sound (North)
WA-PS-0230	Puget Sound (North-Central)
WA-PS-0240	Puget Sound (Central)
WA-PS-0250	Hood Canal (South)
WA-PS-0260	Great Bend/Lynch Cove
WA-PS-0270	Puget Sound (South-Central)
WA-PS-0280	Dalco Passage and East Passage
WA-PS-0290	Nisqually Reach/Drayton Passage
WA-PS-0300	Puget Sound (South)