Puget Sound and the Straits Dissolved Oxygen Assessment

Impacts of Current and Future Human Nitrogen Sources and Climate Change through 2070

DEPARTMENT OF
ECOLOGY
State of Washington

March 2014

Publication No. 14-03-007

Publication and Contact Information

This report is available on the Department of Ecology's website at
https://fortress.wa.gov/ecy/publications/SummaryPages/1403007.html

The Activity Tracker Code for this study is 09-503.

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 by Teizeen Mohamedali:
Marine waters of the Salish Sea (Strait of Georgia, Strait of Juan de Fuca, and Puget Sound).

Puget Sound and the Straits Dissolved Oxygen Assessment

Impacts of Current and Future Nitrogen Sources and Climate Change through 2070

by

Mindy Roberts, Teizeen Mohamedali, and Brandon Sackmann
Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

and

Tarang Khangaonkar and Wen Long
Pacific Northwest National Laboratory
Richland, Washington 99352

Water Resource Inventory Area (WRIA) and 8-digit Hydrologic Unit Code (HUC) numbers for the study area

WRIAs

- 1 through 19

HUC numbers

- 17110001 through 17110021

Table of Contents

List of Figures

List of Tables

Abstract

Pacific Northwest National Laboratory and the Washington State Department of Ecology developed and applied a three-dimensional circulation and dissolved oxygen (DO) model of the Salish Sea (Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia) to evaluate DO impacts of human nutrient loads, Pacific Ocean conditions, and climate change. Previous reports documented the calibration results. This report summarizes current (2006) and future (for 2020, 2040, and 2070) predicted impacts on DO.

Human nitrogen contributions from the U.S. and Canada to the Salish Sea have the greatest impacts on DO in portions of South and Central Puget Sound. Marine point sources cause greater decreases in DO than watershed inflows now and into the future. Both loads will increase as a result of future population growth and land use change. Most of the Salish Sea reflects a relatively low impact from human sources of nitrogen. However, future human nutrient contributions could worsen DO declines in regions of Puget Sound.

The Pacific Ocean strongly influences DO concentrations under both current and future conditions. If 50-year declining trends in North Pacific Ocean DO concentrations continue, Salish Sea DO would decline far more than from human nutrient loads. However, future ocean conditions are highly uncertain.

Climate change will alter the timing of freshwater flow reaching the Salish Sea. This could worsen impacts in some regions but lessen others. Future air temperature increases would further decrease DO, particularly in shallow inlets.

This is the first assessment of how Salish Sea DO concentrations respond to population increases, ocean conditions, and climate change. Additional analyses are needed to link sediment-water interactions and increase scientific certainty.

Acknowledgements

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

- Ben Cope (EPA Region 10) provided guidance on the technical approach as well as review and interpretation of the results as part of the project team and as EPA's technical liaison for the National Estuary Program grant.
- Alan Hamlet (University of Notre Dame, formerly with the University of Washington Climate Impacts Group), provided climate model results for future river flow conditions in the Puget Sound region.
- Theogene Mbabaliye and Jessica Saffell (EPA Region 10) managed the National Estuary Program grant.
- The Department of Fisheries and Oceans provided quarterly monitoring data from the Strait of Juan de Fuca and Georgia Straits monitoring stations.
- The project advisory committee met at key points in project development and offered review:
    - George Boggs – Whatcom Conservation District
    - David Brookings – Snohomish County
    - Betsy Cooper – King County
    - Bill Dewey – Taylor Shellfish Co.
    - Tom Eaton – EPA Region 10
    - Lincoln Loehr – Stoel Rives
    - Parker MacCready – University of Washington
    - Paul McElhany – NOAA Northwest Fisheries Science Center
    - Bruce Nairn – King County
    - Jan Newton – PSP Science Panel
    - Tony Paulson – U.S. Geological Survey
    - Scott Redman – Puget Sound Partnership
    - Lynn Schneider – Washington State Department of Health
    - Eugene Sugita – West Point Treatment Plant
    - John Thomas – Washington On-Site Sewage Association
    - Heather Trim – Futurewise (formerly People for Puget Sound)
    - Robert Waddle – Kimberly-Clark (Everett)
    - Phil Williams – City of Edmonds
    - Jeff Wright – City of Everett WPCF

- Betsy Cooper (King County) provided current and future sewered population for the three King County wastewater treatment plants.
- Comments on the external review draft report were provided by Bruce Nairn, Patrick Roe, Shirley Marroquin, Lincoln Loehr, and Parker MacCready.
- Washington State Department of Ecology staff:
  - Josh Baldi, Bob Cusimano, Rob Duff, Karol Erickson, Kevin Fitzpatrick, Melissa Gildersleeve, Will Kendra, Andrew Kolosseus, Kelly Susewind, Sally Toteff, Mark Henley, and Greg Zentner provided review of initial findings.
  - Several Department of Ecology and EPA Region 10 permit writers provided assistance in locating future population served by WWTPs, including Mike Dawda, David Dougherty, Laura Fricke, Mark Henderson, Tonya Lane, and Shawn McKone.

This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement PC-00J279-01 to Department of Ecology. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This page is purposely left blank

Introduction

Pacific Northwest National Laboratory (PNNL) developed a three-dimensional circulation and dissolved oxygen (DO) model of Puget Sound and the Salish Sea under the direction of the Washington State Department of Ecology (Ecology). The project team also included the Environmental Protection Agency Region 10 and the University of Washington Climate Impacts Group. An advisory committee of regional experts provided review of interim findings.

The model was developed to investigate whether human sources of nitrogen are contributing to low levels of DO measured in parts of Puget Sound. The investigation focused not only on current impacts but also potential future impacts due to population growth and climate change. Figure 1 presents the study area.

Low DO levels can result from natural factors, but human contributions can worsen conditions. Phytoplankton, or algae, grows in the presence of nutrients and sunlight. Excess nutrients, primarily nitrogen, can fuel algae blooms. Decomposition of dead algae and other organic matter draws down oxygen concentrations near the bottom, where the atmosphere cannot replenish oxygen. This document describes the application of the calibrated model to quantify the relative influences of human nutrient contributions, Pacific Ocean conditions, and climate change on DO in Puget Sound and the Straits.

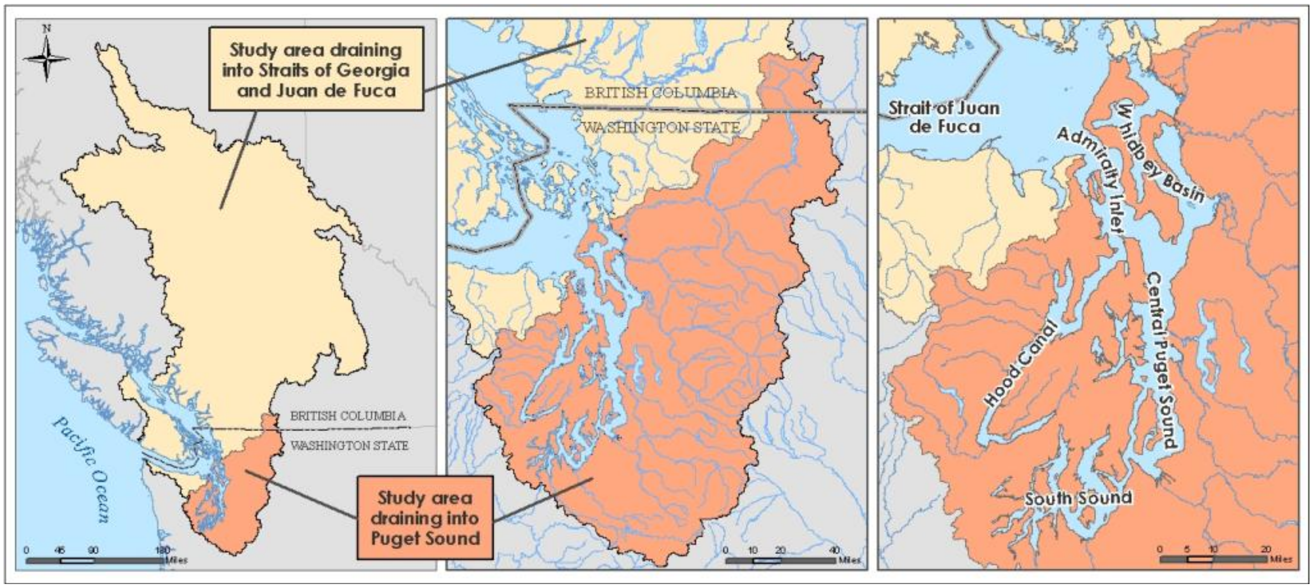


Figure 1. Puget Sound and the Straits of the Salish Sea with land areas discharging to marine waters evaluated in this study.

Pacific Ocean Conditions

Pacific Ocean water enters the Salish Sea primarily through the Strait of Juan de Fuca, with a lesser exchange through Johnstone Strait and around the north end of Vancouver Island in Canada. The marine water that enters the Salish Sea reflects conditions in the northeast Pacific Ocean that are influenced by complex circulation and water quality processes.

Water that upwells off the coast of Washington and enters the Strait of Juan de Fuca was last in contact with the atmosphere in the western Pacific Ocean. The North Pacific Current carries subarctic water eastward across the Pacific Ocean from the coast of Japan and Russia where it splits into north and south currents. The Alaska Current carries water northward to the Alaska gyre in the Gulf of Alaska. The California Current travels southward along the continental shelf of the west coast. The California Undercurrent carries subtropical waters northward from the Pacific equatorial region to Washington. Pacific equatorial subtropical waters are warmer, have higher salinity and nutrients, and have lower oxygen than subarctic waters. Both water masses influence the Strait of Juan de Fuca (Thomson and Krassovski, 2010).

Mesoscale eddies, which are large circulating currents hundreds of miles in diameter, transport water near the Strait of Juan de Fuca as well. Coastal processes along the west coast of North America, such as increased primary productivity (Sackmann et al., 2004) and the Columbia River plume (Banas et al., 2009) also influence water near the Strait. Finally, the direction and magnitude of coastal winds affects the strength of upwelling.

Small changes in these phenomena affect the water properties that enter the Strait of Juan de Fuca. Water in the Alaska gyre is cool and fresh, while water from the California Undercurrent is warm and saline. Mesoscale eddies are associated with warm freshwater. Climate cycles, such as the Pacific Decadal Oscillation (PDO) and El Nino-Southern Oscillation, have been linked to changes in large-scale meteorology and terrestrial hydrology (Mote et al. 2003; Hamlet and Lettenmaier 1999b, 2007). Climate cycles also influence circulation patterns and temperatures in the northeast Pacific (Whitney et al., 2007). All potentially influence stratification, which affects deep-water DO concentrations due to enhanced or restricted vertical mixing. Changes in these processes affect the incoming water through the Strait of Juan de Fuca.

Oxygen concentrations, which reflect complex interactions of physical, chemical, and biological processes, have declined in the North Pacific over a 50-year period in water masses representing a mix of subarctic and subtropical characteristics (Whitney et al., 2007; Pierce et al., 2012). Climate cycles and circulation patterns explain some of the variability in the long-term records. However, the rate of decline has increased recently compared with the 50-year trend, and researchers are unclear if this is part of a longer-term cycle or an acceleration of a downward trend.

Climate change could further decrease oxygen levels in waters that enter the Strait of Juan de Fuca. Freshening of the surface waters and increased heat flux due to climate change could reduce vertical mixing of oxygen to deeper waters by increasing stratification in the upper layer of the ocean (Whitney et al., 2007). Higher alongshore winds from north to south near the coast could also increase upwelling and pull more water from depths of 100 to 250 meters (Whitney et al., 2007). The Pacific Ocean is the dominant source of both water and nitrogen to Puget Sound and the Straits (Mackas and Harrison, 1997). Small changes in nitrogen concentrations entering the Salish Sea could produce large loads to Puget Sound and the Straits.

Contributions from Watershed Inflows and Marine Point Sources

The Salish Sea watershed delivers freshwater through rivers, streams, stormwater infrastructure, and overland flow from shoreline areas as well as from wastewater treatment plant effluent. This freshwater mixes with Pacific Ocean water. The Fraser River is the largest single source of freshwater to the Salish Sea and drains most of the province of British Columbia in Canada. Most of the freshwater reaching the Strait of Georgia comes from British Columbia, but the Nooksack and Samish Rivers, along with many smaller streams, drain to the Strait of Georgia from U.S. watersheds. Similarly, the Strait of Juan de Fuca receives freshwater inputs from the southwest coast of Canada's Vancouver Island as well as from U.S. rivers draining the north side of the Olympic Peninsula.

Within Puget Sound, defined as the area south of Admiralty Inlet, watersheds deliver different amounts of freshwater to marine waters and the amount varies over the year. Whidbey Basin receives water from the Skagit River, the largest freshwater source to Puget Sound**,** as well as the Stillaguamish and Snohomish Rivers. Hood Canal receives water flowing off the eastern slope of the Olympic Mountains and the western Kitsap Peninsula, and Central Puget Sound receives watershed inflows from the Cedar, Green, and Puyallup River watersheds and portions of the Puget Lowland to the east and west. The two largest rivers draining to South Puget Sound are the Nisqually and Deschutes, but South Puget Sound also receives freshwater from portions of the Puget Lowland.

Watershed inflows entering Puget Sound and the Straits deliver loads of nitrogen. Nitrogen naturally occurs in rivers and streams entering marine waters. However, human activities have increased nitrogen loads above naturally occurring levels. As detailed in Mohamedali et al. (2011), the relative load contributions vary among watersheds. While the Fraser River delivers the largest single freshwater nitrogen load to the Salish Sea, the load per unit watershed area is the lowest in the study area (Figure 2). Smaller watersheds such as the Nooksack River and the Deschutes River have significantly higher unit-area loads of nitrogen.

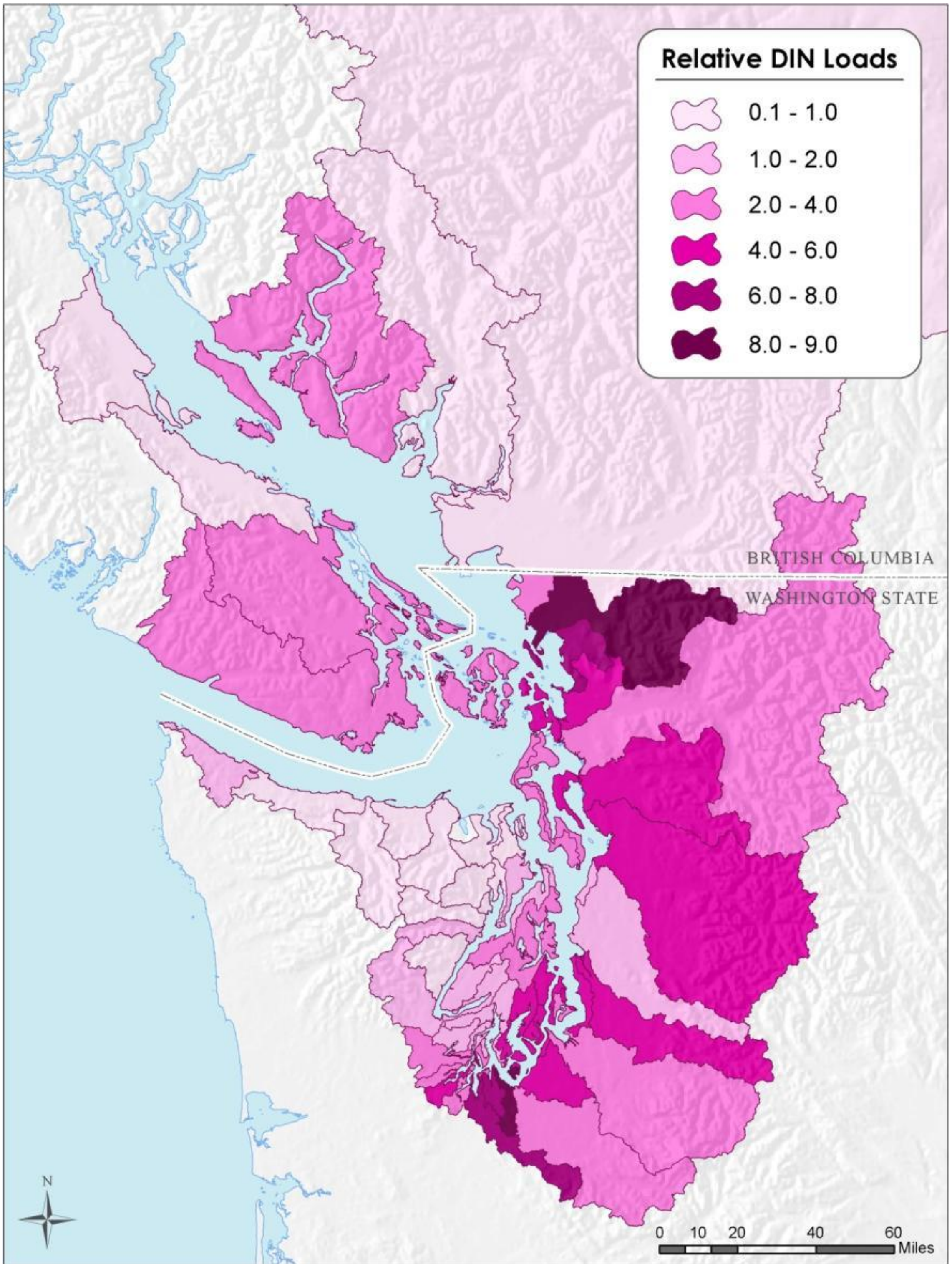


Figure 2. Annual relative dissolved inorganic nitrogen (DIN) loads from watersheds (individual watershed unit-area load compared with entire study area) for the period 1999-2008.

Source: Mohamedali et al. (2011).

Watershed nitrogen concentrations and loads reflect the combination of natural and human contributions. Natural nitrogen concentrations in rivers are governed by nitrogen concentrations in rainfall and processes within a forested watershed. This baseline condition can change if regional air emissions alter the rainfall nitrogen concentration or forest is converted to other developed land uses. In the watersheds, human contributions include point source discharges, such as wastewater treatment plants. Nonpoint sources from lands not covered by native forests also increase human contributions above natural levels. Not all nitrogen generated in a watershed reaches Puget Sound and the Straits. The amount of nitrogen delivered varies seasonally due to changes in flow rates, sources of nitrogen, and attenuation through processes such as plant uptake and denitrification.

The marine waters of the Salish Sea also receive direct discharge of treated effluent from wastewater treatment plants. These include plants serving greater Vancouver and Victoria as well as other communities in Canada. In the US, 78 municipal wastewater treatment plants and 10 industrial facilities discharge treated effluent through outfalls to Puget Sound and the Straits. While the volume of water is small relative to watershed inflows, municipal WWTP effluent contains higher concentrations of nitrogen. Industrial plants generally have lower concentrations of nitrogen than municipal plants but are included for completeness. Municipal marine point source nitrogen loads increase from current loads with increasing population served by the plants. Figures 3 and 4 summarize loads of dissolved inorganic nitrogen discharged to the Salish Sea as described in Mohamedali et al. (2011).

Population will continue to increase in the watershed draining to Puget Sound and the Straits. In addition, the proportion of the watershed covered by developed (non-forested) lands will also continue to increase. If no changes to current management actions occur, this increase in population and developed lands will result in increased nitrogen loads delivered to marine waters. A fundamental question is how much higher population and increased development could decrease marine water DO concentrations. Climate change could also alter the amount and timing of nitrogen loads reaching Puget Sound and the Straits, primarily through changes in hydrology.

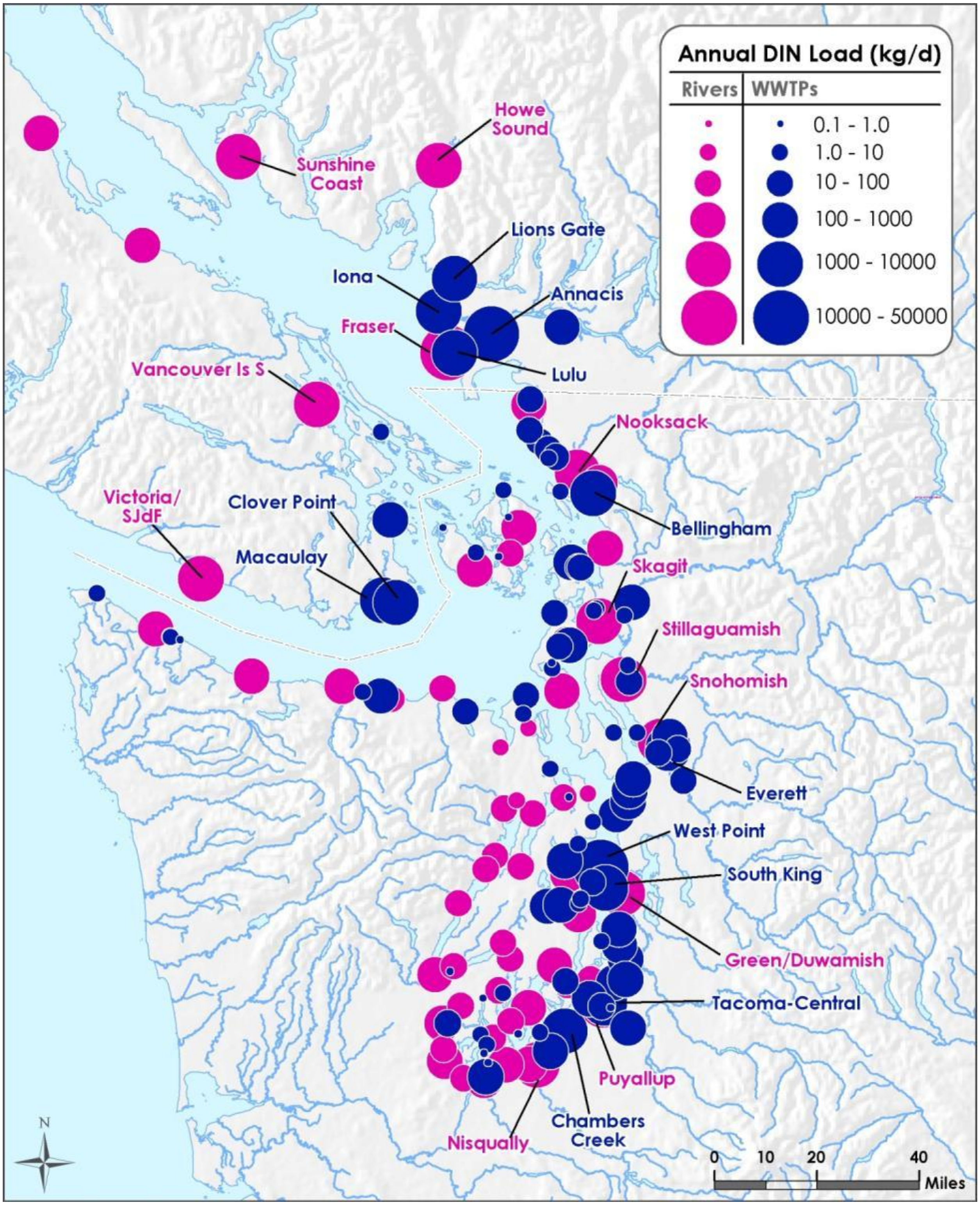


Figure 3. Mean annual dissolved inorganic nitrogen (DIN) loads from watershed inflows (rivers) and marine point sources (WWTPs) for 1999 to 2008.

Source: Mohamedali et al. (2011).

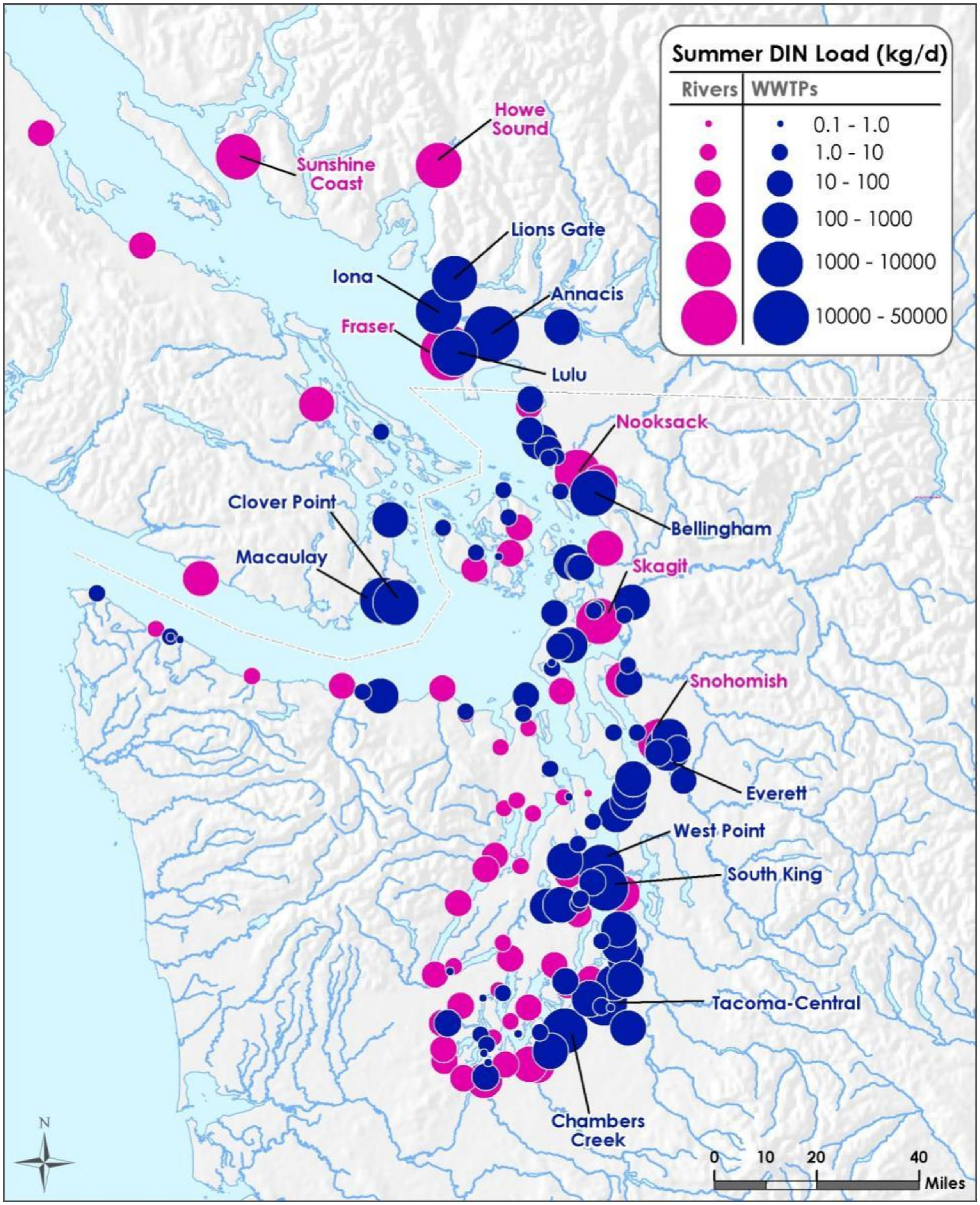


Figure 4. Summer dissolved inorganic nitrogen (DIN) loads from watershed inflows (rivers) and marine point sources (WWTPs) for 1999 to 2008.

Source: Mohamedali et al. (2011).

Circulation Patterns within the Salish Sea

Circulation within Puget Sound and the Straits is driven by tidal exchanges, estuarine circulation, winds, and the shape of the bottom and the shoreline. Tides cause water to circulate into and out of the Salish Sea through the Strait of Juan de Fuca and Johnstone Strait. Tides are semi diurnal, meaning most days have two high tides and two low tides. However, the interaction of the moon and the sun leads to the spring-neap tidal cycle. Each 28-day lunar cycle includes two spring tides and two neap tides. During spring tides, the sun and moon align and cause the tide range between high and low tide to increase. During neap tides, the sun and moon partially cancel each other out and the difference between high and low tide decreases. This affects circulation because water travels faster during spring tides than neap tides.

Estuarine circulation also influences overall Salish Sea circulation. Freshwater is less dense than marine water and rides over denser water (more saline, colder, or both) at depth. Because rivers discharge the bulk of the freshwater to the surface layer, this causes a net outflow of freshwater near the surface. This also results in a net inflow of denser marine water near the bottom. Depth profiles of salinity and temperature show the fresher water near the surface and more saline water near the bottom. Temperature also varies, but salinity has a stronger effect on density. Estuarine circulation resulting from differences in density physically transports less water than an incoming or outgoing tide but is responsible for the net circulation throughout the Salish Sea. Shallow sills, such as those at Admiralty Inlet and the Tacoma Narrows also strongly influence both vertical and horizontal mixing.

Water within Puget Sound and the Straits exhibits a wide range of salinity mostly due to variations in freshwater inflows. Each marine basin receives different annual freshwater inflows, and these flows also vary seasonally. Temperature also affects density, which also affects circulation. The combined effects of tidal exchanges, estuarine circulation, and the presence of sills results in complex circulation patterns.

Future population growth could affect the amount and timing of freshwater inflows due to hydropower modifications, consumptive water use, or wastewater discharge. Climate change could affect Salish Sea circulation through changes in the salinity and temperature of the Pacific Ocean, changes in the timing and magnitude of freshwater inflows, and changes in solar radiation, air temperature, and wind over the marine waters.

Dissolved Oxygen in Puget Sound and the Straits

Measurements confirm low DO concentrations occur in several basins and inlets of Puget Sound and the Straits (Figure 5). Dissolved oxygen measurements cannot distinguish whether these occur due to natural conditions or human sources.

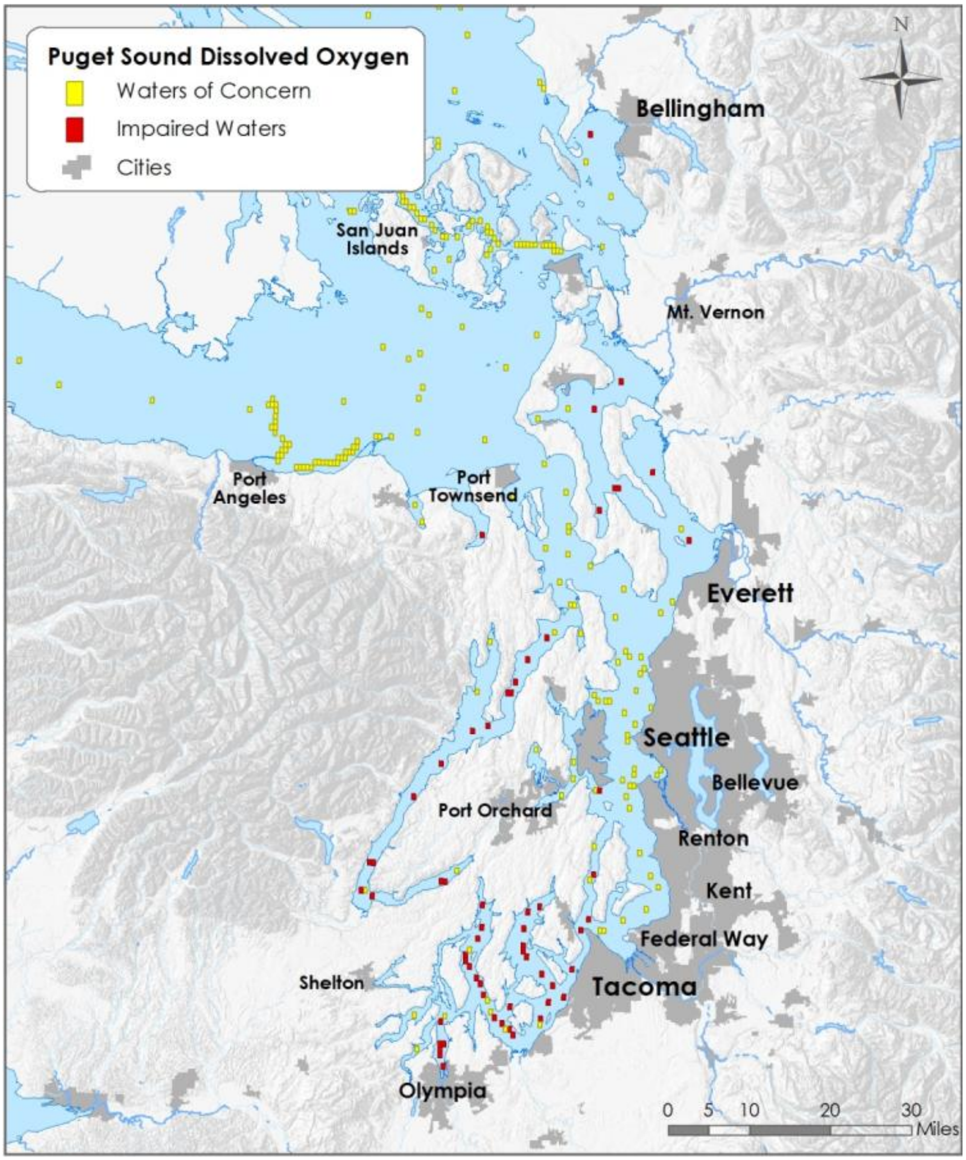


Figure 5. Areas with low dissolved oxygen (impaired waters) or waters of concern, based on the 2012 Water Quality Assessment for dissolved oxygen in Puget Sound.

In addition to monitoring ambient concentrations of DO, Ecology developed the Marine Water Condition Index (MWCI) to synthesize several variables that could influence oxygen levels (Krembs, 2012 and 2013). The MWCI includes ventilation based in part on DO levels but it also considers whether physical conditions could explain changes in DO. Krembs (2012) found declines in the 2010 MWCI (Figure 6, left). The PDO and upwelling strongly correlated with ventilation. Much of Puget Sound and the Straits experienced changes between 2003 and 2006 coinciding with a warmer period attributed to large-scale ocean and climate variability. However, the 2012 index that include data from the high-oxygen years of 2011 and 2012 indicate no significant trend (Figure 6, right). Ratios between nitrate and silicate and between phosphate and silicate are changing in ways that cannot be explained by the ocean alone.

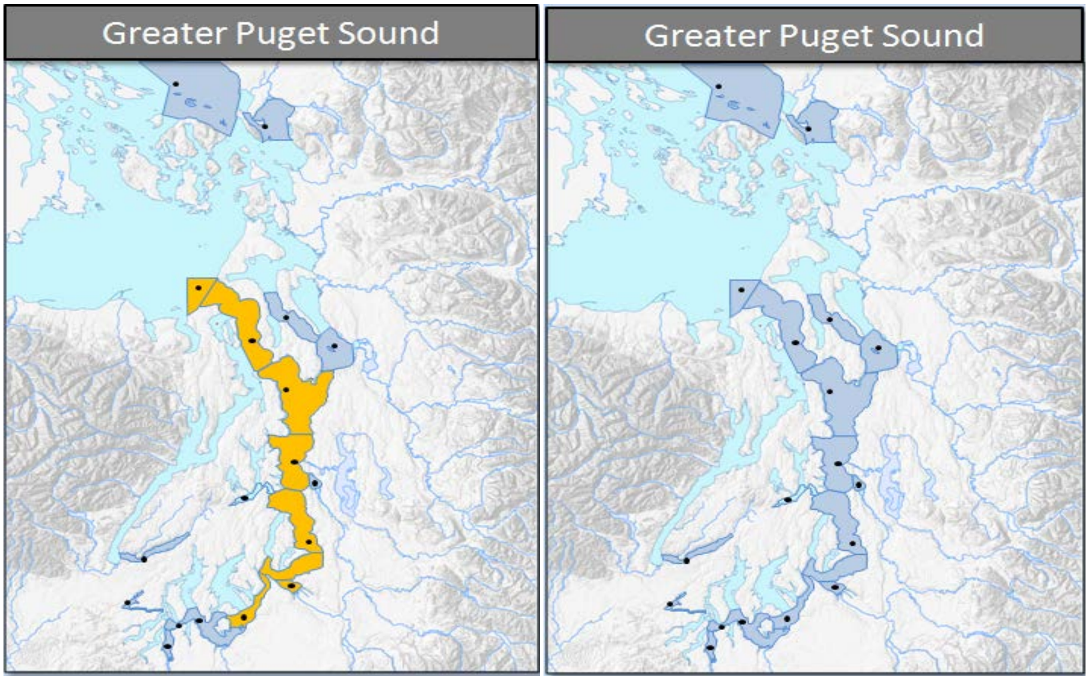


Figure 6. Significant trends in the Marine Water Condition Index (MWCI) by region in Puget Sound and the Straits for 2010 (left) and 2012 (right).

Orange indicates significant change. Blue indicates no significant change.
Source: Krembs (2012) and Krembs (2013).

Washington State Water Quality Standards

Ecology has established water quality standards under the federal Clean Water Act to protect aquatic life. The health of fish and other aquatic species depends upon maintaining an adequate supply of oxygen dissolved in the water. Oxygen levels can fluctuate over the day and night in response to changes in sunlight as well as the respiratory requirements of aquatic plants and algae. The criteria apply to the daily minimum concentration within the water column.

The standards include provisions for the minimum concentrations needed to protect aquatic life, and these vary by basin (Figure 7). Most of the U.S. waters of the Salish Sea have the most protective Extraordinary water quality requirements to protect aquatic life with a minimum concentration of 7.0 mg/L. Several bays and inlets have a lower Excellent standard to protect aquatic life where DO must be >6.0 mg/L. Urban bays must maintain minimum concentrations above 5.0 mg/L to protect Good aquatic life uses. If a water body is naturally lower in oxygen than these thresholds, then the combined effects of all human activities must not cause the naturally lower oxygen to decrease by more than 0.2 mg/L. As discussed in the next section, computer models are needed to determine whether the effects of human contributions violate standards.

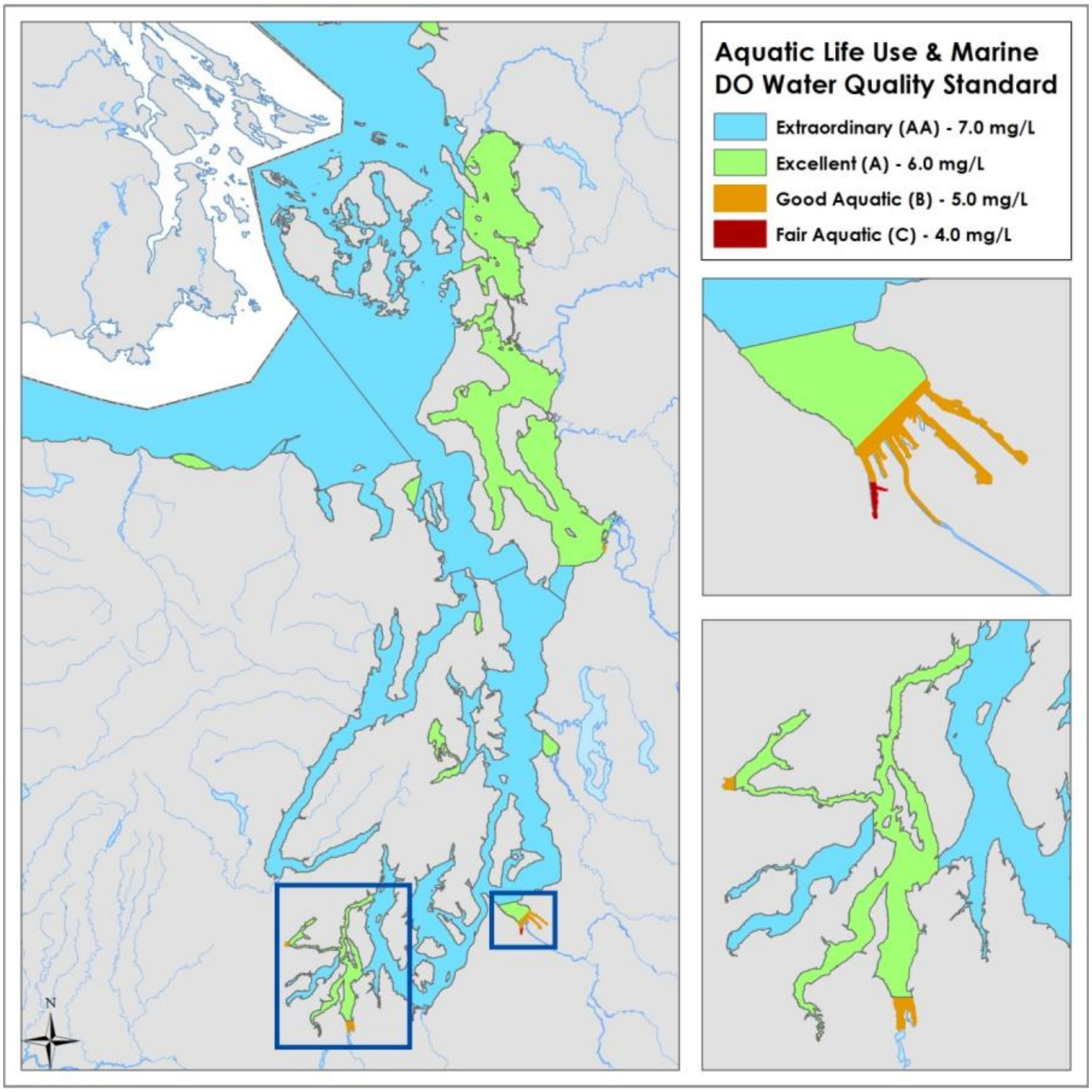


Figure 7. Washington State water quality standards for marine dissolved oxygen.

Using Models to Distinguish Human Contributions from Natural Conditions

Measurements of DO concentrations cannot distinguish the relative contributions of human nutrient sources and natural conditions. We developed models of current circulation and water quality in Puget Sound and the Straits. We then estimated past and future conditions based on adjustments to the baseline year used for calibration (2006). By adjusting model inputs, we can isolate the effects of different human sources, Pacific Ocean conditions, and climate change.

The Salish Sea Water Quality (SSWQ) model is a linked circulation and water quality model that includes Puget Sound, Georgia Basin, and the Strait of Juan de Fuca. The model domain is represented by an unstructured grid with approximately 14,000 cells that vary in size from an average dimension of 800 meters in the Straits to 250 meters in inlets and bays, as shown in Figure 8 (Khangaonkar et al., 2011; Yang et al., 2010). Ten layers represent the water column, with thinner levels near the surface and thicker layers near the bottom. The model uses a sigma coordinate system, which means the thickness of each layer expands and contracts to represent the tidal range throughout the model domain.

The hydrodynamic conditions are simulated using the Finite Volume Coastal Ocean Model (FVCOM) developed by the University of Massachusetts (Chen et al., 2003). Yang et al. (2010) and Khangaonkar et al. (2011) detail the FVCOM circulation model calibration and results for the 2006 simulation. Output from the circulation model is used as input to the water quality model.

The U.S. Army Corps of Engineers originally developed the integrated compartment model (CE-QUAL-ICM) to simulate biogeochemistry using 32 state variables. The Puget Sound application has been set up using 19 variables including two types of algae, dissolved and particulate carbon and nitrogen, as well as other components of the carbon cycle used to calculate algal production, decay, and impacts on DO. In collaboration with the University of Massachusetts and U.S. Army Corps of Engineers, PNNL completed the development of the unstructured biological model, including the FVCOM-ICM code that runs CE-QUAL-ICM kinetics using the FVCOM finite-volume computational transport framework. The model runs in a parallel mode on a 184-core computer cluster. The 2006 simulation requires 24 hrs using 35 cores per simulation. Khangaonkar et al. (2012) details the model calibration and results for 2006 while Kim and Khangaonkar (2011) describe the model development.

The calibrated model simulates the seasonal patterns of DO, algal productivity, and nutrients. Algae biomass is low during the summer months but increases in the spring with sunlight and temperature. A spring bloom of diatoms occurred in April and May 2006, with the timing and intensity varying by basin. Summer blooms occurred between June and August 2006, and chlorophyll returned to low levels by late fall. Surface waters in shallow basins developed supersaturated oxygen levels while nutrients declined as a result of algal production and reaeration. Deeper waters developed lower oxygen levels by fall as the Pacific Ocean water entered Puget Sound and organic matter decomposition decreased oxygen in the lower water column.

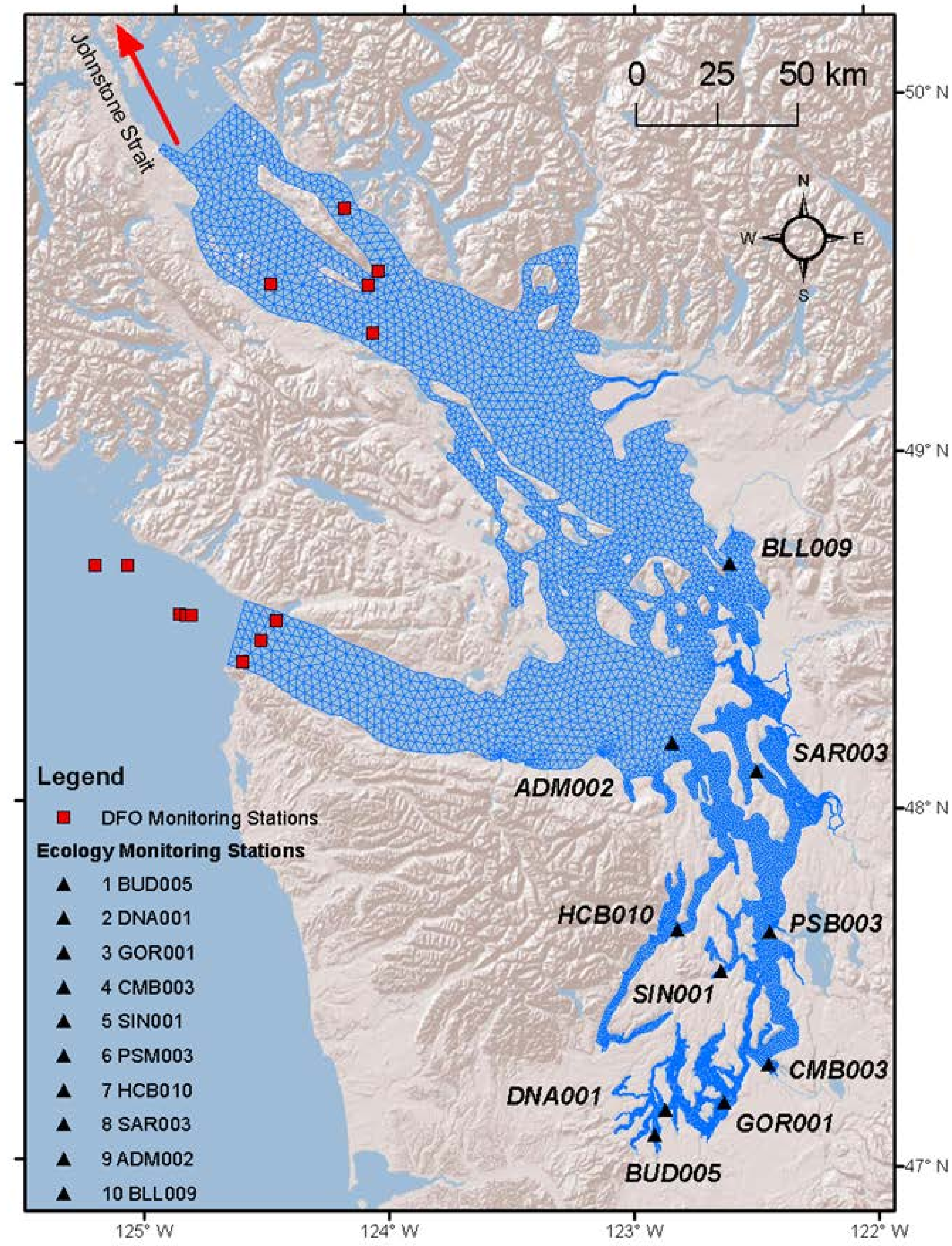


Figure 8. Circulation and water quality model grid.

DFO: Canada's Department of Fisheries and Oceans.
Source: Yang et al. (2010).

Current and Future Scenarios

The calibrated circulation and water quality models were applied to two groups of scenarios:

1. **Current Scenarios –** Compare the relative effects of current human and natural sources of nutrients on Salish Sea water quality by turning on and off various sources.
2. **Future Scenarios –** Compare the relative effects of future population, land use, and climate on Salish Sea water quality for years representing 2020, 2040, and 2070 conditions.

This report (1) describes the methods used to develop the various model scenarios and boundary conditions, (2) compares loads associated with the scenarios, and (3) compares the relative effects of these scenarios on water quality in Puget Sound and the Straits.

Puget Sound, defined as waters south of Admiralty Inlet, represents the primary region of interest. However, Puget Sound is connected to the Strait of Juan de Fuca and the Strait of Georgia and cannot be considered in isolation. Therefore, this analysis includes all major U.S. and Canadian influences on circulation and water quality in the Salish Sea.

Methods for Developing Boundary Conditions

We developed alternative boundary conditions to simulate current and future scenarios. The model runs with nutrient loads varying at a daily time step, meteorological conditions updated every 6 hours, and with ocean boundary conditions varying at a monthly time step for a full calendar year. Each scenario is represented by updated boundary conditions. Table 1 summarizes parameters varied in the different boundary conditions for each scenario.

Table 1. Parameters changed in time-varying boundary conditions for scenarios

Boundary condition type	Parameters modified for current or future scenarios	Other parameters not varied in scenarios
Ocean Conditions	Nutrient and dissolved oxygen concentrations	Temperature, salinity, phytoplankton biomass, and tidal elevations
Meteorological Conditions	Upward and downward shortwave radiation, upward and downward longwave radiation (net heat flux is calculated)	Wind speed and direction
Watershed Inflows	Streamflow and nutrient concentrations[1]	Dissolved and particulate organic carbon, dissolved oxygen, temperature
Marine Point Sources	Nutrient concentrations[1]	Effluent flow, dissolved and particulate organic carbon, dissolved oxygen

[1] Nutrient concentrations include: nitrate + nitrite (NO3+NO2), ammonium (NH_4) dissolved and particulate organic nitrogen (DON and PON), phosphate (PO4), and dissolved and particulate organic phosphorus (DOP and POP).

While the model requires multiple water quality parameters to characterize the boundary conditions, this report focuses on comparing nitrogen loads among scenarios, and more specifically, dissolved inorganic nitrogen (DIN). Nitrogen is the limiting nutrient for algae growth in marine waters. DIN is the most bioavailable form of nitrogen, and is typically the largest fraction of total nitrogen (~90%) in marine waters.

Current Scenarios

Current scenarios were developed to compare the relative effects of current nutrient loading into Puget Sound from various sources, and to understand the relative effects of regional human and natural sources of nutrients on Puget Sound water quality. The year 2006 was selected as the baseline condition for scenarios because it was used for calibration and has data available for watershed inflows from rivers and wastewater treatment plants. We also compiled 2007 and 2008 loading estimates. We include these with the load comparisons but did not include model results in this report.

One of the project objectives is to evaluate the relative influence of various human sources on DO compared with natural sources. The 2006 calibration (Khangaonkar et al., 2012) includes ocean contributions, natural contributions, human sources within watershed inflows, and human contributions discharging directly to marine waters through marine point sources. Atmospheric deposition to water was not included as a separate load, although atmospheric deposition to the land surface is included in the watershed inputs. Boundary conditions were modified to isolate (1) only natural contributions from watershed inflows, (2) the combination of human and natural contributions from watershed inflows, and (3) marine point sources. The complete list and brief descriptions of current scenarios are presented in Table 2 and detailed below.

Watershed inflows (natural and human sources)

Watershed inflows include all freshwater inflows into Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca. These include large rivers, smaller streams, unmonitored watersheds, and the shoreline fringe. Sixty-four freshwater inflows are included in the Salish Sea domain (Figure 9). This includes several freshwater inflows that drain parts of Canada. Mohamedali et al. (2011) provides estimated flows and nutrient concentrations at a daily interval from each watershed inflow for the years 1999-2008.

Flow estimates were based on 32 stations with long-term USGS streamflow gage data or from Canada. In Puget Sound, gaging stations capture approximately 69% of the watershed area south of Deception Pass. Mohamedali et al. (2011) describes how streamflow data were normalized and scaled (by drainage area and average annual precipitation of each watershed) to estimate streamflow from watersheds and shoreline fringes. This provides a complete set of streamflow estimates for 64 freshwater inflows, from 1991-2008. In general, U.S. inflows are more detailed while Canadian inflows are coarser. The intent is to ensure all freshwater is accounted for in the model domain.

Estimates of time-varying water quality were also developed by Mohamedali et al. (2011) for the period 1999-2008, based on a statistical method that related concentrations to flow and time of year using a best fit to monitoring data. Natural conditions for these watershed inflows were also established by Mohamedali et al. (2011) using a meta-analysis to estimate natural nitrogen concentrations and loads in the absence of human influence. The difference between existing and natural conditions quantifies the human contributions within watershed inflows. Several watersheds receive nutrient inputs from permitted point source discharges. These were not distinguished from nonpoint source contributions in watershed inflows. Human contributions from watershed sources include the combined effects of point and nonpoint sources.

Table 2. Current scenarios that were developed; all concentrations refer to nitrogen concentrations.

Scenario Name	Scenario Nickname	Scenario Description	Watershed Inflows		Marine Point Sources		Ocean Conditions	Meteoro-logical Conditions
			Concentrations	Flows	Concentrations	Flows		
2006 Baseline	2006 Baseline	2006 baseline (existing conditions for marine point sources and watershed inflows)	2006 concentrations	2006 streamflows	2006 concentrations	2006 effluent flow	2006 conditions	2006 conditions
Natural conditions (point source flow in)	Natural Conditions	Natural conditions for watershed inflows; no marine point sources	Natural concentrations	2006 streamflows	Zero concentrations	2006 effluent flow		
Point sources removed (flow in)	No Point Sources	2006 conditions for watershed inflows; no marine point sources	2006 concentrations	2006 streamflows	Zero concentrations	2006 effluent flow		
Human watershed inflows removed	No Human Watershed Sources	Natural conditions for watershed inflows; marine point sources at 2006 levels	Natural concentrations	2006 streamflows	2006 concentrations	2006 effluent flow		

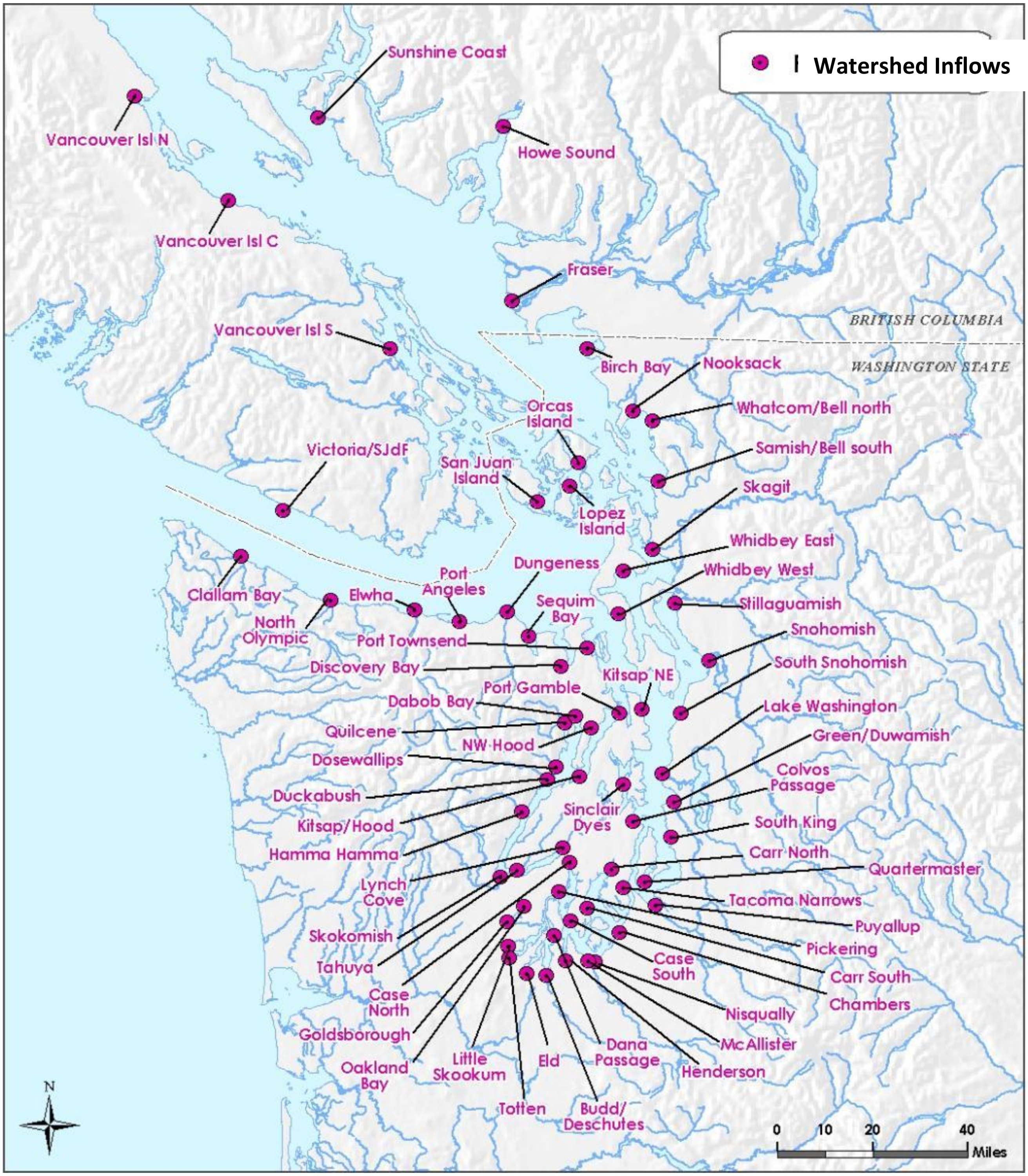


Figure 9. Watershed inflows to Puget Sound and the Straits from rivers, streams, and other freshwaters.

Marine point sources

A total of 97[1] municipal wastewater treatment plants (WWTPs) and industrial facilities discharge into marine waters of Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca (Figure 10). This count includes nine[2] WWTPs located in Canada, 78 municipal WWTPs located in the US, five oil refineries, four active pulp/paper mills, and an aluminum facility. Additional point sources discharge to rivers that reach the Salish Sea. These sources are not individually quantified, but their contributions are included in the watershed inflow estimates.

In Mohamedali et al. (2011), we estimated nutrient loading at daily intervals for these point-sources for the years 1999-2008. In summary, we used effluent monitoring data collected from 29 facilities (28 municipal wastewater treatment plants and 1 pulp and paper plant discharging to South and Central Puget Sound) (Roberts et al., 2008). Results from the municipal plants exhibited concentration patterns that varied by discharge volume, so they were grouped into categories: large plants >10 mgd, medium plants 4 to 10 mgd, and small plants <4 mgd. Concentration data were analyzed to develop daily concentrations by plant size. We developed plant-specific regressions with flow and fraction of the year for carbonaceous biochemical oxygen demand (CBOD) and any available ammonium data from discharge monitoring reports. Template concentrations were applied in the absence of site-specific data. Plant-specific flows were used to generate loads.

For industrial WWTPs, characteristic concentrations were developed using best available information for the pulp and paper mills, oil refineries, and an aluminum facility. Plant-specific data for Canadian WWTPs were used where available. Because these are not the focus of this study but loads are needed for completeness, we applied constant year-round concentrations based on the treatment levels in place at each plant.

Under natural conditions, in the absence of human activities or influence, none of these point sources would be in operation. While some portion of the freshwater would reach marine waters, we were unable to estimate this fraction. Therefore, we evaluated natural conditions with marine point source flow at 2006 levels but set nutrient load to zero.

---

[1] This count includes King County's new Brightwater plant which came online in 2012.

[2] The Gulf Islands have several small treatment plants that are combined into a single load discharge for the purposes of modeling.

Figure 10. Marine point sources (wastewater treatment plants and industrial facilities) located in the U.S. and Canada that discharge into Puget Sound and the Straits of Juan de Fuca/Georgia.

This map does not include the new King County Brightwater WWTP, which began discharging wastewater into Puget Sound in 2012 through an outfall just south of the Edmonds WWTP outfall.

Ocean conditions

The Salish Sea model has two open boundaries where incoming Pacific Ocean water enters the Straits, and eventually, Puget Sound. One is the boundary at the Strait of Juan de Fuca, while the second is at Johnstone Strait at the north end of the Strait of Georgia. Water quality conditions were characterized at both these open boundaries during model calibration using available marine water quality data collected either by Fisheries and Oceans Canada (DFO) or jointly by Ecology and UW as part of the Joint Effort to Monitor the Strait of Juan de Fuca (JEMS). Details on how data were used to create vertical ocean profiles to characterize this boundary are described by Khangoankar et al. (2012).

The same ocean boundary conditions that were used to represent 2006 baseline conditions were applied to all current scenarios. For the natural conditions estimates, the ocean boundary conditions were assumed to represent natural conditions, recognizing that the true natural state is unknown. By applying this assumption, the ocean boundary does not cause any of the differences seen in direct comparisons of Puget Sound water quality under 2006 conditions and natural conditions.

Meteorology

Meteorological boundary conditions are also required to simulate circulation and water quality. These include wind speed and direction, heat flux, irradiance, and day length. The initial circulation model set up used the North American Regional Reanalysis (NARR) data sets from NOAA (Yang et al. 2010) on a 30 km x 30 km grid. This was improved upon when we transitioned to the Weather Research Forecasting (WRF) model reanalysis data provided by the University of Washington on a finer 12 km x 12 km grid (Khangaonkar et al., 2012). An over-water station near the Triple Junction at the south end of Whidbey Island was used to calculate representative net heat flux applied to the entire domain.

Originally WRF heat flux was biased high and required a 0.8 scalar factor to match existing information. Adjusted heat flux, wind speed and direction, photosynthetically active radiation (PAR), and day length from the 2006 WRF model reanalysis was used for all current conditions runs using 2006 as the baseline.

Initial conditions

All current scenarios use the same initial conditions for DO, nutrients, and chlorophyll a developed through the model spin-up approach for model calibration (Khangaonkar et al. 2012). Initial conditions were developed in several steps. First, Ecology’s marine ambient monitoring data from December 2005 from the main basin of Central Puget Sound (PSB003) were applied throughout the water column to all well mixed regions as a starting point. Because Hood Canal remains stratified in the winter, surface and bottom DO concentrations were developed separately using Hood Canal site-specific monitoring data from station HCB003. We ran the model from December 2005 through December 2006 with time-varying boundary conditions. Water column concentrations evolved from the initial conditions. The results predicted for December 31, 2006 in this conditioning run were used as initial conditions to begin the final spin up model runs on

January 1, 2006. The final results predicted for December 31, 2006 were used to begin the 2007 model runs. The same initial conditions were also used for all scenarios.

Sediment fluxes

The sediment fluxes of oxygen, nitrate plus nitrite, and ammonium are externally specified, as described in Khangaonkar et al. (2012). The existing model does not include a direct link between solids settling from the water column and sediment fluxes. As loads increase, more settling of particles to the sediment layer would result in higher sediment fluxes. Likewise, the sediment fluxes would be reduced if loads were decreased. Instead of simulating these dynamic changes to the sediments based on water column conditions, the model employs user-defined, constant flux values for sediments. The calibration process provides a check on the appropriateness of the assumed fluxes, whereas scenarios are focused on estimates of past (natural) and future conditions. Since the model does not simulate changes to sediment fluxes resulting from scenario assumptions, we must estimate the altered sediment state using a separate analysis.

To account for likely changes in sediment fluxes under different scenarios, we scaled 2006 sediment fluxes to reflect changes in external loads in the scenarios during the growing season defined as April through September. We do not know how changes in watershed inflows or marine point sources would affect water quality at the ocean boundary, so we kept this constant for all current scenario applications. The ocean is the dominant nitrogen source to the Salish Sea (Mohamedali et al., 2011), but we did not include oceanic loading in the scalar calculation. We developed scalars only considering the change in watershed inflows, marine point sources, and atmospheric deposition to the water surface. The scalar is 1.0 for current conditions and 0 for no loading at all from either natural or human contributions. This approach provides a conservative scale factor for the sediment flux conditions in both past (natural) and future scenarios. This conservative approach leads to high-bound estimates of natural DO conditions and low bound estimates for future conditions.

The calibrated sediment fluxes under current conditions have a scalar of 1.0 for external loads representing all current loads from watershed inflows, marine point sources, and atmospheric deposition to the marine water surface. Hood Canal and the Straits of Juan de Fuca and Georgia have large surface areas but smaller proportional human loads than South Puget Sound, Central Puget Sound, and Whidbey Basin. We did not adjust sediment fluxes for alternative loading scenarios in Hood Canal or the Straits and used calibrated values for all current scenarios. We refer to the area where we scaled fluxes as the flux region (Figure 11). We developed the sediment flux scalars in two steps: (1) natural conditions and (2) alternative loading scenarios.

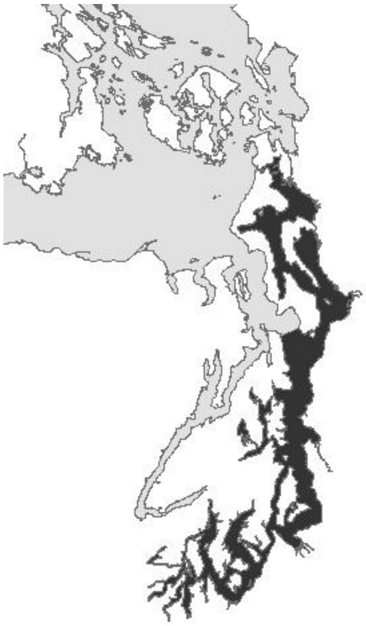


Figure 11. Region where sediment flux scalars were applied for alternative loading scenarios (dark shading).

To develop the natural conditions sediment scalar, we used two methods. The first method assumes that the sediment fluxes scale with the sum of the external loads compared with current conditions. We summed the external loads from the open boundary, watershed inflows at natural conditions, zero for no WWTP discharges, and the atmospheric deposition. That sum represents 89% of the sum of external loads under current conditions. Therefore, we developed a scalar of 0.89 to adjust sediment fluxes under natural conditions.

The second method assumes that the sediment fluxes scale with the ratio of the particulate nitrogen flux to the sediments. We ran the calibrated model with natural loading twice, once with the sediment fluxes of oxygen and nitrogen multiplied by 0.5 and again with no change in sediment fluxes from current conditions, equivalent to a scalar of 1.0. The predicted particulate nitrogen flux to the sediment in kg/d was saved from both runs. The ratio of the particulate nitrogen flux in each run to the current particulate nitrogen flux was used to estimate the scalar for both runs. Scaling sediment fluxes by 0.5 underestimated the particulate nitrogen flux, and scaling by 1.0 overestimated the particulate nitrogen flux. The difference between the estimated and actual scalar was zero at 0.89.

We conducted one final model run with a sediment flux scalar of 0.89 to confirm that the external loads balance (first method) and the particulate nitrogen fluxes balance (second method).

We also developed sediment flux scalars for current loading scenarios that isolate the effects of only human sources in watershed inflows or only marine point sources. We summed external loads for the flux region for the period April through September, as in the first method for the natural conditions sediment flux scalar. Using the relationship between sediment flux scalars and external loads in the flux region for current and natural conditions, we estimated sediment flux scalars for the scenarios that isolate the effects of current watershed inflows (no marine point sources) and marine point sources and natural watershed inflows (no human sources in watershed inflows). Because the marine point sources are the dominant human source, the sediment flux scalar for current watershed sources without any marine point sources (0.90) was close to the value for natural conditions (0.89). The scalar for the run with only marine point sources and watershed inflows at natural conditions (0.98) was close to 1.0 because the loads were close to those for current conditions.

Future Scenarios

Future scenarios were developed to evaluate the relative effects of population growth, land use change, and climate change on Puget Sound water quality. The years 2020, 2040, and 2070 were selected to evaluate future conditions based on the availability of downscaled climate model information from the University of Washington's Climate Impacts Group.

Watershed inflows (natural and human sources)

The analysis incorporates estimates of future streamflows from rivers and streams, as well as nutrient concentrations. Future streamflows and regional hydrology reflect future climate and meteorological forcing. They also reflect future land use changes affecting watershed export of nutrients, how nutrient sources are managed in the future, and other factors that affect the transport, attenuation, and delivery of these nutrients into rivers, and eventually, into Puget Sound and the Straits.

The University of Washington Climate Impacts Group (CIG) has been evaluating the potential influence of future climate on water resources for several years (Hamlet and Lettenmaier 1999a; Elsner et al. 2010; Hamlet et al. 2013). UW CIG simulated historical and future river flows, based on downscaled global climate change scenarios, using the Variable Infiltration Capacity (VIC) hydrology model (Hamlet et al. 2013). Details are provided below. The VIC model only simulates hydrology, and not water quality, so we had to explore other methods to estimate future nutrient concentrations from watersheds. A watershed model that simulates physical, chemical and biological processes could potentially be developed for the whole study domain to predict loading to marine waters from all watersheds under future conditions. However, the development of such a model would require extensive resources and data, and was beyond the scope for this project.

In the absence of a comprehensive watershed model, we projected future nutrient concentrations using statistical tools to identify patterns in existing river concentrations and watershed characteristics. Watershed characteristics that could influence the sources, transport, and fate of nutrients include factors that do not change over time, such as geology and slope, as well as factors expected to change considerably, such as land use and population. Relationships between current concentrations and current watershed characteristics were used to project future river concentrations based on expected changes in watershed characteristics such as land use and population growth.

As mentioned earlier, even though river water quality is characterized by several water quality parameters, we conducted a detailed estimation effort only on DIN, the parameter with the largest influence on marine DO.

Future watershed streamflows

Future estimates of streamflows for the 64 watershed inflows were developed primarily from the output of the VIC hydrology model (Hamlet et al. 2013). UW simulated daily and monthly historical (1991-2005) and future (2010-2069) river flows. Historical simulations are based on historical climate data, while future simulations were developed from downscaled global climate change scenarios (Hamlet et al. 2013; Salathé et al. 2013 [in review]).

The VIC model only provides streamflows for 13 of the largest rivers in the Puget Sound region, and it does not cover the entire Puget Sound / Georgia Basin model domain. We extrapolated the 13 VIC river simulations to the 32 original gaged locations evaluated by Mohamedali et al. (2011). We then extrapolated these flows to all 64 freshwater inflows (Figure 12) using the following extrapolation method:

1. Develop cross-correlations between the 32 gaged streamflow data and all 13 simulated VIC river streamflows for historical (1991-2005) conditions.
2. Identify which VIC streamflow simulations had strong correlations with which of the 32 gaged streamflow records, and then pair each of the 32 gaged watersheds with a VIC river. This was based on the highest correlation coefficients or best professional judgment (Table 3).
3. Develop a linear regression relationship between each of the 32 gaged streamflows (response variable) and its paired VIC streamflow (predictor variable). Analyze regression results and check for statistical significance.
4. Predict historical streamflow at each of the 32 gage locations using the linear regression equation determined in the previous step; compare predicted and observed historical streamflow time series and monthly averages to characterize how well predicted streamflow matched observed streamflow.
5. Use future VIC streamflows for the 13 rivers to predict future streamflows at all 32 gage locations based on these pairings and linear regression relationships.
6. Extrapolate these future streamflow predictions at the 32 gaged locations to all 64 nonpoint source freshwater inflows by scaling streamflows by watershed area and average annual rainfall as described in Mohamedali et al. (2011).

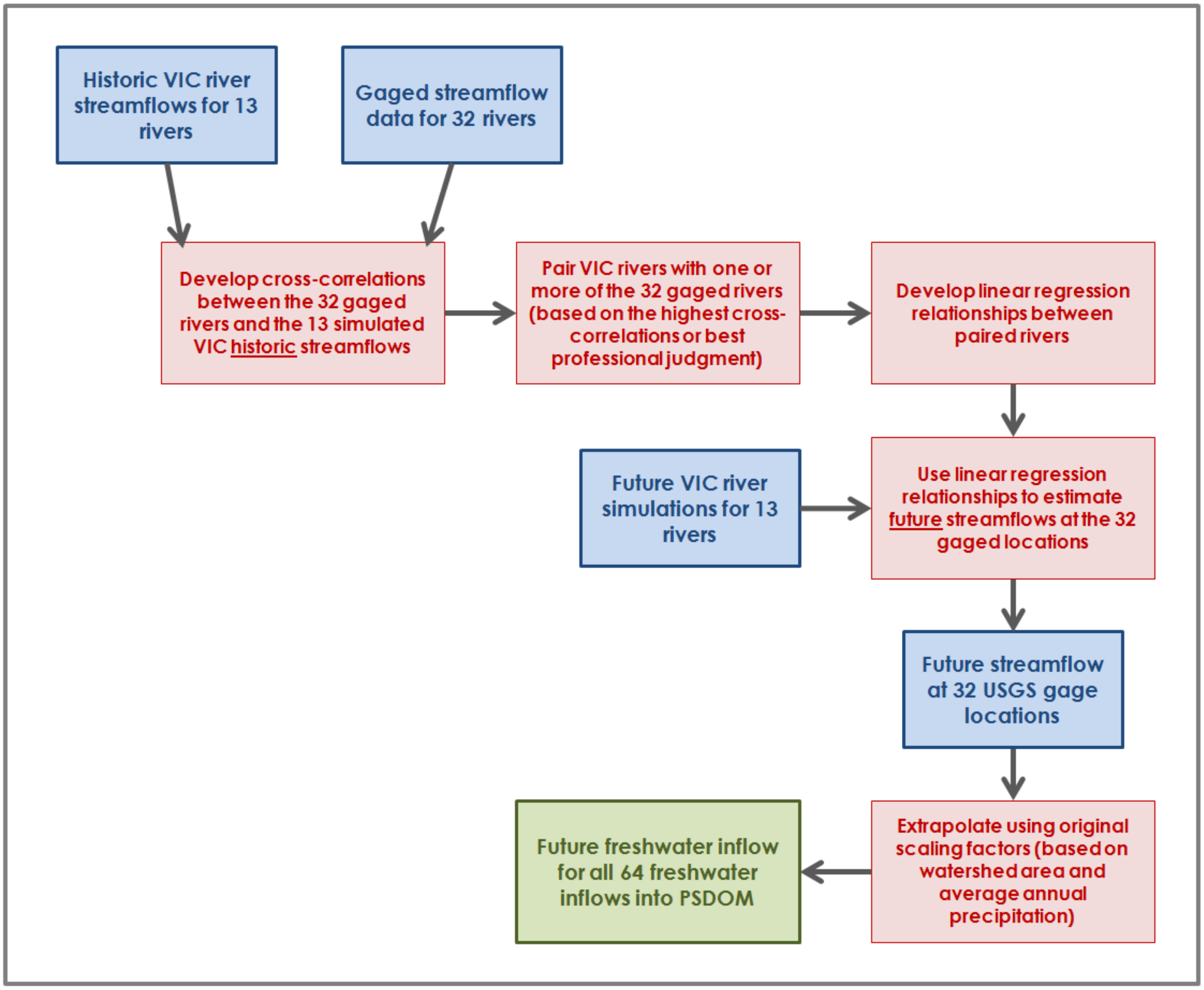


Figure 12. Flow chart illustrating the steps used to develop future flow estimates for the 64 freshwater inflows included in the Salish Sea model using VIC streamflows for 13 rivers.

The VIC model does not extend into Canadian watersheds, but Morrison et al. (2002) estimated future streamflows for the Fraser River in Canada under climate change scenarios. Historical streamflow data from the Fraser River was therefore correlated to other Canadian rivers to establish pairings. However, the Fraser River only correlated well with the rivers draining the mainland (the Squamish and Clowhom Rivers), but not with the rivers on Victoria Island. The Vancouver Island rivers correlated much better with VIC rivers in the Olympic Peninsula (Table 3), which is likely a result of similar climate, topography and land use.

A single calendar year of streamflow predictions from VIC does not adequately capture the range of future variability. The goal is to evaluate future scenarios that represent the years 2020, 2040, and 2070. Future climate models predict high inter-annual variability in hydrology. To select streamflows that represent average conditions in 2020, 2040, and 2070, we analyzed daily future streamflow predictions from VIC (from 2010-2069) to identify long-term trends, anomalies and other patterns. This included time-series plots as well as calculating monthly, annual and decadal metrics.

In general, annual average streamflows do not show a noticeable trend into the future, though several rivers showed an increase in maximum annual (or peak) streamflow, and a decrease in summer baseflows. Strong consistent seasonal changes across all rivers were not identified, though individual rivers do show slight shifts in the timing of flows in the future. Future streamflow predictions exhibited high inter-annual variability, which may mask some longer-term trends. To account for this year-to-year variability, we averaged 10 years of daily streamflow projections centered around 2020 and 2040. Therefore, 2020 flow was represented by the average of daily streamflows from 2015-2024, and 2040 flow was represented by the average of daily flows from 2035-2044. Since streamflow projections end in 2069, we represented 2070 flow as the average of streamflows from 2065-2069.

Table 3. Cross-correlations between VIC rivers (plus Fraser River) and USGS or Canadian gaged river streamflows with final pairings identified by dark/green cells.

USGS or Canadian gaged rivers used to develop current flows	Rivers modeled in VIC (at mouth)													
	Dose-wallips	Ducka-bush	Hamma Hamma	Skokomish	Deschutes	Nisqually	Puyallup	Green	Cedar	Snoho-mish	Stillagua-mish	Skagit	Nooksack	Fraser[1]
U.S. Rivers														
Hoko	0.441	0.636	0.706	**0.817**	0.647	0.695	0.543	0.697	0.727	0.622	0.794	0.402	0.718	--
Elwha	0.840	**0.872**	0.760	0.693	0.553	0.680	0.819	0.760	0.794	0.851	0.731	0.808	0.830	--
Dungeness[2]	**0.815**	0.754	0.570	0.442	0.388	0.504	0.741	0.551	0.583	0.722	0.521	**0.824**	0.684	--
Nooksack	0.708	0.804	0.731	0.714	0.553	0.689	0.790	0.732	0.773	0.834	0.805	0.780	**0.893**	--
Samish	0.509	0.653	0.777	0.842	0.716	0.775	0.618	0.778	0.801	0.694	**0.877**	0.479	0.799	--
Skagit	0.788	0.800	0.647	0.549	0.451	0.585	0.791	0.644	0.697	0.821	0.663	**0.883**	0.836	--
Stillaguamish	0.616	0.790	0.802	0.828	0.653	0.744	0.691	0.831	0.863	0.814	**0.880**	0.599	0.852	--
Snohomish	0.770	0.878	0.783	0.724	0.606	0.720	0.833	0.827	0.870	**0.940**	0.853	0.806	0.893	--
Cedar[2]	0.662	0.759	0.855	0.874	0.803	0.911	0.834	**0.915**	**0.911**	0.817	0.857	0.586	0.786	--
Sammamish	0.663	0.746	0.901	0.928	0.890	**0.935**	0.794	0.880	0.870	0.737	0.854	0.492	0.706	--
Issaquah[2]	0.649	0.770	0.889	**0.932**	0.867	**0.911**	0.771	0.899	0.902	0.754	0.881	0.502	0.745	--
Mercer[2]	0.550	0.720	0.807	**0.896**	0.775	0.818	0.661	0.802	0.799	0.674	**0.833**	0.434	0.699	--
Green	0.694	0.802	0.872	0.866	0.796	0.887	0.844	**0.941**	0.937	0.855	0.875	0.593	0.793	--
Puyallup	0.830	0.858	0.812	0.740	0.690	0.842	**0.931**	0.852	0.857	0.862	0.772	0.767	0.801	--
Chambers	0.527	0.566	0.754	0.739	**0.807**	0.720	0.560	0.715	0.711	0.553	0.683	0.322	0.533	--
Nisqually	0.711	0.792	0.887	0.900	0.838	**0.948**	0.831	0.891	0.880	0.759	0.821	0.553	0.726	--
Deschutes[2]	0.654	0.750	0.898	0.931	**0.907**	**0.934**	0.754	0.873	0.848	0.698	0.842	0.451	0.689	--
Goldsborough	0.651	0.748	0.896	0.931	0.906	**0.934**	0.754	0.875	0.850	0.698	0.845	0.452	0.696	--
Huge	0.635	0.710	0.851	**0.880**	0.844	0.859	0.693	0.815	0.797	0.640	0.749	0.421	0.652	--
Big Beef	0.544	0.655	0.757	**0.819**	0.747	0.789	0.625	0.742	0.725	0.604	0.744	0.402	0.642	--
Skokomish	0.579	0.727	0.806	**0.872**	0.688	0.766	0.631	0.788	0.795	0.684	0.801	0.442	0.722	--
Duckabush	0.782	**0.846**	0.729	0.678	0.525	0.627	0.724	0.719	0.745	0.803	0.726	0.717	0.759	--
Big Quilcene	0.752	**0.803**	0.745	0.680	0.562	0.621	0.662	0.688	0.718	0.736	0.697	0.637	0.689	--
Juanita[2]	0.562	0.733	0.806	**0.879**	0.740	0.803	0.666	0.787	0.788	0.700	**0.836**	0.450	0.678	--
Canadian Rivers														
Squamish	0.067	-0.100	-0.378	-0.515	-0.482	-0.393	-0.066	-0.404	-0.384	-0.151	-0.427	0.233	-0.120	**0.853**
Clowhom	0.374	0.305	-0.023	-0.172	-0.210	-0.103	0.245	-0.052	-0.004	0.286	-0.005	0.552	0.279	**0.750**
Oyster	0.621	**0.720**	0.559	0.492	0.333	0.406	0.554	0.557	0.593	0.714	0.613	0.645	0.707	0.072
Tsolum	0.520	0.686	0.743	**0.803**	0.611	0.651	0.530	0.707	0.726	0.627	0.766	0.396	0.668	-0.474
Englishman	0.557	0.727	0.770	**0.830**	0.623	0.693	0.604	0.786	0.808	0.702	0.800	0.462	0.741	-0.448
Nanaimo	0.574	0.734	0.784	**0.844**	0.649	0.710	0.621	0.790	0.802	0.697	0.794	0.460	0.735	-0.437
Cowichan	0.566	0.716	0.836	**0.897**	0.706	0.782	0.647	0.819	0.832	0.709	0.841	0.462	0.757	-0.511
Harris	0.445	0.645	0.692	**0.790**	0.573	0.634	0.510	0.701	0.730	0.619	0.755	0.368	0.690	-0.496

1. The Fraser River is not included in the VIC model, but is included here to present correlations with the other Canadian gaged rivers
2. For these rivers, the best correlation to a river modeled by VIC is presented (shaded lightly/blue), but these rivers were regressed to another VIC river instead (shaded dark/green) based on the next-best correlation and geographic proximity.

The streamflow projections for the Fraser River (Morrison et al., 2002) were also available at a daily time step, but only as daily averages for 30-year periods centered around 2025 (average of 2010-2039), 2055 (average of 2040-2069) and 2085 (average of 2070-2099). To estimate Fraser River flow for the years 2020, 2040, and 2070, we performed a linear interpolation between the existing 30-year averaged time series to estimate streamflow for 2020, 2040, and 2070 (Figure 13). The trends indicate higher spring flows, lower maximum discharges, and lower summer baseflows.

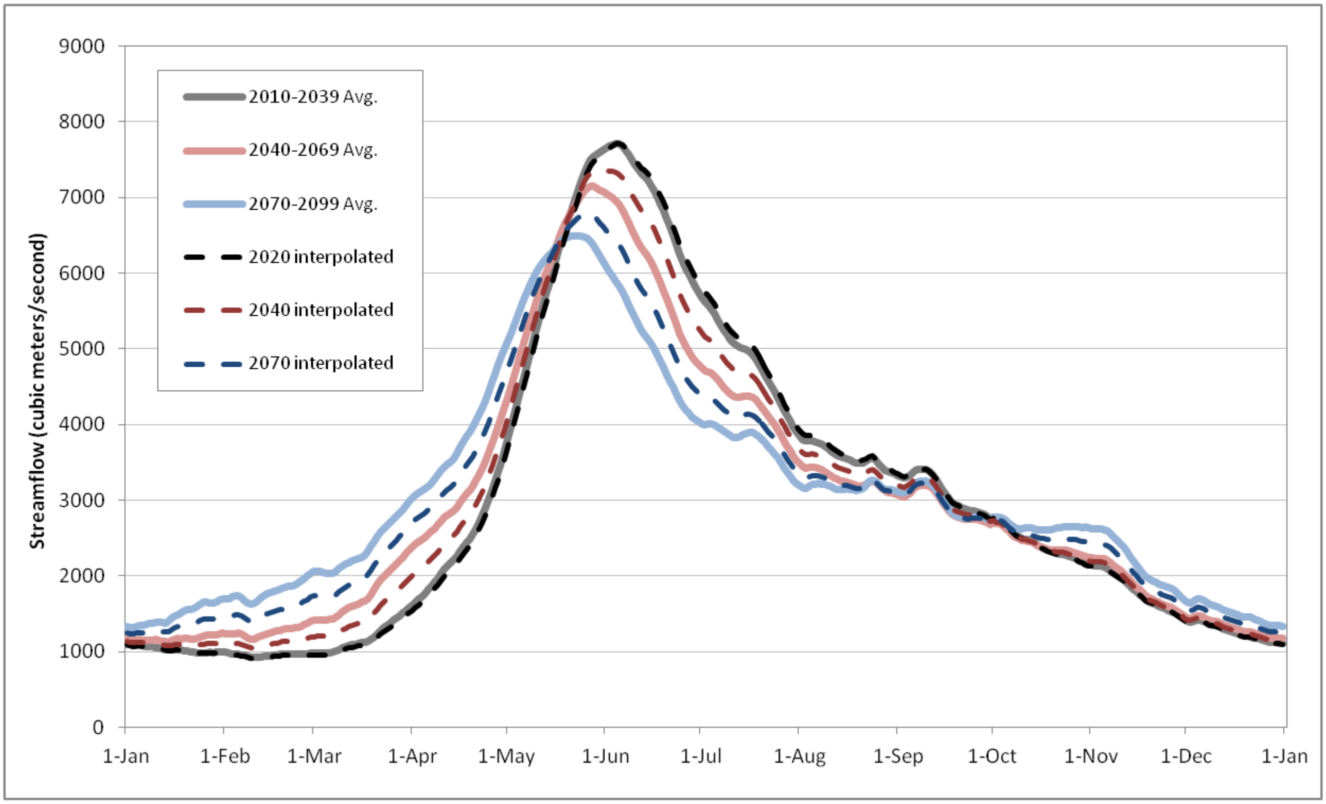


Figure 13. Future flow projections for the Fraser River (at Hope) from Morrison et al. (2002), with dashed line indicating interpolated flows for 2020, 2040, and 2070.

Future nutrient concentrations in watershed inflows

No studies have evaluated future nutrient concentrations for watersheds draining to the Salish Sea. This section provides the detailed methods for how we developed future nutrient concentrations based on land use patterns through 2070. In summary, we analyzed current river data and identified watershed characteristics that explained the greatest variability in annual average DIN concentrations in rivers. We then developed current and future land use metrics on which to scale current DIN concentrations to reflect future land use. As described below, we shifted 2006 monthly average concentrations by the difference in current and future annual average concentration to preserve seasonal patterns. Because the project focuses on U.S. nutrient sources, we kept Canadian inflow concentrations at current conditions for all future scenarios.

To estimate future nitrogen concentrations for the 57 U.S. watersheds, we evaluated relationships between current nitrogen concentrations and several watershed characteristics (Table 4). The goal was to determine which watershed characteristics best predict DIN concentrations under current conditions and then apply the relationships to future conditions. Characteristics that vary with time were limited to those for which future conditions have been or could be predicted using available information.

Table 4. Watershed characteristics evaluated as potential predictors of watershed inflow DIN concentrations.

Watershed Characteristic	Source of Information
Land Use (fraction developed, fraction forested, fraction agriculture, percent grassland, presence of wetlands, and presence of snow)	Oregon State University, Alternative Future Scenarios for Puget Sound, *Status Quo* scenario for 2006 (Bolte and Vaché, 2010).
Population and Population Density	Office of Financial Management, 2010 Census
Atmospheric DIN Concentrations	National Atmospheric Deposition Program, 2006 data from stations in the Olympics and Cascades.
Watershed Area	Digital elevation model
Surficial Geology (fraction bedrock, fraction fine grained, fraction coarse grained and fraction alluvial)	Figure 6 in Vaccaro et al. (1998) – received digital GIS file from Jim Tesoriero at the USGS in April 2012.
Average Watershed Slope	National Hydrography Database (NHDPlus) slope attribute from the flowline characteristics table.

Initial comparisons did not identify obvious relationships when all 57 watersheds were considered. High data variability may have masked relationships. We assessed 23 watersheds with site-specific data only, which did exhibit relationships with land use metrics. Mohamedali et al. (2011) describes the multiple linear regression approach used to develop daily concentrations from monthly ambient monitoring data based on patterns of flow and seasonality.

Statistically significant linear relationships were found between the three major land-use variables (fraction agriculture, fraction developed and fraction forested) and average annual DIN concentrations when the analysis was limited to the 23 watersheds with site-specific data (Figure 14). While other land uses such as grassland and wetlands are present in each watershed, we focused our analysis on the proportion of agricultural, developed, and forested land since these cover more than 80% of the total Puget Sound watershed. DIN concentrations increased with increasing fractions of agriculture or developed land. DIN concentrations decreased with increasing fractions of forested land. Outliers were flagged and removed from this analysis.

The final analysis relied on a subset of 20 watersheds. An outlier was defined as having a residual that was larger than would be expected at the 95% significance level. The three watersheds that were identified as outliers were: McAllister, Samish, and Sinclair Dyes. All three of these watersheds are somewhat anomalous relative to the other watersheds in the Puget Sound region. McAllister Creek is significantly influenced by groundwater nitrogen concentrations. The Samish watershed does not have its headwaters in the Cascades like many of the other Puget Sound rivers do. Sinclair Dyes is a watershed that contains a number of small hydrologically disconnected streams (rather than a single major river system) draining into a large water body. Therefore, 20 watersheds with site-specific multiple linear regression relationships were used to evaluate relationships between DIN concentration and watershed characteristics.

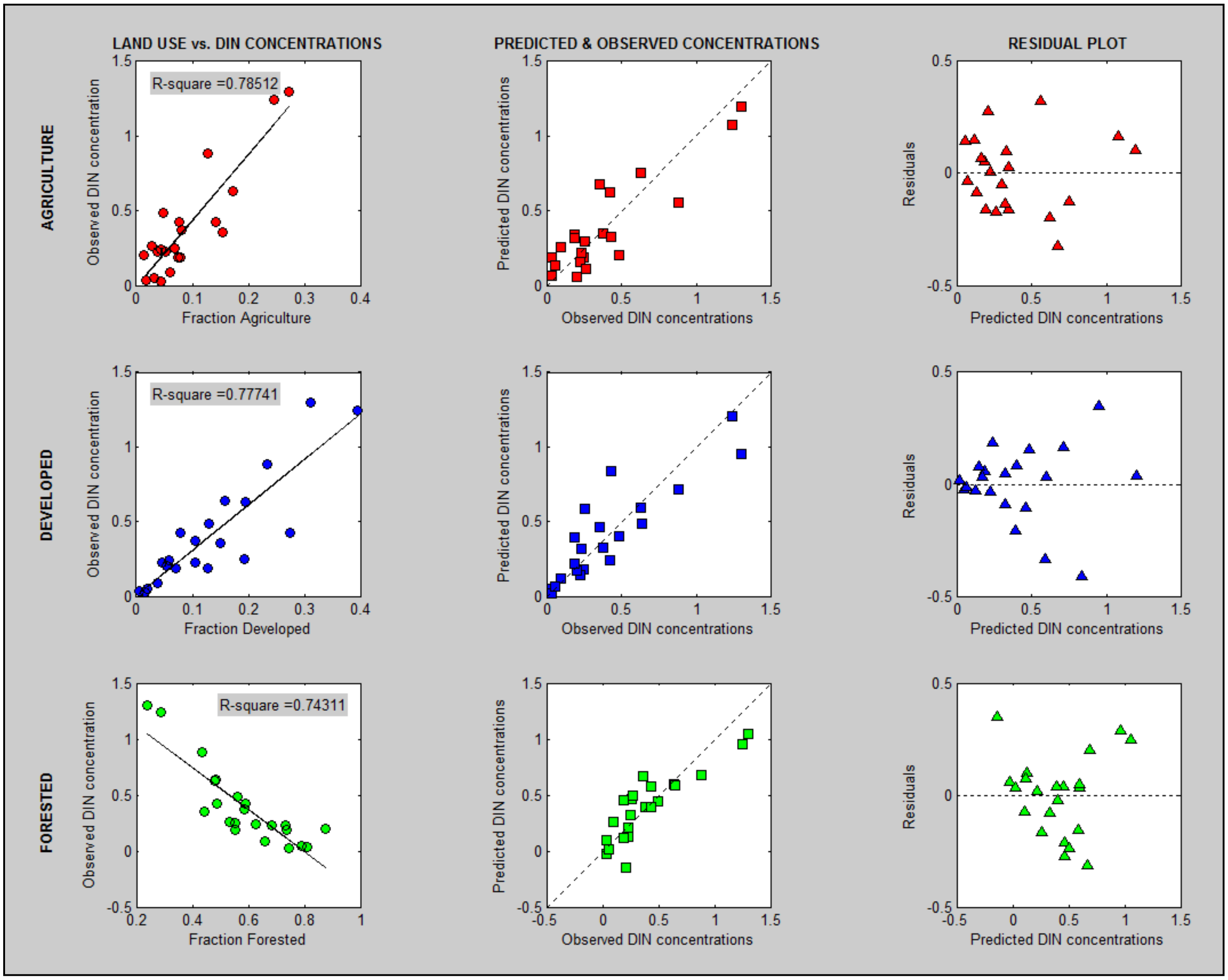


Figure 14. Linear regression between average annual watershed DIN concentrations and fraction agriculture, fraction developed and fraction forested (left), predicted and observed DIN concentrations, based on this linear regression (center), and residual plots of the linear regression (right).

Since these three land use attributes are good predictors of DIN concentrations but not independent of each other, we combined them into a single Land Use Index:

Land Use Index = (Fraction Forested) – (Fraction Agriculture + Fraction Developed)

The value of the Land Use Index (LUI) can range from -1.0 (entirely agriculture or developed) to 1.0 (entirely forested). A value of zero indicates forested and the combination of agriculture and developed land use equal areas.

The LUI accounted for 89.7% of the variability in the average annual DIN concentrations for the 20 watersheds (Figure 15). This relationship between current land use and current watershed DIN concentrations was used to estimate watershed DIN concentrations into the future.

No other study has evaluated future nutrient concentrations for the region and at the scale needed for this evaluation. However, Oregon State University's Alternative Futures Project (OSU, 2012) projects future land use through 2070. These predictions are available as GIS layers, which were analyzed and summarized for each of the 57 watersheds (http://envision.bioe.orst.edu/StudyAreas/PugetSound/index.html).

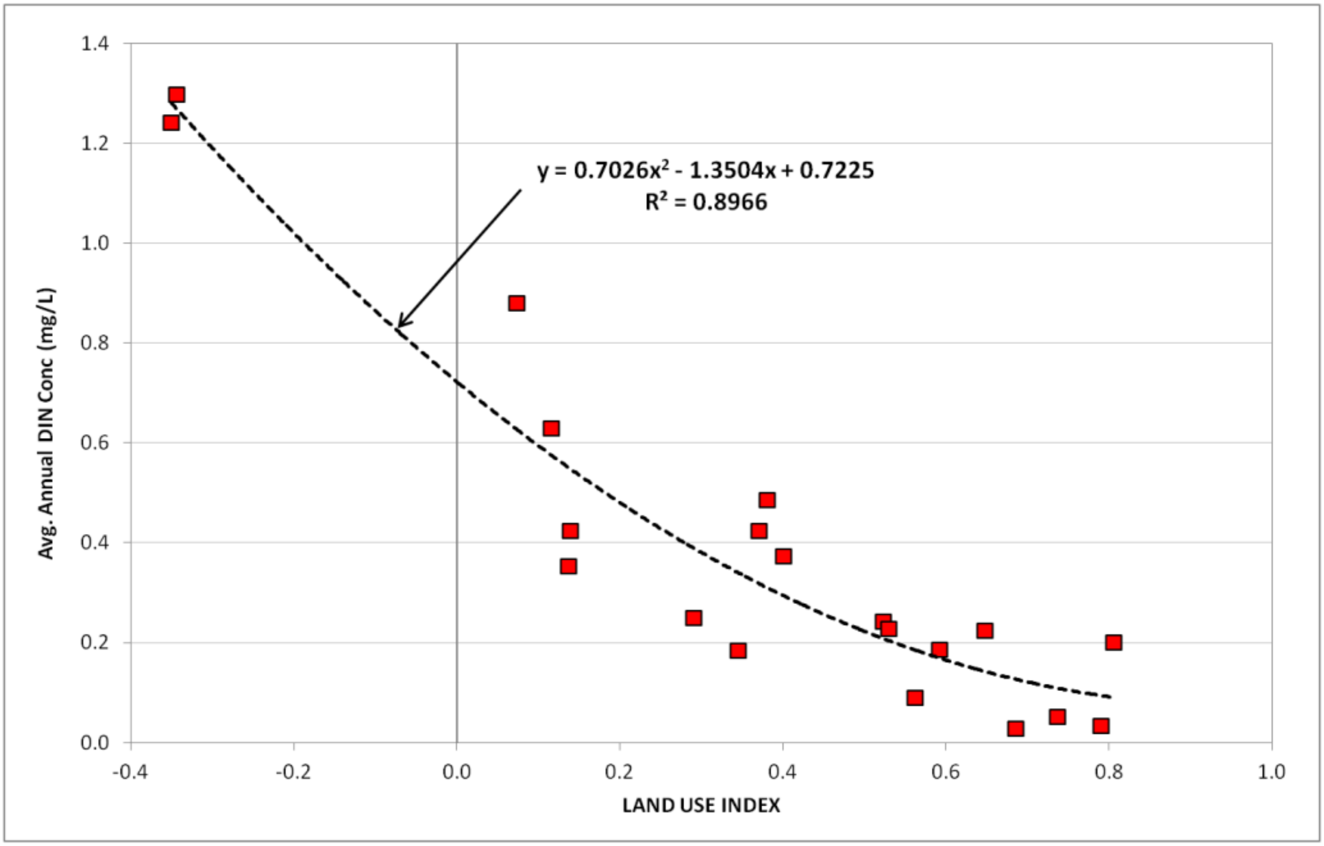


Figure 15. Plot of the Land Use Index and average annual DIN concentrations with a second-order polynomial fit.

The OSU alternative futures study evaluated three potential future land use scenarios:

1. **Status Quo**: a continuation of current land use trends in the region
2. **Managed Growth:** adoption of aggressive land use management policies focusing on protecting and restoring ecosystem function and concentrating growth within Urban Growth Areas and near regional growth centers
3. **Unconstrained Growth:** a relaxation of land use restrictions with limited protection of ecosystem functions.

All three scenarios assume the same population growth rates based on the Office of Financial Management's county-level growth estimates (http://www.ofm.wa.gov/pop/default.asp).

We selected the Status Quo scenario to represent future land use in the Puget Sound region. This scenario reflects current trends and assumes no major changes to management policies in the region. The status quo scenario generally predicts decreasing proportions of forest and agricultural land and increasing proportions of developed land for the Puget Sound region. However, patterns are not uniform. Some watersheds that currently have very low population densities are projected to experience only slight increases in developed land in the future. These include several watersheds on the Olympic Peninsula. Conversely, more populated watersheds such as those draining into South and Central Puget Sound show greater increases in developed land in the future. Appendix A provides maps of projected future land use in 2020, 2040, and 2070 as percent change from current.

We calculated the LUI for each watershed based on the fraction of agricultural, developed, and forested land for the years 2020, 2040, and 2070. Figure 16 presents the LUI values between 2006 and 2070. The LUI generally decreases over time, indicating a loss of forested land to either agriculture or developed land uses. However, the LUI and rate of change vary by watershed.

The relationship between LUI and DIN concentrations does not account for all variability in DIN. In order to preserve existing variability in DIN concentrations across watersheds due to factors other than land use, we corrected DIN estimates using a scaling factor. The factor maintains the residuals to facilitate comparisons of future conditions to 2006 conditions. The scaling factor was calculated as follows:

$$Scale\ Factor = \frac{2006\ average\ annual\ observed\ DIN\ concentration}{estimated\ DIN\ concentration\ \ based\ on\ 2006\ Land\ Use\ Index}$$

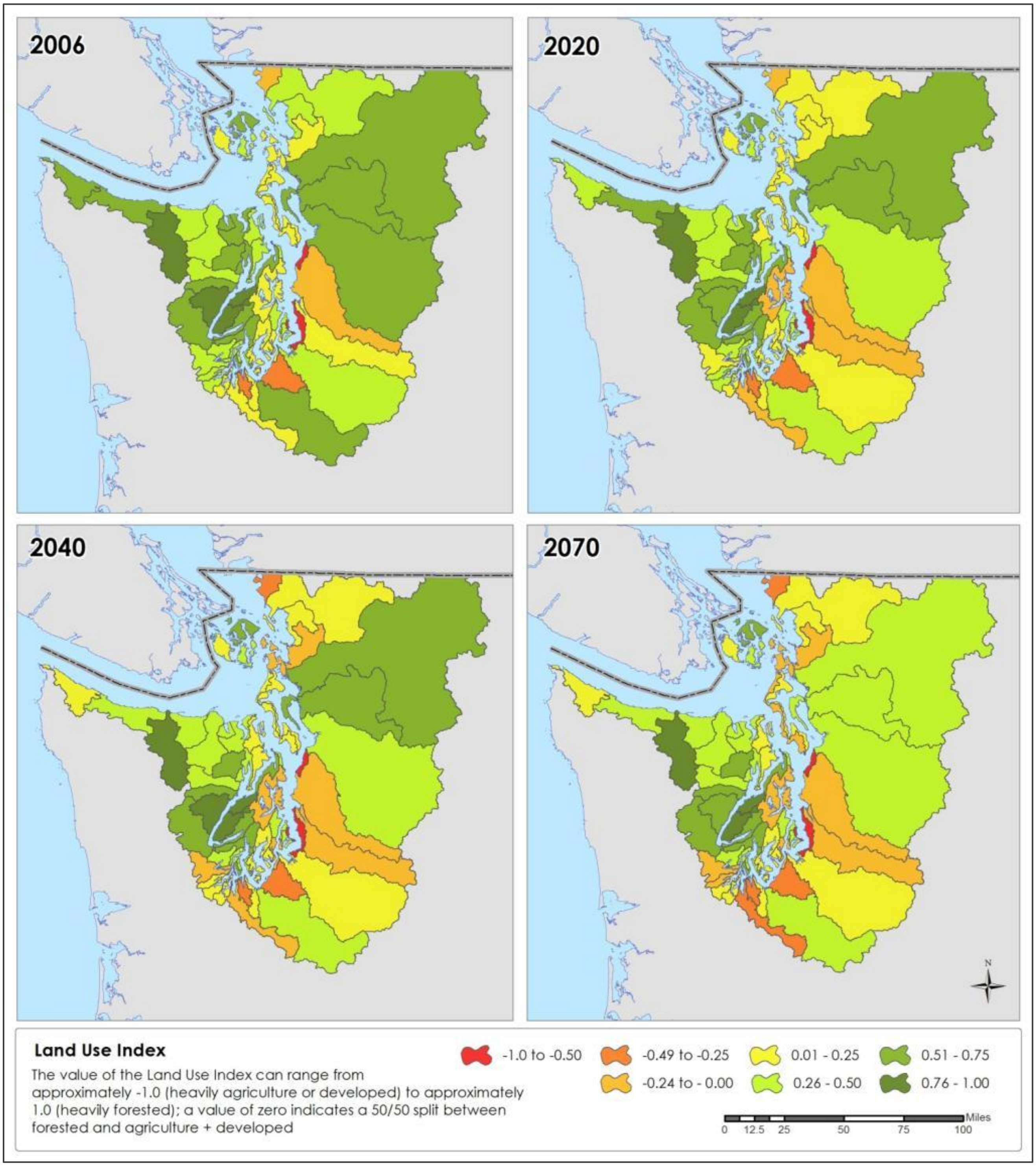


Figure 16. Land Use Index values for each watershed for the years 2006, 2020, 2040, and 2070 based on percent agriculture, developed, and forested.

The final set of future annual average DIN concentrations are presented in Figure 17 in comparison to current 2006 concentrations.

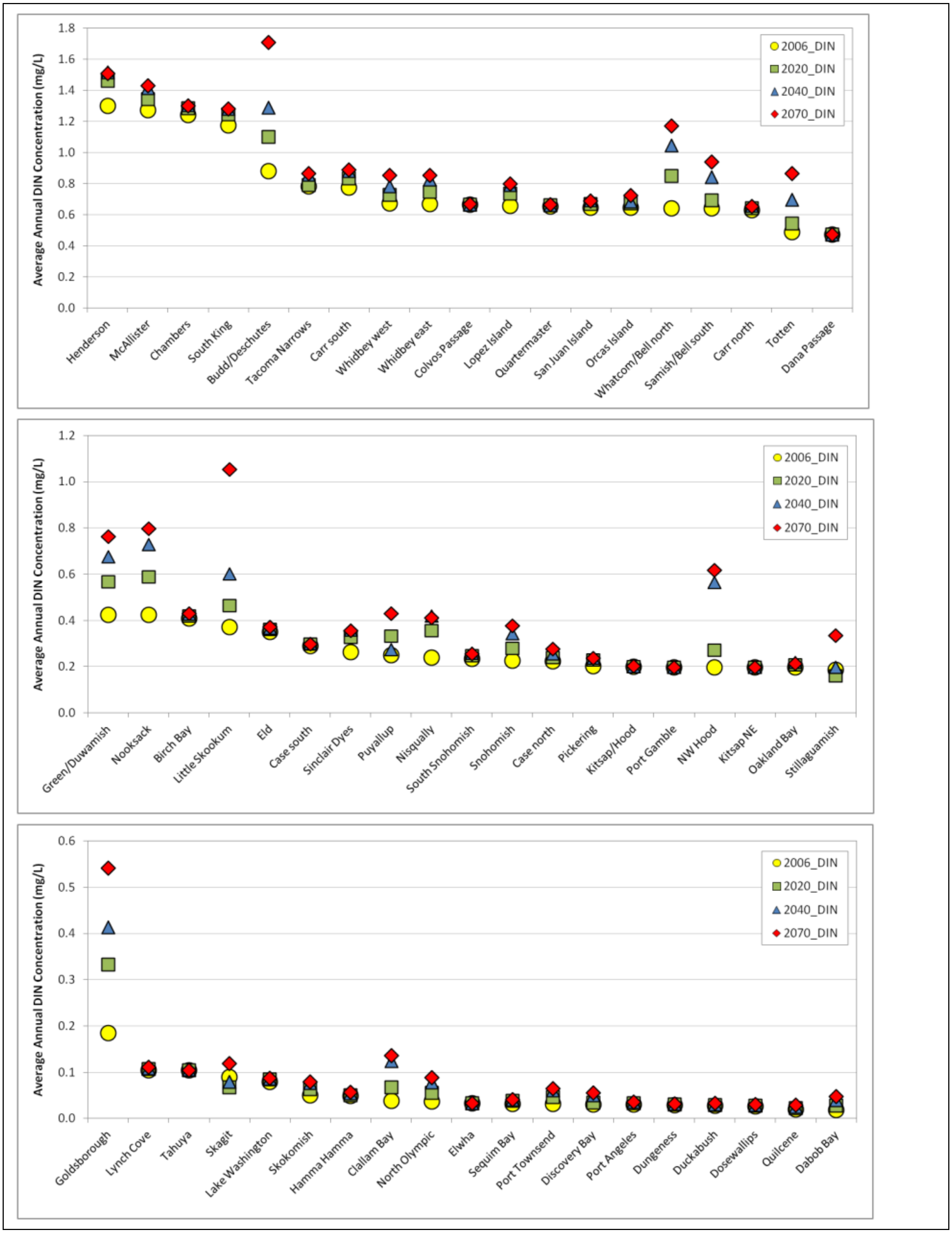


Figure 17. Current (2006) and future (2020, 2040, and 2070) annual average DIN concentration estimates for the 57 U.S. watersheds. *Note: the y axis differs for the three plots.*

DIN concentrations increase relative to current levels for all watershed inflows. The greatest increases occur in those watersheds projected to undergo the greatest decreases in forested land and conversion to developed land. DIN concentrations are estimated to remain at current levels, or increase only slightly, for several watersheds located in the Olympic Peninsula and San Juan Islands. These watersheds are currently less populated than other regions and are not expected to experience as much change in land use into the future.

The regression relationship applies to annual average DIN concentrations. However, the model requires daily time series or at least a monthly average value applied to each day of the month to capture seasonal patterns in inflows to Puget Sound and the Straits. We evaluated two ways to transform future annual average concentrations to monthly concentrations:

1. **Ratio method:** Calculate the current ratio of monthly to annual average DIN concentrations, and keeping these proportions constant into the future.
2. **Vertical shift method:** Apply a vertical shift to 2006 monthly concentrations values by adding the estimated future change in annual average DIN to current monthly concentrations.

Figure 18 illustrates the results of both these methods for three rivers in Puget Sound, comparing current (2006) monthly concentrations to projected 2070 concentrations. These rivers were selected for illustration purposes. Other rivers have bigger or smaller changes in nutrient concentrations or different seasonal patterns. The ratio method exaggerates the seasonal patterns in concentrations.

We selected the vertical shift method, which simply shifts current monthly concentration values by the increase from current to future annual concentrations. This preserves the existing seasonal pattern in monthly concentrations and makes fewer assumptions of how seasonality in concentrations will be affected by future conditions. We do not know if seasonal patterns in DIN concentrations will change in the future as a result of different factors, in which direction, and to what extent. This increase in annual average concentration was applied to all watersheds to develop monthly average DIN concentrations for 2020, 2040, and 2070. The monthly concentrations are used to represent daily concentrations for all days in that particular month.

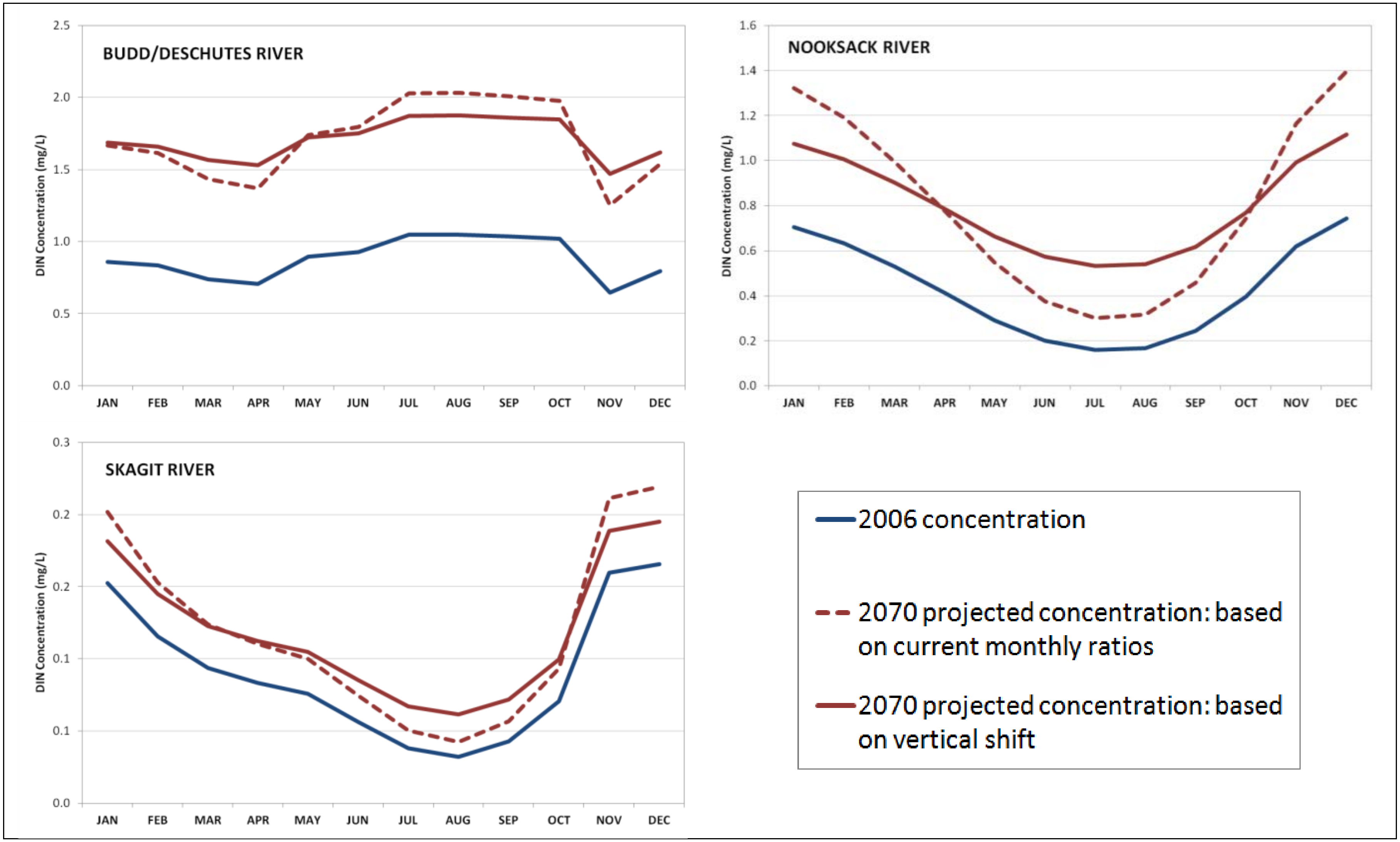


Figure 18. Comparison of two methods to transform projected annual concentration values in 2070 to monthly values: (1) use current ratios of monthly to annual concentrations (dashed red line), or (2) apply a vertical shift to monthly concentrations based on the difference between current annual and projected annual concentrations (solid red line).

Other inflow parameters

Though the focus of this report and future estimates is on DIN, the model does require inflow concentrations for nitrate plus nitrite, ammonia, and organic nitrogen (particulate and dissolved). The current ratios of nitrate plus nitrite and ammonia to DIN in each watershed were applied to future DIN to estimate these nitrogen species concentrations. Future particulate and dissolved organic nitrogen (PON and DON) concentrations were maintained at current levels. These concentrations are relatively low, are generally within the noise of lab analytical noise (Mohamedali et al., 2011).

Since nitrogen is the limiting nutrient and also the parameter of greatest concern, we maintained current concentrations of phosphorus and carbon in rivers into the future. We also did not change current values for temperature, salinity, DO, or other parameters for future scenarios.

Methodology assumptions and limitations

The methodology used to estimate river flows and concentrations into the future required a number of assumptions and limitations:

Assumptions

- Current seasonal patterns in nitrogen concentrations remain the same in the future.
- Future changes in watershed inflow nitrogen concentrations will stem from only changes in land use.
- The relative influence of any WWTP that discharges into freshwater rather than into Puget Sound is adequately described by future land use. This assumption is reasonable because the current land use metrics and DIN concentrations include these in the watershed inflows. In addition, there are few large WWTPs that discharge to rivers and instream processes may assimilate these nutrients before they enter marine water.

Limitations

- In using the output of the VIC model to estimate future river flows, we introduce the scientific and modeling uncertainties involved in future climate change and hydrology modeling to our project. We did not evaluate all the assumptions made in the development of the VIC model and the downscaling of global climate change models to simulate streamflows.
- Our method for estimating future river concentrations only considers changes in DIN concentrations as a result of changes in the fraction of agriculture, developed, and forested land. Many other factors might affect future DIN concentrations that we may not have accounted for through this simpler statistical approach.

Despite these assumptions and limitations, this assessment provides reasonable estimates of future flows, concentrations, and loads from watershed inflows.

Marine point sources

No estimates exist for future municipal WWTP or industrial plant flows and loads into the future. Individual plants may project future conditions as part of facilities planning and management. However, the planning horizons and methodologies may not be consistent. Therefore, we estimated future flows and loads for marine point sources. Many known and unknown factors will likely influence future WWTP and industrial nutrient loads. This section is focused primarily on future WWTPs, but industrial loads are discussed as well.

Since loads are a product of flow and concentration, we considered factors that affect both WWTP flows and WWTP effluent concentrations. The magnitude of WWTP flows is primarily determined by the service area including inflow and infiltration, the number of people served by each WWTP, per capita wastewater flow contributions, and any applicable permit limits that restrict how much effluent can be discharged into Puget Sound. Future population projections are therefore an important factor when predicting future WWTP flows. Future WWTP effluent concentrations will reflect the wastewater treatment processes employed by WWTPs. These could include today's standard of secondary treatment or could shift to increased use of biological nutrient removal, which has decreased effluent nutrient concentrations relative to conventional treatment, either due to plant upgrades or changes in permit requirements.

A number of other factors, other than population and treatment technology, will affect future WWTP nutrient loads. These include, but are not limited to: water and wastewater pricing, shifts to more de-centralized wastewater treatment, diversion of treated wastewater effluent to reclaimed water uses, water conservation, changes in how WWTPs operate (either mandatory or voluntary), future changes in urban growth areas (UGAs), transitioning from on-site sewage systems (OSSs) to municipal wastewater services, and innovative technologies that we may not even have considered yet. We cannot predict which of these factors will affect WWTP loads or how in the future. These confounding factors increase uncertainty.

To account for the uncertainty involved in estimating WWTP loads as far into the future as 2070, we adopt a range of future WWTP loads rather than a single value. This range is based on different assumptions of population growth and changes in future treatment technology, as described in more detail in the following sections. However, due to limited resources, only a selected subset of the full range of future WWTP scenarios presented in this section was evaluated using the model. This section focuses on predicting DIN loads for marine point sources. Other parameters are described in a subsequent section. We used current and projected population, per capita wastewater contributions, potential changes in treatment technology, and WWTP capacity to estimate future WWTP flows and concentrations, as described in more detail below.

We could not evaluate all alternative marine point source loading scenarios described in the following sections. We document these various load estimates should additional scenarios be developed during subsequent project phases. In addition, we present the loading implications in the next section. Given the numerous factors that govern future wastewater, we developed multiple estimates to bracket the options and then selected the most likely scenario to evaluate using the water quality model. We evaluated the DO impacts associated with marine point source loads projected for 2020, 2040, and 2070 using plant-specific sewered populations where available or medium estimates of future population where not. We assumed current treatment technology.

Future U.S. municipal WWTP loads

Figure 19 illustrates the method for estimating future U.S. marine point source loads to the Salish Sea. We estimated future WWTP loads by multiplying future WWTP concentrations by future WWTP flows. We developed three WWTP flow scenarios based on High, Medium, and Low population scenarios and two WWTP concentration scenarios that assume no change from current technology or that plants upgrade to higher nutrient removal (Table 5). Only the Medium population scenario with no change from current treatment technology was evaluated using the water quality model.

Table 5. Description of future marine point source loading scenarios.
Bolded *text indicates scenarios evaluated with the model.*
OFM = Office of Financial Management.

SCENARIO	Population Scenarios	Per Capita Water Use	Treatment Technology Scenarios
2020	1. Low OFM forecasted population **2. Medium OFM forecasted population** 3. High OFM forecasted population	**Current per capita water use**	**No change from current technology**
2040			**1. No change from current technology** 2. Upgrade to higher nutrient removal
2070	1. Linear extension of Low OFM forecasted population **2. Linear extension of Medium OFM forecasted population** 3. Linear extension of High OFM forecasted population		

Future U.S. municipal marine point source flows

Appendix B details the development of future municipal marine point source flow based on population served and per capita contributions.

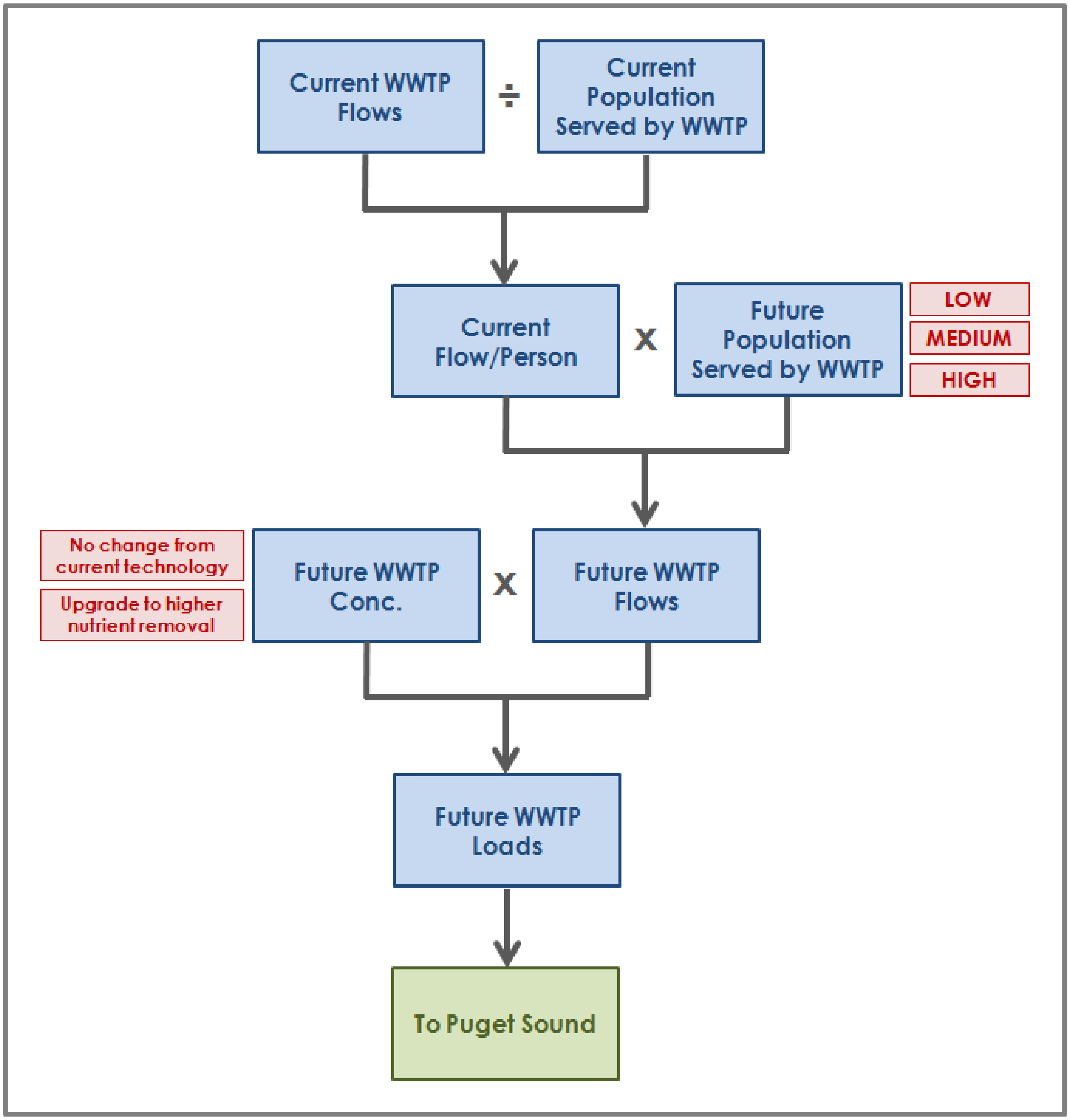


Figure 19. Decision tree for estimating future municipal marine point source loads to marine waters of Puget Sound and the larger Salish Sea.

Future U.S. municipal WWTP concentrations

In addition to predicting future WWTP flows, we also predicted future WWTP nitrogen concentrations. We focused on dissolved inorganic nitrogen (DIN, the sum of ammonium, nitrate and nitrite) for the years 2020, 2040, and 2070.

Currently, median DIN effluent concentrations from the WWTPs in Puget Sound varies from 2.6 – 39 mg/L with an overall median of 8.2 mg/L, and an average of 15 mg/L (Mohamedali et al., 2011)[3]. The median effluent DIN concentration for the largest plants (greater than 10 mgd) is 24 mg/L. The LOTT facility in Olympia has the lowest effluent DIN concentrations (2.6 mg/L) because of more stringent permit requirements which include a seasonal limit on nitrogen loads discharged into Budd Inlet in South Puget Sound.

Biological nutrient removal (BNR) is the general name for treatment methods that remove nutrients (nitrogen, phosphorus or both) from wastewater. Most plants discharging to Puget Sound provide secondary treatment. BNR treatment typically results in effluent nitrogen concentrations in the range of 5 to 8 mg/L for the most common nitrogen removal processes, though lower concentrations are also possible (EPA, 2010).

BNR technologies include membrane bioreactor (MBR) as well as several other treatment technologies/configurations. Though MBR involves nitrification (conversion of ammonia to nitrate), it does not always involve denitrification (removal of nitrate). Nitrogen removal will only take place if denitrification also takes place, which requires the presence of an anoxic zone. Several new WWTPs in the Puget Sound region today are designed to move toward future MBR treatment. These include the Brightwater facility in King County as well as Blaine, Port Orchard, and Alderwood, which are either new or have been recently upgraded. It is likely that in the future, WWTPs may upgrade to some form of BNR treatment with better removal of nitrogen and other pollutants, either voluntarily or if water quality impairments mandate the use of BNR processes.

The assumption of future plants using BNR is intended to bracket the low end of future WWTP loads against the high estimate of continuing with existing technology, and this assumption does not represent a decision by the Department of Ecology to institute BNR.

To project future U.S. WWTP concentrations, we assumed that current treatment technologies would remain in place at least until 2020 since such changes would likely require more than eight years to implement. To accommodate the range of nitrogen concentrations if no treatment technology changes occur or if plants upgrade to BNR treatment after 2020, we developed two concentration scenarios for 2040 and 2070:

1. Status Quo: WWTPs do not upgrade to new treatment technologies. Maintain current median concentrations at current plant-specific concentrations through 2070.

---

[3] The median and average values do not include Carlyon Beach WWTP, which has a median DIN concentration of 53 mg/L. This is much higher than the typical small WWTPs since it receives sewage tank pump outs and does not receive inflow and infiltration like most municipal treatment systems with transmission systems.

2. Advanced Treatment: All WWTPs upgrade to some form of BNR treatment by 2040. Effluent median DIN concentrations will decrease to a constant 8 mg/L or will remain at current concentrations if current plant-specific concentrations are below 8 mg/L.

Though the focus of this report and future estimates is on DIN, the water quality model requires WWTP effluent concentrations for different inorganic (ammonia, nitrite, and nitrate) and organic (particulate and dissolved) nitrogen components. Estimates of future inorganic nitrogen were based on current ratios of ammonia, nitrite and nitrate to DIN in WWTP effluent. However, estimates of future particulate and dissolved organic nitrogen (PON and DON) were maintained at current levels. These concentrations are very low and generally within lab analytical noise.

Since nitrogen is the limiting nutrient and also the parameter of greatest concern, we maintained current plant-specific concentrations of phosphorus and carbon as constant into the future. We also assumed no change in future DO, temperature, or salinity and kept these at current levels through 2070.

Future U.S. industrial wastewater flows, concentrations, and loads

Seven industrial facilities discharge into Puget Sound and the Straits. These include five oil refineries, four pulp/paper mills and one aluminum facility. Effluent discharge from these facilities likely would not scale with future population. No information exists on potential future industrial discharges, and one facility has closed entirely since 2008. Future industrial discharges will depend on economic conditions.

Current industrial WWTP DIN loads are small compared with municipal WWTP loads. In addition, current concentrations of DIN in the effluent of these industrial facilities range from 0.1 – 4.7 mg/L, which is much lower than concentrations in WWTPs effluent. Therefore, we maintained current industrial WWTP loads through 2070 and did not project any changes. Since one facility has ceased operations, this could overestimate future industrial discharges to Puget Sound.

Future Canadian WWTP flows, concentrations, and loads

Nine WWTPs in Canada discharge into the Straits. Future flows were also estimated using similar methods as for U.S. WWTP discharges. We estimated future populations based on population projections for the provincial government of British Columbia (BC Stats, 2011). These projections are available through 2036 at the Regional District level, analogous to counties in Washington. We extended the projections through 2070 assuming a linear trend. We calculated current per capita flows for each WWTP. We then calculated population growth rates for each district and applied these growth rates to the WWTPs within each district.

Since Washington State does not have any jurisdiction over Canadian discharges, we did not make any assumptions about how treatment technologies might change in the future at these facilities. Instead, we set effluent nutrient concentrations at current levels through 2070. Future Canadian loading estimates are therefore based simply on population projections, which were used to scale WWTP flows.

Summary of wastewater load projection methodology assumptions and limitations

The methodology used to project wastewater flows and loads into the future required a series of assumptions:

- Per capita effluent flows for each WWTP do not change from current levels (i.e., current water conservation practices).
- For those WWTPs without plant-specific future population projections:
  - County population growth rates are a reasonable approximation of the growth rate for population served by individual WWTPs located in a particular county.
  - The industrial and commercial water uses served by centralized WWTPs will grow at the same rate as the residential population for those plants.
- Current monthly patterns in WWTP flows and concentrations remain the same. The ratio of monthly flow/concentration to the average annual flow/concentration does not change.
- Changes in the ratio of ammonia:DIN and nitrite + nitrate:DIN through implementation of BNR are negligible.
- No new plants will discharge to the marine waters of Puget Sound or the Straits.
- If future WWTP flows exceed current WWTP capacities, these excess flows will continue to be treated by WWTPs and discharged into Puget Sound. This also assumes that existing plant capacities and NPDES permit limitations will expand to accommodate greater flows in the future.
- Service area expansions are accounted for in the population growth within the service area.

These assumptions simplify a number of potentially confounding factors, such as:

- Regionalization of municipal WWTP facilities. Two currently distinct WWTP service areas could merge together to be served by a single plant in their future. However, the single plant would still discharge flows that are of similar magnitude to the sum of the two original plants.
- Annexations by cities which could increase one WWTP’s service population while decreasing another’s.
- Assuming that excess flows continue to be discharged into Puget Sound avoids making assumptions of how individual WWTPs may respond as they approach existing capacities and permit limitations. The approach does not assume which plants will or will not be granted NPDES permits in the future to accommodate expected growth. This assumption produces a worst-case scenario that presumes no change in policy. WWTPs may adopt other ways to manage excess flows other than discharging into Puget Sound, such as diverting to reclaimed water or implementing more stringent water conservation measures.

Despite these assumptions and limitations, the methods produced reasonable estimates of future flows and loads from the wastewater treatment plants.

Ocean conditions

For the calibrated model, the Strait of Juan de Fuca boundary condition were developed based on monitoring conducted near the entrance and interior to the Strait by Canadian and U.S. programs. No studies have forecast future DO or nutrient profiles near the Strait at the time and space scales required for the model. We consulted global ocean model simulations and projected future Strait of Juan de Fuca boundary conditions based on two programs that have monitored conditions in the North Pacific Ocean for over 50 years.

Canada's Department of Fisheries and Oceans currently oversees monitoring programs along Line P. Line P refers to the transect between British Columbia and Ocean Station Papa located in the North Pacific Ocean. Surveys occur several times per year and include profiles of temperature, salinity, DO, and nutrients in the upper 1000 meters, as summarized in Whitney et al. (2007). Ocean Station Papa and Line P oceanographic observations constitute one of the longest-running ocean time series in the world, with continuous observations since 1956 (Pena and Bograd, 2007).

Oregon State University has monitored conditions along the Newport Hydrographic Line, which extends 160 km offshore from central Oregon (Pierce et al., 2012). Parameters include oxygen, salinity, and temperature. Frequent observations are available for the periods 1961-71 and 1997-2003 from depths of 58 m to 2880 m. Less frequent measurements are available from other time periods.

North Pacific Ocean water quality varies considerably by location and over time. Both subarctic and subtropical conditions influence the region that affects water quality in the Strait of Juan de Fuca.
Researchers identified both trends and cycles that varied with climate indicators.

Observations indicate that water temperatures increased 0.9 °C between 1958 and 2005 at multiple depths (Whitney et al., 2007). Temperatures vary considerably among year. Short-term phenomenon such as mesoscale eddies can produce rapid warming, but temperatures resume more typical interannual variability after they pass. Wind patterns in the North Pacific and Gulf of Alaska associated with the Pacific Decadal Oscillation can influence temperature (Crawford et al., 2007).

Whitney et al. (2007) also found that surface salinity had freshened, with salinity decreasing by 0.36 psu per century at Ocean Station Papa. Intensifying Aleutian low pressure systems that also reduce ocean ventilation were identified as a contributor. Crawford et al. (2007) evaluated salinity and did not find a significant trend over time. The contradictory findings could result from evaluating different depths, regions, or time periods.

Stratification due to the combined effect of salinity and temperature appears to be increasing, which decreases vertical mixing. If current trends continue, temperature could increase by 0.64 °C and salinity could decrease by 0.23 psu by 2070 (Whitney et al., 2007). Changes in density profiles at the Strait of Juan de Fuca would affect circulation within the model domain and potentially complicate comparisons among scenarios. We focused future boundary conditions on the DO and nitrogen trends and did not change the salinity or temperature profiles at the ocean boundary.

Whitney et al. (2007) identified declining oxygen levels in surface and deeper waters of the Pacific Ocean over the 50-year period at Station Papa. The ocean lost oxygen at a rate of 0.013 to 0.023 mg-O_2/L per year (equivalent to 0.39 to 0.70 umol/kg per year) for depths between 100 and 400 m. Water from this region, below the mixed layer, would represent water that flows into the Strait of Juan de Fuca. More rapid declines within a 10-year period coincide with shifts in circulation and stratification (Deutsch et al., 2006). Oxygen declined at a faster rate of 0.040 mg-O_2/L per year (equivalent to 1.2 umol/kg per year) near the mouth of the Strait of Juan de Fuca between 1987 and 2006. The oxygen levels observed at Station Papa exhibit cyclic phenomena that affect ocean circulation in addition to the trends, and high interannual variability occurs. Researchers do not know if the trends will continue, accelerate based on the shorter-term trends for the station nearest the mouth of the Strait of Juan de Fuca, or if oxygen will rebound in the future due to some unidentified cyclic process.

Pierce et al. (2012) found that oxygen decreased over the entire NH Line between 1960 and 2009. Specific rates varied from 0.007 to 0.030 mg/L per year (equivalent to 0.2 to 0.9 umol/kg per year) at different depths and stations. The study identifies 0.023 ± 0.007 mg/L (equivalent to 0.7 ± 0.2 umol/kg per year) as the trend for depths of 150 to 200 m. Results are consistent with Whitney et al. (2007). Both the NH Line and Station Papa are strongly influenced by subpolar conditions, but subtropical water also affects the NH Line.

We combined the results from Whitney et al. (2007) and Pierce et al. (2012) to develop future boundary conditions because both water masses assessed may influence Strait of Juan de Fuca water. Pierce et al. (2012) calculated annual rates of oxygen decline at multiple density layers for 1960 to 2009 at the NH line, while Whitney et al. (2007) calculated similar rates of decline at Ocean Station Papa between 1965 and 2006. Since multiple rates of decline were reported at different density layers, we used best professional judgment to select a rate of oxygen decline of -0.023 mg/L/yr. This value represents the high end of the 50-year trend at Ocean Station Papa but is lower than the more recent trend of 0.040 mg-O_2/L per year for the region near the mouth of Juan de Fuca. The value is identical to that reported in Pierce et al. (2012) for the subsurface region likely to affect the Strait of Juan de Fuca and is based on the Oregon transect.

We also increased nitrate at the boundary to reflect declining DO, since nitrate concentrations generally vary inversely with oxygen concentrations (Whitney et al., 2007). We plotted all available nitrate and DO concentration data from the World Ocean Database (www.nodc.noaa.gov) for the region bounded by latitude 124 to 127 °W and longitude 47 to 49 °N (Figure 20). We found a strong inverse linear relationship. Water with high DO and low nitrate likely represents surface waters influenced by primary productivity. Dissolved oxygen data >7.5 mg/L were excluded from the analysis. We calculated an expected increase in nitrate concentrations of 0.00133 mg/L per year based on a decrease of 0.7 umol/kg per year and -0.057845 mg/L of nitrate per mg/L of DO, a density of 1026.5 kg/m^3, and conversion factors of 1.42903 mg-DO/mL-DO and 44,660 umol-DO/L (Seabird, 2013).

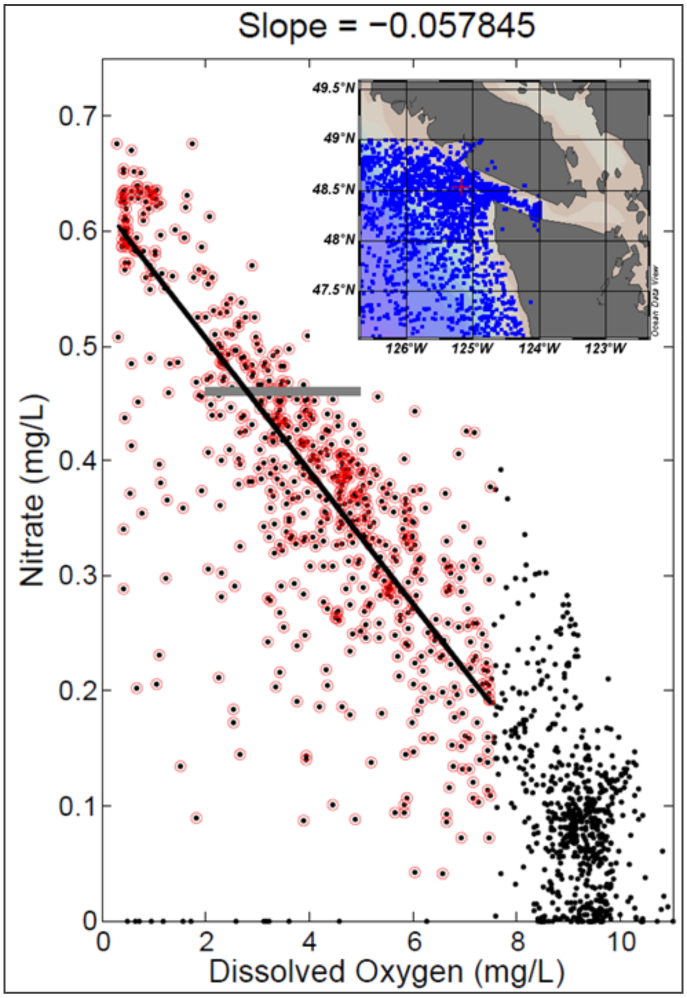


Figure 20. Relationship between nitrate and dissolved oxygen in the Pacific Ocean off the coast of Washington State.

Red circles identify data used to develop the relationship, while black dots with no circles were excluded from the analysis.

Source: World Ocean Database (www.nodc.noaa.gov)

Table 6 lists best available information for future DO and nitrate. We linearly extrapolated future oxygen and nitrate using the rates and applied the net changes throughout the water column. We did not modify Pacific Ocean temperature or salinity for future scenarios so that future scenarios focus on the effects of future DO and nitrate at the Pacific Ocean boundary on Salish Sea DO.

We did not change ocean conditions at the Strait of Georgia boundary because the water volume exchange is very small compared with that through the Strait of Juan de Fuca and likely has little to no influence on Puget Sound. The 2006 ocean boundary conditions at the north end of the Strait of Georgia were used for all future scenarios.

Table 6. Future projections of dissolved oxygen and nitrate (mg/L) in the Pacific Ocean.

Parameter	2020	2040	2070	Source
Dissolved Oxygen (-0.023 mg/L/yr)	-0.32	-0.78	-1.47	Pierce et al. (2012) and Whitney et al. (2007)
Nitrate (0.00133 mg/L/yr)	0.02	0.05	0.09	Analysis of World Ocean Database information

Meteorology

We explored using downscaled WRF model predictions for future meteorology boundary conditions. As described in Khangaonkar et al. (2012), we had originally used NOAA North American Regional Reanalysis (NARR) data to develop the wind and heat flux boundary conditions. We corrected bias by applying scaling adjustments to heat flux terms from the NARR products. However, NARR does not predict future conditions. Also NARR data were available over only a coarse 30 km x 30 km grid. Subsequently the model was upgraded to 12 km x 12 km gridded data from the Weather Research and Forecast (WRF) model.

The University of Washington Climate Impacts Group (UW-CIG) provided WRF output for the Puget Sound region for existing conditions. The WRF model with higher resolution and near water stations required a much smaller adjustment for albedo as part of calibration. The temperature calibration results improved significantly with WRF-based inputs and were retained for all subsequent runs. However we noted that because these climate models do not include coupled atmosphere-ocean interaction, they may not fully describe the dynamics of over-water regions and will require some adjustment of net heat flux terms as part of calibration. The WRF model inputs also required bias correction to provide the best match with observed sea surface temperatures as part of model calibration.

UW CIG provided two sets of WRF products. The existing conditions meteorological data for Year 2006 were from WRF reanalysis model runs (WRF high-resolution simulations forced by the large-scale National Center for Atmospheric Research [NCAR] reanalysis). The WRF model future meteorological predictions, by comparison, were based on inputs from global climate model simulations from 1950 to 2099. These data are based on model simulations using a different climate model and different initial and model forcing conditions than the reanalysis-forced WRF model results for 2006 used in calibration. These two model simulations for 2006 were not normalized with one another, so a relative comparison of future meteorological conditions and base year (2006) meteorological conditions could not be conducted.

To avoid problems with shifting meteorological baselines, 2006 meteorological conditions used in model calibration were also used for most future condition runs. One future run assessed higher air temperature associated with climate change but did not change other meteorological values. Remaining future runs only represent the climate forcing via altered freshwater hydrology, but not from other potentially important forcing variables such as wind or solar radiation. We hypothesize that the most important effects of meteorological change in the future are already captured by altered hydrological inputs and by air temperature increases.

Initial conditions

The initial conditions for all future scenarios were the same as for current scenarios, described earlier.

Sediment fluxes

Sediment fluxes were scaled for future scenarios using ratios of external loads, as described for the current scenarios. The method did not account for changes at the ocean boundary. Future external loads include the sum of marine point sources, natural and human watershed inflows, and atmospheric deposition to the marine water surface. These resulted in slightly higher scalars applied to oxygen, nitrate, and ammonium of 1.02, 1.04, and 1.08 for 2020, 2040, and 2070, respectively.

Summary of future scenarios

Table 7 summarizes the future scenarios evaluated with the Salish Sea model.

Table 7. List and brief descriptions of the full set of future scenarios that were developed; all concentrations refer to DIN concentrations.

Scenario Name	Scenario Description	U.S. Watershed Inflows		Canadian Watershed Inflows		Marine Point Sources						Ocean Conditions[11]	Meteorology[12]	Circulation
						U.S. Municipal		U.S. Industrial		Canadian Municipal				
		Conc.[1]	Streamflow[2]	Conc.[3]	Streamflows[4]	Conc.[5]	Flows[6]	Conc.[7]	Flows[8]	Conc.[9]	Flows[10]			
2020s Human	2020 predictions for marine point sources and watersheds with future circulation	2020 conc.	2020 streamflows	2006 conc.	2020 streamflows	2006 conc.	2020 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2020 effluent flows	2006 conditions	2006 conditions	2020s
2040s Human	2040 predictions for marine point sources and watersheds with future circulation	2040 conc.	2040 streamflows	2006 conc.	2040 streamflows	2006 conc.	2040 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2040 effluent flows		2006 conditions	2040s
2070s Human	2070 predictions for marine point sources and watersheds with future circulation	2070 conc.	2070 streamflows	2006 conc.	2070 streamflows	2006 conc.	2070 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2070 effluent flows		2006 conditions	2070s
2020s Human, 2006 circ	2020 predictions for marine point sources and watersheds with 2006 circulation	2020 conc.	2020 streamflows	2006 conc.	2020 streamflows	2006 conc.	2020 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2020 effluent flows	2006 conditions	2006 conditions	2006
2040s Human, 2006 circ	2040 predictions for marine point sources and watersheds with 2006 circulation	2040 conc.	2040 streamflows	2006 conc.	2040 streamflows	2006 conc.	2040 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2040 effluent flows		2006 conditions	2006
2070s Human, 2006 circ	2070 predictions for marine point sources and watersheds with 2006 circulation	2070 conc.	2070 streamflows	2006 conc.	2070 streamflows	2006 conc.	2070 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2070 effluent flows		2006 conditions	2006
2020s Human and Ocean	2020 predictions for marine point sources and watersheds, future circulation, ocean DO and nitrate	2020 conc.	2020 streamflows	2006 conc.	2020 streamflows	2006 conc.	2020 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2020 effluent flows	2020 DO and NO_3	2006 conditions	2020s
2040s Human and Ocean	2040 predictions for marine point sources and watersheds, future circulation, ocean DO and nitrate	2040 conc.	2040 streamflows	2006 conc.	2040 streamflows	2006 conc.	2040 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2040 effluent flows	2040 DO and NO_3	2006 conditions	2040s

Scenario Name	Scenario Description	U.S. Watershed Inflows		Canadian Watershed Inflows		Marine Point Sources						Ocean Conditions[11]	Meteorology[12]	Circulation
						U.S. Municipal		U.S. Industrial		Canadian Municipal				
		Conc.[1]	Streamflow[2]	Conc.[3]	Streamflows[4]	Conc.[5]	Flows[6]	Conc.[7]	Flows[8]	Conc.[9]	Flows[10]			
2070s Human and Ocean	2070 predictions for marine point sources and watersheds, future circulation, ocean DO and nitrate	2070 conc.	2070 streamflows	2006 conc.	2070 streamflows	2006 conc.	2070 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2070 effluent flows	2070 DO and NO$_3$	2006 conditions	2070s
2070s Human, Ocean, and T$_{air}$	2070 predictions for marine point sources and watersheds, future circulation, ocean DO and nitrate, and 2070 air temperature	2070 conc.	2070 streamflows	2006 conc.	2070 streamflows	2006 conc.	2070 effluent flows	2006 conc.	2006 effluent flow	2006 conc.	2070 effluent flows	2070 DO and NO$_3$	2070 air temp.	2070s

NOTES for Table 7

1. U.S. watershed inflow concentrations were scaled in the future based on projected future land use patterns.
2. U.S. watershed inflow streamflows were decadal averages centered around 2020, 2040, or 2070 based on the UW's VIC model predictions under climate change.
3. Canadian watershed inflow concentrations were not changed because of limited information about future land use changes in Canada.
4. Canadian watershed inflow streamflows were based either on UW's VIC model, or predictions of the Fraser River under climate change made by Morrison et al. (2002).
5. U.S. marine point source effluent concentrations were not changed from 2006 levels, assuming that treatment technologies remain at status quo.
6. U.S. marine point source effluent flows were scaled based on county-level medium population growth projections estimated by OFM.
7. U.S. industrial effluent concentrations were not changed from 2006 levels, assuming status quo operations; their total nitrogen load contributions are small to begin with.
8. U.S. industrial effluent concentrations were not changed from 2006 levels assuming status quo operations.
9. Canadian marine point source effluent concentrations were not changed from 2006 levels, assuming that treatment technologies remain at status quo.
10. Canadian marine point source effluent flows were scaled based on regional district-level population growth projections estimated by British Columbia Stats.
11. Ocean conditions, when changed, were based on an extrapolation of a linear trend in DO and NO$_3$ concentrations observed off the coast of the Pacific Ocean.
12. Current meteorology was used for future circulation and water quality for all but the final scenario. Future streamflows were generated using future climate conditions for all scenarios.

This page is purposely left blank

Scenario Boundary Condition Load Comparisons

This section presents the current and future loads for watershed inflows and marine point sources for the potential scenarios we evaluated. However, we could not simulate all combinations of potential current and future scenarios with the DO model. We evaluated the following scenarios with the water quality model to quantify current source impacts and bound potential future conditions that result from changes in population and land use:

Current loading scenarios:

- Scenario 1 – Natural conditions only for watershed inflows. No human watershed inflow contributions or marine point sources.
- Scenario 2 – Current watershed inflows only. No marine point sources.
- Scenario 3 – Natural watershed inflows plus marine point sources. No human contributions within the watershed inflows.
- Scenario 4 – Current watershed inflows plus marine point sources (2006 baseline conditions).

Future loading scenarios:

- 2020 Human – Future watershed inflows for 2020 land use patterns and river flows. Marine point sources for 2020 population.
- 2040 Human – Future watershed inflows for 2040 land use patterns and river flows. Marine point sources for 2040 population.
- 2070 Human – Future watershed inflows for 2070 land use patterns and river flows. Marine point sources for 2070 population.

Below we include loads calculated for 2007 and 2008 as well as alternative future loading scenarios that were not evaluated with the Salish Sea model. The 2007 and 2008 loads provide context for the selected 2006 base year. Many factors will influence actual future loads, such as whether the high population projection is a better estimate or whether to nutrient management practices change. Alternative future loading scenarios identify the range and characterize how much particular factors influence loads.

We also evaluated water quality impacts from future ocean conditions and increases in air temperatures. This section compares flows and DIN loads only for watershed inflows and marine point sources.

Watershed Inflow Scenarios

Current watershed inflow flows

Figure 21 compares watershed inflows for the regions draining to Puget Sound and the Straits of Juan de Fuca and Georgia. The Straits receive far more freshwater than Puget Sound. The Fraser River discharges flow from most of British Columbia and is the single largest freshwater inflow to the Salish Sea. Flows were 30% higher in 2007 than 2006 or 2008. Watershed inflow to Puget Sound was somewhat higher in 2006 than in 2007 (7% lower) or 2008 (13% lower).

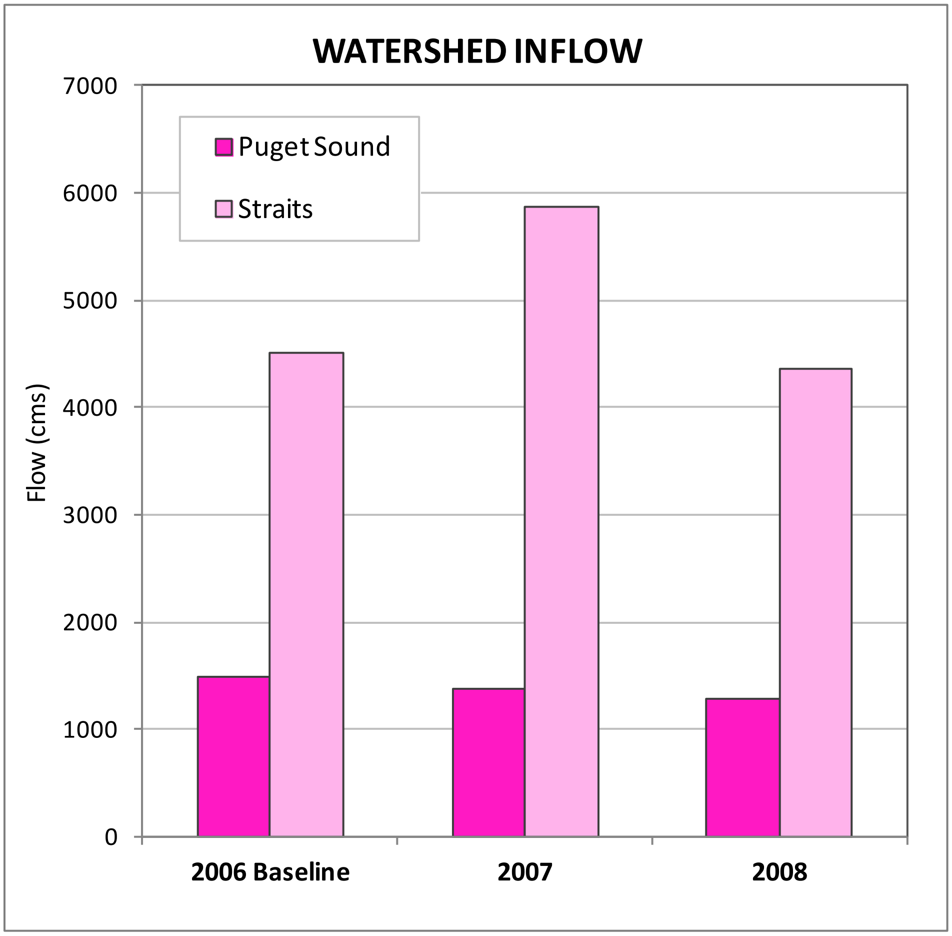


Figure 21. Annual average from all watershed inflows to Puget Sound and the Straits under the 2006 baseline condition compared to 2007 and 2008 conditions.

Under current conditions both U.S. and Canadian watershed inflows exhibit strong seasonality, with winter and early summer peaks associated with precipitation patterns and spring late-summer minima (Figure 22). Canadian contributions are dominated by the Fraser River. Flows were highest in June 2006 at over twice the annual flow. Flows were lowest in October 2006 at 36% of the annual flow. The U.S. contributions exhibit highest flows in January and November (>200% of the annual average) and lowest flows in September and October (24% of the annual average).

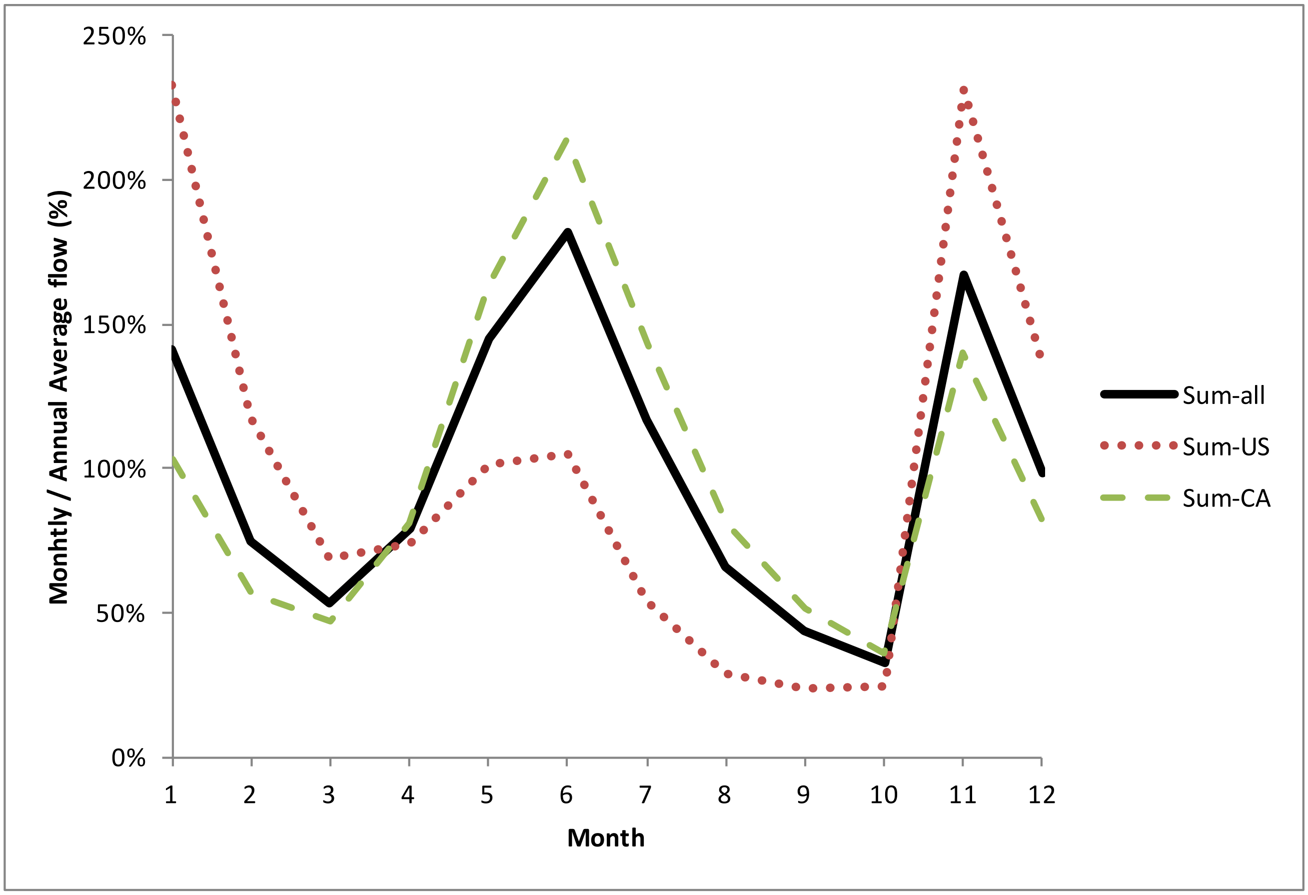


Figure 22. Monthly flows as a proportion of annual average flows for 2006.

Future watershed inflows

The VIC model and Morrison et al. (2002) have projected subtle changes in the total annual average watershed inflow from rivers and streams in the future at the Puget Sound and Straits scale due to climate change (Figure 23). Current interannual variability is high now, and future projections indicate the same range of interannual variability through 2070. Puget Sound inflows range from 1300 to 1500 cms now and are projected to be 1400 to 1500 cms through 2070. This is close to 2007 inflow rates. Inflows to the Straits varied from 4400 to 5900 cms for 2006-2008 but steadily discharge 5600 cms through 2070. Because the Fraser River is so large, total inflows will also tend toward the higher 2007 inflows.

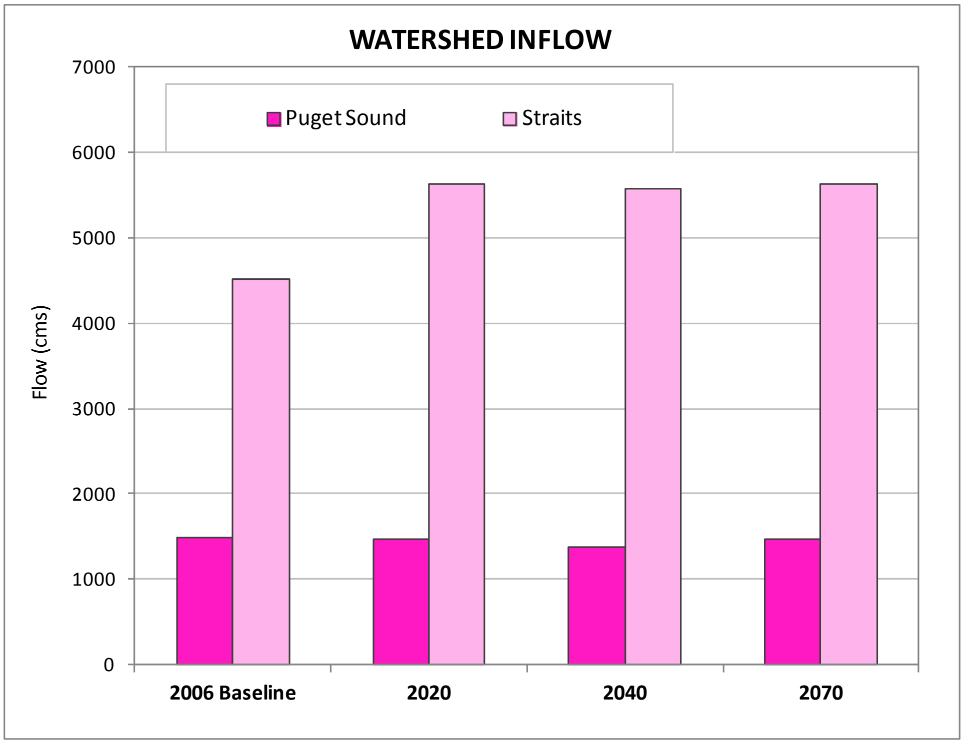


Figure 23. Average annual flows for 2006 watershed inflows to Puget Sound and the Straits compared to projected average annual flows in 2020, 2040, and 2070.

Climate change is expected to shift precipitation regimes from snow to rain with more intense storms. Consistent with these changes, the VIC model predicts general increases in peak winter flows and earlier and more muted spring snowmelt in snow-dominated systems such as the Skagit River (Figure 24). In addition, summer baseflows decrease for basins like the Nooksack, Skokomish, and Skagit Rivers but may increase slightly in the Green River and Puyallup River and remain constant in the Deschutes River. Figure 25 illustrates the higher peak flows in snow-dominated basins including the Nooksack, Skokomish, and Skagit Rivers as well as the rain-dominated Deschutes River. Annual maximum flows may decline slightly for the Green River.

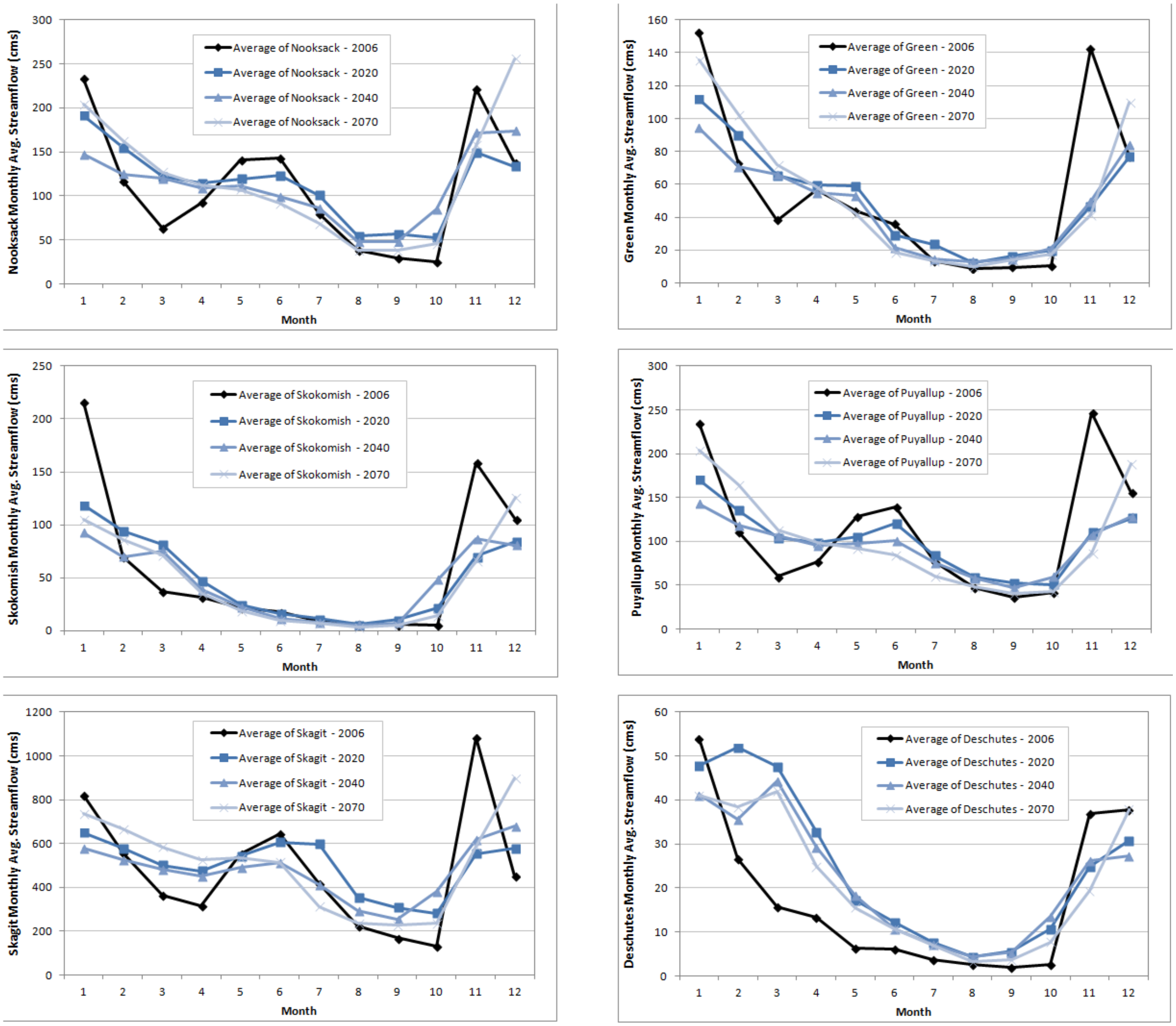


Figure 24. Monthly mean streamflow by decade for representative rivers.

Source: VIC model output, UW CIG.

Figure 25. Annual maximum streamflow for selected rivers.

Source: VIC model output, UW CIG.

Current watershed inflow DIN loads

DIN loads from watershed inflows to Puget Sound were lower in 2007 and 2008 than in 2006. Part of the difference is due to lower flows. Loads to the Straits were higher in 2007 than 2006 or 2008, also due to flow variations. Overall DIN loads vary from 69,000 to 79,000 kg/d (Figure 26). These include the sum of natural and human sources within the watershed inflows.

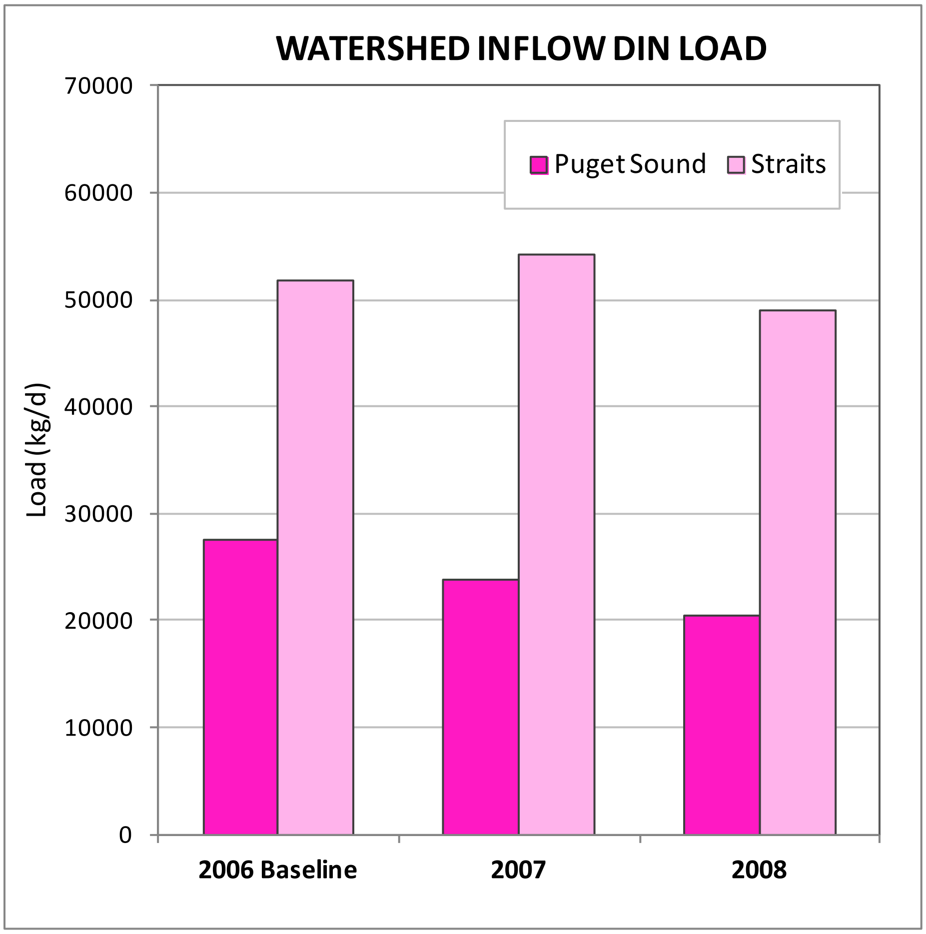


Figure 26. Average annual DIN loads from all watershed inflows to Puget Sound under 2006 baseline conditions compared to 2007 and 2008 conditions.

Mohamedali et al. (2011) did not present natural conditions for Canadian watershed inflows. To establish natural conditions in Canadian rivers, with similar concentrations to U.S. rivers draining to the Strait of Juan de Fuca, we applied the annual average of monthly natural nitrate concentrations from Mohamedali et al. (2011) for Hood Canal and the Strait of Juan de Fuca to represent year-round natural concentrations for Canadian watershed inflows from Vancouver Island. Strait of Juan de Fuca values (0.038 mg/L) were applied to the southern part of Vancouver Island including Victoria while Hood Canal values (0.018 mg/L nitrate, for example) were applied to all others except the Fraser River. We used 50th percentiles of measured nitrate data from the Fraser River to represent natural nitrogen concentrations throughout the year. We assigned Canadian rivers an ammonium concentration of 0.001 mg/L since no ammonium data are available. This is the same value as used for current conditions.

For the Fraser River, this resulted in 18,000 kg/d of DIN from natural sources and 33,500 kg/d of DIN from human sources. Because concentrations are so low in the Fraser River, this method could overestimate the proportion of current loads attributed to human sources. Model runs of natural conditions in the Salish Sea only included the natural component of the Canadian rivers.

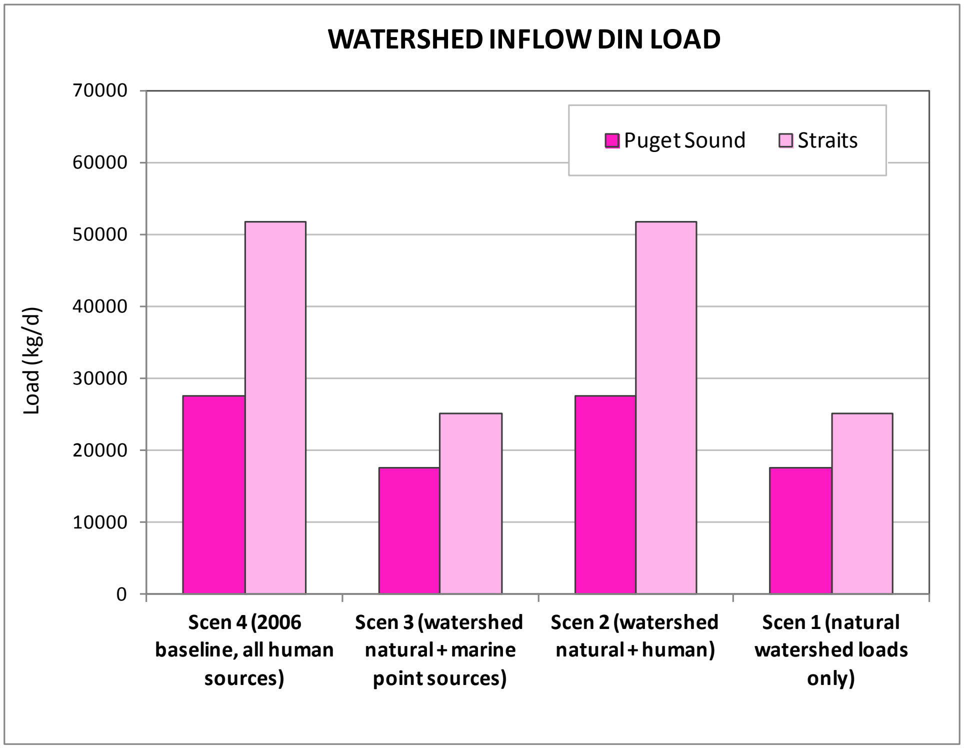


Figure 27. Average annual DIN loads from watershed inflows for current scenarios.

Future watershed inflow DIN loads

Watershed inflow DIN loads to Puget Sound are expected to increase to reflect changes in watershed land use. Relative to the 2006 baseline, watershed inflow DIN loads are projected to increase 7% by 2020, 14% by 2040, and 51% by 2070 due to human sources. Human contributions cause watershed inflows to increase from 10,100 kg/d in 2006 to 12,000, 13,900, and 14,500 kg/d in 2020, 2040, and 2070, respectively.

We did not project changes in concentrations of Canadian watershed inflows into the future. Additional DIN loads to the Straits increase due to higher DIN concentrations from U.S. watersheds that drain into the Straits. Much of the projected increase is due to the 24% higher Fraser River flows (Figure 28).

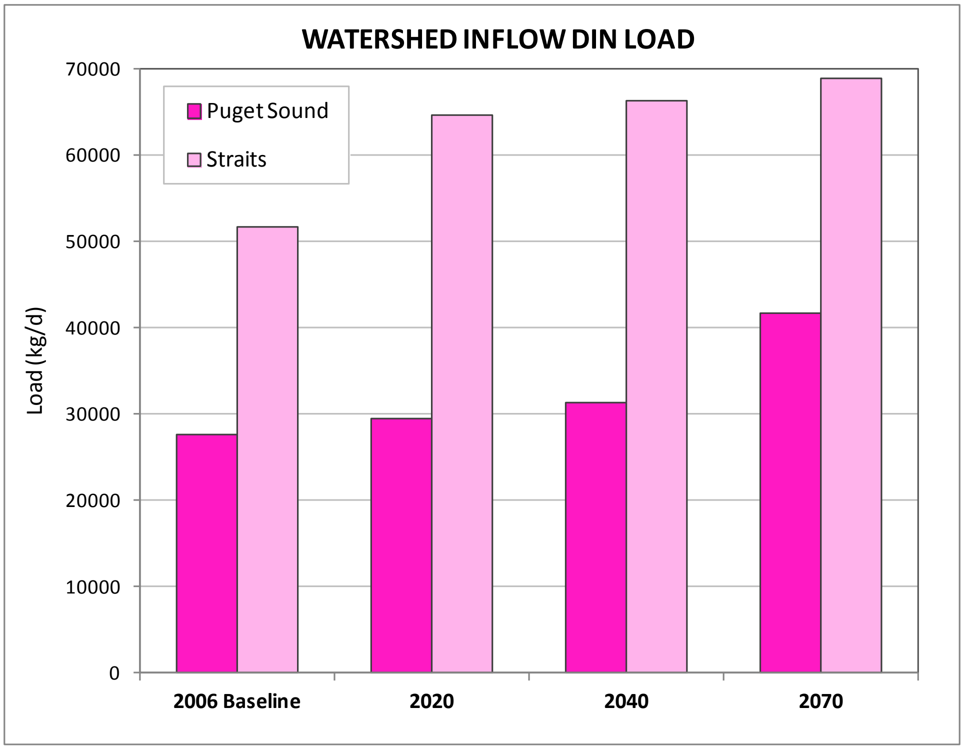


Figure 28. Average annual DIN loads from all watershed inflows to Puget Sound and the Straits under the suite of future scenarios.

Marine Point Source Scenarios

Current marine point source flows

Marine point source flows from municipal WWTPs and industrial discharges do not vary greatly from year to year. Factors that would produce large changes include large increases in population served by municipal WWTP or changes in how industrial facilities are operated. Marine point source flows vary from 15 to 18 cms but stay relatively constant at 18 cms to the Straits (Figure 29). Effluent flows to the Straits are dominated by a few large WWTPs in the metropolitan and Victoria regions of Canada.

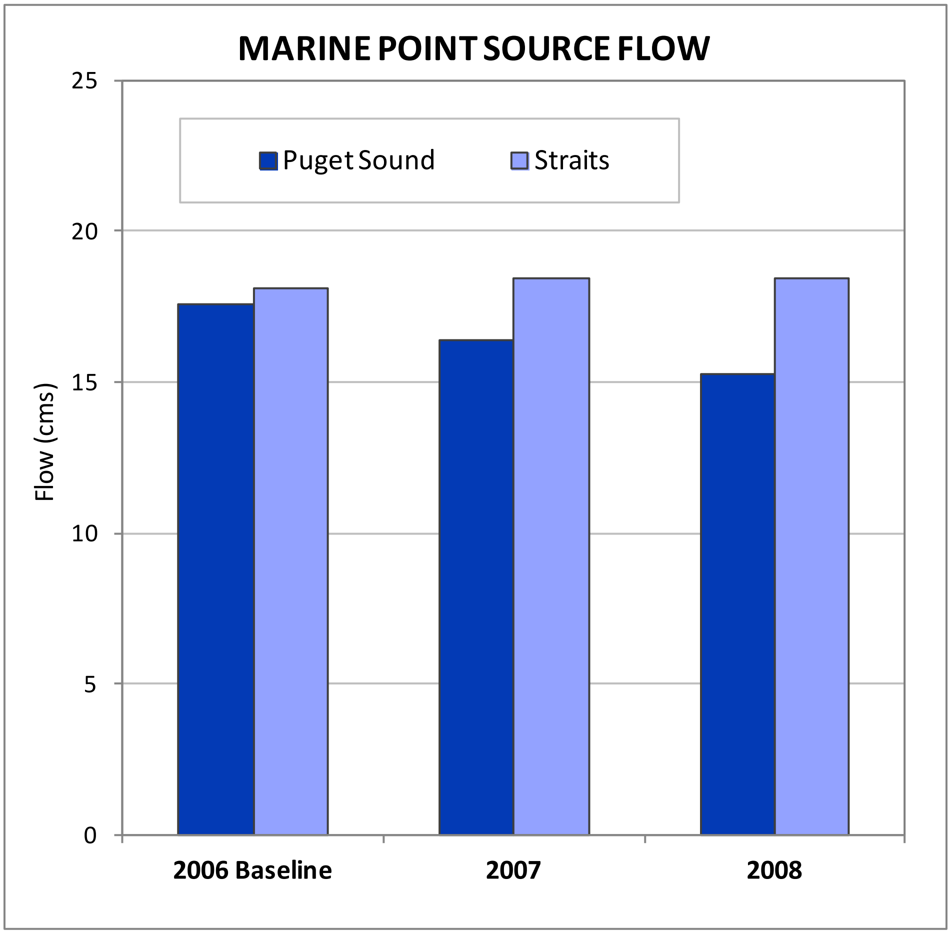


Figure 29. Annual average flow from all marine point sources into Puget Sound and the Straits under the 2006 baseline scenario compared to 2007 and 2008 conditions.

Future U.S. WWTP service area population and flows

Figure 30 and Table 8 present current and future population served by the 78 U.S. municipal WWTPs. The population served by these WWTPs will double by 2070, from 4.2 million served currently to 7.8 – 8.8 million served by the year 2070. Differences between high and low population projections grow into the future, with a range of 0.1 million in 2020, 0.4 million in 2040 and 1.0 million in 2070. Table 8 also translates the population served to the effluent flow rates discharged from these WWTPs for the range of population projections. Compared to current flows from the 78 municipal WWTPs (320 mgd), future flows are projected to grow to 390 to 400 mgd by 2020 and 570 to 660 mgd by 2070. Figure 31 plots total flow projections.

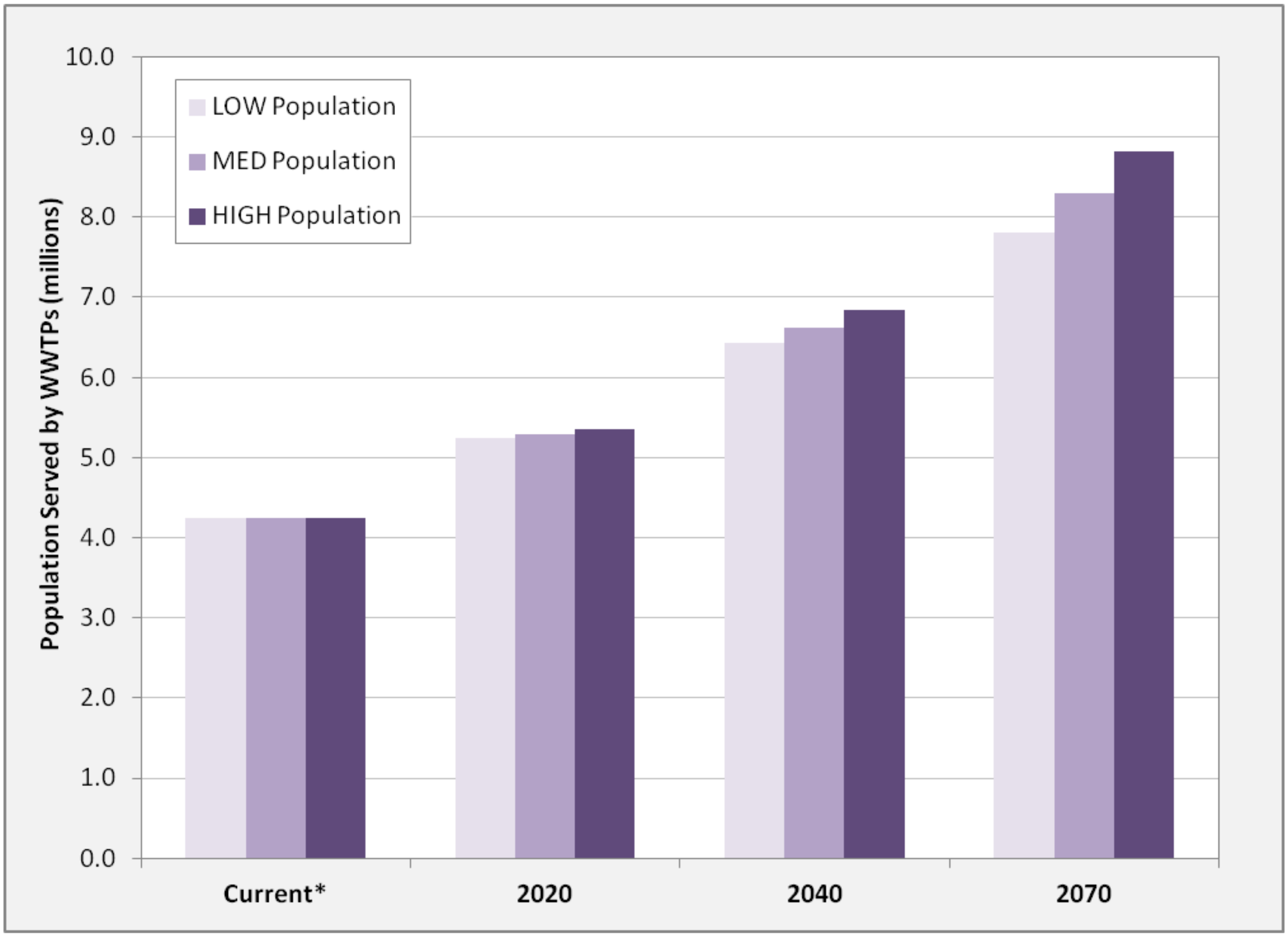


Figure 30. Projected population served by municipal WWTPs discharging to U.S. waters of Puget Sound and the Straits.

**Current represents the most recently documented population served by plants between the years 2000-2011.*

Table 8. Current* and future U.S. marine point source service area population and annual flows for Low, Medium, and High population projection scenarios.

	LOW	MED	HIGH
Population served by WWTPs (in millions)			
Current*	4.2	4.2	4.2
2020	5.3	5.3	5.4
2040	6.4	6.6	6.8
2070	7.8	8.3	8.8
Annual WWTP flows into Puget Sound and the U.S. Straits (mgd)			
Current*	320	320	320
2020	390	395	400
2040	470	590	510
2070	570	615	660

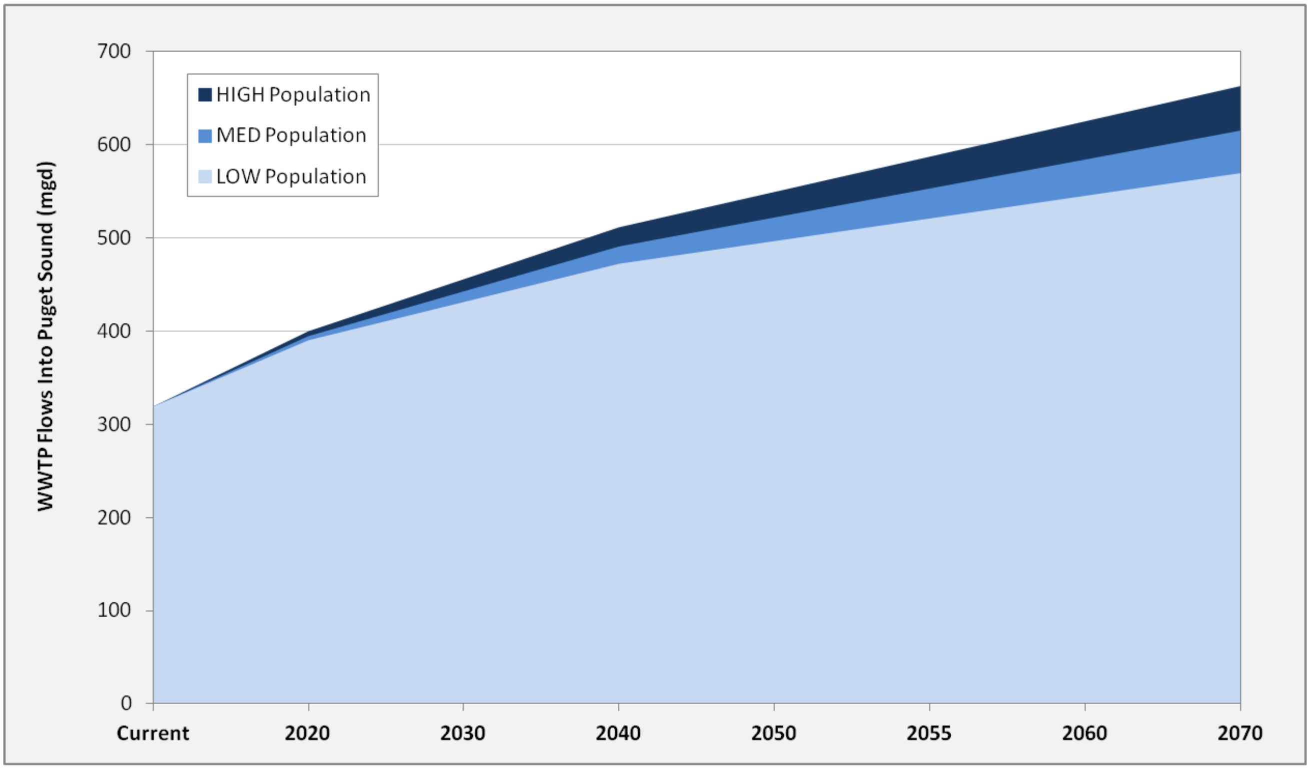


Figure 31. Projected flows from U.S. municipal WWTPs discharging to marine waters of Puget Sound and the Straits through 2070.

These flows represent total average annual municipal wastewater flows into the marine waters of the Salish Sea, including flows above the design flow rate of the plant. This is represented as Q-max month, which is the average of the daily flows in the month with the highest total flow during the design life of the plant.

Table 9 summarizes the number of municipal marine point sources that would exceed current capacity, when, and the magnitude of these excess flows. We calculated excess flows to check the assumption that future flows associated with population growth would continue to discharge to marine locations. If projected flows were much higher than current plant capacity, then the region would need to identify new discharge solutions for the excess flows. Projected average annual flows are within the capacity of the current Q-max month in NPDES permits for most of the 78 U.S. municipal marine point sources. For this assessment, we assume that current discharge locations are sufficient to accommodate increases in service area populations through 2070 for the Low and Medium population projections. However, this does not consider flow peaking that occurs during precipitation events that must be considered in infrastructure capacity from a treatment perspective.

Table 9. WWTPs that would exceed plant capacity for future scenarios through 2070.

	LOW	MED	HIGH
Number of WWTPs exceeding capacity			
2020	1	1	5
2040	2	6	13
2070	6	13	35
Number of large (> 10 mgd) WWTPs exceeding capacity			
2020	0	0	0
2040	1	1	2
2070	3	3	4
WWTP flows in excess of Q-max month (mgd)			
Current	0.0	0.0	0.0
2020	0.4	0.4	0.4
2040	11	12	16
2070	23	37	60
Excess flow as a % of total flow			
2020	0.1%	0.1%	0.1%
2040	2.4%	2.5%	3.1%
2070	4.0%	6.0%	8.5%

In the high population scenario, 35 of the 78 WWTPs would exceed capacity by 2070. However, 31 of these currently discharge <10 mgd and serve relatively small populations. The excess flows from the 35 plants projected to exceed plant capacity would generate 56 mgd by 2070. This is equivalent to 9.0% of the total projected U.S. municipal WWTP flows into Puget Sound and the Straits in 2070. Over 90% of the highest projected municipal WWTP flows could be treated within current plant capacity and discharge at current locations. Under the Low population scenario, only 4.0% of total flows are in excess of existing plant capacities.

Four large plants that currently discharge more than 10 mgd would exceed capacity by 2070 under the High population scenario: Everett, Chambers Creek, Bellingham, and LOTT. The Everett plant would exceed capacity by about 3.5 mgd, or 37% of the current flow. The Chambers Creek is currently being upgraded, and the Q-max month values in the existing permit used in this analysis do not reflect planned improvements. The Bellingham WWTP has already identified the need for additional wastewater treatment capacity and is currently finalizing the plan on how to meet future needs. Construction will be completed in 2014. LOTT is also currently developing a wastewater facilities plan through 2050 that includes additional reclaimed water facilities and less reliance on discharges to marine waters.

In summary, the assumption that future wastewater flows would discharge at existing locations but at higher flows is reasonable. Excess flows above current capacity are <1 mgd in 2020, 11 to 16 mgd by 2040, and 23 to 60 mgd by 2070. However, even the highest excess flows represent <10% of the total U.S. municipal wastewater discharge. While solutions would be needed to treat these flows, routing them other than to marine point source locations would require significant assumptions not justified for this screening-level analysis.

Current marine point source DIN loads

Marine point source DIN loads to Puget Sound range from 30,000 to 33,000 kg/d for 2006 through 2008 (Figure 32). The Straits currently receive about 32,000 kg/d from marine point sources, including 2,000 kg/d from U.S. sources. All marine point sources represent human sources. Figure 33 presents the marine point source loads under the four current scenarios. No marine point sources would discharge under natural conditions or in scenarios with only human watershed inflows, and these loads are zero. All marine point sources would discharge under current conditions and when considering only natural watershed inflows and marine point sources.

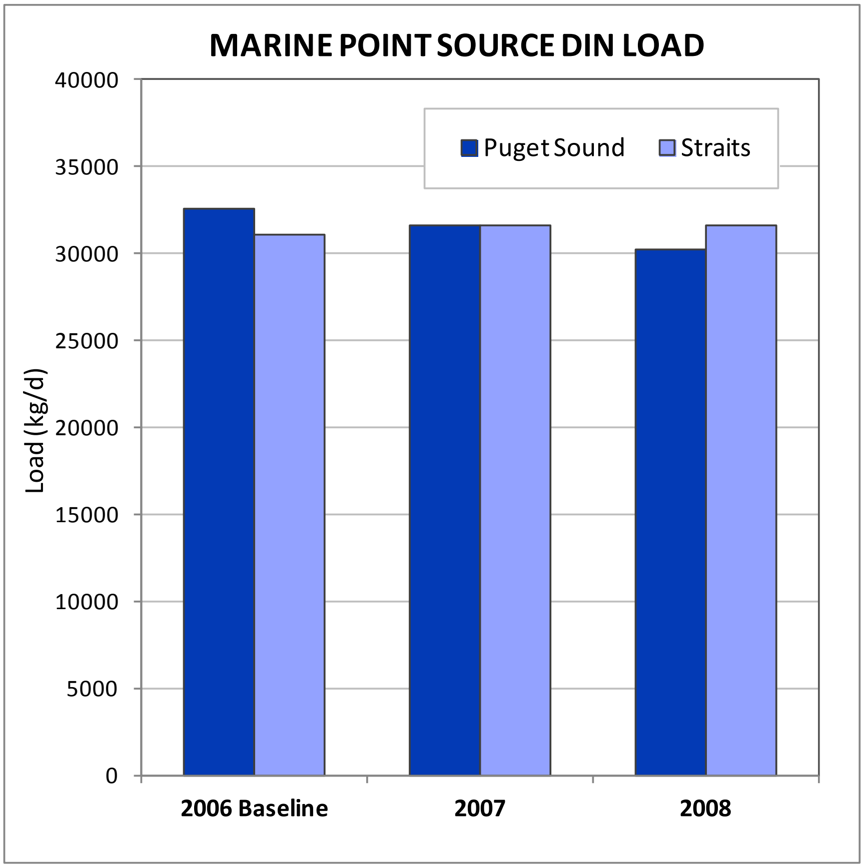


Figure 32. Average annual DIN loads from all point sources into Puget Sound under 2006 baseline conditions compared to 2007 and 2008 conditions.

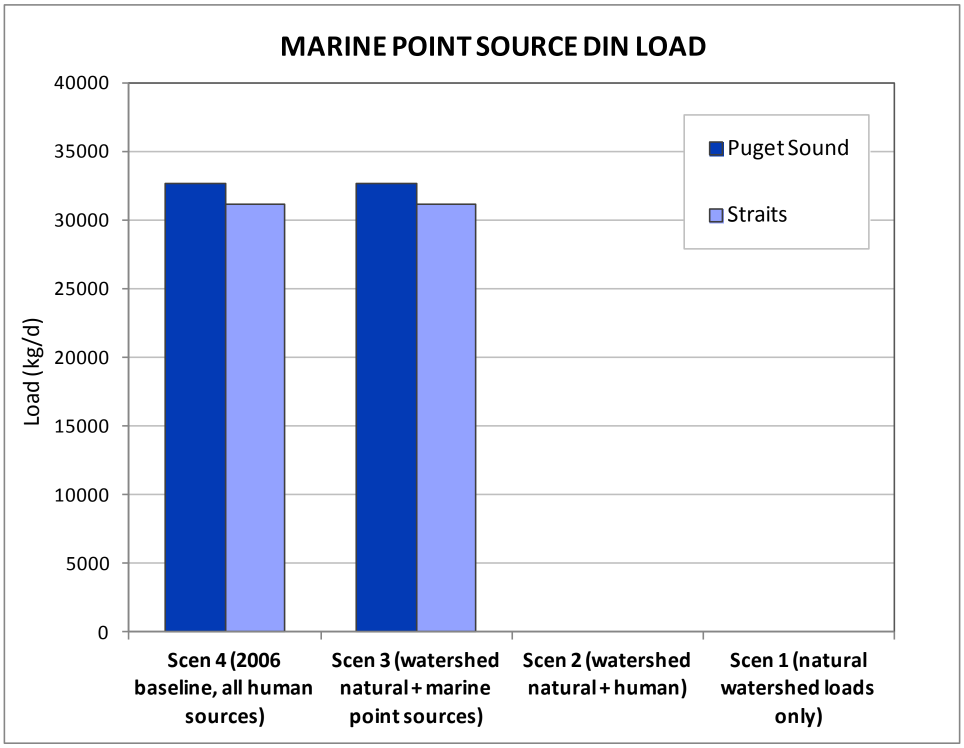


Figure 33. Average annual DIN loads from all point sources into Puget Sound under 2006 baseline conditions compared to the other current scenarios.

Future marine point source DIN loads from U.S. municipal WWTPs

Future loads include the combined effects of future flow and concentration. Future flows documented in previous sections are based on population projections. Future concentrations will vary with treatment technology.

Two options are included for future concentrations, which have a strong influence on future loads. Current median DIN concentration in municipal WWTP effluent for plants >10 mgd is 24 mg/L. This is three times greater than the 8 mg/L concentrations that can be achieved by upgrading to BNR treatment. Figure 34 (top) presents WWTP DIN loads for High, Medium, and Low population projections assuming no change to current treatment technology. Loads would roughly double from 33,000 kg/d today to 55,000 to 65,000 kg/d by 2070. Figure 34 (bottom) illustrates the effect of upgrading to improved nutrient removal after 2020.

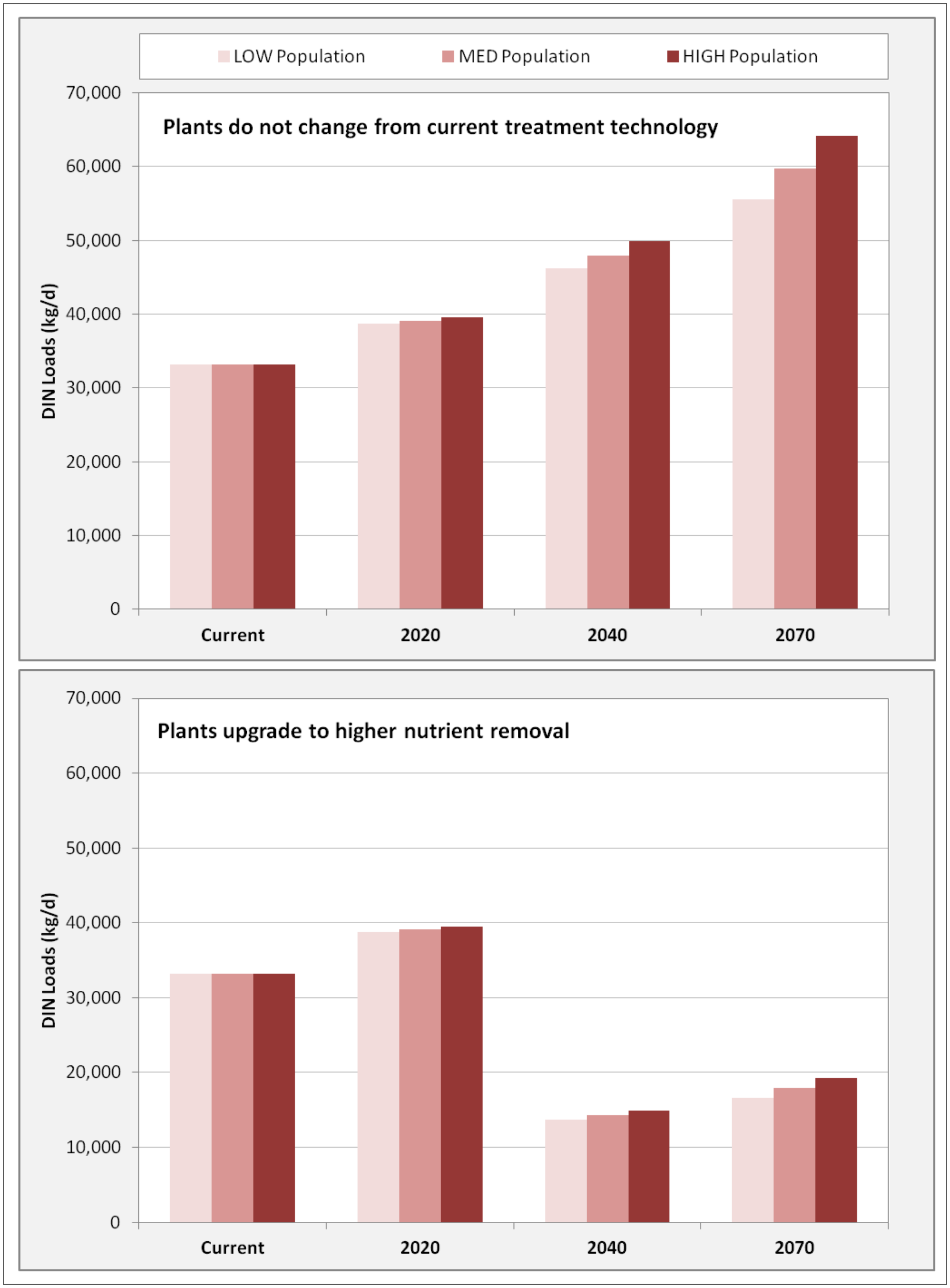


Figure 34. Projected DIN loads from U.S. WWTPs through 2070 based on different population projections and different assumptions about future treatment technologies.

Maximum 2070 load predictions under the High population projection with no change to treatment technology represent a 93% increase in DIN loads from current conditions. Even with the High population projection for 2070, WWTP loads could decrease by 42% compared with current conditions if all WWTPs upgrade to nutrient removal technology. Since the population forecasts predict the population will double and not triple, upgrading to BNR using currently available nutrient-removal technology would more than offset the increases in DIN loads due to increases in population.

We evaluated DO impacts under future U.S. WWTP effluent flow based on the Medium population projection and today's treatment technology, which assumes no change in treatment technologies.

Future marine point sources from industrial discharges

Current industrial effluent flows currently contribute 49 mgd, or about 11% of the total flow from all point sources into U.S. marine waters. DIN loads contributions from industrial facilities, however, are much lower, and contribute 220 kg/d, less than 1% of the DIN load from U.S. marine point sources.

Because future industrial discharges likely would not scale with population, we used current (or status quo) industrial effluent flows and concentrations for all future scenarios. Subsequent projects could perform a sensitivity analysis on industrial discharge flows and loads by scaling current levels by ±25% or ±50%.

Future marine point sources from Canadian WWTP flows and loads

The sum of all Canadian WWTP flows is projected to increase from 340 mgd in 2008 to 395 mgd by 2020, 505 mgd by 2040 and 660 mgd by 2070. Therefore, by 2070, flows from Canadian WWTPs will be about twice current flows. As with the U.S. projections, the population served by Canadian WWTPs is also expected to double by 2070. Projected 2070 flows from Canadian marine point sources (660 mgd) are close to the U.S. marine point source flows in 2070 (615 mgd, under the Medium population scenario).

DIN concentrations were maintained at current levels through 2070. Nitrogen loads from Canadian WWTPs in 2070 would be about twice those of current nitrogen loads because of the doubling of flows. DIN loads from all Canadian WWTPs in 2070 (52,400 kg/d) would be similar in magnitude to those from all U.S. WWTPs (59,800 kg/d, Medium population scenario with no upgraded treatment).

Future DIN loads from all marine point sources

Marine point sources are projected to increase incrementally for each future scenario year, relative to 2006 conditions due to increases in projected populations served by existing WWTPs (Figure 35). Marine point source DIN loads will increase 11% by 2020, 35% by 2040, and more than double to 67% by 2070 relative to 2006 baseline levels.

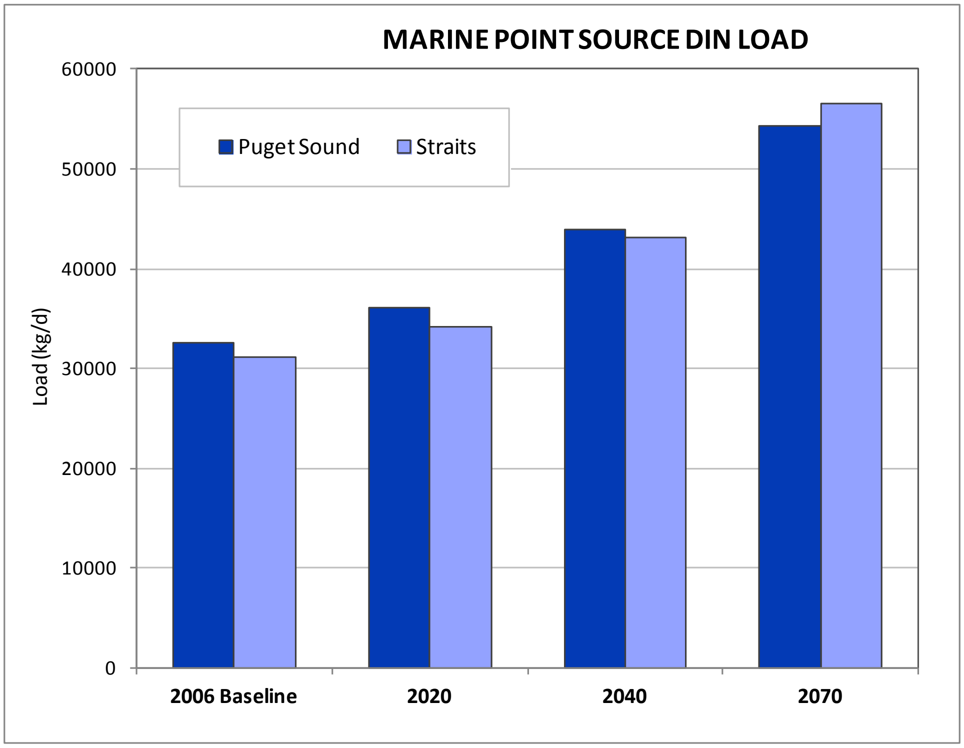


Figure 35. Average annual DIN loads from all marine point sources into Puget Sound and the Straits under the suite of future scenarios.

Comparing Watershed Inflow and Marine Point Sources

Figure 36 compares watershed inflow and marine point source DIN loads entering Puget Sound (not the Straits) under the current conditions. Watershed inflows currently contribute between 40% - 46% of the total DIN load to Puget Sound on an annual basis. The total DIN load from watershed inflows and marine point sources is higher in 2006 (baseline) compared with 2007 and 2008. This is predominantly because of reduced flows in 2007 and 2008 which translated into lower watershed inflow DIN loads.

As described in more detail in Mohamedali et al. (2011), the proportion of watershed inflow load that comes from human point and nonpoint sources within the watersheds varies greatly by season. Human sources contribute about 20% of the total load to Puget Sound in the summer season when streamflows reach the annual minimum. During the summer months, the relative human contribution within watershed inflows is much lower than shown in the annual average in Figure 37. In contrast, marine point source loads to Puget Sound stay relatively constant throughout the year because the population served is relatively constant. Their relative contributions to total loads to Puget Sound increases during summer months because watershed inflows decrease.

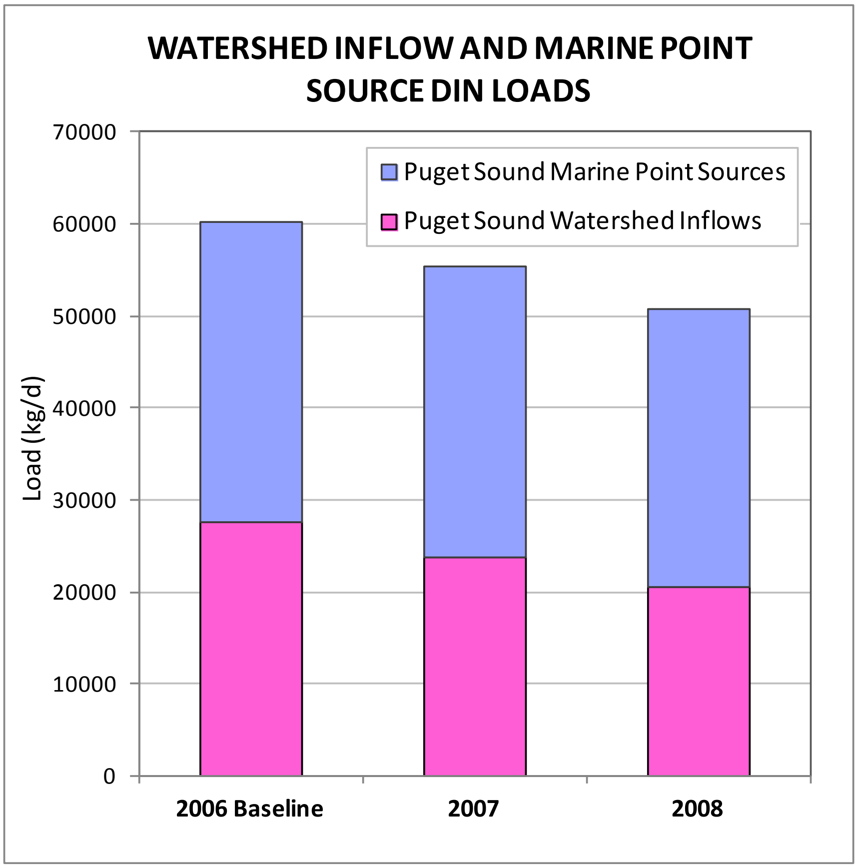


Figure 36. Average annual DIN loads from all watershed inflows and marine point sources entering Puget Sound under 2006 baseline conditions compared to 2007 and 2008 conditions.

The four current scenarios distinguish the effect of different load elements. Under natural conditions (Scenario 1), Puget Sound would receive 17,500 kg/d of DIN, with no human sources in watershed inflows or marine point sources. Total load would increase to 28,000 kg/d with both natural and human sources in the watershed inflows but with no human marine point sources. Scenario 3 considers only natural watershed inflows and human marine point sources, which together would contribute 50,000 kg/d. Under current conditions, the total load from natural and human watershed inflows and marine point sources is 60,000 kg/d. Today Puget Sound receives 42,500 kg/d of DIN from the combined effect of all human sources.

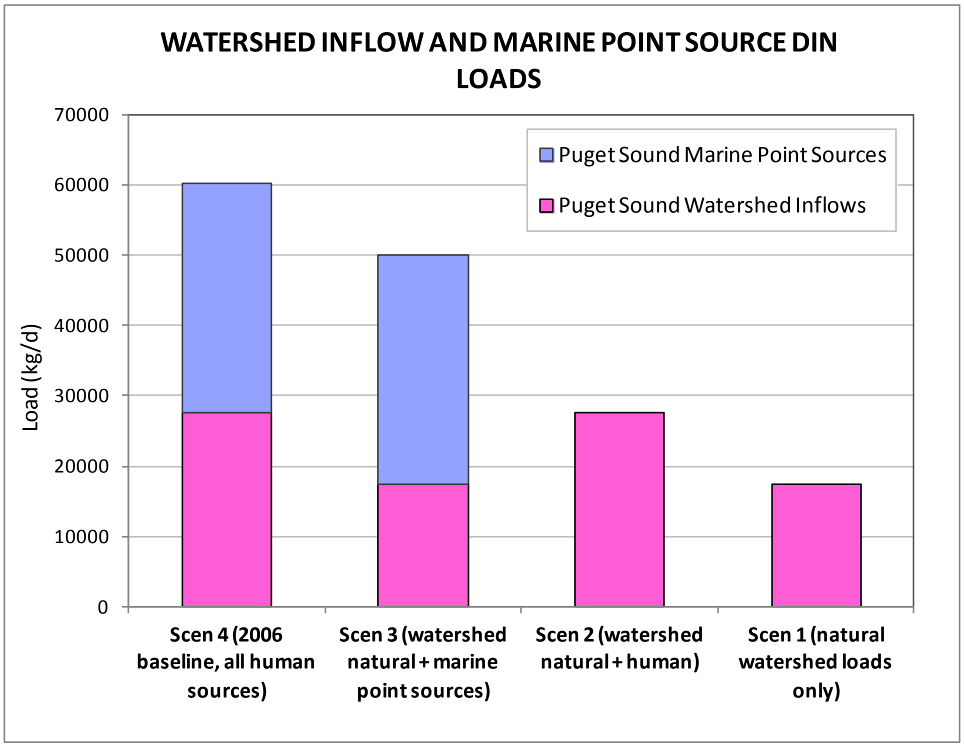


Figure 37. Average annual DIN loads from all watershed inflows and marine point sources entering Puget Sound under 2006 baseline conditions compared to other current scenarios.

Under future scenarios, both watershed inflows and marine point sources increase at similar rates. The proportion of watershed inflows remains about 40% (Figure 38). Using best available estimates of increases in population and watershed development, DIN loads to Puget Sound will increase from 60,000 kg/d today to 96,000 kg/d in 2070.

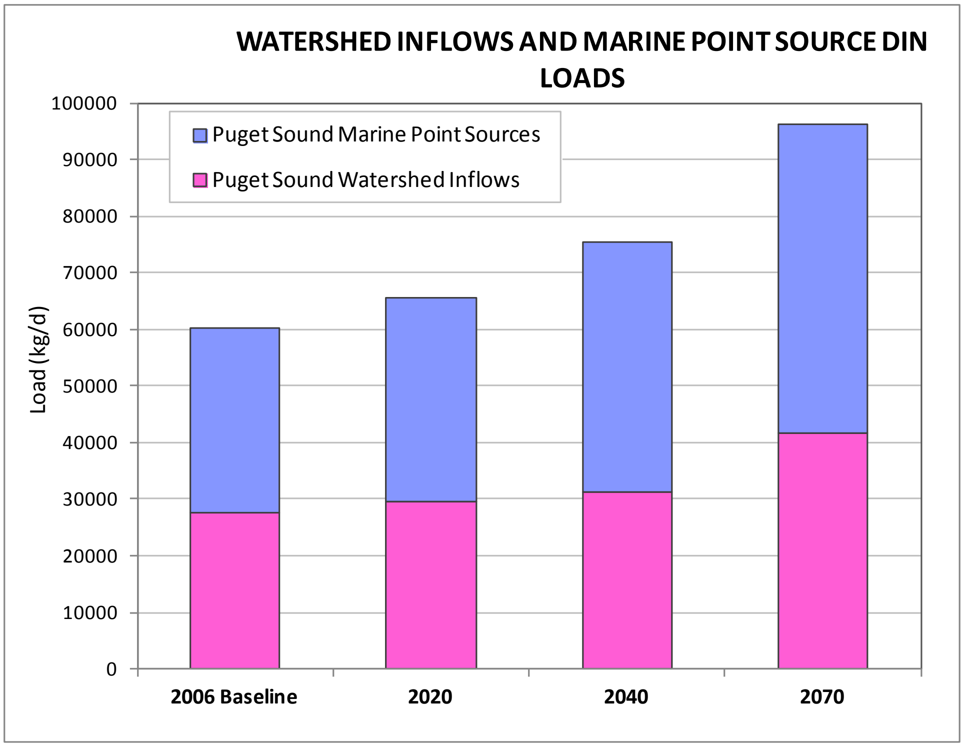


Figure 38. Average annual DIN loads from all nonpoint and point sources into Puget Sound only under the suite of future scenarios.

Scenario Results

The water quality model uses a form of computational elements that precludes cell-by-cell comparisons of DO between scenarios. We calculated the average regional and seasonal DO depletion compared with natural conditions for 40 regions across the Salish Sea. The water quality regions are finer in Puget Sound and coarser in the Straits (Figure 39).

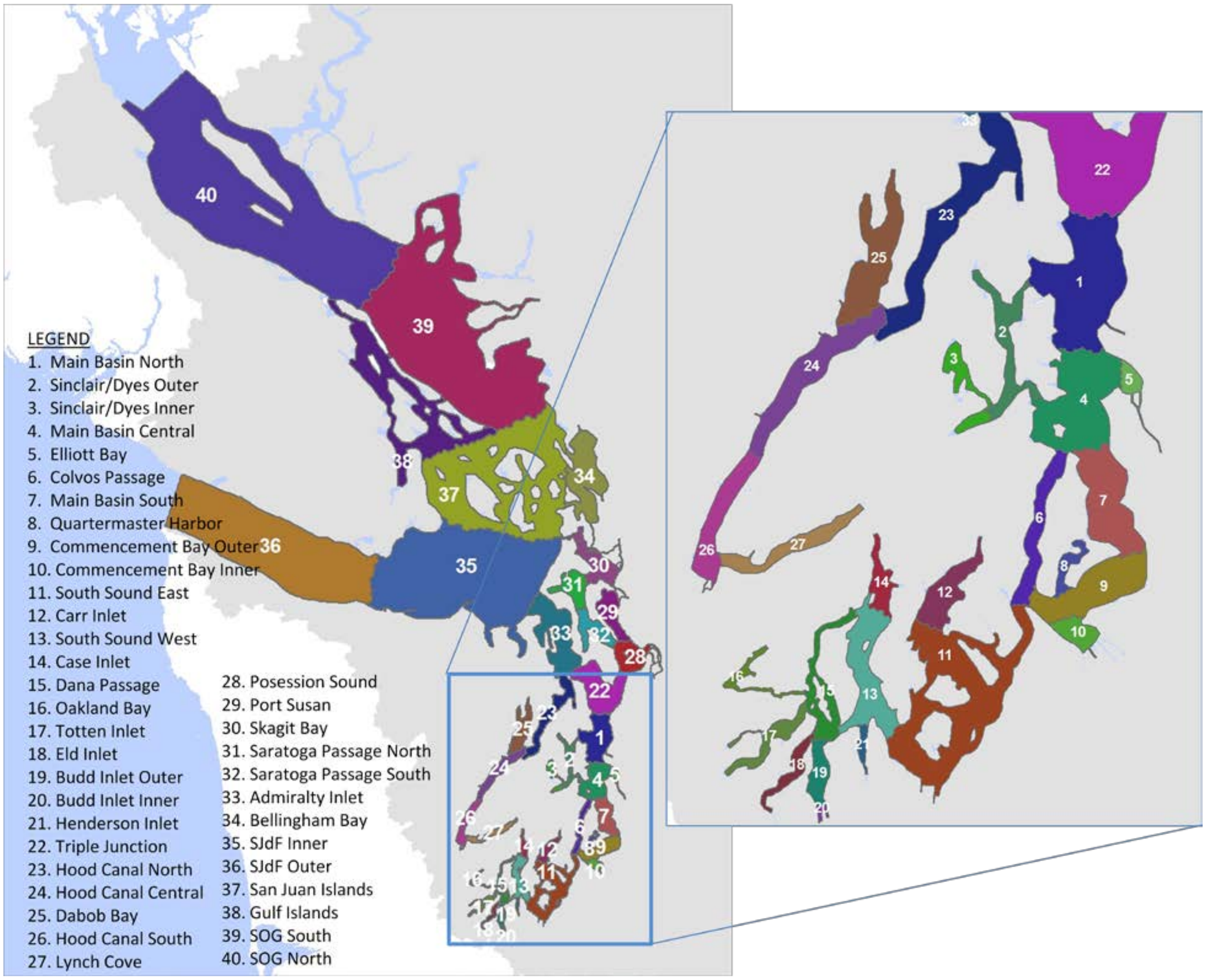


Figure 39. Water quality regions used to report average regional dissolved oxygen depletion.

Dissolved Oxygen Depletion Calculations

Each scenario was compared with natural conditions using the average regional DO depletion. This value represents the average decrease in predicted DO for the period September 1 through October 31 for all computational elements within a given region, and for layers 5 to 10. Layer 5 corresponds to the typical pycnocline depths, although actual pycnocline varies. As detailed in Yang et al. (2010) the 10 layers increase in depth from the surface to the bottom. Layers 5 through 10 generally represent the bottom 70% of the water column in any given location. In a sigma coordinate system, the thickness of each layer expands and contracts to reflect the tidal elevations. Some computational elements and layers represent larger horizontal areas of vertical depths. Therefore, the DO depletion weights the individual computational elements and layers by the equivalent volume.

Each region covers tens to hundreds of computational elements in the horizontal plane with 10 layers over the water column. We pool the instantaneous predicted DO every 6 hours from layers 5 through 10 for all computational elements within a region in the natural conditions run and multiply each value by the equivalent volume it represents. We normalize by the total volume in that region to get the volume-weighted regional DO:

$$C_{DO-vol} = \frac{\sum_{Region\ Element\ 1}^{Region\ Element\ j}\left\{\sum_{layer\ 5}^{layer\ 10}\left[\sum_{time\ step\ 1}^{time\ step\ 4}(c\ x\ V)\right]\right\}}{\sum_{Region\ Element\ 1}^{Region\ Element\ j}\left\{\sum_{layer\ 5}^{layer\ 10}\left[\sum_{time\ step\ 1}^{time\ step\ 4}(V)\right]\right\}}$$

Where $C_{DO\text{-}vol}$ is the volume-weighted DO in mg/L, j is the number of computational elements[4] within any particular region, c is the instantaneous DO concentration in mg/L, and V is the tracer control volume in m^3. Because the concentration is normalized by the overall volume, $C_{DO\text{-}vol}$ can be compared across regions of different sizes.

We calculate this value every 6 hours of the simulation period for plotting purposes to illustrate seasonal patterns. However, the regional depletion only considers data for the period September 1 through October 31. The process is repeated for each of the 40 water quality regions.

Next we evaluate an alternative loading scenario using the same procedure. This produces the year-long time series of predicted volume-weighted DO for a single region, and the process is repeated for all 40 water quality regions.

---

[4] The circulation and water quality model components calculate quantities in different locations. In FVCOM, velocity components and other vectors are calculated at the centroids of the triangular cells. However, the water quality model components calculate dissolved oxygen and other water quality variables at the vertices of the triangular cells, which are called nodes. To get the inventory of oxygen, each node is assigned an equivalent volume. Flux of oxygen between nodes occurs across the common faces of the control volumes (Chen et al., 2003). This is called the tracer control element for each combination of cells and layers. The tracer control elements were used to compute the volume-weighted dissolved oxygen concentration.

Figure 40 provides an example of the regional depletion approach for Main Basin South (region 7). The top graphic plots the daily time series of volume-weighted DO for the entire Main Basin South region under both the current conditions (solid black line) and natural conditions (green dotted line). The bottom graphic presents the time series of the difference in volume-weighted regional DO between existing and natural conditions. Negative values indicate that the volume-weighted DO is lower under existing conditions than the natural volume-weighted regional DO concentration. In this example, existing sources decrease the average regional volume-weighted DO by up to 0.12 mg/L by simulation day 345 (December 11).

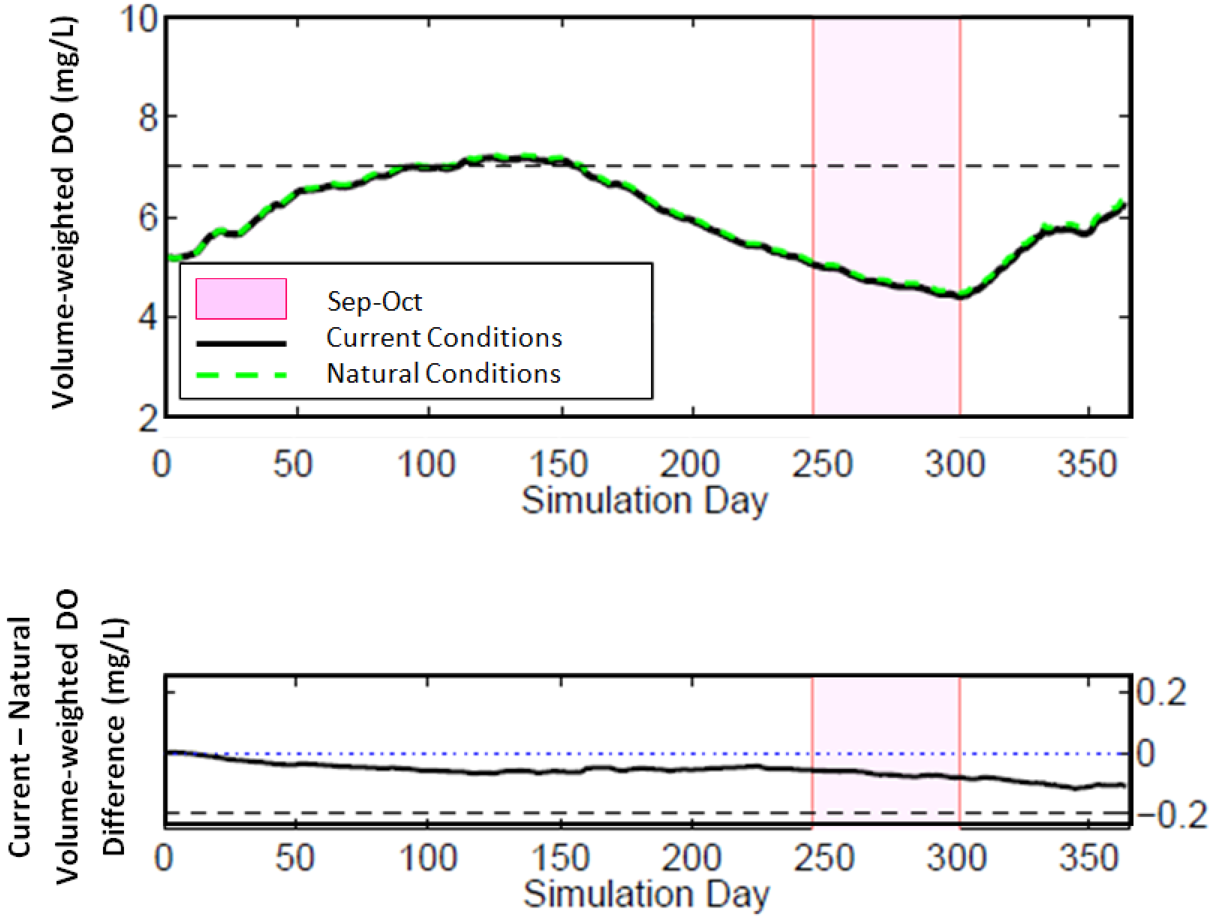


Figure 40. Example volume-weighted dissolved oxygen time series for Main Basin South (region 7) to compare between a scenario and natural conditions by region.

To develop the average regional depletion for the period September 1 through October 31, we consider how much volume has a particular concentration for both natural conditions and the scenario. For the natural condition run, all volume-weighted regional depletion concentrations are pooled for the period September 1 through October 31 and ordered by the volume-weighted DO. The fractional volume is calculated by dividing the cumulative volume by the total volume of each computational element and layer summed four times per day and 365 days per year. We repeat for the scenario. Figure 41 presents the two resulting cumulative frequency distributions of the volume-weighted DO concentrations under natural conditions (right) and the scenario (left) for the region Main Basin South. Half median volume-weighted DO in this region has a concentration below
4.81 mg/L under natural conditions and 4.74 mg/L under the scenario considered, or a decline of 0.07 mg/L.

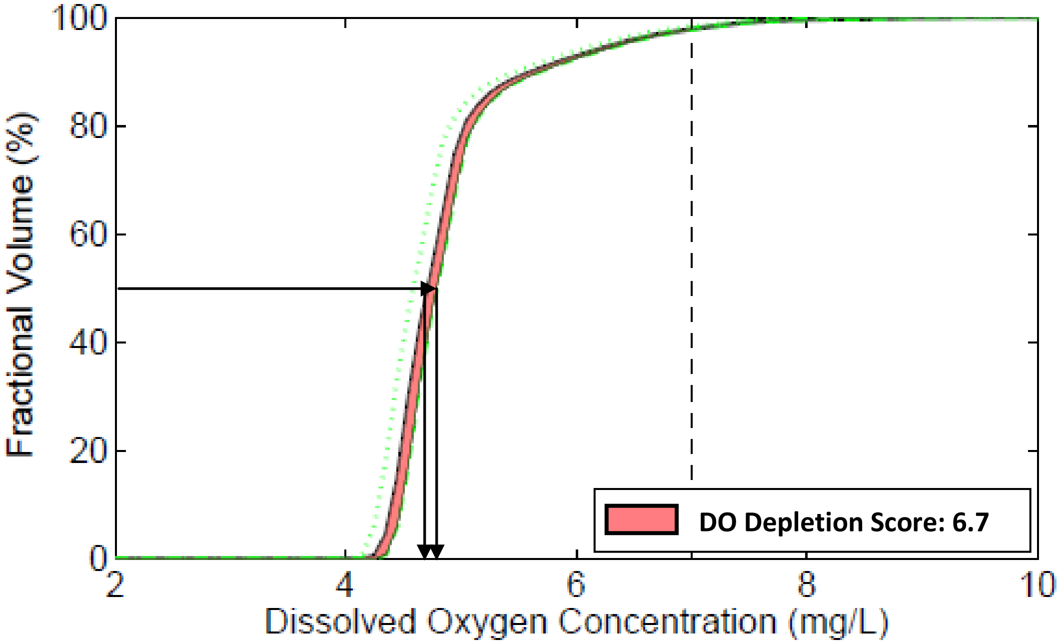


Figure 41. Example for developing the regional average dissolved oxygen depletion for September 1 through October 31 for Main Basin South (region 7).

Pink region represents the area between the curves for the natural condition (right) and scenario (left). The dotted green line is the natural condition minus 0.2 mg/L and the dashed black line is the numeric criteria for this region. Arrows indicate the median volume and the resulting natural and scenario volume-weighted DO values. DO Depletion Score is the average DO depletion times 100.

The dashed green line to the left is the natural condition minus 0.2 mg/L. If the scenario decreases the volume-weighted regional depletion by more than 0.2 mg/L, then the scenario cumulative frequency distribution would plot to the left of the dotted green line. This does not mean that the predicted DO does not decrease by more than 0.2 mg/L in a given computational element and layer. This method accounts for any shifts in low-oxygen water that could occur due to changes in circulation.

The vertical dashed line represents the numerical part of the water quality standards that apply in this region. The pink region represents the DO depletion between the scenario and natural conditions. The DO Depletion Score reported in the figure is the total area between the two curves. Dividing the DO Depletion Score by 100% produces the average decrease in volume-weighted DO (0.067 mg/L). We also calculate the total depletion below the numeric criteria between the scenario and natural conditions from the area below the standard. In this case, the resulting regional depletion (0.067 mg/L) is equivalent to the depletion below the numeric criteria because the criterion truncates a very small portion of the pink area. Because the scenario and the natural condition curves remain fairly parallel, the average depletion is similar to the 0.07 mg/L value reported for the 50th percentile fractional volume. For this example, the maximum September-October depletion is 0.085 mg/L, which is greater than the average.

Results compare the total average regional volume-weighted depletion for the period September 1 through October 31.

Current Scenarios

Three scenarios were evaluated with the model to isolate the effect of current human contributions from marine point sources and watershed inflows. Figure 42 summarizes the total average regional depletions for September and October by region.

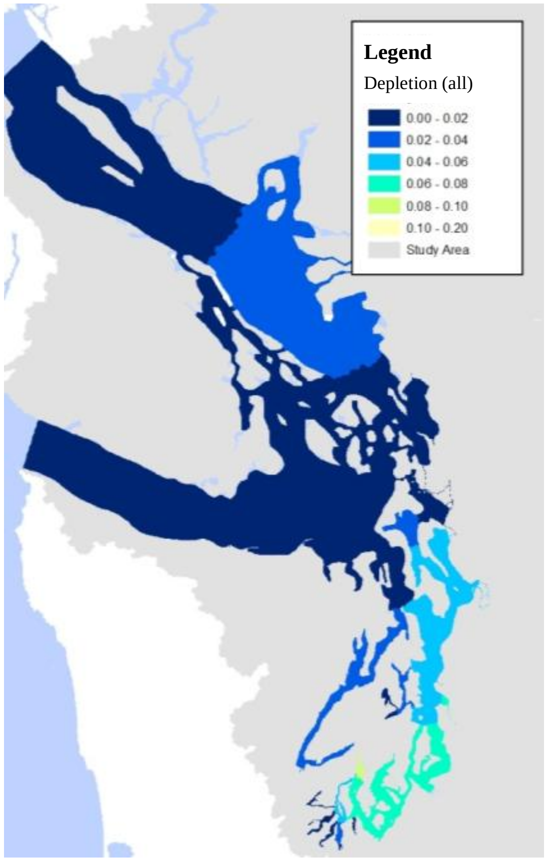
Scenario 4 is the combined effect of all current human contributions. Compared with natural conditions, current human contributions cause the largest average depletion in South Puget Sound and the southern end of Central Puget Sound. Regional depletions range up to 0.1 mg/L. Whidbey Basin and northern Central Puget have the next highest impacts. Average regional DO declines by up to 0.04 mg/L in Hood Canal and the Strait of Georgia. The lowest impacts are in the Strait of Juan de Fuca and northern Strait of Georgia. Current sources produce <0.02 mg/L depletions in the shallow regions of South Puget Sound inlets, Sinclair and Dyes Inlets, northern Whidbey Basin, and Bellingham Bay. These regional and seasonal values are not directly applicable to the water quality standards since they may mask higher depletions in smaller regions or shorter time periods.

Scenario 3 isolates the effect of current marine point sources only, while Scenario 2 isolates the impacts from human sources within watershed inflows. The marine point sources have a greater impact than human sources within watershed inflows.

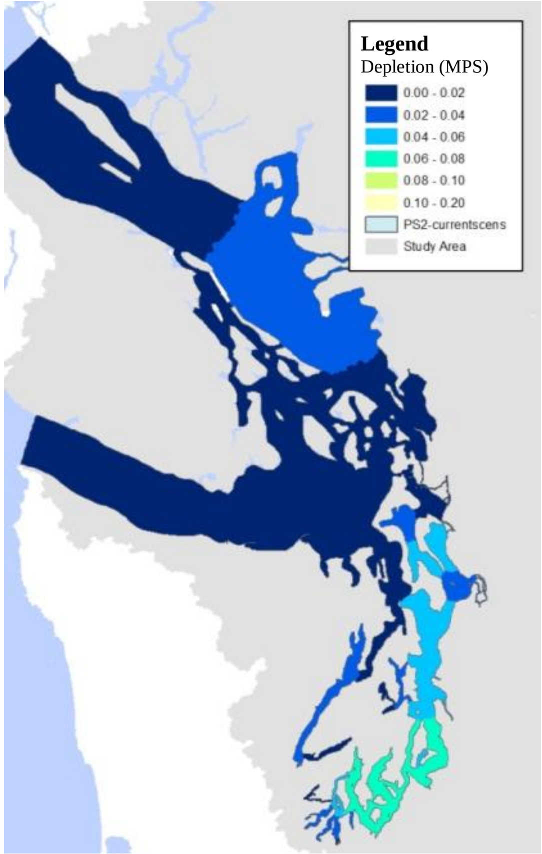
The total regional DO depletion values present as a single number the accumulation of many factors. The DO depletions from different loading scenarios result from small incremental changes in the nutrient and chlorophyll levels. As an example, Figure 43 presents the time series of profiles of DO, chlorophyll a, and nitrate for the four current scenarios at Station SS47 in northern Case Inlet.

The depth-time plots do not show visible differences in the patterns among scenarios. The same processes occur in each one, but the additional nitrogen slightly increases algae (chlorophyll), which adds slightly to the oxygen drawdown later in the year.

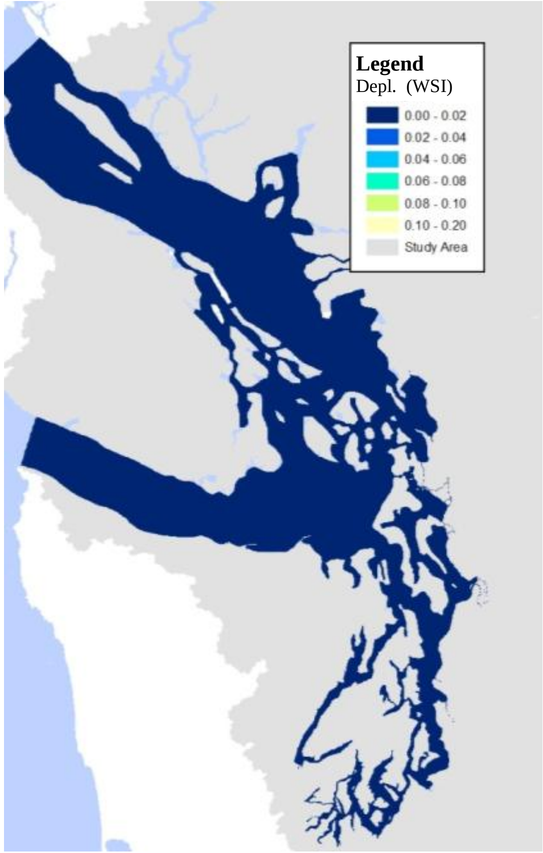
<table>
<tr>
<th>Scenario 4
Average regional depletion from all current human sources
(Run 20)</th>
<th>Scenario 3
Average regional depletion from marine point sources with watershed inflows at natural
(Run 25)</th>
<th>Scenario 2
Average regional depletion from human sources in watershed inflows with no marine point sources
(Run 24)</th>
</tr>
<tr>
<td>



</td>
<td>



</td>
<td>



</td>
</tr>
</table>

Figure 42. Average total regional dissolved oxygen depletion (mg/L) for September 1 through October 31 by region for current scenarios.

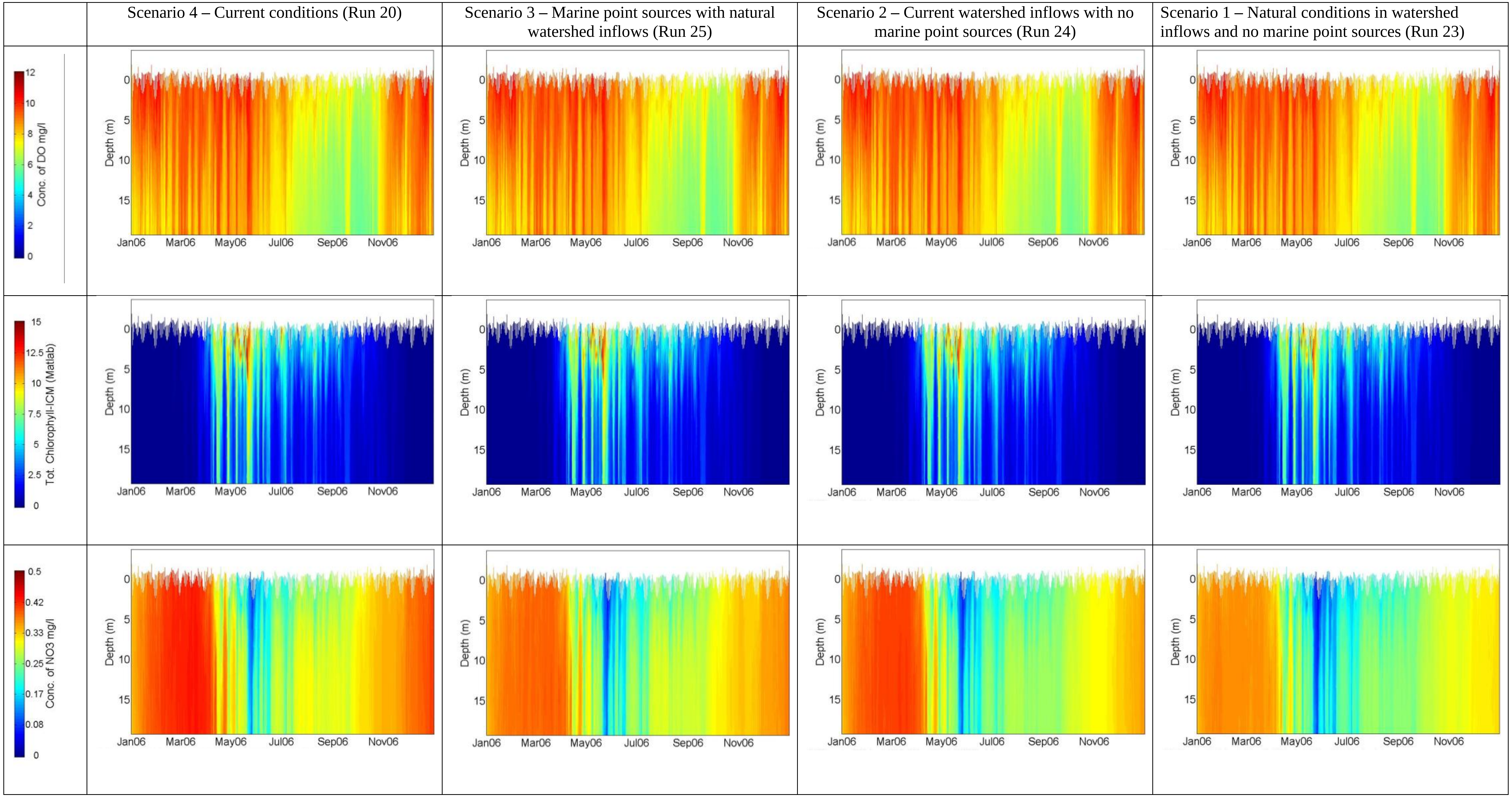


Figure 43. Depth-time profiles of oxygen (top), chlorophyll (middle), and nitrate (bottom) for current conditions, only marine point sources, only current watershed inflows, and natural conditions.

Future Scenarios

We evaluated several groups of scenarios that focus on different single or multiple factors that will change in 2020, 2040, and 2070:

- Increased human sources (watershed inflows and marine point sources) with 2006 ocean conditions.
- Increased human sources (watershed inflows and marine point sources) with future ocean conditions.
- Increased human sources (watershed inflows and marine point sources) with future ocean conditions and higher air temperature (only 2070).

Future human sources (watershed inflows and marine point sources)

We evaluated increased human sources in the future first considering only 2006 circulation patterns (Figure 44) but also future circulation patterns (Figure 45) where other factors could mitigate or exacerbate the effects of increased loading. Regional DO depletion would increase with increasing loads. The same regions that current human sources impact would exhibit the biggest depletions in the future.

Under current circulation patterns, average regional depletion would increase beyond 0.1 mg/L in South Puget Sound, Central Puget Sound, Possession Sound, and Hood Canal by 2070. The average regional depletion would increase beyond 0.2 mg/L in portions of South Puget Sound. As for current scenarios, this finding is not directly applicable to the water quality standards since it compares across regions and two months. The changes in the finger inlets of South Puget Sound warrant additional analysis to understand the factors contributing to these patterns.

Changes in the timing of watershed inflows and other factors could influence overall circulation. Impacts are projected to be higher in Hood Canal and the northern part of Central Puget Sound than if circulation follows 2006 patterns. Conversely, the South Sound finger inlets may experience some mitigating effect on circulation if future hydrology alters patterns there.

2020s Human Sources – Average regional depletion with 2006 ocean conditions and circulation (Run 29)	2040s Human Sources – Average regional depletion with 2006 ocean conditions and circulation (Run 30)	2070s Human Sources – Average regional depletion with 2006 ocean conditions and circulation (Run 31)

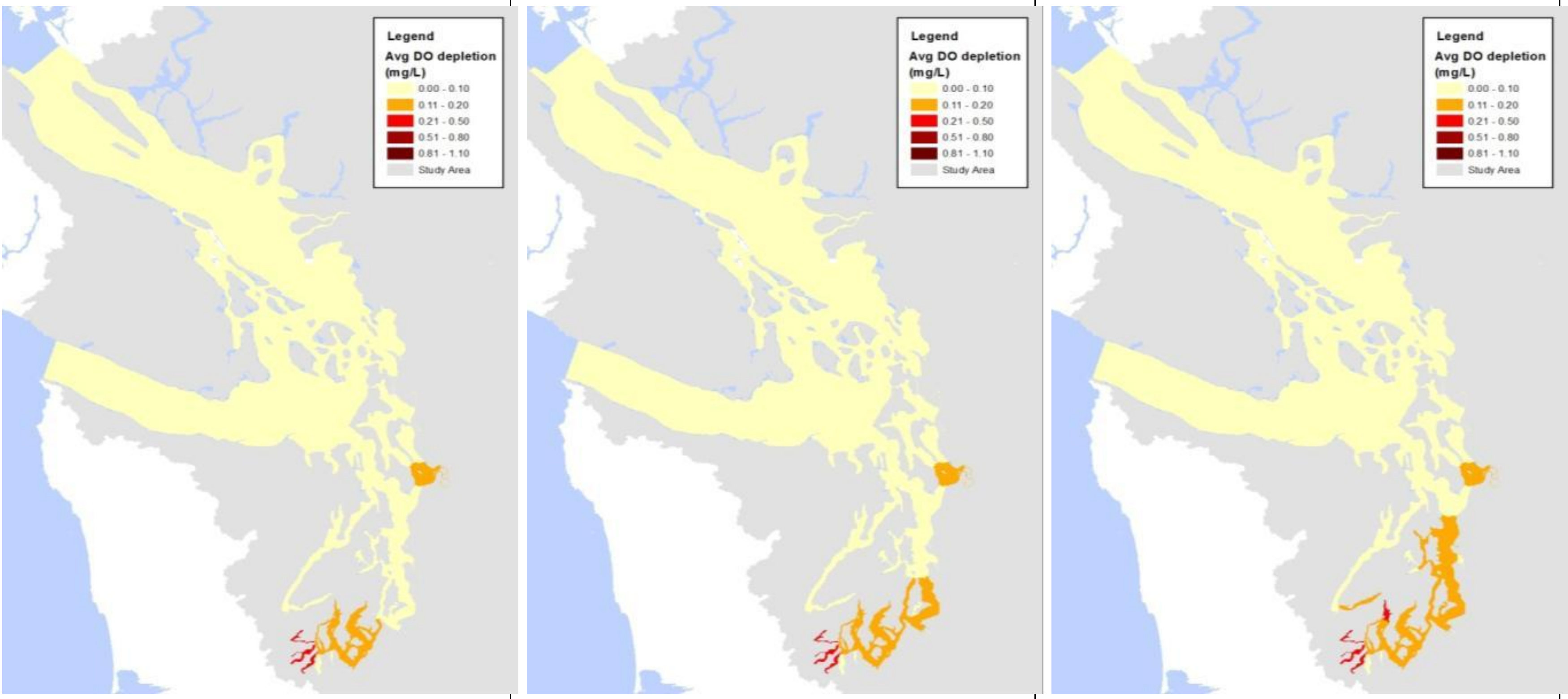


Figure 44. Average total regional dissolved oxygen depletion (mg/L) for September 1 through October 31 by region for scenarios with future human sources, current ocean conditions, and current circulation.

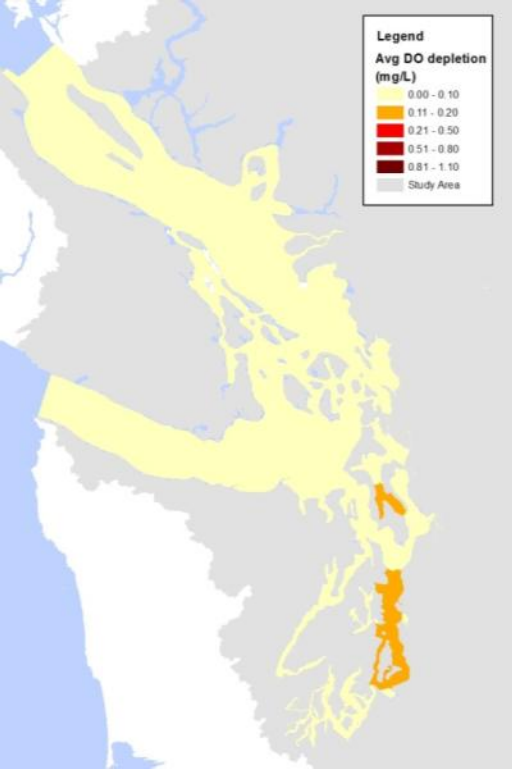
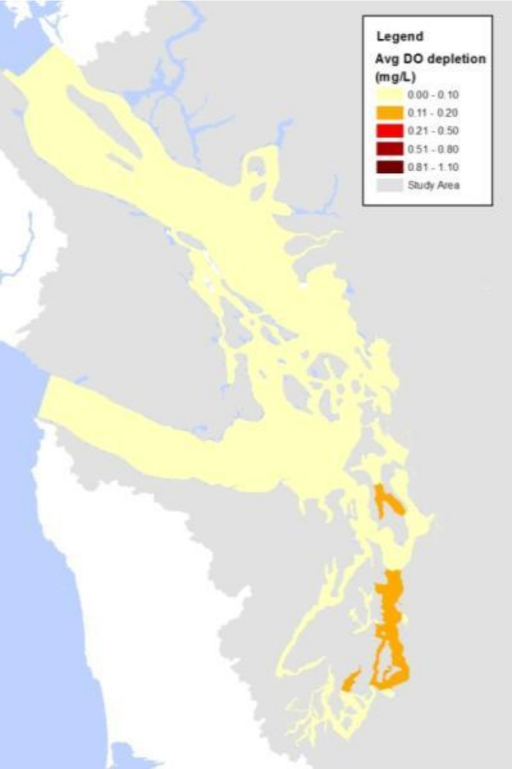
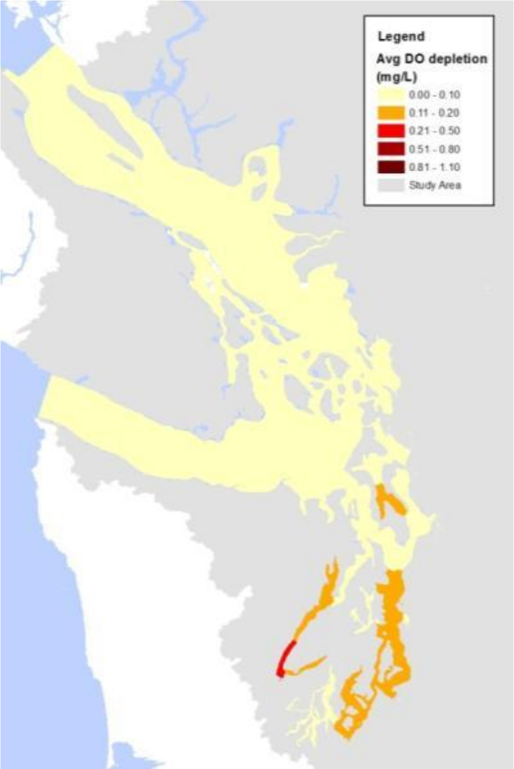
2020s Human Sources – Average regional depletion with 2006 ocean conditions and future circulation (Run 26)	2040s Human Sources – Average regional depletion with 2006 ocean conditions and future circulation (Run 27)	2070s Human Sources – Average regional depletion with 2006 ocean conditions and future circulation (Run 28)
		

Figure 45. Average total regional dissolved oxygen depletion (mg/L) for September 1 through October 31 by region for scenarios with future human sources, current ocean conditions, and future circulation.

Future human sources with future ocean conditions

The projected decline in DO and increase in nitrogen would decrease regional DO depletion through the model domain (Figure 46). The greatest impacts would occur in the Strait of Juan de Fuca beginning in 2020 and would extend south through Admiralty Inlet. The impacts are projected to be lower away from the ocean, such as the landward end of various inlets. Some of these regions responded most to the increase in human sources. The ocean has a larger impact on regional DO depletion, although some regions may be equally or more impacted by the increase in human loads. Shallow inlets may also show increased oxygen if the entire water column is in the euphotic zone.

By 2070, regional oxygen depletion would be over 1 mg/L in the Strait of Juan de Fuca compared with current natural conditions. Average regional DO could decline by over 0.6 mg/L in Central Puget Sound and Hood Canal.

2070 air temperature effects

We also evaluated the effect of increased future air temperatures on DO levels in Puget Sound and the Straits. Run 34 represents 2070 conditions for river flows, watershed inflows, marine point sources, and ocean conditions, with sediment scalars to account for the higher 2070 loads. Using that scenario as a baseline, we also scaled the heat balance the equivalent of increasing air temperatures throughout the region by 2.6 °C. Changes in air temperature could change water temperature and density, which in turn could affect stratification and circulation. Temperature-dependent processes such as algae growth could also be affected.

Air temperature increases will exacerbate regional DO depletion throughout the entire model domain (Figure 47). The additional impacts due to air temperature differences vary across the regions, however. Regional DO depletion in deeper waters of the Strait of Juan de Fuca and Strait of Georgia would not decrease considerably, on the order of 0.01 mg/L compared with the regional depletion in 2070 without considering air temperature increases. Increased air temperature would cause regional DO depletion to grow by 0.03 to 0.04 mg/L in Hood Canal and deeper waters of Central Puget Sound. Shallower regions like Bellingham Bay and Whidbey Basin could worsen up to 0.06 mg/L. Air temperature effects would have the biggest impacts on regional DO depletion in regions of shallow inlets. The finger inlets of South Puget Sound and Sinclair and Dyes Inlets could worsen by over 0.1 mg/L.

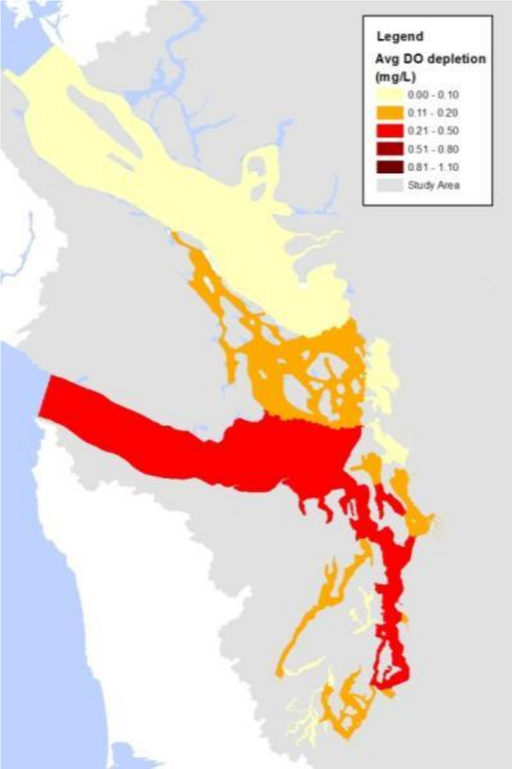
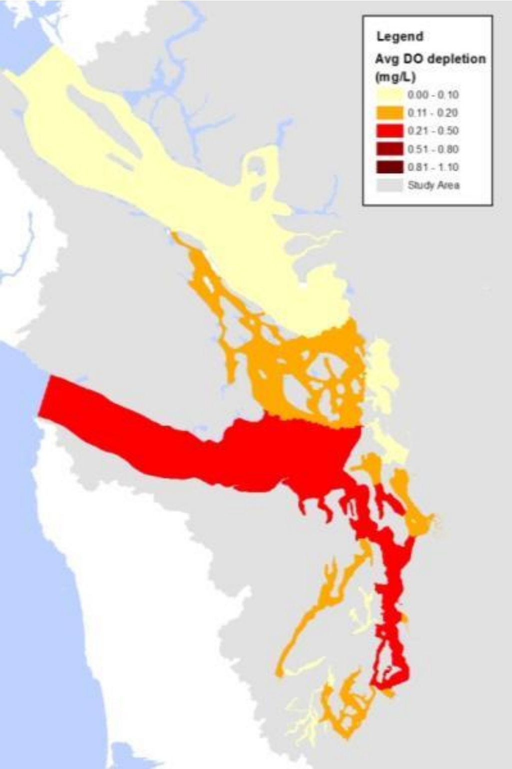
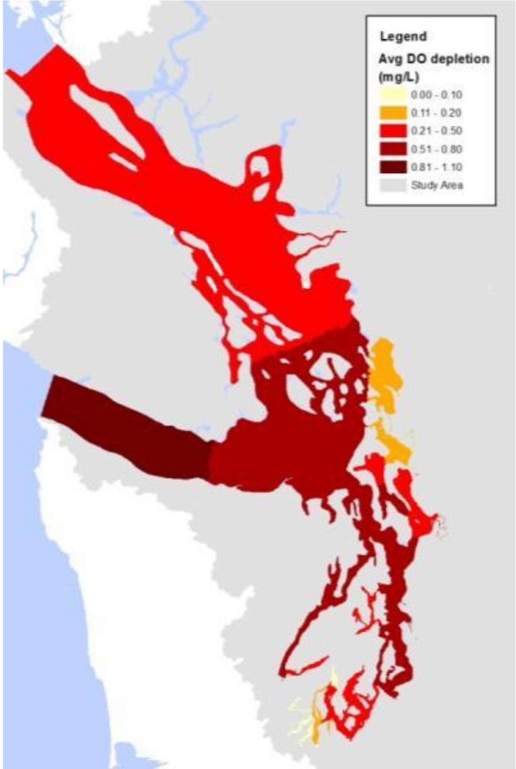
2020s Human Sources and Ocean Conditions – Average regional depletion with future circulation (Run 32)	2040s Human Sources and Ocean Conditions – Average regional depletion with future circulation (Run 33)	2070s Human Sources and Ocean Conditions – Average regional depletion with future circulation (Run 34)
		

Figure 46. Average total regional dissolved oxygen depletion (mg/L) for September 1 through October 31 by region for scenarios with the combined effect of future human sources and ocean conditions.

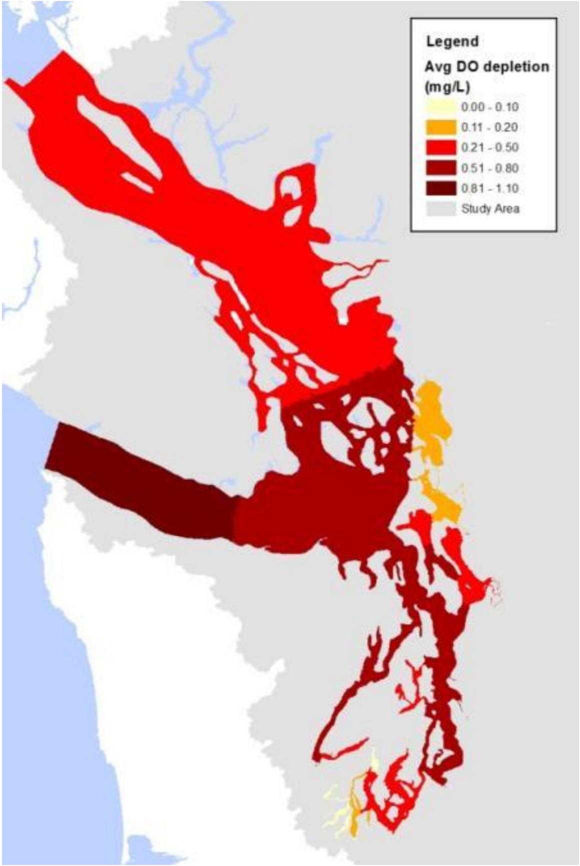
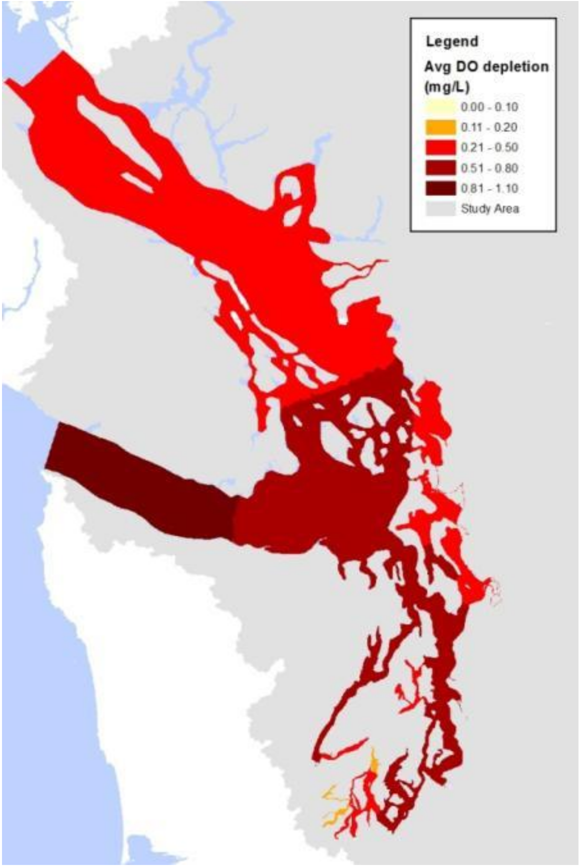
2070 Human Sources and Ocean Conditions with Current Air Temperature (Run 34)	2070 Human Sources and Ocean Conditions with Future Air Temperature) (Run 35)
	

Figure 47. Average total regional dissolved oxygen depletion (mg/L) for September 1 through October 31 by region for 2070 scenarios with current and future air temperature.

Discussion and Conclusions

Using a circulation and water quality model calibrated to 2006 conditions (Yang et al., 2010; Khangaonkar et al., 2011; Khangaonkar et al., 2012), we evaluated several potential influences on DO in the Salish Sea under current and future scenarios:

- Current marine point sources
- Current watershed inflows
- Future marine point sources
- Future watershed inflows with changes in hydrology and land use
- Pacific Ocean trends in DO and nitrate
- Future air temperature changes

We varied boundary conditions to reflect alternative conditions but maintained all other calibration parameters. Mohamedali et al. (2011) presented current marine point source and watershed inflow loads, including natural watershed loads. However, other boundary condition changes that represent alternative future scenarios were developed to support his assessment. No estimates existed for future marine point sources or watershed inflows that represent future population and land use change. These were developed for Puget Sound and the Straits using OFM population projects, wastewater treatment plant per capita flow, projected land use, and other key variables. Future ocean conditions were developed from existing literature (Whitney et al., 2007; Pierce et al., 2012). We relied on UW Climate Impacts Group for future air temperatures in the region. Major findings are described below.

Current Human Sources Decrease Oxygen Below Natural Conditions

The combination of current marine point sources and watershed inflows from the U.S. and Canada cause the greatest impacts in South and Central Puget Sound (Figure 48). The largest U.S. population centers occur around Central Puget Sound and discharge treated wastewater to deep waters. Central Puget Sound sources contribute over 70% of the nitrogen load from Puget Sound marine point sources. The net circulation pattern is landward, which transports some proportion of water from these marine point sources through the Tacoma Narrows and into South Puget Sound. Marine point source discharges from other large population centers in the U.S. and Canada occur closer to the Pacific Ocean boundary where residence time is shorter.

The Salish Sea model predicts declines in average regional DO by as much as 0.1 mg/L below natural conditions in portions of South and Central Puget Sound. These differences are not directly applicable to the Washington State water quality standards because they are aggregated over space and time. Maximum depletions are larger than the average values. The volume-weighted average regional DO enables the comparison across scenarios to understand large-scale patterns in space and time. The method also allows comparison of results from different circulation patterns. Altering the magnitude and timing of freshwater inflows potentially changes circulation so that low-oxygen regions shift. Comparing individual model elements and layers could erroneously identify these shifts as additional depletions. Regional DO inventories were used to account for any shifts.

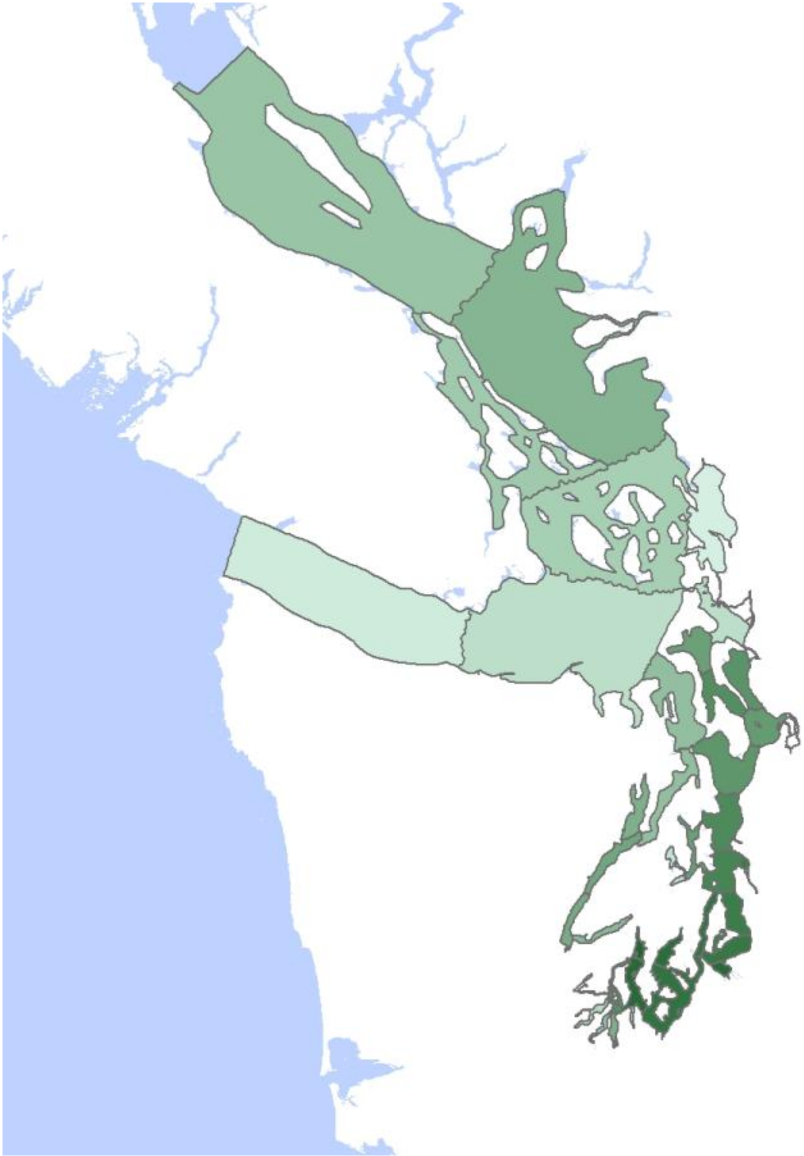


Figure 48. Relative impact of current human sources from marine point sources and watersheds in the U.S. and Canada.

Darker green indicates greater depletion.

Targeted modeling of South and Central Puget Sound (Ahmed et al., 2014) found similar patterns as in the Salish Sea model. That effort found portions of South Sound and the southern extent of Central Puget Sound have the highest impacts from human sources. However, the South and Central Puget Sound model predicts maximum depletions up to 0.4 mg/L in portions of Carr, Case, Totten, Eld, and Budd Inlets plus East Passage in Central Puget Sound. That analysis uses a cell-by-cell and layer-by-layer comparison of DO predictions to compare with the water quality standards. Aggregating larger volumes or longer time periods can mask declines at smaller scales in space or time or both.

The primary contributor to the lesser magnitude predicted with the Salish Sea model is the aggregation of results. Additional factors that may contribute to differences in magnitude include the following:

- The two models have different vertical layering within South and Central Puget Sound. The Salish Sea model describes the water column in 10 vertical layers. In sigma coordinate system, the layer thickness varies to represent depth differences due to bathymetry or tidal heights, but all locations have the same 10 layers. The South and Central Puget Sound model varies the number of layers to represent depth differences due to bathymetry or tidal heights. Some of the South Sound inlets such as Budd Inlet have only two layers. The difference in layering could produce different stratification and circulation in these portions of the model.
- The two models have different horizontal scales in South and Central Puget Sound. The Salish Sea model has wide variation in the horizontal scale with finer elements in ends of inlets and coarser elements in other areas.
- Both efforts externally specify benthic fluxes of oxygen and nitrogen. These are comparable in much of South and Central Puget Sound but the two models were parameterized differently in some areas. For example, the Salish Sea model specifies an oxygen demand that is lower in the deeper regions. The Salish Sea model also specifies a value more than twice that used in the South Sound model for Case Inlet but has a lower demand for Carr Inlet than the South Sound model. Specified values are within the range of the available data (Sheibley and Paulson, 2013) although deep-water values are sparse.
- The two models use different baseline years for the scenarios. The Salish Sea model uses 2006 while the South and Central Puget Sound effort uses 2007. While the annual flows to Puget Sound are comparable between 2006 and 2007 (Figure 21), there may be differences in monthly and seasonal flows within South and Central Puget Sound that alter circulation.
- The two models have similar skill, as measured by error statistics. The South and Central Puget Sound model is tuned to conditions in South and Central Puget Sound. The Salish Sea model is optimized for the entire Salish Sea rather than only South and Central Puget Sound. However, the calibrated rate parameters are similar.

From Figure 48, Whidbey Basin reflects the next highest impacts from human sources. Rivers discharging to Whidbey Basin deliver about 40% of the human sources within watershed inflows of the total generated in the Puget Sound watershed. Whidbey Basin also receives 10% of the Puget Sound marine point sources. The residence time is lower than in other basins, however, decreasing the localized impacts.

Hood Canal receives the lowest amount of human nutrient sources of any basin within U.S. waters of the Salish Sea. However, the residence time is the highest of any basin. The overall magnitude of current impact is higher in Hood Canal than the Straits even though Hood Canal receives lower human inputs. The difference is likely due to circulation. The current human impact on DO is the lowest of any body within Puget Sound. Sediment scalars were not adjusted in Hood Canal or the Straits because nitrogen loading from humans is so low. This could underestimate the differential effect of human contributions. A recent review found that human nitrogen sources are not contributing to the low DO in central Hood Canal (Cope and Roberts, 2013). Naturally low DO contributes to periodic fish kills from a combination of Pacific Ocean inputs and the physics of Hood Canal. However, Cope and Roberts (2013) could not determine whether or not human sources caused >0.2 mg/L impact at the landward end in Lynch Cove.

The Strait of Juan de Fuca currently has the lowest impact on DO from human sources in the Salish Sea. Part of this could be the very large region evaluated in this assessment. Smaller regions nearer to where human nutrient sources enter would likely show a greater relative impact, particularly enclosed regions such as Sequim Bay or Discovery Bay. The Strait of Juan de Fuca has the lowest residence time because it is next to the Pacific Ocean boundary.

The Strait of Georgia has a higher impact from human sources than the Strait of Juan de Fuca but is low overall. Marine point sources from the greater Vancouver region deliver the majority of the contribution from Canadian marine point sources, comparable to the marine point sources to Central Puget Sound. Human sources within the Fraser River also deliver nutrients to the Strait of Georgia and were considered in the impact estimates.

The human impact on DO around the San Juan Islands is intermediate between the Strait of Georgia and the Strait of Juan de Fuca but low overall. Local human sources are low but the region may be influenced by larger population centers nearby. This assessment did not focus on the small bays and inlets of the San Juan Islands, and localized human impacts on DO could occur.

Bellingham Bay exhibits a low impact from current human nutrient sources. The bay receives marine point source discharges and human sources within watershed inflows but exchanges water with the Straits. Localized human impacts on DO could occur at smaller spatial scales.

Overall the model is better at reproducing the processes that govern DO in deeper waters of Puget Sound and the Straits. Dissolved oxygen patterns in shallow inlets are more difficult to predict. This may be due a number of factors, but in general the model overmixes the water column. The entire water column is in the euphotic zone where algal respiration increases DO during daylight hours when most data are collected. Shallow inlets also are strongly affected by sediment processes. Available data suggests higher benthic fluxes in these shallow inlets than in deeper regions (Roberts et al., 2008; Sheibley and Paulson, 2013 in press). While we specified higher fluxes in shallow inlets than deeper waters, they may not adequately describe existing conditions.

The additional nitrogen from human sources increases DO compared with natural conditions in shallow inlets during the spring and summer seasons when algae blooms occur. The pattern can continue into the fall, however, where lingering warmer temperatures, solar radiation, and nitrogen inputs continue to spur algae growth. The increased DO from algal respiration can more than offset the sediment oxygen demand during this time period. Inlets with long residence times would be more prone to declining oxygen levels in the later fall and winter than inlets that flush quickly.

Marine point sources cause more depletion than human sources within watershed inflows

Watershed inflows deliver nitrogen loads to the surface layers where algae growth occurs. Marine point sources generally discharge to the lower water column, especially the largest wastewater plants, where effluent mixes with water below where most algae grow. We distributed marine point source loads from the largest plants across the model layers that correspond to the mixing zone for each large plant. Outfalls are designed to maximize mixing and to trap plumes in lower layers to minimize local impacts. However, nutrients from the lower water column can reach surface waters through vertical mixing, particularly at sills such as the Tacoma Narrows and Admiralty Inlet. Marine point sources appear to have a diffuse impact on surface water nitrogen levels that increases algae growth and decomposition, drawing down lower water column oxygen levels. The impacts are greater than those caused by human sources within watershed inflows.

Marine point sources contribute over four times the annual nutrient load as human sources within watershed inflows to Puget Sound (Mohamedali et al., 2011). Most of this nitrogen load is discharged to Central Puget Sound where the large population centers occur. The net estuarine circulation in the lower water column is landward, toward the regions of the Salish Sea with higher residence times. Marine point source loads are generally constant throughout the year because the population served is constant in most regions.

The largest human contribution within watershed inflows discharges to Whidbey Basin, where three of the five largest rivers discharge. Whidbey Basin water, particularly near the surface, exchanges quickly with Admiralty Inlet and nutrients can be transported out to the Strait of Juan de Fuca with net estuarine circulation patterns. The loads decline as river flows decline in the late summer and fall when lowest seasonal oxygen levels occur. The higher loads from marine point sources compared with watershed inflows produces greater DO depletions. Where and when the loads discharge likely influence the relative impact as well.

These results do not indicate that control of nutrients in rivers is unnecessary. We did not assess impacts of watershed nutrients on river or freshwater quality. Freshwater bodies may be more sensitive to nutrient additions associated with developed land uses. While we assessed DO in many inlets and smaller bays, we did not refine model predictions for these regions. This could have missed smaller-scale impacts. Where we have conducted smaller-scale assessments, such as in Budd Inlet (Roberts et al., 2012), we have found higher impacts.

Canadian sources included in current scenarios

We included but did not distinguish the relative impact of Canada's marine point sources on Salish Sea water quality. Depletion due to current human sources represents the combined effect of all U.S. and Canadian marine point sources discharging to marine waters. To simulate natural conditions, we eliminated all human inputs from the U.S. and Canada. Wastewater from the larger communities of Vancouver and Victoria discharges to the Straits in areas with shorter residence time than in Puget Sound. While some nutrients could reach Puget Sound, they are more likely to influence water quality in the San Juan Islands. However, large tidal exchanges through this region may mitigate potential impacts from any additional nutrients discharged from Canadian sources.

We also included but did not distinguish the differential impact from human sources within Canadian watershed inflows. Natural conditions eliminated all human contributions within U.S. and Canadian watershed inflows. Current scenarios reflect all U.S. and Canadian watershed inflows, including the Fraser River. The Fraser River is by far the largest source of freshwater to the Salish Sea, contributing 2,360 cms of the total 6,000 cms to the Salish Sea. Small changes in nitrogen concentration are equivalent to large changes in load. The methodology used to apportion current loads between natural conditions and human sources within the watersheds was optimized for U.S. watersheds. The proportion of current loads attributed to human contribution within the Fraser River could be overestimated.

Future Human Nutrient Loads Would Decrease Salish Sea Dissolved Oxygen Levels Through 2070

Current human sources have different levels of impacts in different regions. Increasing human sources in the future will increase the impacts in general, but the effect will vary by region.

Marine point sources discharge the largest loads of human nutrients to Puget Sound and the Straits, both currently and through 2070. Human sources also add nutrients from watershed inflows, which would increase in the future with land use change. The method used to estimate future loads is based on current relationships between land use and river nitrogen concentration. Future projections assume no change to management activities that would alter these relationships.

If the population served by municipal WWTPs doubles as projected by 2070 without changes to treatment technology, marine point source loads would increase by an additional 47,200 kg/d discharging to Puget Sound and the Straits. Land use changes would increase loads by 31,300 kg/d by 2070 compared with current conditions due to the conversion of forested land to developed land such as residential and agricultural uses. While wastewater loads are fairly more constant through the year than watershed inflows, exhibit strong seasonal variation.

Future watershed loads also incorporate the influences of future hydrology from climate change. Climate change does not result in significantly different annual watershed inflow rates. However, future precipitation and air temperature do alter the timing of flows. We project this would increase loads during the fall and spring but could decrease loads in the summer due to the flow change alone. We did not evaluate any synergistic or antagonistic effects of changes in flows and sources of nutrients within the watersheds.

The combined effect of nutrient load increases from marine point sources and watershed inflows would increase DO depletion. Average regional and seasonal DO depletion increases steadily in 2020, 2040, and 2070 compared with current conditions (Figures 44 and 45). The biggest changes occur in South Puget Sound and the southern part of Central Puget Sound, where current human sources have the highest relative impact. These population centers would continue to grow.

While the growth rate may be lower in urban areas than rural, the net change in population would be higher. Future marine point source loads scale with population.

Moderate changes are predicted in the rest of Central Puget Sound, Whidbey Basin, and Hood Canal. Dissolved oxygen depletion does not change extensively in the Straits due to future human sources alone. We evaluated the Straits at a coarser resolution than elsewhere, and this very large region is strongly influenced by the Pacific Ocean. Future assessments at higher resolution may identify local areas with greater or lesser DO depletion from human activities. In general, areas further from the Pacific Ocean with higher residence times and higher sources show greater DO depletion than areas nearer to the Pacific Ocean with lower residence times.

Because we compare among scenarios using the average seasonal and regional DO depletion, the results are not directly comparable to the second part of the water quality standards. This assessment may not identify smaller regions where DO would fall by more than 0.2 mg/L below natural conditions due to future loads. Additional analysis would be needed to evaluate these smaller scales.

Canadian sources included in future scenarios

We included impacts from Canadian sources in future scenarios. However, we did not distinguish the relative impacts of Canadian and U.S. sources. Projected impacts include the influence of all sources.

For future scenarios, we scaled Canadian marine point sources with population projections using the same method as for future U.S. marine point sources. The average regional DO depletion between scenarios includes the combined effect of Canadian and U.S. marine point sources. Canadian WWTPs currently serve 2.2 million people in greater Vancouver, comparable to the 1.8 million people in the greater Seattle area. By 2070, Canadian contributions would increase to 52,400 kg/d, similar to the projected 59,800 kg/d for U.S. marine point sources. This approach assumes no change in treatment technology, with two of the five Vancouver plants discharging with primary treatment.

We also projected Canadian flows for future scenarios to reflect climate change impacts on hydrology. We did not change Canadian watershed inflow concentrations because we did not have future land use projections, nor did we have sufficient watershed inflow data on which to develop land use relationships.

The increase in marine point source loads does not cause the same increase in DO depletion in the Strait of Georgia as occurs in Puget Sound with future population. The different relative response is likely the higher circulation and proximity to the Straits and the Pacific Ocean.

Changes in WWTP technology could offset future increases in marine point source nitrogen loads through 2070

Future loads from marine point sources would nearly double if current treatment technology used at each wastewater plant continues as is. The population served by centralized municipal WWTPs that discharge to marine waters is expected to double by 2070. Nutrient-removal treatment technology is capable of reducing typical effluent nitrogen concentrations to one-third of current concentrations. If future loads require reductions, biological nutrient removal technology available today could decrease effluent nutrient loads. This would result in a net decrease in marine point source loads in 2070 compared with current conditions if applied at all wastewater treatment plants (Figure 34).

Because some plants discharge low nitrogen concentrations in the effluent already, biological nutrient removal would not necessarily reduce loads from every plant. Upgrading to nutrient removal at the three largest plants by projected 2070 flow (West Point, South King, Chambers Creek) would nearly offset the future population increases; loads would grow by 4% compared with current conditions if applied to all flow from those three plants. Including nutrient removal at the five largest plants representing 62% of the municipal WWTP flow (West Point, South King, Chambers Creek, Everett/Snohomish, and Brightwater would more than offset future population increases.

Nutrient removal technology may be more or less feasible in some municipal WWTPs than others. Several ongoing and recent WWTP upgrades have planned for the option of adding biological nutrient removal technology should it be required under future NPDES permits. Other WWTPs may be limited by land availability and other constraints. In all cases, nutrient removal technology would increase costs above current levels. Installing existing technology at all plants could lead to 2070 marine point source loads that are 40% less than current loads, while serving twice as many people.

Pacific Ocean Trends Would Decrease Salish Sea Dissolved Oxygen Levels Through 2070

The Pacific Ocean exerts the strongest influence on Salish Sea DO levels, both now and into the future. If 50-year Pacific Ocean trends continue, decreasing DO concentrations coupled with increasing trends in nitrate would cause widespread decreases in DO concentrations in Puget Sound and the Straits compared with current conditions. However, future ocean conditions are highly uncertain.

If this trend continues through 2070, and there is no indication whether or not this is likely from the literature, the changes would decrease DO concentrations by 1.5 mg/L compared with water that currently reaches the Strait of Juan de Fuca. The decrease is occurring at all depths evaluated in the North Pacific Ocean (Whitney et al., 2007; Pierce et al., 2012). The Strait of Juan de Fuca would experience the greatest impact, with a decline over 0.8 mg/L in the average regional DO. The strong decline would extend into the Strait of Georgia as well as Puget Sound. Within Puget Sound, the greatest impact from a change in Pacific Ocean conditions would occur in Hood Canal and in the Main Basin of Central Puget Sound. The relative impact of future ocean conditions declines in a landward direction. The lowest impacts from future ocean conditions occur in the smaller inlets of South Puget Sound and enclosed bays because they are furthest from the ocean and more influenced by local and regional sources.

Future ocean conditions, if the trends continue, would have a greater impact on DO than future increases in human nitrogen loads compared with today's natural conditions. By 2070, the average regional DO depletion would decline by over 0.2 mg/L except in Bellingham Bay, Skagit Bay, and the finger inlets of South Puget Sound.

Future ocean conditions are both highly influential and highly uncertain. We also do not know if these trends result from natural conditions or if human activities contribute. Researchers have not determined whether the 50-year trend in DO will continue or if it is part of a larger cycle that will eventually turn around (Pierce et al., 2012).

Several factors could contribute to the decline in DO measured off the British Columbia and Oregon coasts. Using coarse-scale models and data analyses, research suggests that a slowing of Pacific Ocean circulation or shift in Pacific Ocean currents likely has the strongest influence. This would lead to "older" water upwelling off the coast that has been isolated from atmospheric replenishment longer than occurred historically. Processes that draw down oxygen would extend longer and would produce lower oxygen concentrations.

North Pacific Ocean circulation results from the complex interactions of atmospheric, oceanic, and terrestrial processes. Each process varies by location and with time, and the interactions may be additive or may offset each other. For example, cool-phase Pacific Decadal Oscillations are associated with cooler temperatures, but El Niño can occur at the same time and induce warm temperatures. The strength of coastal upwelling is related to coastal wind patterns, which can impact marine biota as occurred in 2006 off the Washington and Oregon coasts (Chan et al., 2008). Changes in coastal freshwater inputs affect salinity levels, which in turn affect circulation patterns.

Additional analyses are warranted to understand processes behind the trends in the North Pacific. These include both sensitivity analyses using the existing model and also collaboration with US, Canadian, and international researchers.

Several factors may influence future DO levels in Pacific Ocean water:

- Changes in Pacific Ocean circulation.
- Changes in air-water exchanges of DO (ventilation) including changes in stratification.
- Changes in biological systems that include primary productivity and organic matter export and decomposition.

Deutsch et al. (2006) compared oxygen simulations for the 1980s and 1990s using a coupled circulation and simple biogeochemical model. Although the North Pacific exhibits high variability in space and time, the model predicts declines in subpolar region oxygen levels consistent with observations at Ocean Station Papa (Whitney et al., 2007). Deutsch et al. (2006)

identified shifts in currents and changes in ventilation as the dominant contributors. Changes in biological activity had a lower effect.

The North Pacific Ocean varies on an 18.6-year time scale called the lunar nodal cycle. Whitney et al. (2007) attributed high oxygen levels in the North Pacific in 1959, 1978, and 1995 to this process. The highest concentrations in the western Pacific lag those near Japan and Russia by 6 to 7 years, the transport time of the North Pacific Current. Circulation effects could be due to predictable patterns.

The changes in North Pacific Ocean oxygen have not been linked to specific biological responses. Researchers have found little variability in chlorophyll a levels in the northeastern Pacific except near the North American coast from year to year. Mackas et al. (2007) found that zooplankton have shifted north with rising temperatures.

Higher Air Temperatures Would Further Decrease Salish Sea Dissolved Oxygen

Climate change models predict an air temperature increase of 2.6 °C by 2070 for the Puget Sound region (UW Climate Impacts Group, 2013). Climate change models also predict other changes, in addition to air temperature and precipitation, but we focused on these with targeted future scenarios because well established estimates are available. We found that air temperature increases by 2070 would further decrease DO below that predicted considering both future human and natural loads and future ocean conditions. The effect would be greatest in shallow inlets.

Increased temperatures could affect marine DO through several processes. Warmer air temperature leads to warmer surface water in deep regions but warmer temperatures throughout the water column in shallow areas. Because warmer water holds less DO than cooler water at the same saturation, temperature alone can affect marine DO concentrations. In addition, warmer water could accelerate or alter the timing of algae growth and other biological processes that result in lower DO.

Additional Analyses Needed for Sediments, Climate, and Future Circulation

Several factors were incorporated in various scenarios but the effects of individual factors were not evaluated separately. Sediment processes and circulation strongly influence marine DO levels, and additional analyses are needed to refine them.

Sediments exert a strong influence on marine dissolved oxygen levels

Fluxes of oxygen into the sediments decrease oxygen concentrations in the lower water column where atmospheric processes cannot replenish them. Ammonia fluxes (out of the sediment) and nitrate fluxes (into the sediment) represent part of the nitrogen cycle driven by particles settling into the sediments from the water column. Seasonal nitrogen releases from the sediments, particularly in shallow inlets, can be greater than the nitrogen coming in from watershed inflows, including human sources, during the late summer (Roberts et al., 2008; King County, 2012).

For this evaluation, we externally specified benthic fluxes of oxygen and nitrogen because the current model does not dynamically simulate sediment-water exchanges through sediment diagenesis processes. We scaled the sediment fluxes to reflect changes in external loading for alternative loading scenarios. The scaled fluxes add to the relative impact of particular external sources. We applied the sediment flux scalars to benthic environments in Whidbey Basin, South Puget Sound, and Central Puget Sound because these are the regions with the largest external sources of nutrients from the combined effects of watershed inflows and marine point sources. We did not apply the sediment flux scalars to Hood Canal or the Straits because we were concerned that this would overestimate human impacts in regions with relatively low current impacts.

Because sediment fluxes occur across large regions, a small change in this scalar is equivalent to a large mass of oxygen and nitrogen. The sediment flux scalars represent the best available approach.

Very little information exists to characterize natural and enriched sediment fluxes due to human activities (Sheibley and Paulson, 2013). Monitoring programs in Budd Inlet (Aura Nova Consultants et al., 1998), South Puget Sound (Roberts et al., 2008), and Quartermaster Harbor (King County, 2012) evaluated only small portions of South and Central Puget Sound with water depths up to 25 meters maximum. Sheibley and Paulson (2013) summarized nitrogen fluxes from chamber and pore-water measurements and found higher fluxes in shallow-water environments than deep waters. Deep-water environments also exhibited less variability; however, nearly all deep-water data came from one region within Hood Canal and may not be representative of larger regions of Puget Sound or the Straits. Shallow-water fluxes varied greatly by location.

Climate change could mitigate or exacerbate dissolved oxygen impacts

The North Pacific Ocean exhibits warming trends in temperature attributed to climate change in addition to declines in DO throughout the water column (Whitney et al., 2007). Some researchers have identified changes in salinity, although magnitude and direction differ among studies in deeper or shallow water. Stratification overall appears to be strengthening, which could contribute to the downward trend in oxygen. The change in stratification from both salinity and temperature changes would also affect circulation. This assessment focuses on changes in DO and nitrogen alone, but additional analyses are needed that also incorporate changes in temperature and salinity at the ocean boundary to assess other potential effects of climate change. We do not yet know whether this would mitigate or exacerbate DO impacts.

Changes in hydrology associated with climate change could offset some of the DO depletion caused by increasing future nitrogen concentrations. Under current conditions, U.S. watershed inflows peak in the winter months of November through January. A secondary snowmelt peak occurs in May and June. The lowest flows occur in August through October. The VIC model, driven by climate change models, predicts increases in winter peak flow, decreases in summer minimum flows, and a shift about a month earlier of the spring snowmelt peak. The change in flow regime, coupled with future land-cover-based concentrations, would alter the magnitude and timing of nutrient load delivery from watershed inflows. We have not isolated these processes.

The changes in the magnitude and delivery of freshwater flow could alter circulation in Puget Sound and the Straits. Estuarine circulation patterns can mitigate or exacerbate impacts from the addition of human nitrogen. Increasing flow could increase estuarine circulation, which could flush out nutrients more quickly. Decreases in flows could decrease estuarine circulation, which increases residence time and sensitivity to nitrogen addition. We did not isolate the impact of altered hydrology on marine DO concentrations. However, DO depletion scores are higher (worse) for Runs 29-31 (2006 circulation and future loads) than Runs 26-28 (future circulation and future loads). It is possible that future freshwater delivery could partly offset decreases in DO resulting from higher nitrogen loads. Additional investigation is warranted to understand these relationships.

Additional Analyses Needed for Fraser River

The method used to develop natural conditions for the rest of the study area may overestimate current human contributions in the Fraser River loads. Additional analyses could identify better ways of assessing Fraser River natural, current, and future conditions. A sensitivity analysis could be conducted to evaluate how influential these loads are on DO in the Salish Sea.

Freshwater Bodies May Be More Sensitive To Nutrients Than Marine Waters

We did not assess the sensitivity of freshwater bodies to increasing human nutrient loads in this assessment. We evaluated marine responses to the addition of nutrients from freshwaters, including treated wastewater effluent and watershed inflows. While we did not find extreme or widespread DO depletions due to current human nitrogen contributions in watershed inflows, we did not evaluate smaller spatial scales where impacts may be greater. Also, these results cannot be extrapolated to the freshwater bodies in the Salish Sea watershed. These may be more sensitive than marine waters to nutrient addition.

Uncertainty and Limitations

The purpose of this assessment was to evaluate the relative contributions to low DO from various sources now and through 2070. To do so requires a series of assumptions and extrapolations in both time and space. Uncertainty affects each of the potential stressors included in this assessment. Categories of uncertainty include the boundary conditions used to describe alternative scenarios, related parameters adjusted in the scenarios, and the parameters used in the model to describe key processes. Figure 49 portrays conceptually the relative uncertainty and the relative influence of different factors and processes. Uncertainty in future projections is described first because future scenarios are more uncertain than scenarios isolating the impacts of current sources. We have not attempted to provide confidence intervals or other measures of uncertainty, and we selected the best available information or most likely patterns to characterize alternative scenarios.

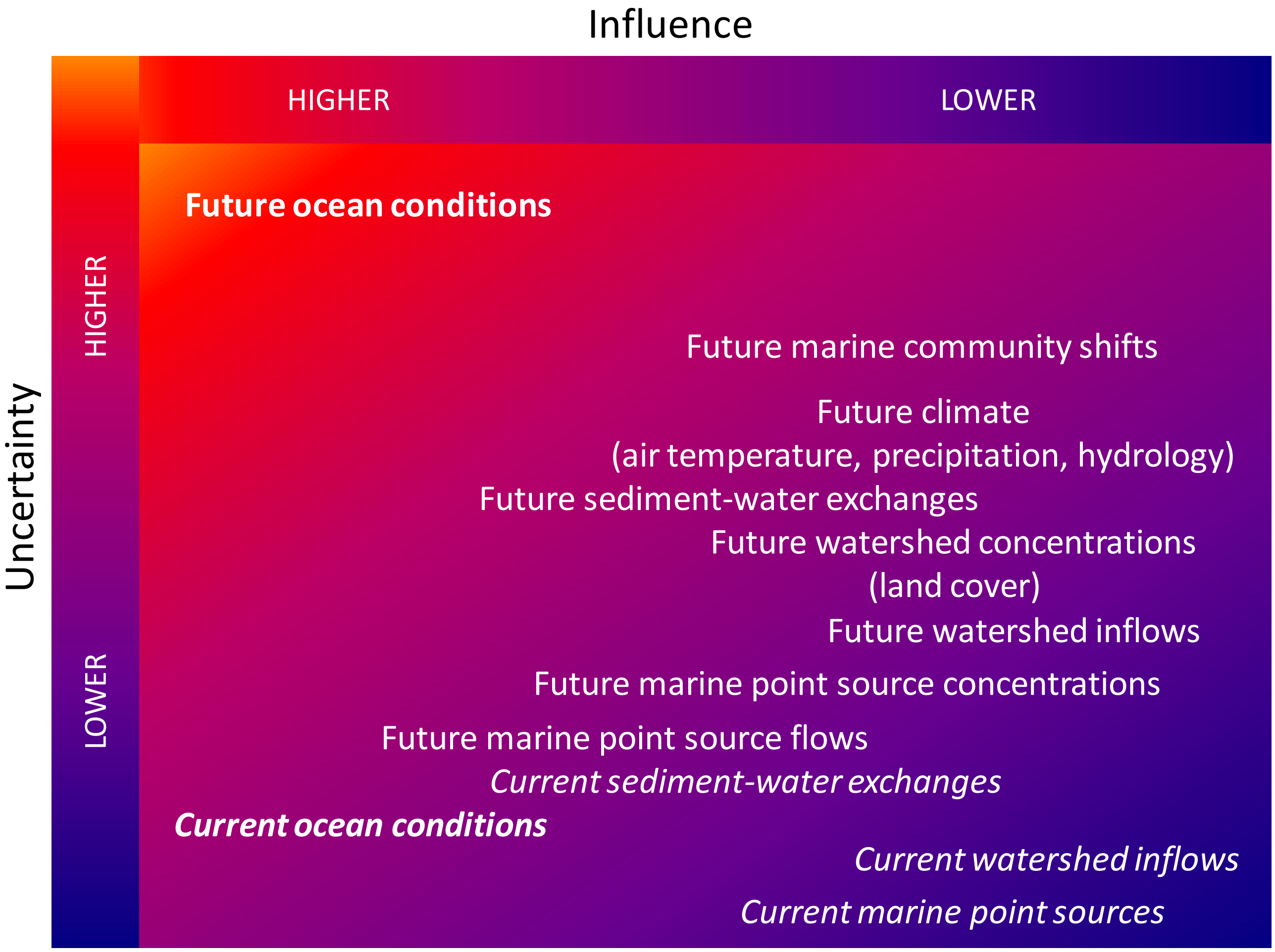


Figure 49. Conceptual diagram of the relative influence and uncertainty surrounding current (italics) and future scenarios.

Future ocean conditions

If current trends continue, future ocean conditions have the potential to fundamentally alter DO in Puget Sound and the Straits. However, even with the Ocean Station P time series, which may be the most detailed, longest-duration oceanographic DO measurements on the planet, we do not know what is driving the decline in North Pacific Ocean DO concentrations. More importantly, we do not know whether this decline is a true long-term trend or if the decline is part of a larger cycle that could improve DO in the near or distant future. We also do not know if these changes are natural or result from human activities. Future ocean conditions are both highly influential and highly uncertain. This assessment includes the best available information on Pacific Ocean DO and nitrogen trends and patterns.

Marine community shifts and model rate parameters

The rate parameters used to calibrate the model to current conditions were developed based on 2007 conditions in Puget Sound and the Straits. Algae growth parameters, for example, represent broad characteristics of two communities of algae that prefer spring conditions and another community that prefers the growth conditions of the summer. We have no information on whether these same communities will be present and static in the future or if they will adapt to changing temperatures or light regimes. Until better information is available to assess these factors, we have no information on which to base a change in the calibration parameters. However, we recognize that biological factors in particular are among the most uncertain in any assessment such as this.

Climate change

Climate change will increase air temperature and alter patterns of precipitation and hydrology (Dalton et al., 2013). The Global Climate Modeling community typically uses an ensemble approach to forecast likely changes due to different factors. The UW Climate Impacts Group used the mid-range forecast on which to base future hydrology modeling. More or less extreme changes in temperature, precipitation, and hydrology are included in the ensemble of forecasts, but we were limited to one future climate scenario for this assessment. However, additional forecasts are available but have not been assessed to date with the Salish Sea model.

Future sediment-water exchanges

Future sediment-water exchanges are moderately uncertain and influential. We expect fluxes to increase or decrease with changes in loading. However, the method used to scale fluxes did not include the ocean contribution, which could overestimate the scalar adjustment. Small changes to the scalars are equivalent to large mass loads of oxygen into the sediments and ammonia out of the sediments. These fluxes also reflect biological processes that are themselves quite complex. We have no additional information on how sediment fluxes would change in the future under alternative loading from the ocean or from the Salish Sea watershed.

The process for adjusting the sediment-water exchanges represents the best available approach. A subsequent phase of DO modeling will include a process called sediment diagenesis. With this capability, we will simulate the deposition of particles to the sediments as well as the remineralization and releases of ammonium to the water column that are so significant in shallow inlets in the summer months. The process will also dynamically simulate the net flux of nitrate and oxygen into the sediment. This is a large area of uncertainty.

Future watershed inflows

Nitrogen concentrations in future watershed inflows are moderately uncertain but only somewhat influential compared with other potential factors. Forecasting future land use is inherently uncertain. Land use patterns reflect a complex array of socioeconomic factors, government policies, and individual decisions. The OSU (2012) Alternative Futures effort represents the best available information on future land use patterns that incorporate our understanding of the primary quantifiable factors. We extrapolate current relationships between land use and nitrogen concentrations to future conditions. This assumes that a future incremental decrease in forested land and incremental increase in developed land (residential, agricultural) will produce the same changes in river nitrogen that occur today.

Future watershed inflows also have uncertainty that is based on future climate and translating future climate to changes in flows. This assessment assumes no change in the extent of dams or interbasin flow transfers and does not consider any changes in flows due to consumptive uses. Because flows seasonally decline when low oxygen levels occur, this process has less influence on relative impact on DO than other factors evaluated.

Future marine point sources

Future marine point sources are driven by future population. Population projections are inherently uncertain, and the uncertainty grows into the future. The methods used to project population today into the future have not been available long enough to test the accuracy of long-term projections. Population projections do include High, Medium, and Low scenarios (OFM, 2012). Because we could not evaluate a large number of future population scenarios with the Salish Sea model, we used the Medium scenario.

Another significant area of uncertainty that dominates future marine point sources is the degree to which nutrient removal technology is adopted in the future. In the US, these decisions can be made based on water quality considerations or could be part of a change to the minimum treatment practices. Some treatment technologies may be adopted at some plants and not others, and the technologies would likely be adopted in phases over decades. We do not know if, when, or where nutrient removal technology will be incorporated. Therefore, we analyzed the DO impacts assuming no change in current management practices. Presently, wastewater plants in Washington State treat wastewater to meet secondary treatment standards but do not necessarily remove nitrogen. However, adoption of nutrient removal in at least some plants could reduce nutrients discharged from marine point sources compared with current loads.

We have less information on industrial marine point sources than municipal plants. Best available information does not indicate high industrial effluent concentrations of nitrogen (Roberts et al., 2008). Because they discharge such a low proportion of marine point source nitrogen load, the uncertainty associated with industrial marine point sources is moderate but potential impact is low.

Current ocean conditions

Current ocean conditions are highly influential, but relatively little monitoring occurs to characterize water quality at the Strait of Juan de Fuca. While quarterly monitoring captures seasonal patterns, which is the time scale of interest to this assessment, it does not capture short-term phenomenon that could influence circulation and water quality in Puget Sound and the Straits (Deppe et al., 2013). Current programs also do not characterize total nitrogen, which could be used to estimate organic nitrogen. We have assumed that organic nitrogen in incoming water is negligible. However, even very small concentrations represent large mass fluxes due to the high volume of water. This could be underestimating the amount of nitrogen entering the model domain.

Current sediment-water exchanges

Of the factors contributing to uncertainty in the current scenarios, the sediment-water exchanges are likely the highest, although not as high as for any of the factors associated with future scenarios. Very little data exist to characterize benthic fluxes, and the limited data favor shallow regions (Sheibley and Paulson, 2013). Sediment fluxes of oxygen and nitrogen were adjusted during calibration. While the calibrated values are reasonable and the process used to adjust fluxes to isolate sources is reasonable, current sediment processes do influence the magnitude of the predicted depletions. As described below, we will add the capability to simulate sediment-water fluxes dynamically, which could help narrow the regions influenced by particular external sources.

Current watershed inflows

U.S. watershed inflows are based on the extensive river flow gaging network of the U.S. Geological Survey, supplemented with other local information. Mohamedali et al. (2011) described how these flows were scaled up to represent the entire watershed draining to U.S. waters of Puget Sound and the Straits. Streamflow gaging has some uncertainty, particularly at very high flow rates, but would be a low source of uncertainty.

Current watershed inflows, considering both natural and human sources, are well characterized with the information presented in Mohamedali et al. (2011). Concentrations are based on measured data. Rather than include a watershed model that could increase uncertainty, we opted for a regression-based approach to provide the best characterization of current concentrations and loads. More uncertain is the designation of natural conditions within the watershed inflows. The human contributions were calculated by difference and are subject to the same uncertainty as the natural conditions within the watershed inflows. The loads were developed by extrapolating from monitored to unmonitored locations based on proximity and watershed characteristics. However, this extrapolation increases uncertainty. Ongoing work by the U.S. Geological Survey is investigating patterns of nutrients in watershed inflows and could improve estimates of natural conditions over time.

We estimated natural conditions within watershed inflows through a meta analysis described in Mohamedali et al. (2011). This is the best available information. However, we lack monitoring data prior to 1980s to check these estimates. Each scenario is compared with natural conditions. This induces uncertainty in the absolute differences between current conditions and natural conditions.

Natural conditions were based on 2006 conditions used for model calibration. Future watershed inflow volumes were based on 10-year ensembles to represent the 2020s, 2040s, and 2070s. This provided decadal patterns in monthly streamflows that were less influenced by a single year’s hydrology. However, 2006 hydrology reflected a few patterns specific to that year (Figure 24). The 2006 summer baseflows were lower than normal, and a flood event in November 2006 produced unusually high monthly flows as well. While hydrology forecasts indicate drops in summer baseflow and increases in late fall flows, the 2006 monthly values were more extreme than forecast for future typical conditions. Differences between current natural and future scenarios that include streamflow alteration could be partly due to comparing a one-year pattern to a 10-year pattern.

We generally had less information for Canadian marine point sources or watershed inflows than for U.S. nutrient sources. We focused this assessment on impacts from U.S. sources but included Canadian sources for completeness.

Current marine point sources

Current marine point source and total watershed loads developed and described in Mohamedali et al. (2011) represent the best available information and are reasonably certain. The marine point source loads were developed from data collected from the larger plants serving the communities of Seattle, Tacoma, Olympia, Shelton, and the counties surrounding South and Central Puget Sound (Roberts et al., 2008). That monitoring program was established for the South Sound Dissolved Oxygen Study to refine wastewater plant loads and covered most of the municipal marine point source volume to the U.S. waters of the Salish Sea. We extrapolated to wastewater plants beyond that study area, which does induce uncertainty because we lack detailed plant-specific nutrient information. However, we have detailed information for the largest sources and also the sources discharging in and near the areas with the highest human impacts. We used Canadian monitoring data for those sources.

Finally, all scenarios were evaluated by comparing to natural conditions in 2006. Each run was one year in duration, based on the same set of initial conditions. We expect that some processes or regions may not have fully responded to the boundary conditions used to describe future scenarios. This should be evaluated in future model applications.

Comparison with Other Studies

This is the first detailed assessment of how current and future factors that potentially affect DO in Puget Sound and the Salish Sea. The absolute magnitudes of the predicted impacts of current human sources have been evaluated previously but using either simple approaches or covering a small region.

- Mackas and Harrison (1997) identified a low likelihood that wastewater and a few other human sources were contributing to eutrophication throughout the Salish Sea using a salt balance. They used a salt-balance model and nitrogen load estimates for wastewater, watersheds, and atmospheric deposition.
- Roberts et al. (2012) found human nutrient contributions cause over 0.2 mg/L in DO depletion compared with natural conditions in Budd Inlet using a cell-by-cell comparison of hourly model output.

- Ahmed et al. (2014) found >0.2 mg/L depletion in Budd Inlet using a cell-by-cell comparison of hourly model output. That analysis also found DO depletions in Carr, Case, Totten, and Eld Inlets in South Puget Sound, plus East Passage in Central Puget Sound.
- Modeling work in Quartermaster Harbor is ongoing (DeGasperi, personal communication).
- Cope and Roberts (2013) found very low impacts from human contributions to Central Hood Canal DO level based on a review of other sources. Cope and Roberts (2013) could not determine whether human sources to Lynch Cove, the landward end of Hood Canal, were causing DO depletion >0.2 mg/L due to limitations in the methodology.

Recommendations for Future Assessments

With this assessment we have learned a great deal about dissolved oxygen (DO) in the complex system of the Salish Sea, including Puget Sound and its many regions. This is the first time that Ecology has been able to evaluate whether the low DO levels measured in Puget Sound are due to natural conditions, human contributions, or both. This is also the first assessment of how predicted changes in the Pacific Ocean and climate change may affect Puget Sound and the Salish Sea. We needed detailed computer modeling to distinguish these influences. However, additional certainty is needed, and we must continue to improve these prediction tools. We recommend two next steps.

1. The model development should focus on adding the capability to dynamically simulate sediment-water exchanges through a process called sediment diagenesis. This effort has been funded by a grant through EPA's National Estuary Program, and the approach is currently in development by Ecology. Results will not be available until 2015 due to the complexity of this type of modeling.

2. The model should be applied to additional scenarios that focus on additional factors. These include sensitivity analyses that can be used to characterize how influential several processes are in terms of DO impacts. We evaluated scenarios in this assessment to focus on known potential influences such as human sources in watershed inflows and marine point sources. However, additional factors were identified during this assessment that warrant follow up.

We evaluated Pacific Ocean influences using the best available information to characterize current and potential future conditions. We found that the Pacific Ocean has a greater influence on DO concentrations than local human nitrogen sources, now and into the future. We recommend further evaluating several future ocean scenarios:

- Sensitivity analysis to different ocean boundary temperature, salinity, DO, chlorophyll, and nutrients.
- Future ocean DO alone and nitrate alone to understand which is more influential.
- Changes in sea-level at the ocean boundary, which was not considered in this assessment.

We also found that DO in the Salish Sea and shallow inlets in particular would be impacted by increased air temperature resulting from climate change. The additional depletion could be comparable to that from increased future human loads. Other parameters that may vary with climate change could also impact DO. The approach we used to evaluate air temperature uses a simplistic representation of the heat budget. We recommend further evaluating future climate scenarios:

- Sensitivity analysis of varying solar radiation in heat budget.
- Future climate change scenario in combination with natural conditions for nutrient concentrations.

To establish natural conditions for DO in the Salish Sea, in the absence of human contributions, we eliminated all human nitrogen sources. We also developed detailed predictions of future marine point source flows and loads and future watershed inflow flows and loads. These combine several different factors into single scenarios. We found that the increase in watershed loads could be offset by changes in freshwater flows. Circulation changes strongly influenced DO, yet we did not isolate these factors. Follow-up scenarios are potentially numerous, but we recommend assessing several that focus on current and future marine point source or watershed inflow scenarios:

- Distinguish relative influence of Canadian marine point sources.
- Future marine point sources with reduced loads from nutrient-removal technology.
- Better resolution Fraser River future flow and load predictions, in addition to natural conditions.
- Does the change in freshwater flow offset impacts from increased nutrient loads in the future?

In addition, we recommend other potential scenarios and next steps that focus on:

- Confirm nitrogen is the limiting nutrient by varying phosphorus and comparing results.
- Isolate the effects of changing circulation due to subtle changes in freshwater inflows.
- Sensitivity analysis of sediment flux rates.
- Improve model performance in shallow inlets.

We recommend continued development of the DO model of Puget Sound and the Straits. We also recommend continued collaboration with colleagues in the U.S. and Canada who are involved with evaluating DO and related parameters in Puget Sound, the Straits, and the northeast Pacific Ocean.

References

Ahmed, A., G. Pelletier, M. Roberts, and A. Kolosseus. 2014. South Puget Sound Dissolved Oxygen Study: Water Quality Model Calibration and Scenarios. Washington State Department of Ecology, Olympia, WA. Publication No. 14-03-004. https://fortress.wa.gov/ecy/publications/SummaryPages/1403004.html

Aura Nova Consultants, Inc., Brown and Caldwell, Evans-Hamilton, J.E. Edinger and Associates, Ecology, and the University of Washington Department of Oceanography. 1998. Budd Inlet Scientific Study Final Report. Prepared for the LOTT Partnership, Olympia, Washington.

Banas, N.S., E.J. Lessard, R.M. Kudela, P. MacCready, T.D. Peterson, B.M. Hickey, and E. Frame. 2009. Planktonic growth and grazing in the Columbia River plume region: A biophysical model study. Journal of Geophysical Research Oceans 114:1978-2012. DOI: 10.1029/2008JC004993. http://onlinelibrary.wiley.com/doi/10.1029/2008JC004993/full.

BC Stats. 2011. Population Projections, British Columbia, Canada. http://www.bcstats.gov.bc.ca/StatisticsBySubject/Demography/PopulationProjections.aspx (Accessed June 14th, 2012)

Bolte, J. and K.B. Vaché. 2010. Envisioning Puget Sound Alternative Futures. Final Report. Submitted to Puget Sound Nearshore Ecosystem Project. 50 pp.

Chan, F., J.A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W.T. Peterson, B.A. Menge. 2008. Emergence of anoxia in the California Current large marine ecosystem. Science 319:920. DOI: 10.1126/science. 1149016.

Chen, C., H. Liu, and R.C. Beardsley. 2003. An unstructured, finite-volume, three-dimensional, primitive equation ocean model: Application to coastal ocean and estuaries. Journal of Atmospheric and Oceanic Technology, 20:159-186.

Climate Impacts Group. 2009. The Washington Climate Change Impacts Assessment. M. McGuire Elsner, J. Littell, and L Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. http://www.cses.washington.edu/db/pdf/wacciareport681.pdf.

Cope, B. and M. Roberts. 2013. Review and Synthesis of Available Information to Estimate Human Impacts to Dissolved Oxygen in Hood Canal. Washington State Department of Ecology Publication No. 13-03-016 and EPA Publication No. 910-R-13-002. https://fortress.wa.gov/ecy/publications/SummaryPages/1303016.html.

Crawford, W., J. Galbraith, and N. Bolingbroke. 2007. Line P ocean temperature and salinity, 1956–2005. Progress in Oceanography 75:161-178.

Dalton, M., P.W. Mote, and A.K. Snover. 2013. Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities. Washington, D.C., Island Press. 271 pp.

Deppe, R.W., J. Thomson, B. Polagye, and C. Krembs. 2013. Hypoxic intrusions to Puget Sound from the ocean. Proceedings of Oceans 13 MTS/IEEE, San Diego Sept 23-26. http://faculty.washington.edu/jmt3rd/Publications/Deppe_etal_Oceans2013.pdf.

Deutsch, C., S. Emerson, and L.A. Thompson. 2006. Physical-biological interactions in North Pacific oxygen variability. Journal of Geophysical Research 111, DOI: 10.1029/2005JC003179.

Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.Y. Lee, D.P. Lettenmaier. 2010. Implications of 21st century climate change for the hydrology of Washington State. Climatic Change, DOI: 10.1007/s10584-010-9855.

EPA. 2010. Nutrient Control Design Manual. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. EPA/600/R-10/100. http://nepis.epa.gov/Adobe/PDF/P1008KTD.pdf.

Gaffin, S.R., C. Rosenxweig, X. Xing, G. Yetman. 2004. Downscaling and geo-spatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES). Global Environmental Change 14:105-123. http://pubs.giss.nasa.gov/docs/2004/2004_Gaffin_etal.pdf.

Hamlet, A.F. and D.P. Lettenmaier. 1999a. Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin. J. of the American Water Resources Association, 35 (6): 1597-1623.

Hamlet, A.F. and D.P. Lettenmaier. 1999b. Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals, ASCE J. of Water Res. Planning and Mgmt., 125 (6): 333-341.

Hamlet, A.F. and D.P. Lettenmaier. 2007. Effects of 20th Century Warming and Climate Variability on Flood Risk in the Western U.S. Water Resour. Res., 43, W06427, doi:10.1029/2006WR005099.

Hamlet, A.F., M.M. Elsner, G.S. Mauger, S-Y. Lee, I. Tohver, R.A. Norheim. 2013. An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results, Atmosphere-Ocean. (in press)

Khangaonkar, T., B. Sackmann, W. Long, T. Mohamedali , and M. Roberts. 2012. Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and DO in Puget Sound using an unstructured grid model. Ocean Dynamics. (2012) 62:1353–1379. DOI 10.1007/s10236-012-0562-4.

Khangaonkar, T., Z. Yang, T. Kim, and M. Roberts. 2011. Tidally Averaged Circulation in Puget Sound Sub-basins: Comparison of Historical Data, Analytical Model, and Numerical Model. Journal of Estuarine Coastal and Shelf Science, Volume 93, Issue 4, 20 July 2011, Pages 305-319.

Kim, T. and T. Khangaonkar. 2011. An Offline Unstructured Biogeochemical Model (UBM) for Complex Estuarine and Coastal Environments. Environmental Modelling & Software 31 (2012) 47-63.

King County. 2012. Quartermaster Harbor Benthic Flux Study. Prepared by Curtis DeGasperi, Water and Land Resources Division. Seattle, Washington. http://your.kingcounty.gov/dnrp/library/2012/kcr2320.pdf.

Krembs, C. 2012. POSTER: Eyes Over Puget Sound: Integrating Multiple Observations to Report Current Conditions of Water Quality in Puget Sound and the Strait of Juan de Fuca https://fortress.wa.gov/ecy/publications/summarypages/1203034.html.

Krembs, C. 2013. Eutrophication in Puget Sound. In: Irvine, J.R. and Crawford, W.R. 2013. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/032. pp. 106-112. http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2013/2013_032-eng.pdf.

Mackas, D.L. and P.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.

Mackas, D.L., S. Batten and M. Trudel. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. Progress in Oceanography 75:223-252.

Mohamedali, T., M. Roberts, B. Sackmann, and A. Kolosseus. 2011. Puget Sound Dissolved Oxygen Model Nutrient Load Summary for 1999-2008. Washington State Department of Ecology, Olympia, Washington. Publication No. 11-03-057. https://fortress.wa.gov/ecy/publications/summarypages/1103057.html

Morrison J., M. C. Quick, M. G.G. Foreman. 2002. Climate change in the Fraser River watershed: flow and temperature projections. Journal of Hydrology 263: 230-244. http://www.sciencedirect.com/science/article/pii/S0022169402000653

Mote, P.W., E.A. Parson, A.F. Hamlet, K.G. Ideker, W.S. Keeton, D. P. Lettenmaier, N.J. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R., Slaughter, and A.K. Snover. 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest, Climatic Change, 61: 45-88.

OFM. 2012. 2012 Projections, County Growth Management Population Projections by Age and Sex: 2010-2040 Office of Financial Management. http://www.ofm.wa.gov/pop/gma/projections12/GMA_2012_county_pop_projections.pdf.

Oregon State University. 2012. Envisioning Puget Sound Alternative Future Scenarios Project. http://envision.bioe.orst.edu/StudyAreas/PugetSound/index.html.

Peña, M.A. and S.J. Bograd. 2007. Time series of the northeast Pacific. Progress in Oceanography 75:115-119.

Pierce S.D., J.A. Barth, R.K. Shearman, and A.Y. Erofeev. 2012. Declining Oxygen in the Northeast Pacific. Journal of Physical Oceanography. 42: 495-501. http://yo.coas.oregonstate.edu/pubs/Pierce_et_al_2012.pdf

Roberts, M., J. Bos, and S. Albertson. 2008. South Puget Sound Dissolved Oxygen Study, Interim Data Report. Washington State Department of Ecology Publication No. 08-03-037. https://fortress.wa.gov/ecy/publications/SummaryPages/0803037.html

Roberts, M., A. Ahmed, G. Pelletier, and D. Osterberg. 2012. Deschutes River, Capitol Lake, and Budd Inlet Temperature, Fecal Coliform Bacteria, Dissolved Oxygen, pH, and Fine Sediment Total Maximum Daily Load Technical Report: Water Quality Study Findings. Washington State Department of Ecology Publication No. 12-03-008. https://fortress.wa.gov/ecy/publications/SummaryPages/1203008.html

Sackmann, B., L. Mack, M. Logsdon, M.J. Perry. 2004. Seasonal and inter-annual variability of SeaWiFS-derived chlorophyll a concentrations in waters off the Washington and Vancouver Island coasts, 1998–2002. Deep-Sea Research II 51:945-965.

Salathé, E.P. Jr. A. F. Hamlet, M. Stumbaugh, S-Y. Lee, R. Steed. 2013. Estimates of 21st Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations. J. of Hydrometeorology. (in review)

Seabird. 2013. SBE 43 Dissolved Oxygen Sensor -- Background Information, Deployment Recommendations, and Cleaning and Storage. Sea-Bird Electronics Application Note No. 64. http://www.seabird.com/application_notes/an64.htm.

Sheibley, R.W. and A.J. Paulson. 2013. Quantifying benthic nutrient fluxes in Puget Sound – Review of Available Science. U.S. Geological Survey Publication No. XXXX-XXXX. (in press)

Thomson, R.E. and M.V. Krassovski. 2010. Poleward reach of the California Undercurrent extension. Journal of Geophysical Research 115, C09027, doi: 10.1029/2010JC006280.

Vaccaro, J.J., Hansen, A.J., and Jones, M.A. 1998. Hydrogeologic framework of the Puget Sound aquifer system, Washington and British Columbia. U.S. Geological Survey Professional Paper 1424-D, 77 p. http://pubs.er.usgs.gov/djvu/PP/pp_1424_d.djvu

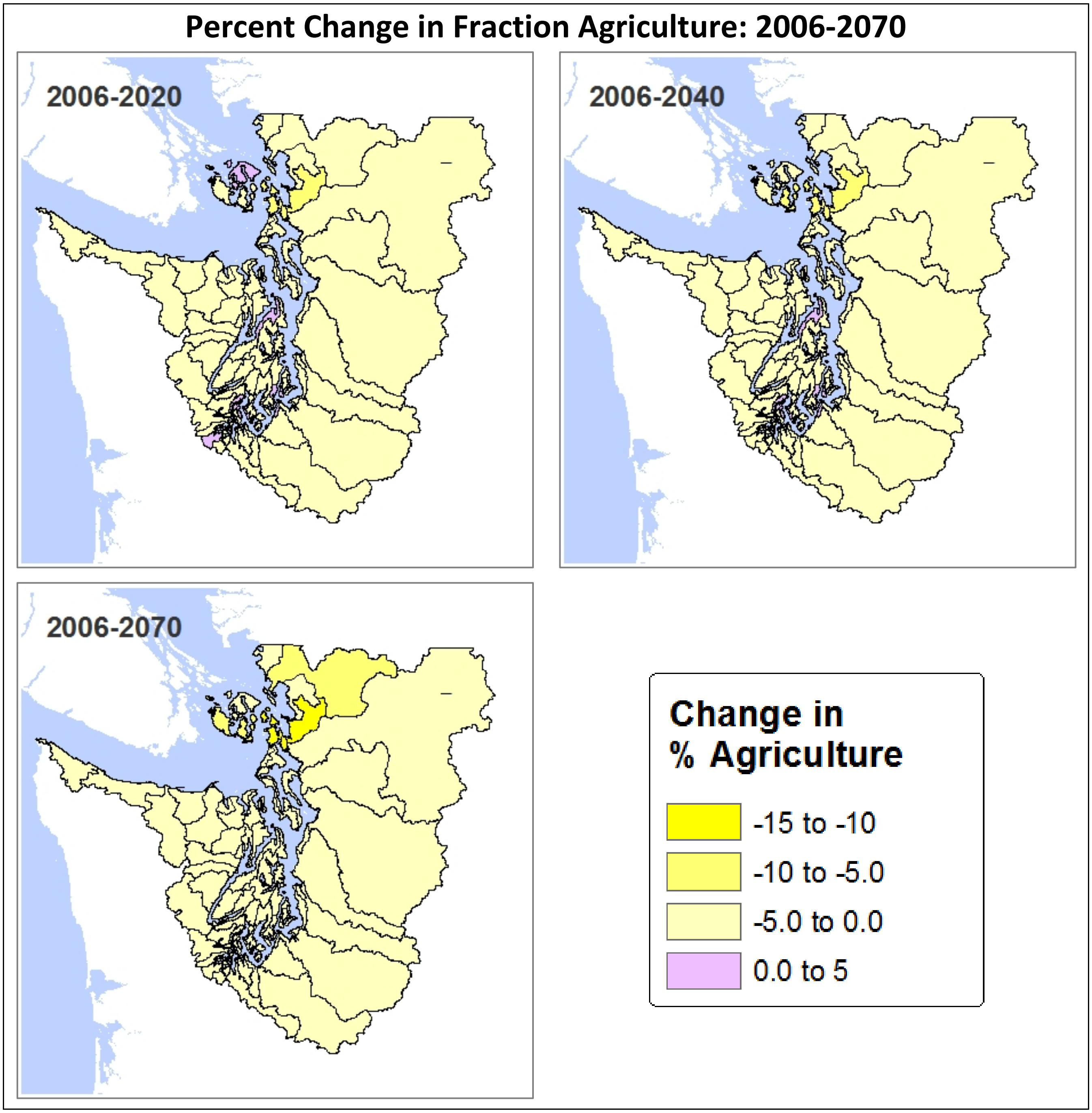
Whitney F. A., H. J, Freeland, M. Robert. 2007. Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. Progress in Oceanography. 75: 179-199.

Yang, Z., T. Khangaonkar, R. Labiosa, and T. Kim. 2010. Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate-Scale Hydrodynamic Model. PNNL-18484, Pacific Northwest National Laboratory, Richland, Washington.

Appendices

This page is purposely left blank

Appendix A. Future Land Use Changes for U.S. Watersheds



Percent Change in Fraction Agriculture: 2006-2070

2006-2020

2006-2040

2006-2070

Figure A-1. Percent change in fraction agriculture between 2006 and 2020, 2040, and 2070.

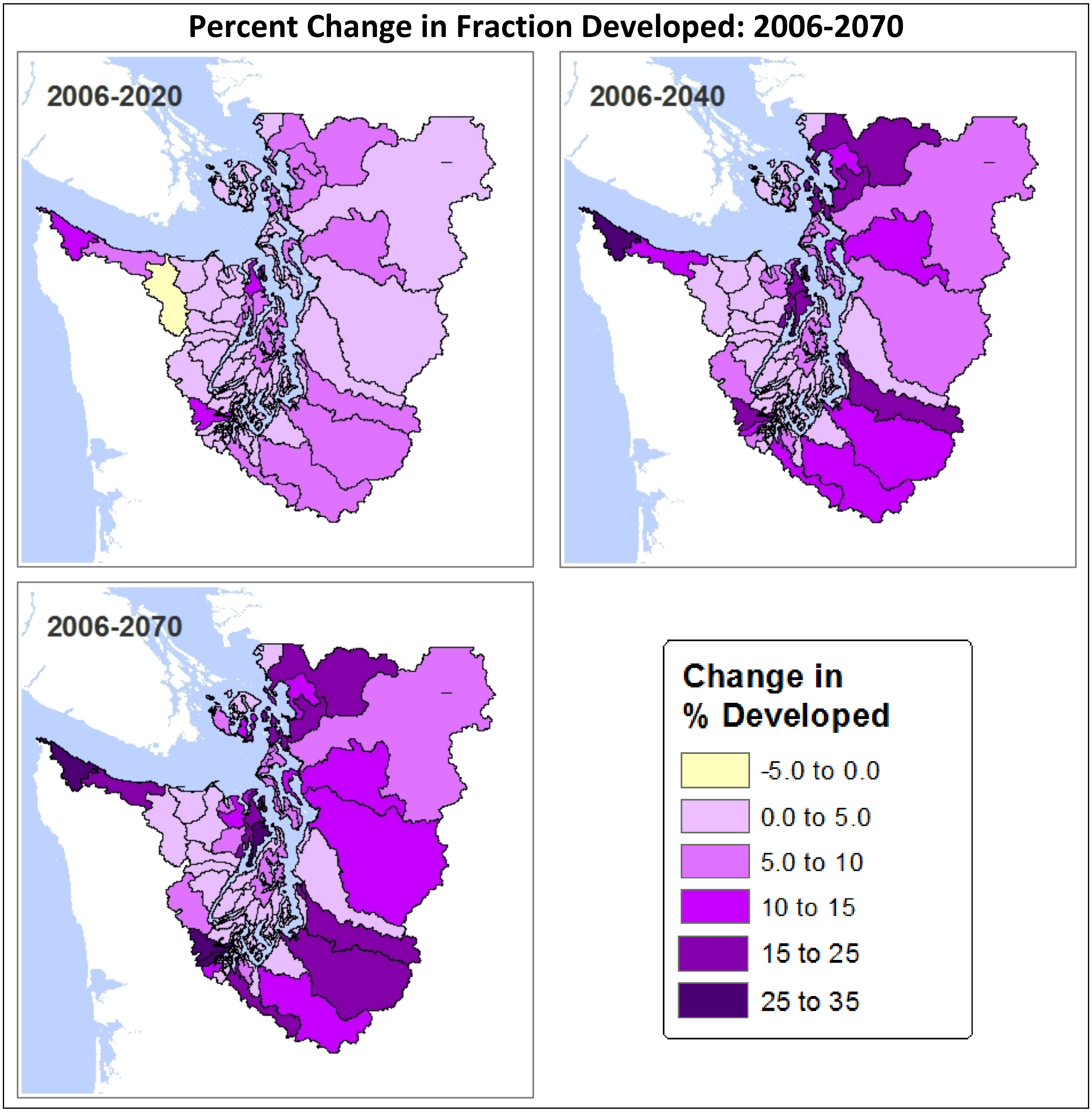


Figure A-2. Percent change in fraction developed between 2006 and 2020, 2040, and 2070.

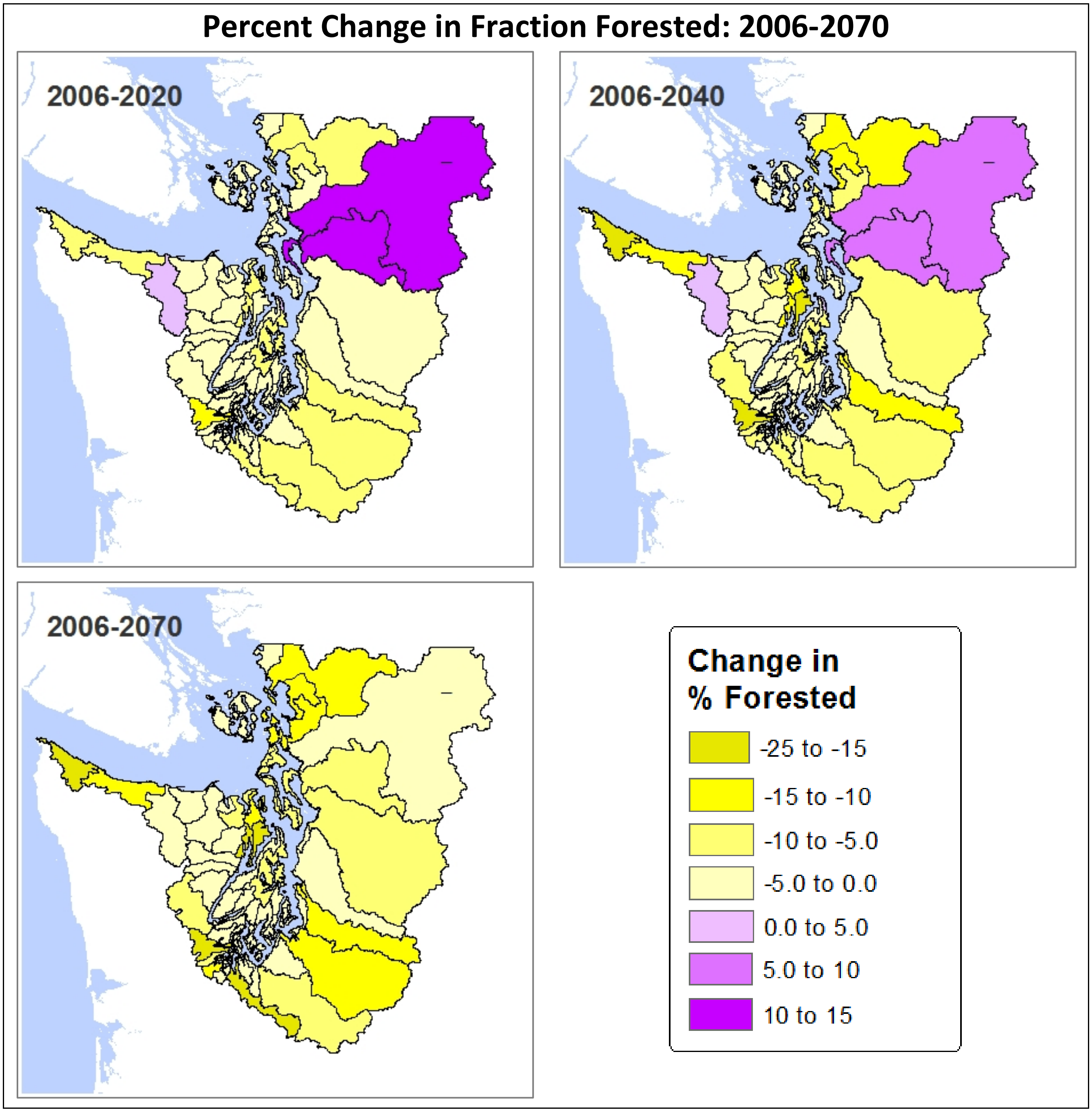


Figure A-3. Percent change in fraction forested between 2006 and 2020, 2040, and 2070.

Appendix B. Future Municipal Marine Point Source Flow Estimates

We estimated future flows discharging through marine point sources from future population served and current per capita contributions.

urrent population served by U.S. municipal WWTPs

We estimated the current population served by centralized municipal WWTPs to forecast future population served by WWTPs. We used plant-specific information for the 10 largest U.S. plants discharging to Puget Sound as well as 19 others with easily obtainable forecasts of future population served. Information sources include the following:

- **NPDES (National Pollution Discharge Elimination System) Fact Sheet**: Every plant has an NPDES permit that is issued either by Ecology or by the U.S. Environmental Protection Agency (EPA) for tribal or federal facilities. The NPDES permit defines the effluent limitations specific to each WWTP. The NPDES fact sheets provide information on the derivation of the permit's limits and other conditions, a description of the WWTP and sometimes information on sewered population.
- **Comprehensive Sewer/Facility Plans**: Many WWTPs, sewer districts, and cities are required to develop comprehensive sewer/facility plans as part of the Growth Management Act (GMA). These plans often include estimates of future sewered population.
- **WWTP Engineering Reports**: When a WWTP evaluates upgrading or expanding an existing facility, an engineering report documents this process and sometimes includes information on populations served.
- **Annual Wasteload Assessment reports submitted to Ecology**: Many WWTPs are required to submit annual reports to Ecology, which include current population served, design population, projected population growth, and an assessment of when the plant's design capacity is expected to be reached and by when.
- **WWTP or municipality websites**: Some include the population served.
- **State or federal permit writers**: Some have supplemental information on the population served.

The service area population data for individual plants that we used to represent current population did not always represent the same year. Data representing population served by WWTPs varied from 2000 through 2011 depending on the plant. However, the largest plants (greater than 10 mgd) all had population information either from 2005 or more recent. The most common year for current population information was 2008. Even though 2006 is the baseline year in terms of model scenarios, we did not always find current population information for the year 2006.

There were two small WWTPs (Roche Harbor and Warm Beach Campground) for which we could not find any information on current population served because they serve a transient or seasonal population. Roche Harbor is a resort and Warm Beach is a retreat center. Instead, we back-calculated this value based on the average annual effluent flows and an estimated per capita effluent of 36.6 gal/day for Rosario Utilities, another small WWTP that also serves a resort. These two plants are all small (< 0.05 mgd) and contributed only 0.02% of the total flow from all WWTPs in the Puget Sound area. Therefore, the assumed nutrient loading from these plants will have negligible influence at the Puget Sound scale.

Where plant-specific information was not available, we projected future population served based on current population served and the county-level growth rate.

Table B-1 summarizes current population served, total flow, and per capita flow by wastewater treatment plant in the model domain. The table also includes plant-specific DIN concentrations or estimates from similar plants.

Table B-1. Current population, flow, and per capita flow by facility.

Facility Name	Facility Type	Current Population Served[1]		Current Annual Flow (mgd)[2]		Current Per Capita Flow (gal/d)[3]	2006 Annual Flow (mgd)[4]	2006 Median DIN Concentrations (mg/L)
Alderbrook	US WWTP	140	(2010)	0.016	(2008)	111.6	0.01	7.95
Alderwood	US WWTP	28,590	(2006)	2.18	(2006)	76.3	2.18	29.3
Anacortes	US WWTP	16,640	(2010)	1.78	(2008)	106.7	1.79	29.3
Bainbridge Island (City)	US WWTP	7,290	(2006)	0.592	(2006)	81.3	0.59	7.95
Bainbridge Kitsap Co Sewer Dist 7 (Ft Ward)	US WWTP	630	(2011)	0.084	(2008)	133.7	0.09	7.95
Bellingham	US WWTP	137,700	(2006)	12.6	(2006)	91.4	12.6	31.4
Birch Bay	US WWTP	7,500	(2007)	0.858	(2007)	114.5	0.85	7.95
Blaine	US WWTP	5,920	(2010)	0.530	(2008)	89.6	0.55	7.95
Boston Harbor	US WWTP	600	(2008)	0.030	(2008)	50.6	0.04	15.3
Bremerton	US WWTP	42,390	(2010)	4.18	(2008)	98.6	5.29	23.9
Carlyon Beach	US WWTP	1,040	(2008)	0.022	(2008)	21.2	0.02	53.3
Central Kitsap	US WWTP	44,480	(2005)	3.52	(2005)	79.1	3.90	33.3
Chambers Creek	US WWTP	253,000	(2009)	17.5	(2008)	69.0	18.9	30.1
Clallam Bay POTW	US WWTP	300	(2010)	0.025	(2008)	81.9	0.03	7.95
Clallam DOC	US WWTP	1,000	(2007)	0.132	(2007)	131.9	0.13	5.48
Coupeville	US WWTP	1,600	(2009)	0.164	(2008)	102.3	0.17	7.95
East Sound Orcas Village	US WWTP	160	(2009)	0.004	(2008)	22.7	0.00	7.95
Eastsound Water District	US WWTP	1,000	(2006)	0.082	(2006)	82.4	0.09	7.95
Edmonds	US WWTP	39,860	(2005)	5.34	(2005)	134.0	6.18	29.3
Everett Snohomish	US WWTP	161,590	(2010)	19.2	(2008)	118.5	20.3	31.4
Fisherman Bay	US WWTP	770	(2009)	0.016	(2008)	20.8	0.02	7.95
Fort Lewis/Solo Point	US WWTP	29,000	(2009)	3.05	(2008)	105.2	4.08	25.7
Friday Harbor	US WWTP	2,080	(2004)	0.303	(2004)	146.2	0.31	7.95
Gig Harbor	US WWTP	6,700	(2010)	0.789	(2008)	117.7	0.85	13.0
Hartstene Pointe	US WWTP	860	(2011)	0.059	(2008)	68.7	0.08	7.95
Kitsap Co Kingston	US WWTP	1,940	(2007)	0.114	(2007)	58.5	0.12	7.95
Kitsap Co Suquamish	US WWTP	1,870	(2006)	0.181	(2006)	96.6	0.18	7.95
La Conner	US WWTP	1,920	(2007)	0.234	(2008)	122.3	0.24	7.95

Facility Name	Facility Type	Current Population Served[1]		Current Annual Flow (mgd)[2]		Current Per Capita Flow (gal/d)[3]	2006 Annual Flow (mgd)[4]	2006 Median DIN Concentrations (mg/L)
Lake Stevens	US WWTP	30,000	(2008)	2.13	(2008)	71.0	2.08	9.43
Lakota	US WWTP	69,000	(2008)	5.40	(2008)	78.2	4.84	40.8
Langley	US WWTP	620	(2010)	0.081	(2008)	130.7	0.08	7.95
Larrabee State Park	US WWTP	160	(2008)	0.016	(2008)	100.0	0.01	6.01
LOTT	US WWTP	180,960	(2010)	10.2	(2008)	56.4	12.1	3.30
Lummi Goose Pt	US WWTP	2,700	(2004)	0.279	(2004)	103.2	0.29	7.95
Lummi Sandy Pt	US WWTP	1,500	(2003)	0.104	(2003)	69.5	0.10	7.95
Lynwood	US WWTP	36,380	(2003)	4.16	(2003)	114.5	4.75	29.3
Makah	US WWTP	1,700	(2006)	0.209	(2006)	123.0	0.21	7.95
Manchester Kitsap Co	US WWTP	2,220	(2007)	0.196	(2007)	88.2	0.23	7.51
Marysville	US WWTP	28,000	(2005)	4.18	(2005)	149.2	4.71	29.6
McNeil Island/DOC	US WWTP	1,830	(2008)	0.219	(2008)	119.7	0.23	5.16
Midway	US WWTP	60,860	(2010)	4.03	(2008)	66.2	4.30	30.8
Miller Creek	US WWTP	36,010	(2007)	2.95	(2007)	82.0	3.26	29.3
Mt Vernon	US WWTP	35,860	(2010)	3.81	(2008)	106.4	3.64	29.3
Mukilteo	US WWTP	21,160	(2010)	1.56	(2008)	73.5	1.81	29.3
Oak Harbor Lagoon	US WWTP	22,200	(2005)	1.39	(2005)	62.4	1.34	29.3
Oak Harbor RBC	US WWTP	4,400	(2005)	0.512	(2005)	116.4	0.52	7.95
Olympic Water and Sewer Port Ludlow	US WWTP	6,680	(2010)	0.185	(2008)	27.7	0.22	7.95
Penn Cove	US WWTP	450	(2010)	0.023	(2008)	51.9	0.03	7.95
Port Angeles	US WWTP	19,310	(2010)	3.14	(2008)	162.4	2.76	29.3
Port Gamble/Pope Resources	US WWTP	250	(2008)	0.011	(2008)	43.7	0.02	7.95
Port Orchard	US WWTP	11,020	(2006)	1.76	(2006)	159.6	1.76	18.9
Port Townsend	US WWTP	9,000	(2008)	0.900	(2008)	100.0	0.98	7.95
Port Townsend Paper (sanitary)	US WWTP	320	(2004)	0.003	(2004)	9.4	0.01	7.95
Puyallup	US WWTP	26,000	(2009)	3.75	(2008)	144.3	4.66	8.86
Redondo	US WWTP	52,000	(2008)	2.57	(2008)	49.3	3.09	23.2
Roche Harbor	US WWTP	908	(2008)	0.033	(2008)	36.6	0.03	7.95
Rosario Utilities	US WWTP	1,050	(2005)	0.038	(2008)	36.6	0.03	7.95

Facility Name	Facility Type	Current Population Served[1]		Current Annual Flow (mgd)[2]		Current Per Capita Flow (gal/d)[3]	2006 Annual Flow (mgd)[4]	2006 Median DIN Concentrations (mg/L)
Rustlewood	US WWTP	400	(2008)	0.018	(2008)	44.2	0.03	7.95
Salmon Creek	US WWTP	24,410	(2008)	2.08	(2008)	85.1	2.75	29.3
Seashore Villa	US WWTP	430	(2008)	0.007	(2008)	16.2	0.01	7.95
Sekiu	US WWTP	160	(2010)	0.056	(2008)	346.9	0.08	7.95
Sequim	US WWTP	7,010	(2008)	0.482	(2008)	68.7	0.48	5.89
Shelton	US WWTP	8,980	(2010)	1.85	(2008)	206.5	2.50	5.06
Skagit County SD No 2 Big Lake	US WWTP	1,150	(2000)	0.094	(2000)	81.1	0.14	7.95
Snohomish	US WWTP	10,050	(2009)	1.43	(2008)	142.5	1.36	17.8
South King	US WWTP	1,137,950	(2008)	68.8	(2008)	60.5	80.0	31.7
Stanwood	US WWTP	5,590	(2010)	0.557	(2008)	99.6	0.50	4.73
Swinomish	US WWTP	1,280	(2006)	0.113	(2006)	88.6	0.11	7.95
Tacoma-Central	US WWTP	181,730	(2009)	19.3	(2008)	106.1	21.7	33.0
Tacoma-North	US WWTP	51,830	(2009)	4.28	(2008)	82.6	4.93	25.8
Tamoshan	US WWTP	290	(2002)	0.023	(2002)	78.4	0.03	6.92
Taylor Bay (Longbranch)	US WWTP	290	(2005)	0.010	(2005)	35.9	0.01	7.95
Tulalip	US WWTP	3,200	(2009)	0.214	(2008)	67.0	0.22	7.95
Vashon	US WWTP	1,000	(2010)	0.077	(2008)	77.3	0.16	7.95
Warm Beach Campground	US WWTP	890	(2008)	0.033	(2008)	36.6	0.49	7.95
West Point	US WWTP	1,337,000	(2008)	91.4	(2008)	68.4	118	25.9
Whidbey Naval Station	US WWTP	10,000	(2008)	0.509	(2008)	50.9	0.37	7.95
Annacis	Canadian WWTP	1,000,000	(2011)	125	(2008)	125.5	131	26.5
Clover Point	Canadian WWTP	198,530	(1996)	13.2	(2008)	66.3	17.9	22.9
Gulf Islands	Canadian WWTP	3,210	(2011)	0.2	(2008)	66.3	0.21	7.95
Iona	Canadian WWTP	600,000	(2011)	143	(2008)	238.2	155	14.5
Lions Gate	Canadian WWTP	174,000	(2011)	23.8	(2008)	136.6	24.3	18.5
Lulu	Canadian WWTP	120,000	(2011)	19.6	(2008)	163.3	21.1	27.9
Macaulay	Canadian WWTP	150,160	(1996)	11.6	(2008)	77.0	12.8	31.9
NW Langley	Canadian WWTP	18,980	(2011)	2.9	(2008)	153.1	2.61	19.2
Saanich	Canadian WWTP	30,000	(2000)	2.5	(2008)	82.7	2.69	14.8

Facility Name	Facility Type	Current Population Served[1]	Current Annual Flow (mgd)[2]		Current Per Capita Flow (gal/d)[3]	2006 Annual Flow (mgd)[4]	2006 Median DIN Concentrations (mg/L)
Kimberly-Clark	Industrial – Pulp/Paper Mill	N/A	27.9	(2006)	N/A	27.9	0.12
Nippon Paper	Industrial – Pulp/Paper Mill	N/A	8.67	(2006)	N/A	8.67	0.12
Port Townsend Paper	Industrial – Pulp/Paper Mill	N/A	12.3	(2006)	N/A	12.3	0.12
Simpson Tacoma	Industrial – Pulp/Paper Mill	N/A	23.4	(2006)	N/A	23.4	0.14
BP Cherry Point	Industrial – Oil Refinery	N/A	4.59	(2006)	N/A	4.59	4.86
Conoco Phillips	Industrial – Oil Refinery	N/A	1.64	(2006)	N/A	1.64	1.88
Shell Oil	Industrial – Oil Refinery	N/A	3.65	(2006)	N/A	3.65	4.18
Tesoro	Industrial – Oil Refinery	N/A	3.16	(2006)	N/A	3.16	1.11
US Oil & Refining	Industrial – Oil Refinery	N/A	0.52	(2006)	N/A	0.52	0.32
Intalco (sanitary)	Industrial – Aluminum	N/A	3.52	(2006)	N/A	3.52	1.10

Notes

1. Data for population currently served by each facility was found was available for different years (as indicated in brackets).
2. Data for current annual flow for each facility was found for the year that was closest to the year for which population served data were available for that particular facility (as indicated in brackets).
3. Current per capita flow was calculated by dividing the annual flow by the population served in the previous columns.
4. 2006 average annual flow is the flow used in all 'current' modeling scenarios.

Future population served by U.S. municipal WWTPs with plant-specific information

Several WWTPs have plant-specific population projections. These include the ten[5] largest WWTPs in the U.S. that discharge to Puget Sound. These ten plants contribute 80% of the total flow from all 78 WWTPs discharging to U.S. marine waters. Future population served by these larger plants will strongly influence estimates of future wastewater flows into Puget Sound. For these ten plants and a few others, where information was available, we summarized available projections of sewered population.

WWTPs are required to plan for and report expected growth in future population within sewer service areas as part of the Growth Management Act (GMA). These plans are updated periodically as Comprehensive Sewer Plans. Information includes the expected growth in service area populations, although future projections are often limited to the next 20 years. A few of these plans are available online, while others were only available as hard copies sent to Ecology’s permit writers. In the latter case, we contacted individual permit writers for this information.

We requested data from King County for the three large regional King County plants (South King, West Point and Brightwater), which are the three largest plants overall. King County (Betsy Cooper, personal communication) provided both current (2011) sewered population as well as future sewered population for all three plants from 2020 through 2050.

None of the projections in these plans extended as far out as 2070, and few projected to 2040. We used the information in the plans for 2020 sewered population, and then applied county growth rates to predict 2040 and 2070 population using 2020 population as a base. In some cases, we calculated a WWTP-specific population growth rate based on the information available in each plan.

We compiled WWTP-specific population projections through 2020 for all 10 of the largest plants as well as 19 other smaller WWTPs. WWTP-specific population forecasts were also available through 2040 for five of the largest 10 plants. Where WWTP-specific population forecasts were available, these were used for each of the High, Medium, and Low population scenarios.

---

[5] This count includes the new King County Brightwater WWTP, and does not include Canadian WWTPs.

Future population served by U.S. municipal WWTPs without plant-specific information

We estimated population served by each WWTP for the years 2020, 2040, and 2070 to predict future WWTP flows. The initial approach considered population growth both inside and outside urban growth areas (UGAs). The goal was to link this increase in sewered population within a UGA to specific WWTPs by assuming that wastewater from population growth outside UGAs would be served by OSS. However, some UGAs are served by multiple WWTPs, some WWTPs did not serve populations within UGAs, and in some cases, a single WWTP served multiple UGAs. Because of the complications involved in linking specific populations within a UGA to a specific WWTP, we did not use the UGA boundaries to estimate the population served by WWTPs.

The Washington State Office of Financial Management (OFM) conducts a statewide census every 10 years. OFM also develops population projections into the future as required by statute RCW 43.62.35 of the GMA. These population projections are revised every five years. We used projections released in May 2012 that include yearly population forecasts through 2040 at the state and county level. Future projections are identified as High, Medium, and Low population scenarios to capture the variability and uncertainty in the complicated factors that influence population growth. OFM considers birth rates, death rates, migration patterns, and many other socioeconomic factors (OFM, 2012). We considered all three forecasts to represent the range in potential future population.

The Puget Sound Regional Council has also developed county-level population forecasts through 2040. However, these forecasts are only available for four counties in the Puget Sound area (King, Kitsap, Pierce and Snohomish) and do not extend to 2070. For consistency among counties, we used the OFM projections for future populations, but did compare with those developed by the PSRC for these four counties as a check.

Predicting wastewater flows through 2070 required population forecasts at the scale of individual WWTPs. We extended the OFM projections from 2040 through 2070 and then downscaled this population to the WWTP level as described in more detail in the following sections.

Projecting population from 2040 to 2070

Since the OFM county population forecasts were only available through 2040, we used the 2030 estimates as a base from which to project 2070 county population. The Climate Impacts Group (CIG) used county-level OFM population data to project population in Washington State through the 2080s (CIG, 2009). CIG assumed linear population growth after 2030 based on the growth rate calculated between 2000 and 2020 OFM data, and then extrapolated this population linearly through 2085. We calculated the population growth rate for each county in Puget Sound between 2020 and 2040 based on OFM data, and then applied this growth rate to linearly extend the High, Medium and Low population forecasts from 2040 to 2070.

To check whether the linear extension of 2040 population was a reasonable approach, we looked at historic OFM population data to see if the trend in population has been linear. Historical OFM census data is available from 1900 through the latest census in 2010. Figure B-1 illustrates the population trends from 1900 to 2010 based on census data as well as the OFM Medium projection scenario between 2010 and 2040, and our projections from 2040 to 2070 based on the linear extension of the Medium population scenario. Information is available for all counties in Puget Sound. The figure presents the five counties with the largest population.

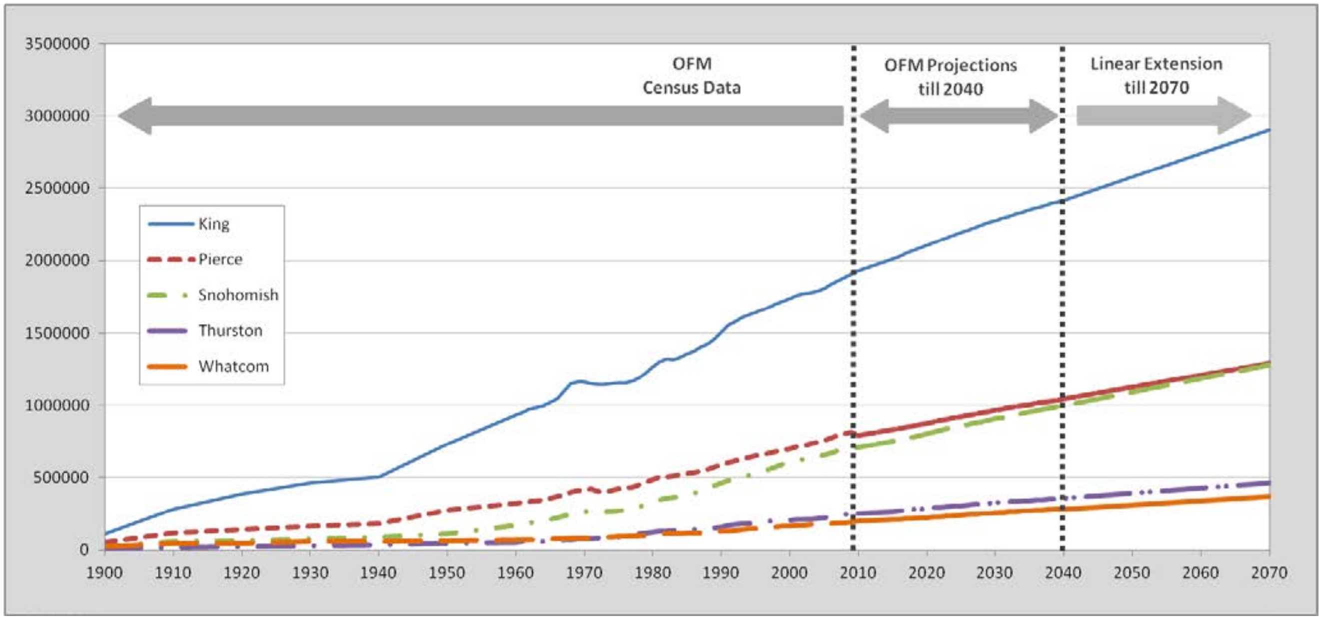


Figure B-1. Population in select counties in Puget Sound from 1900 to 2070, based on historical census data and future projection estimates based on OFM's Medium population scenario.

Historical population has not necessarily followed a completely linear trend throughout the period from 1900-2010. However, OFM Medium population projections from 2010 to 2040 are nearly linear. This does not ensure that future population after 2040 will follow the same trend. However, the patterns do not support other than a linear extension to provide the best estimate of future population. Projections for the High and Low population scenarios follow similar linear patterns. As noted by the CIG (2009), population estimates at these long time scales are very uncertain and may lack an appropriate scientific basis. Therefore, a more complicated approach does not necessarily represent a more realistic scenario.

As a separate check, we compared with the county-level population forecasts through 2040 for King, Kitsap, Snohomish and Pierce counties developed by the PSRC (Figure B-2). OFM projections are lower than those developed by the PSRC for Pierce (-7.4%), Snohomish (-8.0%), and Kitsap Counties (-15%), but slightly higher than the PSRC's estimate for King County (0.7%). The OFM projections have been revised in May 2012 based on the 2010 census, while the PSRC projections were released in 2006, and have not been revised since then. OFM may underestimate 2040 population, at least for the four counties, if the PSRC projections are more accurate.

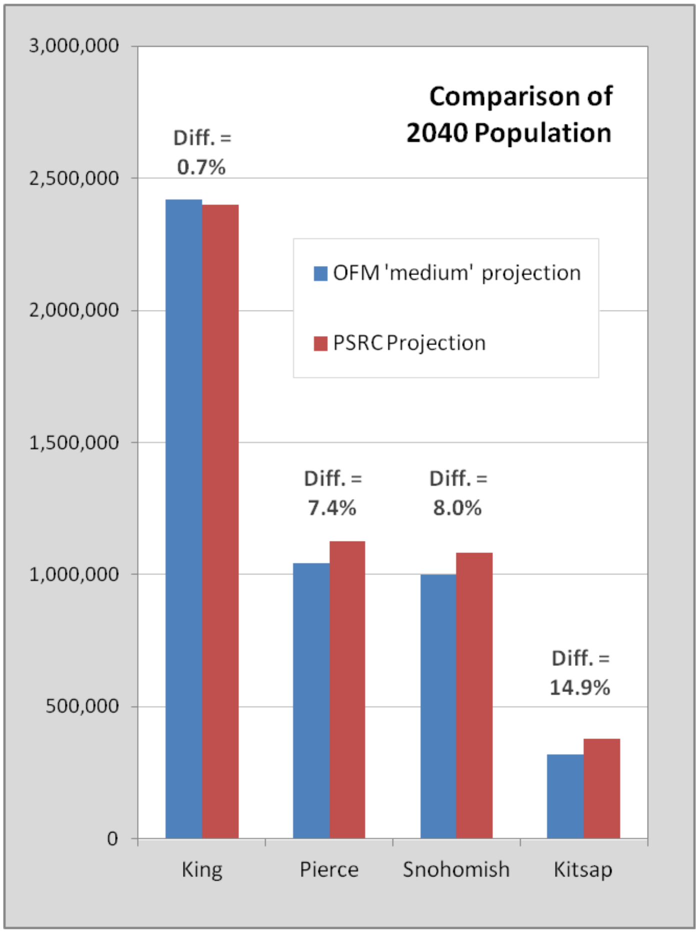


Figure B-2. Comparison of population projections for 2040 made by the Puget Sound Regional Council (PSRC) and by OFM.

Downscaling population data from county to WWTP level

After developing county-level population forecasts for 2020, 2040, and 2070 for High, Medium, and Low projections, we applied a downscaling technique to forecast populations served by individual WWTPs. The downscaling method was adapted from Gaffin et al. (2004), where they downscaled regional world population forecasts to the country level.

The downscaling method first involves calculating the county population growth rate. For example, the growth rate between 2010 and 2020 is as follows:

$$r_{county} = \frac{\ln\left(\frac{P_{county,2020}}{P_{county,2010}}\right)}{(2020-2010)} \qquad (1)$$

where:

r_{county} = county growth rate (/yr)

$P_{county,2020}$ = county population in 2020 (based on OFM forecast)
$P_{county,2010}$ = county population in 2010 (based on 2010 census)

The next step is to apply the growth rate calculated above to the current population served by a particular WWTP that resides within the same county. For example, we calculate the 2020 population for a WWTP based on the county growth rate applied to the 2010 population:

$$P_{WWTP,2020} = P_{WWTP,2010} * e^{[r_{county} * (2020-2010)]} \qquad (2)$$

where:
r_{county} = county growth rate from 2010 to 2020; calculated using Eq.(1) (/yr)
$P_{WWTP,2020}$ = WWTP population in 2020
$P_{WWTP,2010}$ = WWTP population in 2010

Population growth rates were calculated for High, Medium, and Low projection scenarios. This downscaling method assumes that the growth rate of the population served by WWTPs is the same as the growth rate of population in the county within which the WWTP is located. Therefore, population changes at the WWTP level are scaled by population changes at the county level. This assumption may underestimate the actual population growth within wastewater service areas since WWTPs generally serve urban centers within the county that generally experience higher population growth relative to the overall county population growth. Rural areas are served by on-site septic systems and generally experience lower population growth relative to the overall county rate.

The approach uses a consistent method to estimate the population served by each WWTP through 2070. Given the large number of WWTPs in the Puget Sound area, developing WWTP-specific forecasts based on local information such as demographics and socioeconomic factors for each of these plants would require significant additional effort and is beyond the scope of this project. These initial estimates are appropriate for the project objectives, which is to develop future nutrient loading scenarios for the Salish Sea at the Puget Sound scale. However, since a few large WWTPs contribute a large fraction of the total WWTP flows and loads into Puget Sound, we reviewed available WWTP-specific population forecasts, as described below.

Future U.S. municipal WWTP flows

To calculate future flows based on future sewered population for each of the 78 WWTPs, we calculated the current per capita wastewater flow for each WWTP. This was developed from the annual average flow divided by the current population served. Factors that affect per capita flows within sewered areas include the actual domestic wastewater, commercial facilities that serve non-residents, industries, and inflow/infiltration. Table B-2 summarizes future flows for the Medium population scenario for 2020, 2040, and 2070. The table also includes the future DIN concentrations, which do not reflect a change in treatment technology.

Table B-2. Future population and flow.

WWTP Name	PSDOM ID	Type	Future Per Capita Flow (gal/d)[1]	2020 Population	2020 Annual Flow (mgd)	2040 Population	2040 Annual Flow (mgd)	2070 Population	2070 Annual Flow (mgd)
Alderbrook	234	US WWTP	111.6	160	0.018	201	0.022	263	0.029
Alderwood	235	US WWTP	76.3	36,988	2.82	50,265	3.84	64,822	4.95
Anacortes	236	US WWTP	106.7	18,300	1.95	23,221	2.48	30,603	3.27
Bainbridge Island (City)	201	US WWTP	81.3	8,413	0.684	9,785	0.795	11,842	0.96
Bainbridge Kitsap Co Sewer Dist 7 (Ft Ward)	202	US WWTP	133.7	679	0.091	790	0.106	956	0.128
Bellingham	237	US WWTP	91.4	175,751	16.1	222,238	20.3	291,968	26.7
Birch Bay	238	US WWTP	114.5	8,692	0.99	10,991	1.26	14,440	1.65
Blaine	239	US WWTP	89.6	9,886	0.885	12,500	1.12	16,422	1.47
Boston Harbor	203	US WWTP	50.6	704	0.036	875	0.044	1,130	0.057
Bremerton	204	US WWTP	98.6	49,266	4.86	57,299	5.65	69,349	6.83
Brightwater	300	US WWTP	64.4	371,184	23.9	496,695	32.0	675,818	43.5
Carlyon Beach	205	US WWTP	21.2	1,223	0.026	1,519	0.032	1,963	0.042
Central Kitsap	206	US WWTP	79.1	66,146	5.23	76,932	6.08	93,110	7.36
Chambers Creek	207	US WWTP	69.0	373,885	25.8	566,175	39.1	701,243	48.4
Clallam Bay POTW	241	US WWTP	81.9	309	0.025	324	0.027	347	0.028
Clallam DOC	295	US WWTP	131.9	1,040	0.137	1,091	0.144	1,168	0.154
Coupeville	243	US WWTP	102.3	1,695	0.173	1,910	0.195	2,231	0.228
East Sound Orcas Village	244	US WWTP	22.7	163	0.004	175	0.004	193	0.004
Eastsound Water District	245	US WWTP	82.4	1,044	0.086	1,120	0.092	1,234	0.102
Edmonds	246	US WWTP	134.0	42,850	5.74	53,102	7.12	68,481	9.2
Everett Snohomish	247	US WWTP	118.5	182,063	21.6	225,626	26.7	290,970	34.5
Fisherman Bay	248	US WWTP	20.8	799	0.017	858	0.018	945	0.020
Fort Lewis/Solo Point	208	US WWTP	105.2	32,279	3.39	38,384	4.04	47,541	5.00
Friday Harbor	249	US WWTP	146.2	2,178	0.318	2,338	0.342	2,576	0.377
Gig Harbor	209	US WWTP	117.7	7,385	0.87	8,782	1.03	10,877	1.28
Hartstene Pointe	210	US WWTP	68.7	947	0.065	1,190	0.082	1,556	0.107
Kitsap Co Kingston	211	US WWTP	58.5	4,659	0.273	5,418	0.317	6,558	0.384

WWTP Name	PSDOM ID	Type	Future Per Capita Flow (gal/d)[1]	2020 Population	2020 Annual Flow (mgd)	2040 Population	2040 Annual Flow (mgd)	2070 Population	2070 Annual Flow (mgd)
Kitsap Co Suquamish	212	US WWTP	96.6	2,130	0.206	2,478	0.239	2,999	0.290
La Conner	253	US WWTP	122.3	2,160	0.264	2,741	0.335	3,612	0.442
Lake Stevens	254	US WWTP	71.0	34,684	2.46	42,983	3.05	55,432	3.93
Lakota	213	US WWTP	78.2	76,681	6.00	87,955	6.88	104,865	8.20
Langley	255	US WWTP	130.7	654	0.086	737	0.096	862	0.113
Larrabee State Park	296	US WWTP	100.0	184	0.018	233	0.023	306	0.031
LOTT	214	US WWTP	56.4	263,653	14.9	449,212	25.3	580,512	32.7
Lummi Goose Pt	256	US WWTP	103.2	3,237	0.334	4,094	0.422	5,378	0.555
Lummi Sandy Pt	257	US WWTP	69.5	1,819	0.126	2,300	0.160	3,022	0.210
Lynwood	258	US WWTP	114.5	39,124	4.48	48,485	5.55	62,527	7.16
Makah	259	US WWTP	123.0	1,774	0.218	1,861	0.229	1,992	0.245
Manchester Kitsap Co	215	US WWTP	88.2	2,508	0.221	2,917	0.257	3,530	0.311
Marysville	260	US WWTP	149.2	33,568	5.01	41,600	6.21	53,648	8.01
McNeil Island/DOC	216	US WWTP	119.7	630	0.075	749	0.090	928	0.111
Midway	217	US WWTP	66.2	67,588	4.47	77,525	5.13	92,430	6.12
Miller Creek	218	US WWTP	82.0	41,008	3.36	47,037	3.86	56,080	4.60
Mt Vernon	261	US WWTP	106.4	48,722	5.18	61,824	6.58	81,478	8.67
Mukilteo	262	US WWTP	73.5	22,805	1.68	28,262	2.08	36,447	2.68
Oak Harbor Lagoon	264	US WWTP	62.4	26,915	1.68	30,321	1.89	35,431	2.21
Oak Harbor RBC	265	US WWTP	116.4	4,400	0.512	4,400	0.512	4,400	0.512
Olympic Water and Sewer Port Ludlow	267	US WWTP	27.7	7,160	0.198	8,966	0.248	11,675	0.323
Penn Cove	268	US WWTP	51.9	474	0.025	534	0.028	624	0.032
Port Angeles	270	US WWTP	162.4	21,190	3.44	22,229	3.61	23,786	3.86
Port Gamble/Pope Resources	269	US WWTP	43.7	279	0.012	325	0.014	393	0.017
Port Orchard	219	US WWTP	159.6	19,558	3.12	22,747	3.63	27,531	4.39
Port Townsend	273	US WWTP	100.0	9,781	0.98	12,248	1.23	15,949	1.60
Port Townsend Paper	272	US WWTP	9.4	363	0.003	455	0.004	592	0.006

WWTP Name	PSDOM ID	Type	Future Per Capita Flow (gal/d)[1]	2020 Population	2020 Annual Flow (mgd)	2040 Population	2040 Annual Flow (mgd)	2070 Population	2070 Annual Flow (mgd)
(sanitary)									
Puyallup	299	US WWTP	144.3	28,940	4.18	34,413	4.97	42,623	6.15
Redondo	220	US WWTP	49.3	57,789	2.85	66,285	3.27	79,029	3.90
Roche Harbor	274	US WWTP	36.6	942	0.034	1,011	0.037	1,114	0.041
Rosario Utilities	275	US WWTP	36.6	1,099	0.040	1,179	0.043	1,300	0.048
Rustlewood	221	US WWTP	44.2	455	0.020	572	0.025	747	0.033
Salmon Creek	222	US WWTP	85.1	27,122	2.31	31,109	2.65	37,090	3.16
Seashore Villa	223	US WWTP	16.2	505	0.008	627	0.010	810	0.013
Sekiu	276	US WWTP	346.9	165	0.057	173	0.060	185	0.064
Sequim	277	US WWTP	68.7	8,286	0.570	8,692	0.598	9,302	0.639
Shelton	224	US WWTP	206.5	21,291	4.40	26,768	5.53	34,983	7.22
Skagit County SD No 2 Big Lake	279	US WWTP	81.1	1,388	0.113	1,761	0.143	2,321	0.188
Snohomish	280	US WWTP	142.5	11,483	1.64	14,231	2.03	18,352	2.62
South King	226	US WWTP	60.5	1,377,961	83.3	1,674,506	101.3	2,103,786	127.2
Stanwood	281	US WWTP	99.6	6,308	0.628	7,818	0.779	10,082	1.004
Swinomish	282	US WWTP	88.6	1,457	0.129	1,849	0.164	2,437	0.216
Tacoma-Central	227	US WWTP	106.1	208,405	22.1	247,819	26.3	306,939	32.6
Tacoma-North	228	US WWTP	82.6	54,300	4.49	64,569	5.34	79,973	6.61
Tamoshan	229	US WWTP	78.4	369	0.029	458	0.036	592	0.046
Taylor Bay (Longbranch)	230	US WWTP	35.9	336	0.012	399	0.014	494	0.018
Tulalip	285	US WWTP	67.0	3,655	0.245	4,530	0.303	5,842	0.391
Vashon	232	US WWTP	77.3	1,092	0.084	1,252	0.097	1,493	0.115
Warm Beach Campground	297	US WWTP	36.6	1,027	0.038	1,272	0.047	1,641	0.060
West Point	233	US WWTP	68.4	1,336,879	91.4	1,545,071	105.6	1,867,251	127.7
Whidbey Naval Station	298	US WWTP	50.9	10,650	0.542	11,998	0.611	14,019	0.714
Annacis	286	Canadian WWTP	125.5	1,146,877	144	1,467,061	184	1,947,337	244
Clover Point	291	Canadian WWTP	66.3	255,647	16.9	299,274	19.8	364,714	24.2
Gulf Islands	292	Canadian WWTP	66.3	3,577	0.24	4,295	0.28	5,372	0.36

WWTP Name	PSDOM ID	Type	Future Per Capita Flow (gal/d)[1]	2020 Population	2020 Annual Flow (mgd)	2040 Population	2040 Annual Flow (mgd)	2070 Population	2070 Annual Flow (mgd)
Iona	287	Canadian WWTP	238.2	688,126	164	880,237	210	1,168,402	278
Lions Gate	288	Canadian WWTP	136.6	199,557	27.3	255,269	34.9	338,837	46.3
Lulu	289	Canadian WWTP	163.3	137,625	22.5	176,047	28.8	233,680	38.2
Macaulay	293	Canadian WWTP	77.0	193,363	14.9	226,361	17.4	275,858	21.2
NW Langley	290	Canadian WWTP	153.1	21,768	3.33	27,845	4.26	36,960	5.66
Saanich	294	Canadian WWTP	82.7	37,036	3.06	43,357	3.58	52,837	4.37
Kimberly-Clark	252	Industrial - Pulp/Paper Mill	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Nippon Paper	263	Industrial - Pulp/Paper Mill	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Port Townsend Paper	271	Industrial - Pulp/Paper Mill	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Simpson Tacoma	225	Industrial - Pulp/Paper Mill	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BP Cherry Point	240	Industrial – Oil Refinery	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Conoco Phillips	242	Industrial – Oil Refinery	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Shell Oil	278	Industrial – Oil Refinery	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tesoro	284	Industrial – Oil Refinery	N/A	N/A	N/A	N/A	N/A	N/A	N/A
US Oil & Refining	231	Industrial – Oil Refinery	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Intalco (sanitary)	251	Industrial - Aluminum	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Notes

1. Future per capita flow was assumed to equal to current per capita flow. For the new Brightwater facility, per capita flow was calculated as the average of the two King County WWTPs (South King and West Point)

Per capita wastewater flows observed at the two regional King County WWTPs (South King and West Point) exhibit a downward trend despite increases in sewered population. These downward trends reflect national patterns and are attributed to effective water conservation measures. Conversations with Ecology's wastewater permit writers and with King County staff concluded that per capita flows are not expected to decrease much more, at least for these two plants. To be conservative, we assumed that the current per capita flows will remain constant into the future. Since the Brightwater WWTP is new as of 2011, we did not have current flow or population information for this plant. Instead, we calculated per capita flow for this plant as an average of the per capita flows at each of the other two King County plants (South King and West Point). Brightwater's service area includes areas previously served by either South King or West Point.

Per capita flows vary greatly among the other WWTPs in Puget Sound and may not reflect trends attributed to water conservation practices. We assumed that current per capita flows will remain constant into the future for all WWTPs. This resulted in a consistent approach for all U.S. plants. Figure B-3 illustrates the range in current per capita flows for WWTPs of different sizes. Per capita flows typically vary from 50 to 150 gpcd in large and medium sized WWTPs, but exhibit much greater variability in smaller WWTPs.

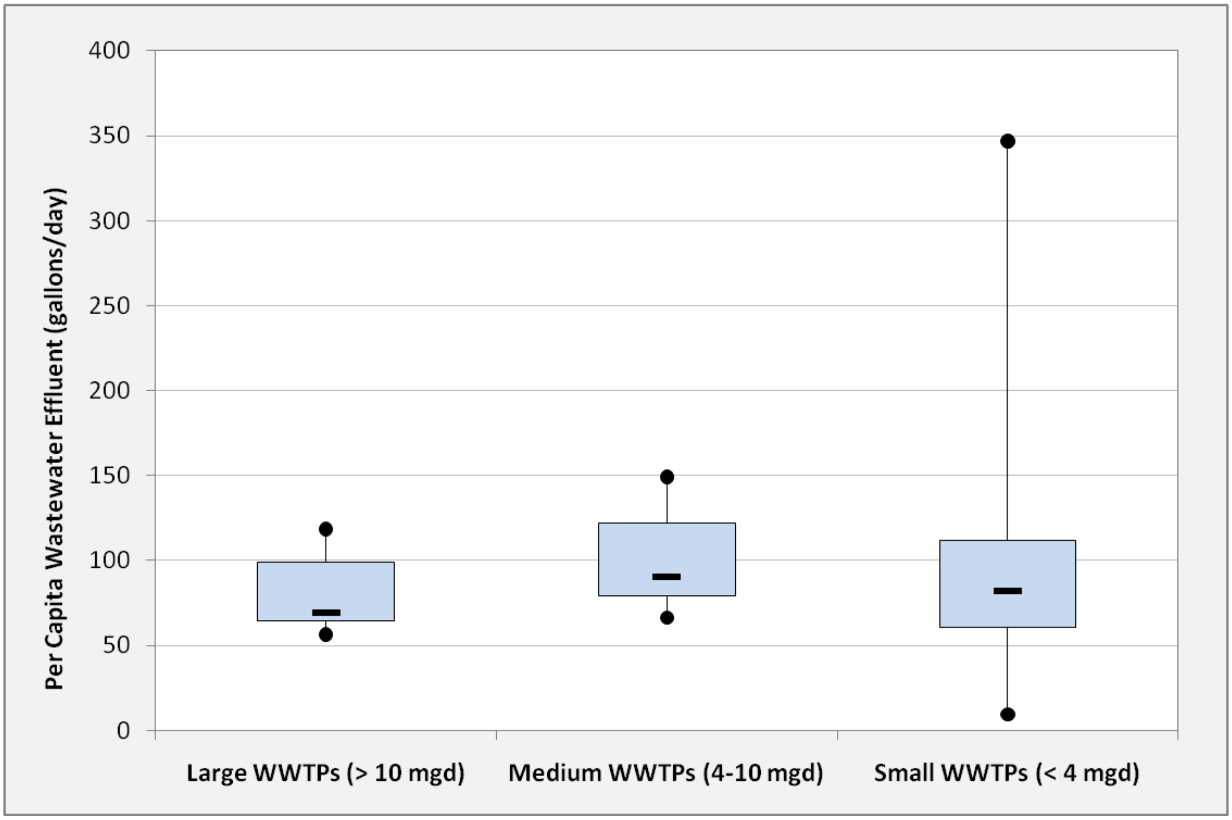


Figure B-3. Range of current per capita wastewater flows for large, medium and small WWTPs.

The plot indicates the maximum and minimum values (black dots), 25th and 75th percentiles (upper and lower sides of rectangular box), and the median values (black dash).

Future wastewater flows were then calculated as a simple product of current per capita flows with future population scenarios for each year of interest (2020, 2040, and 2070).

Since most WWTPs will experience some growth in sewered population into the future, their effluent flows will increase into the future if current per capita flows remain constant. We compared future wastewater flows to each WWTP's hydraulic capacity to treat these flows to determine if and when future flows exceed current plant capacity.

NPDES permits do include mass effluent limits of biological oxygen demand (BOD) and total suspended solids (TSS). However, the annual average hydraulic/flow capacity of the treatment system, in units of flow, is rarely reported in NPDES permits or fact sheets. Each NPDES permit, however, reports the Q-max month, or maximum monthly flow. The Q-max month is defined as the average of daily flows for the month with the highest total flow during the design life of the plant and is also referred to as the design criteria or design flow. The Q-max month is always greater than the average annual flow for the plant, and relates to the plant's organic loading capacity.

We used the Q-max month value as a surrogate for the plant's actual current hydraulic capacity (in terms of flow). The Q-max month is almost always well above the average daily WWTP discharge. Each plant is designed to treat more than what they treat on an average day. In addition, since permits may change in the future to allow greater Q-max month, using Q-max month to determine when *average* daily loads exceed capacity is a conservative approach.

We compared estimates of future flows for individual WWTPs to the Q-max month value in the existing permit. We identified the plants exceeding existing capacity and calculated the total magnitude of excess flows and the percentage of total future WWTP flows in excess of existing Q-max month flows. This was completed for all three population scenarios (Low, Medium, and High).

We assumed that WWTPs that currently discharge into Puget Sound will continue to discharge all their flow, even if it exceeds the Q-max month into Puget Sound. We also assumed that future wastewater would be discharged through existing marine outfalls. We cannot predict how individual plants will manage future flows. Some plants may expand capacity to treat future wastewater, which would increase the discharge volume of treated effluent to the Puget Sound, while other plants may reduce a portion of their discharge by increasing the amount of reclaimed water used.

Few WWTPs have NPDES permit limits for effluent flow discharged to Puget Sound, although some have influent flow limits. WWTPs may request an increase in their permitted discharge due to a plant expansion or testing to prove that existing capacity is greater than what was originally permitted. WWTPs may increase efforts to reduce wastewater flows through more stringent water conservation measures. Permit increases cannot be granted if the permittee discharges to a water body with a water quality impairment. These assumptions do not presume any change to current wastewater management or policy.

Appendix C. Glossary, Acronyms, and Abbreviations

Glossary

Anthropogenic: Human-caused.

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

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

Effluent: An outflowing of water from a natural body of water or from a man-made structure. For example, the treated outflow from a wastewater treatment plant.

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

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

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

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.

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

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.

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

Acronyms and Abbreviations

BNR	Biological nutrient removal
BOD	Biological oxygen demand
CIG	Climate Impacts Group
DFO	Fisheries and Oceans Canada
DIN	Dissolved inorganic nitrogen
DO	Dissolved oxygen
DON	Dissolved organic nitrogen
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
FVCOM	Finite Volume Coastal Ocean Model
GIS	Geographical Information Systems
GMA	Growth Management Act
JEMS	Joint Effort to Monitor the Strait of Juan de Fuca
LOTT	Lacey, Olympia, Tumwater, and Thurston
LUI	Land Use Index
MBR	Membrane bioreactor
MWCI	Marine Water Condition Index
NARR	North American Regional Reanalysis
NCAR	National Center for Atmospheric Research
NHDPlus	National Hydrography Database
NPDES	(See Glossary above)
OFM	Office of Financial Management
OSSs	On-site sewage systems
PDO	Pacific Decadal Oscillation
PNNL	Pacific Northwest National Laboratory
PON	Particulate organic nitrogen
PSRC	Puget Sound Regional Council
SSWQ	Salish Sea Water Quality
TSS	Total suspended solids
UGAs	Urban growth areas
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity
WAC	Washington Administrative Code
WPCF	Water Pollution Control Facility
WRF	Weather Research Forecasting
WRIA	Water Resource Inventory Area
WWTP	Wastewater treatment plant

Units of Measurement

°C	degrees centigrade
cfs	cubic feet per second
cms	cubic meters per second, a unit of flow
ft	feet
gpcd	gallons per capita per day
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	milligram
mgd	million gallons per day
mg/L	milligrams per liter (parts per million)
mL	milliliters
mmol	millimole or one-thousandth of a mole
mole	an International System of Units (IS) unit of matter
psu	practical salinity units
uM	micromolar, a chemistry unit