DEPARTMENT OF
ECOLOGY
State of Washington

Puget Sound Nutrient Synthesis Report, Part 2

Comparison of Watershed Nutrient Load Estimates

October 2019
Publication 19-03-019

Publication Information

This report is available on the Department of Ecology's website at:
https://fortress.wa.gov/ecy/publications/SummaryPages/1903019.html.

The Activity Tracker Code for this study is 18-026.

Suggested Citation:
McCarthy, S. 2019. Puget Sound Nutrient Synthesis Report, Part 2: Comparison of Watershed Nutrient Load Estimates. Publication 19-03-019. Washington State Department of Ecology, Olympia. https://fortress.wa.gov/ecy/publications/SummaryPages/1903019.html.

Contact Information

Publications Coordinator
Environmental Assessment Program
Washington State Department of Ecology
P.O. Box 47600, Olympia, WA 98504-7600
Phone: (360) 407-6764

Washington State Department of Ecology – https://ecology.wa.gov

- Headquarters, Olympia 360-407-6000
- Northwest Regional Office, Bellevue 425-649-7000
- Southwest Regional Office, Olympia 360-407-6300
- Central Regional Office, Union Gap 509-575-2490
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Puget Sound Nutrient Synthesis Report, Part 2

Comparison of Watershed Nutrient Load Estimates

by

Sheelagh McCarthy

Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington

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Acknowledgments

The author of this report would like to thank the following people for their contributions:

- Naomi Detenbeck and Ryan Sullivan, U.S. Environmental Protection Agency (EPA) Atlantic Ecology Division, for discussion and collaboration on development of a decision support system tool.
- Andy James, Puget Sound Institute, for reviewing this report.
- Bob McKane, EPA, for discussion and information on the VELMA model.
- Tanya Roberts, Puget Sound Institute, for reviewing this report.
- Gary Shenk, United States Geological Survey (USGS), for discussion and information on the Chesapeake Bay program.
- Dan Wise, USGS, for providing information on SPARROW and reviewing this report.

The following Ecology staff:

- For reviewing this report:
  - Environmental Assessment Program: Scott Collyard, Chad Larson, and Dale Norton.
  - Water Quality Program: Dustin Bilhimer, Kelly Ferron, Melissa Gildersleeve, and Ben Rau.
- For providing information, guidance, review, and support:
  - Environmental Assessment Program: Cristiana Figueroa-Kaminsky and Teizeen Mohamedali.

This project received funding from grants to the Washington State Department of Ecology from the United States Environmental Protection Agency (EPA), National Estuary Program, under EPA grant agreements PC-00J20101 and PC00J89901, Catalog of Domestic Assistance Number 66.123, Puget Sound Action Agenda: Technical Investigations and Implementation Assistance Program. The content of this document does not necessarily reflect the views and policies of the EPA, nor does mention of trade names or commercial products constitute an endorsement or a recommendation for their use.

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Abstract

Puget Sound has areas of low dissolved oxygen that do not meet Washington State Water Quality Standards due to the influence of excess nutrients from anthropogenic sources (Ahmed et al., 2019; Ahmed et al., 2014; Albertson et al., 2002; M. Roberts et al., 2014). Nutrient sources influencing dissolved oxygen conditions include both marine point sources (e.g., wastewater treatment plants) and upstream watershed sources (Ahmed et al., 2019).

The United States Geological Survey (USGS) Spatially Referenced Regressions On Watershed Attributes (SPARROW) model estimates nutrient (nitrogen and phosphorus) loads in a Pacific Northwest application (Wise and Johnson, 2013). Nutrient load estimates for the Puget Sound region (2002) are used to identify nutrient loading patterns and nutrient source contributions. Approximately half of the total nitrogen loading to Puget Sound is from urban sources, a quarter is from forested areas, and the remainder is from a combination of agricultural sources and atmospheric deposition. The Snohomish and Skagit Rivers have the highest overall total nitrogen loads into Puget Sound. The Stillaguamish, Nooksack, and Snohomish Rivers have the highest total nitrogen yield (load per unit area).

SPARROW results were compared with nutrient load estimates used as inputs for the Salish Sea Model. Nutrient load estimates are similar, with SPARROW results (25.45 million kg/yr) slightly higher than Salish Sea Model nutrient inputs (25.43 million kg/yr). The largest differences occur in nitrogen loads to the Main Basin of Puget Sound, due to differences in load estimates from large wastewater treatment plants.

The Washington State Department of Ecology's (Ecology) Puget Sound Nutrient Source Reduction Project (PSNSRP) seeks to address human sources of nutrients and identify actions needed to control nutrients from point and nonpoint sources to improve dissolved oxygen conditions. Results from this report may be used to characterize watershed nutrient loading for the PSNSRP and a related management effort, the Marine Water Quality Implementation Strategy for Puget Sound.

Background

Puget Sound is a dynamic, complex estuary and provides important environmental, cultural, and economic benefits. The greater Puget Sound region refers to Puget Sound and its adjoining waterways and bays (Figure 1). The regions include the watersheds draining into major basins with similar characteristics (Strait of Juan de Fuca; Strait of Georgia; Admiralty; Hood Canal; South Sound; Main Basin; Whidbey Basin; and Bellingham, Samish, and Padilla Bays).

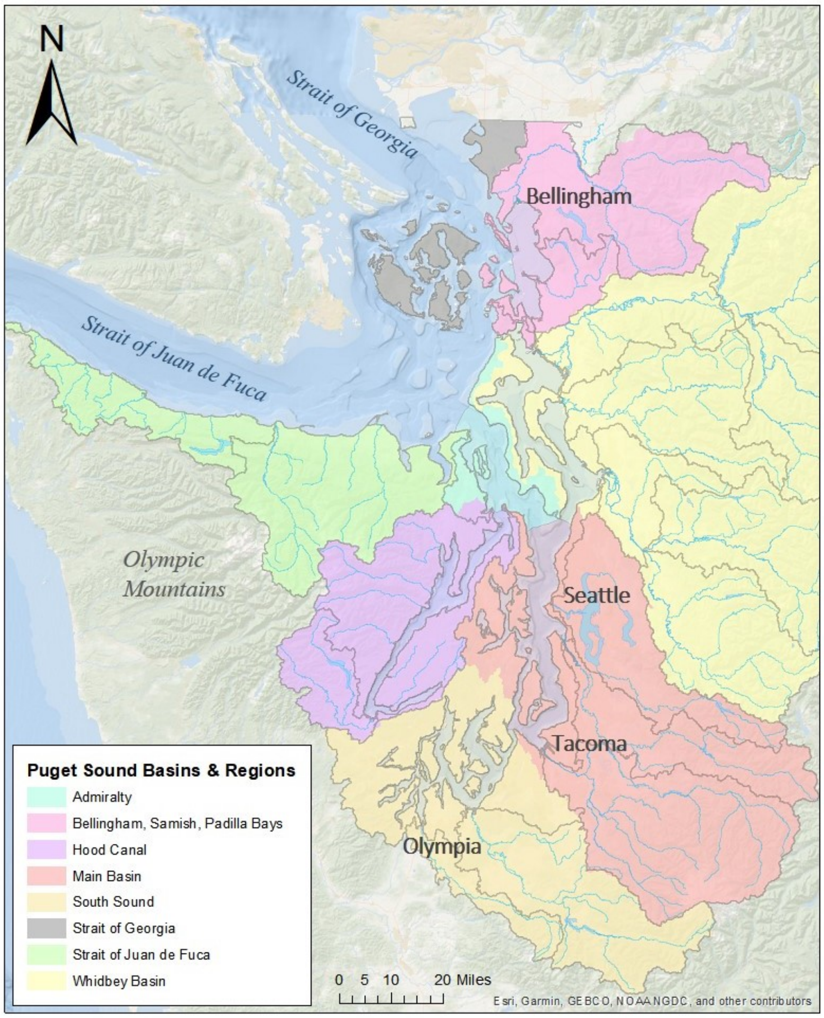

Figure 1. Map of greater Puget Sound region.

Nutrients play a critical role in the health of aquatic ecosystems in Puget Sound. While these nutrients are naturally present in the environment and are needed for a healthy ecosystem, excess nutrients can cause environmental issues. Nitrogen is the limiting nutrient in Puget Sound (Newton and Van Voorhis, 2002). Excess nitrogen can fuel algal growth resulting in algal blooms. Algae are a source of organic carbon, as are terrestrial sources of detritus that are delivered to marine waters. During the decomposition process of organic carbon, dissolved oxygen is consumed, resulting in a reduction of dissolved oxygen. This process is called *eutrophication* and can hinder the ability of an ecosystem to support aquatic life (Diaz and Rosenberg, 2008; Glibert et al., 2005).

Recent studies show that human activities have increased nitrogen and carbon inputs above naturally occurring levels and have contributed to reductions of dissolved oxygen in Puget Sound (Ahmed et al., 2019; Albertson et al., 2002; Mohamedali et al., 2011; M. Roberts et al., 2014). Future population growth in the Puget Sound region is expected to further increase nutrient loads from urban sources (M. Roberts et al., 2014). Additionally, excess nitrogen can also influence the following issues in Puget Sound:

- Ocean acidification (Feely et al., 2010; Pelletier et al., 2017).
- Changes to benthic (bottom-dwelling) community structure and diversity (Diaz and Rosenberg, 2008).
- Changes to micronutrient availability that may lead to increased occurrence and duration of harmful algal blooms (Howarth et al., 2011).
- Impairments to eelgrass beds, an important habitat for aquatic species in Puget Sound (Burkholder et al., 2007; Hessing-Lewis et al., 2011), and declines in eelgrass shoot density (Bittick et al., 2018; Nelson and Lee, 2001).

Phosphorus plays a critical role in freshwater systems. Local studies show the influence that excess phosphorus has on dissolved oxygen levels and water quality in freshwater systems in the Puget Sound region (Bell-McKinnon, 2010; Edmondson, 1970; Embrey and Inkpen, 1998). Additionally, excess phosphorus may contribute to eutrophication downstream as well (Howarth et al., 2011).

Nutrient Synthesis Report (Part 2) Objectives

Part 1 of the Puget Sound Nutrient Synthesis Report is an overview of nutrient management and scientific application and research projects funded by the National Estuarine Partnership (NEP) Toxics and Nutrients Prevention, Reduction, and Control Cooperative Agreement (McCarthy, 2019). The Part 1 report indicated a need to more fully understand and assess the type and magnitude of watershed nutrient sources in order to guide nutrient management projects and decisions.

This report (Part 2) seeks to identify and quantify nutrient sources within watersheds draining into Puget Sound by using available nutrient load estimates from regional water quality models and studies. Objectives of this report include:

- Provide background and overview of watershed nutrient sources to Puget Sound and regional models with nutrient load estimates (United States Geological Survey's [USGS] SPARROW and Ecology's Salish Sea Model [SSM]).
- Provide exploratory analysis of nutrient load estimates in the Puget Sound region from results of the USGS SPARROW model Pacific Northwest application (Wise and Johnson, 2013).

- Identify watersheds with high nutrient loading and relative nutrient source contributions into Puget Sound based on SPARROW results.

- Compare SPARROW nitrogen load estimates with Salish Sea Model nitrogen load inputs.

Nutrient Management in Puget Sound

Presently, there are two concurrent regional management efforts for nutrients in Puget Sound: the Puget Sound Nutrient Source Reduction Project and the Marine Water Quality Implementation Strategy.

Puget Sound Nutrient Source Reduction Project

Ecology's Puget Sound Nutrient Source Reduction Project[1] (PSNSRP) is working to develop and implement a Puget Sound nutrient source reduction plan to guide regional investments in point and nonpoint source nutrient controls so that Puget Sound will meet dissolved oxygen water quality criteria and aquatic life designated uses by 2040. This collaborative process involves communities, stakeholders, and those already working to manage and address human sources of nutrients.

PSNSRP uses results from the SSM studies to inform nutrient management decisions. Therefore, a series of modeling results are part of the project. Results from the first phase of PSNSRP modeling are documented in the report *Puget Sound Nutrient Source Reduction Project, Volume 1: Model Updates and Bounding Scenarios* (Ahmed et al., 2019). The model scenarios estimate the range of response of Puget Sound water quality conditions from different nutrient loads. Model scenarios evaluated water quality conditions with (1) current levels of nutrient loading from marine point sources and watersheds into Puget Sound and (2) load reductions due to potential improvements in nutrient removal technologies applied to municipal wastewater treatment plants (WWTPs). PSNSRP will use results from the SSM as guidance for management decisions to reduce nutrients to meet dissolved oxygen water quality criteria.

[1] https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Helping-Puget-Sound/Reducing-Puget-Sound-nutrients

Marine Water Quality Implementation Strategy

The Puget Sound Partnership, an agency guiding Puget Sound ecosystem recovery, creates a recovery plan captured in the Action Agenda, a routinely updated document describing recovery goals and needs. The Puget Sound Action Agenda identifies work needed to protect and restore Puget Sound, based on science and clear, measurable goals for recovery. Part of the Action Agenda framework involved the establishment of Vital Signs for various aspects of the ecosystem, along with numerical indicators of each Vital Sign's status, or health, and targets to achieve to maintain that particular Vital Sign's health.

Marine water quality (MWQ) is a Vital Sign that includes nutrients and dissolved oxygen. It reflects the impacts of human-caused stresses on Puget Sound marine waters. Implementation strategies, plans to guide regional actions, are being created to support the achievement of Vital Sign targets. An implementation strategy is currently being developed for the MWQ Vital Sign in collaboration with EPA, Ecology, the Puget Sound Partnership, the Puget Sound Institute, and many volunteers from local government, tribes, other state and federal agencies, conservation districts, and nongovernmental organizations. The MWQ Implementation Strategy will provide the Puget Sound Action Agenda with priority actions and strategies to improve dissolved oxygen levels in marine waters.

The Puget Sound Institute supports implementation strategy development by compiling a starter package for each strategy. The starter package serves as a primer on the current state of research, regulations, and practices important to the Vital Sign. The MWQ starter package contains a collection of science, information, considerations, related programs, and ongoing work related to nutrients and dissolved oxygen in Puget Sound (T. Roberts et al., 2018). As the implementation strategy progresses, the starter package will evolve into a state-of-knowledge report that accompanies the final MWQ Implementation Strategy narrative product.

Puget Sound Region Land Cover & Nutrient Sources

Land Cover

Land cover and land use patterns influence the delivery of nutrients to rivers and streams that ultimately discharge into Puget Sound. The distribution of land cover from the 2001 National Land Cover Database (NLCD) (Homer et al., 2004) in the greater Puget Sound region is shown in Figure 2.

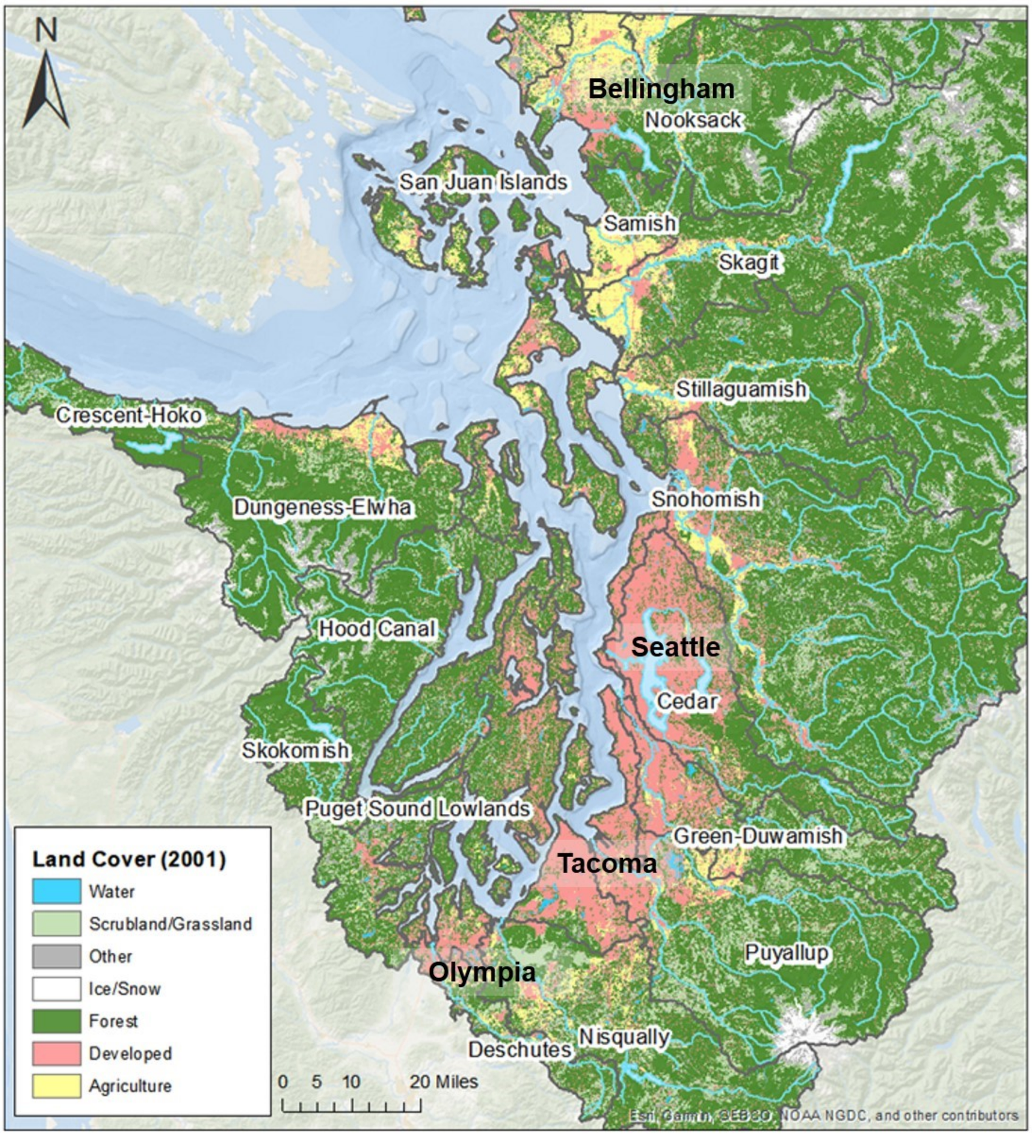

Figure 2. Map of land cover and major watersheds in greater Puget Sound region (2001 National Land Cover Database).

Land cover was aggregated by watershed to develop a land use analysis. Table 1 is a summary of major watersheds, the Puget Sound basin they drain into, and land cover data. Major land cover types includes developed land, agricultural land (farmland and pasture), forests, and other land types. Other land cover includes open water, barren land, scrubland, grassland, and wetlands.

Forests are the dominant type of land cover in all watersheds, except for the Cedar watershed, where developed land is the most dominant. Following forests, agricultural land was the second-highest land use in the San Juan Islands and Samish watershed areas, and developed land in the Green-Duwamish watershed and Puget Sound Lowlands. The Puget Sound Lowlands refer to coastal areas that drain into the Main Basin, South Sound, and Whidbey Basin, including the Kitsap Peninsula and coastal areas around Tacoma and Seattle. Other land use categories (open water, barren land, scrubland, grassland, and wetlands) were the second-highest fraction in the remainder of watersheds.

Table 1. Land cover by watershed based on the 2001 National Land Cover Database.

Basin	Watershed	Area (acres)	Developed (%)	Forest (%)	Agriculture (%)	Other (%)
Bellingham, Samish, Padilla Bays	Nooksack	735,000	7	58	12	22
	Samish	205,000	15	42	26	17
Hood Canal	Skokomish	155,000	4	73	1	22
	Hood Canal	510,000	5	75	0	20
Main Basin	Green-Duwamish	310,000	28	49	4	20
	Puyallup	630,000	13	58	3	26
	Cedar	390,000	46	39	1	14
Main Basin, South Sound, Whidbey Basin	Puget Sound Lowlands	955,000	33	49	3	14
South Sound	Nisqually	490,000	10	58	6	26
	Deschutes	110,000	20	50	5	24
Strait of Georgia	San Juan Islands	105,000	11	64	13	12
Strait of Juan de Fuca	Dungeness-Elwha	530,000	6	70	4	20
	Crescent-Hoko	245,000	2	76	1	22
Whidbey Basin	Stillaguamish	450,000	7	72	6	15
	Snohomish	1,165,000	10	67	3	20
	Skagit	1,785,000	3	66	3	29

Nutrient Sources

Nutrients from various sources are delivered to Puget Sound via multiple pathways (Figure 3).

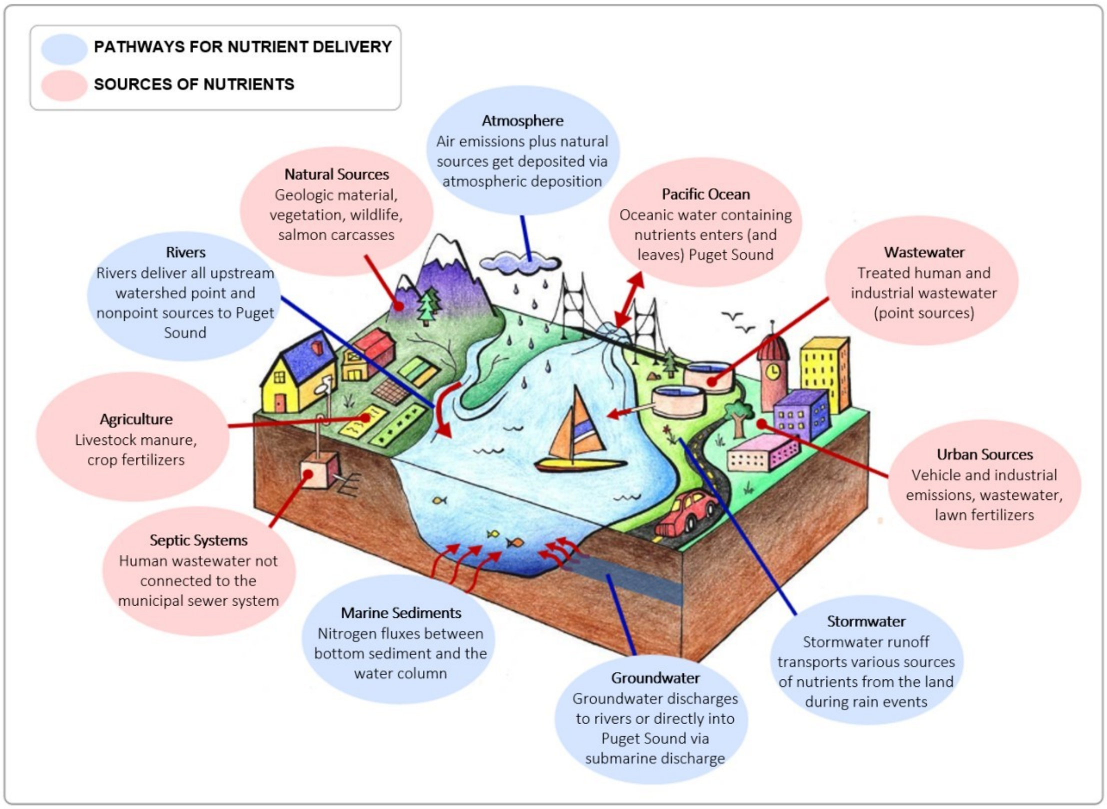

Figure 3. Pathways and sources of nutrients in Puget Sound. Figure adapted from Nitrogen in Puget Sound Story Map (Mohamedali and McCarthy, 2018).

Agricultural Sources

Agricultural activities contribute nutrients into waterways that discharge into Puget Sound. Agricultural sources of nutrients can be from livestock manure and crop fertilizer. Livestock that have direct access to streams and waterways can impact dissolved oxygen conditions downstream (Sheffield et al., 1997; Belsky et al., 1999;). Overapplication of manure to cropland enters surface waters through runoff (Almasri and Kaluarachchi, 2004). Excess nutrients, both nitrogen and phosphorus, from fertilizer application can enter surface waters and groundwater (Almasri and Kaluarachchi, 2004; Ongley, 1996). Studies in the Sumas-Blaine aquifer (Nooksack watershed area in Whatcom County) have found elevated levels of nitrate in groundwater in areas with high rates of fertilizer application and manure application (Carey and Harrison, 2014; Carey and Cummings, 2012).

Agricultural sources of nutrients are delivered to rivers and streams through stormwater runoff, overland flow, and groundwater.

Agriculturally dominated watersheds are located north of Bellingham (Figure 2). There is also a large expanse of agricultural land, between Bellingham and Seattle, in the Skagit and Stillaguamish watersheds. Agricultural activities are dispersed throughout South Sound.

Urban Sources

Urban sources of nutrients include both point and nonpoint sources from developed areas, including both urban and suburban environments. Point sources are permitted facilities discharging wastewater, and can include wastewater treatment plants, industrial facilities, and hatcheries. Nonpoint urban sources may include transportation and vehicle emissions, fertilizer application on lawns, and on-site septic systems. Nutrients may be transported to streams and rivers through atmospheric deposition, stormwater runoff, and groundwater that ultimately lead to Puget Sound.

Highly urbanized areas near Seattle and Tacoma have the greatest amount of developed land. These highly urbanized areas are found within the Cedar, Green-Duwamish, and Puyallup watersheds and along nearshore watersheds draining into Puget Sound at the shoreline (Table 1). Heavily developed urban areas have large municipal wastewater treatment facilities that service large populations, with many of these facilities discharging directly into Puget Sound through marine outfalls.

Regional studies indicate that the largest local sources of nitrogen into Puget Sound are marine point sources, including wastewater treatment plants (WWTPs), followed by upstream watershed sources transported via rivers and streams (Ahmed et al., 2019; Mohamedali et al., 2011; M. Roberts et al., 2014).

Forests and Other Sources

Forests and other sources of nutrients refer to nutrients originating from both biological and abiotic processes. Nitrogen is found naturally in streams and rivers through atmospheric deposition (naturally occurring and from human emissions), instream processes (e.g., salmon carcasses), and forests (e.g., alder trees). Due to the expanse of active forestry throughout the Pacific Northwest, activities such as timber harvesting, forest fertilization, and other associated forestry management activities can increase the export of nitrogen in streams directly and indirectly (Anderson, 2002; Binkley and Brown, 1993; Gravelle et al., 2009; Harr and Fredriksen, 1988).

The most common hardwood species throughout the Pacific Northwest is red alder (Deal and Harrington, 2006). Red alders favor areas with direct sunlight and exposed soil. Due to this, land use practices such as timber harvesting and burning have favored alder growth throughout the region (Deal and Harrington, 2006). Historical pollen records indicate higher distributions of alder stands since the twentieth century than in previous centuries (Heusser, 1964; Davis, 1973). Alders fix atmospheric nitrogen and contribute nitrogen to surrounding soil (Berg and Doerksen, 1975; Tarrant and Miller, 1963). In a coastal Oregon watershed, nitrogen leaching from alder stands to surface waters is estimated at 14.2 $kg \cdot acre^{-1} yr^{-1}$ (Compton et al., 2003).

A study by the Washington State Department of Natural Resources and Ecology (McIntyre et al., 2018) evaluated the effects of timber harvesting in western Washington headwater streams. One component of this study quantified instream nitrogen (total nitrogen, nitrate) and phosphorus (total phosphorus) export from forested headwater streams (Ehinger and Estrella, 2018). Nutrient exports for a set of different buffer systems, or the width of area designated to remain during a timber harvest, were compared with sites without timber harvesting (reference sites).

Major findings in the buffer treatment study showed that the greatest difference in nitrogen exports occurred between sites with no riparian buffer and those with two-sided 50-foot riparian buffers (Ehinger and Estrella, 2018). Nitrogen export increased in proportion with the harvest area and correlated with annual runoff. Compared with the annual export of total nitrogen at the unharvested reference sites, there was a 6.9 and 2.2 $kg \cdot acre^{-1} yr^{-1}$ increase in export from harvested sites with no riparian buffer and 50-foot riparian buffer system, respectively.

The report *Toxics in Surface Runoff to Puget Sound: Phase 3 Data and Load Estimates* (Herrera, 2011) identified that residential and agricultural sources of nitrogen contribute a significant amount of the nonpoint nutrient loading to Puget Sound's rivers and streams. Unit-area loading rates for nitrogen in stormwater are generally higher for residential and agricultural land uses (1.2 and 1.5 $kg \cdot acre^{-1} yr^{-1}$, respectively) than forested and industrial/commercial land uses (0.4 and 0.6 $kg \cdot acre^{-1} yr^{-1}$, respectively) (Herrera, 2011).

Many of the same sources and pathways of nitrogen also deliver phosphorus into Puget Sound, with weathering of geologic materials as an additional major source of phosphorus. Because nitrogen is the limiting nutrient in Puget Sound (Newton and Van Voorhis, 2002), research on nitrogen loading to Puget Sound is more extensive than phosphorus. However, phosphorus loading is also of interest because it plays a critical role in the health of freshwater systems, and it can influence water quality downstream that ultimately discharges into Puget Sound.

Atmospheric Deposition

Atmospheric deposition of total nitrogen includes both natural and anthropogenic sources. The major human sources of nitrogen emissions come from transportation, agriculture, power plants, and industry (Fenn et al., 2003). In the Puget Sound region, anthropogenic sources contribute more to nitrogen emissions than natural sources (Herron-Thorpe et al., 2018). Atmospheric deposition of nitrate/nitrite and ammonium includes wet deposition, absorbed by precipitation, and dry deposition that is directly deposited to the surface. Figure 4 shows the atmospheric deposition of total nitrogen during 2002.

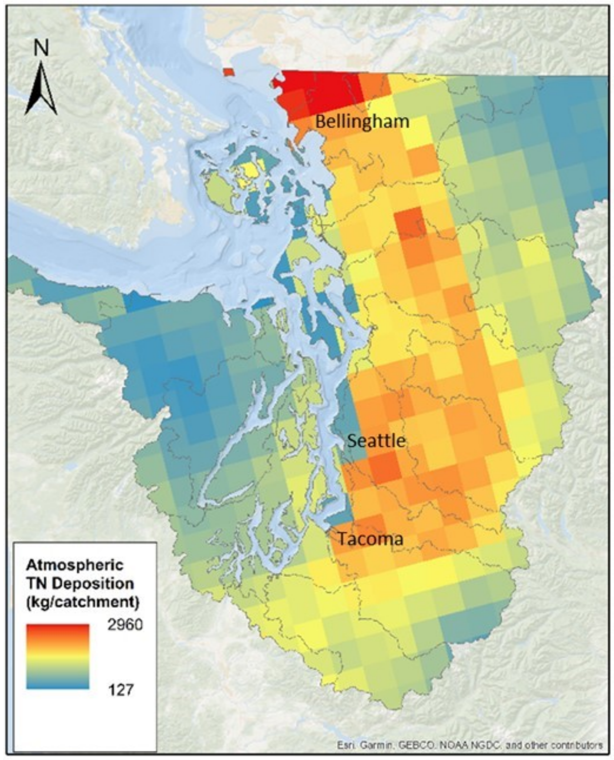

Figure 4. Atmospheric deposition of total nitrogen,
2002 CMAQ, 2002).

Pacific Ocean

The Pacific Ocean influences circulation and water quality conditions in Puget Sound. Oceanic waters that are nutrient-rich and low in oxygen are brought into Puget Sound through the Strait of Juan de Fuca and Admiralty Inlet through upwelling processes. The Pacific Ocean results in an annual net input of nitrogen (Mackas and Harrison, 1997). Regional studies estimate that most of this nitrogen does not become available for algal uptake; instead it flows back into the ocean through the Strait of Juan de Fuca (Davis et. al. 2014; Khangaonkar et al., 2018).

Regional Water Quality Models

Water quality models are used to simulate biological, chemical, and physical processes, because limited data and observations are unable to fully capture the complexities of freshwater and marine systems. Models are developed in varying levels of complexity across different spatial (e.g., estuary or watershed) and temporal (e.g., daily or annual) scales. This section provides an overview of three different types of models adapted for the Pacific Northwest, including a highly complex estuarine model (Salish Sea Model [SSM]) and two watershed models (Spatially Referenced Regressions On Watershed Attributes [SPARROW] and Visualizing Ecosystem Land Management Assessments [VELMA]).

SSM is a complex computational tool that simulates the hydrodynamic and water quality processes throughout Puget Sound and the greater Salish Sea. Alternatively, watershed models are developed at varying resolutions for a certain watershed or sub-watershed. These watershed models generally use geospatial data pertaining to hydrology, land use, and various physical and biological characteristics. Watershed models adapted for applications within the Pacific Northwest, SPARROW and VELMA, are presented in the following sections. Currently, SPARROW is developed on a Puget Sound–wide watershed scale, and VELMA has been adapted for sub-watershed applications.

Salish Sea Model

Pacific Northwest National Laboratory (PNNL), in collaboration with Ecology, developed the Salish Sea Model (SSM) as a predictive ocean-modeling tool (Khangaonkar et al., 2011, 2012). The SSM is a state-of-the-science computer-modeling tool that simulates the complex physical, chemical, and biological patterns inherent in this system. SSM simulates connected estuarine process, including hydrodynamics (tides, stratification, mixing, freshwater inflows, salinity, and temperature) and water quality (algal biomass, nutrients, carbon, dissolved oxygen, and pH) (Ahmed et al., 2019; McCarthy et al., 2018). The model domain includes all of Puget Sound, the Strait of Juan de Fuca, the Strait of Georgia, and expands out to the continental shelf in the Pacific Ocean and around Vancouver Island (Figure 5).

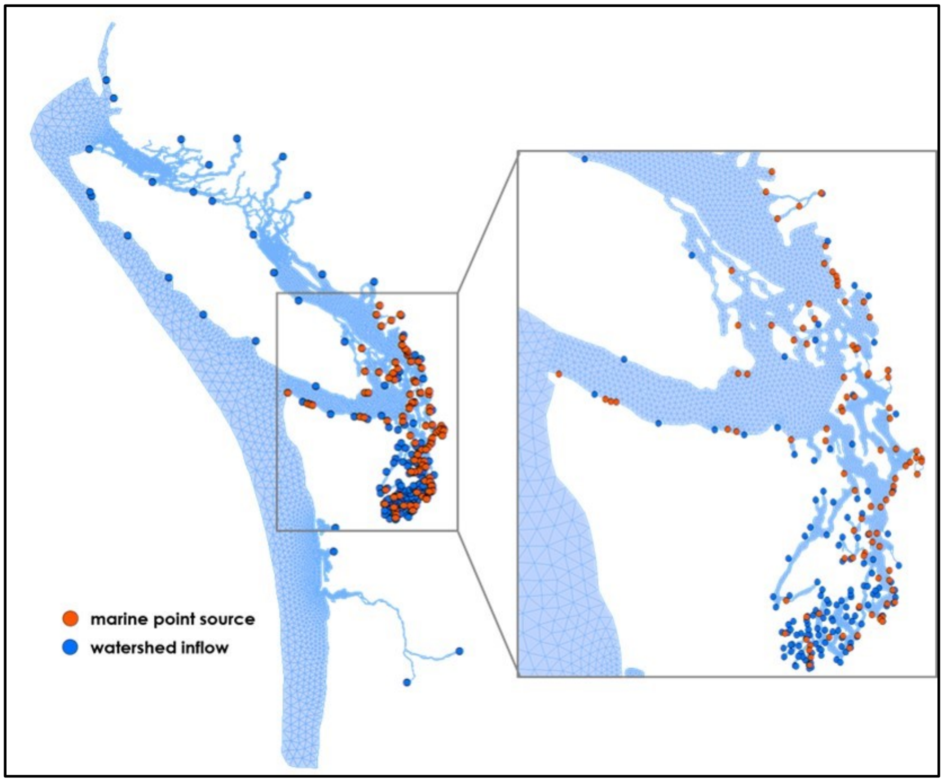

Figure 5. Salish Sea Model (SSM) domain and locations of marine point sources and watershed inflows.

The SSM uses nutrient load estimates as model inputs to simulate water quality conditions in Puget Sound. SSM model inputs are separated and quantified into two categories:

1. **Marine point sources:** 99 point sources (United States and Canada) that discharge into the marine waters of Puget Sound and the greater Salish Sea (WWTPs and industrial facilities).
2. **Watershed sources**: 161 watersheds (United States and Canada) that represent nutrients entering marine waters at the mouth of each river or stream. In the SSM, watershed nutrient loading estimates are based on monitoring data collected close to the mouth of watersheds, and thus integrate all upstream sources (including upstream point sources that do not discharge to marine waters).

Nutrient loads from the above two categories were estimated using a multiple linear regression technique using flow data and monthly water quality data to develop daily time series of water quality conditions entering Puget Sound (Ahmed et al., 2019; McCarthy et al., 2018; Mohamedali et al., 2011).

SPARROW

SPARROW (Spatially Referenced Regressions On Watershed Attributes) is a watershed model developed by the United States Geological Survey (USGS). SPARROW estimates stream loads, including nutrients, throughout a stream network. The statistical model calculates nutrient loading based on water quality measurements at distributed stations linked with watershed characteristics based on geospatial data sets (Smith et al., 1997). These geospatial data sets describe land cover and other attributes and are used to quantify nutrient loads from a variety of sources throughout the watershed. SPARROW is used nationwide. A list of publications and associated materials for model applications can be found on the SPARROW webpage.[2]

The SPARROW model uses a combination of deterministic and empirical approaches for water quality modeling (Schwarz et al., 2006). Monitoring data and watershed attributes are used to identify and explain factors affecting water quality. The model examines the statistical significance of nutrient sources, environmental factors, and transport processes to estimate nutrient loads (Smith et al., 1997). Using this statistical approach, SPARROW estimates stream nutrient loads in river or stream segments without monitoring data.

Wise and Johnson (2013) developed a Pacific Northwest application of SPARROW to simulate nutrient loading during the year 2002. SPARROW results include annual nutrient load (total nitrogen and total phosphorus) estimates for 2002. The model uses land cover information and water quality data from monitoring stations to estimate nutrient loads throughout Pacific Northwest stream segments, and attributes those loads to different nutrient sources. In the Wise and Johnson (2013) Pacific Northwest application, nutrient loads (reported as kg/yr) are calculated as the product of nutrient concentration and streamflow for the year 2002. These estimates can be used to identify the relative nutrient loads and sources in different watersheds in the Puget Sound region.

In addition to the Pacific Northwest application, regional SPARROW applications include Chesapeake Bay, New England, Mississippi River, and others. Many of these regional applications also include web-mapping tools that allow for visualization and interaction with results.

SPARROW continues to go through refinements and model improvements, including updated results for a 2012 Pacific Northwest application expected in late 2019. These more recent model results will be useful for additional analyses and comparisons.

Hydrologic Framework

The SPARROW application for the Pacific Northwest region uses the National Hydrography Dataset Plus (NHD) (Horizon Systems, 2013) for the hydrologic framework (Figure 6). Previous model versions used River Reach File 1 (RF1) hydrologic framework (Brakebill et al., 2011; Wise and Johnson, 2011). The use of this NHD framework updated the number of stream reaches from 12,039 stream reaches (RF1 framework) for the region to 232,811 stream reaches

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[2] https://www.usgs.gov/mission-areas/water-resources/science/sparrow-modeling-estimating-nutrient-sediment-and-dissolved?qt-science_center_objects=0#qt-science_center_objects

(NHD). Updated model estimates based on the NHD framework showed an improvement in fit statistics for both total nitrogen and total phosphorus compared to estimates based on the RF1 framework (Wise and Johnson, 2013).

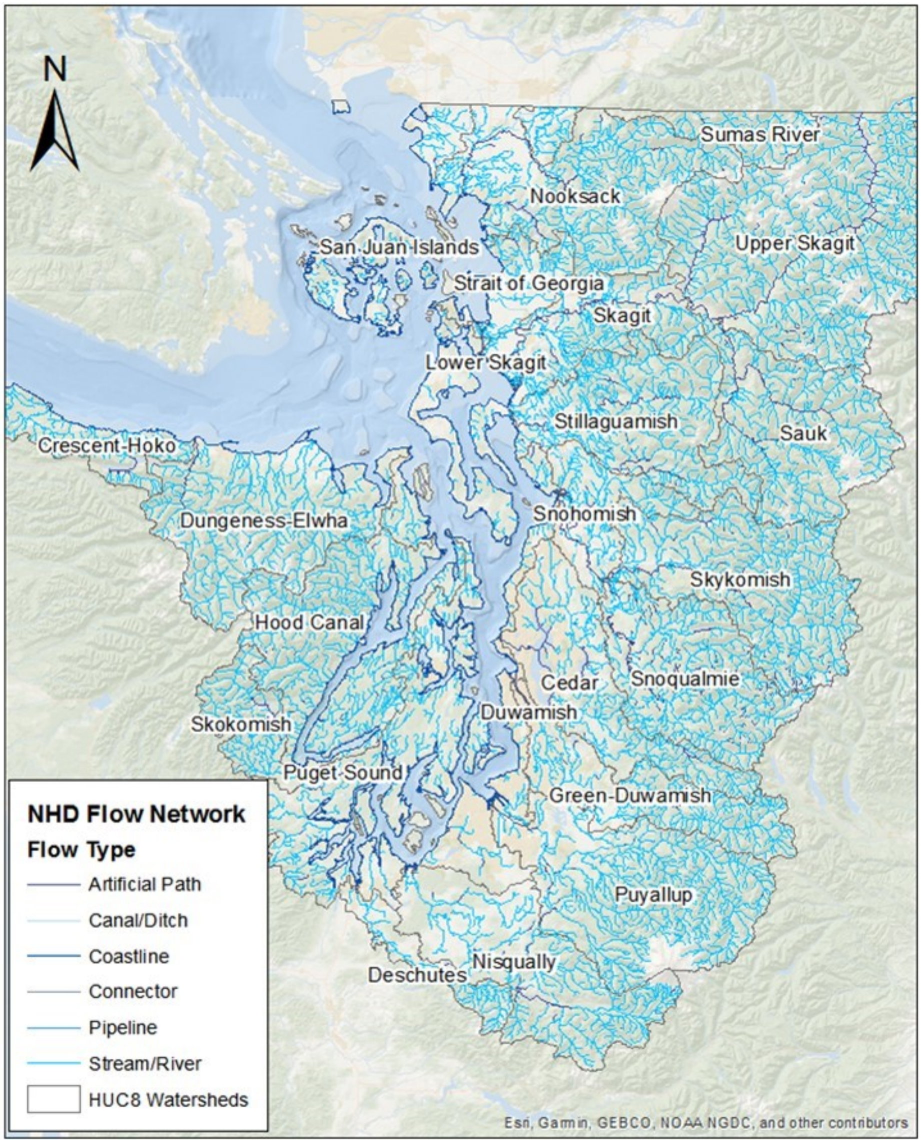

Figure 6. SPARROW hydrological framework using National Hydrography Dataset Plus (NHD).

Model Input: Nutrient Sources

SPARROW uses data and information from multiple sources to estimate nutrient loading (Smith et al., 1997; Alexander et al., 2008; Wise and Johnson, 2011, 2013). Nutrient sources include both point sources and nonpoint sources. Point source pollution comes from a single, identifiable discharge at a specific location into the natural environment (e.g., pipes, outfalls, WWTP discharges). Nonpoint sources refer to pollution from dispersed activities (e.g., atmospheric deposition, runoff from urban and agricultural lands).

Geospatial data (e.g., land cover) provide the explanatory variables for potential sources of nutrients and land-to-water delivery factors. Instream attenuation and nutrient delivery are estimated based on watershed characteristics, such as soils and morphology. Regional data sets (e.g., fertilizer use) are used to improve representation of regional conditions for the Pacific Northwest application (Wise and Johnson, 2013).

For this report, nutrient sources are grouped into the following categories (Table 2):

- Atmospheric deposition.
- Urban sources: urban and suburban runoff from developed land, wastewater facilities, on-site septic systems, and power returns from river diversions.
- Agriculture sources: fertilizer application, livestock manure (cattle and noncattle grazing and confined cattle at dairies and feedlots).
- Forests/geologic materials: forested land, red alder trees, springs, and geologic materials.

Table 2. Nonpoint and point sources of nitrogen and phosphorus used for SPARROW model input grouped into categories of atmospheric deposition, urban, agricultural, and forests/geologic materials.

Nutrient Source		**Nutrient**		**Source**	
Source	Category	Nitrogen	Phosphorus	Nonpoint	Point
Atmospheric deposition	Atmospheric deposition	X		X	
Urban	Developed land	X	X	X	
	Wastewater facilities	X	X		X
	On-site septic systems	X		X	
	Power returns	X	X	X	
Agriculture	Fertilizer	X	X	X	
	Livestock Manure	X	X	X	
Forests/ geologic materials	Forests	X		X	
	Red alder trees	X		X	
	Springs	X	X	X	
	Geologic materials		X	X	

Appendix A includes further descriptions of SPARROW methods for considering nutrient sources and a summary table of nutrient source information.

Nutrient Load Estimates

SPARROW estimates total nutrient loading (nitrogen and phosphorus) and the relative contribution of nutrients from distinct sources based on land use patterns and other geographic characteristics (Smith et al., 1997; Wise and Johnson, 2013). The analysis in this report uses SPARROW results from the Pacific Northwest application (Wise and Johnson, 2013), specifically within the Puget Sound watershed region. These model results are estimates based on 2002 data and are presented as an annual load.

A nutrient load is calculated as the product of nutrient concentration and streamflow for the year and is reported in kilograms per year (kg/yr). The model estimates nutrient loads (total nitrogen and total phosphorus) for each incremental subbasin and as a total load. An incremental subbasin is the area that drains directly to a reach without passing through another reach. The total load is the predicted load with contributions from all upstream landscape nutrient sources, while accounting for instream attenuation processes, including nutrient loss from uptake or nutrient decay, based on stream categories. For the Pacific Northwest application, stream attenuation is estimated using a first-order decay process that is a function of the time of travel for each reach within streamflow classes (Wise and Johnson, 2013; Wise and Johnson,2011). Model results showed that attenuation was not a significant removal mechanism in Pacific Northwest rivers (Wise and Johnson, 2013).

Nutrient load estimates are attributed to specific NHD segments by a distinct identifier code. SPARROW results are joined to its corresponding NHD river or stream reach in GIS to analyze the results spatially and identify results at a specific river segment.

Total Nitrogen Load Estimates

SPARROW model results for total nitrogen loading in 2002 are shown in Figure 7. Total nitrogen equals the sum of dissolved nitrate, nitrite, and total Kjeldahl nitrogen (organic nitrogen and ammonia) (Smith et al., 1997). These load estimates are representative of all nitrogen sources draining into Puget Sound via river and stream outlets and at the shoreline from nearshore watersheds.

Snohomish and Skagit watersheds have the highest overall total nitrogen loading based on these results. These watersheds are also the largest watersheds discharging into Puget Sound (Table 1). Nearshore watersheds draining into Puget Sound along the shoreline near Seattle also have high overall total nitrogen loading. These nearshore watershed estimates include loads from point sources that are discharging into marine waters. Generally, less-developed watersheds in the Olympic Peninsula have lower total nitrogen loading than other human-influenced areas of Puget Sound region.

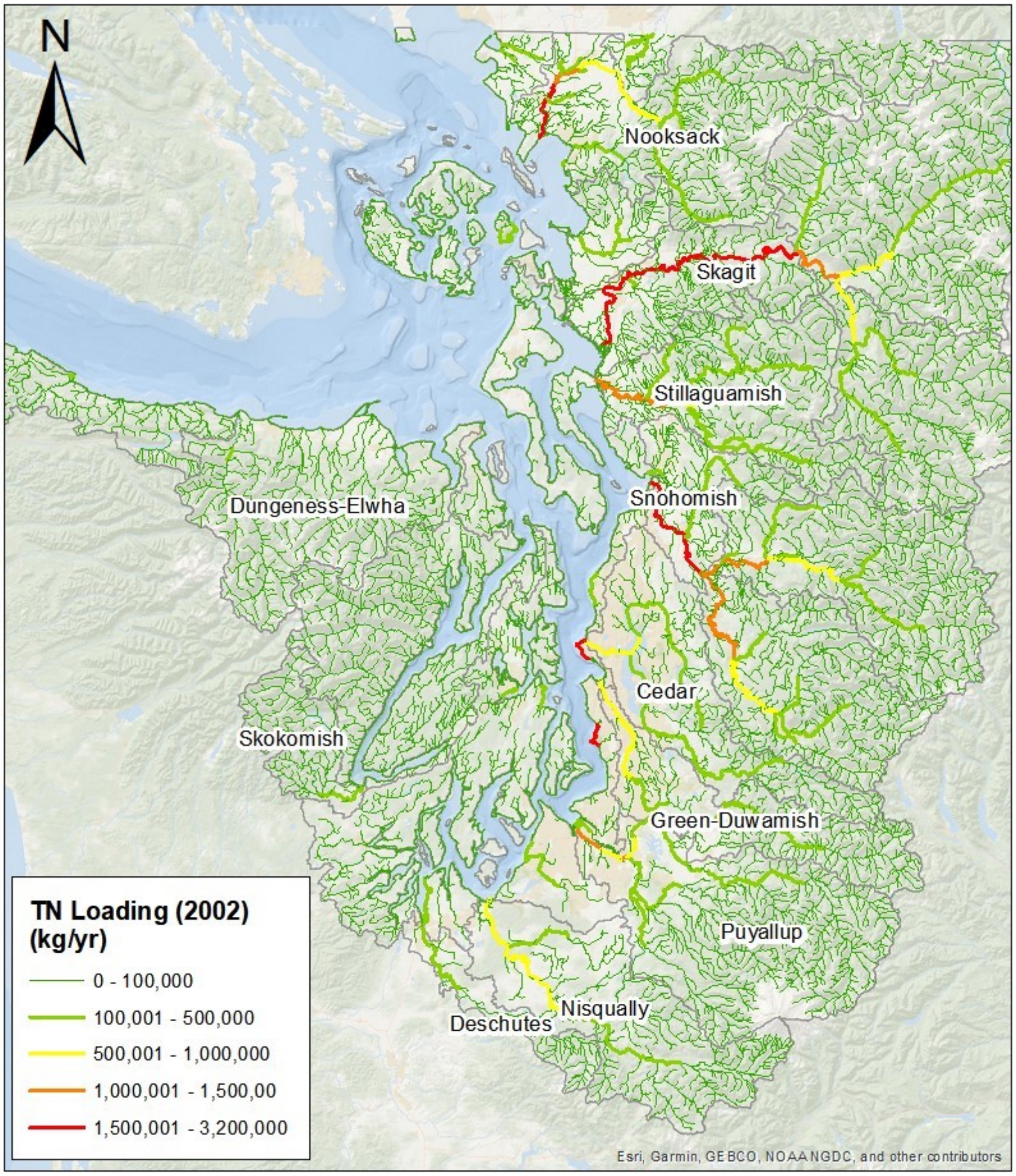

Figure 7. SPARROW total nitrogen (TN) load results for Puget Sound region (2002).

Comparisons of total nitrogen loading from urban sources (developed land, wastewater facilities, and on-site septic systems), agricultural sources (livestock and fertilizer), and forests are shown in Figure 8. Watersheds in Puget Sound Main Basin include densely populated urban areas (Seattle and Tacoma) and have high total nitrogen loading in their surrounding watersheds, extending from the Snohomish River down through the Puyallup River. Nooksack and Skagit Rivers have the highest nitrogen loading into Puget Sound from agriculture sources (Figure 8). These watersheds have a high fraction of farmland area (Table 1). Skagit, Stillaguamish, and Snohomish Rivers are large, forest-dominated watersheds (Table 1) and contribute high loads of nitrogen from forested areas (Figure 8).

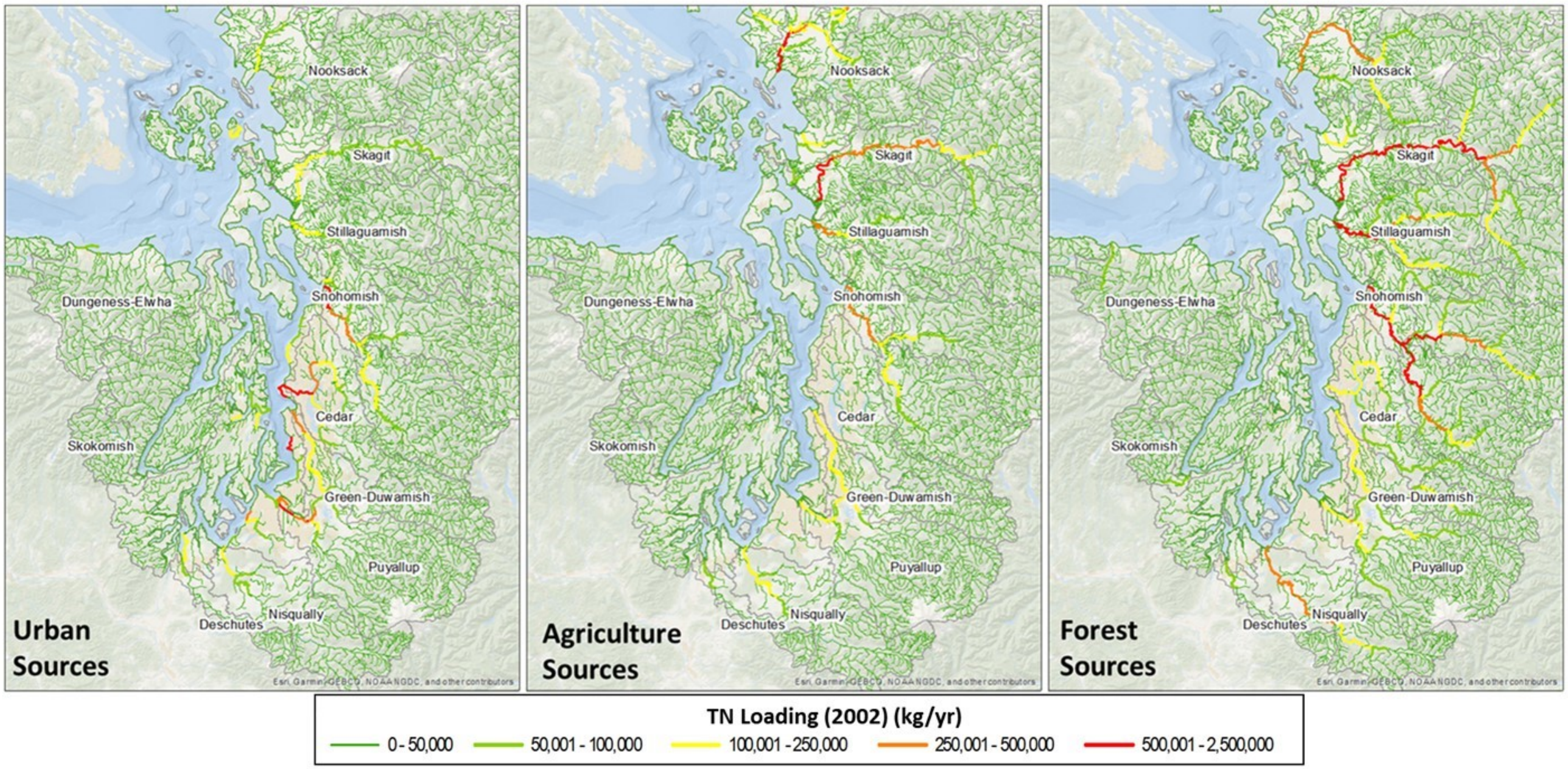

Figure 8. SPARROW total nitrogen (TN) load results from urban sources (left), agriculture sources (center), and forests (right) for 2002.

The overall total nitrogen load into Puget Sound from rivers and streams and nearshore watersheds loads is about 25.45 million kg/yr. Approximately half of this load is from urban sources (46.9%), about a quarter of the load is from forests (26.5%), and the remainder is from agricultural sources (16.7%) and atmospheric deposition (9.8%) (Figure 9).

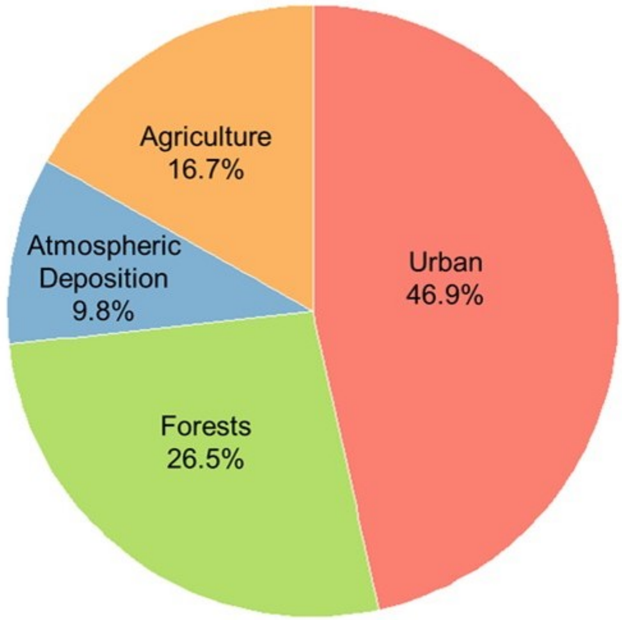

Figure 9. Relative contribution of nutrient sources discharging into Puget Sound from SPARROW results (2002).

The contribution of loads from individual major rivers at their outlet into Puget Sound is shown in Figure 10. The total nitrogen loads at river mouths were determined from the most downstream SPARROW river reach and were selected using SPARROW results, NHD data, and GIS. These loads were then aggregated by nutrient source categories.

Snohomish River (3.2 million kg/yr), Skagit River (2.5 million kg/yr), and Nooksack River (1.7 million kg/yr) are the largest watersheds (Table 1) and contribute the highest total nitrogen load to Puget Sound. Rivers with the lowest total nitrogen loads are the Skokomish and Elwha Rivers, located in the Olympic Peninsula.

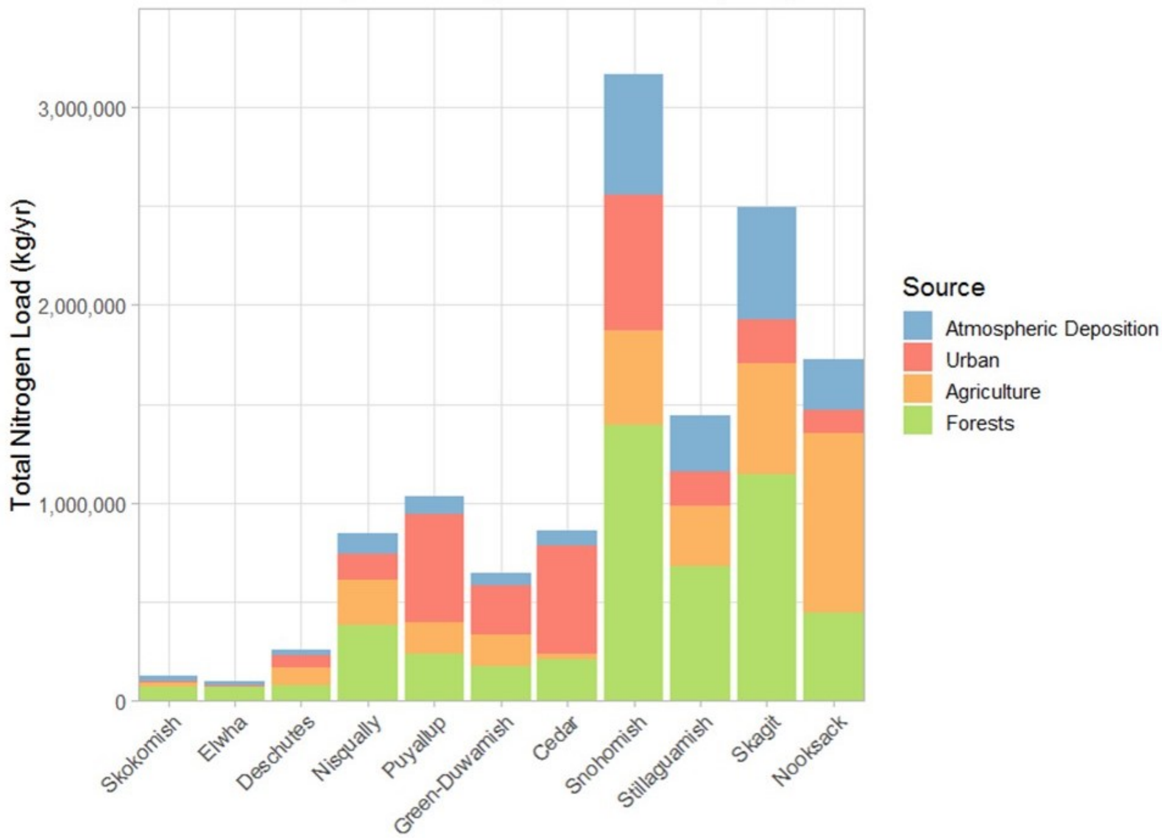

Figure 10. SPARROW results for total nitrogen load at river mouth by nutrient source (2002).

Table 3. SPARROW results for relative total nitrogen load at river mouth by nutrient source (2002).

River	Atm. (%)	Urban				Agriculture		Forests	
		Dev. (%)	Point sources (%)	OSS (%)	Power returns (%)	Fertilizer (%)	Manure (%)	Forests (other) (%)	Alder (%)
Skokomish	19	1	3	5	0	11	4	8	49
Elwha	20	0	3	2	0	1	3	23	48
Deschutes	9	17	0	8	0	21	16	2	27
Nisqually	12	5	3	9	0	13	15	3	42
Puyallup	9	13	12	7	21	5	10	2	21
Green-Duwamish	10	27	1	12	0	9	16	1	25
Cedar	9	46	0	17	0	1	2	1	23
Snohomish	19	5	9	8	0	3	12	4	40
Stillaguamish	20	3	4	5	0	7	14	3	44
Skagit	23	2	4	3	0	10	13	8	38
Nooksack	15	2	2	4	0	18	34	2	24

Atm. = atmospheric sources; Dev. = developed land; OSS = on-site septic systems.

Forests are the dominant nutrient source for the two largest rivers, the Snohomish and Skagit Rivers, along with the Elwha, Skokomish, Stillaguamish, and Nisqually Rivers (Table 3). Their watersheds vary in size and in spatial distribution throughout the greater Puget Sound region, with rivers located on the Olympic Peninsula draining into the Strait of Juan de Fuca (Elwha

River) and Hood Canal (Skokomish River), South Sound (Nisqually River), and Whidbey Basin (Snohomish, Skagit, and Stillaguamish Rivers). These rivers are located in predominantly forested areas with forest land comprising over 50% of land use throughout the watersheds (Table 1).

Nitrogen is naturally occurring in forests and is delivered to streams and rivers. However, forestry activities can increase the export of nitrogen in these watersheds (Anderson, 2002; Binkley and Brown, 1993; Gravelle et al., 2009; Harr and Fredriksen, 1988; McIntyre et al., 2018). Additionally, alder stands play a critical role in delivering nitrogen to waterways throughout this region (Compton et al., 2003). The Snohomish and Skagit Rivers receive about 40% of their total nitrogen delivered to Puget Sound from alder forests.

Agricultural sources are the largest contributors of nitrogen for the Nooksack River (about 50% or 900,000 kg/yr). The Nooksack watershed has a large area of agricultural land(Table 1). Other rivers with high relative contributions of nitrogen from agricultural sources include the Deschutes and Nisqually Rivers, both located in South Sound.

Both the Cedar and Puyallup Rivers receive over half of their total nitrogen load to Puget Sound from urban sources. Almost half of the Cedar River watershed is developed (Table 1), and Seattle is located within this watershed. The Puyallup River watershed includes the City of Tacoma and receives contributions from several WWTPs (e.g., Puyallup) in its downstream reaches.

Total nitrogen yields were calculated for major rivers draining into Puget Sound, where yield represents the load (kg/yr) per unit watershed area (acre) (Table 4).

Table 4. Total nitrogen (TN) loads and total nitrogen yields (load per unit area) at river mouths discharging into Puget Sound (2002).

River	TN Load (kg/yr)	Area (acres)	TN Yield ($kg \cdot acre^{-1} yr^{-1}$)
Skokomish	122,000	155,000	0.8
Elwha	95,000	205,000	0.5
Deschutes	254,000	110,000	2.3
Nisqually	842,000	490,000	1.7
Puyallup	1,032,000	630,000	1.6
Green-Duwamish	643,000	310,000	2.1
Cedar	862,000	390,000	2.2
Snohomish	3,171,000	1,165,000	2.7
Stillaguamish	1,443,000	450,000	3.2
Skagit	2,498,000	1,785,000	1.4
Nooksack	1,729,000	580,000	2.4

Nutrient yields allow for comparison of the relative intensity of river loads by normalizing the size of the watershed. The Stillaguamish River has the highest yield (3.2 $kg \cdot acre^{-1} yr^{-1}$), followed by the Snohomish River (2.7 kg·acre^{-1}yr^{-1}). Despite the Skagit River having the largest watershed, it has a relatively low yield (1.4 kg·acre^{-1}yr^{-1}).

SPARROW total nitrogen load estimates are aggregated by the Puget Sound basin they discharge into, where each basin represents a distinct marine area (Figure 11). Spatially grouping nitrogen loads by the basin they drain into illustrates patterns in the magnitude of nutrient loading to Puget Sound by geographic area. Whidbey Basin contains a group of rivers (Snohomish, Stillaguamish, and Skagit Rivers) with high total nitrogen loads. Main Basin has high nitrogen loads from rivers and along the shoreline from nearshore watersheds. The Strait of Juan de Fuca, Hood Canal, and Admiralty regions have generally low levels of total nitrogen loading.

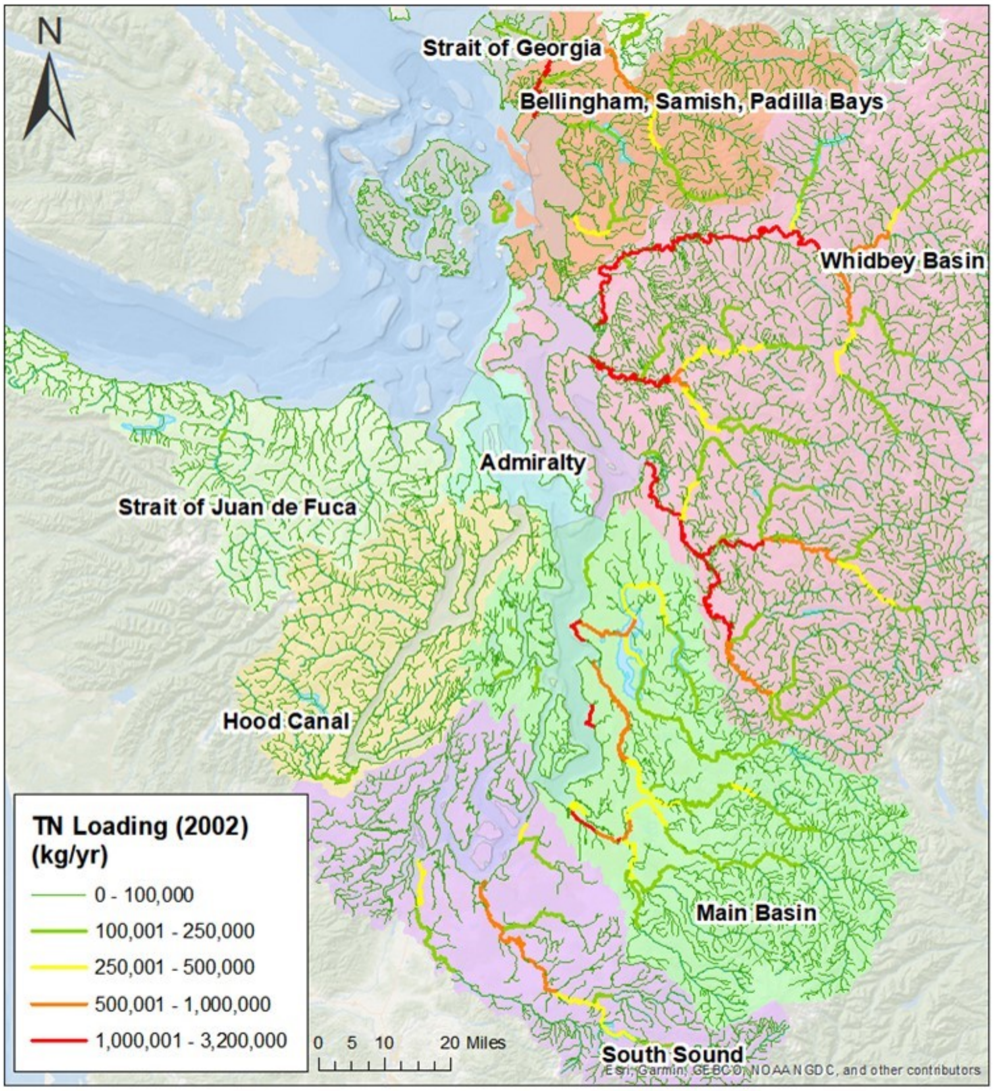

Figure 11. SPARROW total nitrogen (TN) load estimates and regions draining into Puget Sound basins (2002).

The nutrient loads at all river and stream mouths, including nearshore basins, were totaled for each basin receiving these loads. The overall magnitude of total nitrogen loading directly into

Puget Sound basins is shown in Figure 12. Puget Sound Main Basin and Whidbey Basin have the highest amount of total nitrogen loading (between 8 and 9 million kg/yr), significantly more than the other basins. South Sound and Bellingham, Samish, and Padilla Bays have similar total nitrogen loads (about 3 million kg/yr).

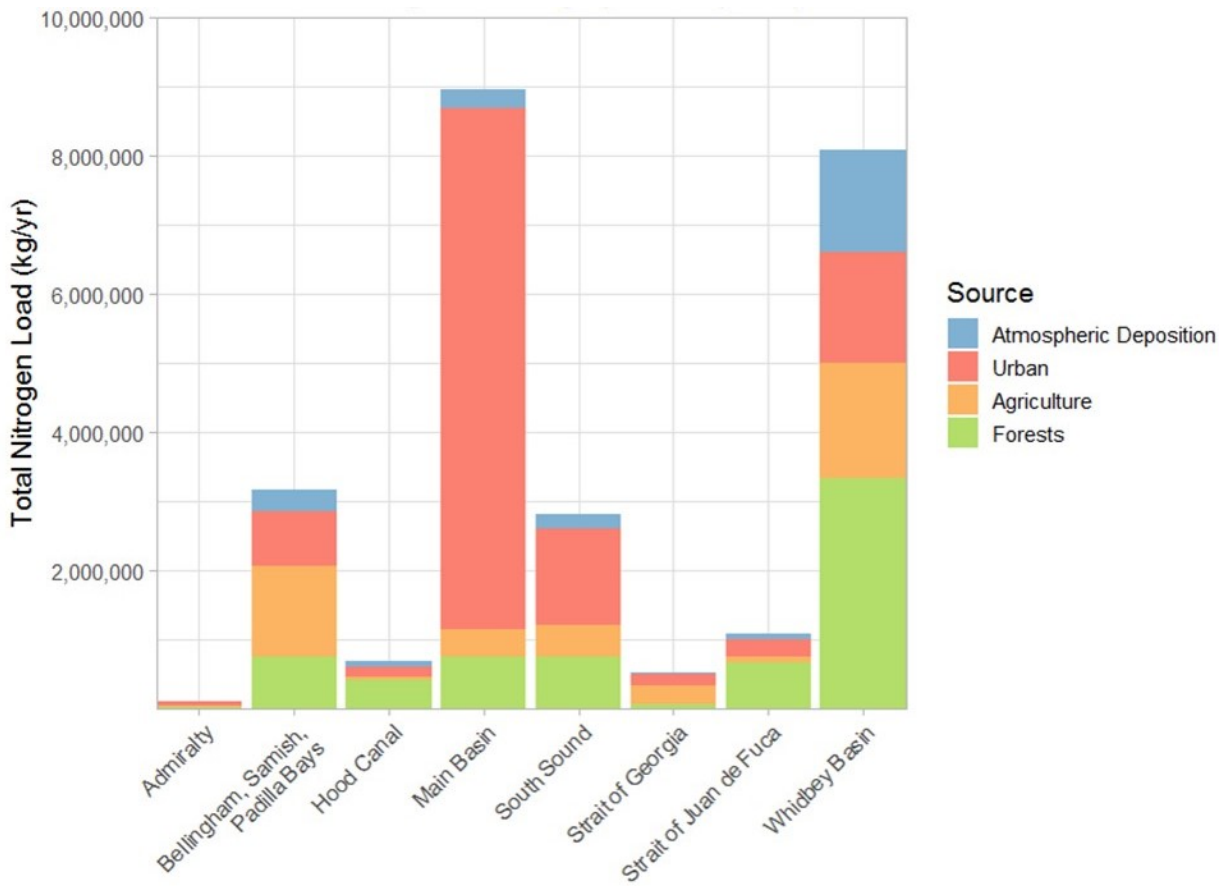

Figure 12. SPARROW total nitrogen (TN) load results into Puget Sound basins by nutrient source (2002).

Total nitrogen loads discharging directly into the Main Basin of Puget Sound via river and stream terminuses and from nearshore watersheds at the shoreline are dominated by urban sources of nitrogen (84%). These loads include urban sources of nitrogen from Seattle and Tacoma and surrounding urban areas. Urban sources include point sources (mainly WWTPs) throughout the watershed, including those discharging into nearshore marine waters and nonpoint sources (runoff from developed land) (Table 2). Half of the total nitrogen load into South Sound is due to urban sources as well. South Sound includes watersheds (Deschutes and Nisqually) that have large areas of development and large WWTPs (Table 1).

Bellingham, Samish, and Padilla Bays have the highest contribution of nitrogen from agricultural sources (42%). This region includes the Nooksack and Samish watersheds with a large fractional area of agricultural land (Table 1).

Total nitrogen yields were also calculated for the regions of rivers, streams, and nearshore watersheds draining at the shoreline into major basins (Table 5). The Main Basin has both the overall highest total nitrogen load (about 9 million kg/yr) and yield (5.6 kg·acre^{-1}yr^{-1}). Although the watersheds draining into Whidbey Basin are the largest area (3.8 million acres), it has a lower yield than smaller regions draining into the Main Basin, Strait of Georgia, South Sound, and Bellingham, Samish, Padilla Bays.

Table 5. Total nitrogen loads and total nitrogen yields (load per unit area) discharging from regions into Puget Sound basins (2002).

Basin	TN Load (kg/yr)	Area (acres)	TN Yield (kg/acre*yr)
Admiralty	111,000	93,000	1.2
Bellingham, Samish, Padilla Bays	3,171,000	734,000	4.3
Hood Canal	692,000	682,000	1.0
Main Basin	8,962,000	1,591,000	5.6
South Sound	2,808,000	1,073,000	2.6
Strait of Georgia	522,000	166,000	3.2
Strait of Juan de Fuca	1,092,000	777,000	1.4
Whidbey Basin	8,092,000	3,778,000	2.1

Total Phosphorus Load Estimates

Total phosphorus loading for 2002 estimated from SPARROW is shown in Figure 13. Rivers with the largest overall total phosphorus loads are mostly located in northern Puget Sound watersheds (Nooksack, Skagit, Stillaguamish, and Snohomish), as well as the Puyallup River.

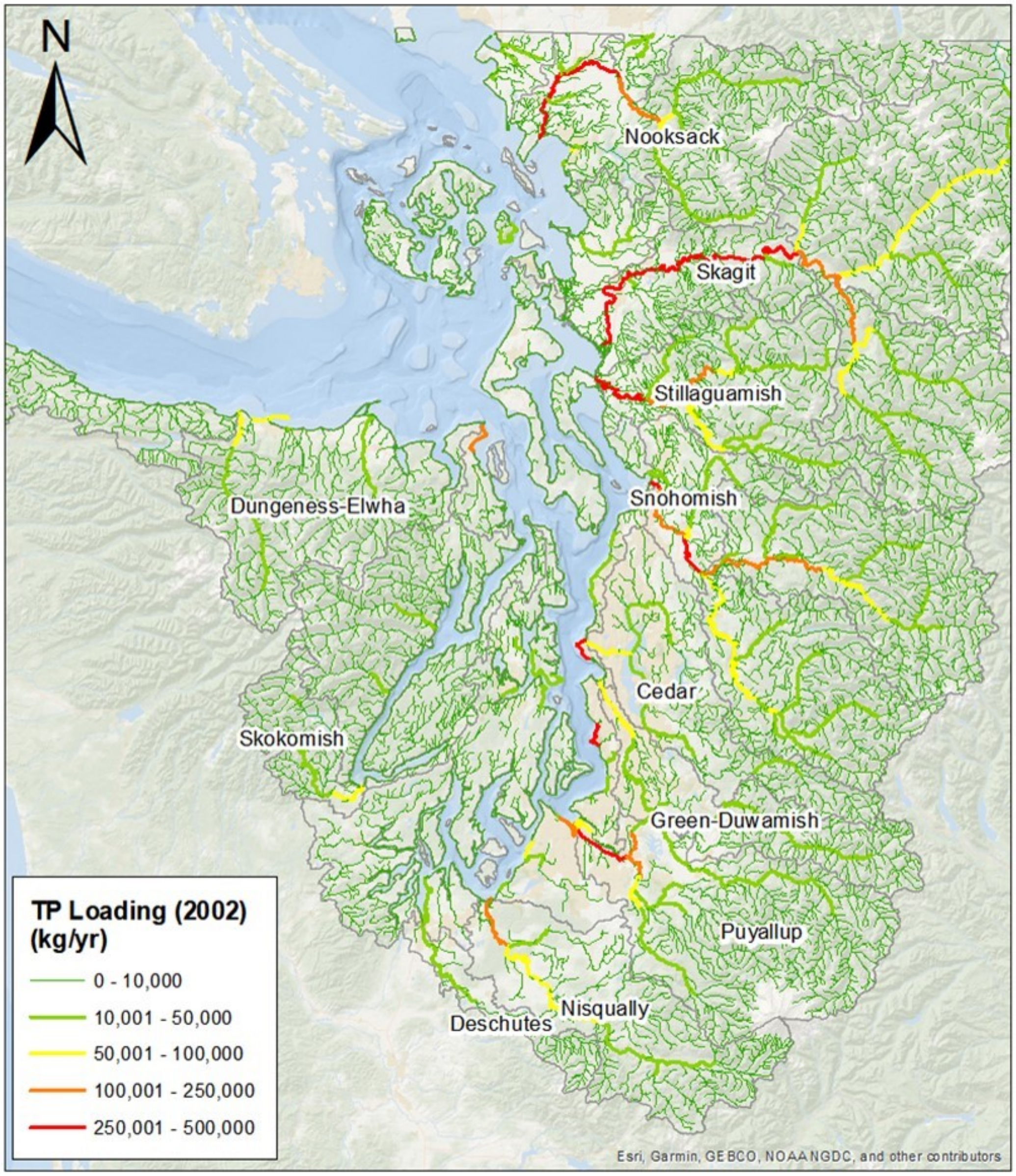

Figure 13. SPARROW results for total phosphorus (TP) load in the Puget Sound region (2002).

Total phosphorus loads from urban sources, agricultural sources, and geologic materials are compared in Figure 14. Agricultural sources of total phosphorus are higher than loading from urban sources, particularly in northern watersheds (Nooksack, Skagit, Stillaguamish, and Snohomish). Contributions to phosphorus load from geologic materials are highest in the Nooksack, Skagit, Stillaguamish, and Snohomish Rivers.

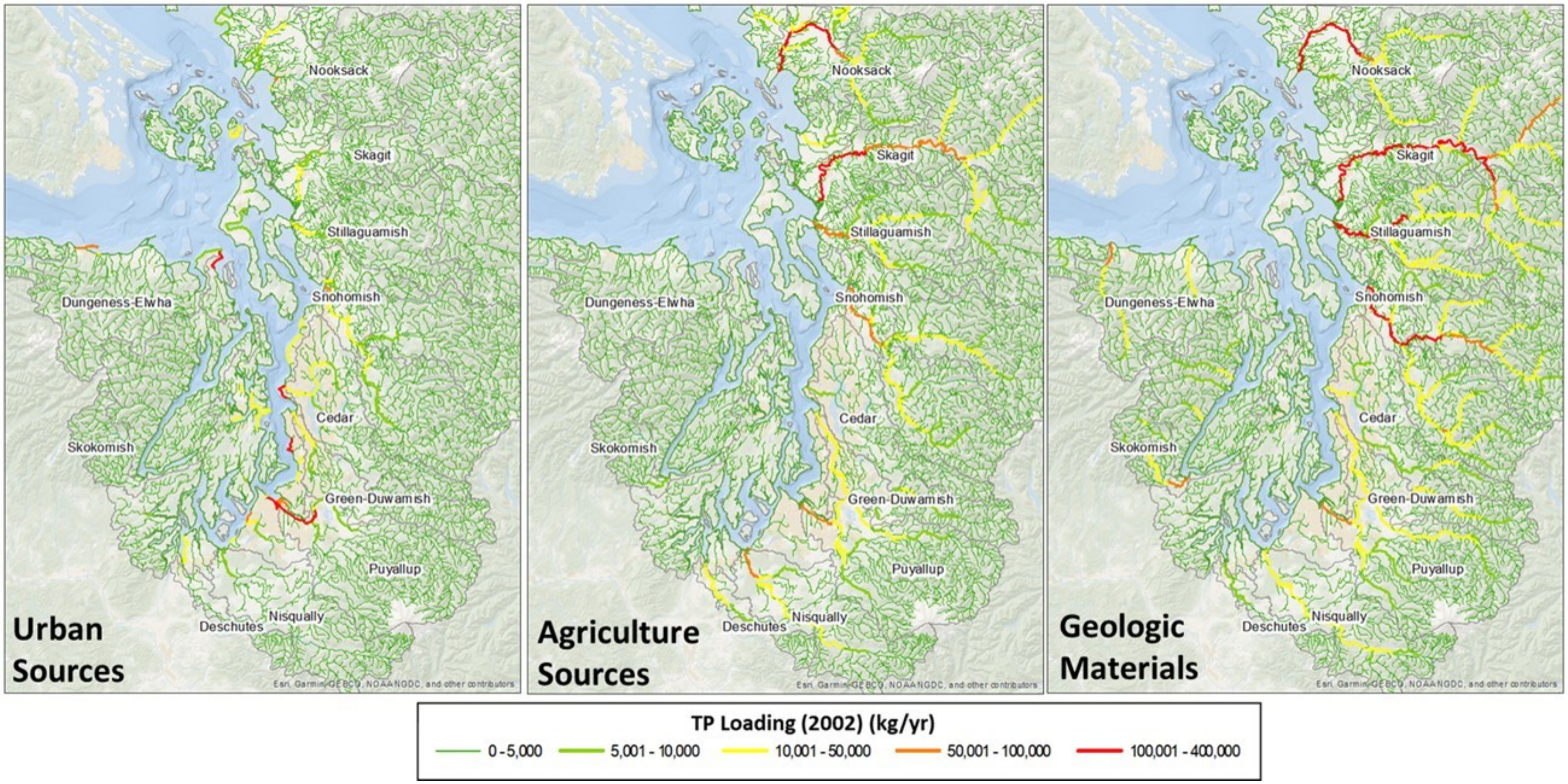

Figure 14. SPARROW results for total phosphorus (TP) load from urban sources (left), agriculture sources (center), and geologic materials (right) (2002).

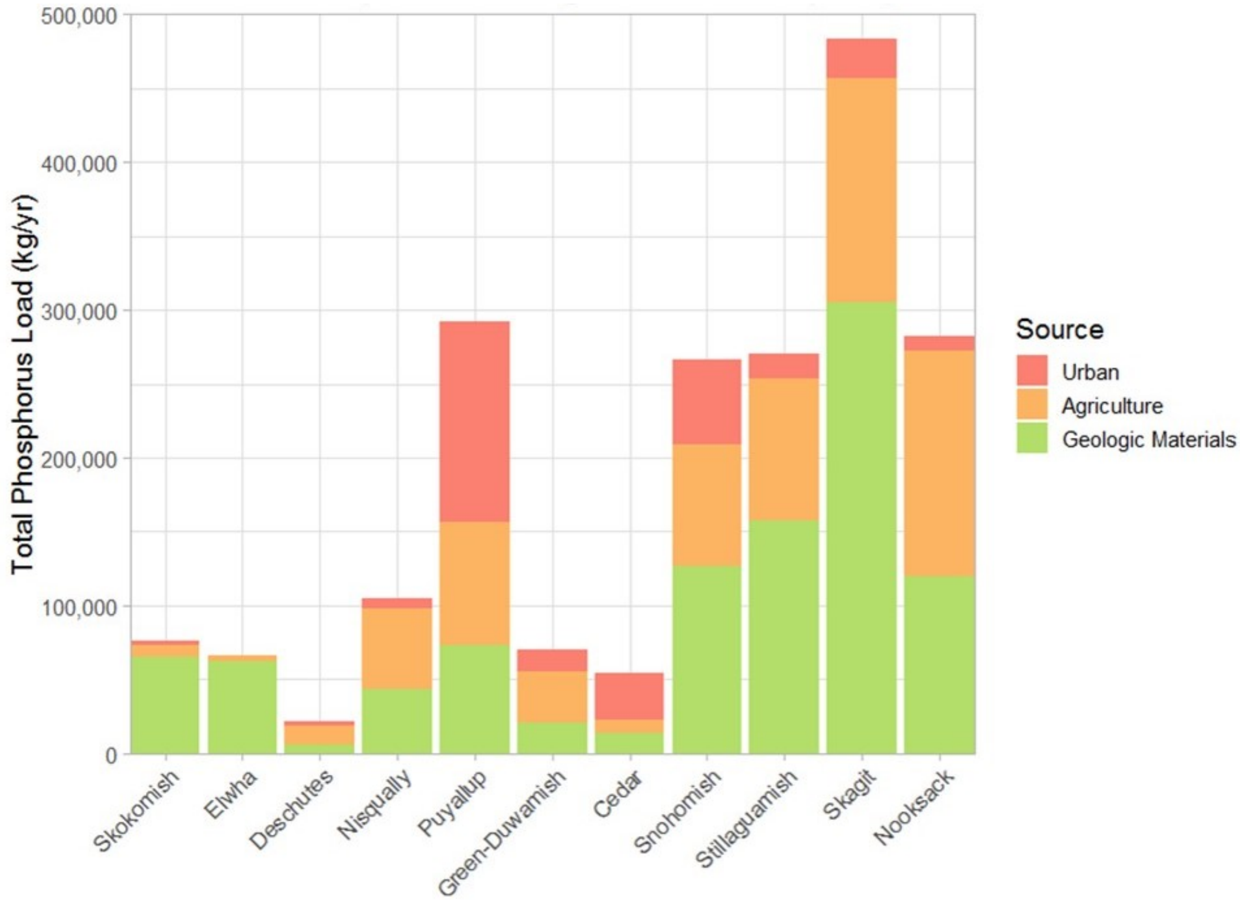

Figure 15. SPARROW results for total phosphorus load at river mouth by nutrient source (2002).

Table 6. SPARROW results for relative total phosphorus load at river mouth by nutrient source (2002).

River	Urban			Agriculture		Geologic materials (%)
	Dev. (%)	Point sources (%)	Power returns (%)	Fertilizer (%)	Manure (%)	
Skokomish	0	4	0	1	9	86
Elwha	0	1	0	0	5	94
Deschutes	13	0	0	4	59	25
Nisqually	3	4	0	2	50	41
Puyallup	5	14	27	1	28	25
Green-Duwamish	19	2	0	2	47	30
Cedar	58	0	0	0	15	25
Snohomish	4	17	0	1	30	48
Stillaguamish	1	5	0	1	35	58
Skagit	1	4	0	1	30	63
Nooksack	1	3	0	2	52	43

Dev. = developed land

The Skagit River contributes the highest amount of total phosphorus loading into Puget Sound (Figure 15), with 63% of the phosphorus contribution from geologic materials (Table 6). Geologic materials are the most dominant source of phosphorus loading in rivers located on the Olympic Peninsula (Skokomish, Elwha) and those draining into Whidbey Basin (Snohomish, Stillaguamish, Skagit). Rivers draining into South Sound (Deschutes and Nisqually) are dominated by agricultural sources. Urban sources contribute to over half of the total phosphorus load in the Puyallup and Cedar Rivers.

Comparing total phosphorus and total nitrogen load estimates shows that for all major rivers, nitrogen loading into Puget Sound is substantially higher than phosphorus loading (Figure 16). Nitrogen is the primary nutrient of concern for Puget Sound; however, excess phosphorus levels upstream in these rivers and lakes can cause eutrophication and water quality issues downstream as well (Howarth et al., 2011).

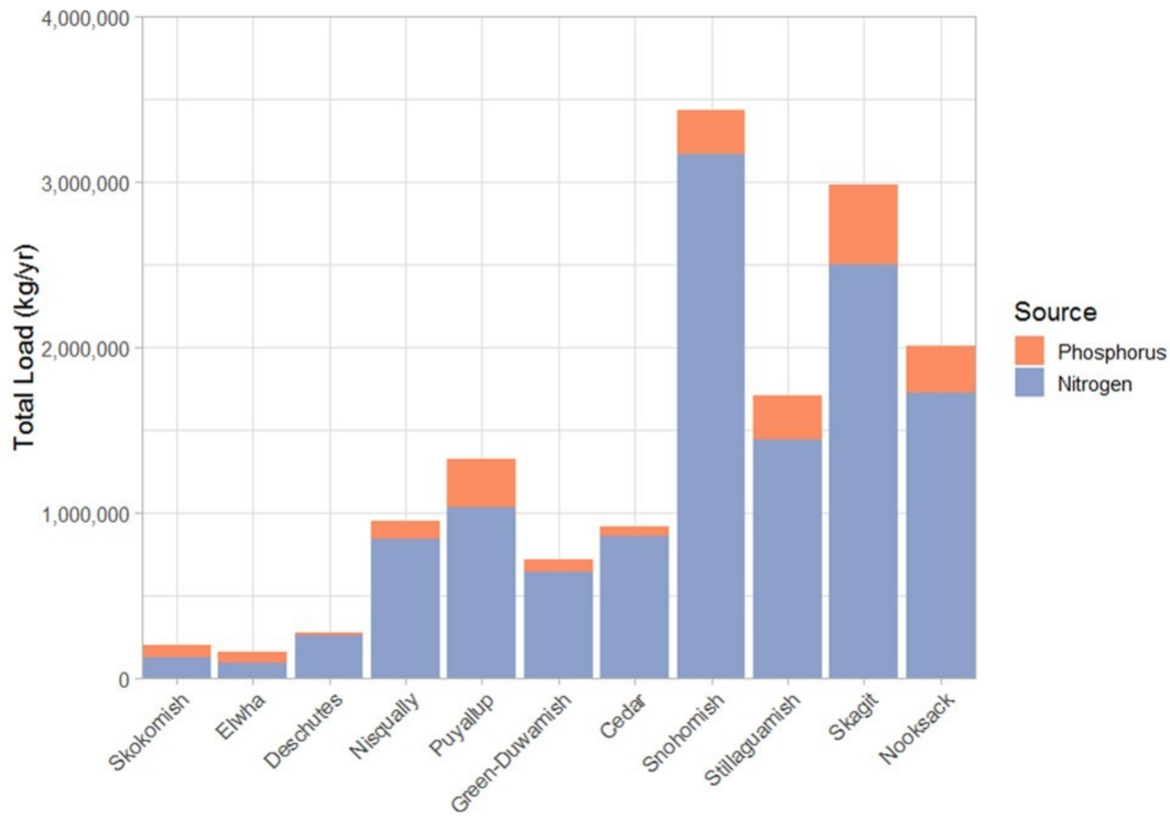

Figure 16. SPARROW results for total phosphorus and total nitrogen loads at river mouths (2002).

VELMA

Visualizing Ecosystem Land Management Assessments (VELMA) ecohydrological model is a spatially distributed, process-based model that dynamically simulates the interaction of hydrological and biogeochemical processes (Abdelnour et al., 2011, 2013; McKane et al. 2014). VELMA models the effects of climate, land use, fire, and other disturbances on streamflow, evapotranspiration, vertical and lateral flow, plant and soil carbon nitrogen dynamics, and transport of dissolved nutrients and contaminants to streams and estuaries. The model links a land surface hydrology model with a terrestrial biogeochemistry model for simulating the integrated responses of vegetation, soil, and water resources to interacting stressors.

VELMA synthesizes available data and uses a daily time step, but the time series can be altered (e.g., monthly scale) depending on the modeling scenario (Abdelnour et al., 2011, 2013; McKane et al. 2014). Data input requirements includes daily climate data, daily streamflow data, water quality data, and various geospatial data sets including elevation, vegetation, land use, and soil properties. The model is used to characterize land use and mitigation within a watershed, and it serves as a tool for watershed restoration planning that may be used by a variety of stakeholders.

VELMA is currently adapted for the Mashel watershed within the Nisqually River Basin, and the model is being applied to the Nisqually Community Forest to evaluate effects of forest management scenarios on streamflow and salmon habitat (Hall et al., 2018).

Compared with the framework of the SPARROW model, VELMA strives for higher spatial and temporal resolution and is applied on a specific watershed scale. There is potential for applying the model for other watersheds throughout the greater Puget Sound region. Using VELMA for nutrient management will involve validating model results with other nitrogen load estimates, such as SPARROW results or estimated inputs for the SSM.

Comparison of Nutrient Load Estimates

The Salish Sea Model (SSM) requires nutrient load inputs to model marine water quality conditions in the Salish Sea. At this time, the SSM has not been run for the year 2002. However, model inputs for nutrient load estimates at river and point source inflows (2002) are available, and these data are used for comparison with SPARROW estimates during 2002. SSM nutrient load inputs are estimated as a daily time series using a regression approach (Ahmed et al., 2019; McCarthy et al., 2018; Mohamedali et al., 2011). In contrast, SPARROW results are based on a statistical model that uses geospatial data to account for different land use patterns. SPARROW reports results as an annual load (kg/yr), and SSM requires a continuous daily time series of nutrient load inputs. Due to these differences, SSM nutrient load inputs were totaled for the entire year as an annual load (2002).

Nutrient Load Estimates

Total nitrogen load inputs to SSM and SPARROW load estimates are compared to assess similarities and evaluate major differences in load estimates between the models. In accounting for nutrient sources:

- SPARROW combines nonpoint and point sources (freshwater and marine) in its nutrient load estimates discharging into Puget Sound. These load estimates can be separated out by nutrient sources.
- SSM uses nutrient load estimates for model inputs that represent (1) point sources discharging into marine waters (e.g., WWTPs) and (2) watershed inflows to marine waters at the river mouth. These watershed inflows do not differentiate the relative contribution of nutrients from different sources, and therefore nutrient sources cannot be identified separately.

Nutrient load inputs to SSM and SPARROW results are estimated at different geographical scales. In order to compare load estimates for both models, nutrient loads were grouped by (1) watershed and (2) drainage area into Puget Sound basins. SPARROW nutrient load estimates at shorelines and terminal reaches of rivers and streams were aggregated by SSM watershed area for comparison with SSM inputs. For SSM inputs, marine point source nutrient load estimates were combined with the watershed inflow of closest proximity. Appendix B provides further descriptions of this aggregation method.

Overall, SPARROW and SSM input estimates for total nitrogen loading into Puget Sound are similar (25.45 million kg/yr and 25.43 million kg/yr, respectively). When comparing nutrient load estimates on a more refined geographic scale, such as the drainage area into major Puget Sound basins, differences in regional estimates are apparent (Figure 17).

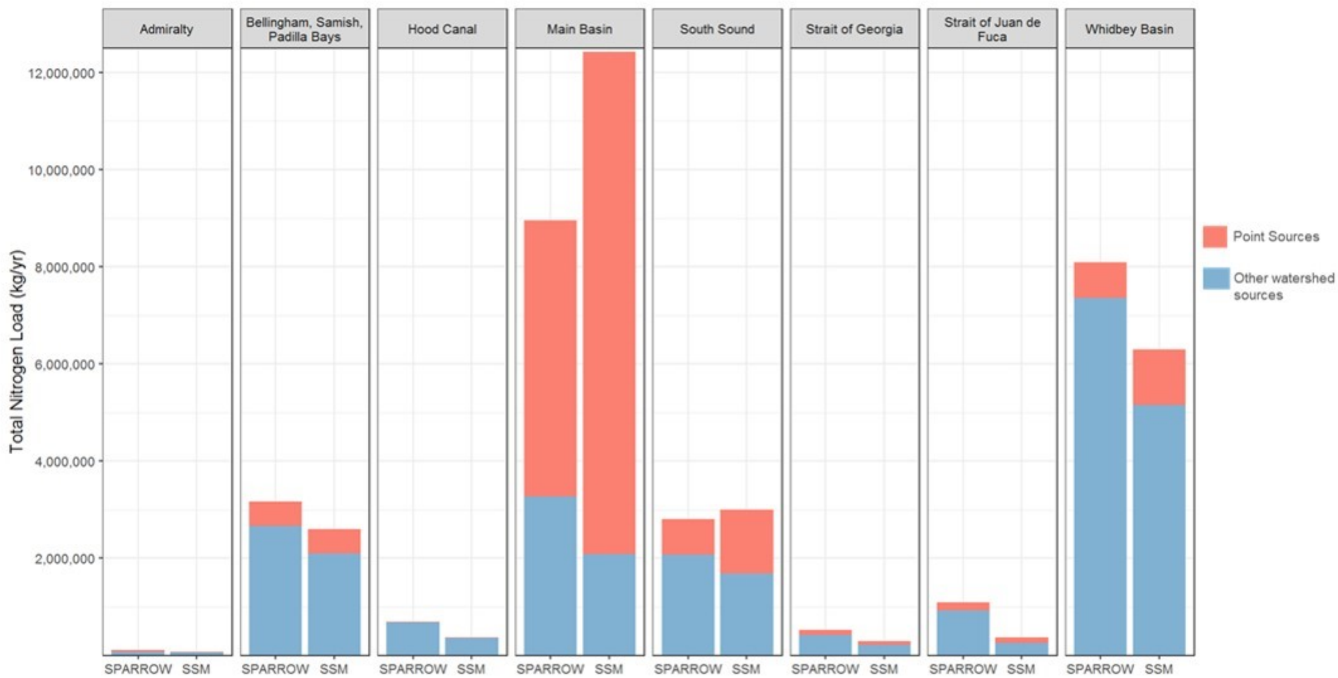

Figure 17. Comparison of SPARROW total nitrogen load estimates and inputs to the Salish Sea Model (SSM) from point source contributions (red) and all other watershed sources (blue). Load estimates are grouped by region draining into different Puget Sound basins.

For the watershed area draining into the Main Basin of Puget Sound, nutrient load estimates used in SSM were higher by about 3.5 million kg/yr. This variance is primarily due to differences in total nitrogen load estimates for point sources, with estimated SSM inputs from marine point sources higher (10.3 million kg/yr) than in SPARROW point source estimates (5.7 million kg/yr). The contribution of total nitrogen from point sources in SPARROW estimates includes all point sources upstream, not just those with marine outfalls. The influence of upstream point sources are diluted by the point of discharge to Puget Sound. Even with considering this difference, point source load estimates used in SSM are still higher. Differences in point source load estimates are discussed in further detail in the next section.

After the Main Basin, the largest difference in total nitrogen load estimates is in Whidbey Basin. Whidbey Basin has the largest disparity in total nitrogen load estimates from other watershed sources (excluding point sources). SPARROW estimates other watershed sources to be 2.2 million kg/yr higher than the regression estimates used for SSM watershed loads. Whidbey Basin includes Skagit, Stillaguamish, and Snohomish watersheds, and the region is predominantly forestland (Table 1). These watersheds have the highest overall difference between SPARROW nutrient load estimates and SSM inputs (Figure 18).

The differences between SPARROW nitrogen load estimates, aggregated by SSM watershed, and load inputs to SSM are shown in the map in Figure 18 (see Appendix B for further description of the aggregation method). Watersheds with similar nitrogen load estimates are shown in neutral tones, watersheds with higher predicted loads from SPARROW are in red tones, and watersheds with higher estimated SSM input loads are in blue tones. The median difference in total nitrogen load estimates is about 8,000 kg/yr, indicating higher loads estimated from SPARROW than used for inputs to SSM.

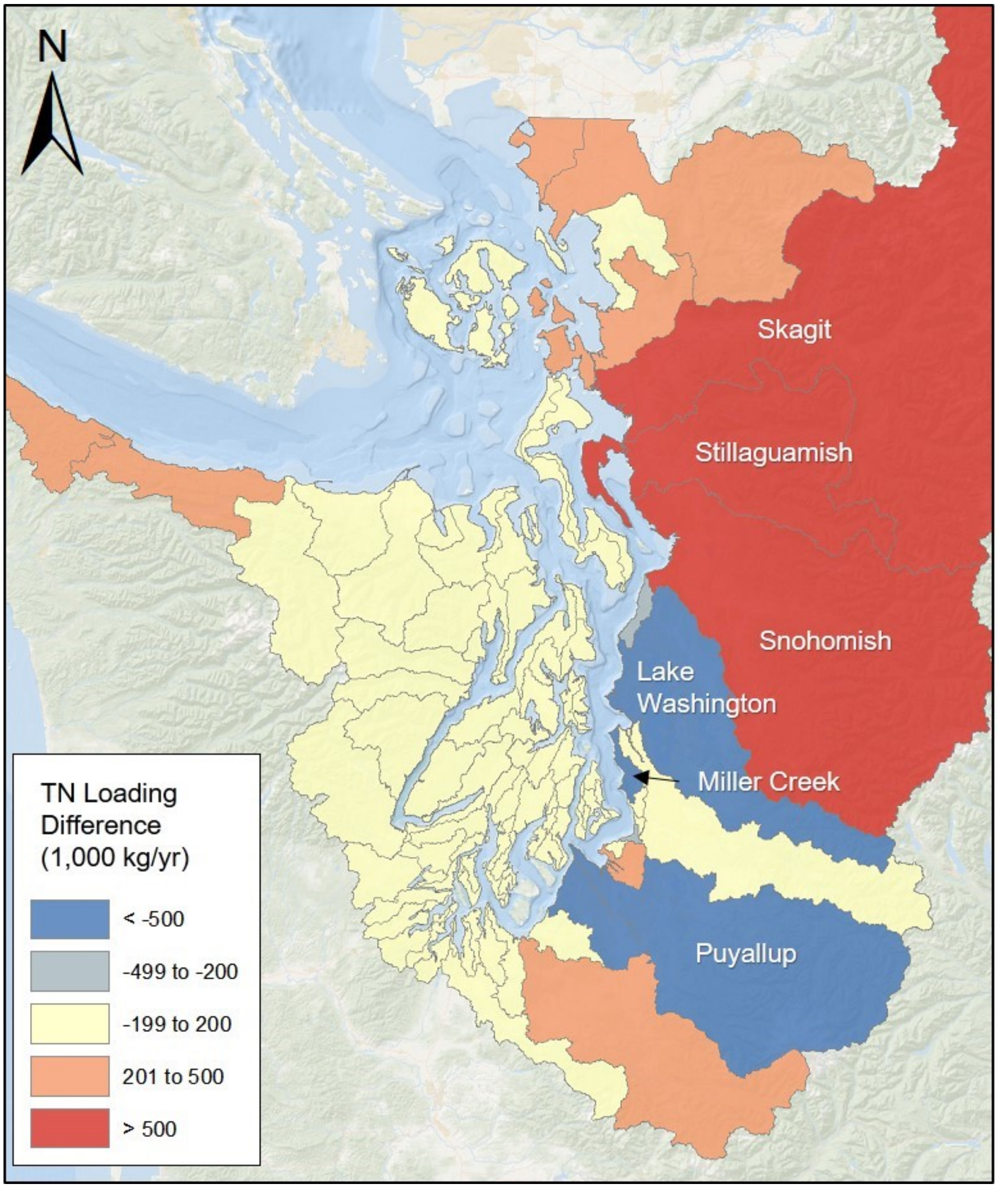

Figure 18. Total nitrogen load estimate differences (SPARROW estimates minus load inputs to SSM) by SSM watershed. Neutral tones indicate similar estimates, red tones indicate SPARROW estimates are higher, and blue tones indicate higher estimates for SSM inputs.

The largest difference between SPARROW load estimates and SSM inputs (over 500,000 kg/yr) are for the group of large watersheds draining into Whidbey Basin with mixed land use (Skagit, Stillaguamish, and Snohomish watersheds). All of these watersheds received the largest contribution of nutrients from forests, particularly alder forests (about 40%, Table 3).

Alternatively, differences of nitrogen load estimates for SSM inputs were higher compared with SPARROW estimates for Miller Creek and Lake Washington watersheds (2 million and 1 million kg/yr difference, respectively). Both of these watersheds are within the Seattle urban area and contain large WWTPs (West Point and South King facilities) that contribute to the point source portion of the total nitrogen load. The reason for this discrepancy is examined further in the next section.

A final comparison of SSM and SPARROW total nitrogen load estimates is shown in Figure 19. This map shows the spatial distribution of total nitrogen load estimates at each SSM watershed and SPARROW streams, rivers, and nearshore watershed loads at the shoreline.

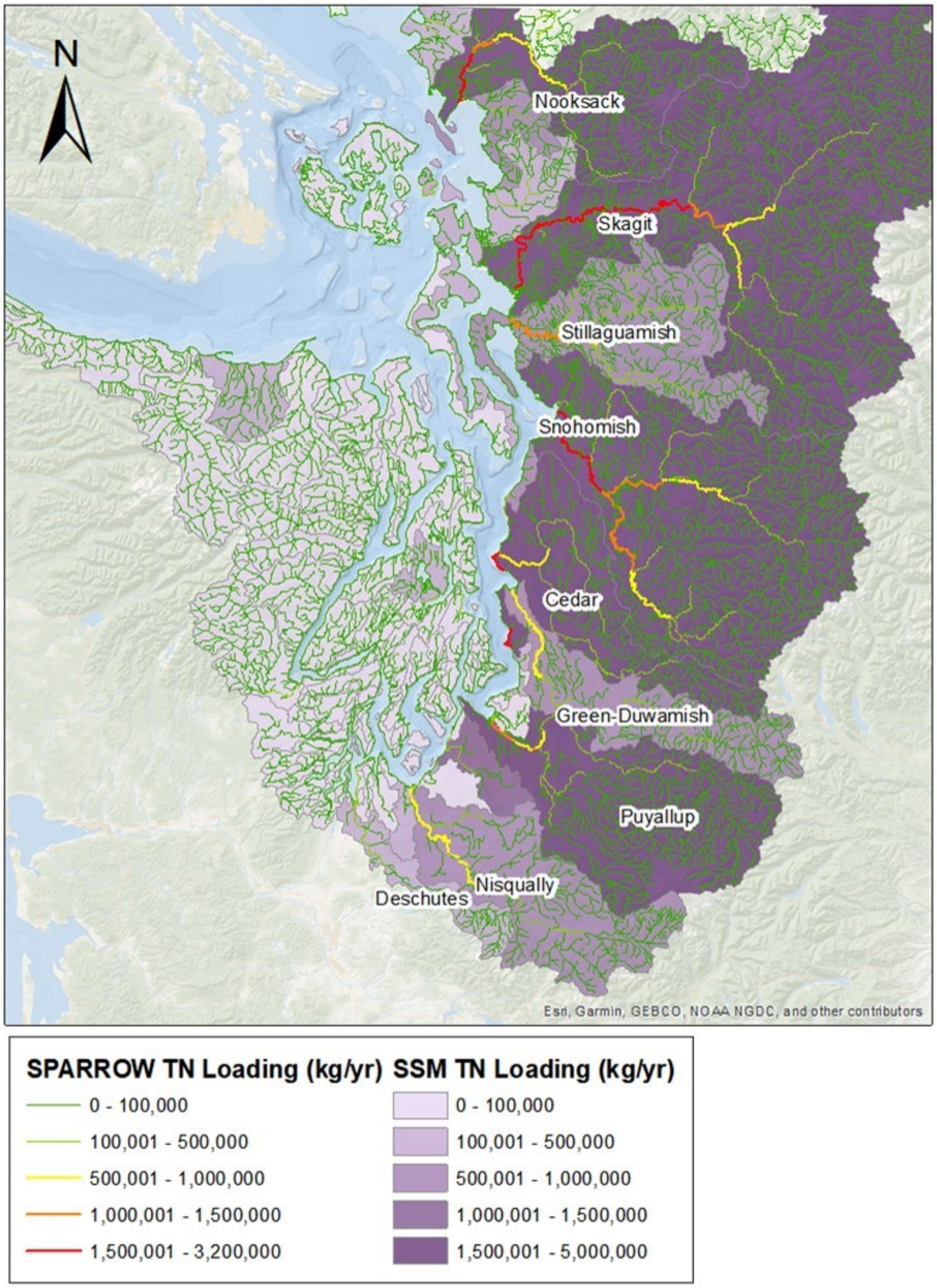

Figure 19. Map showing Salish Sea Model (SSM) and SPARROW total nitrogen load estimates (2002).

Comparing these estimates, watersheds with high total nitrogen loading are identified similarly as the Skagit, Snohomish, and Cedar watersheds. Model estimates are also in agreement in identifying watersheds with the lowest total nitrogen loads (Olympic and Kitsap Peninsulas), particularly when compared with southern and eastern Puget Sound watersheds.

Point Source Total Nitrogen Loading Estimates

SPARROW uses estimates of nutrient loads from point source facilities, including wastewater treatment plants, industrial facilities, net pens, and fish hatcheries, with a National Pollutant Discharge Elimination System (NPDES) permit (Wise and Johnson, 2013). Total nitrogen loads were estimated using either measured flow from facilities and on-site measurements of nutrients or a regional average for a specific industrial classification. Nutrient load estimates from net pens and hatcheries were estimated using a mass balance of annual fish production and feed usage and an estimate of nutrient content for fish and feed. Point source loads are included in river and stream load estimates and shoreline load estimates that represent point sources with marine outfalls (e.g., WWTPs with marine outfalls and net pens).

Marine point source loads used as inputs for SSM (municipal WWTPs and industrial facilities) that discharge directly into marine waters are estimated using reported measurements. Data for marine point sources are from Ecology's Water Quality Permitting and Reporting Information System (PARIS) and from EPA for federal facilities (Ahmed et al., 2019; McCarthy et al., 2018; Mohamedali et al., 2011). These data were used to create a continuous time series of nutrient loads using a multiple linear aggression approach.

Table 7 compares the number of point sources in SPARROW and SSM. Overall, SPARROW includes a higher count of point sources, because it includes facilities that discharge into freshwater upstream.

Table 7. Summary of point sources accounted for in SPARROW and the Salish Sea Model (SSM) (2002).

	SPARROW	SSM*
Marine Outfalls		
Hatchery	4	0
Industrial	7	12
Net Pens	8	0
WWTP	67	76
Marine subtotal	**86**	**88**
Freshwater Outfalls		
Hatchery	35	N/A
Industrial	9	N/A
WWTP	22	N/A
Freshwater Subtotal	**66**	**N/A**
All Outfalls		
Hatchery	39	0
Industrial	16	12
Net Pens	8	0
WWTP	89	76
Total	**152**	**88**

*Includes only United States marine point sources.

For point sources discharging into marine waters, SSM includes estimates from more marine point sources (88 total U.S. facilities) than SPARROW (86 total). This difference reflects SPARROW including hatcheries and net pens, which SSM currently does not include (Table 7). SPARROW nutrient load estimates for hatcheries and net pens in marine waters accounts for a total nitrogen load of 391,000 kg/yr (5,000 kg/yr from hatcheries and 386,000 kg/yr from net pens). SSM includes a more comprehensive number of WWTPs and industrial facilities throughout the greater Puget Sound region.

Point source total nitrogen load estimates (2002) used as SPARROW and SSM inputs are shown in Figure 20. This comparison used only point sources considered in both models. Marine point source loads used in the SSM are generally higher than SPARROW point source inputs. The median difference between SSM point sources and SPARROW point source estimates is 200 kg/yr.

The largest differences in estimation of nutrient loads are at the largest WWTPs (West Point and South King). Scatter between these nutrient load estimates is likely due to differences in estimation techniques. SSM inputs use facility-specific water quality and flow data to estimate nutrient loads at point sources, whereas SPARROW used regional averages for these large facilities. Because point source load inputs to SSM use facility-specific data, these nutrient load estimates are likely more representative than techniques used for SPARROW point sources.

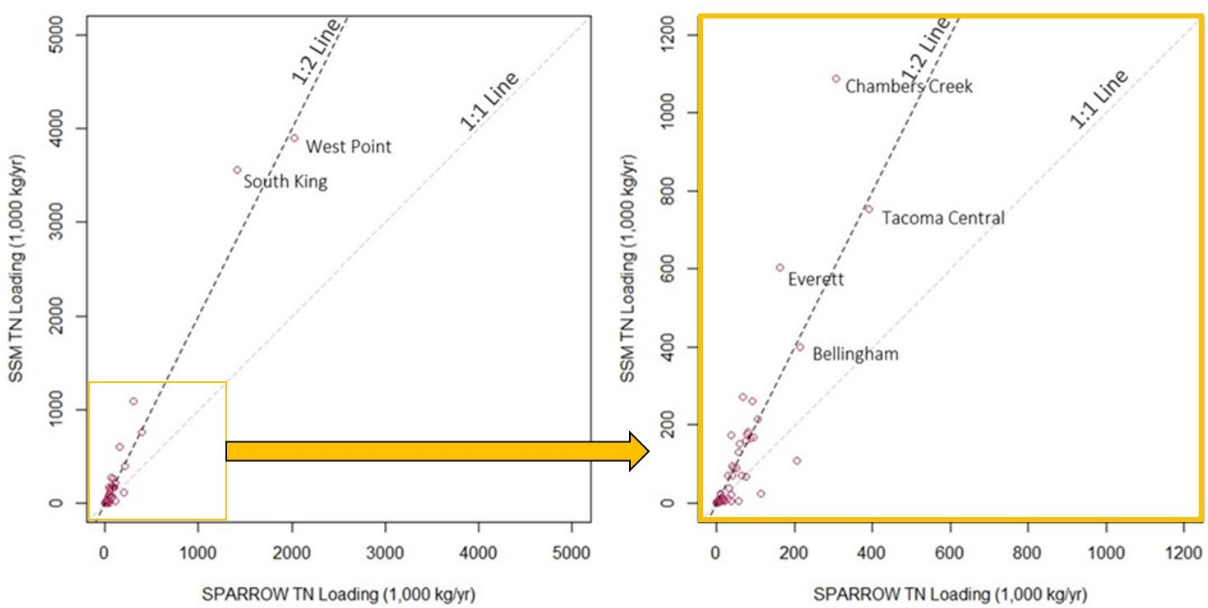

Figure 20. Comparison of point source total nitrogen (TN) load estimates used in SPARROW and Salish Sea Model (SSM) (2002). *Left* — full graph. *Right* — partial graph (magnified lower left corner of full graph).

A full list of point sources considered in each model is in Appendix A.

Differences in Nitrogen Load Estimates

This comparison between SPARROW results and SSM nutrient inputs allows for an assessment in load estimate differences between the two models. Generally, the models are in agreement for the overall total nitrogen loading into Puget Sound. Differences are highlighted when nitrogen loads are characterized by basin and watershed. This comparison determined the following differences:

- Aggregation of watersheds by the basin into which they drain indicates that SPARROW generally predicts higher total nitrogen loads, except in the Main Basin (Figure 17). SSM inputs to the Main Basin are much higher (3.1 million kg/yr). This difference is attributed to higher total nitrogen point source loads in SSM.
- Differences in watershed loads are largest in the Skagit, Stillaguamish, and Snohomish watersheds (SPARROW estimates are higher) and Miller Creek and Lake Washington watersheds (SSM inputs are higher).
    - The Skagit, Stillaguamish, and Snohomish watersheds cover large areas of mixed land use dominated by forested land, particularly alders. SPARROW load estimation methods at these watersheds should be further explored.
    - Miller Creek and Lake Washington have higher loads in SSM inputs than from SPARROW estimates due to differences in point source load estimates at large WWTPs.
- The largest differences in point source total nitrogen load estimates were for large WWTPs (West Point, South King, Chambers Creek), where estimated inputs to SSM are higher. Load estimation techniques differ for these facilities between the two models. Point source load estimates considered in SSM use a more refined, facility-specific approach using facility flow and water quality data, whereas SPARROW uses a more broad approach using regional averages at these facilities.
- SPARROW explicitly accounts for point sources discharging to freshwater and marine waters, including hatcheries and net pens, whereas SSM inherently includes freshwater point sources within its watershed loads (since its model domain is limited to marine waters). SSM does not currently use nutrient load estimates for individual hatcheries and net pens (total nitrogen load of 391,000 kg/yr).
- SPARROW does not include nutrient loads from drainages on small islands that are included in SSM. However, these islands contribute a low amount of total nitrogen (43,000 kg/yr). Most of these islands, such as Anderson Island and McNeil Island, are located in South Sound.

Implications for Nutrient Management

The first phase of modeling for the PSNSRP assessed the response of water quality in Puget Sound to reductions in nutrient loads from WWTPs (Ahmed et al., 2019). The next step in the project is the optimization phase, which will involve additional model runs to evaluate various management scenarios. These optimization scenarios will consider different combinations of nutrient reductions at marine point sources and watersheds.

The optimization phase of PSNSRP will consider the influence of watershed contributions of nutrients. Since the SSM domain does not extend up into the watersheds, it does not differentiate between upstream nutrient sources. Nutrient load estimates from SPARROW will be helpful to fill this gap and identify nutrient sources at the watershed and sub-watershed scale and their relative contribution to marine waters. Understanding these relative contributions of nitrogen from different upstream sources can help prioritize watersheds for nutrient management decisions.

In addition to PSNSRP, the Marine Water Quality Implementation Strategy may draw on results from this report for the state-of-knowledge report developed by the Puget Sound Partnership to potentially inform strategies and actions.

Chesapeake Bay TMDL: Chesapeake Assessment Scenario Tool (CAST)

The Chesapeake Bay Total Maximum Daily Load (TMDL) is an example of a nutrient management effort that is underway and has already worked to address watershed sources of nutrients discharging to the bay. Below is a brief overview of this TMDL and watershed tools used to guide nutrient management.

The Chesapeake Bay TMDL is working to restore the health of the bay and its local streams, creeks, and rivers by setting limits on nitrogen, phosphorus, and sediment pollution to improve water quality and meet standards.

The Chesapeake Bay Suite of Modeling Tools[3] is an assortment of models for understanding nutrient processes and management in the bay and watershed. These modeling tools consist of a watershed model, estuary model, scenario builder, airshed model, and land change model. The most current Phase 6 Watershed Model evaluates the influence of land use types and land management decisions on nutrient and sediment pollution levels using a combination of different models. It incorporates data and information about land use, fertilizer applications, wastewater treatment plant discharges, septic systems, air deposition, farm animal populations, weather, and other variables to estimate the amount of nutrients and sediments reaching the Chesapeake Bay and where these pollutants originate.

The Chesapeake Bay watershed model is comprised of sub-models describing different hydrologic and nutrient processes, including information from a regional application of

[3] https://www.chesapeakebay.net/what/programs/modeling

SPARROW. The Chesapeake Bay SPARROW application estimated the sources, fate, and transport of total nitrogen and total phosphorus and annual nutrient flux to the bay (Ator et al., 2011; Preston and Brakebill, 1999). Specifically within the new Phase 6 Watershed Model, SPARROW average loads, land-to-water factors, and stream-to-river factors are used to estimate nutrient load inputs in small order streams based on land use information at an NHD catchment scale. In addition to SPARROW results, the Phase 6 Watershed Model also draws on information from the previous Chesapeake Bay Program Phase 5.3.2 Watershed Model and USDA Conservation Effects Assessment Project Chesapeake Model for average loads.

Chesapeake Assessment Scenario Tool (CAST)[4] is the time-averaged watershed model that combines the output of the land use change and airshed model with other data sources to predict the loads of nitrogen, phosphorus, and sediment that result from the given inputs. CAST is a web-based nitrogen, phosphorus, and sediment load estimator tool that streamlines environmental planning (Chesapeake Bay Program, 2017). It allows a user to specify a geographical area within the Chesapeake Bay watershed and evaluate the effects of various best management practices to that area. Within CAST, users build scenarios to estimate nutrient and sediment load reductions. CAST also incorporates information to estimate the cost of different scenarios to evaluate the most cost-effective scenarios to reduce nutrient loads.

[4] https://cast.chesapeakebay.net/About

Conclusions

This report provides an overview of the USGS SPARROW model and its application within the greater Puget Sound region. SPARROW results indicate the magnitude of nitrogen and phosphorus loads at rivers and identifies the relative contribution of nutrients from upstream sources. Based on the 2002 Pacific Northwest application of SPARROW (Wise and Johnson, 2013), model results showed the following:

- Approximately half of the total nitrogen load into Puget Sound is from urban sources, a quarter is from forests, and the remainder is from agricultural sources and atmospheric deposition.
- The Snohomish and Skagit Rivers have the highest overall total nitrogen loads into Puget Sound. The Skagit River has the highest overall total phosphorus load into Puget Sound. For total nitrogen yield (load per unit area), the Stillaguamish, Nooksack, and Snohomish Rivers are the highest.
- Aggregating loads discharging into Puget Sound by basin indicates that the Main Basin receives the overall highest total nitrogen load (9 million kg/yr) followed by Whidbey Basin (8 million kg/yr).
    - Urban sources, including large WWTPs, are the main contributors of nitrogen to the Main Basin and South Sound.
    - The rivers with the largest nitrogen load enter Whidbey Basin. Nitrogen sources from these large watersheds are not dominated by a single upstream source, but are comprised of a mix of sources (forests, agriculture, urban, and atmospheric).
    - Nitrogen loads to Bellingham, Samish, and Padilla Bays have the highest fraction of nitrogen from upstream agricultural sources.
- Overall total nitrogen loads are similar between SPARROW total nitrogen load estimates and load inputs to SSM (25.45 million kg/yr and 25.43 million kg/yr, respectively). Differences are apparent when comparing nutrient loads at the watershed level.
    - SPARROW estimates higher total nitrogen loads in large, mixed land use watersheds (Skagit, Stillaguamish, and Snohomish watersheds) than SSM nutrient load inputs. Nutrient load estimates for these specific watersheds should be further explored.
    - SSM marine point source total nitrogen loads are generally higher than SPARROW point source loads, particularly at large WWTPs. This causes a large discrepancy in watersheds with large WWTPs discharging to the Main Basin and South Sound. Because SSM uses facility-specific water quality and flow data to estimate nutrient loads, we expect these load estimates to be more representative than SPARROW point source load estimates.

These model results may be used to characterize watershed nutrient loading for Ecology's Puget Sound Nutrient Source Reduction Project and the Marine Water Quality Implementation Strategy.

Recommendations

1. Compile Regional Watershed Data

Watershed models require a large quantity of high-resolution data. Ecology recommends developing a compilation of data sets for developing and running a watershed model, including the following:

- High-resolution geospatial data sets for elevation, vegetation, land use, and soil properties.
- Daily climate and flow data.
- Atmospheric deposition data, such as those available from the Community Multiscale Air Quality modeling system (CMAQ, 2002).
- Groundwater data to characterize surface water–groundwater exchange and influence on nutrients.
- Water quality data, particularly continuous nitrogen data for rivers and streams. USGS installed a continuous nitrate monitoring sensor in early 2019 on the Nooksack River, and these data will be useful for comparing with model results at a finer resolution than ambient monthly data.
- Point source data set that includes facility-specific flow and water quality data to estimate nutrient loads, such as the methods used to develop nutrient load estimates for SSM inputs.
- Data and rates related to different land use activities, such as rates of fertilizer and manure applications, animal production, forest management practices, instream attenuation, and others.
- Information regarding the location, type, and nutrient reductions from best management practices (BMPs) and associated BMP effectiveness data.

The Nooksack-Fraser Transboundary Nitrogen Project is an example of a watershed project that is a collaboration of local constituents for nitrogen management in the airsheds and watersheds of the Nooksack River, Lower Fraser Valley, and associated Sumas-Blaine aquifer. This project involves the development of a nitrogen budget that relies on using data for energy use, transportation, fertilization, wastewater treatment plants, livestock operations, wildlife, and more (Lin et al., 2018).

2. Collaborate with Local Stakeholders

A key component of developing representative watershed models will be through collaboration that draws on the expertise of federal and state agencies, tribes, local governments, conservation districts, nonprofit organizations, and academia. This accumulation of knowledge will be necessary to organize and synthesize the large amount of data needed for model inputs, running scenarios, and evaluating results.

Due to the range of facets incorporated within a watershed model, extensive information and guidance is needed relating to physical and biogeochemical characteristics and processes, current land use practices, BMP effectiveness, and modeling. Watershed models may magnify errors in nutrient load estimates that were not apparent in larger-scale models due to the finer resolution that these watershed models represent. Therefore, it will be critical to rely on the knowledge and information from local, on-the-ground stakeholders to fully capture the characteristics of a watershed.

For example, the Chesapeake Bay Program Partnership involves hundreds of experts that represent multiple federal agencies, state agencies, local governments, nonprofit organizations, and academic institutions. Local partnerships are key, particularly when identifying site-specific details within a watershed, such as on-the-ground surveys of land use patterns. Additionally, the Nooksack-Fraser Transboundary Project involves a range of collaborators from a variety of academic institutions, agencies, tribes, and nongovernmental organizations.

3. Develop Decision Support System Tool for Puget Sound Region

Ecology recommends developing a decision support system (DSS) tool specific to the greater Puget Sound region. The adaptation and implementation of a DSS tool could be applied to prioritize sub-watersheds within a larger watershed for nutrient management. A DSS would typically incorporate land use characteristics and geospatial data, and it can draw on information and results like that provided by SPARROW.

Currently, EPA’s Atlantic Ecology Division is developing an optimization tool that may be applied to Puget Sound (Naomi Detenbeck, pers. comm., 2019). With region-specific refinements, it can also be used to evaluate best management practices (BMPs) throughout the watershed that will reduce nutrients and improve water quality. Additionally, this tool will have the ability to draw on SPARROW information and results.

Once the tool application or model code is available, Ecology recommends evaluating and applying the DSS tool to the Puget Sound watershed. The Puget Sound DSS tool can then be used to run various scenarios to quantitatively predict nutrient reduction from management activities throughout the greater Puget Sound region. Ultimately, coordinating the Puget Sound optimization DSS tool with Salish Sea Model results may be used to guide nutrient management decisions to improve water quality conditions in Puget Sound.

4. Improve Nutrient Estimates for the Salish Sea Model

Using the information gained from reviewing SPARROW results for nutrient load estimates, Ecology recommends reviewing estimates of nutrient loads used as inputs for the Salish Sea Model. While the total nitrogen load estimates are in general agreement overall, some differences suggest the following actions:

- Evaluate incorporating net pens and hatcheries in marine waters as nutrient inputs.

- Identify and resolve discrepancies of point sources used in both models. For example, SPARROW accounts for two small facilities with marine outfalls that SSM currently does not include.
- When finer temporal resolution data becomes available, such as the data from continuous nitrogen monitoring, compare these load estimates with SPARROW results and inputs into the SSM.
- When updated SPARROW results are available (model results for the year 2012), compare these estimates with 2012 SSM nutrient load inputs.

5. Develop Watershed Management Optimization Support Tool (WMOST)

When recommendations 1 through 4 are implemented, DSS tools at a higher temporal and spatial resolution, such as a watershed-specific scale), should be developed and calibrated for specific watersheds within the Puget Sound region. An example of this type of tool is EPA's Watershed Management Optimization Support Tool[5] (WMOST).

WMOST is a decision support tool that facilitates integrated water management at the local or small watershed scale (EPA, 2013). It evaluates the direct and indirect effects of management decisions. The tool is intended to be used by water resources managers and planners to assess various management options to determine cost-effective and sustainable solutions (Zoltay et al., 2010). The model considers flow and water quality, with additional modules for the most recent model version (Detenbeck et al., 2018).

WMOST would need to be adapted and calibrated for use in specific watersheds within the Puget Sound region. Additionally, WMOST would be improved with the incorporation of higher temporal resolution watershed models, such as VELMA when it is fully implemented. Once a Puget Sound–wide DSS tool has been developed, WMOST may be useful to guide local management decisions at the watershed scale.

6. Further Investigate Using SPARROW as Part of Nutrient Management in Puget Sound Region

Currently, SPARROW model results for the Pacific Northwest are available only for 2002. Future plans for SPARROW include running the model for the year 2012, updating the model version, making it available through an online mapping tool, and integration into the R-SPARROW software for more detailed analyses (Dan Wise, pers. comm., 2019). Ecology recommends the following:

- Running the archived SPARROW model used for the Pacific Northwest application (Wise and Johnson, 2013) to:

[5] https://www.epa.gov/ceam/wmost#description

    - Further understand and identify model processes and results in the Puget Sound region.
    - Evaluate the spatial influence of nutrient source contributions, particularly focused in downstream reaches that discharge directly into Puget Sound.
- Running the updated version of SPARROW for a more recent year, when available.
- Using updated, more recent SPARROW results to compare with Salish Sea Model inputs for nutrient load estimates.

These recommendations will allow for further connections between the relationship of watersheds and regions with high nutrient loads and descriptive information on sources of these nutrients, such as agriculture, urban, or forest management sources. This continued analysis will help to fill key data gaps to inform nutrient management work in the greater Puget Sound region.

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Glossary, Acronyms, and Abbreviations

Glossary

Acidification: Reduction in the pH of the ocean over an extended period of time, caused primarily by the update of carbon dioxide from the atmosphere.

Anthropogenic: Human-caused.

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.

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

Greater Puget Sound region: Includes watershed areas draining into greater Puget Sound.

Marine point source: Point sources (see "point source" definition below) that discharge specifically to, or in close proximity to, marine waters.

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

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

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

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

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

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

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

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

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

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

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

Toxics: Toxic chemicals.

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

Acronyms and Abbreviations

BMP	best management practice
CAST	Chesapeake Assessment Scenarios Tool
CMAQ	Community Multiscale Air Quality model
DSS	decision support system tool
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System software
HAB	harmful algal blooms
HUC	hydrologic unit
MWQ	marine water quality
NEP	National Estuarine Program
NHD	National Hydrography Dataset Plus
NLCD	National Land Cover Database
NPDES	National Pollutant Discharge Elimination System
NWRO	Ecology's Northwest Regional Office
OSS	on-site septic system
PNNL	Pacific Northwest National Laboratory
PSEMP	Puget Sound Ecosystem Monitoring Program
PSNSRP	Puget Sound Nutrient Source Reduction Project
SPARROW	Spatially Referenced Regressions On Watershed Attributes model
SSM	Salish Sea Model
TMDL	Total Maximum Daily Load (see glossary)
TN	total nitrogen
TP	total phosphorus
USGS	United States Geological Survey
VELMA	Visualizing Ecosystem Land Management Assessments model
WMOST	Watershed Management Optimization Support Tool
WWTP	Wastewater treatment plant

Units of Measurement

ft	feet
kg	kilograms, a unit of mass equal to 1,000 grams
kg/yr	kilograms per year
km	kilometer, a unit of length equal to 1,000 meters
m	meter
mg/L	milligrams per liter (parts per million)
yr	year

Appendices

Appendix A. SPARROW Inputs

Nutrient sources used in SPARROW were synthesized into atmospheric deposition, agriculture, urban, forests, and other sources for this report. Wise and Johnson (2013) and other SPARROW publications (Wise and Johnson, 2011; Smith et al., 1997) provide in-depth descriptions of methodologies for estimating contributions from differing land use types. Below is an overview of the general categories of nutrient sources for the SPARROW Pacific Northwest application. Table A-1 is a summary table of the nutrient source subcategories and data sources.

Atmospheric Deposition

Atmospheric deposition data used in SPARROW were obtained from EPA's Community Multiscale Air Quality (CMAQ) model. SPARROW accounts for atmospheric deposition of total nitrogen within its in-stream estimates of total nitrogen loads. The atmospheric deposition of phosphorus is assumed to be a negligible source (Smith et al., 1997). Natural and urban sources of nitrogen emissions are inherently included within the atmospheric deposition source.

Agriculture

Data sets pertaining to agricultural fertilizer application and livestock manure are used to estimate agricultural nutrient loads using SPARROW. Agricultural sources of nutrients can be from crop fertilizer and livestock manure. For the SPARROW Pacific Northwest application, estimates of manure from cattle in confined dairies and feedlots were combined with cattle and noncattle grazing livestock (Wise and Johnson, 2013). Location and population information for cattle at dairies and feedlots were determined from permitting and inspection records. Land use data from the 2001 NLCD (Homer et al., 2004) was used to estimate the agricultural area for application of fertilizer on cropland and potential land for grazing livestock.

Urban Sources

SPARROW uses geospatial data from the 2001 National Land Cover Database (NLCD) (Homer et al., 2004) to estimate the amount of nutrients from developed land throughout the greater Puget Sound region. Developed land was used as a surrogate for nutrient sources originating from residential, commercial, and industrial land. These sources are intended to contain nonpoint sources of nutrients from commercial fertilizer, animal waste, and failing sewer systems.

Point sources represent municipal wastewater treatment plants, industrial facilities, hatcheries, and net pens with National Pollutant Discharge Elimination System (NPDES) permits. Loads were estimated using measured flow and either on-site measurements or a regional average for a specific industrial classification.

Forests and Other Sources

The extent of forestland is determined based on the National Land Cover Database (NLCD) (Wise and Johnson, 2013). Total nitrogen from forests in SPARROW are estimated using the fixation rate of atmospheric nitrogen in forests. Nitrogen leaching from alder trees was estimated based on the spatial distribution and basal area of alder forests throughout the Pacific Northwest (USGS, 2011).

For total phosphorus, SPARROW uses land cover of forestland, grassland, and scrubland to account for the weathering of geologic materials.

Table A-1. SPARROW nutrient source input description and data source summary. Further descriptions on estimation methods are found in Wise and Johnson (2013).

Category	Source	Description	Data Source	Method
Agriculture	Fertilizer	County-level estimates of nitrogen and phosphorus from fertilizer use on farmland and nonfarm land.	Statewide sales data from Washington State Department of Agriculture. National Land Cover Database (NLCD) 2001.	County-level estimates of nitrogen and phosphorus from farm fertilizer were disaggregated equally to farmland in each county. County-level estimates of nitrogen and phosphorus from nonfarm fertilizer use were disaggregated equally to developed land in each county.
Agriculture	Confined cattle manure	Nutrient estimates from dairy or feedlot.	Permitting and inspection records from the Washington Departments of Agriculture.	Estimated by multiplying the number of cattle at each dairy or feedlot by the nitrogen and phosphorus generation factors for dairy cows and feedlot cattle.
Agriculture	Livestock manure (cattle)	County-level estimates of nitrogen and phosphorus from rangeland cattle manure.	USGS annual nitrogen and phosphorus generation factors. 2002 animal counts compiled by the U.S. Department of Agriculture.	Calculated by subtracting the amount of nitrogen and phosphorus generated by dairy and feedlot cattle in each county from the total amount generated by all cattle. The county-level estimates of nutrients from rangeland cattle manure were disaggregated equally to the potential grazing land in each county.
Agriculture	Livestock manure (noncattle, grazing)	County-level estimates of manure generated by rangeland cattle and all other noncattle, nonpoultry livestock.	USGS annual nitrogen and phosphorus generation factors. 2002 animal counts compiled by the U.S. Department of Agriculture.	The county-level estimates of nitrogen and phosphorus from noncattle grazing livestock manure were disaggregated equally to grassland and pasture in each county.
Atmospheric Deposition	Atmospheric nitrogen deposition	The nutrient source term representing atmospheric nitrogen deposition.	U.S. Environmental Protection Agency Community Multiscale Air Quality (CMAQ) model.	The CMAQ model provided spatially refined atmospheric deposition data and included estimates of wet and dry nitrogen deposition.

Category	Source	Description	Data Source	Method
Forests	Nitrogen leaching from red alder trees	The nutrient source term representing the leaching of nitrogen from red alder trees (*Alnus rubra*).	USGS spatial data set.	Estimated from total basal area of red alder trees (2002).
Forests	Forestland	The nitrogen source term representing forestland and the phosphorus source terms representing forestland, scrubland, and grassland were used as surrogates for natural sources.	NLCD 2001.	In the total nitrogen model the natural source of nitrogen was fixation of atmospheric nitrogen in forests, and in the total phosphorus model the natural source of phosphorus was the weathering of geologic material.
Urban Sources	Point sources	The nutrient source terms representing point sources of facilities having a National Pollutant Discharge Elimination System (NPDES) permit.	Individual point source facilities permits (2002).	The discharge of total nitrogen and total phosphorus point sources were estimated using measured flow at plant outflows and either on-site measurements or a regional average for a specific industrial classification.
Urban Sources	Developed land	The nutrient source term representing developed land was used as surrogate for various nutrient sources originating from residential, commercial, and industrial land.	NLCD 2001.	Developed land was equal to the summed areas of NLCD developed land categories, minus areas representing roads.
Urban Sources	Non-sewered population	The nutrient source term representing the non-sewered population (the number of people not served by a municipal wastewater treatment plant) was used as a surrogate for nitrogen leaching from septic tanks.	Census blocks data from 2000 United States census grid. Municipal sewers data 2002.	The extent of the non-sewered population was computed by overlaying census blocks polygons and distributing populations through developed land, removing areas serviced by municipal sewers.
Urban Sources	Power returns	Returned flow of water that is diverted upstream for power generation.	NA	The nutrient loads from power returns were estimated using the fraction of streamflow received from an upstream reach at the point of diversion.

Table A-2. List of point sources included within SPARROW and the Salish Sea Model (SSM), including estimates of average annual total nitrogen (TN) load for the year 2002. Note: the Salish Sea Model includes point sources in the United States and Canada, but only U.S. facilities are listed in this table.

Name	Category	SPARROW TN (kg/day)	SSM TN (kg/day)	Model
Marine Outfall				
Enetai Hatchery	Hatchery	0.3	–	SPARROW
Hoodsport Hatchery	Hatchery	5.3	–	SPARROW
Lummi Bay Hatchery	Hatchery	7.7	–	SPARROW
Port Gamble Hatchery	Hatchery	0.1	–	SPARROW
BP Cherry Point Facility	Industrial	–	73.6	SSM
Conoco Phillips Facility	Industrial	–	3.0	SSM
Georgia Pacific Facility	Industrial	44.0		SPARROW
Intalco Facility	Industrial	106.7	11.5	SPARROW/SSM
Kimberley Clark Facility	Industrial	312.5	70.0	SPARROW/SSM
Nippon Paper Facility	Industrial	45.3	17.4	SPARROW/SSM
Port Townsend Paper Facility	Industrial	82.1	27.1	SPARROW/SSM
Rosario Utilities Facility	Industrial	–	0.7	SSM
Shell Oil Facility	Industrial	–	66.0	SSM
Simpson Facility/West Rock	Industrial	152.0	42.6	SPARROW/SSM
Tesoro Facility	Industrial	–	20.0	SSM
U.S. Oil & Refining Facility	Industrial	–	0.5	SSM
Whidbey Naval Station Facility	Industrial	17.4	14.7	SPARROW/SSM
American Gold Seafoods Facility	Net Pens	314.0	–	SPARROW
Global Aqua Fort Ward Hatchery	Net Pens	80.7	–	SPARROW
Icicle Acquisition Orchard Rock Hatchery	Net Pens	126.8	–	SPARROW
Icicle Acquisition Port Angeles Hatchery	Net Pens	176.6	–	SPARROW
Icicle Acquisition Site 1 Hatchery	Net Pens	102.0	–	SPARROW
Icicle Acquisition Site 2 Hatchery	Net Pens	69.3	–	SPARROW
Icicle Acquisition Site 3 Hatchery	Net Pens	173.9	–	SPARROW
Icicle Acquisition Site 4 Hatchery	Net Pens	15.4	–	SPARROW
Alderbrook Resort	WWTP	0.5	0.4	SPARROW/SSM
Alderwood WWTP	WWTP	108.7	260.0	SPARROW/SSM
Anacortes WWTP	WWTP	82.7	197.0	SPARROW/SSM
Bainbridge Island City WWTP	WWTP	30.6	18.1	SPARROW/SSM
Bellingham WWTP	WWTP	584.6	1093.2	SPARROW/SSM
Birch Bay Water & Sewer WWTP	WWTP	26.6	–	SPARROW
Birch Bay WWTP	WWTP	30.1	68.8	SPARROW/SSM
Blaine WWTP	WWTP	43.8	22.1	SPARROW/SSM
Boston Harbor WWTP	WWTP	1.9	3.3	SPARROW/SSM

Name	Category	SPARROW TN (kg/day)	SSM TN (kg/day)	Model
Bremerton WWTP	WWTP	255.7	717.9	SPARROW/SSM
Carlyon WWTP	WWTP	1.2	2.9	SPARROW/SSM
Chambers Creek WWTP	WWTP	842.7	2983.1	SPARROW/SSM
Clallam Bay POTW WWTP	WWTP	1.3	0.3	SPARROW/SSM
Clallam DOC WWTP	WWTP	–	4.6	SSM
Coupeville WWTP	WWTP	13.3	14.5	SPARROW/SSM
Eastsound Orcas Village WWTP	WWTP	0.3	0.1	SPARROW/SSM
Eastsound Water District WWTP	WWTP	5.6	7.5	SPARROW/SSM
Edmonds WWTP	WWTP	292.9	587.6	SPARROW/SSM
Everett Snohomish WWTP	WWTP	443.5	1657.7	SPARROW/SSM
Everett-Marysville WWTP	WWTP	–	0.0	SSM
Fisherman Bay WWTP	WWTP	1.0	0.6	SPARROW/SSM
Fort Lewis WWTP	WWTP	176.4	197.0	SPARROW/SSM
Friday Harbor WWTP	WWTP	20.5	10.4	SPARROW/SSM
Gig Harbor WWTP	WWTP	38.0	38.7	SPARROW/SSM
Harstene WWTP	WWTP	4.1	1.4	SPARROW/SSM
Kitsap Co. Central WWTP	WWTP	214.8	486.7	SPARROW/SSM
Kitsap Co. Kingston WWTP	WWTP	–	3.4	SSM
Kitsap Co. WWTP	WWTP	3.6	1.1	SPARROW/SSM
Kitsap Manchester WWTP	WWTP	14.7	7.1	SPARROW/SSM
La Conner WWTP	WWTP	14.0	25.3	SPARROW/SSM
Lake Stevens 1 WWTP	WWTP	107.6	194.4	SPARROW/SSM
Lakota WWTP	WWTP	185.1	743.6	SPARROW/SSM
Langley WWTP	WWTP	7.7	2.7	SPARROW/SSM
Larrabee State Park WWTP	WWTP	0.2	0.3	SPARROW/SSM
LOTT WWTP	WWTP	565.0	295.8	SPARROW/SSM
Lummi Goose Pt WWTP	WWTP	9.9	9.1	SPARROW/SSM
Lummi Sandy Pt WWTP	WWTP	1.1	3.6	SPARROW/SSM
Lynnwood WWTP	WWTP	224.3	501.3	SPARROW/SSM
Makah WWTP	WWTP	–	7.3	SSM
Marysville WWTP	WWTP	261.2	457.9	SPARROW/SSM
McNeil Island DOC WWTP	WWTP	17.9	21.4	SPARROW/SSM
Messenger House WWTP	WWTP	–	0.2	SSM
Midway WWTP	WWTP	210.6	438.3	SPARROW/SSM
Miller Creek WWTP	WWTP	161.2	417.6	SPARROW/SSM
Mt. Vernon WWTP	WWTP	152.0	356.4	SPARROW/SSM
Mukilteo WWTP	WWTP	158.8	15.4	SPARROW/SSM
Navy - Kitsap	WWTP	0.6	–	SPARROW
Navy - Port Townsend	WWTP	0.7	–	SPARROW

Name	Category	SPARROW TN (kg/day)	SSM TN (kg/day)	Model
Oak Harbor Lagoon WWTP	WWTP	–	172.7	SSM
Oak Harbor WWTP	WWTP	27.9	56.3	SPARROW/SSM
Penn Cove WWTP	WWTP	2.6	2.1	SPARROW/SSM
Port Angeles WWTP	WWTP	139.4	247.0	SPARROW/SSM
Port Gamble WWTP	WWTP	–	0.5	SSM
Port Ludlow WWTP	WWTP	12.7	11.2	SPARROW/SSM
Port Orchard WWTP	WWTP	–	244.1	SSM
Port Townsend WWTP	WWTP	51.1	30.6	SPARROW/SSM
Puyallup WWTP	WWTP	208.9	182.2	SPARROW/SSM
Redondo WWTP	WWTP	117.8	248.8	SPARROW/SSM
Roche Harbor WWTP	WWTP	2.1	0.6	SPARROW/SSM
Rustlewood WWTP	WWTP	3.9	0.5	SPARROW/SSM
Salmon Creek WWTP	WWTP	105.9	473.0	SPARROW/SSM
Seashore Villa WWTP	WWTP	1.6	0.3	SPARROW/SSM
Sekiu WWTP	WWTP	5.9	3.6	SPARROW/SSM
Sequim WWTP	WWTP	–	27.3	SSM
Shelton WWTP	WWTP	101.4	59.1	SPARROW/SSM
Skagit Co. 2 WWTP	WWTP	9.8	3.7	SPARROW/SSM
Snohomish WWTP	WWTP	85.9	100.6	SPARROW/SSM
South King WWTP	WWTP	3861.7	9741.1	SPARROW/SSM
Stanwood WWTP	WWTP	58.6	15.3	SPARROW/SSM
Suquamish WWTP	WWTP	6.2	6.8	SPARROW/SSM
Swinomish WWTP	WWTP	7.7	4.0	SPARROW/SSM
Tacoma Central WWTP	WWTP	1071.6	2065.5	SPARROW/SSM
Tacoma North WWTP	WWTP	233.7	451.9	SPARROW/SSM
Tamoshan WWTP	WWTP	1.4	0.7	SPARROW/SSM
Taylor Bay WWTP	WWTP	–	0.4	SSM
Tulalip WWTP	WWTP	–	6.5	SSM
Vashon WWTP	WWTP	10.5	3.5	SPARROW/SSM
Warm Beach Campground WWTP	WWTP	–	1.7	SSM
West Point WWTP	WWTP	5554.3	10679.1	SPARROW/SSM
Freshwater Outfall				
Arlington Hatchery	Hatchery	2.7	–	SPARROW
Chambers Creek Hatchery	Hatchery	0.2	–	SPARROW
Clear Creek Pond Hatchery	Hatchery	5.7	–	SPARROW
Crisp Creek Hatchery	Hatchery	1.8	–	SPARROW
Eells Springs Hatchery	Hatchery	11.3	–	SPARROW
Elwha Hatchery	Hatchery	2.7	–	SPARROW

Name	Category	SPARROW TN (kg/day)	SSM TN (kg/day)	Model
Garrison Springs Hatchery	Hatchery	1.1	–	SPARROW
George Adams Hatchery	Hatchery	2.1	–	SPARROW
Gorst Creek Hatchery	Hatchery	0.1	–	SPARROW
Grovers Creek Hatchery	Hatchery	1.8	–	SPARROW
Kalama Creek Hatchery	Hatchery	2.2	–	SPARROW
Kendall Creek Hatchery	Hatchery	4.6	–	SPARROW
Keta Creek Hatchery	Hatchery	1.6	–	SPARROW
Lower Elwha Klallam Hatchery	Hatchery	4.1	–	SPARROW
Lummi Skookum Creek Hatchery	Hatchery	5.1	–	SPARROW
Mckernan State Hatchery	Hatchery	0.4	–	SPARROW
Nisqually Hatchery	Hatchery	25.6	–	SPARROW
Quilcene Fish Hatchery	Hatchery	1.5	–	SPARROW
Reiter Ponds Hatchery	Hatchery	2.8	–	SPARROW
Samish Hatchery	Hatchery	0.2	–	SPARROW
Stillaguamish WWTP	Hatchery	0.2	–	SPARROW
Tokul Creek Hatchery	Hatchery	2.9	–	SPARROW
Tulalip Hatchery	Hatchery	5.9	–	SPARROW
Upper Skagit Hatchery	Hatchery	0.0	–	SPARROW
WADFW Auburn Hatchery	Hatchery	4.5	–	SPARROW
WADFW Barnaby Hatchery	Hatchery	1.1	–	SPARROW
WADFW Bellingham Hatchery	Hatchery	0.7	–	SPARROW
WADFW Dungeness Hatchery	Hatchery	2.2	–	SPARROW
WADFW Issaquah Hatchery	Hatchery	3.6	–	SPARROW
WADFW Marblemount Hatchery	Hatchery	5.4	–	SPARROW
WADFW Minter Creek Hatchery	Hatchery	6.0	–	SPARROW
WADFW Palmer Ponds Hatchery	Hatchery	2.1	–	SPARROW
WADFW Wallace Hatchery	Hatchery	1.9	–	SPARROW
WADFW Whitehorse Ponds Hatchery	Hatchery	4.8	–	SPARROW
White River Hatchery	Hatchery	0.1	–	SPARROW
Abitibi Facility	Industrial	1.3	–	SPARROW
Arkema Facility	Industrial	2.0	–	SPARROW
Birds Eye Foods Facility	Industrial	0.0	–	SPARROW
Blau Oyster Shellfish Facility	Industrial	0.3	–	SPARROW
Coast Seafood Shellfish Facility	Industrial	7.5	–	SPARROW
Olympia Oyster Shellfish Facility	Industrial	0.2	–	SPARROW
Pioneer Americas Facility	Industrial	0.9	–	SPARROW
Sonoco Industrial	Industrial	0.4	–	SPARROW
Taylor Shellfish Facility	Industrial	0.1	–	SPARROW

Name	Category	SPARROW TN (kg/day)	SSM TN (kg/day)	Model
Arlington WWTP	WWTP	61.0	–	SPARROW
Buckely WWTP	WWTP	23.1	–	SPARROW
Carbonado WWTP	WWTP	2.1	–	SPARROW
Cherrywood WWTP	WWTP	1.0	–	SPARROW
Concrete WWTP	WWTP	7.9	–	SPARROW
Duvall WWTP	WWTP	27.4	–	SPARROW
Eatonville WWTP	WWTP	12.9	–	SPARROW
Enumclaw WWTP	WWTP	54.0	–	SPARROW
Everson WWTP	WWTP	14.0	–	SPARROW
Ferndale WWTP	WWTP	99.3	–	SPARROW
Granite Falls WWTP	WWTP	17.8	–	SPARROW
Lynden WWTP	WWTP	43.9	–	SPARROW
North Bend WWTP	WWTP	25.0	–	SPARROW
Orting City WWTP	WWTP	30.4	–	SPARROW
Seattle Light Diablo WWTP	WWTP	0.2	–	SPARROW
Seattle Light Newhalem WWTP	WWTP	0.4	–	SPARROW
Sedro Woolley WWTP	WWTP	50.0	–	SPARROW
Snoqualmie WWTP	WWTP	35.4	–	SPARROW
Sumner WWTP	WWTP	73.4	–	SPARROW
WADNR Indian Ridge DOC WWTP	WWTP	3.9	–	SPARROW
Water Dept. WWTP	WWTP	46.4	–	SPARROW
Wilkeson WWTP	WWTP	3.0	–	SPARROW

*SPARROW includes estimates for two WWTPs for Birch Bay. However, there is only one facility.
WWTP = wastewater treatment plant.

Appendix B. Nutrient Load Estimates Comparison

Due to differences in model requirements and results, the following methods were used to minimize spatial differences between the two models and allow for a more accurate comparison of load estimates. To compare SSM nutrient load inputs with SPARROW estimates loading into Puget Sound marine waters, SPARROW loads from terminal outlets for rivers and streams were selected, along with shoreline loads that represent nearshore watersheds. These loads were aggregated and totaled by the region draining into Puget Sound basins (Figure B-1) and by SSM watershed area. SSM marine point source loads were added to the SSM watershed load of closest proximity.

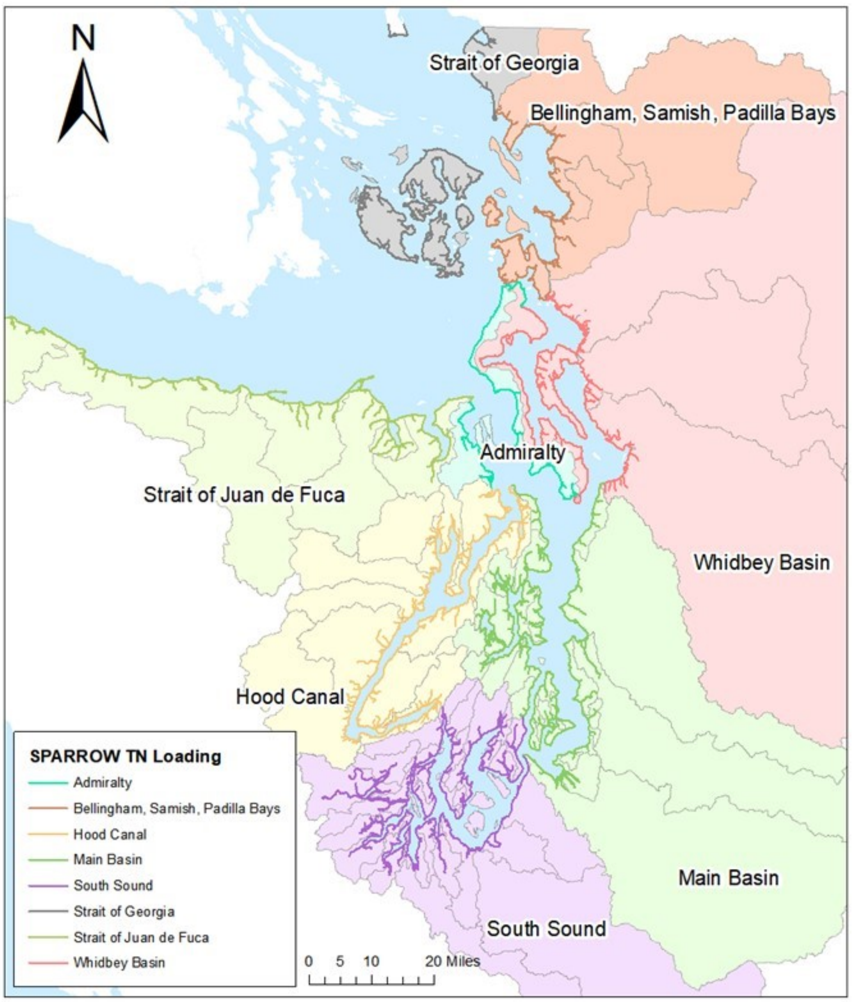

Figure B-1. Map of SPARROW total nitrogen (TN) load results aggregated by region draining into Puget Sound basins.

Miller Creek Watershed Comparison

On a regional scale, differences between SPARROW and SSM nitrogen load estimates were greatest for loads entering the Main Basin, specifically regarding point source estimates. This section provides an in-depth comparison of differences in nutrient load estimates from point sources considered in both models for the Miller Creek watershed in the Main Basin.

SPARROW and SSM both account for the same three facilities: South King WWTP, Salmon Creek WWTP, and Miller Creek WWTP. All of these WWTPs discharge directly into the marine waters of Puget Sound. There are some spatial differences in the exact location of these facilities (Figure B-2). This is partly because SPARROW accounts for nitrogen inputs from marine in its stream outlets and shoreline loads. These load estimates represent nearshore watersheds using a land-based location (Figure B-2). Alternatively, SSM marine point source locations are based on the outfalls of these WWTPs, and are therefore located on the coast (Salmon Creek WWTP) or in the nearshore (South King and Miller Creek WWTPs).

Figure B-2. Miller Creek Watershed point source locations (located in Puget Sound Main Basin).

The 2002 total nitrogen load estimates for each facility are shown in Figure B-3. This comparison highlights the contrasting model estimates of total nitrogen loads for the year and shows that SSM loads are significantly higher than SPARROW estimates. South King WWTP has the largest difference, with SSM estimating a total nitrogen load 2.1 million kg/yr greater than SPARROW estimates. For the South King WWTP, SSM used facility-specific water quality and flow data to determine average loads, whereas SPARROW estimation methods relied on regional averages. Because SSM uses facility-specific flow and water quality data to estimate point source nutrient loads, we expect these to more accurately reflect nutrient loads from WWTPs.

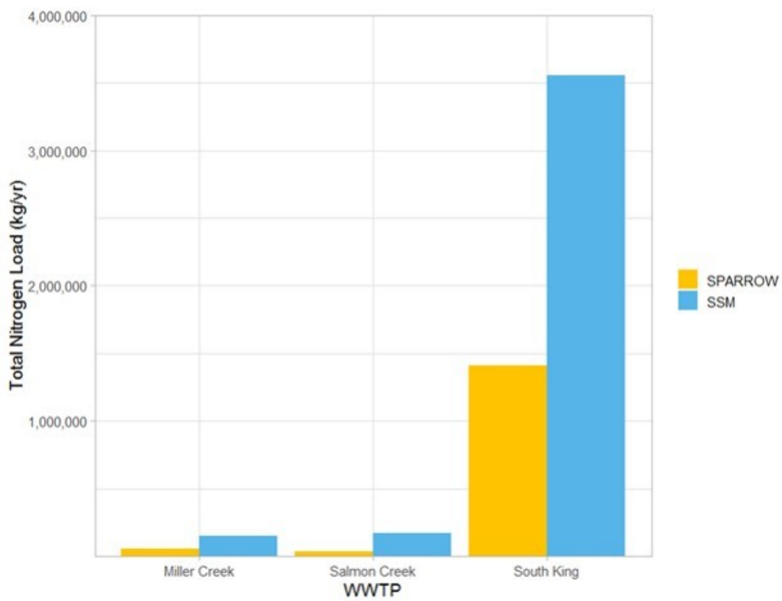

Figure B-3. Miller Creek watershed point source total nitrogen load estimates used in SPARROW and SSM (2002).