South Puget Sound
Water Quality Study
Phase 2: Dissolved Oxygen

Quality Assurance Project Plan

August 2007

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Study Codes

Data for this project are available at Ecology's Environmental Information Management (EIM) website at www.ecy.wa.gov/eim/index.htm. User Study ID is SPSMEM_M (marine data) and MROB0004 (freshwater data).

The Environmental Assessment Program Study Code is 06-509-01.

Waterbody Numbers

303(d) listing ID	Waterbody Name	Waterbody Code	Parameter
5852	Budd Inlet (inner)	47122A9F0	Dissolved Oxygen
5862	Budd Inlet (inner)	47122A9G0	Dissolved Oxygen
5863	Budd Inlet (inner)	47122A9E0	Dissolved Oxygen
5863	Budd Inlet (inner)	47122A8F9	Dissolved Oxygen
5864	Budd Inlet (inner)	47122A8G9	Dissolved Oxygen
7587	Budd Inlet (inner)	47122A9H1	Dissolved Oxygen
40581	Budd Inlet (inner)	47122A9F0	Dissolved Oxygen
7585	Budd Inlet (outer)	47122A9I1	Dissolved Oxygen
7582	Budd Inlet (outer)	47122A9I0	Dissolved Oxygen
7584	Budd Inlet (outer)	47122A8J9	Dissolved Oxygen
7583	Budd Inlet (outer)	47122B9A1	Dissolved Oxygen
7586	Budd Inlet (outer)	47122B9A0	Dissolved Oxygen
3769	Budd Inlet (outer)	47122B9E2	Dissolved Oxygen
3770	Budd Inlet (outer)	47122B9E1	Dissolved Oxygen
43003	Carr Inlet	47122D6D9	Dissolved Oxygen
43002	Carr Inlet	47122D7B0	Dissolved Oxygen
10229	Carr Inlet	47122C7H0	Dissolved Oxygen
43001	Carr Inlet	47122C6F9	Dissolved Oxygen
43000	Carr Inlet	47122C6D5	Dissolved Oxygen
42999	Carr Inlet	47122C6B2	Dissolved Oxygen
10175	Commencement Bay	47122C4J4	Dissolved Oxygen

Old Waterbody Numbers

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

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Acronyms and Abbreviations

Following are acronyms and abbreviations used frequently in this document:

BOD	biochemical dissolved oxygen demand
CTD	Conductivity, Temperature, and Depth recorder
EAP	Environmental Assessment Program (Ecology)
Ecology	Washington State Department of Ecology
EFDC	Environmental Fluid Dynamics Code
EIM	Environmental Information Management database (Ecology)
GEMSS	Generalized Environmental Modeling System for Surface Waters
GLLVHT	Generalized Longitudinal Lateral and Vertical Hydrodynamic & Transport model
JEEAI	J. E. Edinger and Associates, Inc.
LOTT	Lacey, Olympia, Tumwater and Thurston County
MLLW	mean lower low water
NPDES	National Pollutant Discharge Elimination System
PRISM	Puget Sound Regional Synthesis Model (UW)
PSP	Paralytic Shellfish Poisoning
QA	quality assurance
ROMS	Rutgers Ocean Modeling System
RSD	relative standard deviation
STP	sewage treatment plant
TMDL	Total Maximum Daily Load (water cleanup plan)
UW	University of Washington
WQP	Water Quality Program (Ecology)
WWTP	wastewater treatment plant

Abstract

The Washington State Department of Ecology is starting a study on low dissolved oxygen levels in South Puget Sound. Fish and other marine life need dissolved oxygen to survive. Dissolved oxygen levels decrease when excess nitrogen enters Puget Sound, producing excessive algae growth. These algae die off and decay, consuming dissolved oxygen. Excessive nitrogen is considered a pollutant. Sources of nitrogen (above natural conditions) include wastewater treatment plants and septic systems.

The purpose of this study is to determine how nitrogen from a variety of sources affects dissolved oxygen levels in South Puget Sound. The complete study (not yet fully funded) consists of collecting data, calibrating a three-dimensional hydrodynamic and water quality model, running model scenarios, and writing a final report. Collection of water quality data occurs over a 16-month time span (July 2006 through October 2007) from 90 Puget Sound marine sites at various depths, 20-30 wastewater treatment plants (direct discharge to Puget Sound), and 15-30 freshwater tributary sites.

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

Introduction

The Washington State Department of Ecology (Ecology) is starting a study on low dissolved oxygen levels in South Puget Sound. Marine animals need dissolved oxygen to survive. This study will help determine how human activities (along with natural factors) affect low dissolved oxygen levels in South Puget Sound.

Fish Need Dissolved Oxygen

In areas with low levels of dissolved oxygen, fish and other marine life become stressed and die or are forced to flee their habitat. There are many areas in Puget Sound with very low levels of dissolved oxygen.

We Must Solve the Problem Before it Gets Worse

In Hood Canal, low levels of dissolved oxygen have caused major fish kills. Other sensitive areas in Puget Sound (especially Budd, Case, and Carr Inlets) face the same fate unless we work to solve the problem.

Nitrogen is the Main Pollutant that Causes Low Dissolved Oxygen Levels

Discharges from wastewater treatment plants, septic systems, and other sources add nitrogen to Puget Sound. This excess nitrogen can cause algae blooms, which consume oxygen as the algae sink and decompose. The challenge is that once nitrogen is discharged to Puget Sound, it moves around—nitrogen discharged at one location may cause low dissolved oxygen levels many miles away.

We Need to Study the Effects of Nitrogen Discharges

The purpose of this study is to determine how nitrogen from a variety of sources affects dissolved oxygen levels in South Puget Sound. This study is a critical first step in determining what might need to be done to improve water quality. The results of the study may show that human-related sources of nitrogen need to be reduced to keep South Puget Sound healthy. If reductions are needed, the study will also help determine where the reductions need to occur.

Why is Ecology Conducting this Study?

Study Area

This study focuses on the marine waters of South Puget Sound, defined as the area south of the Narrows near Tacoma. Figure 1 shows both the marine water and the watersheds that drain to (and potentially contribute pollutants to) South Puget Sound. The hydrodynamic model boundary for the South Puget Sound region will be at Alki Point, consistent with the model domain of the Phase 1 part of the study (Albertson et al., 2002). However, pollutant sources in the region between Alki and Edmonds also will be evaluated for potential impacts on South Puget Sound water quality, although this is not the primary area of interest of the study. If the central Puget Sound sources do not influence water quality in South Puget Sound, only the Alki boundary will be used. However, if interim modeling indicates that these sources could influence South Puget Sound water quality, the final model boundary may be as far north as Edmonds.

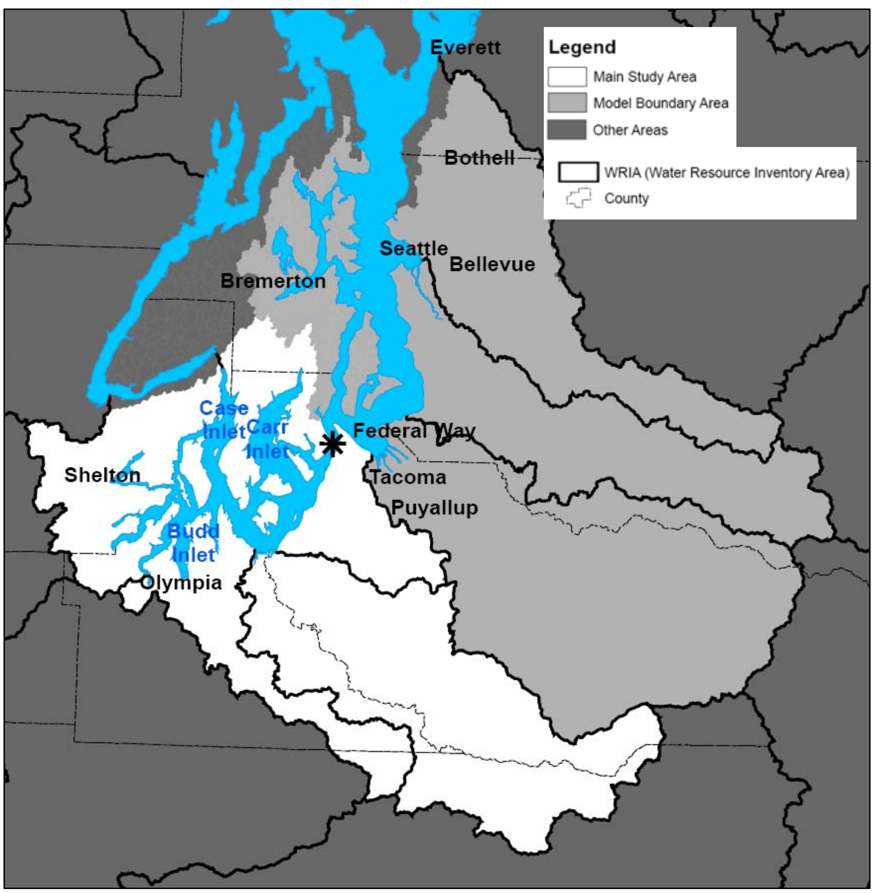


Figure 1. Study area for the South Puget Sound Dissolved Oxygen Study. Tacoma Narrows is indicated by the asterisk.

Pollutants Addressed by this Study

This study addresses dissolved oxygen levels. Dissolved oxygen levels are affected by many factors, but nitrogen is the main pollutant that reduces it to unhealthy levels in Puget Sound.

The Problem

Ecology's earlier work in South Puget Sound has shown low levels of dissolved oxygen (Albertson et al., 2002). Although it has been known for many years that Budd Inlet had dangerously low dissolved oxygen levels, this study showed that Case and Carr Inlets also appear to be threatened (Figure 2).

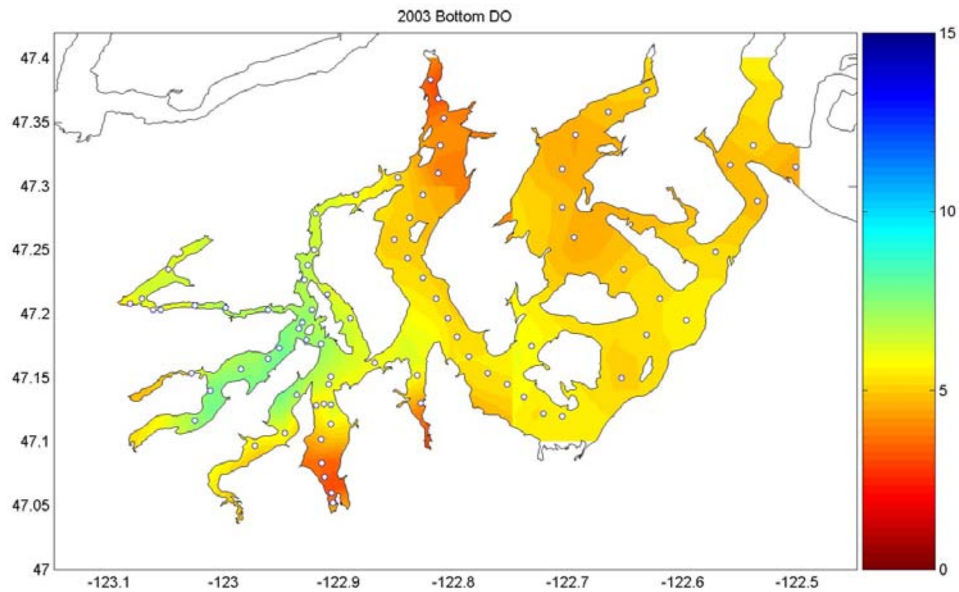


Figure 2. Dissolved oxygen levels (mg/L) at near-bottom depths for South Puget Sound in 2003.

Low dissolved oxygen concentrations in Puget Sound are found naturally, but in some areas may be exacerbated by human input of nitrogen, stimulating algal growth (eutrophication). The production of excessive algae can then lead to water quality problems such as low dissolved oxygen in the bottom waters. Other impacts from eutrophication are less well-known, but concerns exist about the impact of human-caused nutrient loading on the prevalence of harmful algal blooms (e.g., Paralytic Shellfish Poisoning [PSP] and Amnesiac Shellfish Poisoning).

The first known outbreak of PSP in South Sound was recorded in November 1997. The PSP outbreak resulted in closure of commercial shellfish growing areas to harvest in several South Sound Inlets. More recently, in August of 2000 an outbreak of PSP in Carr Inlet afflicted seven people who had eaten mussels there. One person required extensive hospitalization and treatment on a respirator. PSP events are thought to be increasing in frequency and extending farther south into South Puget Sound than previously reported, including first-ever reported blooms in Totten and Eld Inlets in the summer of 2001 (Olympian, 2001).

Numerous factors control nutrient enrichment, eutrophication, and dissolved oxygen depletion. Nutrient inputs from atmospheric deposition, tributary inflows, point source discharges, nonpoint source inputs, and sediment-water exchange determine the loads to South Puget Sound. Hydrodynamic characteristics, such as tides, stratification, mixing, and freshwater inflows, govern transport of nutrients and other parameters. Photosynthesis rates (influenced by light and nutrient availability, temperature, and species assemblages) and other processes (growth, death, respiration, and settling) determine nutrient transformations and dissolved oxygen depletion.

Excessive nutrient inputs can accelerate negative impacts from the eutrophication process and affect water quality in several ways:

- Increase the algal growth and cause shifts in community structure, leading to the predominance of undesirable forms (e.g., toxic phytoplankton blooms).
- Alter the balance between phytoplankton, zooplankton, fish, and shellfish that may result in an unusually high accumulation rate of organic matter on bottom sediments, which may depress bottom dissolved oxygen concentrations.
- Change the aerobic bacteria populations to anaerobic sulfate-reducing bacteria, which can increase the water column levels of hydrogen sulfide that may lead to further community structure changes.
- Affect recreational activities due to objectionable odors and unsightly algal mats.

Every two years, states are required to prepare a list of waterbodies—lakes, rivers, streams, or marine waters—that do not meet water quality standards. This list is called the 303(d) list, after the relevant section of the federal Clean Water Act. To develop the list, Ecology compiles its own water quality data along with data submitted by local, state, and federal governments, tribes, industries, and citizen monitoring groups. All data are reviewed to ensure that they were collected using appropriate scientific methods before the data are used to develop the 303(d) list. The 303(d) list is part of the larger Water Quality Assessment.

The Water Quality Assessment is a list that tells a more complete story about the condition of Washington's water (Ecology, 2005). This list divides waterbodies into one-of-five categories:

Category 1 – Meets standards for parameters for which it has been tested.

Category 2 – Waters of concern.

Category 3 – Waters with no data available.

Category 4 – Polluted waters that do not require a Total Maximum Daily Load (TMDL) because:

- 4a – Has a TMDL approved and being implemented.
- 4b – Has a pollution control plan in place that should solve the problem.
- 4c – Impaired by a non-pollutant such as low water flow, dams, culverts.

Category 5 – Impaired waters (the 303(d) list).

In the 2004 Water Quality Assessment, 22 locations in South Puget Sound were deemed impaired due to a lack of dissolved oxygen. Another 43 locations were identified as waters of concern. Carr, Case, and Budd Inlets are the locations of greatest concern (Figure 3).

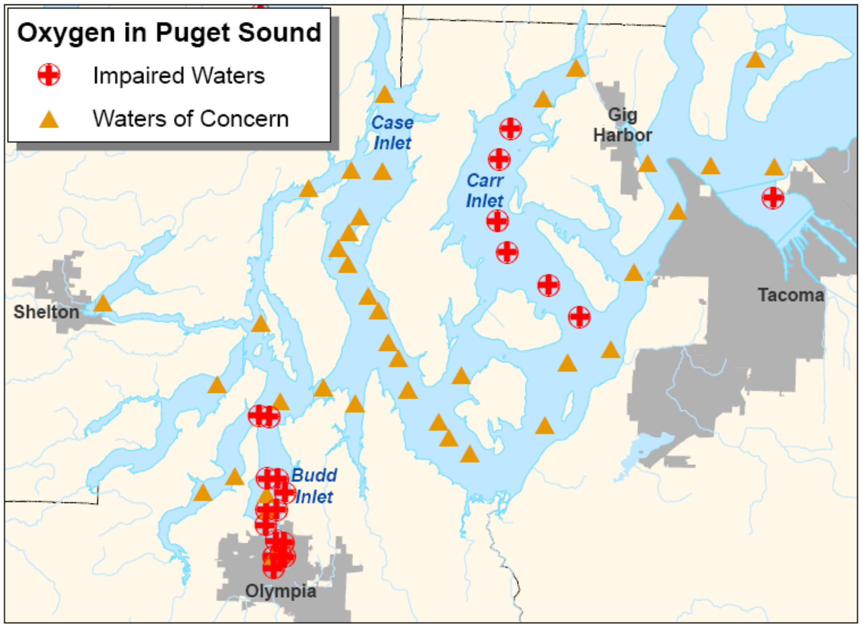


Figure 3. 2004 Water Quality Assessment for dissolved oxygen in South Puget Sound.

Why Are We Doing this Study Now?

We must solve the problem before it gets worse. In Hood Canal, low levels of dissolved oxygen have caused major fish kills. Other sensitive areas in Puget Sound (especially Budd, Case, and Carr Inlets) face the same fate unless we work to solve the problem.

There are about $200 million worth of investments in wastewater treatment plants being planned, designed, or constructed right now in South Puget Sound. These include work by Tacoma, LOTT (Lacey, Olympia, Tumwater, and Thurston County), Shelton, Buckley, Enumclaw, and Sumner. King County is investing heavily in the Brightwater plant. The capacity of wastewater treatment plants will need to increase as the population in the Puget Sound region grows. The population in the Puget Sound area is expected to increase from 4.2 million in 2005 to 5.1 million in 2020 (WOFM, 2003). That is a 21% increase in the next 15 years and a 51% increase between 1991 and 2020. Every additional person in the region produces about ten pounds of additional nitrogen every year (Metcalf and Eddy, 2003), and much of that nitrogen makes its way to Puget Sound. With this much ongoing work and future expansions, it makes sense for everyone to understand how our activities impact dissolved oxygen levels in Puget Sound before it is too late.

How Will the Results of this Study be Used?

Excess nitrogen is the main pollutant that causes low dissolved oxygen levels and may lead to the increase in harmful algal blooms. Human-related sources of nitrogen come from both point sources (such as wastewater treatment plants) and nonpoint sources (such as fertilizer use and septic systems).

The results of the study may show that human-related sources of nitrogen need to be reduced to keep South Puget Sound healthy. If reductions are needed, the study will also help figure out where the reductions need to occur.

Water Quality Standards

Under the Clean Water Act, every state has its own water quality standards designed to protect, restore, and preserve water quality. Water quality standards consist of designated uses for protection (such as aquatic life) and criteria, usually numeric, to achieve those uses.

All marine water in South Puget Sound falls under the extraordinary, excellent, or good quality category. The water quality standards are found in the Washington Administrative Code, WAC 173-201A.

Aquatic organisms are very sensitive to reductions in the level of dissolved oxygen in the water. The health of fish and other aquatic species depends upon maintaining an adequate supply of oxygen dissolved in the water. Growth rates, swimming ability, susceptibility to disease, and the relative ability to endure other environmental stressors and pollutants are all affected by dissolved oxygen levels. While direct mortality due to inadequate dissolved oxygen can occur, the state's criteria are designed to maintain conditions that support healthy populations of fish and other aquatic life.

Dissolved oxygen levels can fluctuate over the day and night in response to changes in climatic conditions as well as the respiratory requirements of aquatic plants, algae, phytoplankton, and bacteria. Since the health of aquatic species is tied predominantly to the pattern of daily minimum dissolved oxygen concentrations, the criteria are expressed as the lowest one-day minimum dissolved oxygen concentration that occurs in a waterbody.

The numeric criteria for South Puget Sound are to:

1. Protect the designated *Extraordinary Quality* category of aquatic life use, the lowest one-day minimum dissolved oxygen level must not fall below 7.0 mg/l more than once every ten years on average.
2. Protect the designated *Excellent Quality* category of aquatic life use, the lowest one -day minimum dissolved oxygen level must not fall below 6.0 mg/l more than once every ten years on average.
3. Protect the designated *Good Quality* category of aquatic life use, the lowest one -day minimum dissolved oxygen level must not fall below 5.0 mg/l more than once every ten years on average.

The described criteria above are used to ensure that where a waterbody is naturally capable of providing full support for its designated aquatic life uses, that condition will be maintained. The standards recognize, however, that not all waters are naturally capable of staying above the fully protective dissolved oxygen criteria. When a waterbody is naturally lower in dissolved oxygen than the criteria, an additional allowance is provided for further depression of dissolved oxygen conditions due to human activities. In this case, the combined effects of all human activities (including both point and non-point sources) must not cause more than a 0.2 mg/l decrease below that naturally lower (inferior) dissolved oxygen condition.

Criteria generally apply throughout a waterbody. They are not intended to apply to discretely anomalous areas such as in shallow stagnant eddy pools where natural features unrelated to human influences are the cause of not meeting the criteria. For this reason the standards direct that measurements be taken from well-mixed portions of the waterbody. For similar reasons, samples should not be taken from anomalously dissolved oxygen rich areas for direct comparison to water quality standards. For example, in a poorly flushed embayment with nutrient problems, sampling the surface layer during mid day may produce an anomalously high reading that is caused by the peak photosynthesis cycle of the algae.

Watershed Description

South Puget Sound is not flushed as rapidly as the deeper waters of northern Puget Sound and includes many blind-end inlets with sluggish circulation. Newton et al. (1997) assessed dissolved oxygen concentrations at locations throughout Puget Sound and suggested that depletion of bottom dissolved oxygen concentrations can be exacerbated in areas that have (1) strong density stratification (e.g., in areas with freshwater input), (2) high production due to inhibited mixing, and (3) oxidation of sunken organic material (i.e., dead phytoplankton). Eutrophication (nutrient addition which promotes more carbon production) will likely have the greatest impact in South Puget Sound areas where (1) flushing is low, (2) strong density stratification occurs, and (3) phytoplankton growth may be nutrient limited, such as in bays and inlets. Increases in nutrient loads can accelerate the negative consequences of the eutrophication process. Like many other western Washington locations, the South Puget Sound watershed receives significant development pressure.

Hydrographically, South Puget Sound is very different from the main basin of Puget Sound. Physical characteristics of the South Puget Sound basin include distance from the Strait of Juan de Fuca, complex morphology, and slow flushing rates (the rate at which the water is exchanged with incoming water). As a result of shallower depths and longer residence times, land-derived nutrients are not diluted or transported out of the South Puget Sound basin as much as in the deeper, more tidally mixed areas of central Puget Sound.

Biologically, South Puget Sound is also different from other regions within Puget Sound. Because of the slow flushing time and physical stability of the water column, many of the inlets and bays are exceptionally productive. For example, despite a water column of about 10 meters, the annual depth-integrated primary production in Budd Inlet is actually higher than the 110-meter water column in Dabob Bay (Newton, 1998).

The geomorphology of South Puget Sound is also different than the deep, open basins of central and northern Puget Sound.

The hydrological, biological, and geomorphological attributes of the South Puget Sound region make it susceptible to adverse effects from eutrophication.

South Puget Sound is divided into numerous inlets, which results in a high shoreline-to-water volume ratio. The extensive shorelines attract significant residential development. Recently, many of the stream corridors and shorelines in the area have experienced considerable growth. As a result of increases in human activities, nutrient loading to South Puget Sound likely exceeds past loads and will likely increase in the future.

Potential Sources of Pollution

Excess nitrogen can come from a variety of sources. The term *nonpoint* is used to describe diffuse sources that do not come through a pipe (such as rainfall runoff from agricultural fields and residential yards) and groundwater (including contributions from septic systems). Most of the nonpoint nitrogen loading from the watersheds surrounding South Puget Sound enters the sound via rivers and streams that drain to the sound.

The term *point source* generally refers to sources that are regulated under the federal Clean Water Act through the National Pollutant Discharge Elimination System (NPDES). NPDES permits are issued to municipal and industrial wastewater treatment and stormwater systems, constructions sites, boatyards, and other facilities. With respect to point sources, municipal wastewater treatment plants that discharge directly to Puget Sound are thought to represent the largest source of direct nitrogen loading to the sound.

Historical Data Review

Hydrographic Data Collection History in South Puget Sound

The earliest hydrographic data available from South Puget Sound dates from the R/V Catalyst cruises around 1936. After a hiatus during World War II in the 1940s, the R/V Brown Bear resumed regular visits in the 1950s and 1960s, which are summarized in the Puget Sound Atlas (Collias et al., 1975). At the conclusion of these, the Washington State Department of Ecology (Ecology) began occupying monthly seaplane stations, which were often suspended during the winter months. The only depths sampled between 1973 and 1989 were at the surface, 10 m and 30 m. In addition, the National Oceanic and Atmospheric Administration (NOAA) has a 29-day time series of sea surface heights from eight locations south of the Tacoma Narrows.

Beginning in November 1989, Ecology began making complete vertical profiles of the water column with a modern CTD (Conductivity, Temperature, and Depth recorder) at the behest of the Puget Sound Action Team. Under the same auspices, Ecology sampled intensively in Budd Inlet during the summers of 1992-1994 and again in 1996-1997 as part of the Budd Inlet Scientific Study (Aura Nova Consultants et al., 1998). More intensive surveys of the entire South Puget Sound basin began in 1994 with the R/V Barnes; these surveys resumed in September 1997. Since then, there have been late-summer research voyages of this type every year with the exception of 1998, when sampling occurred in December, as summarized in Table 1. Starting in 1999, these research voyages were performed in support of the South Puget Sound Phase 1 Study (Albertson et al., 2002).

Water velocity (current) data have been collected along transects in Budd, Carr, and Case Inlets as well as in Oakland Bay. Scientists at The Evergreen State College have also collected data not reported here, as have those at LOTT.

Table 1. Ecology's historical marine monitoring surveys in South Puget Sound.

Cruise	Vessel	Dates
1	Barnes 549	14-15 Dec 1994
2	Barnes 613	3-4 Sept 1997
3	Barnes 646	14-17 Dec 1998
4	Barnes 652	20-23 April 1999
5	Barnes 664	20-23 Sept 1999
6	Barnes 675	11-14 Dec 1999
7	Barnes 692	10-14 Jul 2000
8	Barnes 697	25-29 Sept 2000
9	Barnes 723	24-28 Sept 2001
10	Barnes 764	30 Sept - 3 Oct 2002
11	Barnes 811	22-25 Sept 2003
12	Barnes 851	27 Sept - 1 Oct 2004
13	Barnes 866	26 - 29 Sept 2005

South Puget Sound Phase 1 Study Findings and Conclusions

The South Puget Sound Water Quality Study Phase 1 report (Albertson et al., 2002) addressed concerns that rapid population growth was outpacing South Puget Sound's capacity to assimilate nutrients and potentially degrading dissolved oxygen levels. In Phase 1, Ecology (1) analyzed historical data, (2) conducted oceanographic field studies to examine the relationship between nutrients and dissolved oxygen, (3) collected additional nutrient and dissolved oxygen data, (4) estimated watershed and point-source pollutant loading, (5) developed a hydrodynamic and water quality model, and (6) performed an initial model calibration.

Phase 1 had the following findings and conclusions:

- Based on field observations and experimental measurements, South Puget Sound appears to be sensitive to nutrient addition. When more nitrogen was added experimentally, dissolved oxygen decreased. (This report confirmed the potential for serious water quality degradation due to increased nutrient loads.)

- Case, Carr, and Budd Inlets appear to have the lowest dissolved oxygen levels within South Puget Sound and may be the most sensitive areas to increased nutrient loads. Budd Inlet has been studied in detail; additional focus on Case and Carr Inlets is warranted.

- While point sources discharging directly to South Puget Sound contribute 2% of the total inflows, point sources contribute 30% of the dissolved inorganic nitrogen load and 54% of the total phosphorus load. Fecal coliform loads from watershed inflows are two orders of magnitude greater than point sources.

- Water quality modeling shows that dissolved oxygen is more sensitive to nutrient-driven processes than direct biochemical oxygen demand (BOD) loading.

- A coupled hydrodynamic and water quality model was successfully developed for South Puget Sound that can be applied to evaluate the sensitivity of dissolved oxygen levels to increased nutrient loading. However, the model requires further refinement and testing before the results can be used for management decisions. Additional monitoring data are needed for model calibration and verification.

National Oceanographic Partnership Program (NOPP) Support

The National Oceanographic Partnership Program (NOPP) grant #05PR01848-00 helps support this project for hydrodynamic modeling of South Puget Sound. A preliminary scientific understanding of the circulation in South Puget Sound was partially underwritten by data collected under this grant. A summary report will be published in the Georgia Basin Puget Sound Research Proceedings in 2007.

Other

In partnership with Ecology, the University of Washington PRISM (Puget Sound Regional Synthesis Model) program has been conducting approximately twice-annual monitoring cruises throughout Puget Sound starting in June 1998 (www.prism.washington.edu/). Five of these stations are located south of the Tacoma Narrows.

King County's Marine and Sediment Assessment Group supports a comprehensive, long-term marine monitoring program that assesses water quality in the Central Puget Sound Basin (dnr.metrokc.gov/wlr/waterres/marine/).

Ecology maintains a freshwater ambient monitoring network, described at www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html. The network includes numerous sites on rivers and streams within the South Puget Sound drainage area. Water quality is measured monthly. Pierce, Thurston, Kitsap, and Mason counties also monitor the water quality of streams at sites within the study area.

The United States Geological Survey maintains a network of streamflow gaging stations, including sites in the study area (waterdata.usgs.gov/wa/nwis/rt). Ecology supplements this network with additional streamflow gaging sites, described at www.ecy.wa.gov/programs/eap/flow/shu_main.html.

The National Atmospheric Deposition Program maintains a network of sensors throughout the country, and three stations surround Puget Sound (nadp.sws.uiuc.edu/). Ecology previously used the results from this program to estimate nitrogen loads to the water surface of South Puget Sound. The same approach will be used in the current study. Atmospheric deposition to land areas will be characterized within the freshwater monitoring approach.

Project Description

Project Goal

The purpose of this study is to determine how nitrogen from a variety of sources affects dissolved oxygen levels in South Puget Sound. Individual discharges of nitrogen at one spot may affect dissolved oxygen levels many miles away. This study is a critical first step in determining what will need to be done to improve water quality. The results of the study may show that human-related sources of nitrogen need to be reduced to keep South Puget Sound healthy. If reductions are needed, the study will also help determine where the reductions need to occur.

Study Objectives

Study objectives are:

- Collect sufficient marine and freshwater input data to calibrate a three-dimensional hydrodynamic and water quality model of South Puget Sound.
- Calibrate the 3-D model to collected data.
- Run model scenarios to show:
  - The effect of current nitrogen loading on South Puget Sound dissolved oxygen levels, compared to natural conditions.
  - The effect of future nitrogen loading on South Puget Sound dissolved oxygen (DO) levels, assuming continued population growth and increasing nitrogen loads.
  - The reductions in nitrogen loading that are needed to meet the state water quality standard, if such reductions are necessary.
  - The geographic areas and seasonal time period most susceptible to reduced dissolved oxygen levels due to nitrogen loading.
- Publish final report summarizing the results of the model scenarios.

Note that funding has not yet been obtained to complete all project objectives. Funding as of March 2007 is sufficient for the data collection phase. Additional funding is needed for calibrating the model, running model scenarios, and producing the final report.

Advisory Committee

Ecology formed a Technical Advisory Committee for the South Puget Sound Dissolved Oxygen Study. The Technical Advisory Committee is comprised of scientifically knowledgeable people representing a full range of interests. Committee members represent tribes, wastewater treatment plants, conservation districts, department of health, universities, business interests, environmental groups, municipalities, counties, and federal agencies.

The role of the committee is to make recommendations on the study, promote education, and encourage discussion of issues. The committee does this by reviewing the Draft Study Plan, reviewing data when available, scoping modeling scenarios, and sharing information on related projects. The committee meets approximately once per quarter, with additional ad hoc subcommittee meetings as needed.

Experimental Design

Study Design Overview

The overall design of the project is:

- Collect field data to describe environmental conditions within South Puget Sound and its boundary influences (open boundary and tributaries).
- Develop a three-dimensional numerical model that describes the hydrodynamics and biogeochemical processes in South Puget Sound.
- Apply the numerical model to evaluate the sensitivity of water quality in South Puget Sound to changes in boundary conditions (e.g., increased nutrient loading).
- Estimate the loading capacity of South Puget Sound for assimilation of nutrients and compliance with water quality standards for dissolved oxygen.

The marine and freshwater sampling plans are described below. Marine sampling will capture the conditions within South Puget Sound as well as the northern boundary of the study area. Freshwater sampling will capture pollutant loading that enters the sound from two sources: wastewater treatment plant discharges (direct into Puget Sound) and tributaries (rivers and streams). Note that loading from wastewater treatment plants and other sources (such as stormwater and other rainfall/runoff) that discharge into rivers and streams will be captured in the measurements taken at the mouths of the streams.

Pollutant loading from some relatively small sources will be estimated rather than measured, as described below under Other Sources. These include atmospheric deposition, groundwater flowing directly into the sound, and rainfall-runoff from land that drains directly into the Sound.

Marine Sampling

Marine sampling consists of two types of surveys:

- Marine boundary station sampling using the King County Department of Natural Resources (KCDNR) R/V Liberty and the University of Washington R/V Thomas G. Thompson.
- Marine sampling of South Puget Sound stations using either the University of Washington R/V Barnes or the Ecology R/V Skookum.

Marine boundary sampling using the R/V Liberty and R/V Thomas G. Thompson

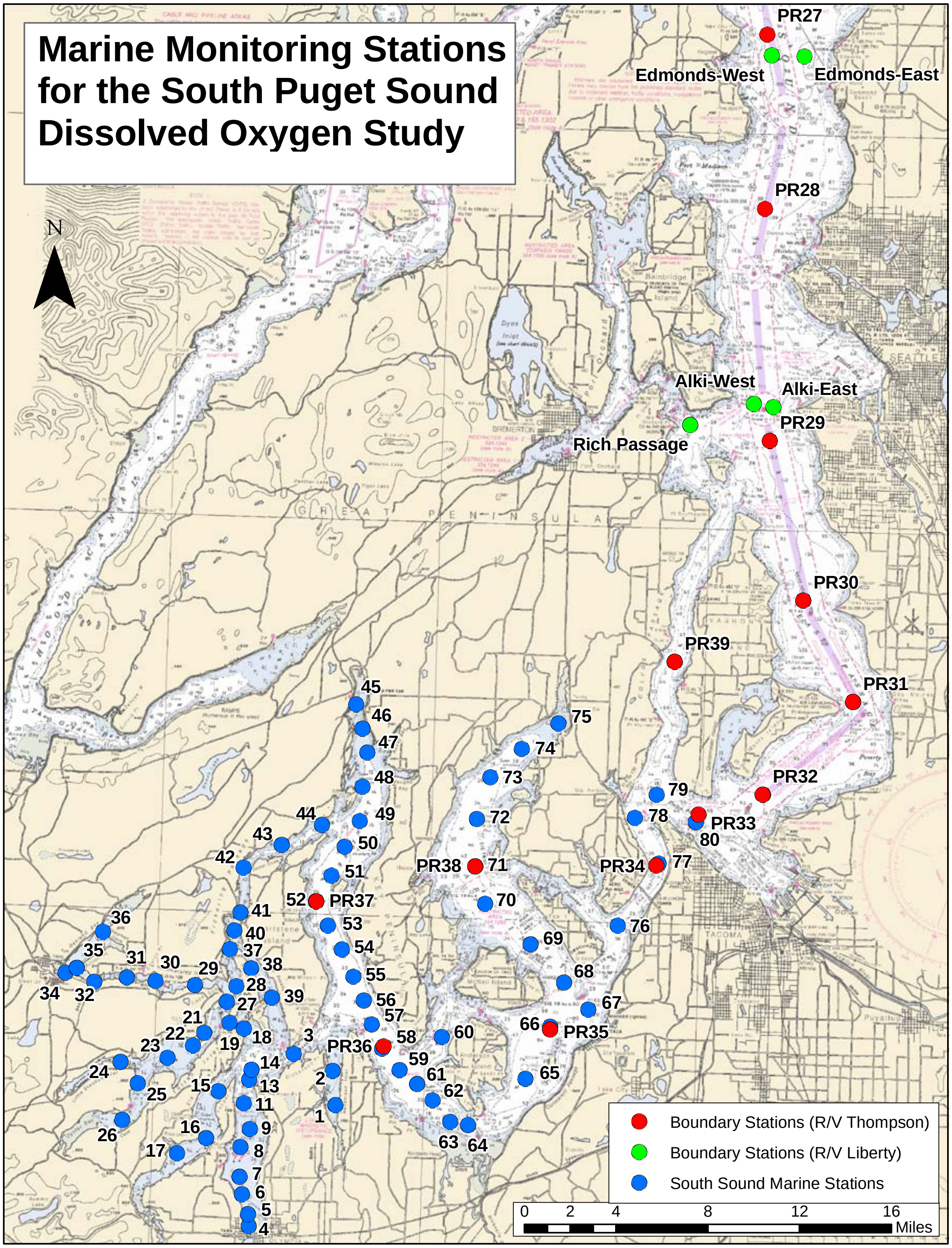
R/V Liberty stations will be sampled at approximately monthly intervals between July 2006 and October 2007. Station locations are shown on Figure 4 and listed in Table 2a. Depths for discrete sample collection are shown in Table 3. Up to 13 stations will be sampled in conjunction with the University of Washington's (UW's) PRISM cruises from the R/V Thompson (station locations are listed in Table 2b). PRISM cruises will occur in June and December 2006 and June 2007. For both types of boundary sampling, the laboratory and field analyses listed in Table 4 will be done at each discrete sample depth. In addition to the water sample collection at discrete depths, casts of continuous vertical profiles from surface to bottom will be recorded at each station for: (1) temperature, (2) salinity, (3) density, (4) dissolved oxygen, (5) *in vivo* fluorescence, (6) light transmission, and (7) pH.

Table 2a. Longitudes and latitudes of R/V Liberty sampling stations. Depth is in meters at the tidal height of mean lower low water (MLLW).

Name	Depth (m MLLW)	Longitude (decimal degrees NAD83)	Latitude (decimal degrees NAD83)
Alki-East	229	-122.440633	47.578200
Alki-West	237	-122.458891	47.579827
Rich Passage	41	-122.518083	47.565583
Edmonds-East	210	-122.419842	47.800081
Edmonds-West	196	-122.450286	47.800186

Table 2b. Longitudes and latitudes of R/V Thomas G. Thompson (PRISM) sampling stations. Depth is in meters at the tidal height of mean lower low water (MLLW).

Name	Depth (m MLLW)	Longitude (decimal degrees NAD83)	Latitude (decimal degrees NAD83)
PR29	232	-122 26.4	47 33.4
PR30	229	-122 24.5	47 27.4
PR31	220	-122 21.6	47 23.6
PR32	181	-122 26.5	47 20.0
PR33	152	-122 30.0	47 19.2
PR35	58	-122 38.0	47 10.9
PR36	96	-122 47.2	47 10.1
PR37	60	-122 51.2	47 15.9
PR38	97	-122 42.5	47 16.6
PR34	58	-122 32.3	47 17.2
PR39	120	-122 31.6	47 24.9
PR28	199	-122 27.2	47 42.2
PR27	200	-122 27.3	47 48.8



R/V = research vessel

Figure 4. Station locations for R/V Barnes, Skookum, and (partial) Thompson surveys. Six stations have duplicate names (PR33=80, PR34=77, PR35=66, PR36=58, PR37=52, PR38=71).

Table 3. Depths for discrete water sample collection at each station for laboratory analysis.

Description	Depths (m)
Alki-East	0, 5, 10, 30, 50, 100, 150, NB
Alki-West	0, 5, 10, 30, 50, 100, 150, NB
Rich Passage	0, 5, 10, 30, NB
Edmonds-East	0, 5, 10, 30, 50, 100, 150, NB
Edmonds-West	0, 5, 10, 30, 50, 100, 150, NB

NB = Near-bottom.

Table 4. Laboratory and field analyses conducted at each discrete sample depth for the full suite of parameters.

Full Suite of Parameters
Ammonia (NH4-N) (filtered sample)
Nitrate plus nitrite (NO2+NO3-N) (filtered sample)
Total dissolved persulfate N (TDN) (filtered sample)
Total persulfate nitrogen (TN) (unfiltered sample)
Soluble reactive phosphorus (SRP) (filtered sample)
Total dissolved phosphorus (TDP) (filtered sample)
Total phosphorus (TP) (unfiltered sample)
Particulate organic C and nitrogen (CHN analyzer)
Dissolved organic carbon (DOC) (filtered sample)
Chlorophyll a (CHLA)
Silicon (SiO2) (filtered sample)
Alkalinity (unfiltered sample)
Temperature (field)
Salinity (field with laboratory check)
Dissolved oxygen (field with laboratory check)
pH (field)

A single-depth sample from the euphotic zone at each station will be collected and preserved for analysis of phytoplankton population and biovolume identification (fractions of phytoplankton biomass as diatoms, dinoflagellates, or other).

Marine South Puget Sound sampling using the R/V Barnes and Skookum

Fifteen cruises will collect samples from up to 85 stations within South Puget Sound during the period July 2006 through October 2007 using the R/V Barnes and Skookum. Table 5 presents the schedule of cruises and Figure 4 shows the station locations. Six of the cruises will be conducted with the UW R/V Barnes, which is the larger research vessel and allows more intensive sampling. All 85 stations will be sampled on the Barnes cruises. The smaller research vessel Skookum will be used to collect supplemental information more frequently at a subset of 40 stations for the remaining nine cruises.

Table 5. Planned cruises for the South Puget Sound study (July 2006 through October 2007).

Cruise	Type	Dates
1	**Intensive**	**31 July - 4 August 2006**
2	Supplemental	21-24 August 2006
3	**Intensive**	**25-29 September 2006**
4	Supplemental	23-24 October 2006
5	Supplemental	13-14 November 2006
6	**Intensive**	**18-21 December 2006**
7	Supplemental	26-27 Feb 2007
8	Supplemental	26-27 March 2007
9	**Intensive**	**23-26 April 2007**
10	Supplemental	21-22 May 2007
11	**Intensive**	**25-29 June 2007**
12	Supplemental	30-31 July 2007
13	Supplemental	27-28 August 2007
14	**Intensive**	**24-28 September 2007**
15	Supplemental	23-24 October 2007

Each station will be sampled according to one of three sampling schemes:

- CTD (Conductivity, Temperature, and Depth recorder) and full suite of parameters (Table 4).
- CTD and limited suite of parameters (Table 6)
- CTD only.

Table 6. Laboratory and field analyses conducted at each discrete sample depth for the limited suite of parameters.

Limited Suite of Parameters
Ammonia (NH4-N) (filtered sample)
Nitrate plus nitrite (NO2+NO3-N) (filtered)
Total persulfate nitrogen (TN) (unfiltered sample)
Soluble reactive phosphorus (SRP) (filtered)
Total phosphorus (TP) (unfiltered sample)
Chlorophyll a (CHLA)
Silicon (SiO2) (filtered sample)
Temperature (field)
Salinity (field with laboratory check)
Dissolved oxygen (field with laboratory check)
pH (field)

Table A-1 in Appendix A shows the sampling scheme to be used at each site. As shown in the table, the two September Barnes cruises have a higher resolution of analyses than the other four Barnes cruises, because September is the critical time period for dissolved oxygen. Table A-1 also shows the discrete depths at which samples will be taken.

A single-depth sample in the euphotic zone at each full-suite nutrient profile station will be collected and preserved for analysis of phytoplankton population and biovolume ID (fractions of phytoplankton biomass as diatoms, dinoflagellates, or other). ^{14}C uptake experiments to determine growth rates, nutrient saturation values, and primary production will be conducted in September 2006, April, June, and September 2007 from the R/V Barnes at stations 8, 25, 35, 52, 64, and 71.

Freshwater Sampling

Sampling of freshwater sources to South Puget Sound consists of two types of inputs:

- Rivers and streams (tributaries).
- Wastewater treatment plant discharges.

Table 7 lists the laboratory and field analyses to be completed at each freshwater station.

Table 7. Laboratory and field analyses conducted at each freshwater station.

Freshwater Laboratory and Field Analyses
Ammonia (NH4N) (filtered sample)
Nitrate plus nitrite (NO2+NO3N) (filtered sample)
Total dissolved persulfate N (TDN) (filtered sample)
Total persulfate nitrogen (TN) (unfiltered sample)
Soluble reactive phosphorus (SRP) (filtered sample)
Total dissolved phosphorus (TDP) (filtered sample)
Total phosphorus (TP) (unfiltered sample)
Total organic carbon (TOC) (unfiltered sample)
Dissolved organic carbon (DOC) (filtered sample)
Carbonaceous BOD5 (wastewater samples only)
Alkalinity (unfiltered sample)
Temperature (field)
Conductivity (field for tributaries and lab for wastewater discharges)
Dissolved oxygen (field with lab check for 5% of tributary samples)
pH (field)
flow (field)

The surface water inflows into the main basin and South Puget Sound, including rivers, streams, and wastewater treatment plant discharges, are presented in Appendix B.

Rivers and streams

Sampling of rivers and streams includes six stations that are part of Ecology's freshwater ambient monitoring network (Table 8).

Table 8. Ecology freshwater ambient monitoring stations included in the study.

Station	Station Name
09A080	Green River @ Tukwila
09D070	Miller Creek near mouth (by SeaTac)
09K070	Fauntleroy Creek near mouth (by White Center)
10A070	Puyallup River @ Meridian Street
11A070	Nisqually River @ Nisqually
13A060	Deschutes River @ E Street Bridge

Note: 09D070 and 09K070 will only be sampled through September 2006.

An additional 15 tributary sampling stations (through June 2007) and up to 30 stations (July - October 2007) will be established during the study selected from the list in Table 9 in order from largest to smallest (locations shown in Figure B-1 in Appendix B). Together, the ambient and supplemental monitoring networks will characterize loads from 89% of the overall watershed area.

Table 9. Ecology supplemental tributaries to be sampled.

Sampling period	
August 2006 to October 2007	July to October 2007
Chambers Creek	Cranberry Creek
Sequalitchew Creek	Purdy Creek
McAllister Creek	Campbell Creek
Woodland Creek	Deer Creek
Rocky Creek	Miller Creek
Goldsborough Creek	Fauntleroy Creek
Coulter Creek	Hylebos Creek
Kennedy Creek	Curley Creek
Sherwood Creek	Olalla Creek
Woodard Creek	DesMoines Creek
Skookum Creek	Moxlie Creek
McLane Creek	Johns Creek
Perry Creek	Judd Creek
Minter Creek	Shingle Mill Creek
Burley Creek	Ellis Creek
	Mission Creek
	Goodnough Creek
	Butler Creek
	Schneider Creek
	Mill Creek

Wastewater treatment plant discharges

Samples will be collected from up to 20 wastewater treatment plant dischargers through June 2007, then from up to 30 wastewater treatment plant dischargers between July and October 2007). They will be selected from the list of major and minor NPDES (National Pollutant Discharge Elimination System) dischargers listed in Table 10 and shown in Figure B-1. For the period August – December 2006, sampling will be conducted only at those facilities that were asked and agreed to participate on a voluntary basis.

Table 10. Major and minor NPDES dischargers.

Major NPDES Dischargers	Minor NPDES Dischargers
Chambers Creek STP	Gig Harbor
LOTT AWTP	Beverly Beach STP
Lakehaven Redondo STP	Boston Harbor STP
Lakehaven Lakota STP	Carlyon Beach STP
King Co. Alki STP[1]	Central Kitsap
Miller Creek STP	Hartstene Pointe STP
Salmon Creek STP	Manchester STP
Shelton STP	Midway STP
Simpson Tacoma Kraft WTP	Rustlewood STP
Tacoma Central #1 STP	Seashore Villa STP
Tacoma North #3 STP	Tamoshan STP
King Co. West Point[1]	Taylor Bay STP
Bremerton	Vashon STP
South King Co	WA DOC McNeil Island STP[2]
Port Orchard	WA Parks Black Island STP
	Kitsap County Suquamish
	Lynwood Center
	Kitsap County Kingston
	Kitsap County Sewer District 7
	Fort Lewis Solo Point

Note: Underlined plants have collected samples since August 2006 under the voluntary program.
[1] All King County CSO discharges are covered under the West Point permit.
[2]This site was not to be sampled due to access challenges; effluent characteristics would be estimated based on other WWTP data.

Other Sources

The river and stream monitoring network represents 89% of the total watershed tributary to South Puget Sound (Albertson et al., 2002). Contributions from the watershed area directly adjacent to South Puget Sound will be estimated by extrapolating loads from monitored locations. Septic system contributions will be estimated using the approaches and results of ongoing Hood Canal research and the Hood Canal Dissolved Oxygen Program. The National Atmospheric Deposition Program network will be used to estimate loads directly to water surfaces from atmospheric deposition. Previous estimates of direct groundwater contributions will supplement groundwater that reaches the sound through the stream network (Albertson et al., 2002).

Modeling Approach

Model selection

The most important criteria for selecting the modeling framework for South Puget Sound include:

1. Framework uses state-of-the-art algorithms and solution techniques for 3-dimensional hydrodynamics and transport that are appropriate for estuarine applications, especially in South Puget Sound.
2. Biogeochemical module is integrated with the hydrodynamic and transport module and includes important kinetic processes that are known to be necessary for simulation of dissolved oxygen dynamics in South Puget Sound.
3. Peer review of model theory and past applications has occurred.
4. Technical documentation is available.
5. Active development of the framework is ongoing and technical support is available.

In addition to these key criteria, other considerations that would be beneficial include:

- Successful past applications in Puget Sound.
- Program source code availability for review as part of program documentation.
- Graphical user interface should be provided, preferably in a Geographic Information System environment, for preprocessing, model execution, and post-processing of model input and output. It includes tools for preparing input files and displaying output results and comparisons of model predictions with observed data. Output post-processing capabilities should ideally include display-of-time series, profiles, contour plots, animations, and error analysis statistics.
- Linkage of 1-dimensional river grids with 3-dimensional estuarine grid.

A variety of 3-dimensional modeling frameworks have been applied in South Puget Sound over the past several years and include:

- Lacey, Olympia, Tumwater, and Thurston County (LOTT) conducted a modeling study of Budd Inlet to determine whether discharges of highly treated effluent into Budd Inlet would adversely impact water quality. Aura Nova Consultants et al. (1998) used the J. E. Edinger and Associates, Inc. (JEEAI) Generalized Longitudinal Lateral and Vertical Hydrodynamic and Transport model (GLLVHT) as the framework for the model application for Budd Inlet. Boatman et al. (1999) found that it was necessary to simulate the diel vertical migration of dinoflagellates in order to accurately represent dissolved oxygen dynamics in inner Budd Inlet.
- Ecology (Albertson et al., 2002) used the Environmental Fluid Dynamics Code (EFDC) as the framework for the initial phase of the South Puget Sound water quality study. EFDC offers a public-domain platform that simulates hydrodynamics, salinity, temperature, nutrient

cycling, two phytoplankton groups, sediment transport, sediment diagenesis, and other conservative and non-conservative substances. The EFDC model tended to over predict the dissolved oxygen in the bottom layer of Budd Inlet. This finding was hypothesized to result from the action of dinoflagellates, which settle at night and take up oxygen. The diel vertical migration of dinoflagellates appears to be a key process to describe dissolved oxygen dynamics in shallow inlets of South Puget Sound and it is not represented in the EFDC framework, which is consistent with the findings of Boatman et al. (1999).

- Ongoing Total Maximum Daily Load study of Budd Inlet, Ecology (Roberts et al., 2004) is using the latest version of the GLLVHT program, which is currently called the Generalized Environmental Modeling System for Surface Waters (GEMSS). Ecology contracted with JEEAI to update LOTT's application of GLLVHT for Budd Inlet into the latest version of the GEMSS framework. Since then JEEAI was purchased by Environmental Resources Management which currently leads the development of GEMSS.
- UW and KCDNR have used the Princeton Ocean Model to simulate hydrodynamics in the entire Puget Sound domain as part of the UW's PRISM and KCDNR's evaluation far-field dilution of effluent from the proposed Brightwater Sewage Treatment Plant. UW is also using the Rutgers Ocean Modeling System (ROMS) modeling framework for hydrodynamics and biogeochemical simulations in Hood Canal.

The importance of diel vertical migration of dinoflagellates for influencing the ability to predict dissolved oxygen profiles in the shallow inlets of South Puget Sound with the lowest bottom layer dissolved oxygen is (1) a recurring finding in the work for the LOTT scientific study, (2) the first phase of Ecology's South Puget Sound water quality study, and (3) hypothesized to be important in Budd Inlet starting with the early work of URS (1986) and Boatman and Buchak (1987). Dinoflagellates appear to act as a biological pump by (1) swimming downward into the lower layer to respire and reduce the DO of bottom water at night and then (2) swimming upward to a level of optimum light during the daytime to photosynthesize and increase the DO of surface waters to super-saturation levels.

A comparison of GEMSS, EFDC, and Rutgers Ocean Modeling System (ROMS) with the criteria for model selection is presented in Table 11. The preferred framework for biogeochemical modeling in South Puget Sound is GEMSS. GEMSS meets the five key criteria identified above as well as the other considerations identified to be important for model selection. While many frameworks meet most of the criteria identified above, GEMSS is the only known framework that includes the important kinetic process of diel vertical migration of dinoflagellates.

Table 11. Comparison of modeling frameworks with criteria for South Puget Sound (0 = least desirable, 3 = most desirable)

	GEMSS	EFDC	ROMS
1. Algorithms and solution techniques for hydrodynamics and transport			
- curvilinear orthogonal or cartesian grid	3	3	3
- higher order turbulence closure schemes (e.g. Mellor Yamada)	3	3	3
- z, sigma, or general vertical coordinates for vertical layering	2	3	1
- wetting/drying of cells	3	2	0
- higher order transport schemes (e.g. QUICKEST-ULTIMATE)	3	3	3
- term-by-term heat budget	3	3	3
2. Algorithms and solution techniques for biogeochemical processes			
- biogeochemical processes module	3	2	1
- sediment diagenesis	3	3	1
- dinoflagellates diel vertical migration	3	0	0
3. Peer-review of model theory and applications	3	3	3
4. Technical documentation	2	2	0
5. Active development or user group	3	3	3
6. Other			
- Successful past applications in Puget Sound	3	2	1
- Program source code is available	3	3	3
- Graphical User Interface for pre- and post-processing	3	0	0
- Linkage of 1-D river with 3-D estuary grids	3	1	0
Total score	46	36	25

The preference for the GEMSS framework includes the following considerations:

- GEMSS includes biological kinetic processes that have been identified to be necessary to accurately represent dissolved oxygen dynamics in South Puget Sound. Diel vertical migration of dinoflagellates is considered to be an essential kinetic process for Budd Inlet and likely other areas of South Puget Sound. EFDC and ROMS do not include this kinetic process.
- LOTT's Budd Inlet study showed that GEMSS is capable of accurately simulating dissolved oxygen in Budd Inlet, which is a representative subset of the model domain for South Puget Sound.
- Ecology will be completing the Budd Inlet/Deschutes River TMDL project based on GEMSS prior to the completion of the South Puget Sound Dissolved Oxygen Study.
- Budd Inlet calibration parameters for GEMSS may be appropriate for the entire South Puget Sound model domain. In that case it would be relatively straightforward to calibrate the South Sound GEMSS model compared with a different framework that uses different kinetic processes, resulting in a more cost-effective project. It may not be possible for frameworks that exclude the simulation of diel vertical migration of dinoflagellates to represent dissolved oxygen dynamics accurately in shallow inlets of South Puget Sound.
- GEMSS is capable of simulating 1-D channels connected to the 3-D grid of South Puget Sound. This allows GEMSS to be used for extending the model domain to include rivers and streams if necessary. This may be important for the South Puget Sound Dissolved Oxygen Study if there is a need to incorporate NPDES dischargers that are some distance upstream from river mouths.

- Ecology is collaborating with Environmental Resources Management to incorporate QUAL2Kw (Pelletier et al., 2006) kinetics and sediment diagenesis. Ecology is using GEMSS as the preferred framework for other TMDL projects in estuarine and riverine systems (e.g., Old Stillaguamish River Channel (Pelletier and Sullivan, 2006) and Palouse River (Carroll and Mathieu, 2006)).
- GEMSS includes a relatively easy to use for graphical user interface for pre- and post-processing.

The hydrodynamic basis for GEMSS was presented in Edinger and Buchak (1980, 1985), and details of the model were further published in Edinger and Buchak (1995), and other publications by Edinger et al. (e.g., 1994 and 1997). At the time of the LOTT project, the GLLVHT program had over 35 applications to hydrodynamic, transport, and water quality problems.

The GEMSS/GLLVHT Model includes the following computational and numerical properties:

- *Grid and Coordinate Transformations*. The three key components of grid and coordinate transformations include a: (1) rectilinear (quasi-curvi-linear) grid used for mapping to different detail in different parts of a waterbody, (2) space-staggered finite-difference grid with elevations and constituent concentrations at cell centers and velocities through cell interfaces (a scheme facilitating implementation of a control volume approach resulting in perfect water balance), and (3) Z-level fixed layer in the vertical direction with no transformation (an approach which facilitates implementation of the layer cell add and subtract algorithm; i.e., different thickness layers with depth).
- *Wetting and Drying*. The basic model variable for water surface elevation, Z, is relative to a local datum at the top of a fixed horizontal layer. When the rising surface floods dry cells, they are also activated (and deactivated when dried again). Wetting and drying is important to account for tidal flats and wetlands.
- *Time Step*. The variable time step is based on a Torrence limitation. A typical time step for 3-dimensional baroclinic circulation is approximately 15 minutes depending on the horizontal grid size.
- *Array Structure*. The hydrodynamic variables are identified by the surface cell number "n" and the vertical layer "k", i.e., U(n,k), V(n,k), W(n,k), Az(n,k). In addition, constituent and water quality variables are identified with a water quality constituent number, "nc", i.e., C(n,k,nc). This approach reduces array storage and simplifies computational loops.
- *Solution Method*. GLLVHT used an implicit spatial scheme that allows for long time steps. The preconditioned conjugate gradient is used to solve the surface wave equation on each time step. The preconditioned conjugate gradient method uses very little computer storage, processing time, and has a high convergence speed. These properties make computations on a personal computer feasible.
- *Sources, Sinks, and Specific Momentum*. Discharges and intakes (e.g., river inflows, outfalls, marine disposals, thermal intakes, and discharges) are introduced as sources or sinks to the continuity and transport equations. In addition, sub grid scale jet discharge can be accommodated using a source term for the momentum of discharges. Sources and sinks for

inclusion of inflows and outflows in continuity are applied using the flow rate variable Q(n,k), and for constituent transport the constituent flux variable, H(n,k,nc) is used. Constituent fluxes are also computed from water quality routines.

Biogeochemical processes in GEMSS are simulated using a subroutine of the GLLVHT program called Water Quality Carbon Based Model, which is described in detail in Aura Nova Consultants et al. (1998) and Boatman et al. (1999).

Modeling Methods

The model will be calibrated by selecting parameter values for the kinetic rates and constants to closely match the predicted water quality with the observed conditions. After the model is calibrated, then it will be used to evaluate various alternative loading scenarios and to estimate response to natural background conditions. Critical conditions for dissolved oxygen occur in the late summer and are influenced by conditions that occur at least in the preceding several months. The simulation period for parameter estimation (calibration) to the measured conditions will include the entire continuous period of data collection during 2006-2007. Various alternative loading scenarios will be evaluated using simulation periods of no less than several months preceding and through the critical dissolved oxygen condition in late summer.

Natural conditions are characterized by the absence of human impacts on the nutrient loading and dissolved oxygen regime. Modeling natural conditions typically involves creating a natural background model run corresponding to the existing conditions model run, except that human influences have been removed as much as possible. Generally, this means removing all point sources and setting tributaries to natural flows and loads. Accurate estimation of pre-development conditions may be difficult, so reasonable estimation methods will need to be developed. Some of the constituents may be left unchanged between natural and existing if no information is available to estimate pre-development conditions.

The model will be used to predict the dissolved oxygen response to alternative scenarios of nutrient loading. If existing conditions are found to meet the water quality standards for dissolved oxygen, then load allocations will be recommended to match those conditions, and allocations may also be set for future growth in nutrient loading. If load reductions are required to meet standards, one or more alterative scenarios may be developed initially with human impacts reduced. Modeling of allocations will continue interactively with development of an implementation plan until the optimal allocations and implementation approach are found.

To evaluate model performance and the variability of results, sensitivity analysis and error analysis can be used. Model accuracy and precision will be quantified with statistical measures of goodness-of-fit comparing predicted and measured conditions. A sensitivity analysis will also be performed using multiple model runs with the model variables and input parameters that are most significant or most variable adjusted, to evaluate the corresponding change in predicted dissolved oxygen. This sensitivity analysis provides an assessment of which input parameters and variables are most likely to alter model results because of their variability.

Modeling Objectives

Specific quality objectives are not being specified for existing data or for modeling results. However, the following acceptance criteria will be applied:

- *Data Reasonableness*. Data quality of existing data will be evaluated where available. Sources within well-established programs will be acceptable based on the data quality standards of the source (e.g., UW PRISM and King County DNR data). Data will be reviewed for whether the amount of variability is appropriate, based on statistical measures, expected values, and comparison between data sets. Data with too much or too little variability will not be used.
- *Data Completeness*. Data sets will be used that are reasonably complete during the period of interest. Incomplete data sets will be used if they are considered representative of conditions during the period of interest.
- *Data Representativeness*. Data will be used that are representative of the location or time period under consideration. For example, attention will be paid to the variations in meteorological conditions throughout the study area, and to differences in seasonal conditions.
- *Model Calibration and Verification*. The primary measure of calibration and verification success will be by comparing observed versus predicted concentrations in the water column. Bias will be measured by the average residual of paired values (predicted-observed) and precision by the root mean square error of paired values. Numeric targets for precision and bias are not specified but will be generally the same as the standard of practice for similar studies such as the LOTT study of Budd Inlet, the Hood Canal Dissolved Oxygen Program, and the UW PRISM modeling study of Puget Sound. Precision and bias will be considered acceptable if within the range that has been reported for these and other similar modeling studies. In addition to the quantitative statistics for goodness-of-fit, visual comparison of the predicted and observed time series will also be used to assess model performance.

Quality Objectives

Measurement Quality Objectives

Marine data

Table 12 summarizes the measurement quality objectives for both laboratory measurements and *in situ* values for marine data. Individual sampling entities and laboratories are responsible for adherence to objectives. Ecology will be responsible for verifying that all MQOs are met.

Table 12. Measurement quality objectives for *in situ* field values and laboratory analyses conducted by Ecology's Marine Laboratory, Manchester Environmental Laboratory, and the UW Marine Chemistry Laboratory.

Measurement	Precision (Relative Standard Deviation, RSD*)	Bias (% Deviation from True Value)	Lowest Value or Range of Interest
Field			
pH	0.05 SU	N/A	1 to 14 SU
Temperature	0.025 °C	0.05 °C	0.1 °C
Dissolved Oxygen	5%	5%	0.05 mg/L
Specific Conductivity	10%	5%	1 uS/cm
Secchi Depth	0.5 m	N/A	N/A
Pressure	5%	1%	0.1 db
Density	10%	5%	0.1 σ_t
Chlorophyll Fluorescence	10%	5%	0.1 FU
Light Transmission	10%	5%	0.01 %
Laboratory			
Dissolved Oxygen	5%	5%	0.05 mg/L
Marine Nitrate	10%	5%	0.15 µM
Marine Nitrite	10%	5%	0.01 µM
Marine Ammonium	10%	5%	0.05 µM
Marine Orthophosphate	10%	5%	0.02 µM
Marine Silicate	10%	5%	0.21 µM
Chlorophyll a	10%	N/A	0.02 µg/L
Salinity	5%	5%	0.002 PSU
Dissolved Organic Carbon	10%	10%	50 µg/L
Particulate Organic Carbon	10%	10%	10 µg C
Particulate Nitrogen	10%	10%	1 µg N
Total Persulfate Nitrogen	10%	10%	.38 µM
Total Persulfate Phosphorus	10%	5%	.02 µM
Alkalinity	10%	5%	1µM/kg

*RSD is calculated as the ratio of the standard deviation and the mean of several values.

Freshwater data (tributaries and wastewater treatment plants)

Table 13 summarizes the measurement quality objectives for freshwater, including both in situ and laboratory measurements. The laboratory objectives are based on historical performance of Manchester Environmental Laboratory for these parameters (Mathieu, 2006). Data quality in this range will be adequate to meet the study objectives.

Table 13. Measurement quality objectives (precision and lowest value or range of interest) for *in situ* field measurements and laboratory analyses conducted by Ecology's Manchester Environmental Laboratory.

Measurement	Precision RSD	Lowest Value or Range of Interest
Field (with meter)		
Velocity	0.1 ft/s*	0.05 ft/s*
pH	0.05 SU	1 to 14 SU
Temperature	0.025 °C	0.1 °C
Dissolved Oxygen	10%	0.1 mg/L
Specific Conductivity	5%	1 µS/cm
Laboratory		
Dissolved Oxygen	10%	0.1 mg/L
Specific Conductivity	5%	1 µS/cm
Ammonia Nitrogen	10%	10 µg/L
Nitrate + Nitrite Nitrogen	10%	10 µg/L
Total Dissolved Persulfate Nitrogen	10%	25 µg/L
Total Persulfate Nitrogen	10%	25 µg/L
Soluble Reactive Phosphorus (orthophosphate)	10%	3 µg/L
Total Dissolved Phosphorus	10%	1 µg/L
Total Phosphorus	10%	1 µg/L
Total Organic Carbon	10%	1 mg/L
Dissolved Organic Carbon	10%	1 mg/L
Carbonaceous BOD5	25%	2 mg/L
Alkalinity	10%	10 mg/L

* Equipment native units are in the English system; 0.1 ft/s = 0.03048 m/s.

Representativeness

This study is designed to collect data that adequately represents the study area, including spatial and temporal variations. By collecting data monthly over a 16-month time span, a wide variety of conditions will be represented. By sampling combinations of 85 select marine sites with vertical resolution, 15 to 30 freshwater tributary sites, and 20 to 30 wastewater treatment plants, the data will adequately represent the study area, including spatial variation. The model will be calibrated to measured conditions and then extrapolated to critical conditions.

Completeness

The U.S. Environmental Protection Agency (EPA) has defined completeness as a measure of the amount of valid data needed to be obtained from a measurement system to meet study objectives. The completeness objective for this study is to collect 95% of the data to be collected as described in this Quality Assurance (QA) Project Plan. Reasons why all data may not be collected:

1. Dry streambeds (cannot be mitigated).
2. Flooding streambeds. To mitigate this, tributary sampling dates may be adjusted during the month to avoid flooding conditions.
3. Severe weather that precludes seagoing vessels from sailing. To mitigate this, Ecology schedules backup cruise dates when feasible
4. Malfunctioning equipment. To minimize this risk, we utilize auxiliary equipment whenever feasible, ensure equipment is well maintained, and check functionality prior to starting field work.
5. Access problems for freshwater sites. This problem will be mitigated to the extent possible through coordinating with County and Conservation District personnel to use previously established sampling sites.

Comparability

It is important that data collected and analyzed by different groups are comparable. Only Ecology staff will collect freshwater tributary and wastewater treatment plant samples. For marine data collection, in order to ensure comparable data collection techniques, Ecology staff will be present on all PRISM, Barnes, Liberty, and Skookum research voyages. Standard protocols will be followed for all sampling events and laboratory analyses.

For wastewater treatment plant sampling, aliquots of effluent water will be collected by Ecology staff from flow or time-weighted composited effluent samples that each wastewater treatment plant has prepared prior to Ecology's arrival onsite. Ecology staff will evaluate the sampling configuration and inspect the compositing equipment for adequate temperature control and for any indication of contamination.

Each marine data element will be analyzed by a single laboratory and all the freshwater tributary data will be analyzed by one laboratory, which will minimize any laboratory comparability issues.

Sampling Procedures

Marine Water

Sampling in marine waters will follow protocols used in the long-term program conducted for the Puget Sound Marine Assessment Program (PSAMP) as described in Stutes and Bos (2007a). Marine water samples and measurements will be obtained with a CTD (Conductivity, Temperature, and Depth recorder) instrument package, and operated and maintained as described in Newton et al. (2002).

Samples will be processed within established holding times and stored frozen or refrigerated as necessary. Ecology personnel will be present during all phases of sample collection.

Freshwater

Sampling at tributaries will follow the protocols described in Ecology (1993).

Wastewater samples will be obtained by coordinating with wastewater treatment plant personnel. The wastewater treatment plants (WWTPs) collect 24-hr composite samples once per week or more frequently. WWTP auto samplers are refrigerated to keep samples cool. Ecology samples will be split samples from each facility's autosampler. When Ecology personnel are not present at the time samples are collected, WWTP personnel will keep the sample refrigerated until it is picked up within 24 hours of completion of the compositing period and analyzed within the recommended laboratory hold times.

Wastewater samples are collected as grabs or as composite samples[1]. Composite samples are obtained with ISCO or other type of portable automatic samplers. The samplers can be programmed to collect either time-proportional or flow-weighted samples. In the time-proportioned mode, the sampler collects sub-samples every 30 minutes for 24 hours, depositing the sub-samples into a single collection container.

Flow-weighted samples are delivered as sub-samples to 24 bottles in the sampler. After the 24-hour collection period, continuous wastewater plant flow data are obtained and the sub-samples are poured into a single collection container, the amount from each sub-sample proportioned by that hour's flow.

Most samplers utilize a peristaltic pump to deliver set volumes to the collection container. The silastic tubing of the pump and Teflon™-lined collection tubing are the only sampler components in contact with the sample. The equipment components are maintained by each plant on a regular schedule.

[1] Grab samples may be substituted for those facilities that do not discharge continuously.

Ecology personnel will fill sample collection bottles and filter as necessary, on site. Samples will be kept on ice until delivered to Manchester Environmental Laboratory.

Measurement Procedures

Marine Water

Field measurements

A CTD instrument package will be used to measure temperature, pH, dissolved oxygen, specific conductivity, pressure, density, *in vivo* chlorophyll fluorescence, and light transmission. A Secchi disk will be used to measure light attenuation in the photosynthetically active region of the water column (euphotic zone). Sampling and analytical methods are described in Newton et al. (2002) and Stutes & Bos (2007a).

Primary productivity measurements

The standard ^{14}C uptake experimental protocol will be used (Strickland and Parsons, 1972). For the experiments conducted in this study: (1) radioactive ^{14}C in the form of aqueous sodium bicarbonate will be added to the seawater samples and (2) then incubated in closed containers for 24 hours at their respective light intensities (simulated by screens in seawater-plumbed deck incubators). During photosynthesis, inorganic carbon, including any from the radioactively labeled bicarbonate, is taken up by phytoplankton and converted to cell biomass. At the end of the incubation, the amount of ^{14}C that is incorporated into phytoplankton biomass will be determined by filtration of the sample and measured via liquid scintillation counting.

This procedure yields a measure of ambient primary production rates at each depth sampled, which can be integrated over the euphotic zone. In addition, Ecology will be testing for nutrient limitation by adding excess nutrients (ammonium and phosphate) to a duplicate set of experimental samples to determine if there is a change in the production rate due to the increased nutrient concentrations.

Primary production (P), the phytoplankton population growth rate, is the product of the phytoplankton population biomass (B) and the specific growth rate (μ) of the individuals in that population (i.e., normalized to biomass):

$$P = B * \mu$$

Chlorophyll *a* will be measured and integrated through the euphotic zone (mg chl *a* m^{-2}) as an estimate of the water column phytoplankton biomass (B) and integrated primary production (P) via ^{14}C uptake (mg C m^{-2} d^{-1}). Thus, with measurements of both P and B, an approximation of specific growth rate (P/B) can be made.

Estimates of the specific growth rate will be used as a check on the calibration of the phytoplankton kinetic parameters for the biogeochemical model. Productivity measurements will also be useful for analysis of trends comparing all available measurements at various locations over time.

Laboratory measurements

Laboratory measurement methods for marine data are listed in Table 14.

Table 14. Measurement methods and reporting limits for marine data.

Analyte	Lab	Analytical Method	Reporting Limit
Dissolved Oxygen	ML	Carpenter, 1966	0.01 mg/L
Marine Nitrate	MCL	Armstrong et al., 1967	0.15 µM
Marine Nitrite	MCL	Armstrong et al., 1967	0.01 µM
Marine Ammonium	MCL	Slawyk and MacIsaac, 1972	0.05 µM
Marine Orthophosphate	MCL	Bernhardt and Wilhelms, 1967	0.02 µM
Marine Silicate	MCL	Armstrong et al., 1967	0.21 µM
Chlorophyll a	ML	EPA, 1977	0.01 mg/L
Salinity	MCL	Grasshoff et al., 1999	0.01 PSU
Dissolved Organic Carbon	MCL	Grasshoff et al., 1999	50 µg/L
Particulate Organic Carbon	MCL	Grasshoff et al., 1999	10 µg
Particulate Organic Nitrogen	MCL	Grasshoff et al., 1999	1 µg
Total Persulfate Nitrogen	MCL	Valderrama, 1981	.38 µM
Total Persulfate Phosphorus	MCL	Valderrama, 1981	.02 µM
Alkalinity	MEL	Strickland and Parsons, 1968	1 uM/kg
Primary Productivity	ML	Strickland and Parsons, 1972	estimate

ML - Ecology's Marine Laboratory.
MCL - UW's Marine Chemistry Laboratory.
MEL - Ecology's Manchester Environmental Laboratory.

Analytical protocols for Manchester Environmental Laboratory are described in MEL (2005), including holding times and sample preservation requirements. Analytical protocols for UW's Marine Chemistry Laboratory are described in JGOFS (1996), Grasshoff et al. (1999,) and Strickland and Parsons (1968). Analytical protocols for Ecology's Marine Laboratory are described in Stutes and Bos (2007b, 2007c), EPA method 445.0 (1997), and Grasshoff et al. (1999).

Freshwater

Field measurements

For tributaries, temperature, conductivity, dissolved oxygen, and pH will be measured with a pre and post-calibrated Hydrolab® multi-probe. Protocols for Hydrolab use are described in Ecology (1993). Steam-flow will be measured using Marsh McBirney digital flow meters, following the protocols in Ecology (1993).

In situ measurements of wastewater discharges will be made for the same parameters as for rivers and streams, using a Hydrolab dissolved meter (model 55) for temperature and dissolved oxygen and an Orion portable pH meter. Flow values will be obtained from the facilities.

The precision and reporting limit/range objectives from Table 13 will be met by these instruments.

Laboratory measurements

Laboratory measurement methods for freshwater data are listed in Table 15.

Table 15. Measurement methods and reporting limits for freshwater data.

Analyte	Analytical Method	Reporting Limit
Dissolved oxygen	Winkler Titration	0.1 mg/L
Specific Conductance	2510B	1 µmhos/cm
Ammonia Nitrogen	SM 4500NH_3H	10 µg/L
Nitrate + Nitrite Nitrogen	SM 4500NO_3I	10 µg/L
Total Dissolved Persulfate N	SM 4500NO_3B	25 µg/L
Total Persulfate Nitrogen	SM 4500NO_3B	25 µg/L
Soluble Reactive Phosphorus (orthophosphate)	SM 4500P G	3 µg/L
Total Dissolved Phosphorus	EPA 200.8	1 µg/L
Total Phosphorus	EPA 200.8	1 µg/L
Total Organic Carbon	EPA 415.1	1 mg/L
Dissolved Organic Carbon	EPA 415.1	1 mg/L
Carbonaceous BOD5	405.1/521 OB	2 mg/L
Alkalinity	SM 2320	10 mg/L

All measurements will be made by Manchester Environmental Laboratory except dissolved oxygen. Analytical protocols for Manchester Environmental Laboratory are described in MEL (2005), including holding times and preservation requirements.

Dissolved oxygen will be measured with the Azide-modified Winkler Titration method in the Ecology Operations Center for approximately 5% of dissolved oxygen samples, to verify the field meter (Hydrolab®) results. The protocols for use of this method are described in Ecology (1993).

Quality Control

Total variation (field plus lab) will be assessed by collecting duplicate samples for all parameters at 5% of sites. These duplicates will be used to assess whether the data quality objectives for precision were met. If the objectives were not met, the data will be qualified. In addition, Ecology's Manchester Environmental Laboratory, UW's Marine Chemistry Laboratory, and Ecology's Marine Laboratory all routinely analyze duplicate sample analyses in the laboratory for quality control purposes. The difference between field and laboratory variability is a measure of the sample field variability.

Manchester Laboratory's full quality control procedures are documented in the Lab Users Manual (MEL, 2005). The laboratory will be able to assess laboratory bias in sample results. Bias from field procedures will not be able to be assessed directly. However, bias will be minimized by strictly following standard protocols.

Quality control procedures for the UW's Marine Chemistry Laboratory are documented and followed per standard seawater analysis protocols. The laboratory will be able to assess laboratory bias by using standards, replicates, and laboratory splits to analyze error and method detection limits during analyses. Bias will be minimized by strictly following standard methods. The laboratory is accredited or soon to be accredited in 2007 for the methods listed previously in this QA Project Plan by Ecology's Laboratory Accreditation Section.

Full quality control procedures for Ecology's Marine Laboratory are documented in Stutes and Bos (2007b, 2007c). Laboratory bias is assessed by running blanks and standards during all analytical procedures. Bias will be minimized by strictly following standard methods. The laboratory is accredited for the methods listed previously in this QA Project Plan by Ecology's Laboratory Accreditation Section.

Data Management Procedures

Marine Data

Field data will be initially recorded in field notebooks and Excel spreadsheets for conducting the QA analysis, and then entered into an Access database. Laboratory data will then be loaded into Ecology's Environmental Information Management (EIM) System.

Freshwater Data (Tributaries and Wastewater Treatment Plants)

Field data will be initially recorded in field notebooks, and then entered into Excel spreadsheets for conducting the QA analysis. Data will then be loaded into Ecology's EIM system.

Audits and Reports

The project manager and project team have worked closely with the agency QA officer in the design of this project. Good communication, strict adherence to standard protocols, and documentation of any deviation from standard protocols will be essential.

A quality assurance assessment will be conducted prior to using the data for analysis. The QA assessment will be included in the final report for this project.

Data Verification and Validation

Manchester Environmental Laboratory, UW Marine Chemistry Laboratory, and Ecology's Marine Laboratory will each provide verified data packages for all data analyzed.

To assure accurate entry of data into EIM, 10% of all values will be checked against the source data. If errors are found, an additional 10% of values will be checked and the process will continue in this way until no errors are found or all values have been verified.

Data Analysis and Use

Data quality will be evaluated against the objectives set in this document for precision. The data will also be evaluated for obvious errors, such as incorrect units. The sum of dissolved constituents will be compared to the value found for the total constituent (e.g., the sum of nitrate, nitrite, and ammonia should generally be less than the value for total nitrogen; orthophosphorus should be less than total phosphorus, taking into account expected statistical variation).

The data will also be evaluated against the objectives set for representativeness (were we able to capture all relevant spatial and temporal conditions) and completeness (did we collect at least 95% of the data set out to be collected).

The usability of the data will be confirmed by using it in the model and showing relationships between dissolved oxygen and nutrients.

Organization

Staff participating in the study are assigned to several units within the Environmental Assessment Program and Water Quality Program, arranged as follows:

Environmental Assessment Program
- Watershed Ecology Section (WES)
  - Water Quality Studies Unit (WQSU)
- Environmental Monitoring and Trends Section (EMTS)
  - Coastal and Estuarine Assessment Unit (CEAU)

Water Quality Program
- Watershed Management Section
  - Watershed Planning Unit (WPU)

- *Mindy Roberts, WQSU.* Project Manager for overall project management and scientific communications for project. Carol Maloy and Karol Erickson will serve as backup Co-Project Managers when Mindy is unavailable.
- *Carol Maloy, CEAU Supervisor.* Budget Lead for the data collection phase of the project (through October 2007). Reviews and approves QA Project Plan, staffing plan, final reports, and budget.
- *Karol Erickson, WQSU Supervisor.* Budget Lead for the modeling phase of the project (beyond October 2007). Reviews and approves QA Project Plan, staffing plan, final reports, and budget.
- *Skip Albertson, CEAU.* Modeler. Responsible for hydrodynamic modeling.
- *Greg Pelletier, WQSU.* Modeler. Responsible for water quality modeling.
- *Julia Bos, CEAU.* Project Lead for marine data collection, marine laboratory activities, and data management aspects of the project. Responsible for entering marine data into EIM. Chief scientist for marine cruises on R/V Barnes.
- *Ryan McEliece, CEAU.* Field Lead. Responsible for collecting tributary and wastewater discharge data and entering freshwater data into EIM. Leads marine cruises on R/V Liberty and R/V Skookum.
- *Bob Cusimano, EMTS Manager.* Reviews and approves QA Project Plan, staffing plan, final reports, and budget.
- *Will Kendra, WES Manager.* Reviews and approves QA Project Plan, staffing plan, final reports, and budget.
- *Andrew Kolosseus, WPU.* Overall Study Lead. Acts as point of contact between Ecology technical study staff and interested parties. Coordinates information exchange, technical advisory group formation, and organizes meetings. Supports, reviews, and comments on Quality Assurance (QA) Project Plan and technical report.

Project Deliverables, Schedules, and Laboratory Budget

Figure 5 presents the overall project schedule, which is contingent on securing funding for tasks beyond 2007. Current funding includes the QA Project Plan development, data report, and preliminary hydrodynamic modeling report, described below. Table 16 includes internal Ecology and external review dates and availability for these products.

The South Puget Sound Data Report will include:

- A summary of all data collected through October 2007 (including a description of the types of data, dates, and parameters).
- The data quality assessment, which will explain any problems found with data quality and how they were handled.
- The final data sets for data collected through October 2007, accessible through the EIM system.

The South Puget Sound Hydrodynamic Modeling Report will include:

- Findings from simulated tracer studies, showing spatial extent of wastewater treatment plant discharge influences.
- Analysis of collected data including contour plots, profiles, and timeseries graphs of the water quality data.
- Description of circulation patterns of South Puget Sound.

Water quality model results will be documented in additional reports, but the content and schedule are contingent on supplemental funding. Figure 5 includes a preliminary schedule, subject to change, and the draft report will be in development and review in 2009 and 2010.

Months	Cal Yr	Bi	FY	Qtr	Data	Analyses	Model	Reporting
Jul - Sep	2006		FY07	1	Primary Data Collection (from existing QAPP)			
Oct - Dec				2				
Jan - Mar	2007			3				
Apr - Jun				4			Model Setup	
Jul - Sep			FY08	1				
Oct - Dec				2	Supplemental Data Collection (to be continued and scoped, possibly under enhanced ambient monitoring program)	QA, Compilation	Hydrodynamic Model Calibration	
Jan - Mar	2008			3				Data Report
Apr - Jun				4		trends, plots, model input		
Jul - Sep			FY09	1			WQ Model Calibration	Hydrodynamic Model Report
Oct - Dec				2				
Jan - Mar	2009			3			Scenarios	
Apr - Jun				4				Draft Water Quality Model Report
Jul - Sep			FY10	1				
Oct - Dec				2				Report Review/ Final Report
Jan - Mar	2010			3				
Apr - Jun				4				
Jul - Sep			FY11	1				
Oct - Dec				2				
Jan - Mar	2011			3				
Apr - Jun				4				

Figure 5. Project schedule.

Table 16. Report review and data availability.

Quality Assurance Project Plan	
Report Authors	Skip Albertson, Julia Bos, Karol Erickson, Carol Maloy, Greg Pelletier, Mindy Roberts
Draft Report	11/30/06
Final Report	3/31/07
South Puget Sound Data Report	
Report Authors	Julia Bos, Ryan McEliece, Mindy Roberts
Report—Supervisor Draft Due	2/28/08
Report—Client/Peer Draft Due	3/31/08
Report—Final Due	6/30/08
Environmental Information Management (EIM) System Data Set	
EIM Data Engineer - freshwater	Ryan McEliece
EIM User Study ID - freshwater	MROB0004
EIM Study Name - freshwater	South Puget Sound Dissolved Oxygen Study, Phase 2
EIM Data Engineer - marine	Julia Bos
EIM User Study ID - marine	SPSMEM_M
EIM Study Name marine	South Puget Sound Marine Environmental Modeling Project (Dissolved Oxygen Study) for Marine Water
EIM Completion Due	6/30/08
Hydrodynamic Modeling Report	
Report Author Lead	Skip Albertson
Report - Supervisor Draft Due	2/28/08
Report - Client/Peer Draft Due	3/31/08
Report - Final Due (Original)	6/30/08

With full project funding, a final Modeling and Analysis Report will be published, summarizing the:

- Effect of current nitrogen loading on South Puget Sound dissolved oxygen levels, compared to natural conditions.
- Effect of future nitrogen loading on South Puget Sound DO levels, assuming continued population growth and increasing nitrogen loads.
- Amount nitrogen loading would need to be reduced to meet the state water quality standard, if reductions are necessary.
- Geographic areas and seasonal time period most susceptible to reduced dissolved oxygen levels due to nitrogen loading.

Table 17. Manchester Laboratory analytical costs.

Program	Parameters	Unit cost	Total Samples	Total Cost
July 2006 - June 2007				$112,586
(with 5% QA samples)				*$118,215*
Marine Monitoring	Alkalinity	$16.00	821	*$13,136*
Freshwater Monitoring				*$99,450*
WWTP samples	NO23N, NH4N, OP	$38.00	216	$8,208
	TN, DTN, TP, DTP	$82.00	216	$17,712
	TOC	$30.00	216	$6,480
	DOC	$32.00	216	$6,912
	BOD5	$53.00	216	$11,448
	Alkalinity	$16.00	216	$3,456
	Conductivity	$8.00	216	$1,728
Tributary samples	NO23N, NH4N, OP	$38.00	180	$6,840
	TN, DTN, TP, DTP	$82.00	180	$14,760
	TOC	$30.00	180	$5,400
	DOC	$32.00	180	$5,760
	Alkalinity	$16.00	180	$2,880
	Conductivity	$8.00	180	$1,440
Ambient Supplemental	TN/TP	$41.00	54	$2,214
	TOC	$30.00	54	$1,620
	DOC	$32.00	54	$1,728
	Alkalinity	$16.00	54	$864
July 2007 - June 2008				$64,040
(with 5% QA samples)				*$67,242*
Marine Monitoring	Alkalinity	$16.00	396	*$6,336*
Freshwater Monitoring				*$57,704*
WWTP samples	NO23N, NH4N, OP	$38.00	120	$4,560
	TN, DTN, TP, DTP	$82.00	120	$9,840
	TOC	$30.00	120	$3,600
	DOC	$32.00	120	$3,840
	BOD5	$53.00	120	$6,360
	Alkalinity	$16.00	120	$1,920
	Conductivity	$8.00	120	$960
Tributary samples	NO23N, NH4N, OP	$38.00	120	$4,560
	TN, DTN, TP, DTP	$82.00	120	$9,840
	TOC	$30.00	120	$3,600
	DOC	$32.00	120	$3,840
	Alkalinity	$16.00	120	$1,920
	Conductivity	$8.00	120	$960
Ambient Supplemental	TN/TP	$41.00	16	$656
	TOC	$30.00	16	$480
	DOC	$32.00	16	$512
	Alkalinity	$16.00	16	$256
Project Total				**$176,626**
(with 5% QA samples)				***$185,457***

References

APHA, AWWA and WEF, 1998. Standard Methods for the Examination of Water and Wastewater 20th Edition. American Public Health Association, Washington, D.C.

Albertson, S. L, K. Erickson, J. A. Newton, G. Pelletier, R. A. Reynolds, and M. L. Roberts, 2002. South Puget Sound Water Quality Study, Phase 1. Washington State Department of Ecology, Olympia, WA. Publication No. 02-03-021. www.ecy.wa.gov/biblio/0203021.html

Armstrong, F. A. J., C. R. Stearns, and J. D. H. Strickland, 1967. The measurement of upwelling and subsequent biological processes by means of the Technicon AutoAnalyzer and associated equipment. *Deep-Sea Res.* 14(3): 381-389.

Aura Nova Consultants, Brown and Caldwell, Inc., EvansHamilton, Inc., J. E. Edinger and Associates, Washington State Department of Ecology, and Dr. Alan Devol, University of Washington Department of Oceanography, 1998. Budd Inlet Scientific Study Final Report. Prepared for the Lacey, Olympia, Tumwater, Thurston County Partnership (LOTT), Olympia, WA. 2 volumes. August.

Bernhardt, H. and A. Wilhelms, 1967. The continuous determination of low level iron, soluble phosphate and total phosphate with the AutoAnalyzer. Technicon Symp., 1967, Vol. I, p. 386.

Boatman, C. D. and E. A. Buchak, 1987. Application of an ecosystem/water quality model as a tool for managing estuarine water quality. In: Proc. Fifth Sym. on Coastal Ocean Management. ASCE, Vol. 3, Seattle, WA. pp. 3932-3945.

Boatman, C. and J. E. Edinger Associates, Inc., 1999. LOTT NPDES Permit Modifications Modeling Revised Interim Report. Prepared for the Lacey, Olympia, Tumwater, Thurston County Partnership (LOTT), Olympia, WA. Prepared by Aura Nova Consultants and J. E. Edinger and Associates.

Carpenter, J. H., 1966. *Limnol. Oceanogr.* 11, 264.

Carroll, J. and N. Mathieu, 2006. Quality Assurance Project Plan: South Fork Palouse River Dissolved Oxygen and pH Total Maximum Daily Load Study. Washington State Department of Ecology, Olympia, WA. Publication No. 06-03-112. www.ecy.wa.gov/biblio/0603112.html

Collias, E. E., N. McGary, and C. A. Barnes, 1974. Atlas of Physical and Chemical Properties of Puget Sound and Approaches. Washington Sea Grant 74-1, Seattle, WA.

Ecology, 1993. Field Sampling and Measurement Protocols for the Watershed Assessments Section. Washington State Department of Ecology, Olympia, WA. Publication No. 93e04. www.ecy.wa.gov/biblio/93e04.html

Ecology, 2005. 2004 Water Quality Assessment (Final) – Category 5 Listings. Washington State Department of Ecology, Olympia, WA. www.ecy.wa.gov/programs/wq/303d/2002/2004_documents/list_by_categorycat5.html

Edinger, J. E. and E. M. Buchak, 1980. Numerical Hydrodynamics of Estuaries in Estuarine and Wetland Processes with Emphasis on Modeling (P. Hamilton and K. B. Macdonald, eds.). Plenum Press, New York, NY. pp. 115-146.

Edinger, J. E. and E. M. Buchak, 1985. Numerical Waterbody Dynamics and Small Computers. Proceedings of ASCE 1985 Hydraulic Division Specialty Conference on Hydraulics and Hydrology in the Small Computer Age. American Society of Civil Engineers, Lake Buena Vista, FL. Aug. 1316.

Edinger, J. E., E. M. Buchak, and M. D. McGurk, 1994. Analyzing Larval Distributions Using Hydrodynamic and Transport Modelling. Estuarine and Coastal Modeling III. American Society of Civil Engineers, New York, NY.

Edinger, J. E. and E. M. Buchak, 1995. Numerical Intermediate and Far Field Dilution Modeling. *Journal Water, Air and Soil Pollution* 83: 147-160. Kluwer Academic Publishers, The Netherlands.

Edinger J. E., J. Wu and E. M. Buchak, 1997. Hydrodynamic and Hydrothermal Analyses of the Oncethrough Cooling Water System at Hudson Generating Station. Prepared for Public Service Electric and Gas (PSE&G). Prepared by J. E. Edinger Associates, Inc., June 1997.

EPA, 1997. Method 445.0 rev. 1.2. *In Vitro* Determination of Chlorophyll *a* and Pheophytin *a* in Marine and Freshwater Algae by Fluorescence. U.S. Environmental Protection Agency.

Gordon, Jr., D.C., 1969. Examination of methods of particulate organic carbon analysis. *Deep-Sea Res*., 16: 661-665.

Grasshoff, K., M. Ehrhardt, K. Kremling. 1999. Methods of seawater analysis. 3rd. ref. ed. Verlag Chemie GmbH, Weinheim. 600 pp.

JGOFS, 1996. Knap, A., A. Michaels, A. Close, H. Ducklow, and A. Dickson (eds.). Protocols for the Joint Global Ocean Flux Study (JGOFS) Core Measurements. JGOFS Report Nr.19, vi+170 pp. Reprint of the IOC Manuals and Guides No. 29, UNESCO 1994.

Kerambrun, P. and Szekielda, K.H., 1969. Note technique. *Tethys*, 1: 581-584.

Lombard, S. and C. Kirchmer, 2004. Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies. Washington State Department of Ecology, Olympia, WA. Publication No. 04-03-030. www.ecy.wa.gov/biblio/0403030.html

Mathieu, N., 2006. Memorandum: Summary of Replicate Precision for Twelve Total Maximum Daily Load (TMDL) Studies and Recommendations for Precision Measurement Quality

Objectives for Bacteria and Conventional Water Quality Parameters. Environmental Assessment Program, Washington State Department of Ecology, Olympia, WA.

MEL, 2005. Manchester Environmental Laboratory Lab User's Manual, Eighth Edition. Washington State Department of Ecology, Manchester, WA.

Metcalf and Eddy, 2003. Wastewater Engineering, Treatment and Reuse, Metcalf and Eddy, International Ed., McGrawHill.

Newton, J. A., M. Edie, and J. Summers, 1998. Primary productivity in Budd Inlet: seasonal patterns of variation and controlling factors. In: Puget Sound Research '98 Proceedings. Puget Sound Action Team, Olympia, WA. pp.132-151.

Newton, J. A., S. L. Albertson, and A. L. Thomson, 1997. Washington State Marine Water Quality in 1994 and 1995. Washington State Department of Ecology, Olympia, WA. Publication No. 97-316. www.ecy.wa.gov/biblio/97316.html

Newton, J. A., S.L. Albertson, K. Van Voorhis, C. Maloy, and E. Siegel, 2002. Washington State Marine Water Quality in 1998 through 2000. Washington State Department of Ecology, Olympia, WA. Publication No. 02-03-056. www.ecy.wa.gov/biblio/0203056.html

Olympian, The, 2001. Red Tide Closes Shellfish Beaches. Olympia, WA, July 31, pp. B1-B2.

Pelletier, G. J., S. C. Chapra, and H. Tao, 2006. QUAL2Kw - A framework for modeling water quality in streams and rivers using a genetic algorithm for calibration. *Environmental Modelling and Software* 21:419-425.

Pelletier, G. and L. Sullivan, 2006. Quality Assurance Project Plan: Old Stillaguamish River Multi-Parameter Total Maximum Daily Load Study. Washington State Department of Ecology, Olympia, WA. Publication #06–03–108. www.ecy.wa.gov/biblio/0603108.html

Roberts , M., B. Zalewsky, T. Swanson, L. Sullivan, K. Sinclair, and M. LeMoine, 2004. Quality Assurance Project Plan: Deschutes River, Capitol Lake, and Budd Inlet Temperature, Fecal Coliform Bacteria, Dissolved Oxygen, pH, and Fine Sediment Total Maximum Daily Load Study. Washington State Department of Ecology, Olympia, WA. Publication No. 04-03-103. www.ecy.wa.gov/biblio/0403103.html

Sharp, J. H., 1974. Improved analysis for "particulate" organic carbon and nitrogen from seawater. *Limnol. Oceanogr*., 19:984-989.

Slawyk, G. and J. J. Macisaac, 1972. The specificity of an automated phenolhypochlorite ammonium method in a region of coastal upwelling. *Deep-Sea Res*. 19: 521-524.

Strickland, J. D. H. and T. R. Parsons, 1968. A Practical Handbook of Seawater Analysis. Fisheries Research Board of Canada, Bulletin 167, 71–75.

Stutes, A. and J. Bos, 2007a (in Draft). Standard Operating Procedure for Seawater Sampling, Washington State Department of Ecology, Olympia, WA.

Stutes, A. and J. Bos, 2007b (in Draft). Standard Operating Procedure for Chlorophyll *a* Analysis, Washington State Department of Ecology, Olympia, WA.

Stutes, A. and J. Bos, 2007c (in Draft). Standard Operating Procedure for Dissolved Oxygen Analysis, Washington State Department of Ecology, Olympia, WA.

Sugimura, Y. and Y. Suzuki, 1988. A high-temperature catalytic oxidation method for the determination of non-volatile dissolved organic carbon in seawater by direct injection of a liquid sample. *Mar. Chem.*, 24:105-131.

UNESCO, 1994. Protocols for the Joint Global Ocean Flux studies (JGOFS) Core Measurements IOC Manual and Guides 29. (reprint*)* June 1996.

URS, 1986. Comprehensive Circulation and Water Quality Study of Budd Inlet. Prepared for the Washington State Department of Ecology, Olympia, WA. URS Corporation. July 31, 1986.

Valderrama, 1981. The simultaneous analysis of total nitrogen and total phosphorus on natural waters. *Mar. Chem*. (10), 109-122.

Van Hall et al., 1963. Rapid combustion method for the determination of organic substances in aqueous solution. *Anal.Chem*. 35:315-319.

Washington Office of Financial Management, 2003. Washington State Office of Financial Management. www.env.gov.bc.ca/spd/gbpsei/population

Appendices

Appendix A. Station Locations, Types of Samples, and Depths Sampled for R/V Barnes and Skookum Surveys

Table A-1. Station locations, types of samples, and depths sampled for R/V Barnes and Skookum surveys.

Station ID	Description	Longitude (Decimal Degrees)	Latitude (Decimal Degrees)	Depth (m MLLW)	Station Type for Normal Resolution Barnes Cruise	Station Type for High Resolution Barnes Cruise in September	Station Type for Skookum Cruise	Depths Sampled if Nutrient Profiles are Sampled (m)
1	Henderson Inlet	-122.8300	47.1300	-1.31	CTD	CTD & limited suite	CTD	0, NB
2	Henderson Inlet	-122.8333	47.1517	-15.23	CTD & full suite	CTD & full suite	CTD	0, 5, 10, NB
3	Dana Passage	-122.8700	47.1617	-36.6	CTD & limited suite	CTD & limited suite	CTD	0, 5, 10, 30, NB
4	Budd Inlet - Turning Basin	-122.9067	47.0522	-9.53	CTD & full suite	CTD & full suite	--	0, NB
5	Budd Inlet - Spar Buoy 10	-122.9078	47.0597	-0.91	CTD	CTD	CTD	
6	Budd Inlet - Light Buoy 6	-122.9138	47.0720	-8.41	CTD	CTD	--	
7	Budd Inlet - Olympia Shoal	-122.9163	47.0830	-7.2	CTD	CTD	--	0, NB
8	Budd Inlet	-122.9167	47.1020	-11.3	CTD & full suite	CTD & full suite	CTD	0, 5, NB
9	Budd Inlet	-122.9083	47.1135	-11.63	CTD	CTD	--	0, 5, NB
11	Budd Inlet	-122.9145	47.1297	-9.87	CTD	CTD	--	0, NB
13	Budd Inlet	-122.9103	47.1447	-18.65	CTD	CTD	--	0, 5, 10, NB
14	Budd Inlet	-122.9083	47.1508	-47.86	CTD	CTD & limited suite	CTD	0, 5, 10, 30, NB
15	Cooper Pt., SW	-122.9383	47.1367	-14.34	CTD	CTD & limited suite	CTD	0, 5, NB
16	Eld Inlet - Flapjack Pt (nr UW366)	-122.9483	47.1067	-14	CTD	CTD	--	0, 5, NB
17	Eld Inlet - S. Flapjack Point	-122.9750	47.0967	-6.09	CTD & full suite	CTD & full suite	CTD	0, NB
18	E. Hope Isl.	-122.9167	47.1767	-10.2	CTD	CTD	--	0, 5, NB
19	Squaxin Passage	-122.9300	47.1800	-11.48	CTD	CTD & limited suite	CTD	0, 5, NB
21	Windy Pt., E.	-122.9533	47.1733	-35.17	CTD	CTD	--	0, 5, 10, 30, NB
22	Totten Inlet - Windy Point	-122.9633	47.1650	-14.99	CTD	CTD	--	
23	Windy Pt., SW.	-122.9867	47.1567	-8.32	CTD & full suite	CTD & full suite	CTD	0, NB
24	Skookum Inlet, Entrance	-123.0300	47.1533	-1.51	CTD	CTD & limited suite	CTD	0, NB
25	New Kamilche	-123.0133	47.1400	-17.21	CTD	CTD	--	0, 5, 10, NB
26	Burns Point	-123.0267	47.1167	-4.62	CTD	CTD & limited suite	CTD	0, NB
27	N. Hope Isl.	-122.9333	47.1933	-8.54	CTD	CTD	--	0, NB
28	Arcadia	-122.9250	47.2033	-12.41	CTD	CTD	--	0, 5, NB
29	Cannery Pt.	-122.9633	47.2033	-4.69	CTD	CTD & limited suite	CTD	0, NB
30	Skookum Pt.	-123.0000	47.2050	-7	CTD	CTD	--	
31	Church Pt., W.	-123.0267	47.2067	-12.21	CTD	CTD & limited suite	CTD	0, 5, NB
32	Miller Point	-123.0567	47.2033	-6.43	CTD	CTD	--	
33	Eagle Pt., W.	-123.0633	47.2033		CTD	CTD	--	

Station ID	Description	Longitude (Decimal Degrees)	Latitude (Decimal Degrees)	Depth (m MLLW)	Station Type for Normal Resolution Barnes Cruise	Station Type for High Resolution Barnes Cruise in September	Station Type for Skookum Cruise	Depths Sampled if Nutrient Profiles are Sampled (m)
34	Shelton	-123.0833	47.2083	-0.69	CTD	CTD	CTD	
35	Oakland Bay (nr OAK004)	-123.0733	47.2117	-21.16	CTD & full suite	CTD & full suite	--	0, 5, 10, NB
36	Chapman Cove, NW	-123.0500	47.2350	-3.13	CTD	CTD & limited suite	CTD	0, NB
37	Salom Point	-122.9317	47.2267	-16.82	CTD	CTD & limited suite	CTD	0, 5, 10, NB
38		-122.9117	47.2150	-10.31	CTD	CTD	--	
39	Peale Passage	-122.8917	47.1967	-10.49	CTD	CTD & limited suite	CTD	0, 5, NB
40		-122.9283	47.2383	-15.79	CTD	CTD	--	
41	Graham Pt. (near PCK001 (Eco))	-122.9233	47.2500	-18.59	CTD	CTD & limited suite	CTD	0, 5, 10, NB
42	Grant (Walker's Landing)	-122.9217	47.2783	-17.59	CTD	CTD & limited suite	CTD	0, 5, 10, NB
43		-122.8867	47.2933	-14.84	CTD	CTD	--	
44	Dougall Point	-122.8500	47.3067	-33.15	CTD & full suite	CTD & full suite	CTD	0, 5, 10, NB
45	Allyn	-122.8217	47.3833	-3.85	CTD & full suite	CTD & full suite	CTD	0, NB
46		-122.8150	47.3683	-3.57	CTD	CTD	--	
47	Rocky Point	-122.8100	47.3533	-18.45	CTD	CTD & limited suite	CTD	0, 5, 10, NB
48		-122.8133	47.3317	-21.91	CTD	CTD	--	
49	Dutchers Cove	-122.8150	47.3100	-25.86	CTD	CTD & limited suite	CTD	0, 5, 10, NB
50		-122.8283	47.2933	-41.49	CTD	CTD	--	
51		-122.8400	47.2750	-46.99	CTD	CTD	--	
52	Herron Island (PRISM 37)	-122.8533	47.2583	-56.09	CTD & full suite	CTD & full suite	CTD & full suite	0, 5, 10, 30, 50, NB
53		-122.8417	47.2433	-62.97	CTD	CTD	+QA	0, 5, 10, 30, 50, NB
54	Whiteman Cove	-122.8283	47.2283	-77.37	CTD	CTD & limited suite	--	0, 5, 10, 30, 50, NB
55		-122.8167	47.2117	-49.86	CTD	CTD	CTD	
56	N. Johnson Point	-122.8067	47.1967	-82.13	CTD	CTD & limited suite	--	0, 5, 10, 30, 50, NB
57		-122.7983	47.1817	-92.1	CTD	CTD	CTD	
58	Devils Head (PRISM 36)	-122.7883	47.1667	-82.99	CTD & full suite	CTD & full suite	--	0, 5, 10, 30, 50, NB
59		-122.7717	47.1533	-68.93	CTD	CTD	CTD & full suite	0, 5, 10, 30, 50, NB
60	Drayton Passage	-122.7333	47.1750	-57.29	CTD	CTD & limited suite	--	0, 5, 10, 30, 50, NB
61		-122.7550	47.1450	-66.5	CTD	CTD & limited suite	CTD	0, 5, 10, 30, 50, NB
62		-122.7400	47.1350	-50.04	CTD	CTD	CTD	
63		-122.7233	47.1217	-47.54	CTD	CTD	--	
64	Nisqually Reach	-122.7067	47.1200	-58.17	CTD & full suite	CTD & full suite	--	0, 5, 10, 30, 50, NB

Station ID	Description	Longitude (Decimal Degrees)	Latitude (Decimal Degrees)	Depth (m MLLW)	Station Type for Normal Resolution Barnes Cruise	Station Type for High Resolution Barnes Cruise in September	Station Type for Skookum Cruise	Depths Sampled if Nutrient Profiles are Sampled (m)
65		-122.6550	47.1500	-124.14	CTD	CTD & limited suite	CTD	0, 5, 10, 30, 50, 100, NB
66	Gordon Point (GOR001; PR 35)	-122.6333	47.1833	-162.53	CTD & full suite	CTD & full suite	CTD	0, 5, 10, 30, 50, 100, NB
67	Toliva Shoal	-122.5983	47.1950	-125.78	CTD	CTD	CTD & full suite	0, 5, 10, 30, 50, 100, NB
68	Gibson Point, SW of	-122.6217	47.2117	-158.42	CTD	CTD	--	0, 5, 10, 30, 50, 100, NB
69	Still Harbor II	-122.6533	47.2350	-115.77	CTD	CTD & limited suite	--	0, 5, 10, 30, 50, 100, NB
70	South Head II	-122.6967	47.2600	-85.29	CTD	CTD	CTD	
71	Green Point (PRISM 38)	-122.7067	47.2833	-97.36	CTD & full suite	CTD & full suite	--	0, 5, 10, 30, 50, NB
72	Cutts Island, SW of	-122.7067	47.3133	-68.05	CTD	CTD	CTD & full suite	0, 5, 10, 30, 50, NB
73	Glencove, East of	-122.6950	47.3400	-50.43	CTD	CTD & limited suite	--	0, 5, 10, 30, NB
74	Elgin, East of	-122.6667	47.3583	-26.17	CTD	CTD	CTD	
75	Wauna	-122.6333	47.3750	-11.8	CTD & full suite	CTD & full suite	--	0, 5, NB
76	Days Island	-122.5733	47.2483	-59.27	CTD	CTD & limited suite	CTD	0, 5, 10, 30, 50, NB
77	Point Evans (PRISM 34)	-122.5367	47.2883	-53.38	CTD	CTD & limited suite	CTD	0, 5, 10, 30, NB
78	Point Defiance	-122.5600	47.3167	-56.91	CTD	CTD	CTD	
79	Gig Harbor, outer	-122.5400	47.3317	-54.83	CTD	CTD	--	0, 5, 10, 30, NB
80	Dalco Passage (PRISM 33)	-122.5033	47.3150	-150.46	CTD	CTD & limited suite	--	0, 5, 10, 30, 50, 100, NB
91	PR29 S of Alki Pt	-122.4433	47.5568	-227	CTD & full suite	CTD & full suite	--	0, 5, 10, 30, 50, 100, NB
92	PR30 Three Tree Pt	-122.4084	47.4565	-216	CTD & full suite	CTD & full suite	--	0, 5, 10, 30, 50, 100, NB
95	PR39 Colvos Passage	-122.5266	47.4159	-112	CTD & limited suite	CTD & limited suite	--	0, 5, 10, 30, 50, 100, NB
93	PR31	-122.3600	47.3933	-213	CTD	CTD	--	0, 5, 10, 30, 50, 100, NB
94	PR32	-122.4167	47.3333	-178	CTD	CTD	--	0, 5, 10, 30, 50, 100, NB

m – meter
MLLW - mean lower low water
CTD – Conductivity Temperature with Depth
NB – near Bottom

Appendix B. Surface Water Inflows to the Main Basin and South Puget Sound

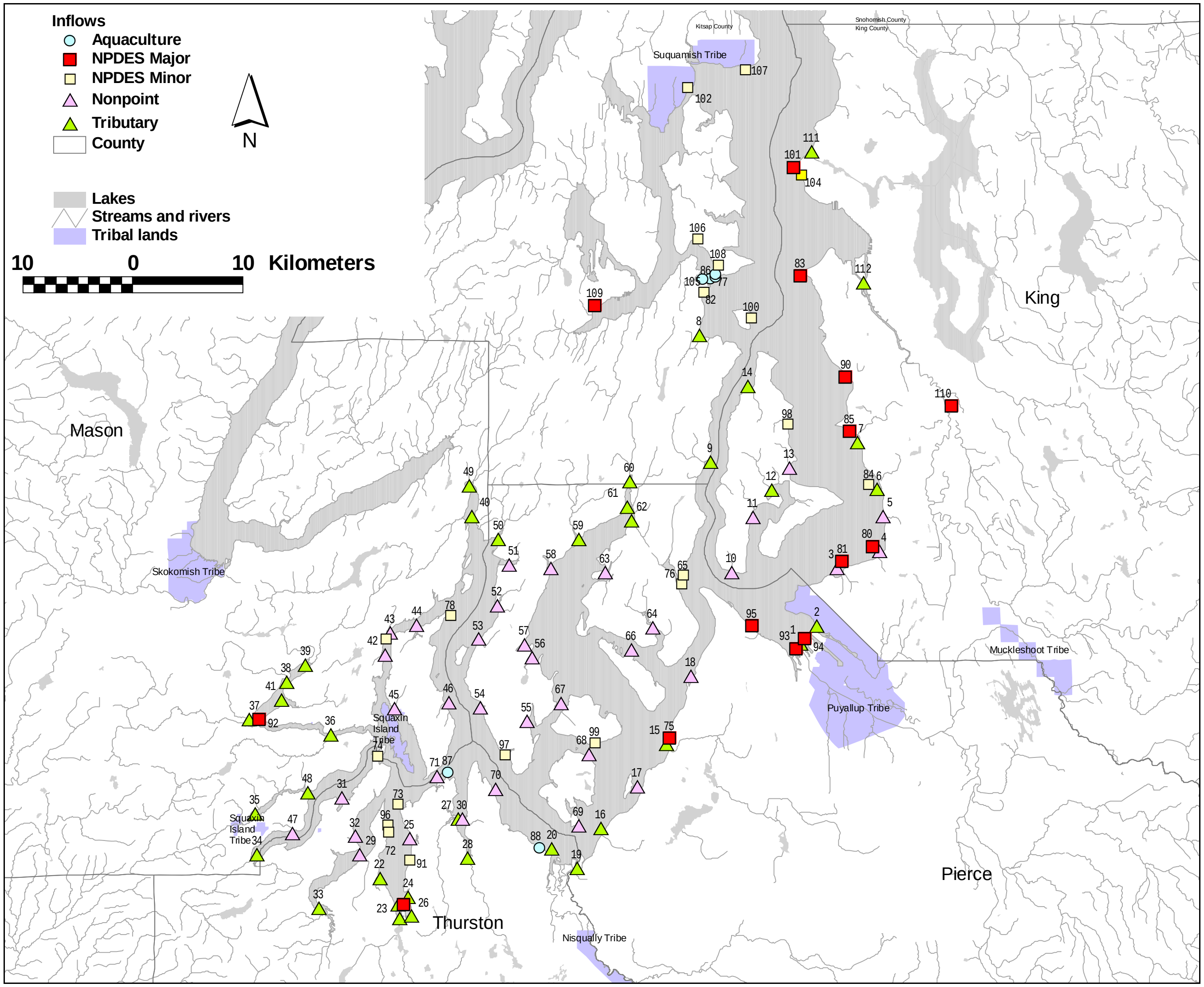


Figure B-1. Locations of freshwater sampling sites.

Table B-1. Inflow type for freshwater sampling sites.

Map Number	Inflow Name	Inflow Type
1	Puyallup River	Tributary
2	Hylebos Creek	Tributary
3	Federal Way	Nonpoint
4	Buenna	Nonpoint
5	Saltwater St Park	Nonpoint
6	Des Moines Creek	Tributary
7	Miller Creek	Tributary
8	Curley Creek	Tributary
9	Olalla Creek	Tributary
10	Tahlequah	Nonpoint
11	Magnolia Beach	Nonpoint
12	Judd Creek	Tributary
13	Ellisport	Nonpoint
14	Shingle Mill Creek	Tributary
15	Chambers Creek	Tributary
16	Sequalitchew Creek	Tributary
17	Ketron	Nonpoint
18	University Place	Nonpoint
19	Nisqually River	Tributary
20	McAllister Creek	Tributary
21	Deschutes River	Tributary
22	Butler Creek	Tributary
23	Schneider Creek	Tributary
24	Ellis Mission	Tributary
25	Gull Harbor	Nonpoint
26	Moxlie Creek	Tributary
27	Woodard Creek	Tributary
28	Woodland Creek	Tributary
29	Green Cove	Nonpoint
30	Henderson Inlet	Nonpoint
31	Gallagher Cove	Nonpoint
32	Frye Cove	Nonpoint
33	McLane/Perry Creek	Tributary
34	Kennedy/Schneider Creek	Tributary
35	Skookum Creek	Tributary
36	Mill Creek	Tributary
37	Goldsborough Creek	Tributary
38	Johns Creek	Tributary
39	Cranberry Creek	Tributary
40	Sherwood Creek	Tributary
41	Campbell Creek	Tributary
42	Grant	Nonpoint
43	Sun Pt	Nonpoint
44	Jarrel Cove	Nonpoint
45	Peale Passage	Nonpoint
46	Wilson Pt	Nonpoint

Map Number	Inflow Name	Inflow Type
47	Snodgrass Creek	Nonpoint
48	Deer Creek	Tributary
49	Coulter Creek	Tributary
50	Rocky Creek	Tributary
51	Vaughn	Nonpoint
52	Dutcher Cove	Nonpoint
53	Herron	Nonpoint
54	Whitman Cove	Nonpoint
55	Filucy Bay	Nonpoint
56	Mayo Cove	Nonpoint
57	Van Gelden	Nonpoint
58	Glen Cove	Nonpoint
59	Minter Creek	Tributary
60	Burley Creek	Tributary
61	Purdy Creek	Tributary
62	Goodnough Creek	Tributary
63	Rosedale	Nonpoint
64	Artondale	Nonpoint
65	Gig Harbor	NPDES Minor
66	Hale Passage	Nonpoint
67	McNeil Island	Nonpoint
68	Anderson East	Nonpoint
69	Anderson West	Nonpoint
70	Tolmie	Nonpoint
71	Dana Passage	Nonpoint
72	Beverly Beach STP	NPDES Minor
73	Boston Harbor STP	NPDES Minor
74	Carlyon Beach STP	NPDES Minor
75	Chambers Creek STP	NPDES Major
76	Gig Harbor STP	NPDES Minor
77	Global Aqua Viking	Aquaculture
78	Hartstene Pointe STP	NPDES Minor
79	LOTT AWTP	NPDES Major
80	Lakehaven Redondo STP	NPDES Major
81	Lakehaven Lakota STP	NPDES Major
82	Manchester STP	NPDES Minor
83	King Co. Alki STP	NPDES Major
84	Midway STP	NPDES Minor
85	Miller Creek STP	NPDES Major
86	NW Sea Farms Clam Bay/Or	Aquaculture
87	NW Sea Farms Dana Passage	Aquaculture
88	National Fish and Oyster	Aquaculture
89	Rustlewood STP	NPDES Minor
90	Salmon Creek STP	NPDES Major
91	Seashore Villa STP	NPDES Minor
92	Shelton STP	NPDES Major
93	Simpson Tacoma Kraft WTP	NPDES Major
94	Tacoma Central #1 STP	NPDES Major

Map Number	Inflow Name	Inflow Type
95	Tacoma North #3 STP	NPDES Major
96	Tamoshan STP	NPDES Minor
97	Taylor Bay STP	NPDES Minor
98	Vashon STP	NPDES Minor
99	WA DOC McNeil Island STP	NPDES Minor
100	WA Parks Black Island ST	NPDES Minor
101	King Co. West Point	NPDES Major
102	Kitsap County Suquamish	NPDES Minor
103	Global Aqua Fort Ward 2	Aquaculture
104	Seattle West Point CSO	NPDES Minor
105	Global Aqua Clam Bay 1	Aquaculture
106	Lynwood Center	NPDES Minor
107	Kitsap County Kingston	NPDES Minor
108	Kitsap Cnty Sewer Dist 7	NPDES Minor
109	Bremerton	NPDES Major
110	King Co. Renton	NPDES Major
111	L Washington Ship Canal	Tributary
112	Green/Duwamish River	Tributary