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Quality Assurance Project Plan

Puget Sound Dissolved Oxygen Modeling Study:

Intermediate-scale Model Development

by

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January 2009

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EAP – Environmental Assessment Program

WQP – Water Quality Program

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3. Evaluation of features of water quality modeling system (hydrodynamic and water quality model).
4. Descriptions of available data sources.

Abstract

Ecology is developing an intermediate-scale model for the entire Puget Sound estuary system to further our understanding of processes that affect dissolved oxygen (DO). This project will help determine if current nitrogen loadings from point and nonpoint sources into Puget Sound are significantly impacting water quality at a large scale and what level of nutrient reductions are necessary to reduce or eliminate human impacts to DO levels in sensitive areas. The northern boundary will be set at the entrance to Johnstone Straits past the Fraser River north of Vancouver B.C. The model resolution will be finer than the large-scale box model, being developed in tandem with this model, ensuring reasonable representation of the various sub basins within Puget Sound.

The model will simulate full eutrophication kinetics. Nutrient loads will be specified as input variables for all important sources. The objective of this intermediate-scale hydrodynamic and water quality model is to develop a large scale understanding of nutrient assimilation capacity of Puget Sound. The preference is to develop the water quality model in a de-coupled configuration so that it may be applied repeatedly using previously computed hydrodynamic solutions. The water quality model will be calibrated using data collected in Puget Sound from 1999-2008 and will be used to simulate the effects of alternative nutrient loading scenarios.

Each study conducted by the Washington State Department of Ecology (Ecology) must have an approved Quality Assurance (QA) Project Plan. The plan describes the objectives of the study and the procedures to be followed to achieve those objectives. After completion of the study, a final report describing the study results will be posted to the Internet.

Background and Project Overview

Nutrient pollution is considered one of the largest threats to Puget Sound (Figure 1). Recognized nation-wide, the following characteristics of nitrogen pollution apply equally and imperatively to Puget Sound (Glibert et al., 2005; Howarth, 2006; Howarth and Marino, 2006):

- Human acceleration of the nitrogen cycle over the past 40 years is far more rapid than almost any other aspect of global change.
- Nutrient pollution leads to hypoxia and anoxia, degradation of habitat quality, loss of biotic diversity, and increased harmful algal blooms.
- Technical solutions exist and should be implemented, but further scientific work can best target problems and solutions, leading to more cost effective solutions.

While eutrophication can be a natural process, anthropogenic nutrient pollution can cause *cultural eutrophication* which is the process of enhanced eutrophication resulting from human activity. Both natural and cultural eutrophication occur when a body of water becomes enriched with nutrients which, in turn, stimulate excessive algal growth. Oxygen consumption resulting from the subsequent decomposition and respiration of the excess algae by bacteria leads to dissolved oxygen (DO) depletion in areas that are not well ventilated (e.g., quiescent bays and near-bottom waters).

Nutrient inputs from oceanic sources, tributary inflows, point source discharges, nonpoint source inputs, sediment-water exchange, and atmospheric deposition determine the loads to Puget Sound. Hydrodynamic characteristics, such as tides, stratification, mixing, and freshwater inflows, govern transport of nutrients and other parameters. Photosynthetic rates (influenced by light and nutrient availability, temperature, and algal species assemblages) and other processes (growth, death, respiration, settling, and bacterial decomposition) determine nutrient transformations and the degree of DO depletion.

In general, large-scale eutrophication in Puget Sound has been thought to be unlikely for two reasons. First, Puget Sound receives relatively high concentrations of nutrients from the Pacific Ocean so incremental nutrient additions were thought to do little to influence overall phytoplankton productivity. Second, estuarine circulation and tidal mixing throughout much of Puget Sound ensures a rapid exchange of water (approximately 1 year turnover time). Vertical mixing, especially in Central Puget Sound, further limits exposure of phytoplankton to light and therefore reduces algal growth and biomass accumulation (Mackas and Harrison, 1997).

These characteristics of Central Puget Sound were responsible for the successful diversion of sewage from Lake Washington to West Point (Puget Sound) in the late 1950's (Edmondson, 1991). While nutrient loading to Lake Washington caused excessive algal growth in the lake, the same loading at West Point did not appear to enhance algal growth in marine waters. Much of the current understanding of Puget Sound phytoplankton dynamics has been based on modeling and measurements of ambient productivity and nutrients at West Point (Winter et al., 1975).

In contrast, a more recent study by Newton and Van Voorhis (2002) observed substantial increases in algal primary production when water samples from Central Puget Sound and Possession Sound were artificially enriched with nutrients. Nutrient-enhanced production was observed at all stations but the degree of enhancement varied both spatially and temporally suggesting that the system is more complex and that there are likely to be a diversity of responses to nutrient addition. These responses are expected to manifest differently at different times and locations within greater Puget Sound.

Mackas and Harrison (1997) evaluated the issue of eutrophication in the Strait of Juan de Fuca, Georgia Strait, and Puget Sound. They judged potential impacts from eutrophication of Central Puget Sound to be relatively low. However, they reported that the most sensitive sub-regions are likely to be small tributary inlets and fjords that have low flushing rates and that adjoin urbanized shorelines. They speculated that the "early warning signs of eutrophication" were already becoming evident in these areas. At present, most of these areas lie along the south and west margins of Puget Sound.

Bricker et al. (1999) later reported the overall level of expression of eutrophic conditions to be moderate in Central Puget Sound and Whidbey Basin and high in Hood Canal and South Puget Sound. They predicted conditions to worsen, especially in Hood Canal and South Puget Sound, due to increasing population pressures. In response to the increasing threat of nutrient-stimulated eutrophication in Puget Sound, Ecology has both initiated and been actively involved with the continuation of focused water quality studies in these specific areas (Roberts et al., 2008a; Albertson et al., 2007; Roberts et al., 2005b; Albertson et al., 2002).

This project capitalizes on what has been learned in these prior studies and seeks to expand this foundation to develop a unified water quality model applicable to the entire Puget Sound estuary system. As part of mandates under the Clean Water Act to manage pollutant loading to meet water quality standards, U.S. EPA, Pacific Northwest National Laboratory (PNNL), and Ecology have jointly initiated this water quality model development project to address the following specific nutrient management questions.

- Are human sources of nutrients in and around Puget Sound significantly impacting water quality?
- How much do we need to reduce human sources of nutrients to protect water quality in Puget Sound?

PNNL is tasked with the development of the hydrodynamic and water quality models for use by the agencies to evaluate the effect of human sources of nutrients on dissolved oxygen across Puget Sound and to define potential Puget Sound-wide nutrient management strategies and decisions. The model development will occur in PNNL's Marine Sciences Laboratory, through an intergovernmental agreement between PNNL and Ecology. This document describes the development of this intermediate-scale model of Puget Sound. A complementary QA Project Plan has been created which details development of the large-scale screening model (Sackmann, 2008).

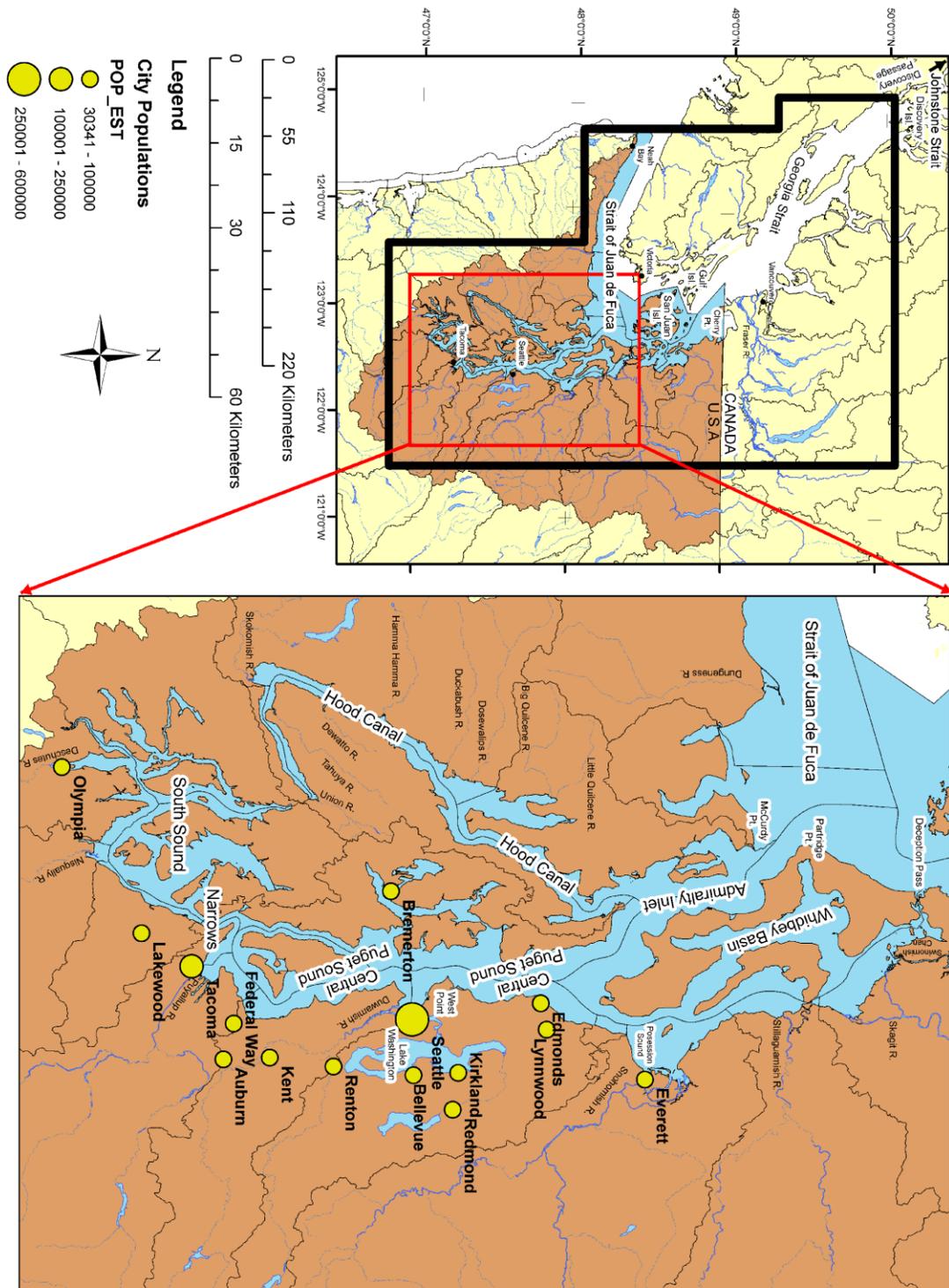


Figure 1. Map of western Washington and lower British Columbia, Canada. Shaded region defines the Puget Sound Action Area. Thick black lines outline the domain of the intermediate-scale model. Thick red lines outline Puget Sound and the domain of the large-scale screening model. Major rivers have been labeled, but the models will include others. Only major Canadian rivers in watersheds that share a border with the U.S.A. have been shown.

Project Goals and Objectives

Mechanistic models provide the quantitative framework necessary to integrate the diverse physical, chemical, and biological information that constitute complex environmental systems and provide a vehicle for an enhanced understanding of how the environment works as a unit (Chapra, 1997). For example, complexities such as the impact of the temporal and spatial distribution of nutrient additions, of when freshwater inputs occur and how that alters circulation patterns, and of co-limitation of production by nutrient and sunlight cannot be determined without a quantitative approach. In this study the water quality models to be developed will identify and assess factors and processes that influence water quality in Puget Sound on a significant scale.

The overall goal of this project by Ecology is to work collaboratively with U.S. EPA, PNNL, and a Project Advisory Committee (PAC) to conduct DO modeling in Puget Sound in a manner that complements and supports concurrent management initiatives. This project consists of the following components:

1. Two multi-purpose hydrodynamic models for the entire Puget Sound, one at a large scale (based on Babson et al., 2006) and one at an intermediate scale. These models can also serve as community tools for other purposes.
2. The large-scale model (also called “box model”) will be used to produce a screening-level evaluation of nutrient effects on DO, Puget-Sound-wide. The results of this effort will inform the intermediate-scale model.
3. The intermediate-scale model (also called the “intermediate-grid model”) will be used to evaluate the effect of human-caused nutrient enrichment on DO across Puget Sound. This model will help inform potential Puget-Sound-wide management strategies and decisions and would support site-specific detailed work that may be completed beyond this project.
4. QA Project Plan for a detailed site-specific analysis for one Puget Sound basin (e.g. Whidbey basin) to determine the nutrient loading reductions needed to meet water quality standards.

The scope and focus of this QA Project Plan is limited to the development of the intermediate-scale model (i.e., items 1 and 3 above) only. The development strategy for the large-scale model is described in a separate QA Project Plan (Sackmann, 2008). Objectives specific to this project are as follows:

- Develop an intermediate-scale water quality model, calibrated to conditions observed in Puget Sound from 1999-2008.
- Estimate effects of nutrient loading on DO and apply the model to various nutrient loading scenarios.
- Evaluate sensitivity of the model to various input parameters and boundary conditions.

Organization and Schedule

The following individuals are involved in this project (Table 1). Except as noted, all are employees of the Washington State Department of Ecology, Environmental Assessment Program (EAP).

Table 1. Organization of project staff and responsibilities.

Staff (all are EAP except as noted*)	Title	Responsibilities
Brandon Sackmann MIS Unit Statewide Coordination Section (360) 407-6684	Principal Investigator	Writes the QAPP, develops model and nutrient loading input files, analyzes and interprets model results, runs model scenarios, and writes the draft and final report.
Mindy Roberts MIS Unit Statewide Coordination Section (360) 407-6804	Project Manager	Develops and oversees all project-related activities, and provides technical guidance and oversight to aid model development and subsequent refinement.
Karol Erickson MIS Unit Statewide Coordination Section (360) 407-6694	Unit Supervisor for the Project Manager	Reviews and approves the QAPP and approves the budget.
Will Kendra MIS Unit Statewide Coordination Section (360) 407-6698	Section Manager for the Project Manager	Reviews the project scope and budget, tracks progress, reviews and approves the QAPP.
Greg Pelletier MIS Unit Statewide Coordination Section (360) 407-6485	Technical Advisor	Provides technical guidance and oversight to aid model development and subsequent refinement.
Ben Cope* U.S. EPA (206) 553-1442	Technical Advisor	Provides technical guidance and oversight to aid model development and subsequent refinement.
Tarang Khangaonkar* PNNL (206) 528-3053	Model Lead	Develops hydrodynamic and water quality models, performs model calibration/evaluation and sensitivity analyses, and writes reports for Ecology.
Bob Cusimano Western Operations Section (360) 407-6596	Section Manager for the Study Area	Reviews the project scope and budget, tracks progress, reviews and approves the QAPP.
Andrew Kolosseus* Watershed Planning Unit Water Quality Program (360) 407-7543	EAP Client	Clarifies scope of the project, provides internal review of the QAPP, and approves the final QAPP.
William R. Kammin (360) 407-6964	Ecology Quality Assurance Officer	Reviews and approves the QAPP.

EPA – Environmental Protection Agency

PNNL – Pacific Northwest National Laboratory

MIS – Modeling and Information Support

QAPP – Quality Assurance Project Plan

Table 2 summarizes the expected project schedule. Tasks are limited to the development of the intermediate-scale model only.

Table 2. Proposed schedule for completing modeling work and reports.

Hydrodynamic model report (PNNL)	
Author lead	PNNL
Schedule	
Draft to Ecology	April 2009
Draft due to client/peer and external reviewers	May 2009
Final report due on web	July 2009
Water quality model report (PNNL)	
Author lead	PNNL
Schedule	
Draft to Ecology	October 2009
Draft due to client/peer and external reviewers	November 2009
Final report due on web	January 2010
Final report	
Author lead	Brandon Sackmann (Ecology)
Schedule	
Draft due to supervisor and project manager	February 2010
Draft due to client/peer and external reviewers	March 2010
Final report due on web	June 2010
Focus Sheet	
Author lead	Brandon Sackmann (Ecology)
Schedule	
Draft due to supervisor and project manager	March 2010
Final version due on web	June 2010

Capabilities for a DO Model of Puget Sound

Success of marine circulation and water quality model development can be affected by the choice of the software tool and modeling framework. Ecology assembled a Model Technical Advisory Committee (MTAC) to seek input on modeling approaches given the project goals and resources. The MTAC is comprised of a group of modeling professionals and is separate from the PAC, although some membership does overlap. The MTAC was tasked with evaluation of key processes needed in the model, extent of model domain, the level of detail, model framework comparison (pros/cons), and model applicability to other Puget Sound projects. Ecology convened a MTAC workshop on 4 November 2008 which was attended by modeling experts and

the project team. The information and feedback received has been summarized and is attached as Appendix 1.

While Ecology is responsible for the final model selection in consultation with the project team and MTAC, Ecology has requested that PNNL also provide input on model selection separately, in the capacity of team member responsible for the model development and implementation. Recommendations are based on Puget Sound hydrodynamic features, experience with various models and tools available, and understanding of project goals. PNNL's assessment of the model performance requirements is provided below. Models and software tools are limited to those available in the public domain, and commercial models such as Delft-3D, WQMAP, MIKE, and other similar tools were not included in this assessment. If the results are used for regulatory purposes, all model information must be available to interested parties, and proprietary or commercial models do not satisfy this need.

Hydrodynamics

Puget Sound is a large estuarine system bounded by 2,597 miles of complex shorelines and consists of several sub basins and many large estuaries with distinct properties of their own. It is the largest such body of water in the contiguous forty-eight states. Pacific Ocean water enters the Puget Sound estuary system and the Georgia Strait through the Strait of Juan de Fuca (SJF) entrance at Neah Bay. SJF is also the outlet for most of the freshwater discharged from the Puget Sound and from the Fraser River in British Columbia.

Admiralty Inlet links the three major branches of Puget Sound together and serves as the primary outlet to the SJF and ultimately the Pacific Ocean. The three main branches of Puget Sound include the deep Main Basin and the shallower South Sound (separated from the Main Basin by a sill and constriction at the Narrows), Hood Canal, and Whidbey Basin. The only other outlet to SJF is the extremely narrow Deception Pass located at the northern end of Whidbey Basin (Figure 1).

The large freshwater discharge from the Fraser River affects stratification and currents in the adjacent waters of the Strait of Juan de Fuca and Georgia Strait including waters around San Juan Islands and the Cherry Point coastline near the United States/Canada border. There is considerable interest in the circulation and transport in the entire region spanning the U.S. and Canadian waters for the assessment of fish migration patterns and pathways. Although not the primary focus, there is also an interest in understanding the effect of nutrient loads entering Puget Sound from Canadian waters. Therefore, there is a need to ensure that the study domain extends well north into Canadian waters to Johnstone Strait near the entrance to Discovery Passage.

The circulation in this estuary shows distinct fjordal three dimensional (3D) characteristics with mean outflow in the surface layers and inflow in the lower layers. Near the mouths of the individual estuaries there is stratification due to freshwater discharge and complex circulation patterns induced by cross flow as the river plumes encounter Puget Sound tidal influences. The model selected must therefore be capable of simulating 3D baroclinic (density-induced) circulation affected by freshwater inflows over shallow mudflats and sharp change in bathymetry to deep fjordal depths of Puget Sound. The currents are also affected by local winds.

A number of models such as EFDC (Roberts et al., 2005a; Khangaonkar and Yang, 2004; King County, 1999), CH3D (Johnston et al., 2007), POM (Kawase, 1998), SUNTANS (Wang et al., 2008), FVCOM (Finite Volume Community Ocean Model; Yang and Khangaonkar, 2008), RMA10 (Breithaupt et al., 1999), UnTRIM (Joshberger, 2005), and ROMS (Bahng et al., 2007) available in the market are capable of addressing the above characteristics and are being used successfully on various studies in progress in Puget Sound and are possible candidates for this study.

Water Quality

The focus of this project is on simulating the response of DO concentrations to nutrient loading. Eutrophication and algal kinetics are of major interest because they are the links between nutrients and dissolved oxygen. Parts of Puget Sound such as the Hood Canal and the nearshore estuarine and riverine reaches have shown evidence of hypoxia. A full listing of various processes of interest and variables which need to be simulated is discussed in *Puget Sound Dissolved Oxygen Modeling Model Technical Advisory Committee Model Selection Workshop Summary* (Appendix 1) and is not repeated here.

The selected model must have the ability to simulate full eutrophication kinetics including the ability to incorporate point sources, address multiple algal groups, nutrient cycling, and include sediment oxygen demand (SOD) and biochemical oxygen demand (BOD) processes. Nutrient loads will be specified as input variables for all important sources. These loads will be estimated by Ecology using data from the National Pollutant Discharge Elimination System (NPDES) database, the river and stream monitoring network data, and the South Puget Sound Dissolved Oxygen Study (Roberts et al., 2008b).

Most of the models described above such as EFDC, CH3D, ROMS, FVCOM, and RMA10 have sophisticated water quality modules which may be applied for this study. In models other than RMA10, the water quality modules are embedded within the codes, coupled to hydrodynamics, and could impose a considerable computational burden. CH3D and EFDC models have been used in decoupled mode with stand alone water quality simulation programs such as WASP (Wool et al., 2006) and CE-QUAL-ICM (Cerco and Cole, 1995).

Ability to Incorporate Nearshore Processes at High Resolution

This phase of the project seeks to establish a model at an intermediate-scale improving in resolution over the large-scale model (also called “box model”) of Puget Sound (Babson et al., 2006). It will be set up at a resolution sufficient for addressing the large-scale questions on the assimilative capacity of Puget Sound. However, the model could be used subsequently to address localized higher resolution processes including the effects of point source discharges and water quality impairment in the nearshore regions associated with sediment and bacteria contamination. Ability of the model to improve resolution as required through the use of nested grid techniques or the use of unstructured grids is considered essential for future applications in Puget Sound such as total maximum daily load (TMDL) calculations or sediment impact zone

(SIZ) assessment for remedial investigations. Therefore, model capabilities to address additional parameters beyond DO are considered but are not essential.

Sediment Contamination and Toxics Fate and Transport

While the project goals clearly focus on DO, this project presents an opportunity to select and establish a tool which can address Puget Sound community needs over the long term. Although not a part of this study, the ability of the model to conduct toxics fate and transport (metals and organics) and address sediment contamination issues will be a major advantage.

Summary

Appendices 2 and 3 show a listing of available hydrodynamic and water quality modeling tools, their capabilities, and ranking based on comments provided by the MTAC. As seen in Appendix 2, hydrodynamic models are largely divided into structured grid models (POM, EFDC, ROMS, CH3D and GEMSS) and unstructured grid models (FVCOM, UnTRIM, ADCIRC, and SELFE). Most of them use high-order transport schemes, wetting/drying option, and sigma-grid system. These models are well known, well tested, and have been applied on many projects. Many of these models have active user groups, and provide well-organized technical documentation.

Recommendation for Model Selection and Model Approach

If the selection were based on immediate project goals and model skill and capabilities alone, a number of available models discussed above could provide the required performance. However, our interest in developing a tool which could be used over a long term by a broader community of scientists requires consideration of the following additional points.

- *Applicability to Ecosystem Model Development Efforts:* A number of agency groups including NOAA Fisheries and King County are engaged in developing an ecosystem / food web model of Puget Sound. A Puget Sound DO / Water Quality Model could be used as a source of information on temperature, salinity, nutrient concentrations, DO and other conventional water quality variables which are desired inputs to ecosystem modeling efforts. In addition, the ability of this model to also provide information about metals, organics, and sediment contamination levels will be a major plus with respect to supporting sediment remediation.
- *Ability to Conduct Long-Duration Model Runs:* Effect of climate change and sea level rise are issues of considerable interest. Ability of the model to be used in the future to conduct simulations over 10 to 100 year time frames is an important consideration.
- *Wetting and Drying, Mudflats, and Nearshore Circulation:* Much of the effort in connection with restoration of Puget Sound is focused on the nearshore. The question often posed is “can we achieve beneficial restoration outcomes at the fine local scale, as well as at a large estuary-wide scale?” Capabilities of the model for simulating the important nearshore

processes, such as circulation in complex multiple tidal channels, wetting and drying of tide flats, and water quality and sediment transport are essential both for immediate DO simulation needs and for potential long term modeling needs of this region.

Based on model performance requirements discussed in the previous section and additional points listed above, model recommendations are as follows:

1. **Unstructured Grid Framework:** The model framework must incorporate an unstructured grid framework to be able to address nearshore processes adequately while simultaneously assessing the circulation and water quality of the entire Puget Sound. The ability to modify the grid efficiently as new information and data become available is considered essential for developing a model of a complex water body such as Puget Sound.
2. **Comprehensive Water Quality Model Decoupled from Hydrodynamics:** It is unlikely that a complete water quality model will be developed through a single effort. It is likely that more features and processes will be added through subsequent project applications. Multiple users may wish to apply the modeling framework to look at other parameters of interest (bacteria, toxics, submerged aquatic vegetation, etc.). It is therefore important to select a water quality model framework with the ability to address a wide range of processes. From a computational efficiency standpoint, access to a water quality module which is independent of the hydrodynamic tool is highly recommended.

PNNL reviewed a number of unstructured grid models and personally contacted the authors to discuss the strengths and weaknesses of their tools. These included the leading 3D unstructured grid models including RMA10 (King, 1998), ADCIRC (Leutlich et al., 1992), ELCIRC (Zhang et al., 2004), SELFE (Zhang and Baptista, 2008), UnTRIM (Casulli and Walters, 2000), and FVCOM (Chen et al., 2003).

The SUNTANS model discussed in the previous section is considered under development with respect to its ability to handle shallow mudflats and wetting and drying and does not include associated water quality. The ADCIRC model is popular for storm surge modeling in barotropic mode but the baroclinic version of the model is not yet available. The UnTrim model is not generally available in public domain. The ELCIRC model of Columbia River and Washington Coast previously developed by Oregon Graduate Institute had a strict limiting requirement of orthogonal grid cells, and has now been replaced by SELFE. The water quality module of SELFE is still under development. PNNL is closely following the development of SELFE and SUNTANS unstructured grid hydrodynamic modeling tools.

Based on testing and application on numerous projects, Ecology recommends the FVCOM model for this project. FVCOM simulates water surface elevation, velocity, temperature, salinity, and sediment and water quality constituents in an integral form by computing fluxes between non-overlapping, horizontal, triangular control volumes. This finite-volume approach combines the advantages of finite-element methods for fitting complex boundaries and finite-difference methods for simple discrete structures and computation efficiency. A sigma-stretched coordinate is used in the vertical plane to better represent the irregular bottom topography.

Unstructured triangular cells are used in the horizontal plan. Key features of FVCOM on which the selection is based are detailed in Appendices 2 and 3 but are summarized as follows.

- Unstructured grid modeling frame work.
- Ability to simulate baroclinic circulation.
- Finite volume technique with good mass conservation properties.
- Wetting and drying simulation.
- Parallelized code (hydrodynamics) for cluster computing.
- Availability of water quality, sediment transport, and particle tracking.
- Public domain and well-tested code on multiple projects with an active research group.

Although a water quality component (NPZD) is available through FVCOM, Ecology recommends selection and application of a water quality tool which may be applied independent of the hydrodynamic model in a decoupled mode. WASP and CE-QUAL-ICM are two water quality models which have been extensively used in the U.S. The coupled water quality modules in many of the tools discussed previously are based on these two models. The models are applicable over an unstructured hydrodynamic model grid, and incorporate a comprehensive suite of water quality processes including conventional eutrophication, and toxics fate and transport kinetics. The CE-QUAL-ICM model provides added capabilities with respect to sediment diagenesis and the ability to incorporate submerged aquatic vegetation.

Based on the above considerations, Ecology's selections for the Puget Sound Do model are as follows:

- Hydrodynamics – An intermediate-scale hydrodynamic model of Puget Sound using the FVCOM model developed by the University of Massachusetts.
- Water quality – A decoupled application of the U.S. Army Corps of Engineers' CE-QUAL-ICM model to be operated using the FVCOM model grid and pre-computed hydrodynamic solution.

Ecology will work with PNNL, U.S. EPA, and the MTAC to develop an approach for model setup including grid resolution (vertical and horizontal), selection of input and output data, model calibration / evaluation, and application.

Hydrodynamic Model Setup

Development of the intermediate-scale hydrodynamic model will consist of several steps including model grid development, model setup involving specification of boundary conditions for the selected period, calibration and sensitivity analysis, and application for scenarios. The grid development activity and preparation of model input files are part of the model setup and are specific to the modeling system selected.

PNNL has previously developed a high resolution model of the Puget Sound. In doing so, a detailed bathymetry file for Puget Sound using a combination of digital elevation maps, LiDAR

data, and hydrographic surveys has been prepared. Using this data set, the Puget Sound domain will be re-gridded extending from the mouth of the Strait of Juan de Fuca to South Puget Sound. The northern boundary will be set at the entrance to Johnstone Straits past the Fraser River north of Vancouver B.C. (Figure 1). The resolution selected will be considerably finer than the large-scale model ensuring reasonable representation of the various sub basins within the Puget Sound. However, the grid will be coarse relative to the PNNL Puget Sound model, which has a resolution as fine as 30 ft in certain sub-basins.

We expect that the model will be set up with sufficient layers (10 to 30) in the vertical to address the highly stratified nature of residual circulation in Puget Sound. In Puget Sound, a synoptic data set for currents and tides covering the entire domain is not available. Therefore the hydrodynamic model setup will need to be tested against the multiple periods of 9/96, 9/04, 10/06, and 9/07 during which data were collected. These periods also match the calibration periods for the fine resolution PNNL hydrodynamic model previously completed.

There are 17 major rivers that discharge into Puget Sound and its adjacent waters. Most of these rivers have real time USGS stream flow gages. Contributions from the rest of the land surface will also be included for completeness but not necessarily representing each stream mouth. The model will be set up with flows from these rivers included as boundary source terms. However, the estuarine circulation, the movement of salt wedge, and the upstream tidal intrusion generated by these river inflows are beyond the scope of the intermediate-scale model.

Tidal elevations at the open boundaries will be specified using the XTIDE predictions based on NOAA National Oceanic Service algorithms. At the water surface, wind stress will be specified. Wind will be included for completeness with wind stress being initially applied uniformly across the entire model domain for simplicity. Meteorological forcing terms including wind and heat flux or air temperature and solar radiation will be specified using either direct measurements or using MM5 or WRF meteorological model simulations if the latter are sufficient for this model application.

Model calibration, described below, will be conducted by comparing the predicted tides, currents, and salinity and temperature profiles to observed data. The process of calibration will consist of steps such as refining the model grid as required, adjusting bottom roughness and friction, and varying tidal phase along open boundaries. Once the model calibration is completed, sensitivity analysis will be performed testing the stability and reliability of the model to a wide range of inputs. Tidal residual calculations will also be performed as part of the sensitivity analysis.

Water Quality Model Setup

The objective of this intermediate-scale water quality and nutrient model is to develop a large-scale understanding of nutrient assimilation capacity of Puget Sound. The selected water quality model will simulate conventional water quality constituents such as nitrogen, phosphorus, dissolved oxygen, BOD, SOD, phytoplankton, and temperature. The focus of this modeling effort is on the response of the above listed variables to nutrient loads, which is conventionally known as the eutrophication cycle. Nutrient loads will be specified as input variables for all

important sources. These loads will be estimated by Ecology using data from the National Pollutant Discharge Elimination System (NPDES) database and river and stream monitoring network data.

PNNL will set up the selected model over the same domain and grid developed for the hydrodynamic model. The initial preference is to develop the water quality model in a decoupled configuration so that it may be applied repeatedly using previously computed hydrodynamic solutions. Although this not a requirement, it does provide benefits in terms of model runtimes.

Loading Estimation

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 Puget Sound enters via rivers and streams.

The term *point source* generally refers to sources that are regulated under the federal Clean Water Act through the NPDES. NPDES permits are issued to municipal and industrial wastewater treatment and stormwater systems, construction sites, boatyards, salmon net pens, and other facilities. With respect to point sources, municipal wastewater treatment plants that discharge directly to Puget Sound are thought to represent the largest anthropogenic source of direct nitrogen loading from the watershed to the Sound. A few industrial facilities discharge directly to Puget Sound, and these will be included where discharge information is available or can be estimated. Point source loads will be estimated using data from the NPDES database and the South Puget Sound Dissolved Oxygen Study (Roberts et al., 2008b). In some cases, smaller wastewater discharges may be lumped as for the smaller streams.

While all rivers are generally considered nonpoint sources, some have upstream wastewater treatment plants that discharge to freshwater. For this project, upstream wastewater treatment plants will not be separated out of the river and stream inputs. In addition, rivers and streams receive discharges from other permitted areas, such as municipal stormwater, which are considered point sources. Again, for this project, permitted sources will not be separated out of the river and stream inputs.

A major activity as part of the model setup will be developing nutrient loading input files for all major wastewater treatment plants and rivers. Ecology's goal is to develop these files as a separate stand-alone product to facilitate their use by other projects and agencies. This project will require the following information for specifying nutrient loads from all sources including all major effluent dischargers and river loads:

- Flow rates and temperature data
- Organic phosphorus (particulate and dissolved)
- Dissolved phosphorus (soluble reactive phosphorus)
- Organic nitrogen (particulate and dissolved)
- Ammonia nitrogen
- Nitrate + Nitrite nitrogen
- Dissolved oxygen (DO)
- pH
- Total organic carbon (TOC)
- Dissolved organic carbon (DOC)
- Carbonaceous biochemical oxygen demand (CBOD to be estimated from DOC or DOC to be estimated from CBOD, as needed)

When available, measured effluent quality for a particular point source will be used to estimate its constituent loadings. If such data are not available for a particular source, it will be necessary to estimate effluent quality based on measurements from similar facilities.

Organic nitrogen may be estimated as the difference between total Kjeldahl nitrogen and ammonia nitrogen for wastewater treatment plants and between total nitrogen and the sum of ammonium, nitrate, and nitrite for rivers. Organic phosphorus may be estimated as the difference between total phosphorus and orthophosphate phosphorus.

As mentioned earlier under „Hydrodynamics Model Setup’, there are 17 major rivers that discharge into Puget Sound and its adjacent waters, most of which have real time USGS streamflow gages. Calculation of river loads requires both constituent-concentration and streamflow data. As part of the USGS National Water Quality Assessment, Embrey and Inkpen (1998) estimated nutrient loads to Puget Sound from several major rivers based on existing nutrient concentrations and discharge data for the period 1980-1993. Using an analogous approach, time-resolved stream loads will be estimated for the time period from 1999-2008 using constituent-concentration data compiled from databases maintained by agencies operating water-quality monitoring stations in the Puget Sound Basin and streamflow estimates made at the time of water-quality sample collection (Appendix 4).

The intermediate-scale model will be set up with flows from rivers included as boundary source terms. The model will require daily time series of flows, temperature, DO, pH and nutrient loads from discrete watershed inflow points to simulate seasonal and subseasonal variations in Puget Sound water quality. The total ungaged discharge to Puget Sound may be as high as 10% of the total gaged inflow but with potentially higher nutrient concentrations due to agricultural and urban runoff. Flows from ungaged rivers will be estimated by first choosing a representative gaged reference river based upon its similarity to an ungaged area and then multiplying the

reference flow by the ratio of the ungaged to gaged areas (Lincoln, 1977). In cases where rivers are gaged well upstream from the river mouth the drainage area downstream of the station is used as the ungaged area in the calculation and the estimated flow is added to the gaged flow to obtain total discharge for that river.

Following Mohamedali (2008) and Roberts and Pelletier (2001) daily time series of various parameters and nutrient concentrations will be estimated using multiple linear regressions (Cohen et al., 1992). This analysis is based on the premise that parameter concentrations can be predicted based on flow and time of year. The multiple linear regression equation to be used in this analysis is given by:

$$\log(c) = b_0 + b_1 \log(Q/A) + b_2 [\log(Q/A)]^2 + b_3 \sin(2\pi f_y) + b_4 \cos(2\pi f_y) + b_5 \sin(4\pi f_y) + b_6 \cos(4\pi f_y) \quad (1)$$

where c is the observed parameter concentration (mg/L) or in the case of temperature or pH it is in °C and pH units (respectively), Q is discharge (m^3/s), A is the area drained by the monitored location (km^2), f_y is the year fraction (dimensionless, varies from 0 to 1), and b_i are the best-fit regression coefficients.

All six variables in the above equation are known values (from available concentration data, streamflow data, watershed area and time of year) except for the coefficients (b_i). The multiple linear regression model attempts to solve equation (1) and determine the optimum combination of b_i coefficients that will yield the best fit between predicted and observed concentrations of a specific parameter. Once these coefficients are determined, the above equation can be used to predict parameter concentrations continuously over any time period, for example, at a daily interval. Daily concentrations will be multiplied with daily streamflow data to predict daily loads for time periods of interest.

In previous applications of this regression model methodology certain water quality parameters were better characterized by the regression model than others, particularly those highly influenced by flow and seasonality. Though the statistical results from some parameters suggested a poor fit for *concentration*, predicted daily *loads* often compared well with observed loads for most parameters across a wide variety of streams.

There is also evidence that groundwater may contribute significant amounts of freshwater to some basins and should be evaluated as a potential source of distributed nutrients (e.g., Hood Canal). One proposed application of the model will be to test the relative sensitivity of this source, using published and/or order-of-magnitude groundwater flow estimates, to the overall nutrient and DO balance of Puget Sound (Simonds et al., 2008).

Loads from Canadian sources will be calculated to determine Puget Sound's sensitivity to nutrients coming into the system through its northern boundary. Daily loads will be estimated using methods analogous to those used in Puget Sound. However, initially loads will only be estimated for major rivers and wastewater treatment plants (WWTP) which are likely to include (but will not be limited to) loads from the Fraser river, Victoria-area WWTP, and Vancouver-area WWTP. Should the water quality model results in Puget Sound prove sensitive to these Canadian sources then additional analyses will be performed to more accurately quantify and include the effects from more of the smaller rivers/streams and WWTP within the model domain.

Available Data Sources

Acceptance criteria

No data collection is planned for this project and specific quality objectives are not being specified for existing data or for modeling results. However, data from existing repositories will be used for model calibration and evaluation purposes and the following acceptance criteria will be applied:

- *Data Reasonableness.* Data quality of existing data will be evaluated where available. Best professional judgment will be used to identify erroneous or outlier data and these observations will be removed from the data set.
- *Data Representativeness.* Data will be used that are reasonably complete and representative of the location or time period under consideration. Incomplete data sets will be used if they are considered representative of conditions during the period of interest. Data from outside the period of interest will be used only if no other data are available. In this case, best professional judgment will be used to determine the utility of the available data.
- *Data Comparability.* Long-term water quality monitoring programs often collect, handle, preserve, and analyze samples using methodologies that evolve over time. Best professional judgment will be used to determine whether/if data sets can be compared. The final project report will detail any caveats or assumptions that were made when using data collected with differing sampling or analysis techniques.

Data set descriptions

This list identifies those repositories that contain relevant data; however, additional sources of information may be considered as needed and/or as new sources are identified. Below is a description of each repository identified in Appendix 4 along with a URL describing each program in more detail. In most cases data are available in electronic format.

Ecology Marine Waters Monitoring Data

The Department of Ecology has monitored water quality at approximately 40 stations within Puget Sound on a monthly basis since 1975. Some stations are monitored every year while some are monitored on a rotating schedule.

URL: http://www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html

Ecology South Puget Sound Field Studies

Ecology has been conducting a water quality study focused on low DO levels in South Puget Sound. Field surveys occurred from 1994 to 2007. Data include both river and wastewater treatment plant effluent water quality.

URL: http://www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html

Ecology Central Basin/Possession Sound Primary Production Study

From October 1998 through October 2001 Ecology conducted a study to assess whether primary production in Central Puget Sound and Possession Sound would be affected by the addition of nutrients (Newton and Van Voorhis, 2002). Data collected during this study will provide rate estimates for algal production as a function of light, season, and other controlling factors.

URL: <http://www.ecy.wa.gov/biblio/0203059.html>

Ecology Puget Sound Mooring Data

Since 2005 the Department of Ecology has maintained three moorings in Puget Sound in order to provide continuous data for investigation of status and trends of marine water quality. The moorings are located at piers and docks in Budd Inlet, Squaxin Passage, and Clam Bay and provide 15-minute values for temperature, conductivity (used to calculate salinity), DO, and chlorophyll *a* fluorescence.

URL: http://www.ecy.wa.gov/programs/eap/mar_wat/moorings.html

Ecology Freshwater Ambient Monitoring Data

Ecology maintains a freshwater ambient monitoring network that includes numerous sites on rivers and streams within the greater Puget Sound area.

URL: http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html

Hood Canal Dissolved Oxygen Program

Hood Canal Dissolved Oxygen Program (HCDOP) is a partnership of 28 organizations that conducts monitoring and analysis to determine sources of and potential corrective actions for the low DO in Hood Canal and its effects on marine life. HCDOP monitors marine water quality as well as water quality in rivers, streams, and groundwater sources that discharge into Hood Canal. Monitoring of present-day water properties in the canal is done using a combination of target field efforts, citizen volunteers, and by moorings with near-realtime data transmission capabilities (see description of 'APL ORCA Mooring Data' below).

URL: <http://www.hoodcanal.washington.edu/>

APL ORCA Mooring Data

Oceanic Remote Chemical Analyzers (ORCA) are autonomous moored profiling systems that provide real-time data streams of water and atmospheric conditions. They consist of a profiling underwater sensor package and a surface mounted weather station. Currently there are four ORCA mooring systems deployed, all in Hood Canal. Past deployments of the ORCA system have been in South Puget Sound (Carr Inlet) and in Central Puget Sound (near Point Wells).

URL: <http://orca.ocean.washington.edu/>

UW PRISM Field Studies

In partnership with Ecology, the University of Washington PRISM (Puget Sound Regional Synthesis Model) program conducted approximately twice-annual monitoring cruises encompassing approximately 40 stations located throughout Puget Sound starting in June 1998 and continuing through July 2004.

URL: <http://www.prism.washington.edu/>

King County DNR Puget Sound Marine Monitoring Data

King County's Marine and Sediment Assessment Group supports a comprehensive, long-term marine monitoring program that assesses water quality in Central Puget Sound. Their program consists of offshore water quality, beach water quality, intertidal sediment, algae, and clam monitoring.

URL: <http://green.kingcounty.gov/marine/Index.htm>

King County DNR Stream and River Monitoring Data

Many streams and rivers in the King County service area are assessed as part of the routine monitoring efforts by the King County Major Lake and Stream Monitoring Program. Monthly baseflow water quality samples have been collected at many of these sites since 1976. Data are analyzed to characterize the general water quality of the stream, determine if applicable state and federal water quality criteria are met, and to identify long-term water quality trends.

URL: <http://green.kingcounty.gov/WLR/Waterres/StreamsData/>

USGS Freshwater River/Stream Data

The United States Geological Survey maintains a network of streamflow gaging stations, including sites in the study area.

URL: <http://waterdata.usgs.gov/wa/nwis/rt>

Sinclair/Dyes Inlet Flow Data

The U.S. Navy's Puget Sound Naval Shipyard, in partnership with a variety of federal, state, and local governments, tribes, and community groups, developed and maintained a flow network for streams and creeks tributary to Sinclair and Dyes Inlets from 2001 to 2005 (May et al., 2005).

URL: http://www.ecy.wa.gov/programs/wq/tmdl/sinclair-dyes_inlets/sinclair_cd/DATA/Data_Directory.html

NPDES Data

Wastewater treatment plant monthly data reported under National Pollution Discharge Elimination System (NPDES) permits are available through Water Quality Permit Life Cycle System (WPLCS).

URL: <http://www.ecy.wa.gov/programs/wq/permits/wplcs/index.html>

Canadian data set descriptions

This list identifies those repositories that contain relevant data for Canadian waters; however, additional sources of information may be considered as needed and/or as new sources are identified. A URL has been provided that describes each program in more detail. In most cases data are available in electronic format.

Water Survey of Canada National Water Quantity Survey Program Data

The Water Survey of Canada (WSC) is the national agency responsible for the collection, interpretation and dissemination of standardized water resource data and information in Canada which includes data on aquatic quality, water quantity and sediment transport. The Water Survey of Canada provides real-time, current year and historical information for a network of over 2,200 sites in Canada and maintains a database containing historic data for some 5,300 non-active sites for the country.

URL: http://www.wsc.ec.gc.ca/index_e.cfm?cname=main_e.cfm

Environment Canada Municipal Water and Wastewater Survey Data

The Municipal Water and Wastewater Survey (MWWS) provides basic data on municipal water and wastewater. It is the latest in a series of such surveys. Survey information is available on a municipality specific basis.

URL: <http://www.ec.gc.ca/water/MWWS/en/index.cfm>

Environment Canada Pacific and Yukon Region Water Quality Monitoring Program Data

Pacific and Yukon Region's Environment Canada has been monitoring surface water quality for many years throughout British Columbia and the Yukon Territory. The larger part of the program is implemented with the BC Ministry of Environment in BC, with a smaller program being conducted with the Yukon Territory or solely by Environment Canada. These monitoring programs play an important role in determining long term trends in water quality, identifying emerging issues related to the aquatic environment and providing information to Canadians.

URL: <http://waterquality.ec.gc.ca/EN/home.htm>

Model Calibration and Evaluation

Once the model setup is completed, the model will be calibrated through comparison with observed data collected in Puget Sound. The term *calibration* is defined as the process of adjusting model parameters within physically defensible ranges until the resulting predictions give the best possible match with observed data. In some disciplines, calibration is also referred to as parameter estimation. Model *evaluation* is defined as the process used to generate information to determine whether a model and its analytical results are of a quality sufficient to serve as the basis for a decision and whether the model is capable of approximating the real system of interest (USEPA, 2008). In some disciplines, evaluation is also referred to as validation, confirmation, or verification.

To help ensure that the process of model calibration and evaluation remain independent, a subset of the available data will be withheld during model calibration. The withheld data will be used to evaluate the model output. In situations involving data scarcity it may be necessary to use all available data for calibration purposes. The final report will detail those data sets (or subsets thereof) that were used for both calibration and evaluation of the model.

Model calibration is an iterative procedure that is achieved using a combination of best professional judgment and quantitative comparison with a subset of the measured data. For example, the nitrogen balance will involve adjustment of nitrification and organic nitrogen hydrolysis rates, as well as uptake rates by phytoplankton. The phosphorus balance will include adjustment of organic phosphorus decay rate and uptakes rates by phytoplankton. Chlorophyll *a* data will represent phytoplankton density and will be used to adjust algal growth, die-off, respiration, and settling. Finally, phytoplankton growth, re-aeration, and BOD₅ in combination with nearshore SOD, will be specified to obtain the best match with observed DO data. When possible, direct measurements of the rate constants for key processes will be used to calibrate the model (e.g., maximum growth rates of phytoplankton, half-saturation constants, etc.).

Both calibration and evaluation of the model will rely on a combination of quantitative statistics for goodness-of-fit and visual comparison of predicted and observed time series and depth profiles (Krause et al., 2005). This methodology is consistent with the standard of practice that has been established for similar modeling programs and other detailed studies such as the Hood Canal Dissolved Oxygen Program, the UW PRISM Modeling Program, the Budd Inlet Scientific Study (Aura Nova Consultants et al., 1998), the Deschutes River/Capitol Lake/Budd Inlet Water

Quality Study (Roberts et al., 2008a), and the South Puget Sound Dissolved Oxygen Study (Roberts et al., 2008b). Bias will likely 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 it is our intention to minimize these discrepancies between observed and modeled data as much as possible, consulting with U.S. EPA (2008) and the MTAC.

Data for model calibration and evaluation will be used in a hierarchical fashion. Preference will be to use data that are coincident in both time and space (i.e., Puget Sound from 1999-2008) to the model simulations. If data are scarce then only spatially coincident data may be considered (i.e., Puget Sound from any time period). Should data or published guidance for a particular parameter value be lacking entirely for Puget Sound (or a region thereof) then published values from similar aquatic systems may be used. In all cases, best professional judgment will be used for the final determination of what data are used to calibrate and evaluate the model, and the process will be documented in the final reports.

Sensitivity and Uncertainty Analyses

To evaluate model performance and the variability of results, *sensitivity* and *uncertainty* analyses will be carried out. Uncertainty can arise from a number of sources that range from errors in the input data used to calibrate the model, to imprecise estimates for key parameters, to variations in how certain processes are parameterized in the model domain. Regardless of the underlying cause it is good practice to evaluate these uncertainties and reduce them if possible (USEPA, 2008; Taylor, 1997; Beck, 1987).

A model's sensitivity describes the degree to which results are affected by changes in a selected input parameter. In contrast, uncertainty analysis investigates the lack of knowledge about a certain population or the real value of model parameters. Although sensitivity and uncertainty analyses are closely related, uncertainty is parameter specific, and sensitivity is algorithm-specific with respect to model variables. By investigating the relative sensitivity of model parameters, a user can become knowledgeable of the relative importance of parameters in the model. By knowing the uncertainty associated with parameter values and the sensitivity of the model to specific parameters, a user will be more informed regarding the confidence that can be placed in the model results (USEPA, 2008).

During the calibration process the responsiveness of the model predictions to various assumptions and rate constants specified will be evaluated. The model setup will likely include parameters based on literature recommendations and best professional judgment, and estimates of loads in the absence of data. Specific areas to address with sensitivity and uncertainty analyses include boundary conditions, meteorologic forcing, sediment fluxes, watershed loads, as well as process rate parameters. Fundamental parameters will be varied by increasing and decreasing by a factor of two or an order of magnitude, and the resulting predictions compared to understand whether a factor has a discernible effect on circulation or water quality predictions. The final report will document the parameters that are varied and will identify any parameters that have great uncertainty and strongly influence the results.

Model Scenarios

After sensitivity analyses have been performed, the calibrated model will be used to evaluate water quality conditions observed in Puget Sound from 1999 – 2008 and to simulate the effects of various alternative nutrient loading scenarios. Results from this time period will also be compared to estimated natural background conditions. Natural conditions are characterized by the absence of human impacts on the nutrient loading and DO regime.

Modeling natural conditions typically involves creating a natural background model run corresponding to the existing conditions model run, except that estimated human influences have been removed as much as possible. Generally, this means removing all point sources and setting tributaries to natural loads. Accurate estimation of pre-development conditions may be difficult, so reasonable estimation methods will need to be developed. One possible strategy would be to set nutrient levels using reference streams/rivers in Puget Sound with the lowest (or nearly the lowest) nutrient levels observed from 1999 – 2008. Additional, more statistically sophisticated methods are also being considered. Some of the constituents may remain unchanged between natural and existing if no information is available to estimate pre-development conditions. The current marine boundary will be assumed to be natural for the purposes of this study.

Ecology will use the model to determine the impact of human activities on DO concentrations in Puget Sound. Using the initial calibration to the current point and nonpoint source loads the model will be applied to 4 to 6 alternate scenarios. The exact scenarios to be evaluated may change during the project, but likely candidates are as follows:

- Scenario 1 – Natural conditions.
- Scenario 2 – Current rivers and no point sources.
- Scenario 3 – Current point sources and natural conditions for rivers.
- Scenario 4 – Current rivers and maximum permitted point sources.
- Scenario 5 – Current rivers and point sources at projected loadings in 25 years.

Scenario results will be evaluated both as predicted patterns for that scenario and as differences between scenarios. The water quality standards call for no more than 0.2 mg/L degradation below water quality standards, or below natural conditions if natural conditions result in concentrations that are less than the values used to define the water quality standards (WAC 173-201A). It is expected that Ecology will apply the model for numerous scenarios and longer durations in the future.

Model Output Quality (Usability) Assessment

Final assessment of model performance will be conducted and summarized in the final report. This summary will evaluate whether the outcomes have met the project's original objectives. Criteria to be evaluated include whether or not the water quality model:

- Behaves in a manner that is consistent with the current understanding of processes known to affect water quality in the Puget Sound estuary system.
- Realistically reproduces variations in water quality observed within individual sub basins of Puget Sound on inter-annual, seasonal, and possibly intra-seasonal timescales.

Project Deliverables and Schedule

The following deliverables will be developed for this project according to the schedule presented in Table 2:

- Hydrodynamic model report (PNNL).
- Water quality model report (PNNL).
- Final project report and summary (including detailed documentation of the results and methods used to estimate loading from nonpoint and point sources).
- Focus sheet.

PNNL will prepare a draft report summarizing the development of the hydrodynamic model of Puget Sound. The report will present a review of available data used in model development. Model setup section will include a summary of bathymetry data, model grid, and a description of initial and boundary conditions. Qualitative and quantitative calibration of the model will be discussed along with model behavior and the ability to reproduce salient Puget Sound features.

PNNL will also prepare a draft report summarizing the development of the nutrients and water quality model of Puget Sound. The report will present a review of available data used in model development. The model setup section will include a summary of the point source and the tributary load data, the model grid, and a description of initial and boundary conditions. The qualitative and quantitative calibration of the model will be discussed along with a description of the model behavior and its ability to reproduce the salient Puget Sound features. The responsiveness of the model and the uncertainty associated with the model predictions will be discussed to summarize the sensitivity analysis results. Also, application of the model for the selected scenarios will be included along with a discussion of the implication of the results.

For each of PNNL report outlined above a draft report will be provided to Ecology for comments; once these comments are addressed, revised draft reports will be distributed to the PAC, and possibly the MTAC, for additional comments. Final reports will be prepared after incorporating Ecology's and the PAC's comments on draft reports.

Ecology will prepare a draft report summarizing the development of the intermediate-scale hydrodynamic and water quality models for Puget Sound. The report will present a comprehensive overview and synthesis of the two PNNL reports outlined above and serve as final documentation for the project. Following internal review by the project team and the Department of Ecology, the project report will be sent to the PAC for external review. After external review comments are addressed, the comprehensive Ecology report will be finalized. A focus sheet will then be created to summarize and highlight major findings from the project.

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