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Memorandum

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Subject: Draft Review of Puget Sound Hydrodynamic Model

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This document summarizes the review of a hydrodynamic model representing Puget Sound and adjacent waters, referred to as the intermediate scale model, developed by Pacific Northwest National Laboratory (PNNL) and the Washington Department of Ecology (ECY) for simulating circulation and water quality, [3,6]. The review follows the format outlined in the Puget Sound Model Review Memorandum previously provided to EPA and ECY. For this draft version of the review, the actual review task descriptions are retained in italics for reference. This same format was used for a previous memorandum [4] which summarized a similar review for ECY of the South Puget Sound Hydrodynamic Model [7]. Reference is made in this document for various comparative purposes since the models have common spatial sub-domains, simulation periods, and data sets [5].

Overall the modeling study was conducted and documented to a level consistent with similar studies of important large coastal water bodies. However, since a number of study components, including validation and sensitivity analysis are not included, the study is more appropriately viewed as a proof of concept or work in progress. A discussion of the relationship of this modeling study to the South Sound study with appropriate references would be useful in providing a historical perspective. No major flaws were identified with the work presented and comments provided herein are intended to further the credibility of the study and provide additional documentation

1. Review Appropriateness of Selected Models

This task will review and evaluate the appropriateness of selected models to determine that the models include the fundamental physical and biogeochemical processes necessary to simulate circulation and dissolved oxygen and nutrient dynamics in the corresponding physical domains consistent with project objectives. The task will briefly review the reasons for model development, the model selection process, identification of principal study questions, and associated modeling objectives as summarized in the project QAPP and related documents. This will provide the context for the review of the appropriateness of selected models. It will also provide important information relative to the degree of accuracy required in different aspects of the model configuration, calibration, and validation.

In addition to material provided by ECY, secondary material including model documentation and reports and papers describing previous model applications may be reviewed. Model source code will be reviewed only to the extent necessary to clarify insufficient detail or uncertainly in reviewed material. Model formulation and process representation limitations that could impact model performance relative to meeting project objectives will be identified and short- and long-term resolution strategies proposed.

The selection of the FVCOM [1] model is well described in the QAPP [5] for this study and the model's capabilities meet the defined needs of the study. A substantial amount of information, including referred articles, user documentation and source code is publicly available. A discussion of the relative importance of model vertical grid discretization, sigma or terrain following in the case of FVCOM, would be useful since the current South Sound model uses a Cartesian or Z vertical grid while an earlier South Sound model used a sigma vertical grid. Going from sigma to Z, and back to sigma tends to imply that the vertical discretization is relatively unimportant as compared to other model features and capabilities. It is also noted that two other unstructured grid models discussed in the model selection section of the QAPP [6], UNTRIM and SUNTANS, utilize Cartesian vertical grid discretizations. Since the recent South Sound model uses a Cartesian or Z grid in place of an earlier South Sound model with a sigma grid, the switch back to sigma vertical grid for the full sound model is curious and reasons for doing so should be addressed in this report.

2. Summarize Observational Data to Support Model Configuration, Calibration and Validation, and Scenario Simulation

The purpose of this task is to summarize and obtain documentation as necessary for observational data sources used for model configuration, calibration and validation, and scenario simulation development. It is designed to streamline subsequent tasks, which will look more closely at specific data types and usage, by ensuring that appropriate information is available.

Observational data sources used for model configuration and calibration are well documented. A more detailed and readily available reference for the X Tide predictions would be useful. A discussion or comparison of X Tide predictions with PS Tides [2] inside Puget Sound might be in order.

3. Review Model Configuration

Model configuration is defined as the sequence of steps leading to an operational model and includes selection of spatial resolution and grid development, selection of temporal simulation periods and assembly of corresponding forcing functions, boundary and initial conditions, and preliminary selection of adjustable model parameters. This task evaluates the forcing functions, boundary, and initial conditions from a general perspective as to suitability and use of appropriate processes. Detailed quality review of model input data is addressed separately in optional task 8. Subtasks include:

3.1. Model Spatial Resolution and Grid Development

The selection of model spatial resolution generally involves balancing trade offs between resolving important physical and biogeochemical processes, spatial data density, overall model accuracy and model computational performance. For example extremely fine spatial resolution may not be supported by corresponding dense data and could yield an operational model having high computational requirements and excess run time relative to desired simulation duration. Spatial resolution or grid sensitivity analysis, with respect to both horizontal and vertical resolution, is often appropriate to optimize between these competing requirements. This task will review and evaluate how these issues are addressed and consider associated topics of grid quality and bathymetric data and its interpolation to the model grid.

The model grid resolution is consistent with the intermediate scale concept defined in the QAPP [6]. Horizontal resolution within Puget Sound is similar with that used in the South Sound model [7], while resolution becomes coarser outside of the Sound. As noted in the model selection comments, a discussion of the selection of a sigma versus a Cartesian or 'Z' vertical grid would be useful. The trade off between model resolution and run time performance appears to be reasonable if a high performance computational cluster is available. It is presumed the 64 CPU run times are based on an MPI (message passing interface) parallel implementation. Since such systems are very costly to maintain, the computational performance on commodity 4 or 8 core desktop hardware under MPI or OpenMP would be of interest.

3.2. Selection of Model Temporal Simulation Period

The rationale for selection of the overall model simulation period, including identification of subintervals for calibration, validation, and scenarios simulations, will be reviewed and evaluated relative to the temporal density of supporting observational data and the computational requirements imposed by the combination of spatial and temporal resolution.

The model calibration was based on a simulation spanning calendar year 2006 which includes the observational data sets used for calibration of the South Sound model [7, 4]. A reference to 2007 observational data was not made; however it is anticipated that the 2007 data will be subsequently used for validation or to extend the calibration period. Since a number of previous model studies of Puget Sound have been conducted and calibrated to older observational data sets, a brief discussion of why these data were not used or the superiority of the 2006 data set would be useful. It is noted that the use of least squares harmonic analysis to compare observations and predictions allows tidal frequency elevation and current data of sufficient duration to be compared between different years.

3.3. Circulation Model Boundary Conditions and Forcing Functions

This task will review the major groups of boundary conditions and forcing functions required by the hydrodynamic and circulation model components. Emphasis will be placed on evaluating model boundary condition and forcing function formulations and options, selection of boundary condition locations, and use of observational data to define the boundary conditions and forcing functions. Specific groups of boundary conditions and forcing functions to be reviewed and evaluated will include:

3.3.1 – Hydrodynamic open boundary conditions for water surface elevation and/or inward-outward wave propagation

There is a short discussion of the problem of specification of the water surface elevation open boundaries when there are no nearby observational data. In this case predictions by the X Tides software is used to specify what is assumed to be a water surface elevation condition rather than the more general inward propagating wave conditions. Decomposition of the forcing function into tidal harmonics and sub-tidal frequency sea level would allow a formal determination of the open boundary tidal frequency boundary conditions in harmonic form which would result in a best fit to the six long-term NOAA tide gauges in the model domain. Also there is no discussion of sub-tidal frequency water surface elevation forcing. Analysis of the NOAA record at Elliott Bay indicates a sub-tidal variation in water surface elevation, however this variation is relatively small compared the principal harmonic amplitudes. A discussion of sub-tidal forcing and how it is incorporated or why it is neglected should be included.

3.3.3 – Open boundary conditions for salinity and temperature

Section 2.4 discusses the use of monthly salinity and temperature profile observations near the open boundaries to specify inflow conditions. These conditions were abandoned in favor of constant salinity and temperature profiles during the calibration process. From one perspective, the use of the constant profiles is desirable if model simulations outside of the observation period are conducted. It might be useful to discuss the alternative of constant profile boundary conditions in this section and note that the two alternatives will be evaluated during calibration.

3.3.4 – Point and distributed fresh water inflows and associated temperatures

The development of fresh water inflows to the systems appears thorough and reasonably well documented.

3.3.5 – Surface wind stress forcing functions and its spatial representation

See next section.

3.3.6 – Atmospheric forcing including surface wind stress and thermal forcing functions and water column-sediment bed thermal coupling

The report discusses the use of actual observational data or meteorological model output data for specification of wind and atmospheric thermal forcing. Following a brief discussion on potential incompleteness of observational data sets, the choice was made to use meteorological model output, specifically the NOAA NARR data sets generated by the NCEP Eta model. The description of how

this model output is used implies that the net surface heat flux is externally calculated and input to the FVCOM model at hourly intervals at a 32 km spatial scale. This leaves some confusion as to whether the FVCOM model has a full internal thermal formulation or can only accept net surface heat flux, which should be clarified. For comparison, the South Sound hydrodynamic model was thermally forced with meteorological observations. It is suspected that there are sufficient additional US and Canadian observation stations to do the same for this model which merits further discussion particularly since the atmospheric thermal forcing is discussed as a source of uncertainty.

Additional groups will be considered as appropriate. This subtask will evaluate the appropriateness of or identify any deficiencies in specification of boundary conditions and forcing functions and methods for resolution proposed.

3.4. Circulation Model Initial Conditions

Circulation models are relatively insensitive to initial conditions after an appropriate initialization period. However, for salinity this period can be long and can be eliminated with initial conditions which are approximately dynamically balanced. Circulation model initial conditions will be reviewed relative to these considerations and methods for refining initial conditions recommended if appropriate.

Initial conditions for the start of the 2006 model simulation are stated to be based on restart conditions from a 2005 simulation, which is quite appropriate. No discussion of the model configuration for 2005 is presented, but it is presumed that corresponding boundary conditions and forcing functions were developed allowing simulation of all or part of 2005.

3.5. Circulation Model Options and Parameters

Circulation and transport models have a variety of options and parameters that require initial specification and possible subsequent adjustment during calibration. Areas to be reviewed include, but are not necessarily limited to:

3.5.1 – Numerical solution options and time step size, which influence model accuracy and stability.

Important numerical solution options are listed in Table 3-1. The external mode time step is consistent with the bathymetry and grid. Table 3-1 indicates that the water surface elevation open boundary condition is applied in a radiation form, as opposed to clamped form. The clamped condition specifies only water surface elevation and can lead to reflection of outward propagating waves back into the model domain. The radiation condition generally specifies the characteristic of the incoming wave leaving the boundary free to radiate outgoing waves without back reflection. This was not discussed in the section on boundary conditions, which implied a clamped implementation. This should be clarified and further discussed in the boundary condition section.

3.5.2 – Bottom boundary resistance and wind stress parameter specification.

Both a bottom roughness height and a quadratic law coefficient are listed in Table 3-1. Generally the roughness height and depth are used to determine the quadratic law coefficient. Further explanation is desirable including the choice of the roughness height and its possible adjustment during calibration. A reference to the wind stress formulation would also be useful.

3.5.3 – Adjustable turbulence closure and mixing parameters

The coefficient for the Smagorinsky horizontal turbulence closure is provided and reasonable. A number of variants of the stability functions used in the Mellor-Yamada scheme have been proposed over the years. Reference to the functions would be useful.

3.5.4 – Adjustable atmospheric thermal forcing and heat exchange parameters

The model was thermally forced with net surface heat flux and no adjustments to this flux were discussed

As appropriate, various model parameters will be compared with accepted by ranges for similar water body and geographic locations.

4. Review Model Calibration

Model calibration is defined as the adjustment of model boundary conditions and forcing functions and selected model parameters to achieve a desired or defined level of agreement between model predictions and observations of circulation and water quality state variables. Procedures to measure of the level of agreement range from qualitative visual comparison to a range of rigorous quantitative measures. The purpose of this task is to determine if calibration methods and parameters were appropriately selected, their adjustment constrained to remain within acceptable ranges, and the resulting levels of agreement between predicted and observed state variables are consistent with intended model use. Defining acceptable levels of agreement is often difficult, however results for similar modeling studies that have undergone extensive independent peer review provides a generally accepted basis and will be summarized in this review for comparison with results obtained in this study. Model calibration will also be evaluated in relation to the modeling objectives identified in the QAPP.

4.1. Circulation Model Calibration

Circulation model state variables used for calibration include water surface elevation, horizontal current velocities, salinity concentration, and temperature. These variables respond to changes in boundary conditions, forcing functions, and adjustable model parameters. Adjustments to boundary conditions and forcing functions to improve the level of agreement must be soundly supported in relation to the observational data used. Appropriate quantitative measures include time series error measures such as mean absolution error and root mean square error, linear regression, least squares harmonic analysis, and empirical orthogonal function analysis. Variables, observational data, and quantitative measures used for calibration will be reviewed and compared with published calibration performance from similar model studies.

4.1.1 – Water Surface Elevation Calibration

A set of 9-month long time series plots are presented that qualitatively confirm the model's ability to predict tidal frequency water surface elevation. Six of the plots are comparisons of observational stations and the remaining three are comparisons with X Tide predictions. Time series error measures for the nine comparison locations are presented in tabular form. It is assumed that the quantity referred to as absolute mean error is actually the mean absolute error between observations

and predictions at the comparison interval, normally taken to be one hour or less. A relative error is formed by normalizing the so-called AME with respect to the tide range, which is assumed to be the average range of a spring-neap cycle. Root mean square errors at Seattle and Tacoma are larger than those reported for the South Sound model [7] however the time period used to compute the errors is not reported in either study.

Since the model is forced on the open boundary by harmonic constituent generated forcing, harmonic analysis and comparison of observed and model predicted constituents would also be appropriate to refine water surface elevation calibration. There are no water surface elevation comparisons in the Canadian portion of the model domain. The Canadian Tides and Water Level Data Archive show six stations, including one at the north end of the Georgia Strait, which could potentially be used. There is some concern about sub-tidal sea level forcing and response as noted in comment 3.3.1.

4.1.2 – Velocity Calibration

Velocity calibration utilized data from four bottom mounted continuous ADCP deployments. Results from the bottom mounted, continuously deployed ADCP measurements were compared with model predictions in visual time series format. The vertical scale of the Pickering Passage plots should be adjusted for better visual comparison. Comparisons were made for near surface, mid-depth and near bottom velocities along the principal flow axis. Corresponding AME (assumed to actually be mean absolute error) and RMSE measures were presented. Errors were within accepted ranges. Normalization of either of the dimensional errors with observation root mean square magnitudes should be considered to provide relative errors. Additional ADCP data sets in Puget Sound exist for years other than 2006 and the use of vector least squares harmonic analysis to compare these observations with model predictions would allow across-year comparison if the observational data sets spanned 14 days or longer. This approach would allow comparison of principal direction, major axis amplitude and major axis phase by constituent.

4.1.3 – Temperature and Salinity Calibration

Temperature and salinity calibration included visual comparison of monthly interval salinity and temperature profiles at 10 of 25 available locations during 2006. Although this is a useful form of comparison the small scale of the plots hinders visual judgment. The lumped error measures for the 10 locations is difficult to interpret but appears to be the time average of the absolute vertically integrated difference between observed and predicted profiles. In general a simple mathematical equation definition of an error measure serves to eliminate confusion. This approach for defining a quantitative measure tends to yield errors that are below readily evident visual estimates

Another widely used approach for comparing routinely sampled observational data, such as the monthly profiles, with continuous model predictions is to show continuous surface, mid-depth and bottom time series of model predicted salinity and temperature with the observations plotted as discrete points. This tends to provide a better portrayal of seasonal behavior and the tendency of the model predictions to follow observations. This approach also allows separate mean absolute and root mean square errors characteristic of the vertical position to be determined. This approach is considered a standard for water quality.

4.1.4 – Additional Comments

5. Review Model Validation and Sensitivity and Uncertainty Analysis

This task will evaluate the validation of the models and also consider sensitivity and uncertainly analyses if they were conducted during the modeling study.

5.1. Model Validation

Model validation is defined as the evaluation of the level of agreement between model predictions and observations of circulation and water quality state variables over a time interval not used in the calibration process. The model is considered validated if a similar level of agreement similar to that obtained during calibration is achieved. Strict separation of calibration and validation is often difficult to achieve in practice as limitations in the extent of the observational dataset necessitates the use of the entire dataset in a combined calibration and validation activity. In this mode, high variability of conditions during the combined interval and corresponding consistent model performance is an important consideration. This subtask will evaluate validation of the circulation and water quality models or, if independent validations were not conducted, address the appropriateness of the calibration with respect to level of variability during the calibration period.

5.1.1 – Water Surface Elevation Validation

5.1.2 – Velocity Validation

5.1.3 – Temperature and Salinity Validation

5.1.4 General Comment on Calibration and Validation

No validation results were presented in this report. It is presumed that validation will be undertaken using the 2007 observational data as the development of the model continues. Comments on presentation and analysis of calibration results would apply also to future validation.

5.2. Sensitivity and Uncertainty Analysis

Sensitivity analysis is also important in demonstrating that the model is sufficiently calibrated, particularly in the absence of an independent validation period. Sensitivity analysis is also important in demonstrating that the model will be responsive to the range of load variations anticipated in management scenario simulation. Sensitivity analysis can also contribute to understanding the propagation of uncertainty in the water quality model when perturbations in loads and parameters represent the range of uncertainty in these variables. This subtask will evaluate the extent to which sensitivity and uncertainty analysis were incorporated into this study and make recommendations for further analysis if deemed appropriate as applicable to specific study components.

No sensitivity or uncertainty analyses are reported, but the final chapter of the report does include a discussion of various sources of uncertainty. Formal probabilistic uncertainty analysis is seldom done on hydrodynamic models; instead sensitivity analysis is often done to evaluate the model's

response over a range of specific parameters with that range being a measure of uncertainty. Specific areas addressed in the report and corresponding comments include:

Bathymetry in Shallow Areas. The use of a minimum depth of 4 meters is alluded to as a source of uncertainty and is definitely a computational limitation of the model. Many estuarine and coastal models can operate in drying and wetting mode and the choice to use a model not having this capability suggests that this was not an important issue at the time of model selection. Some tuning of the existing shallow bathymetry and estimation of the effect of the minimum depth requirement on the tidal prism of the Sound might resolve this.

Uncertainty in X Tide Prediction to Provide Open Boundary Forcing. This would seem be more of a problem of not fully exploring alternative approaches to specifying the open boundary forcing in a manner that is compatible with an optimization approach to calibration than a sensitivity issue. There is extensive literature of how to specify tidal open boundary conditions in a manner that minimizes the interior difference between observed and predicted water surface elevations. Further information can be provided if this is of interest.

Uncertainty in Meteorological Model Outputs for Net Surface Heat Flux Forcing. This would seem to be an issue with the choice of how to force the thermal component of the model. Many operational coastal and estuary models have full thermal formulations and readily accept standard hourly time scale observational data available form the National Climate Data Center and in this specific case, Environment Canada. It is suggested that implementation of observational data based thermal forcing be considered rather than attempting to quantify uncertainty in the output of the meteorological model necessary to design sensitivity simulations.

Uncertainty in River Temperatures. This is not viewed as a significant source of uncertainty in and of itself. Water temperature responds locally and rapidly to atmospheric thermal forcing and in many cases where data are lacking, setting the river inflow temperature to the hourly air temperature is sufficient.

Boundary Salinity and Temperature. As noted above, temperature responds locally and rapidly to atmospheric thermal forcing. Likewise temperature has a strong annual signal which has much less variation form year to year than salinity. Monthly temperature profiles near the open boundary could be used to fit a smoothly varying Fourier function to eliminate saw tooth interpolation. Open boundary salinity specification is more difficult since the open boundary salinity represents a response to interior fresh water sources. One approach that has met with some success, is to correlate observed salinity near the boundary with time-lagged river discharges. This has the potential to extend the boundary condition to years where there is no observational data. The salinity boundary condition is also the main forcing function that should be subjected to sensitivity analysis with respect to profile shape and reflux of outgoing water back into the model domain.

6. Review Model Scenario Selection and Results

This task will review and evaluate the procedures used to define model scenarios if applicable to the specific study components. As applicable, modifications to model configurations necessary to simulate the scenarios would be evaluated. Results of the scenarios will be evaluated for reasonableness and consistency with sensitivity and uncertainty analyses in the event that these

analyses were performed. Methods for quantifying the management effectiveness of the scenarios will be reviewed and alternate methods proposed if necessary.

No specific model scenarios, which are more relevant to water quality simulations, were provided in this report. Representative graphics showing distributions of salinity, temperature and horizontal velocity were presented.

7. Review Model Report and Associated Documentation

This final task will evaluate the model report and associate supporting documentation and software. It is assumed that draft reports will provide the primary source of information upon which the overall review will be based and reference readily available supporting documents necessary of completeness.

7.1. Model Report

The final review of the model report will validate that all issues identified in subsequent steps of the review have been addressed. The final review will also focus on ensuring that modeling objectives, limitations, findings, and conclusions are clearly stated.

The model report is well organized and written. It would be useful to expand the executive summary and/or introduction to better define the scope and extent of the study and reference previous and other ongoing studies. The lack of validation or an integrated calibration/validation and the concluding recommendations suggest that this is a proof of concept or work in progress.

7.2. Supporting Documentation

This sub-task will confirm that adequate support documentation for the model study and model are available. Documents to be considered would include data reports, work plans, QAPPs, model theory reports, and model user manuals.

Support documentation was included in the QAPP [6]. A data report [5] was available from the previous review of the South Sound hydrodynamic model. Documentation for the FVCOM model is readily available to the public on the Internet.

7.3. Links to Modeling Software and Input Files

If public domain modeling software was utilized, links to source code, executables, and input files should be provided or explanations as to why they are not available should be provided.

Links to the model documentation and code were readily found on the Internet. No access to input files was provided.

8. References

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[3] Pacific Northwest National Laboratory, 2009. Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate-Scale Hydrodynamic Model. Prepared for Washington Department of Ecology. PNNL-18484, November 2009, 80 pp.

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[7] Washington Department of Ecology, 2009. South Puget Sound Dissolved Oxygen Study – South and Central Puget Sound Water Circulation Model Development and Calibration. External Draft Review Version Dated October 15, 2009, 155 pp.