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Memorandum

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Subject: Draft Review of South Puget Sound Hydrodynamic Model

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This document summarizes the review of the South Puget Sound hydrodynamic model developed by Washington Department of Ecology (ECY) for simulating circulation and water quality, [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.

Overall the modeling study was conducted and documented to a level consistent with similar studies of important large coastal water bodies. No major flaws were identified and comments provided herein are intended to further the credibility of the study and provide additional documentation. Assigning chapter, section and sub-section numbering to the report sections would more easily allow referencing both internally and externally.

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 GEMSS model is well described in the cited reference [3] and the model's capabilities meet the defined needs of the study. It is noted that a number of other available modeling systems were omitted from the score-based evaluation in [3], however ECY's previous experience with GEMSS and it capabilities would tend to make its selection none controversial even in the absences of numerical rating. The description of the GEMSS model provided is adequate, but the few references that are cited are difficult to obtain. A more definitive list of references including detailed technical documentation, such as [1], and referred journal articles would be desirable.

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, calibration and validation, and scenario simulation are well presented in the report. A number of additional documents, including [1,2,4] were obtained and reviewed.

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.

A somewhat more detailed discussion of the origin of the horizontal model grid and its unique mapping features would be appropriate as well as how this grid was accommodated into the GEMSS model. The separate Appendix A, [5] provides a very detailed description of interpolation of bathymetry onto the model grid and the vertical layering. Some discussion of the selection of a Cartesian or 'Z' vertical grid as opposed to terrain following or sigma vertical grids used in a number of previous model applications to Puget Sound would be in order.

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 calibration and validation period are based on 2006-2007 field observation periods. Partitioning of the period into separate calibration and validation periods follows well accepted procedures. 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 used data set would be useful.

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 boundary at Edmond using the results of a previous one-dimensional tidal model [2] since the only long-term observation stations in Elliott Bay and Commencement Bay are far away. Since the model is harmonically forced, a harmonic boundary condition at Edmonds can be readily generated by calibration to the Elliott Bay and Commencement Bay harmonics. As noted the water surface open boundary condition is based on harmonic generated water surface elevation. There is not 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 discuss 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

Monthly time scale salinity and temperature observations near the west and east side for the open boundary were used for boundary conditions. Liner interpolation was used to produce model time step scale temporal values. This approach is generally acceptable. The approach was illustrated using depth-time contour plots of salinity and temperature which are somewhat difficult to visually evaluate. Time series plots for salinity and temperature at a number of depths would be complimentary. A question to consider if longer term water quality simulations are to be conducted is how to extend the boundary conditions to different time period. Fourier analysis has been shown to work well for temperature, while regression relationships between global fresh water inflow and spring-neap tidal phase are promising for salinity.

3.3.4 – Point and distributed fresh water inflows and associated temperatures

The development of fresh water inflows to the systems is thorough and well documented in the model report and referenced data reports.

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

Observational data for wind and atmospheric thermal forcing are associated with four observational stations. How the various locations are used in described in a context of refining the model calibration. A summary table listing parameters such as wind speed and direction, air temperature, relative humidity, solar short wave radiation and cloud cover and which stations were used to provide data would clarify the final configuration. Also when data from multiple locations is used, the method of interpolation onto the model grid should be described.

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.

The method of defining initial conditions for salinity and temperature is well described. The rationale for using three zonal averages rather than interpolation of actual profiles merits some discussion. There are a number of procedures for level surface profile interpolation. Repetitive simulation of a short spin up period such as the first month would also be an option.

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.

A short paragraph summarizing alternate numerical solution schemes used should be included, particularly the advection scheme which influences the time step and stability. The time step, or range of times steps, if dynamic time stepping is used should be stated.

3.5.2 – Bottom boundary resistance and wind stress parameter specification.

A short description of bottom roughness and its sensitivity is presented based on dimensionless Chezy coefficients which are not widely used in three-dimensional hydrodynamic models. The relationship between the Chezy coefficient and absolute roughness measures such as the log law roughness height, z_o, or equivalent sand grain roughness, k_s, should be provide with appropriate reference as to how the Chezy coefficient is used in GEMSS.

3.5.3 – Adjustable turbulence closure and mixing parameters

The GEMSS model has options for a number of turbulence closure schemes and the particular scheme used should be stated.

3.5.4 – Adjustable atmospheric thermal forcing and heat exchange parameters

The section on atmospheric thermal forcing provide some discussion of refinement of the thermal forcing to achieve temperature calibration

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

An extensive set of time series plots are presented which qualitatively confirm that the model's ability to predict tidal frequency water surface elevation is very good. Quantitative RMS errors are also shown in the time series plots and are within acceptable ranges. Presenting these RMS errors in tabular form is suggested. It would also be useful to normalize the RMS using the RMS of the PStide predict which is used in lieu of actual observations, Since the model is forced by harmonic constituent generated open boundary water surface elevations, harmonic comparison in Table 4 provides an additional quantitative measure of calibration. Agreements between predicted amplitudes and phases and corresponding observation based amplitudes and phases from Elliott Bay and Commencement Bay are good with the larger M2 and K1 amplitudes being within 5 percent. Phase errors are somewhat easier to interpret when stated in minutes rather than degrees, however making the conversion indicates that phase error are less than 15 minutes for all constituents and less than 5 minutes for the M2. There is some concern about sub-tidal forcing and response as noted in comment 3.3.1.

4.1.2 – Velocity Calibration

Velocity calibration utilized both surface mounted ADCP transects and bottom mounted continuous deployments. Considering the variety of sources of error and uncertainty in making transect comparisons, many of the section average velocities agree well with observations, particularly when areas are in close agreement. Alternative comparisons for transect data might consider interpolation of sub-sections of transects into horizontal model grid cells and comparing transports at the grid cell level.

Results form bottom mounted, continuous deployed ADCP measurements were compared with model predictions in visual time series format with corresponding error measures. Comparisons were made for near surface east and north velocity components with corresponding RMS error measures. The vertical scaling of the time series plots should be increased to facilitate better visual comparison. Since the comparison periods are on the order of 14 days, an alternate comparison would involve estimation of principle current direction for observations and model predictions and showing a single time series plot of the velocity vector component along the principal direction and corresponding principal direction based RMS errors. These RMS errors could also be normalized by the RMS of the observations. Summary presentation of principal directions and errors in a tabular form would also be useful.

4.1.3 – Temperature and Salinity Calibration

Temperature and salinity calibration included visual comparison of surface patterns for six days encompassing the calibration and validation periods, visual and quantitative time series comparison at different levels in the water column, and visual and quantitative comparison of profiles. The graphical comparison of observed and predicted surface temperature and salinity shows good agreement, however the different formats used for observations and model predictions make the comparison somewhat tedious. Displaying observations on the model grid rather than a map would provide a better visual grounding for the viewer. Another alternative is to show the colored observational circles on the model grid based predictions, with the size of the graphics expanded to a full page. Using this approach, differences between observation values and the immediate surrounding predicted values tend to stand out. This comparison could also be made quantitatively using spatial summed mean absolute errors or RMS errors.

Visual and quantitative time series comparisons of salinity and temperature follow standard procedure and the results appear reasonable. Tabular summary of RMS errors by station and position in the water column would make overall comparison easier. Although RMS errors generally provide the most stringent measure, other measures including mean absolute errors might be considered. Also normalization of the errors by the RMS or average of the observations would be useful.

4.1.4 – Additional Comments

The comparison of Brunt-Vaisala frequency is interesting and generally shows that the model reproduces the general profiles.

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

Time series plots and RMS errors are presented for a validation time period different than the calibration period. Similar levels of performance seem to be obtained. A table showing RMS errors for the calibration and validation periods would be helpful for quick comparison as opposed to going back and forth between plots. This would be the same table suggested in comment 4.1.1.

5.1.2 – Velocity Validation

Comparisons of observed and predicted velocities were not separated in calibration and validation periods.

5.1.3 – Temperature and Salinity Validation

Temperature and salinity time series and profile comparisons are presented for the validation period in the same format as was used for calibration. Generally the level of agreement appears consistent; however tabular comparison of errors by station and/or water column level would provide a useful summary.

5.1.4 General Comment on Calibration and Validation

Summaries of errors for both calibration and validation in tabular form are recommended, as well as additional normalized errors. Regression measures might also be considered. Comparison of error ranges for this study with other larger estuary studies would also be useful.

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.

The report contains a short paragraph discussing sensitivity to open boundary conditions which is sufficient. Two other sensitivity considerations are also addressed in relation to calibration. The first was respect to bottom friction and is addressed in comment 3.5.2. The second considered sensitivity to vertical layering and presented a strong argument to support using 17 rather than 35 vertical layers at the expense of a slight change in water surface elevation prediction. The sensitivity also considered vertical layer thickness near the water surface. It is somewhat troubling that the model is unstable with a surface layer thickness of 3 meters. The report also indicates that using a stable 4 meter thick layer increased run time, however the report and Appendix A document the use of a 4 meter surface layer. The fact that vertical profiles are well predicted may make these comments moot.

Questions: Does the quoted 35 layer run time of 9 CPU days per 17 months refer to hydrodynamics with salinity and temperature and no water quality? Also does the model tend to scale by number of layers with the 17 layer version running approximately twice as fast?

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 conducted. Flushing or residence time simulation experiments and dye release experiments were conducted. Experiments of this type are useful to gain some insight into system behavior. The difference in time scales obtained using different definitions of flushing time vary significantly and the most appropriate value is difficult to determine in the absence of field observations.

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.

Assigning chapter, section and sub-section numbering to the report sections would more easily allow referencing both internally and externally. This task will be concluded if the model report is revised subject to provided comments.

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 including QAPP, data reports, and model documentation were provided and are judged to be acceptable for external review purposes.

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.

Access to the model code, executables, and input files has been provided. A readme file describing the contents of the directories would be useful for further review and essential for archival purposes. Additional comments are anticipated with further review of this material

8. References

[1] ERM, 2006. GEMSS-HDM, Hydrodynamic and Transport Module, Technical Documentation. April 2006, 42 pp.

[2] National Oceanic and Atmospheric Administration, 2002. Tidal Datum Distributions in Puget Sound Washington Based on a Tidal Model. Technical Memorandum OAR PMEL-122, November 2002, 39 pp.

[3] Washington Department of Ecology, 2007. South Puget Sound Water Quality Study, Phase 2: Dissolved Oxygen, Quality Assurance Plan. Publication No. 07-03-101, August 2007, 70 pp.

[4] Washington Department of Ecology, 2008a. South Puget Sound Dissolved Oxygen Study, Interim Data Report. Publication No. 08-03-037, August 2007, 70 pp.

[5] Washington Department of Ecology, 2008b. South Puget Sound Dissolved Oxygen Study – South and Central Puget Sound Water Circulation Model Development and Calibration: Appendix A, Model Grid Development Dated December 18, 2008, 4 pp.

[6] 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, 155p.