Green-Duwamish Pollutant Loading Assessment (PLA)
Receiving Water Fate and Transport Model Development Update
5/17/2018

The PLA modeling approach consists of a linked watershed/receiving water/food web modeling system describing hydrology, hydrodynamics, and pollutant loading in the Green/Duwamish River watershed. The PLA tool will represent sediment transport, resuspension and sedimentation, as well as the dominant processes affecting the transformations and transport of toxic pollutants throughout the watershed. The Modeling Quality Assurance Project Plan (QAPP) for the PLA project envisioned modeling components include a Loading Simulation Program - C++ (LSPC) watershed model, the Environmental Fluid Dynamics Code (EFDC) receiving water model, and the Arnot and Gobas food web model (FWM). The watershed modeling component was changed to the Hydrologic Simulation Program Fortran (HSPF) following recommendations of the project team. Currently the project team is considering changing the receiving water model component from EFDC to the Salish Sea Model (SSM) that is being jointly developed by the Department of Ecology and the Pacific Northwest National Laboratory. The purpose of this memo is to compare pros and cons of EFDC versus SSM for the receiving water model in order to provide information to Technical Advisory Committees (TAC) to decide: **which receiving water model should the project use (EFDC or SSM)?**

Background on originally considering EFDC

Receiving water models were considered as a part of the PLA evaluation given the complex flow dynamics in the LDW, coupled with the variable hydrologic inputs from the Green/Duwamish River watershed. Several receiving water studies have been completed in the LDW over the past 15 years (see Section 3.2.2 of the QAPP). The Environmental Fluid Dynamics Code (EFDC) framework was used to support these studies with minor exceptions. The previous efforts provide the basis for originally envisioning using an EFDC framework for the PLA. The EFDC model has been applied worldwide for both hydrodynamic and water quality applications and can be easily linked to the watershed models that have been evaluated for representation of watershed source loadings.

EFDC is a general purpose modeling package for simulating one- or multi-dimensional flow, transport, and bio-geochemical processes in surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions. The EFDC model was originally developed by Hamrick (1992) at the Virginia Institute of Marine Science for estuarine and coastal applications and is considered public domain software. This model is now EPA-supported and has been used extensively to support receiving water modeling studies throughout the world.

Two LDW EFDC models were developed for different purposes:

1. King County's hydrodynamic, sediment transport and contaminant model in support of food web model simulated PCBs.
2. QEA's extensive EFDC-SEDZLJ hydrodynamic and sediment transport model in support of sediment bed contaminant study.

The comparisons of the two versions are listed in Table 1. Alternatively, other latest EFDC version could be evaluated as needed.

Background on the Salish Sea Model (SSM)

Khangaonkar et al (in review to be published in JGR) provide a review of the background of the current status of development of a comprehensive water-quality model of the entire Salish Sea that was initiated in response to eutrophication concerns about management of nutrient pollution and the assimilative capacity of the Salish Sea. Past hydrodynamic and biogeochemical model developments in the Salish Sea by U.S researchers have focused on Puget Sound and those by Canadian researchers have focused on Georgia Strait and coastal waters surrounding Vancouver Island. While numerous hydrodynamic models of varying complexity, ranging from simplified box models to fully three-dimensional (3-D) baroclinic formulations, have been developed, few studies using the associated biogeochemical models have been conducted. Ecology developed a biogeochemical model of South Puget Sound to simulate DO levels in response to phytoplankton primary production, oxidation of organic material, and sediment flux (Ahmed et al. 2014; Ahmed et al., 2017). The University of Washington (UW) developed a model of Hood Canal related to hypoxia concerns (Kawase & Bahng, 2007). The above efforts were relatively localized and restricted to sub-basins within the Salish Sea. UW also developed a Regional Ocean Modeling System (Haidvogel et al., 2000) based model of the Salish Sea and adjacent coastal waters (Giddings et al,. 2014; Davis et al., 2014; and Siedlecki et al., 2015) through studies aimed at understanding the formation of harmful algal blooms and transport pathways, the influence of freshwater inputs on primary productivity, and the seasonal and regional variability of DO. The focus of these larger scale modeling studies at UW has mostly been on the Pacific Northwest coastal shelf waters away from inner Salish Sea waters.

To resolve the inter-basin exchange and biogeochemical response to nutrient pollution from over 100 wastewater outfalls and numerous non-point sources in the inner waters of the Salish Sea, Pacific Northwest National Laboratory, in collaboration with Ecology, developed an externally coupled hydrodynamic and biogeochemical model of the entire Salish Sea (Khangaonkar et al., 2011; 2012). The model was constructed using the unstructured grid Finite Volume Community Ocean model (FVCOM; Chen et al., 2003) version 2.7 framework and integrated-compartment model biogeochemical water-quality kinetics (CE-QUAL-ICM; Cerco and Cole, 1994; 1995). The early version of the model was limited by the fact that the ocean boundaries were set near the entrances to the Strait of Juan de Fuca and the north boundary of Georgia Strait. As a result, accurate simulation of estuarine exchange with the Pacific Ocean through the Strait of Juan de Fuca and Johnstone Strait required extensive boundary adjustment as part of model calibration. Another limitation was that sediment water interaction was prescribed as being uniform fluxes of nutrients and DO. The model worked reasonably well in most sub-basins but could not achieve domain-wide calibration for near-bed DO levels. With prescribed uniform sediment fluxes, hypoxia in regions such as Lynch Cove region of Hood Canal could not be reproduced satisfactorily.

The model code and model grid have since been updated to overcome the limitations of the prior version. An improved version of the unstructured grid FVCOM-based Salish Sea Model was recently completed and presented in Khangaonkar et al (in review). To facilitate enhanced exchange with the Pacific Ocean, the Salish Sea Model grid was expanded to include coastal waters around Vancouver Island and the continental shelf from Canada's Queen Charlotte Strait to Oregon's Waldport (south of Yaquina Bay). Willapa River, Chehalis River, and Columbia River discharges to the shelf were also included in the domain. Johnstone Strait at the north end of Georgia Strait offers a second pathway for exchange with the Pacific Ocean along the east shores of Vancouver Island. In an earlier effort, Khangaonkar et al. (2017) showed that this pathway could be significant, so it is now explicitly included in the model. The model now also includes a sediment diagenesis module (Pelletier et al., 2017a; Bianucci et al., under review), which allows direct coupled interaction between the water column and sediments through the processes of organic sediment settling, burial, and remineralization. The sediment module generates nutrient fluxes including sediment oxygen demand. The model also includes carbonate chemistry with dissolved inorganic carbon, total alkalinity, pCO2, and pH (Pelletier et al., 2017b; Bianucci et al., under review).

A toxics module is not currently part of the SSM framework, but could be added with funding support from EPA. The toxics module would be adapted from already existing model codes that are part of another modeling framework (e.g. EPA's WASP-TOXI modeling framework).

An overlay of the computational grids used in past EFDC and SSM applications in the vicinity of the PLA project area is presented in Figure 1. The spatial resolution of the already existing SSM grid is greater than the EFDC grid. In addition the unstructured SSM grid is adaptable to constructing higher resolution with better conformance with shorelines and bathymetry compared with the curvilinear orthogonal grid used in EFDC.

Other modeling frameworks used in past and ongoing projects in the Salish Sea

In addition to EFDC and the SSM, two other major modeling frameworks are currently being used in projects in the Salish Sea:

- Dr. Parker MacCready, at the University of Washington, is currently applying the ROMS modeling framework to predict hydrodynamics and biogeochemical processes in a large area including a large part of the NE Pacific Ocean and the Salish Sea.
- The USGS is developing a project they call CoSMoS that uses the DELFT-3D modeling framework. DELFT-3D is also being used in research modeling in the Duwamish River by Dr. Alexander Horner-Devine at the University of Washington.

Neither the ROMS or DELFT-3D modeling frameworks include toxics kinetics modules with the level of complexity that is needed to support the PLA project, and no funding source has been identified that could add this capability. Therefore, these frameworks will not be considered for use in the PLA project.

Comparison between EFDC and SSM

EFDC Pros:

1. Some model files are already set up for past applications by King County, QEA and others.
2. QEA's EFDC is linked with the State-of-the-art SEDZLJ via a hydrodynamic linkage file.
3. Toxic fate and transport kinetics are already part of the EFDC modeling framework.
4. The nutrient modeling support from EPA is possible.
5. Useful routines and functions from other EFDC versions can be obtained and incorporated for LDW use.
6. EFDC will run in the Windows operating system using Ecology's modeling server.
7. Run times are reasonable for low to moderately complex models.
8. Ecology project staff and King County modelers are experienced using EFDC.

EFDC Cons:

1. The past applications by King County and others require extensive modifications and improvements to meet the PLA project needs, including concept, sub-model linkage, domain and grid cells.
2. Structured curvilinear model grid limits the balance of reasonable conformance with shorelines and bathymetry and model run times.
3. Not capable of parallel processing. Each model runs uses a single CPU for the numerical integration. Therefore model run times are many times longer than an SSM model run which can use up to 100 CPUs or more as needed.
4. It might not be practical to run EFDC for much longer than two years.
5. The current EFDC does not have nutrient module calibrated. It might still require the output from SSM if nutrient input is needed.

SSM Pros:

1. Ecology is using SSM to support the Puget Sound Nutrient Source Reduction Project. SSM will be used for management decisions for a TMDL-like project to address managing nutrient loading to meet water quality standards related to eutrophication
2. The application of SSM for future toxics projects throughout the entire Salish Sea provides an opportunity to spin-off SSM applications in many potential study areas in addition to the PLA study area.
3. Modelers in Ecology's Environmental Assessment Program are familiar with SSM.
4. Uses up to 100 CPUs or more for parallel processing during numerical integration. This makes model runs many time faster than an EFDC model of similar complexity which can only use one CPU.
5. Can readily program needed modules in the model code with funding support from EPA.
6. SSM already include the nutrient module which includes organic carbon. It is possible to run nutrient and toxic simultaneously. It can provide linkage for eutrophication application.
7. The code is publicly available.

SSM Cons:

1. Will require additional training time learning for NWRO staff to use SSM and for EAP staff when the toxic module is ready
2. Does not run in the Windows OS, therefore can not be used on a computing platform owned by Ecology. Runs in the Linux OS using a super-computer cluster. Ecology currently uses the Constance cluster owned by PNNL.
3. Does not currently contain a toxics module, but potential funding may be available from EPA. EPA is considering to build SSM Toxics next year (FY19).

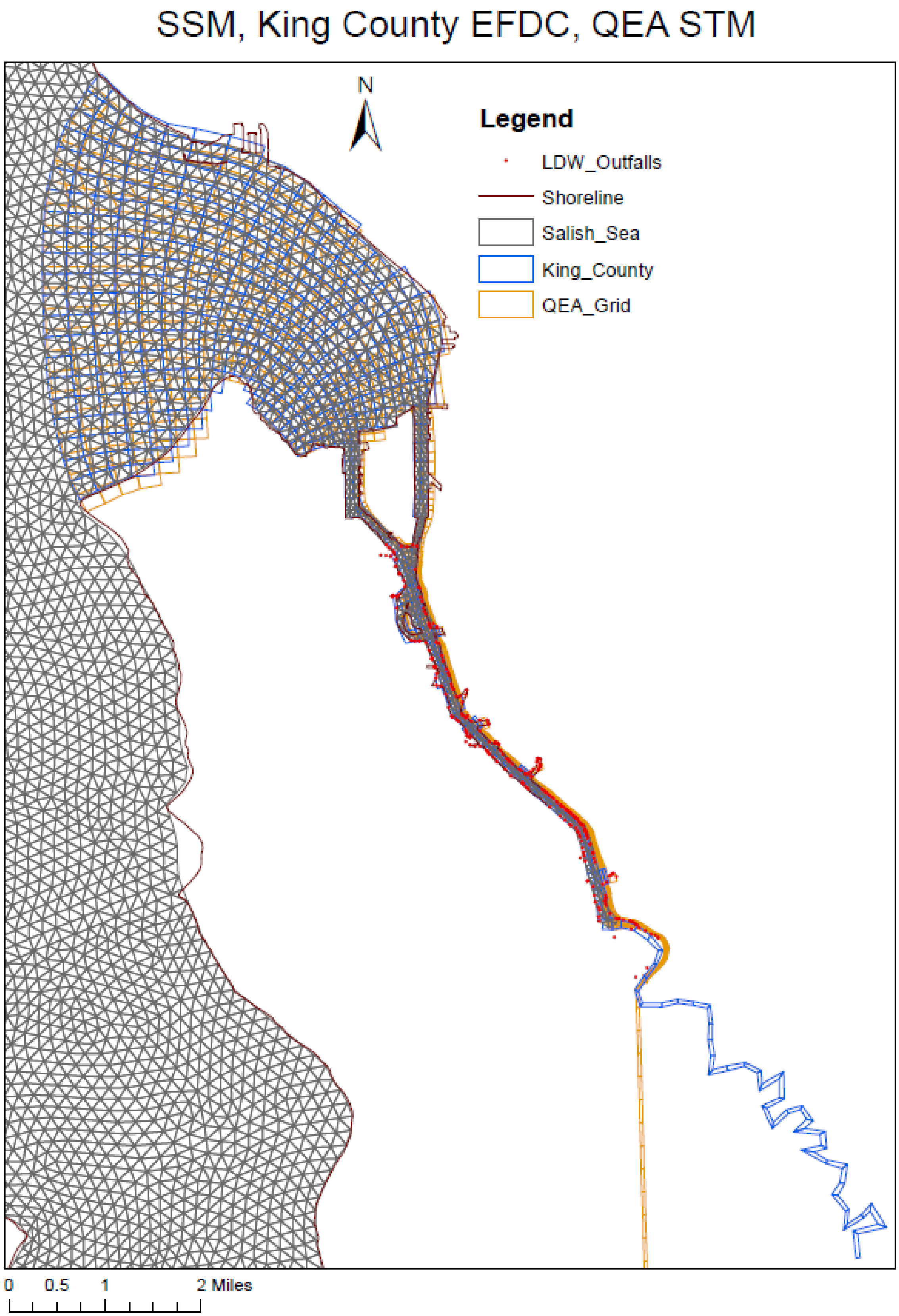

Figure 1. Overlay of grids used in past modeling studies in the vicinity of the PLA project area

Figure 2. LDW Outfalls

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Table 1. Comparisons of 2 existing LDW EFDC models

	King County EFDC Model	QEA EFDC-SEDZLJ Model
Model Scope	Hydrodynamic (Turbulence, Salinity) Sediment Transport (with Conventional Formulations) Total PCBs	Hydrodynamic (Turbulence, Salinity) Sediment Transport (Formulations and Sedflume Data)
Modeling Framework	EFDC Hydrodynamic with internally direct linked Sediment Transport with internally direct linked Toxic Fate and Transport	EFDC Hydrodynamic with indirect linked Sediment Transport (EFDC + SEDZLJ)
Code Availability	Yes	Yes
Grid	521 Horizontal Cells 58 x 62 GEFDC grid generation	1312 Horizontal Cells 23 x 389
Number of Water Column Layers	10	10
Drying and Wetting	Yes	Yes
Number of Sediment Bed Layers	4 (for sediment transport and toxic simulation)	5 (for sediment transport simulation)
Sediment Classes	3 (2 Cohesives + 1 Noncohesive) Clay (1 - 4 μm): 1.0×10^{-10} m/s Silt (4 - 62 μm): 2.0×10^{-4} m/s Sand (62 - 500 μm): 0.04 m/s	4 (2 Cohesives + 2 Noncohesives) Clay and Fine Silt (< 10 μm): D50 = 5 μm Medium and Coarse Silt (10 - 62 μm): D50 = 20 μm Fine Sand (62 - 250 μm): D50 = 130 μm Medium and Coarse Sand (250 - 2,000 μm): D50 = 540 μm
Bedload	Not Simulated	Simulated for medium and coarse sand
Simulation Period	2005 - 2006 (hot-started)	1960 - 1989 (30 years) Hydrodynamic model: 7 days spin-up for each year Sediment Transport model: hotstarted for each year
Computational Time	~6 hours for 360-day simulation	~12 hours for 1-year hydrodynamic simulation > 4 hours for 1-year sediment transport simulation
Grid Generator Availability	Yes, GEFDC	No
Post-processor Availability	Yes	No