Modeling Quality Assurance Project Plan

for

Green/Duwamish River Watershed Pollutant Loading Assessment

Contract: EP-C-12-055

Task Order Control Number PR-R0-13-0092

Prepared for:

U.S. Environmental Protection Agency Region 10
1200 6th Avenue, Suite 900 (OWW-134)
Seattle, WA 98101-3140

Prepared by:

Tetra Tech, Inc.
One Park Drive, Suite 200
P.O. Box 14409
Research Triangle Park, NC 27709

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This quality assurance project plan (QAPP) has been prepared according to guidance provided in *EPA Requirements for Quality Assurance Project Plans* (EPA QA/R-5, EPA/240/B-01/003, U.S. Environmental Protection Agency, Office of Environmental Information, Washington, DC, March 2001, [Reissued May 2006]) and *EPA Guidance for Quality Assurance Project Plans for Modeling* (EPA QA/G-5M, EPA/240/R-02/007, U.S. Environmental Protection Agency, Office of Environmental Information, Washington, DC, December 2002) to ensure that environmental and related data collected, compiled, and/or generated for this project are complete, accurate, and of the type, quantity, and quality required for their intended use. Tetra Tech will conduct the work in conformance with the quality assurance program described in the quality management plan for Tetra Tech's Fairfax Center and with the procedures detailed in this QAPP.

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Approvals

7/13/16 Jayne Carlin — Date Task Order Manager U.S. Environmental Protection Agency, Region 10	7/14/2016 Donald Brown — Date Quality Assurance Manager U.S. Environmental Protection Agency, Region 10
7/14/16 Laurie Mann — Date Technical Lead U.S. Environmental Protection Agency, Region 10	7/13/16 Ben Cope — Date Environmental Engineer U.S. Environmental Protection Agency, Region 10
7/13/16 J Todd Kennedy — Date Task Order Leader and Project Manager Tetra Tech	
7/13/16 Jonathan Butcher — Date Modeling Co-Lead Tetra Tech	7/13/2016 Brian Watson — Date Modeling Co-Lead Tetra Tech
7/13/2016 Jon Ludwig — Date Modeling Quality Control Officer Tetra Tech	7/13/2016 John O'Donnell — Date Quality Assurance Officer Tetra Tech

Distribution

This document will be distributed to the following personnel who will be involved in this project.

Name/title	Phone/e-mail	Mailing address
U.S. Environmental Protection Agency (EPA) Region 10		
Jayne Carlin Task Order Manager	(206) 553-8512 carlin.jayne@epa.gov	EPA Region 10 1200 6th Ave., Suite 900 Seattle, WA 98101
Donald Brown Quality Assurance Manager	(206) 553-0717 brown.donald@epa.gov	
Laurie Mann Technical Lead	(206) 553-1583 mann.laurie@epa.gov	
Ben Cope Environmental Engineer	(206) 553-1442 cope.ben@epa.gov	
Washington Department of Ecology		
Joan Nolan Management Lead	(425) 649-4425 joan.nolan@ecy.wa.gov	Washington Department of Ecology 3190 160th Ave SE Bellevue, WA 98008
Bo Li Technical Lead	(425) 649-7284 bo.li@ecy.wa.gov	
Rachel McCrea Coordination Lead	(425) 649-7223 rachel.mccrea@ecy.wa.gov	
Dave Garland Watershed Unit Manager	(425) 649-7031 dave.garland@ecy.wa.gov	
Mahbub Alam Toxic Cleanup Program Representative	(425) 649-7202 mahbub.alam@ecy.wa.gov	
Greg Pelletier Environmental Assessment Program Representative	(360) 407-6485 greg.pelletier@ecy.wa.gov	
Tetra Tech, Inc.		
J Todd Kennedy Task Order Leader and Project Manager	(919) 485-2067 todd.kennedy@tetratech.com	Tetra Tech One Park Drive, Suite 200 PO Box 14409 Research Triangle Park, NC 27709
Jonathan Butcher Modeling Co-Lead	(919) 485-2060 jon.butcher@tetratech.com	
Brian Watson Modeling Co-Lead	(770) 738-6030 brian.watson@tetratech.com	Tetra Tech 2110 Powers Ferry Road SE, Suite 202 Atlanta, GA 30339
Jon Ludwig Modeling Quality Control Officer	(703) 385-1973 jon.ludwig@tetratech.com	Tetra Tech, Inc. 10306 Eaton Place, Suite 340 Fairfax, VA 22030
John O'Donnell Quality Assurance Officer	(703) 385-6000 john.odonnell@tetratech.com	

Abbreviations and Acronyms

ACOE	US Army Corps of Engineers
BASS	Bioaccumulation and Aquatic System Simulator
BCM	Bed Composition Model
BOD	biological oxygen demand
BSAF	biota-sediment accumulation factors
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CM	conceptual model
COC	contaminant of concern
COR	Contract Officer's Representative
cPAHs	carcinogenic polycyclic aromatic hydrocarbons
CREM	Council for Regulatory Environmental Modeling
CSO	combined sewer overflow
CSS	combined sewer system
CTD	conductivity, temperature and depth
CWA	Clean Water Act
DEHP	Diethylhexyl phthalate (bis-2-ethylhexyl phthalate)
DEM	digital elevation model
DMR	discharge monitoring report
DO	dissolved oxygen
DQO	data quality objective
DYMBAM	Biodynamic Model of Bioaccumulation
Ecology	Washington Department of Ecology
EFDC	Environmental Fluid Dynamics Code
EIM	Environmental Information Management System
E-MCM	Everglades Mercury Cycling Model
EMC	event mean concentration
ENS	Nash-Sutcliffe coefficient of model fit efficiency
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
ET	evapotranspiration
FOVA	First Order Variance Analysis
FS	feasibility study

FWM	Food Web Model
GIS	geographical information system
HHRA	human health risk assessment
HRU	hydrologic response unit
HSG	hydrologic soil group
HSPF	Hydrologic Simulation Program – FORTRAN
IA	index of agreement
Kow	octanol-water partition coefficient
LA	load allocation
LDW	Lower Duwamish Waterway
LDWG	Lower Duwamish Waterway Group
LSPC	Loading Simulation Program in C++
MAE	mean absolute error
MDAS	Mining Data Analysis System
MS4	municipal separate storm sewer system
MTCA	Model Toxics Control Act (Washington State)
NCDC	National Climatic Data Center
NLDAS	North American Land Data Assimilation System
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRMSE	normalized root mean squared error
NSE	Nash-Sutcliffe Efficiency
NWIS	National Weather Information System
NWS	National Weather Service
PAHs	polycyclic aromatic hydrocarbons
PBDEs	polybromiated diphenyl ethers
PCBs	polychlorinated biphenyls
PLA	pollutant loading assessment
PP	Proposed Plan
PRISM	Parameter Elevation Regression on Independent Slope Model
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control

QEAFdChn	Qualitative Environmental Analysis Food Chain
RE	relative error
RI	remedial investigation
RMSE	root mean squared error
SEATAC	Seattle-Tacoma International Airport
SPAF	species predictive accuracy factor
SSC	suspended sediment concentration
STM	Sediment Transport Model
SWAT	Soil and Water Assessment Tool
SWMM	Stormwater Management Model
TAC	Technical Advisory Committee
TCDD	tetrachloro dibenzo-p-dioxins
TEFs	toxicity equivalence factors
TMDL	total maximum daily load
TOL	Task Order Leader
TOM	Task Order Manager
TSS	total suspended solids
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WARMF	Watershed Analysis Risk Management Framework
WASP	Water Quality Analysis Simulation Program
WLA	wasteload allocation
WQ	water quality
WRDB	Water Resources Database
WRIA	Water Resource Inventory Area

1 Introduction

1.1 Background, Study Area, and Project Objectives

Washington Department of Ecology (Ecology) and the U.S. Environmental Protection Agency (EPA) are developing a Pollutant Loading Assessment (PLA) to understand the relationship of water, sediment, and fish tissue quality to the overall health of the Green/Duwamish River watershed and Lower Duwamish Waterway (LDW) in Washington (Figure 1 and Figure 2). The Green/Duwamish River watershed is identified on Washington's 303(d) list as being impaired for over 50 different pollutants (including both toxic and conventional parameters) under the Clean Water Act (CWA). Portions of the study area are also on the National Priorities List under and are in various stages of sediment cleanup under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or Superfund, and Washington State Model Toxics Control Act (MTCA) programs.

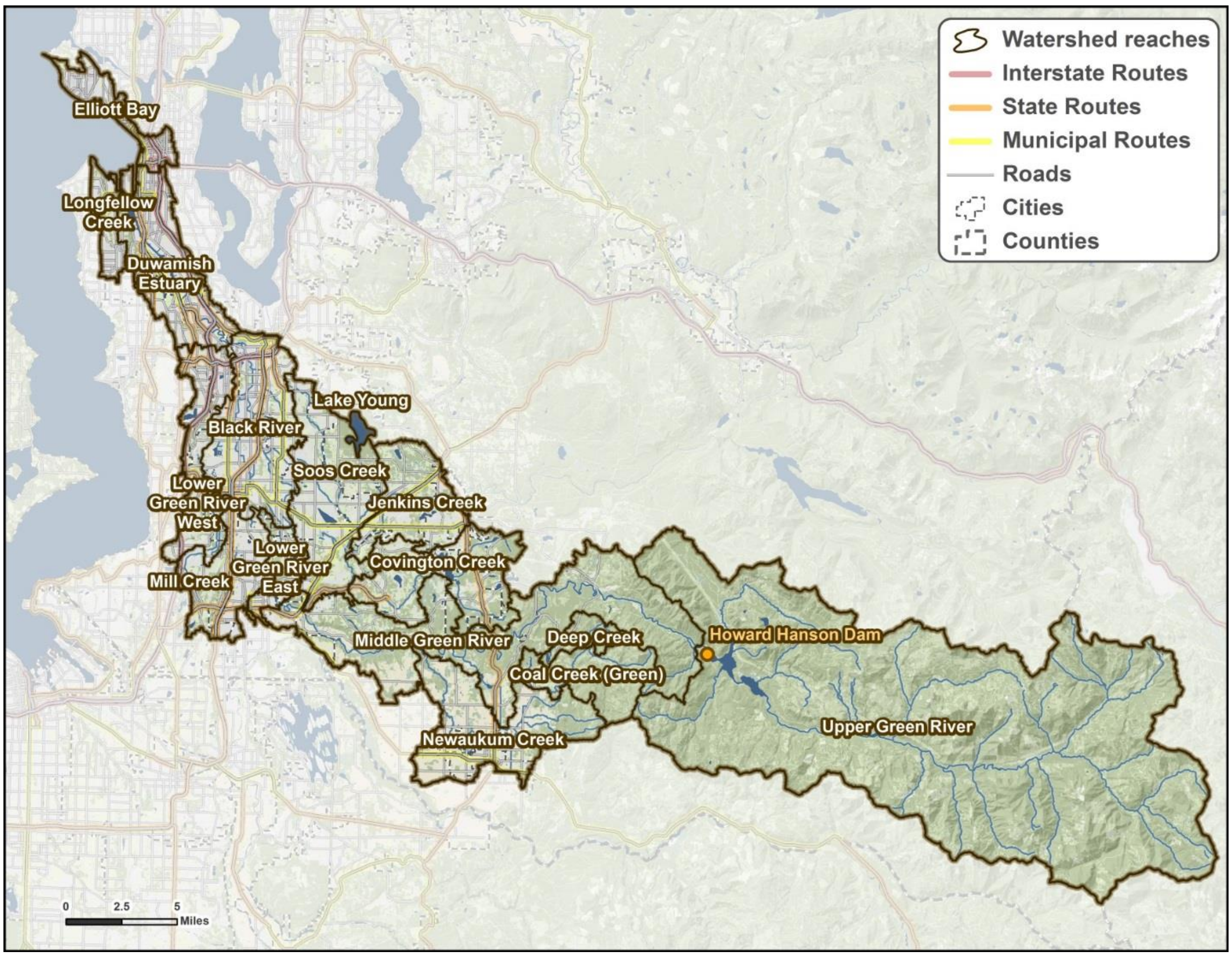

Figure 1. Green/Duwamish River watershed

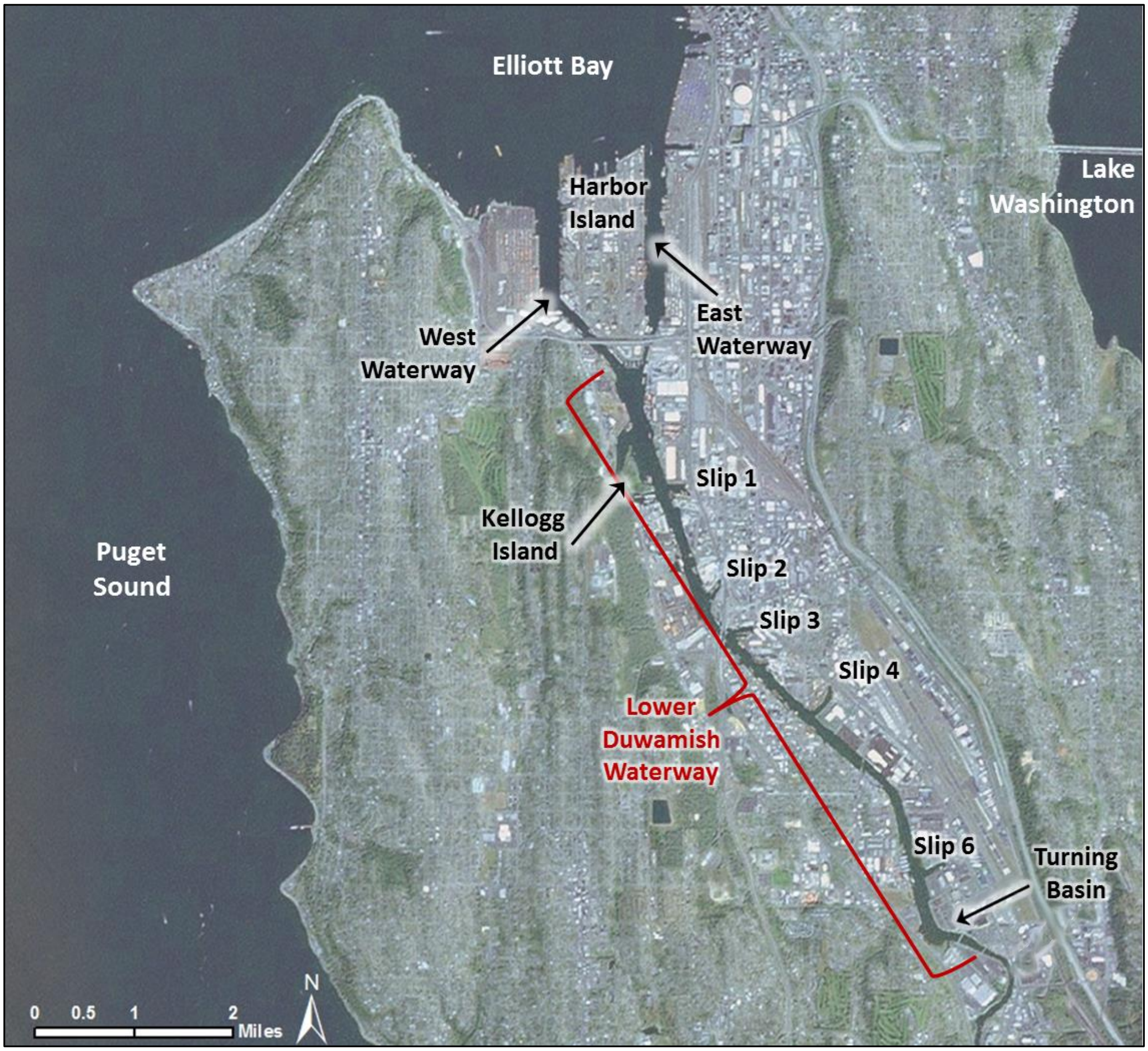

Figure 2. Lower Duwamish Waterway

A group of linked modeling tools are proposed for development as part of the PLA focusing initially on a number of toxic pollutants including a diverse mix of lipophilic chlorinated hydrocarbons (polychlorinated biphenyls [PCBs],), polycyclic aromatic hydrocarbons (PAHs), phthalates, and metals. Under Task Order 05 of contract EP-C-12-055, EPA issued a technical directive to Tetra Tech to assist EPA and Ecology in conducting scoping analyses and developing a quality assurance project plan (QAPP) to guide future modeling activities.

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. 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). Model selection is discussed further in Section 2.3.

The objective of the PLA is to develop an assessment tool that considers existing watershed and receiving water conditions, as well as ongoing and future Superfund and MTCA cleanup efforts. The tool can be used to assess potential recontamination of post-cleanup sediments from incoming loads from the entire drainage area, including all lateral loads to the LDW; improve the effectiveness of the sediment remedial action; and address CWA water, sediment, and tissue quality impairments in the Green/Duwamish River watershed, including the LDW. The assessment tool can also help identify load reductions from various sources in the watershed and the receiving waters; and can be used to estimate loadings during and after sediment cleanup.

The PLA tool can be used to assist with the following needs:

- Understand the pollutant loading associated with point sources and the uncontrolled release of chemical pollution from diffuse sources throughout the watershed.
- Compare different pollutant reduction alternatives to allow for more informed decision-making.
- Predict the resulting short and long term improvements in fish tissue (within the LDW), and water column and sediment quality throughout the watershed.
- Minimize recontamination of post cleanup sediments and improve the effectiveness of natural recovery.
- Support adaptive management over time in response to measured progress in meeting water quality targets.

This QAPP provides a general description of the modeling and associated analytical work that Tetra Tech will perform for the project, including following data quality objectives (DQOs) and quality control (QC) procedures to ensure that the final product satisfies EPA requirements. This QAPP also addresses the use of secondary data (data collected for another purpose or collected by an organization or organizations not under the scope of this QAPP) to support model development and application.

1.2 Initial Planning

EPA and Ecology began planning for the Green/Duwamish River PLA in 2013. Initial work was devoted to developing a Technical Approach document (Tetra Tech, 2014). In late 2014, an Agency Steering Committee was formed to manage the development of the PLA and includes representatives from Ecology and EPA involved in cleanup and water quality activities.

Next, in late 2014, a Technical Advisory Committee (TAC) and an Interested Parties group was formed to help inform the development of the PLA. These groups includes a range of participants and provides a means for key technical stakeholders and the general public to provide input to the Agency Steering Committee on the PLA development. The first meeting of the TAC was held in December 2014, and five additional meetings have been held as of September 2015. Current TAC membership is shown Table 1.

The purpose of the Interested Parties group is to provide an open forum for all stakeholders to provide input on the development of the PLA, regardless of their participation in the TAC. The Interested Parties group will review key technical questions and topics and hear about the work of the TAC and progress on the PLA overall. Participation in the Interested Parties group is open to all stakeholders and members of the public. An initial Interested Parties meeting was held in summer of 2015.

Table 1. TAC membership

TAC Member	Representative
City of Auburn	Chris Andersen, Environmental Services Manager
City of Kent	Mike Mactutis, Environmental Engineering Section Manager
City of Kent	Shawn Gilberston, Environmental Supervisor
City of Renton	Ron Straka, Utility Engineering Manager
City of Seattle	Kevin Buckley, Integrated Planning Program Manager
City of Seattle	Pete Rude, Strategic Advisor
City of Tukwila	Ryan Larson, Senior Surface Water Program Manager
Duwamish River Cleanup Coalition	James Rasmussen, Coordinator
Duwamish River Cleanup Coalition	Heather Trim, Board Member
King County	Chris Townsend, Environmental and Community Services Section Manager
King County	Jeff Stern, Sediment Management Program Manager IV
Muckleshoot Tribe	Glen St. Amant, Habitat Program Manager
Muckleshoot Tribe	Nancy Rapin, Water Team Leader
Port of Seattle	Kathy Bahnick, Environmental Program Manager
Suquamish Tribe	Rich Brooks, Environmental Program Manager
US Army Corps of Engineers, Seattle District	Kristen Kerns, Physical Scientist
WSDOT	Jana Ratcliff, TMDL Lead
Ecology Environmental Assessment Program	Greg Pelletier, Environmental Engineer
WRIA 9 Watershed Ecosystem Forum	Elissa Ostergaard, Stewardship Coordinator

1.3 Project Plan Overview and Time Line

The Duwamish PLA is a long term project involving development and testing of multiple models to assess existing conditions and predict future conditions. Due to the number pollutants to be assessed, the complex fate and transport of these pollutants, and the data and knowledge gaps to surmount in building the models there is a high degree of uncertainty in the project schedule. As such this QAPP describes all the key elements of the model development plan that can be determined at this time, including management objectives, model parameters, model framework selection, data availability and quality, selected time frame for modeling analysis, and documentation of model quality. However, due to the complexities of the project, this QAPP cannot answer all of the model development planning questions at this time. In some cases, the document identifies a specific modeling challenge and defers decisions on how to address the challenge until more information is available. One notable example is the selection of specific PCB forms (e.g., total, congeners, and/or homologs) to be used as prediction variables. This decision will be made in the future after additional analysis of available PCB data.

The currently anticipated sequence of events and project timeline is shown below in Figure 3.

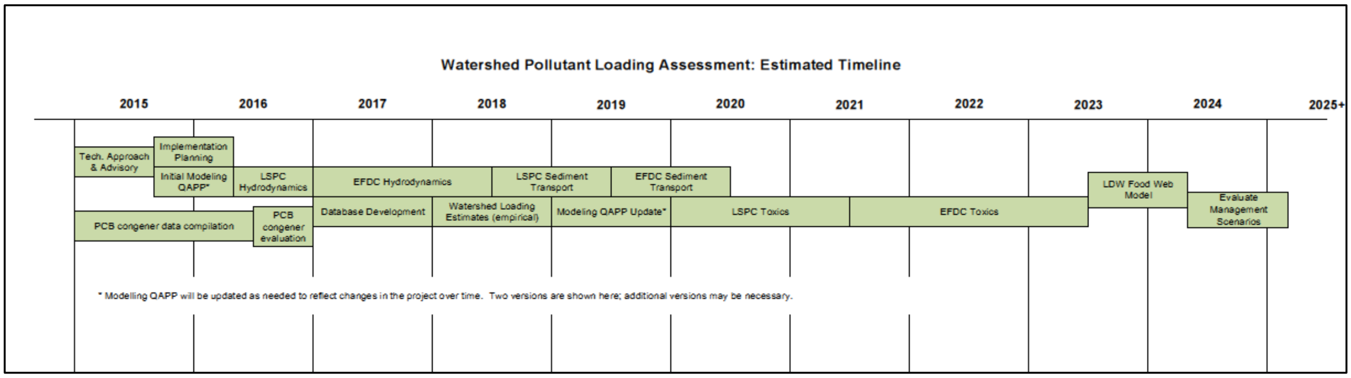

Figure 3. Estimated PLA timeline

It is expected that EPA will be the primary funding source for the modeling work. There is no federal budget set-aside for this project, so obtaining funding for contractors to build and document models will require annual funding requests from sources within EPA (e.g., Total Maximum Daily Load or TMDL program funds). For this reason, while EPA Region 10 and the Department of Ecology are committed to the project, the overall project schedule is uncertain and subject to unforeseeable funding constraints and opportunities. At expected annual levels of funding from EPA's TMDL program, we anticipate that development and application of the proposed system of linked models will take several years to a decade to complete.

As noted above, the specific dates of task completion are contingent on funding. Regardless of the pace of funding, model development tasks will proceed in the sequence shown in the time line. These tasks are sequenced to tackle increasingly complex tasks over time. The project steps through hydrology /hydrodynamic prediction (e.g., flow, velocity, water elevation), sediment transport prediction (suspended solids, landscape erosion, river bed sediment erosion/deposition), and, finally, toxic pollutant models (water quality and food web). Each of these steps involves model development, evaluation, and documentation. Because the most significant unanswered questions in this QAPP involve the specific approaches and assumptions for the toxic pollutant models in the latter stages of the project, the project can proceed in the near term with basic model setup (e.g., grid, tributary network setup) as well as hydrodynamic and sediment calibration. At the same time, database development and data assessment can proceed and inform QAPP updates. Given the timeframe of the project it is anticipated that QAPP updates or addenda will be periodically needed during the project to make course adjustments.

The first tasks of the project involve set up of the hydrodynamic model of the Green/Duwamish watershed. Several of these tasks are straightforward and unlikely to be affected by review of this document. These tasks may be initiated prior to final signature of this document in the interest of meeting the deliverable schedule. A listing of these early tasks are provided in the watershed modeling chapter.

The PLA is also occurring in parallel with the EPA's Superfund program cleanup of the Lower Duwamish Waterway, Ecology's upland site remediation projects, numerous stormwater and Combined Sewer Overflow (CSO) control projects, and other studies within the Green/Duwamish River. All information generated by these activities will be considered for use in the modeling effort. The goal of the PLA model development is to incorporate, to the extent feasible, all available data and knowledge of the system into the models.

1.4 Parameter Selection

There are over 250 waterbody segment-pollutant combinations on the 2012 303(d) list in the study area. These include impairments for sediment, tissue, and water for over 50 pollutants. In addition, the Superfund Proposed Plan (PP) identified pollutants that are the primary human health risk-drivers based on the human health risk assessment (HHRA) conducted as part of the remedial investigation (RI) as well as ecological risk drivers.

Ecology and EPA developed a tiered, prioritization process to identify the initial focus of the PLA. The criteria included the following:

Tier 1

- Focus on toxics.
- CWA impairments.
- CERCLA human health and ecological risks.
- Does the chemical bioaccumulate (octanol-water partition coefficient [K_{ow}] >5)?
- Chemical linked to fish tissue consumption advisory.

Tier 2

- Chemical linked to endangered species concerns.
- Is there a sediment recontamination concern?
- Do we have data to support modeling?
- Can the chemical be simulated with the proposed models?
- Can the chemical represent similar chemicals in terms of sources and pathways?

As a result of the prioritization, Ecology and EPA identified an initial set of pollutants that are candidates for modeling in the Green-Duwamish River Watershed Pollutant Loading Assessment. These candidate parameters constitute a fairly diverse mix of lipophilic chlorinated hydrocarbons (PCBs, dioxins/furans), PAHs, one phthalate (Bis-2-ethylhexyl phthalate or diethylhexylphthalate; DEHP), and metals (Table 2). Total PCBs contain a mixture of up to 209 individual congeners, which can be sorted into 10 homolog groups based on the number (1 to 10) of chlorine atoms attached to the biphenyl ring structure. In addition, there is interest in both dissolved and total metals.

Table 2. Initial list of candidate chemicals considered for modeling (listed in order of priority)

Parameter	Tier	Fate and Transport	Food Web	Justification
PCBs	1	Y	Y	High concern to both water quality (WQ) and CERCLA, accumulate in biota, fish consumption advisory, ecological concern, recontamination potential
Carcinogenic PAHs (cPAHs; benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h) anthracene, indeno(1,2,3-cd) pyrene)	1	Y	Y	High concern to both WQ (most 303d listings) and CERCLA, accumulate in biota, ecological concern, recontamination potential
Dioxins/Furans (2,3,7,8 TCDD)	1	Y	Y	High concern to both WQ (most 303d listings) and CERCLA, accumulate in biota, ecological concern, recontamination potential
Arsenic (inorganic)	2	Y	N	Concern for both WQ and CERCLA- natural background issue
Phthalates (Bis-2-ethylhexyl phthalate; DEHP)	2	Y	Y	Primarily concern for CERCLA, benthic toxicity, recontamination potential, accumulates in biota- surrogate for other phthalates
Copper	2	Y	N	Aquatic toxicity concern for Endangered Species Act (ESA) species- indicator for built environment, CERCLA contaminant of concern (COC)
Zinc	2	Y	N	Aquatic toxicity concern for ESA species- indicator for built environment, CERCLA COC
Mercury	2	Y	Y	Limited 303d listings, concern for CERCLA, fish consumption advisory

1.4.1 Parameters Selected for Analysis

An evaluation of existing data and models was conducted in Tetra Tech (2015a) and Tetra Tech (2015b). The key parameter-based knowledge gaps, options to address these gaps, and recommendations for selecting among the options are presented in Table 3 (Tetra Tech, 2015b).

Table 3. Summary of knowledge gaps and options for candidate pollutants

Knowledge Gap	Options and Recommendations
There is a lack of paired filtered/unfiltered data for site-specific determination of partition coefficients for PCBs, PAHs, dioxin/furans, and phthalates in both the water column and the sediments. Information on recent work on sediment-porewater partitioning in the LDW is provided in Gschwend et al. (2014, 2015). LDWG is also commissioning a study (activated carbon pilot) in 2016/17 that will have paired porewater and sediment data.	Options: 1. Use literature values of partition coefficients to estimate dissolved fraction based on solids or carbon concentrations that may not reflect local conditions. 2. Collect paired data to evaluate coefficients and improve accuracy Recommendation: Team should consider Option 2. Recent and future data reported by Gschwend et al. (2014 and 2015) for USACE and data from LDW activated carbon pilot study by LDWG can be incorporated into the analysis. However, an initial model will be built and used for sensitivity analysis to inform the final decision on additional data collection.
No data are currently available to directly constrain rates of exchange from the sediment into the water column of non-polar organic pollutants (PCBs, dioxin/furans, PAHs, phthalates), which may be enhanced above typical diffusion rates by biological action.	Options: 1. Treat exchange rates as calibration parameter. 2. Constrain rates based on field evidence. Recommendation: Ongoing work by MIT for USACE (Gschwend et al., 2014 and 2015) provides field data for the LDW, enabling use of Option 2. Ecology will contact USACE to determine if additional data are being collected.
Data for PCBs reported as Aroclors is problematic for comparison to congeners and homologs due to changes in composition from differential weathering. This creates uncertainty in estimating total PCBs as well as the concentration of individual congeners with high TEFs.	Options: 1. Use Aroclor data only, providing a consistent basis for analysis. 2. Assume unaltered Aroclors to interpret congener concentrations and total PCBs from Aroclors; combine with congener data. 3. Use samples analyzed for both Aroclors and congeners to evaluate site-specific relationships between environmentally altered Aroclors and congeners in the LDW. Recommendation: Option 3 is preferable for accurate analysis of PCBs. This takes advantage of available data and allows better specification of kinetic parameters. Leidos (2015) summarizes information on conversion from congener data to Aroclors provided the sample does not contain mixture of aroclors, uses specific congener method, and specific GC column.
Dioxin/furan data are limited, with few water column and biological samples available at this time.	Options: 1. Simulate behavior of selected dioxins/furans using available data and literature coefficients. 2. Delay simulation of dioxins/furans until ongoing data collection efforts produce sufficient information to calibrate a model. Recommendation: Option 2. The same simulation framework employed for PCBs can be used for dioxins/furans once additional monitoring data are available. Do not model until additional data is collected.
For mercury, there is a lack of methylmercury data as well as	Options: 1. Simulate total mercury only.

Knowledge Gap	Options and Recommendations
information on factors that influence methylation (redox, sulfate balance).	2. Attempt to simulate mercury methylation using literature values. 3. Collect methylmercury data to support modeling. Recommendation: Option 3 is preferable if mercury is to be modeled; however, lack of data suggests that mercury should not be modeled at this time (see below). Mercury will not be modeled at this time.
For copper, zinc, and arsenic, the information on competing common ions and chemical conditions appears insufficient for a full analysis of solid and aqueous speciation incomplete to support redox chemistry.	Options: 1. Simulate ionic metals as general quality constituents that can deposit to or erode from the sediment but are otherwise conservative. 2. Represent ionic metals partitioning to solids and solubility using the method recommended by USEPA (1996); modify EFDC and LSPC model codes to represent this behavior. 3. Collect additional data and develop a detailed geochemical simulation. Recommendation: Option 2 appears to be the most feasible alternative for copper and zinc. Option 1 should be sufficient for arsenic. Options 2 has been selected by the Project Team.

The knowledge gaps summarized in Table 3 together with the further discussions in Tetra Tech (2015b) have implications regarding the specific constituents that can or should be simulated in the model. The candidate chemicals from Table 2 are revisited in Table 4.

Table 4. Final chemicals and groupings selected for modeling

Parameter	Fate and Transport	Food Web	Issues	Decision
PCBs	Y	Y	Group of 209 congeners with a wide range of chemical properties. Simulating total PCBs as a single state variable will lead to inaccuracies, but it is not feasible to simulate 209 congeners individually.	Simulate a reduced set of PCB homolog groups. Select specific PCBs and/or PCB homologs for modeling based on data review and analysis.
Carcinogenic PAHs	Y	Y	Group of 8 chemicals with differing properties.	Simulate cPAHs as a group with approximated characteristics; reassess based on data analysis if necessary.
Dioxins/Furans	N	NA	Data are limited; simulating only 2,3,7,8-TCDD will not represent full toxic potential associated with this group.	Delay modeling until additional data are collected. (Model *structure* for PCBs will also work for dioxins/furans.)

Parameter	Fate and Transport	Food Web	Issues	Decision
Arsenic (inorganic)	Y	N	Determination of natural background concentrations may be an issue.	Simulate inorganic arsenic only using a simplified mass balance approach
Phthalates	Y	N	DEHP was suggested as a surrogate for other phthalates. Rapidly metabolizes in fish tissue, not a food web concern	Simulate DEHP. Use as a surrogate appears reasonable;
Copper	Y	N	Aquatic toxicity evaluation requires dissolved concentration.	Simulate dissolved and sorbed inorganic forms using USEPA translator guidance (1996) methods adjusted to local data.
Zinc	Y	N	Aquatic toxicity evaluation requires dissolved concentration.	Simulate dissolved and sorbed inorganic forms using USEPA (1996) methods adjusted to local data.
Mercury	N	NA	Lack of data for methylmercury hampers evaluation of fate, transport, and bioconcentration potential.	Do not model mercury at this time.

1.4.2 Remaining Work Needed

1.4.2.1 PCBs

The project teams plans to complete additional evaluation of PCB data. This will support a decision of which PCBs or PCB homologs to include in the models.

1.4.2.2 Dioxin/furans

There is limited data at present but high interest in modeling. Models will be set up for this constituent but full calibration will be deferred until more data is collected.

1.4.2.3 Watershed Data Collection

Additional data collection in the watershed to support watershed model development and evaluation is being considered.

2 Modeling Approach

2.1 Goals and Objectives

The goals and objectives for the Green/Duwamish River watershed PLA modeling are to:

- Address CWA 303(d) listings (relate water, bed sediment, and tissue concentrations).
- Protect investment in LDW cleanup (recontamination potential) under CERCLA.
- Develop watershed, receiving water, and food web tools to describe source, transport, and fate of subject pollutants, compare model output to environmental quality targets[1], and facilitate evaluation of management actions.

2.2 Conceptual Model

A conceptual model (CM) of the Green/Duwamish River watershed and LDW was developed for the Technical Approach (Tetra Tech, 2014). The CM describes (natural and anthropogenic sources of pollutants, chemical migration pathways, chemical transformations, and bioaccumulation (see Figure 4, Figure 5, and Figure 6). Additional discussion is provided in Tetra Tech (2014).

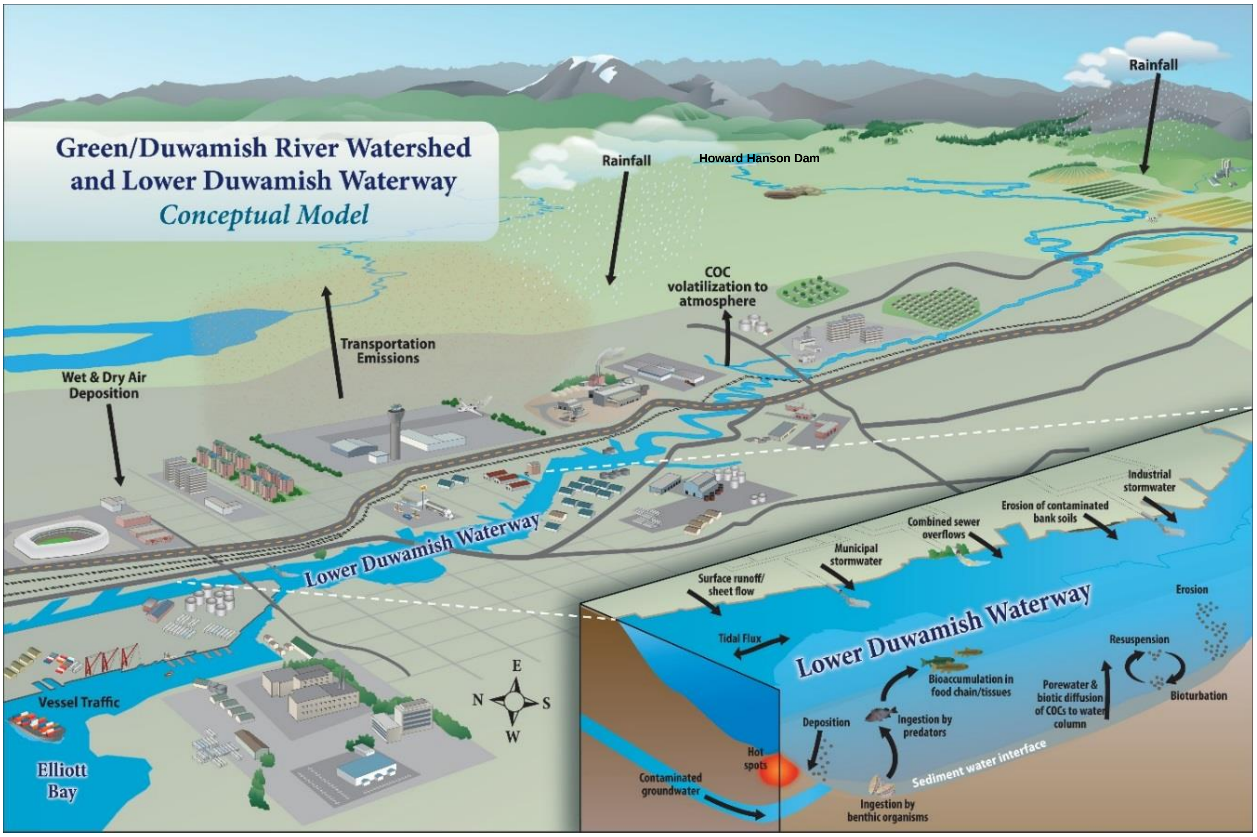

Figure 4. Green/Duwamish River general conceptual model

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1 Decisions on which numeric targets to apply have not been made. Discussion on potential targets was provided in the Technical Approach document (Tetra Tech, 2014).

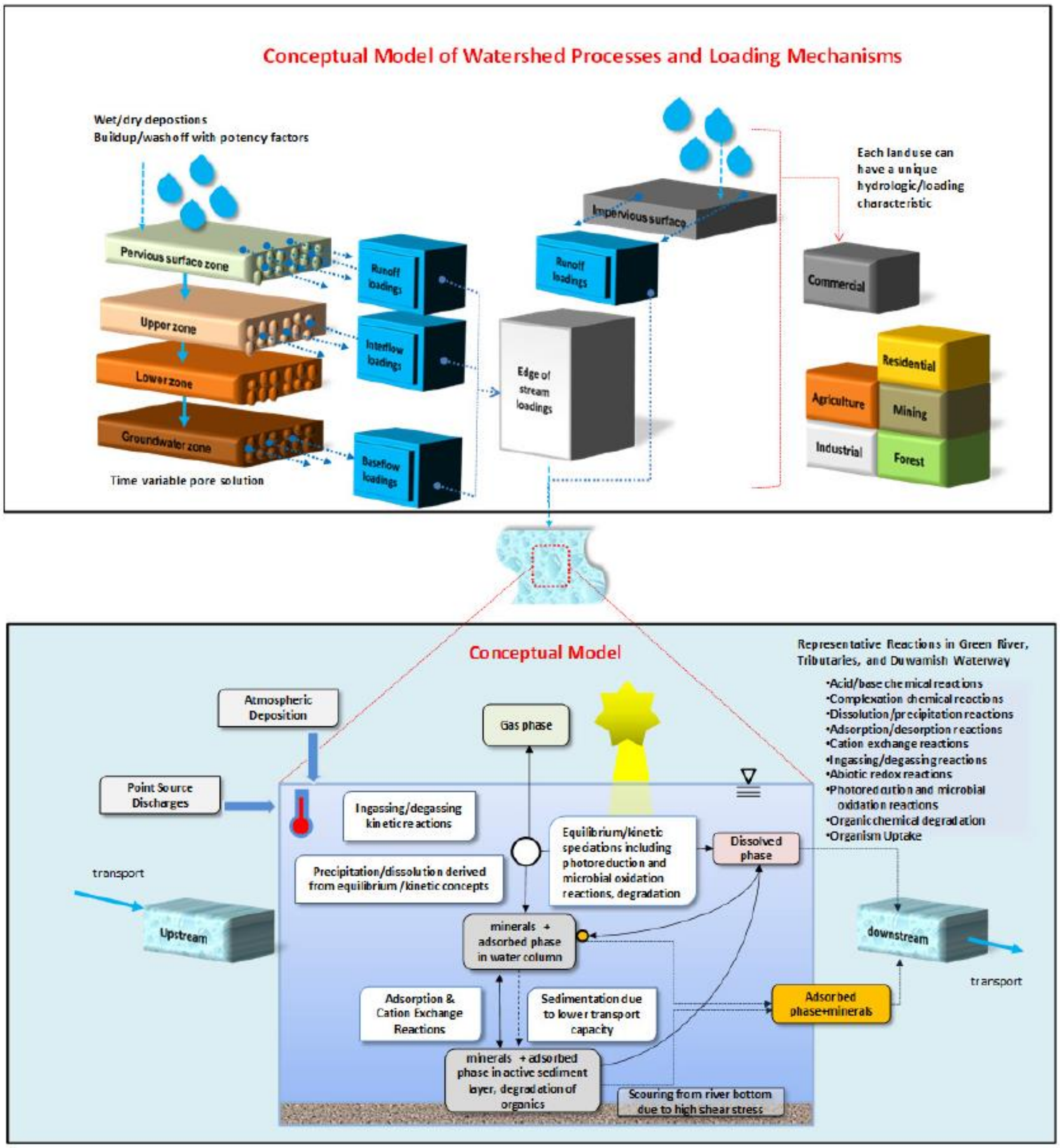

Figure 5. Watershed process and loading mechanisms

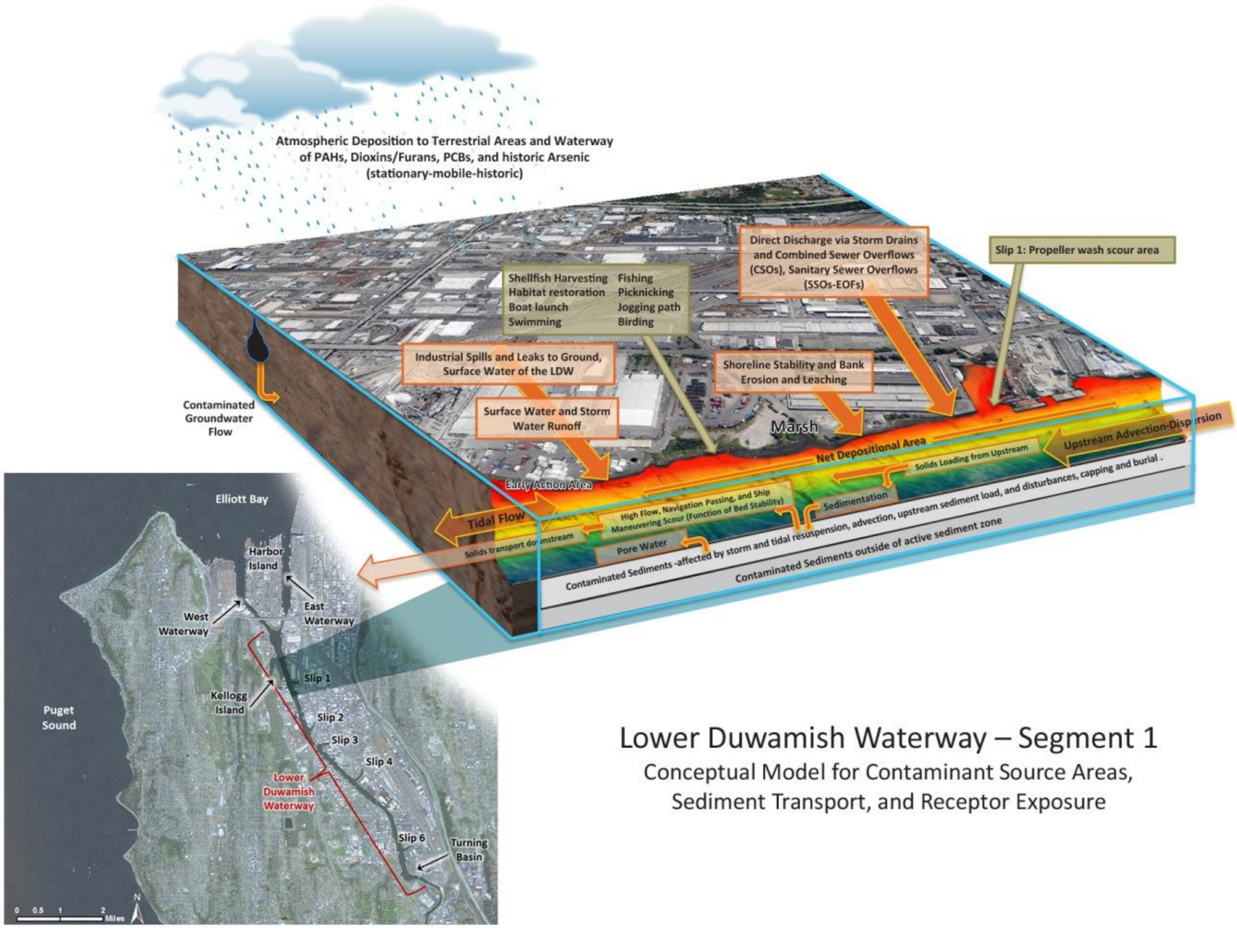

Figure 6. Conceptual model of LDW, segment 1

2.3 Model Selection

The work described in this QAPP does not involve creating new simulation modeling software. Rather, it involves developing and applying existing modeling frameworks of LSPC, EFDC, and the Arnot and Gobas FWM, as described further below. The selection of the modeling framework was described in detail within Tetra Tech (2014). A summary of this information follows.

In selecting an appropriate technical approach for a comprehensive PLA, technical, regulatory, and user criteria were considered. Technical criteria include the physical system in question, including watershed or receiving water characteristics and processes and the constituent(s) of interest (considering the details presented in the CMs). Regulatory criteria include water quality standards or procedural protocols. User criteria are the operational constraints imposed by the end-user and include factors such as hardware/software compatibility and financial resources. The following discussion details the considerations for each of these categories. Based on these considerations, a recommended framework is presented below to represent watershed and receiving water conditions and their subsequent impact on tissue quality.

Establishing the relationship between the numeric targets and source loading is a critical component of a PLA and load reduction analysis. It allows for the evaluation of management options that will achieve various load reduction scenarios, including bed sediment remedial actions and attainment of water quality standards and designated uses. The link can be established through a number of techniques, ranging from qualitative assumptions based on sound scientific principles to sophisticated modeling techniques. Ideally, the linkage will be supported by monitoring data that associate certain waterbody responses to flow and loading conditions. In addition, selection of a recommended technical approach also involves consideration of the technical, regulatory, and user criteria described above.

To support the objectives for this project, the development of a comprehensive linked watershed/receiving water/food web bioaccumulation modeling system is needed to represent the LDW and the Green/Duwamish River watershed. Potential modeling systems are described below.

A watershed model is essentially a series of algorithms applied to watershed characteristics and meteorological data to simulate land-based processes over an extended period, including rainfall-runoff, interflow, groundwater flow, flow routing, water temperature, and pollutant loadings. Watershed models often use build-up and wash-off representations of pollutants on the surfaces and can accommodate air deposition of pollutants. Many watershed models are also capable of simulating in-stream processes using land-based contributions as input.

Receiving water models are composed of a series of algorithms to simulate water circulation, water temperature, suspended sediment transport, fate and transport of contaminants, and kinetics and transport of conventional water quality constituents of the waterbody. External forces are applied including meteorological data, flow and pollutant loadings from point and nonpoint sources, and other boundary conditions. The models are used to represent physical, chemical, and biological aspects of a lake, river, or estuary. These models vary from simple 1-dimensional box models to complex 3-dimensional models capable of simulating water movement, salinity, temperature, sediment transport, pollutant transport, and bio-chemical interactions occurring in the water column.

Watershed models can provide flow and pollutant loading to a receiving water model and can also simulate water quality processes within streams and lakes with relatively simple algorithms. Receiving water models can simulate detailed processes in rivers, lakes, and estuaries. The receiving water model results, including water temperature and contaminant levels in the water column and bed sediment, can be used as inputs to a food web/bioaccumulation model to estimate contaminant levels in tissue. With a food web/bioaccumulation model integrated with a watershed model and a receiving water model, the sources of contaminants and the fate and transport of these contaminants are described and management scenarios can be evaluated. Representation of these three model domains are discussed below.

Watershed Representation

The primary methods considered to represent the Green/Duwamish River watershed included complex approaches that acknowledge the variety of pollutants and pathways in the system. A data-driven, statistical approach was also considered; however, a number of parameters have data that is limited in time and space within the watershed, and not all sources or pathways are represented. A calibrated watershed model can be used to characterize loadings from the Green/Duwamish River watershed beginning at the Howard Hanson Dam, ensuring that all major watershed sources and pathways are represented, including catchments adjacent to the LDW. A watershed model can estimate the relative pollutant contributions from multiple sources and can connect these contributions to the spatial distribution of contamination over time. Modeling scenarios can be developed that link changes in management in the watershed to changes in loading and instream concentrations of contaminants.

For the watershed component of the modeling, the Hydrologic Simulation Program – FORTRAN (HSPF) and LSPC models were the primary tools considered given the historical use of these frameworks by King County. LSPC is built from the same underlying code and algorithms in HSPF, and HSPF parameters can be readily transferred to an LSPC input format.

Both LSPC and HSPF require considerable data for configuration and calibration, providing the ability to represent complex pollutant interactions in detail. These models are able to provide a variety of hydrologic and pollutant loading outputs, which facilitate linkages to a receiving water model. To simulate these complex loading processes and to model chemical constituents effectively on a watershed scale, a watershed model must be coupled to an advanced chemical loadings/reactive transport model. The selected model should possess the following capabilities to be a scientifically sound representation of the watershed loading and transport system and to be an advantageous management tool:

- Simulate hydrologic variations due to time variable weather patterns and the related transient saturation or unsaturated condition of the surface/subsurface.
- Simulate time variable chemical loadings from various sources in the watershed.
- Simulate interactions within a stream channel.
- Provide model results with a broad range of spatial and temporal scales.
- Evaluate source loading abatement scenarios for water quality control/management design with different spatial scales (e.g., lateral sources to LDW and loads from the Green River).
- Evaluate source loading abatement scenarios for water quality control/management design.

To meet these criteria, the LSPC model (EPA, 2009) is proposed for watershed simulation (specifically, LSPC version 5, developed by Tetra Tech). The model is a dynamic watershed hydrology/loading model and uses a one-dimensional channel. The model includes hydrological and chemical/sediment loading simulation to predict chemical fate and transport on a basin scale. LSPC simulates hydrology and pollutant accumulation and wash-off, and represents flow and water quality in the streams that drain to the LDW including the Green River and major tributaries (Shen et al., 2004; EPA, 2003b). The model can generate either hourly results or daily average results to predict and compare the modeled outcome with the existing observed data and/or to further utilize the results for advanced management decision support. LSPC provides added flexibility in addressing the needs of the Green/Duwamish River watershed relative to HSPF (e.g., in response to array size limitations associated with HSPF, flexibility with assignment of meteorological stations, a linked database, enhanced user interface, and the ability to include all of the watersheds under one common system as opposed to a series of separate models). In addition, LSPC is tailored to interface with EFDC.

The MDAS (Mining Data Analysis System) module can also be associated with LSPC. It can provide reactive chemical transport capability in a one-dimensional channel with an equilibrium computational code for ionic speciation of cationic/anionic components and adsorption in aqueous systems. The use of MDAS with LSPC for the watershed modeling is not currently anticipated, but is an option if needed.

Other dynamic watershed models considered include models that are widely used for loading studies. They include Stormwater Management Model (SWMM), Watershed Analysis Risk Management Framework (WARMF), and Soil and Water Assessment Tool (SWAT). Models that are fully proprietary, models that are considered experimental or academic tools, and models that do not have a track record of successful performance on similar projects were eliminated from consideration. The SWMM model is often used in urban areas for stormwater drainage system representation and at a smaller scale. It is not well suited for the large scale associated with the Green/Duwamish watershed, is not designed to represent agricultural features well, can experience difficulty representing baseflow processes, and its instream sediment transport and nutrient kinetics capabilities are relatively limited. Next, the WARMF model was not recommended given that it runs on a daily time step, which limits its usefulness in representing urban stormwater, and its lack of use in projects like the PLA relative to LSPC and HSPF. Finally, the SWAT model’s strength is primarily in simulating agricultural land uses and management practices. It runs on a daily time step, its approach to estimating solids delivery limits representation of urban land use hydrology and pollutant transport, and it has limited instream water quality kinetics capabilities for describing fate and transport.

Receiving Water Representation

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). The Environmental Fluid Dynamics Code (EFDC) framework was used to support these studies with minor exceptions. The previous efforts provide a strong basis for 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.

An important distinction between the recommended approach and the previous approaches (e.g., the Bed Composition Model or BCM) is the inclusion of contaminant transport and transformations processes directly in the EFDC model framework. The previous modeling was focused on the hydrodynamics and sediment transport in the LDW. Contaminant concentration estimates were developed by using estimates of the contaminant concentration in the three major sediment sources (upstream, lateral, and bed) and the output of the STM for these three sediment sources in a spreadsheet calculation of the future concentration in what was referred to as the BCM. The BCM assumed that the contaminants were only associated with sediments and that there was no dissolved phase, adsorption/desorption, or degradation. The recommended approach would replace the contaminant calculation preformed for arsenic and PCBs (in the BCM) with a process-driven simulation that includes the important processes regulating the transport and fate of dissolved and particulate contaminants relevant for the assessment of future conditions and effectiveness of the management strategies implemented in the LDW.

Additional approaches were considered and include the use of simple box models and the EPA Water Quality Analysis Simulation Program (WASP) model. WASP is designed to link to EFDC, but the linkage is cumbersome and requires transfer through enormous binary files. In addition, EFDC includes robust sediment transport and water quality modules. Its historic use in the LDW gives it the edge in terms of model selection. In the case of box models, while they could provide useful scoping level insights, the complexity of the LDW system makes their use in developing management strategies limited. In addition, the long term historic use of EFDC provides a good foundation for its continued use to support the PLA. Specifically, EFDC v. 2, developed by Tetra Tech, will be used for receiving water representation.

Food Web/Bioaccumulation Representation

Food web/bioaccumulation models are needed to link contaminant levels in the water column and bed sediment to contaminant levels in aquatic life. Various food web/bioaccumulation models have been developed by EPA and other agencies including Arnot and Gobas, AQUATOX, BASS, Biotic Ligand Model, Ecofate, E-MCM, QEAFDCHN, RAMAS, DYMBAM and TRIM.FaTE. Different models cover different contaminants, and most of the food web/bioaccumulation models simulate the bioaccumulations of PCBs and PAHs. For example, the Arnot and Gobas (2004) Food Web Model (FWM) has been applied to the LDW for bioaccumulations of PCBs and polybromiated diphenyl ethers (PBDEs). The

FWM model assumes that the bioaccumulation processes reach steady-state for a given time period. The previous use of the Arnot and Gobas model provides a strong basis for its use for the PLA.

Other approaches such as simple empirical approaches using data or biota-sediment accumulation factors (BSAF) may not provide sufficient reliability for predicting how contaminants in fish and aquatic life tissue will respond to potential management practices. The FWM is proposed for continued application in the LDW modeling system. Specifically, the current version known as AQUAWEB v. 1.3 will be used (http://www.arnotresearch.com/#!/page_AQUAWEB).

Summary of Recommended Framework

The recommended framework for this PLA is a comprehensive linked watershed/receiving water/food web modeling system representative of the processes essential for accurately modeling hydrology, hydrodynamics, and water and bed sediment quality (Figure 7). This framework involves the configuration, calibration, and corroboration of a modeling system to available data, and building from and incorporating lessons learned in previous modeling studies to address PLA modeling objectives.

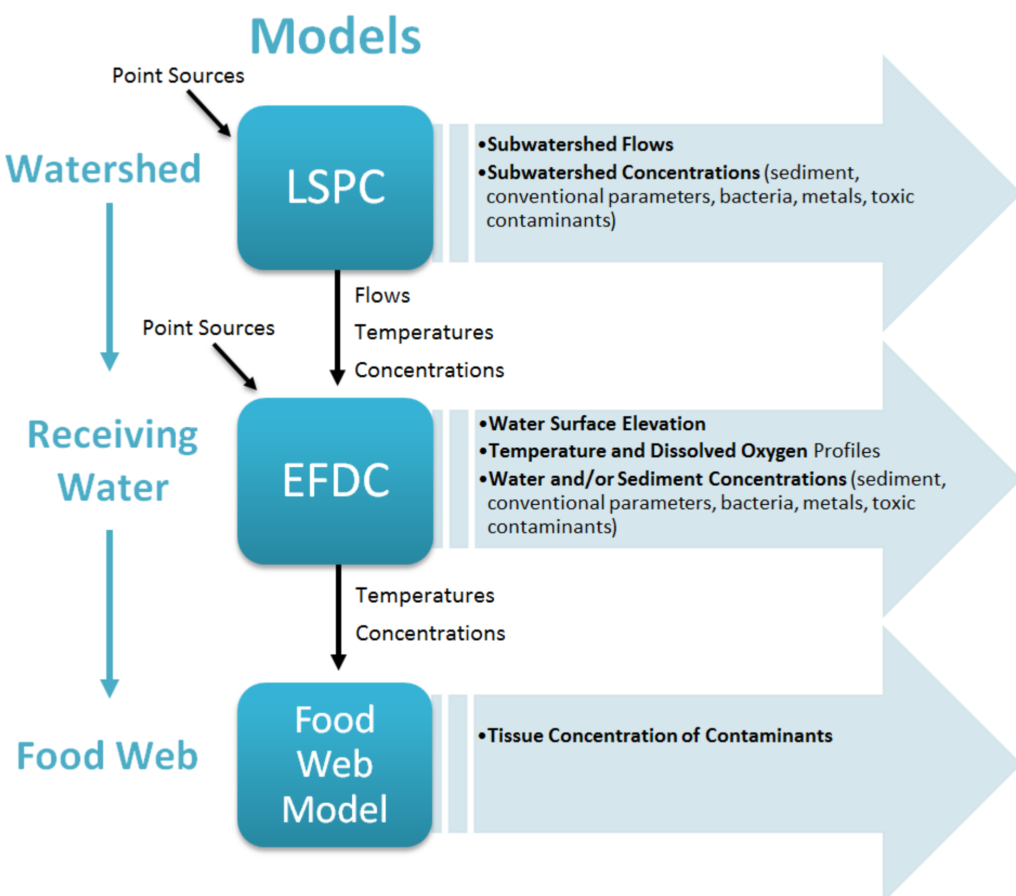

Figure 7. Linked modeling system for the PLA

2.4 Quality Objectives and Criteria for Model Inputs/Outputs

The Green/Duwamish River watershed PLA modeling and technical analyses are being planned consistent with EPA's Data Quality Objectives Process (USEPA, 2006a). A key component of the process is identifying and documenting the decision context for the project, addressed as general goals and objectives in Section 2.1. Model-specific objectives are described for LSPC (Section 3.1.1), EFDC (Section 3.2.1), and the Food Web Model (Section 3.3.1). Methods for evaluation of model performance are described further in Section 3.1.6.4 (LSPC), Section 3.2.6 (EFDC), Section 3.3.6 (Food Web Model), and Section 3.5.

3 Model Development

The general project goals and objectives presented in Section 2 are translated into specific model development activities related to characterizing watershed pollutant loading in the Green/Duwamish River watershed.

Environmental simulation models are simplified mathematical representations of complex real-world systems. Models cannot accurately depict the multitude of processes occurring at all physical and temporal scales. Models can, however, make use of known interrelationships among variables to predict how a given quantity or variable would change in response to a change in an interdependent variable or forcing function. In this way, models can be useful frameworks for investigating how a system would likely respond to a perturbation from its current state. To provide a credible basis for predicting and evaluating mitigation options, the ability of the model to represent real-world conditions should be demonstrated through a process of model calibration and corroboration (CREM, 2009).

Model calibration and evaluation is conducted to ensure that the model is adequate to provide reasonable and appropriate information to answer the study questions. The objectives of model development for the PLA are to develop a set of linked tools that can address CWA impairments and analyze the recontamination potential for LDW. To address these objectives, the models must be able to provide credible representations of (1) water movement, (2) sediment movement, (3) pollutant load generation and transport, and (4) tissue concentrations. In addition, the model should facilitate comparisons to targets and evaluation of management actions.

The next subsections address each of the components of the modeling system: the watershed model (LSPC), the receiving water model focusing on the LDW (EFDC), and the FWM.

3.1 Watershed Model – LSPC

3.1.1 Objectives

The PLA requires a source-response linkage and the estimation of existing loadings and target loadings to attain goals, as well as the distribution of those loads among sources and pathways to inform source reductions. As part of the linked modeling system, the watershed model, using the LSPC framework, not only includes the physical and chemical processes within the Green/Duwamish River watershed itself, but also integrates with the LDW by supplying inputs of hydrology, suspended sediment, and pollutants representing upstream sources.

The watershed model will provide a dynamic representation of flow and pollutant loads entering the LDW from the surrounding drainage area represented by a series of connected subwatersheds and stream reaches. Specifically, the watershed model will address several of the objectives identified in the CMs (Section 2.2), including

- Evaluation of hydrologic variations due to time variable weather patterns and the related transport in surface water.
- Examination of time variable chemical loadings of organics, metals, and major ions from industrial, urban, agricultural, and various natural pollutant sources in the watershed.
- Evaluation of source reduction and watershed management scenarios for water quality control.

To meet these objectives, the watershed model will need to address pollutant loading from various sources and pathways including industrial and other point sources, agricultural runoff, stormwater point and nonpoint sources, natural sources (e.g., forests), atmospheric deposition, and others.

As described in Section 2.3, the LSPC model is the selected framework for the watershed simulations. In addition to providing an optimal choice to meet the objectives identified through the CMs, LSPC is an efficient version of the well-established HSPF model (Bicknell et al., 2014). Prior work with HSPF models in the Green/Duwamish watershed is available and will facilitate development of the watershed model framework for the PLA.

3.1.2 Existing Watershed Models

Existing models of the area draining to the LDW include HSPF models of the upstream watershed and specialized models of the combined sewer system that include combined sewer overflows that go to the Duwamish waterway. Both are discussed below.

Aqua Terra in conjunction with King County prepared a series of HSPF models for sub-watersheds draining to Greater Lake Washington and to the LDW (Aqua Terra and King County, 2003). The report contains individual subwatershed sections for Black River and Springbrook Creek (July 2003), and Newaukum Creek (July 2003).

The original HSPF models of Green-Duwamish sub-watersheds were developed to support the Green River Water Quality Assessment studies. The models were set up and configured similarly. Model segmentation involved delineating watershed area into drainage basins and then into hydrologic response units (HRUs) based on 1) pervious/impervious land units and receiving water reaches and 2) physical parameters (e.g., pervious land use composition, pervious geology and soils composition, elevation, slopes, channel length, etc.). GIS datasets for setup and configuration were obtained from King County, USGS and created by Aqua Terra. In addition, a number of historical and ongoing data sets collected by King and Snohomish counties, the University of Washington, federal agencies (e.g., NOAA, National Weather Service [NWS]), and various local jurisdictions were incorporated into the watershed models and used for calibration.

The HSPF models were calibrated for flow, water temperature, suspended sediment, dissolved oxygen (DO), nutrients, biological oxygen demand (BOD), and bacteria. Initial model parameterization was generally obtained from work performed to generate nonpoint target loading rates. These rates, by land use and constituent were developed by reviewing literature values for the region and a study of the Puget Sound Basin by the USGS. Generally, the calibration results suggested a good fit for the constituents that had monitoring data.

In 2009 King County was awarded a Puget Sound Watershed Management Assistance Program grant to develop a stormwater retrofit plan for Water Resources Inventory Area (WRIA) 9. This project built upon the existing HSPF models and extended the coverage for the LDW watershed by creating additional HSPF models for the entire portion of the Green-Duwamish watershed between Howard Hanson Dam and the boundary of the City of Seattle (King County, 2013). More recently, the Muckelshoot Tribe and King County collaborated in a refinement of the model for the Soos Creek watershed (2015). Models were not developed upstream of Howard Hanson Dam or for the direct drainage area to the LDW within the City of Seattle.

The updated WRIA 9 HSPF models were supplied by King County. These were tested and verified to work, and the correct “final” models were identified in conjunction with King County staff. These consist of 17 individual HSPF models, of which 13 are linked and represent the drainage through the Green River to the LDW. The other four models are separate drainages within King County that connect directly to the LDW (Figure 8).

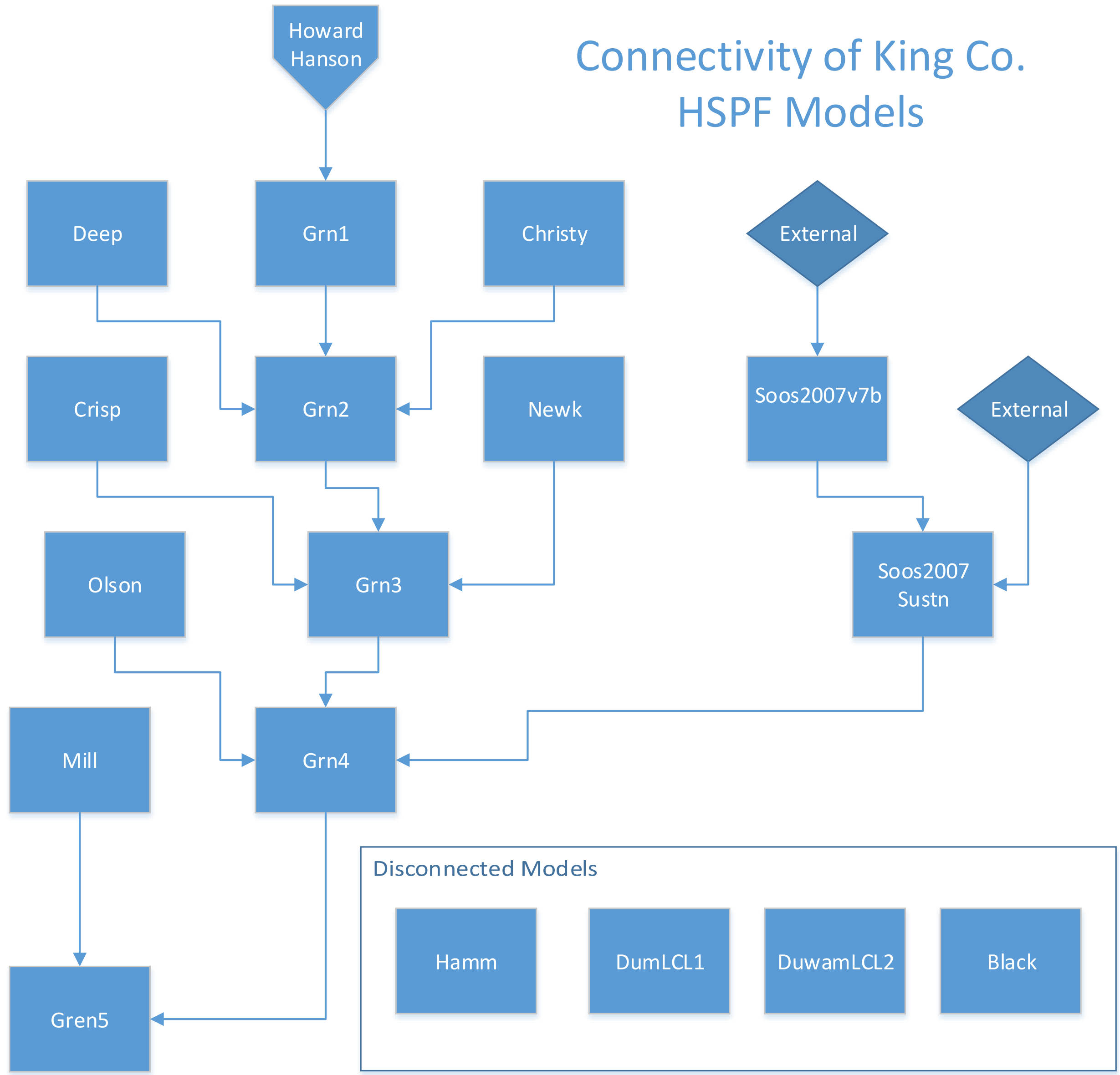

Figure 8. King County WRIA 9 model linkages

The performance of these models has been assessed by King County (2013a). Additional refinements of the flow and suspended sediment calibration may be needed; however, the report on existing models gives an indication of the degree of calibration that is likely to be achieved. The area covered in the WRIA 9 models that drains to the LDW constitutes 20 linked HSPF models. Half (10) of these models do not have calibration data. For the other 10 (excluding the WRIA models that drain directly to Puget Sound), the quality of hydrologic calibration is generally rated as "good." In contrast, the suspended solids calibration ratings range from "poor" (Black River and Covington) to "excellent" (Big Soos). If additional suspended solids data is available, the PLA project will include an effort to improve the poorly calibrated suspended solids models, because the transport of most of the constituents of concern for this project depends in large part on the movement of sediment.

Portions of the watershed area adjacent to the LDW have separated and partially separated systems for sewage and stormwater. The LSPC model is not an appropriate tool for simulating combined sewer systems (CSS) and CSO inputs that flow directly to the LDW. Areas with partially separated storm drainages are generally areas in which street drainage is separated but roof drainages go to the CSS. These areas will need to be addressed by developing LSPC watershed models that represent and route only those portions of runoff that goes directly to the LDW and not to the CSS. Development of LSPC models for areas with partially separated storm sewer systems will be informed by analyses undertaken by King Co.

Stormwater runoff that goes to the CSS is conveyed out of the watershed for treatment under normal flow conditions; however, CSOs occur during certain storm events and can contribute significant flow and loads to the LDW under those conditions. Representation of CSOs will rely on the monitoring and CSS/CSO models developed by King Co. and the City of Seattle.

3.1.3 Planned Refinements/Additions to Previous Models

The existing King County HSPF models appear to provide good performance for hydrology, although this performance should be further tested and verified (and enhanced where needed) when the model implementation period is extended (discussed below in Section 3.1.6.2). Performance of the suspended sediment simulation will be improved if possible based on additional data.

The primary refinement to the previous models will be to take the 17 individual HSPF models and convert them to one LSPC model. (Note that the model can have multiple terminal points that provide input to the EFDC model of the LDW). The unified model will be extended in time, rechecked/refined for hydrologic performance, and recalibrated for suspended sediment simulation. The second major refinement will be to extend the model area to cover direct drainage to the LDW that lies within the City of Seattle. Once hydrology and suspended sediment simulation is refined, the third major refinement to the previous models will be to add and calibrate the simulation of selected toxics.

The existing HSPF models are based on 2007 land use. An evaluation of land use change over time is an important factor in the construction of a watershed model that relies (at least in part) on calibration to historical data collection from periods where land uses may have been different. An analysis of this will be conducted and recommendations will be made on whether land use change should be considered in the model. A feature of LSPC is that it is able to consider representation of land use change. The 2007 land use is likely most appropriate for model comparison to recent monitoring data; however, more recent land use coverages may be needed for future scenarios.

In order to meet the project schedule, a number of early sub-tasks may commence during the finalization of this QAPP:

- Compile/organize data to support watershed model development (e.g., meteorological time series, flow data, CSO data/model output, stream hydraulics, pumping data, land use/land cover, soils, topography, etc.).
- Convert existing HSPF models to the LSPC platform.
- Process met data to include filling, patching, etc.
- Organize flow data into calibration tool spreadsheets.
- Construct/refine F-tables.
- Configure LSPC models for areas lateral to LDW (note, these are new models where existing HSPF models do not exist).

3.1.4 Model Representation of Sources and Processes

A key function of the watershed model is to develop an estimate of source loads and their impact on receiving streams loads. Watershed-based sources and pathways include:

- Urban runoff and associated loads (of solids and pollutants).
- Agricultural runoff and associated loads.
- Other runoff such as from natural areas and associated loads.
- Atmospheric deposition, including spatial variation in deposition rates.
- Point source discharges (industrial, regulated stormwater outfalls, etc.).
- Spills and/or leaks (contaminated sites and industrial operations areas contributing high contaminant loads).
- Legacy COCs in bed sediments above the LDW.
- Groundwater contributions to both watershed-based streams and to the LDW directly.

Pollutant loads are delivered to tributaries via surface runoff, subsurface flows, groundwater flows, direct point source discharges, and other pathways. LSPC provides mechanisms for representing all of these pathways of pollutant delivery.

LSPC is a lumped model in that the watershed area is divided into numerous sub-basins. Within each sub-basin, processes are simulated for each type of land area on a per-acre basis, then multiplied by the relevant acreage to develop the total local load to the stream reach within the sub-basin. Individual land areas are represented as hydrologic response units (HRUs), which combine land use/cover, soil, slope, and other characteristics. Each HRU is a generalized representation of a specific type of source area within the sub-basin. For example, all parking lots within the sub-basin would be represented by a single unit-area HRU with appropriate runoff and pollutant generating characteristics, rather than simulating each parking lot individually. Where necessary, HRUs can be further divided – for instance, if one parking lot or type of parking lot generates higher pollutant loads than the typical parking lot, it can be specified by a separate HRU. The HRU approach allows incorporation of a high degree of detail into the model while also allowing for efficient simulation and relatively short model run times.

The toxic pollutants that will be addressed in the LSPC watershed model are:

- PCBs (specifics yet to be determined).
- Carcinogenic PAHs as a single group.
- Inorganic arsenic.
- DEHP as a surrogate for other phthalates.
- Copper, dissolved and sorbed inorganic forms.
- Zinc, dissolved and sorbed inorganic forms.

3.1.4.1 Hydrology

LSPC/HSPF provide a dynamic, continuous simulation of hydrology and water quality processes. The simulation occurs at a user-specified time step. For water quality applications, an hourly time step is typically appropriate. This is sufficient to capture the storm event hydrograph and to represent major washoff and erosion events.

Hydrology in LSPC is identical to HSPF. Multiple hydrologic components are contained within LSPC including precipitation, interception, evapotranspiration (ET), overland flow, infiltration, interflow, subsurface storage, groundwater flow, and groundwater loss. The figure below provides a graphical representation of these processes (capitalized acronyms are computer code routine names). Rain falls and lands on constructed landscapes, vegetation, and soil. Varying soil types allow the water to infiltrate at different rates (using the Philip infiltration algorithm) or enter shallow interflow pathways, while evaporation and plant matter exert a demand on available water. Water flows overland and through the soil matrix. The land representation in the LSPC model contains three major flow pathways: surface, interflow, and groundwater outflow.

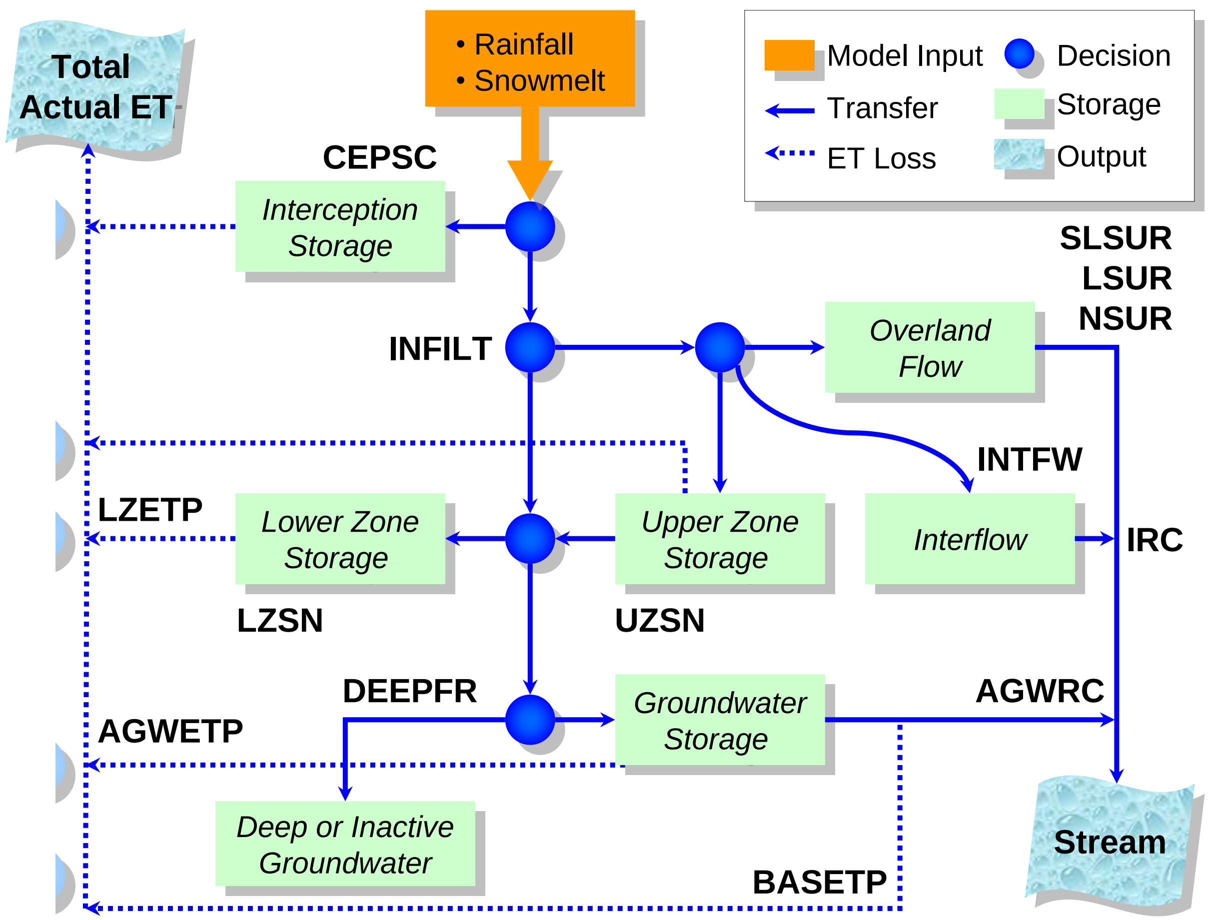

Figure 9. Hydrologic representation in the LSPC model

Note: Entries in **ALL CAPITALS** identify key model parameters that determine the magnitude of different pathways.

3.1.4.2 Upland Sediment

HSPF simulates sediment yield to streams in two stages. First, HSPF calculates the detachment rate of sediment by rainfall (in tons/acre) as

$$DET = (1 - COVER) \cdot SMPF \cdot KRER \cdot P^{JRER} \qquad \textbf{Equation 1}$$

where *DET* is the detachment rate (tons/acre), *COVER* is the dimensionless factor accounting for the effects of cover on the detachment of soil particles, *SMPF* is the dimensionless management practice factor, *KRER* is the coefficient in the soil detachment equation, *JRER* is the exponent in the soil detachment equation, which is recommended to be set to 1.81, and *P* is precipitation depth in inches over the simulation time interval. Direct addition of sediment (e.g., from wind deposition) is also added via the parameter *NVSI*. Actual detached sediment storage available for transport (*DETS*) is a function of accumulation over time and the reincorporation rate, *AFFIX*.

The transport capacity for detached sediment from the land surface (*STCAP*) is represented as a function of overland flow:

$$STCAP = KSER \cdot (SURS + SURO)^{JSER}$$ **Equation 2**

where *KSER* is the coefficient for transport of detached sediment, *SURS* is surface water storage (inches), *SURO* is surface outflow of water (in/hr), and *JSER* is the exponent for transport of detached sediment.

3.1.4.3 Instream Sediment

HSPF/LSPC representation of instream sediment transport is described in Bicknell et al. (2014): The details of the transport, deposition, and scour techniques are outlined below. Following these calculations, the depth of sediment in the bed is determined.

As a one-dimensional reach model, HSPF does not directly distinguish between channel bed and bank erosion. As a result, all scour and deposition is represented as a nominal change in sediment bed depth. LSPC adds a component that can simulate bank erosion as a potential source of sediment independent of storage in the channel bed. It is desirable to correctly represent the division between upland sources and channel sources of sediment load. These issues will be addressed in the model calibration report,providing decision-relevant information on the extent to which the model is able to accurately distinguish relative contributions from upland and channel sources and between different upland sources.

HSPF/LSPC uses a single sediment bed layer. Initial bed composition in each reach would be based on any available field data or, barring data, best professional judgment. The simulation will continuously update the bed composition in each reach based on relative amounts of scour or deposition of the three defined size classes (sand, silt, and clay).

<u>Noncohesive Sediment</u>

Erosion and deposition of sand, or noncohesive sediment, is affected by the amount of sediment the flow is capable of carrying. If the amount of sand being transported is less than the flow can carry for the hydrodynamic conditions of the bed, sand will be scoured from the bed. This occurs until the actual sand transport rate becomes equal to the carrying capacity of the flow or until the available bed sand is all scoured. Conversely, deposition occurs if the sand transport rate exceeds the flow's capacity to carry sand.

Subroutine SANDLD allows the user to calculate sand transport capacity for a reach by any one of three methods. Depending on the value of SANDFG specified in the User's Control Input, either the Toffaleti equation (SANDFG=1), the Colby method (SANDFG=2), or an input power function of velocity (SANDFG=3) is used.

The potential scour from, or deposition to, the bed storage is found using the continuity equation. The potential scour is compared to the amount of sand material of the bottom surface available for resuspension. If scour demand is less than available bottom sands, the demand is satisfied in full and the bed storage is adjusted accordingly. The new suspension concentration is PSAND. If the potential storage cannot be satisfied by bed storage, all the available bed sand is suspended, and bed storage is exhausted.

If a reach goes dry during an interval, or if there is no outflow from the reach all the sand in suspension at the beginning of the interval is assumed to settle out, and the storage is correspondingly increased.

Cohesive Sediment

Exchange of cohesive sediments with the bed is dependent upon the shear stress exerted upon the bed surface. The shear stress within the reach is calculated in subroutine SHEAR of the HYDR section. Whenever shear stress (TAU) in the reach is less than the user-supplied critical shear stress for deposition (TAUCD), deposition occurs; whenever shear stress is greater than the user-supplied critical shear stress for scour (TAUCS), scouring of cohesive bed sediments occurs. If the amount of scour calculated is greater than available storage in the bed, the bed scour is set equal to the bed storage, and the bed storage is set equal to zero. Since the value specified for TAUCS should be greater than that for TAUCD, only one process (deposition or scour) occurs during each simulation interval.

3.1.4.4 Toxics

The LSPC model provides a general and flexible framework for simulating pollutants, including hydrophobic organic toxics. As with the simulation of sediment, there are three major components to simulating toxic constituents derived from the land surface: availability of contaminant mass on the land surface, washoff of contaminants to stream, and fate and transport within receiving waterbodies. Toxic constituents are tracked in the model as dissolved and particulate mass in surface flow pathways and dissolved mass in subsurface pathways.

Availability of pollutants on the land surface

Loading processes for pollutants in LSPC will be represented for each land unit (HRU) using the PQUAL modules (simulation of pollutants for pervious land segments) and IQUAL (simulation of quality constituents for impervious land segments) modules. These modules allow for the simulation of pollutant loading as solids/sediment-associated, as a buildup-washoff relationship, as a concentration in land segment surface and subsurface outflow, or as a combination of the three.

For the purposes of developing watershed loading models of contaminants of concern in the Duwamish PLA (PCBs, PAHs, arsenic, and several metals), the King County models provide a strong hydrologic foundation at the large watershed scale. One limitation is that these models do not model the combined sewer area and separate storm sewer urban drainages near the LDW. There is also limited capacity to specify different loading rates from specific parcels without additional refinement of the models. It appears that the King County models can be directly built upon to address loading from rural areas with diffuse sources. In the urban areas, it will likely be necessary to refine the models to distinguish certain source areas as specific upland pervious and impervious HRUs. It may also be necessary to retabulate urban HRUs on the basis of whether they are served by combined or separate storm sewers and to reflect specific information on upland sites.

These modifications would likely not require any major changes to the hydrologic calibration of the HSPF models. Hydrologic representation refers to the LSPC modules or algorithms used to simulate hydrologic processes (e.g., surface runoff, ET, and infiltration). The LSPC PWATER (water budget simulation for pervious land segments) and IWATER (water budget simulation for impervious land segments) modules, which are identical to those in HSPF, will be used to represent hydrology for all pervious and impervious land units (Bicknell et al., 2001). During hydrology calibration, land segment hydrology parameters are adjusted iteratively to achieve agreement between simulated and observed stream flows at specified locations throughout the basin.

Source areas, such as specific urban industrial areas, could be separated into specific HRU categories that inherit the hydrologic parameters of their parent HRU, but have different pollutant loading characteristics. This may be informed, in part, by source area investigations conducted for the LDW. For instance, areas known to be sources of PCBs and connected to the LDW by separate stormwater drainages could have their own pollutant characteristics.

For the Green-Duwamish watershed, and given the focus on PCBs, cPAHs, arsenic, DEHP, copper, and zinc, buildup/washoff (with atmospheric deposition) is most likely the best choice for impervious land segment simulation of pollutant generation. For pervious land, a combination approach of sediment potency (e.g., pounds of the COC per ton of sediment eroded) plus specification of concentrations in subsurface flow pathways, is proposed. A buildup/washoff or fixed concentration component on pervious land can also be included in addition to potency if atmospheric deposition onto saturated surfaces is a particular concern.

When using the buildup-washoff method, pollutants, including atmospheric deposition to land, are modeled as accumulating and then washing off based on rainfall and overland flow. Accumulation rates are assigned to HRUs to simulate buildup of pollutants on the land surface, along with an asymptotic maximum storage limit. Accumulation rates and storage limits can be assigned on a monthly basis and can be estimated on the basis of typical pollutant production rates for sources associated with different HRU types. Both local data and literature will inform these rates. These values serve as starting points for water quality calibration.

The load generation of diffuse pollutants in urban areas is quite different from the process that operates on rural lands. Novotny and Olem (1994) summarize the key differences as follows:

- Urban areas have high impervious cover, resulting in greater hydrological activity and a greater ratio of runoff to rainfall.
- The hydrological response to precipitation in urban areas is faster, resulting in greater storm peaks.
- Urbanization typically reduces groundwater levels, resulting in lowered base flow in urban streams.
- Polluted runoff from impervious surfaces is generated by precipitation that exceeds a certain minimal threshold value of depression storage (typically 1 to 2 mm), which is a much lower threshold than is needed for surface runoff from most pervious land, resulting in more frequent pollutant loading events.
- Except for construction sites, most pervious land surfaces in urban areas are protected by lawns and vegetation, resulting in reduced land surface erosion relative to agriculture; however, faster runoff and higher storm event peaks typically result in increased stream bank erosion.
- Pollution deposited on impervious surfaces is generally not incorporated into the soil; thus, all of the pollution deposited on impervious surfaces that is not removed by street cleaning, wind, or decay will eventually end up in surface runoff.

The conceptual process of pollutant loading from urban impervious surfaces is typically described by general accumulation and washoff processes proposed by Amy et al. (1974) and Sartor and Boyd (1972). This assumes that pollutants accumulate at a constant rate; however, as they build up there are also losses due to factors such as wind, traffic, and decay such that apparent accumulation rate asymptotes toward a limit. If $P(t)$ is the accumulated pollutant mass present on day t, then the rate of accumulation during dry periods (without washoff) is

$$\frac{dP}{dt} = p - \beta P \qquad \textbf{Equation 3}$$

where p is a constant accumulation rate (M/T) and β is a depletion rate constant (T^{-1}). Solving Equation 3 for a dry period ending in an event on day t and accounting for any mass removed by washoff (W_t) on day t yields

$$P(t) = P(0)\, e^{-\beta t} + (p/\beta)\left(1 - e^{-\beta t}\right) - W_t \qquad \textbf{Equation 4}$$

where *P(0)* is the mass present at time zero. As *t* increases, this equation asymptotes to a limiting value of p/β when no washoff occurs. Sartor and Boyd (1972; see also summary in Novotny and Olem, 1994) presented information on the time to reach 90 percent of the storage limit (order of 10 to 20 days), from which the value of the ratio p/β can be estimated. In LSPC, the user specified the accumulation rate p as ACCUM and the storage limit ratio p/β as SQOLIM, thus implicitly defining the depletion rate.

During calibration for chemical parameters, the first step is to assign groundwater concentrations to pervious land segments based on available data and literature. The next step is to assign initial build up washoff and/or potency and modify iteratively to verify that unit area loading rates are reasonable compared to literature values (e.g., Ecology, 2010) or local land use loading information. After ensuring reasonable upland loading rates, calibration to instream observations will be carried out to refine the simulation. The data sources currently available to support the calibration are described in Section 4.1.1.1. Where data exist or become available to better characterize loads of toxics from specific land uses or source areas this information will be used to further test and constrain model performance.

Washoff of contaminants to stream

When pollutant loading is simulated via a sediment potency approach the transport of contaminants from the land surface to waterbodies is directly tied to the transport of sediment. Similarly, if loading is specified via a seasonal concentration pattern in runoff, then delivery to stream is a direct function of the hydrologic simulation. For the buildup/washoff formulation, the mass removed by washoff is a function of the depth of flow (Q) and the stored mass at the start of the time step ($P(t)$). This is typically represented as a first-order relationship (Amy et al., 1974), such that

$$W_t = P(t) \cdot \left(1 - e^{-\alpha Q}\right) \qquad \textbf{Equation 5}$$

where α (WSQOP in LSPC) is a parameter that is based on an estimate of the depth of runoff that will wash off 90 percent of the accumulated pollutant mass.

These conceptual relationships indicate that the pollutant mass present in a runoff event will reflect the characteristics of the accumulation and depletion rates (which will vary by land use, but may also be affected by temperature, patterns of human activity, and other factors) and also by the magnitude of a runoff event and the elapsed time since a previous washoff event. Further, concentration (W/Q) is not a linear function of flow (Q), even if accumulated pollutant mass ($P(t)$) is held constant. It is thus expected that pollutants in urban stormwater will exhibit highly heterogeneous characteristics with loads and concentrations that vary in space and time.

Instream fate and transport

The LSPC RCHRES component provides for a highly flexible representation of instream processes affecting water and sediment quality. Options include (in addition to advection and dispersion) representation of sorption to sediment, volatilization, and decay and transformation processes applicable to dissolved and sorbed phases in the water column and bed sediment. Processes selected for the representation of each COC will be based on literature review and analysis of structural/chemical properties. For low solubility non-polar organics such as PCBs and PAHs, the model representation will likely include sorption to solids in the water column and bed sediment, exchanges between the water column and bed sediment, volatilization, and general first-order decay (where appropriate). The approach to partitioning for toxics in LSPC is the same two-phase partitioning approach as for the EFDC model and is described below in the Section 3.2.4.

Ionic metals also sorb to particulate matter, although the process is different from nonpolar organics. Sorption-desorption reactions for metals are likely to be of limited importantance in flowing reaches, but may be of greater importance in wetlands, lakes, and other low gradient areas. For metals, the model will represent exchanges of sediment-associated metals between the water column and the bed. An analysis will be undertaken to determine whether this needs to be described via an equilibrium partitioning approach for sorption to solids. If needed, this will be represented (as in EFDC) with a simplified representation of ionic metal sorption as a function of simulated suspended sediment concentrations using the approach documented in USEPA (1996) and described below in Section 3.2.4.

3.1.5 Model Configuration

The Green/Duwamish River watershed includes four primary subwatersheds from upstream to downstream:

- Upper Green River from the Howard Hanson Dam to the headwaters, covering 220 square miles of mostly forested land.
- Middle Green River from Auburn Narrows (RM 32.0) to the Howard Hanson Dam (RM 64.5), which includes nearly 180 square miles of residential, forest, and agricultural land uses.
- Lower Green River from Tukwila (RM 11.0) to Auburn Narrows (RM 32.0), encompassing about 64 square miles of residential, industrial, and commercial land.
- Duwamish Estuary from Elliott Bay/Harbor Island to Tukwila (RM 11.0) near the confluence with the Black River, covering 32 square miles of industrial and residential areas; this subwatershed includes lateral drainage to portions of the Duwamish River downstream of the Black River as well the LDW itself.

The spatial extent of the LSPC watershed model will focus on the three subwatersheds below the Howard Hanson Dam. As discussed in the Technical Approach, the land area upstream of the dam is almost entirely forested and undeveloped, includes high elevations, and is not anticipated to be a significant source of most toxic parameters or subject to source control actions. The dam is expected to be used as a boundary condition to represent inflow into the Green River.

3.1.5.1 Model Boundaries and Boundary Conditions

LSPC is a one-dimensional, uni-directional model. Hydraulic behavior of stream reaches is represented by externally specified functional tables that do not allow reversing flow or upstream dispersion. For this reason, the downstream boundary of the LSPC model and its interface with the EFDC model is set at the point of upstream tidal influence and no downstream water quality boundary conditions are required.

The primary upstream boundary of the LSPC model will be Howard Hanson Reservoir, as is also the case for the existing King County HSPF models. The Technical Approach proposes simulating the Lower and Middle Green Rivers up to the Howard Hanson Dam. A USGS gage located just downstream of the Howard Hanson Dam provides flow data encompassing the modeling time period of 1993-2013, and will be used as a boundary condition for inflow data. The area upstream of Howard Hanson Dam drains approximately 200 square miles of mostly forested land.

The USGS gage below Howard Hanson Dam described above does not include temperature data. Stream gages further downstream do collect water temperature data (predominantly the USGS gage at Tukwila, 12113390), as have discrete studies, and can be used to check the simulated temperature. Water temperatures at this boundary are likely to exhibit relatively small daily variations as they represent releases from a large upstream reservoir. The large volume stabilizes water temperature to a greater degree than a free-flowing river. In addition, the lower water column of Howard Hanson Reservoir is discharged through two Tainter Gates, which control the reservoir and release colder flows.

There are additional external boundaries specified in the Soos Creek and Black River sub-models, including releases from Youngs Lake and Lake Sawyer (Soos Creek) and groundwater inflows. The groundwater inflows will be assigned pollutant concentrations that are consistent with other groundwater sources in the model. Pumping simulated in the Black River sub-model is represented as an outflow demand from Reach 520 that will automatically simulate transfer of pollutants as well.

3.1.5.2 Hydrologic Response Units

LSPC, like HSPF, is a partially "lumped" model. This means that the land surface is not represented by a grid in which every grid cell is represented explicitly. Rather, the land surface area is divided into sub-basins, each of which is characterized by adding up the responses of unit-area simulation blocks. For instance, if the subbasin contains 10 acres of a low density residential land, the contribution of flow and pollutants from low density residential land within the subbasin is estimated by simulating a 1-acre unit of low density residential land and multiplying it by 10 acres to estimate the total contribution from this land surface. This enables a relatively fast and efficient simulation. The King Co. HSPF models contain a total of 446 subbasins or catchments, with an average size of 146 acres.

The unit-area building blocks of the upland model are referred to as HRUs. Each HRU represents a unique combination of land use/land cover, soils, slope, and associated weather inputs. For the above example, the low density residential land cover may be scattered across areas with 3 different soil types, and 3 HRUs could be set up to capture these differences. In practice, the base HRUs are developed through a GIS overlay of land use/cover, soils/geology, and slope, then replicated according to weather station assignments.

Land use/land cover categories for the King Co. HSPF models are derived from 2007 satellite imagery (University of Washington, 2007) and identify 16 classes of pervious and impervious land use/land cover (see Table 2 in King Co., 2013). Soils are differentiated between areas of glacial till, outwash, and saturated soils. These are the major indices of hydrologic behavior, as till typically has low permeability, outwash has high permeability, and saturated soils that exhibit high permeability with low capacity because of frequent saturation. Bedrock outcrops are grouped with till. Areas of glacial till are further differentiated into classes of low and moderate slope, with a break at 5% slope. Outwash and saturated soils are not differentiated by slope because runoff responses of these soils are typically not sensitive. Effective (i.e., directly connected) impervious areas are identified for each of the developed land uses. Prior to differentiating by weather station association, this leads to a set of 45 base HRUs (see Table 4 in King Co., 2013).

Two tables from the King County report are reproduced below. These define the modeled land use/cover categories and model HRU descriptions.

Table 5. Land cover categories used in the development of the HSPF model

Land Use	Description	Land Cover
Heavy Urban	Commercial / industrial with lawns, rooftops, pavement, roads	High grass and Impervious surfaces
Medium Urban	Medium to high density residential with lawns, rooftops, pavement, roads	Medium grass and Impervious surfaces

Land Use	Description	Land Cover
Light Urban	Low density residential with lawns, rooftops, pavement, roads	Low grass and Impervious surfaces
Cleared for Development	Compacted lands cleared for development	Cleared Lands
Grass, Grasslands	Lawns, parks, meadows, golf courses, etc. with some roads	Grass
Deciduous and Mixed Forest	Forested lands with some roads	Forest
Coniferous Forest	Forest lands with some roads	Forest
Clear cut Forest	Recently cleared forested lands with some roads	Clear cut
Regenerating Forest	Early stages of tree growth with some roads	Regenerating Forest
Agriculture	Agriculture lands used for animal or crops with some roads	Agriculture
Non-forested wetlands	Visible wetlands with some roads	Wetlands
Open Water	Open water	Open Water
Snow, Bare rock	Higher elevations, dominated by snow cover and/or bare rock with some roads. For this study the amount of areas are inconsequential and are reassigned to keep permutations to a minimum.	Modeled as medium grass and Impervious surfaces
Shorelines	Slivers of landscape buffering larger receiving bodies of water with some roads	Modeled as grass
Roads	External dataset applied	Road impervious surface and grass
Added wetlands	Added wetlands using alternative data source	Wetlands

Table 6. HRU numbering scheme from King County (2013b) with associated surficial geology, land cover, slope

HRU Number	Surficial Geology	Land Cover	Slope	Description	Short Descr.
1	Till	Roads grass	Flat	Till Road Grass Flat	TR1
3			Moderate	Till Road Grass MED	TR3
11		Commercial grass	Flat	Till Road Grass Flat	TC1
13			Moderate	Till Road Grass MED	TC3
21		High Density Residential grass	Flat	Till Road Grass Flat	THR1
23			Moderate	Till Road Grass MED	THR3

HRU Number	Surficial Geology	Land Cover	Slope	Description	Short Descr.
31		Low Density Residential grass	Flat	Till Road Grass Flat	TLR1
33			Moderate	Till Road Grass MED	TLR3
41		Cleared Lands	Flat	Till Road Grass Flat	TCLR1
43			Moderate	Till Road Grass MED	TCLR3
51		Grasslands	Flat	Till Road Grass Flat	TGR1
53			Moderate	Till Road Grass MED	TGR3
61		Forest	Flat	Till Road Grass Flat	TF1
63			Moderate	Till Road Grass MED	TF3
71		Clear Cuts	Flat	Till Road Grass Flat	TCC1
73			Moderate	Till Road Grass MED	TCC3
81		Forest Regeneration	Flat	Till Road Grass Flat	TFRG1
83			Moderate	Till Road Grass MED	TFRG3
91		Agriculture	Flat	Till Road Grass Flat	TAG1
93			Moderate	Till Road Grass MED	TAG3
100	Outwash	Roads grass	N/A	OUTWASH, Road Grass	OR
101		Commercial grass		OUTWASH, COM Grass	OC
102		High Density Residential grass		OUTWASH, HD Grass	OHD
103		Low Density Residential grass		OUTWASH, LD Grass	OLD
104		Cleared Lands		OUTWASH, Cleared	OCLR
105		Grasslands		OUTWASH, Grassland	OGR
106		Forest		OUTWASH, Forest	OF
107		Clear Cuts		OUTWASH, Clear Cut	OCC
108		Forest Regeneration		OUTWASH, Forest Regen	OFRG
109		Agriculture		OUTWASH, Agriculture	OAGR
110	Saturated	Roads grass		SATURATED, Road grass	SRds

HRU Number	Surficial Geology	Land Cover	Slope	Description	Short Descr.
111		Commercial grass		SATURATED, Com grass	SC
112		High Density Residential grass		SATURATED, HD Grass	SHR
113		Low Density Residential grass		SATURATED, LD Grass	SLR
114		Cleared Lands		SATURATED, Cleared	SCLR
115		Grasslands		SATURATED, Grass	SGR
116		Forest		SATURATED, Forest	SF
117		Clear Cuts		SATURATED, Clear Cut	SCC
118		Forest Regeneration		SATURATED, Forest Reg	SFRG
119		Agriculture		SATURATED, Agriculture	SAGR
120		Wetlands		SATURATED, Wetland	WET
150	Impervious	LD Residential		EIA Low Den Residential	L-EIA
151		HD Residential		EIA High Den Residential	H-EIA
152		Commercial		EUA Commercial	C-EIA
153		Roads		EIA Roads	R-EIA

Tetra Tech has reviewed the King County HRU definitions and found them to be reasonable, and model performance was good to excellent for hydrology. Model development in LSPC can proceed, at least as regards hydrology and sediment transport, using the HRUs already established by King County. For the eventual simulation of organic toxic pollutants, it will likely be necessary to subset some of the HRUs to reflect areas with different degrees of stored pollutant concentrations or ongoing pollutant loads. Those pollutant characteristics will not, however, affect hydrologic or sediment erosion characteristics, so this refinement can be done after the initial phases of model development and would likely not require modifying parameters for hydrology and sediment transport. Fortunately, the structure of LSPC makes such refinements easy to implement, and there is no limit on the eventual number of HRUs that can be used (beyond the general size limits for Microsoft Access databases).

To ensure correct jurisdictional or other boundary (e.g., MS4) representation, HRUs can also be used to aggregate runoff and loading from distinct political boundaries. HRUs are simulated on a unit-area basis. The modeling system can provide source loads generated from selected areas within the watershed by tabulating the individual HRU responses. In addition, source parameters can be varied by individual HRUs and by specific HRUs within a given geographic area to account for site-specific information on pollutant loading.

For the added direct drainage to the the LDW within the City of Seattle, we propose to define HRUs based on applicable types of stormwater infrastructure. Fully combined areas that do not contribute surface flow to the LDW may still be a source of groundwater inputs, while partially separated and fully separated areas will be represented as contributing surface flow in varying amounts. These will have different flow pathways for the conveyance of runoff to the receiving systems. For example, aside from routing impervious (IMPLNDs) to storm conveyances, it may make sense to route the pervious surface (SURO) land segments to the same conveyances, while the shallow interflow (IFWO) and shallow active groundwater (AGWO) are routed differently to the receiving water bodies. If the storm conveyances are leaky and the shallow interflow and groundwater are intercepted, then this is a moot point and runoff from the three flow pathways all go to the same storm conveyance.

3.1.6 Model Calibration and Evaluation

3.1.6.1 Objectives

Model calibration consists of the process of adjusting model parameters to provide a match to observed conditions. Calibration is necessary because of the semi-empirical nature of water quality models. Although these models are formulated from mass balance principles, most of the kinetic descriptions in the models are empirically derived. These empirical derivations contain a number of coefficients that are usually estimated by calibration to data collected in the waterbody of interest.

3.1.6.2 Approach and Time Period

The watershed model will be calibrated and evaluated through a sequential process, beginning with hydrology, followed by suspended sediment and then water quality. Details for each sequential component are provided in Sections 3.1.6.2.2 through 3.1.6.2.4.

3.1.6.2.1 Time Period

Calibration of watershed models benefits from a relatively long time period that covers a range of climatic conditions and allows full stabilization of water stores. Previous hydrologic model calibration work undertaken by King County focused on 1996-2009. For this project, the simulation period will be extended to 2016 or 2017 depending on the timing of the calibration effort and data availability.

The existing hydrologic representation is believed to be in good shape, but it will be refined as needed. The existing suspended sediment calibration appears to need some improvement, while no calibration has taken place for toxics of interest. For these water quality constituents, additional data collected in recent years will be important for calibration.

3.1.6.2.2 Hydrologic Calibration

Hydrologic calibration will use standard operating procedures. Those are described for the HSPF (and LSPC) model in BASINS Technical Note 6 on *Estimating Hydrology and Hydraulic Parameters for HSPF* (USEPA, 2000). Modeling will build on work conducted by King County.

Model output will be compared to, among other things, the annual water balance, low/high flow distribution, storm peaks, and hydrograph shape. It is expected that during hydrology calibration, HRU (land segment) hydrology parameters will be adjusted iteratively to achieve agreement between simulated and observed stream flows at specified locations throughout the basin. Agreement between observed and simulated stream flow data are evaluated on annual and seasonal bases using quantitative and qualitative measures. Specifically, annual water balance, groundwater volumes and recession rates, and surface runoff and interflow volumes and timing are evaluated, along with composite comparisons (e.g., average monthly stream flow values over the period of record). Calibration for hydrology will take into account information on the reliability of gaging records where data quality flags and associated notes are available. Where gage records are subject to high amounts of uncertainty (e.g., due to low gradients and backwater effects in the Black River area or due to equipment problems during individual flow events), this uncertainty will be noted and discussed. Higher levels of apparent discrepancy between model and data may be acceptable where and when the quality of gage records can be determined to be poor.

In sum, the level of performance and overall quality of hydrologic calibration will be evaluated in a weight of evidence approach that includes both visual comparisons and quantitative statistical measures. The calibration will proceed in a sequential manner through (1) general representation of the overall water balance, (2) assurance of consistency with satellite-based estimates of actual ET and soil moisture, and (3) detailed calibration relative to flow gaging for seasonal flows, shape of the flow duration curve, and hydrograph shape.

Key parameters for hydrologic calibration and information on their potential ranges are as described in USEPA (2000). Initial values of key parameters can be related to soil and climatological properties where appropriate. Specifically, infiltration rates (INFILT) can be initialized by (and subsequently varied by) the NRCS hydrologic soil group (HSG), while initial values of lower zone nominal soil storage capacity (LZSN), upper zone soil storage capacity (UZSN), and interflow inflow (INTFW) can be set based on annual average rainfall, consistent with recommendations in USEPA (2000). Seasonal patterns based on vegetative cover and leaf area development (MON-LZETPARM, MON-INTERCEP, and MON-MANNING) will be initialized based on past experience with HSPF models in the Pacific Northwest.

3.1.6.2.3 Sediment Transport Calibration

Suspended sediment is one of the more difficult water quality parameters to calibrate in watershed models because observed instream concentrations depend on the net effects of a variety of upland and stream reach processes, only some of which are directly observed. Further, conditions in one stream reach may depend strongly on erosion and deposition patterns in the upstream reaches. Thus, mass balance checks need to examine every reach in the model. Suspended sediment calibration will be undertaken consistent with the guidelines in BASINS Technical Note 8: *Sediment Parameters and Calibration Guidance for HSPF* (USEPA, 2006b). Sediment calibration requires an iterative approach. The first step in calibration involves setting channel erosion to values that achieve a reasonable fit to TSS observations and values that are consistent with the literature and soil survey data. The erosion parameters for the upland simulation are then calibrated. Next, the long-term behavior of bed sediment in channels is constrained to a reasonable representation in which degradation or aggradation amounts are physically realistic and consistent with available local information. Finally, results from detailed local stream studies can be used to further ensure that the model provides a reasonable representation in specific areas.

Sediment transport calibration must address the generation of sediment load on the land surface, transport from the land surface to waterbodies, and fate and transport within waterbodies, including scour and deposition of sediment. The upland parameters for sediment can be related to soil and topographic properties. The process representation of upland sediment generation and washoff was discussed above in Section 3.1.4.2. There are two approaches that may be pursued for setting the relevant parameters. One is to develop a formal approximation between the HSPF/LSPC soil detachment coefficient (*KRER)* and the similar *K* factor in the universal soil loss equation (USLE), as has been done in several past Tetra Tech applications of HSPF. The other approach is to simply assume *KRER* = *K*, as is recommended in USEPA (2006b). In areas of generally mild slopes, such as the lower Green River/Duwamish, it is sufficient to use the approach recommended in USEPA (2006) and equate *KRER* and *K*, and this approach will therefore be employed for the PLA model.

Once *KRER* is established, the primary upland calibration parameter for sediment is *KSER*, which determines the ability of overland flow to transport detached sediment. HSPF/LSPC can also simulate gully erosion in which sediment generated from the land surface is not constrained by rainfall detachment. If there is not strong visual evidence for significant gully erosion in the watersheds, this component, which is difficult to calibrate, will not be used.

For in-channel sediment transport, key parameters controlling channel erosion, deposition, and sediment transport within streams and rivers are initialized as follows (USEPA, 2006b):

KSAND/EXPSND: *KSAND* (the coefficient in the sand transport equation) is typically set to 0.1 and *EXPSND* (the exponent in the equation) to 2 to start calibration and adjusted to improve the comparison between simulated and observed suspended sediment concentrations at flows where cohesive silt and clay sediments do not scour as well as to ensure a reasonable evolution of sand storage over time.

TAUCD: Initial values of TAUCD (critical shear stress for deposition) for silt and clay are estimated by reach by examining the cumulative distribution function of simulated shear stress and setting the parameter to a lower percentile of the distribution in each reach segment, as recommended by USEPA (2006b). The 20^{th} percentile was used to establish initial values for clay and the 25^{th} percentile for silt.

TAUCS: Initial values of TAUCS (critical shear stress for scour) are set at upper percentiles of the distribution of simulated shear stress in each reach (the 90^{th} percentile for clay and the 95^{th} percentile for silt). Values for some individual reaches will be modified during calibration.

M: This coefficient is the maximum rate of potential scour of cohesive sediment (mass per area) and is a calibration parameter in the sediment simulation. It will be initially set to typical values of 0.004 for silt, 0.003 for clay, based on past experience, and adjusted during calibration in some reaches.

An important issue for sediment calibration is representing the correct division between sediment derived from uplands and sediment derived from reach scour. In some watersheds, radionuclide analysis using ^{210}Pb and ^{10}Be, both of which are derived from the atmosphere and decay over time into more stable forms, has been used to identify the fraction of sediment that derives from upland sources in recent contact with the atmosphere. While data of this type are not believed to be available for the LDW, if such information is or becomes available for the model, it will be used to further refine sediment calibration in the future.

3.1.6.2.4 Water Quality Calibration

For water quality calibration, Tetra Tech will use both visual inspection and statistics comparing observed and modeled data. This is can be most rigorously applied for continuous or daily data, but that type of data is only available for water temperature and turbidity from the USGS station on the Duwamish River at Tukwila (12113390). For other locations and for toxics, continuous data are not available, so visual inspection coupled with summary statistics over paired data from the model and the available observations will be the main approaches to evaluate if calibration is acceptable. A two-stage approach will be used for water quality calibration. In the first stage, the model calibration will be guided by a visual comparison approach aimed at reproducing the trend and overall dynamics of the system. After the model has been calibrated to the trend and overall dynamics, the second stage involves fine tuning the parameters and then calculating various error statistics.

Many of the candidate pollutants (with exception of DEHP, Cu, Zn, and arsenic) are strongly sorbed to sediments and thus the ability to simulate sediment/solids loading, together with the potency (mass per mass of sediment) is key to simulating these compounds in the watershed. LSPC has a capability to simulate sediment loading, and parameters can be associated with soil properties available in the USDA SSURGO database. Solids accumulation and washoff from urban impervious surfaces is also relatively well documented (see summary in Novotny and Olem, 1994). In addition, the available WRIA 9 models are already calibrated for solids/sediment, including scour, deposition, and transport in stream channels. Potency data are less readily available and are likely to reflect site-specific circumstances (e.g., industrial areas where PCBs were used). The LDW source control-related reports from Ecology will be useful in identifying potency ranges for some of the more polluted areas.

3.1.6.3 Calibration Data

The model calibration effort depends on the availability of data. A discussion of key data sources relevant to model calibration is provided in Section 4.

3.1.6.4 Evaluation Metrics

The LSPC model will be sequentially calibrated for flow, sediment transport, and toxics fate and transport. The evaluation approaches for flow/hydrology and water quality are provided below.

3.1.6.4.1 Hydrology

The level of performance and overall quality of hydrologic calibration is evaluated in a weight of evidence approach that includes both visual comparisons and quantitative statistical measures. Given the inherent errors in input and observed data and the approximate nature of model formulations, absolute criteria for watershed model acceptance or rejection are not generally considered appropriate by most modeling professionals. In most cases, model acceptance is based on a number of factors and constraints confronting modelers and decision makers, including but not limited to inherent modeling uncertainty, site-specific system complexity, data limitations, impact of model-based decisions, project budget, project schedule, peer review findings, and likelihood of model improvement with additional calibration effort.

For the PLA project, quantitative measures of model performance will be constructed based on relative error and the Nash-Sutcliffe coefficient of model fit efficiency (NSE; Nash and Sutcliffe, 1970). Relative error is calculated as:

$$E_{rel} = \frac{\sum |O-P|}{\sum O} X100$$

Equation 6

where E_{rel}= relative error in percent. The relative error is the ratio of the absolute mean error to the mean of the observations and is expressed as a percent. A relative error of zero is ideal.

The model calibration attempts to achieve a good balance between the relative error metrics and the NSE (Nash and Sutcliffe, 1970),

$$NSE = 1 - \frac{\sum (O-P)^2}{\sum (O-\bar{O})^2}$$

Equation 7

in which the overbar indicates the average.

Unlike relative error, NSE is a measure of the ability of the model to explain the variance in the observed data. Values may vary from -∞ to 1.0. A value of NSE = 1.0 indicates a perfect fit between modeled and observed data, while values equal to or less than 0 indicate the model's predictions of temporal variability in observed flows are no better than using the average of observed data. The accuracy of a model increases as the value approaches 1.0.

For HSPF, LSPC, and similar watershed models, a variety of performance targets have been documented in the literature, including Donigian et al. (1984), Lumb et al. (1994), Donigian (2000), and Moriasi et al. (2007). Based on these references and past experience, the LSPC model will be evaluated in terms of relative error for simulation of hydrology measures summarized in Table 7.

Table 7. Model evaluation components for HSPF/LSPC hydrologic simulation

Model Component
1. Error in total volume
2. Error in 50% lowest flow volumes
3. Error in 10% highest flow volumes
4. Error in storm volume
5. Winter volume error (JFM)
6. Spring volume error (AMJ)
7. Summer volume error (JAS)
8. Fall volume error (OND)
9. NSE on daily values
10. NSE on monthly values

3.1.6.4.2 Water Quality

Calibration for suspended sediment and other water quality parameters differs from calibration for hydrology in that pollutant concentrations are in most cases not continuously monitored. (An important exception is USGS monitoring at 12113390 starting in 2013, which includes continuous monitoring of flow and turbidity, which is a potential surrogate for suspended sediment concentration.) Instead, observations typically provide measurements of conditions at a point in time and point in space via a grab sample. The discrete nature of these samples presents problems for model calibration: A sample that represents a point in time could have been obtained from a system where conditions are changing rapidly over time – for instance, the rising limb of a storm hydrograph. Such samples cannot be expected to be matched by a model prediction of a daily average concentration. On the other hand, there may be large discrepancies between dynamic model predictions of hourly concentrations and data that are a result of small timing errors in the prediction of storm event flow peaks. Spatially, grab samples reflect conditions in one part of a stream reach (which may or may not be composited over the width and depth of a cross section). HSPF model results, in contrast, represent average concentrations over the length of a stream reach which is assumed to be fully mixed. Model predictions and field observations inevitably have some degree of mismatch in space and time and, even in the best models, will not fully match. Accordingly, a statistical best fit approach is needed.

The primary comparisons will be based on simulated daily average concentrations and point-in-time observations, but finer time scales will also be considered. Time series comparison at an hourly time step can be very useful if and when there are detailed observations throughout the hydrograph. Comparison of hourly model output to point-in-time measurements can be problematic as the hydrology model could well have small time shifts relative to actual conditions. It will most likely be appropriate to compare the diel range of model output to point-in-time measurements.

The precision of the water quality simulation for sediment-associated pollutants depends on the precision of both the flow and sediment transport simulations. Uncertainty in those components will propagate into uncertainty in the water quality calibration.

Performance for water quality calibration, based on Donigian (2000), will be evaluated using the magnitude of annual and seasonal relative average error (RE) on daily values (see Section 3.1.6.4.1). These are evaluated for both concentration and load, where load is estimated from concentration, on paired data, and should only be applied in cases where there are a minimum of 3 observations. It should be noted that the relative error evaluation for water quality is based on the assumption that a good representation has been obtained for flow and sediment transport. Where greater uncertainty is present in the flow and sediment simulation, there will be a concomitantly higher uncertainty in the toxic constituent predictions.

3.2 Receiving Water Model – EFDC

3.2.1 Objectives

As previously mentioned, the PLA requires a source-response linkage and the estimation of existing loadings and target loadings to attain goals, as well as the distribution of those loads among sources and pathways to inform source reductions. As part of the linked modeling system, the EFDC model will provide a dynamic representation of hydrodynamic conditions, conventional water quality conditions, sediment transport, and toxic pollutant concentrations in the tidal portions of the Green/Duwamish River and LDW. Flows, suspended sediment, and pollutant loads from the of the Green and Duwamish Rivers and catchments adjacent to the LDW are described using the LSPC model. The LSPC model results will feed the boundary conditions of the EFDC model. Direct point sources into the LDW including CSOs would also be incorporated into the EFDC model.

The EFDC model will address several of the objectives identified in the CMs (Section 2.2), including:

- Evaluation of hydrologic variations due to time variable weather patterns and the related transport in surface water;
- Examination of time variable chemical loadings of organics, metals, and major ions from industrial, commercial urban, agricultural, and natural pollutant sources in the watershed;
- Addressing a broad range of spatial and temporal scales, simulated pathways, and represented constituents; and
- Evaluation of source reduction and watershed management scenarios for pollutant control.

The model also has a wide range of sediment deposition and erosion process options, and its modular sediment processs library formulation allows for future options including site specific parameterizations such as the SEDZLJ formulation (Jones and Lick, 2001; James et al., 2005).

3.2.2 Existing EFDC Models

EFDC has been used for pollutant transport and fate in the LDW (as described above, largely using the Bed Composition Model BCM) to support CSO management and studies of bed sediment contamination over the last two decades (Table 8) (Arega and Hayter, 2004; Hayter, 2006; King County, 1999; QEA, 2008; Windward Environmental and QEA, 2008; AECOM, 2012a; AECOM, 2012b). An informational basis for the current model planning effort is supplied in the extensive reports, data collection, data analysis, and modeling work undertaken as part of the Superfund investigation of the LDW and studies previous to that effort. Summaries are provided in Tetra Tech (2014) and Tetra Tech (2015b).

Hydrodynamic, sediment transport, and contaminant transport fate modeling studies of the LDW began with the King County CSO water quality assessment of the Duwamish River and Elliott Bay in the late 1990’s (King County, 1999). Follow on work was conducted by EPA (Hayter, 2006; Arega and Hayter,

2004) and by the LDWG as part of the RI and subsequent feasibility study (FS) involving the EPA and Ecology in association with Superfund status and bed sediment contamination in the waterway (Windward Environmental and QEA, 2008; QEA, 2008; AECOM, 2012b).

Table 8. Previous EFDC modeling studies of the LDW

Study	Assessment Tool	Contaminants	Sources Represented	Pathways Addressed for LDW	Notes
King County (1999)	EFDC	Contaminants of concern (COCs) included six metals and twelve non-metals (see next section for listing)	Upstream river flow and loads, CSOs to LDW	Hydrodynamic, sediment transport, and contaminant transport; upstream and internal loading	Served as foundation for subsequent work in the 2000's
Arega and Hayter (2004); Hayter (2006)	EFDC	Primary source documentation for this work is limited	Primary source documentation for this work is limited	Built upon the earlier King County (1999) work	Primary source documentation for this work is limited
Windward Environmental and QEA (2008); QEA (2008)	EFDC, SEDZLJ	Sediment transport	Same as King County (1999)	Re-calibrated hydrodynamics based on earlier work	Refinements made to King County (1999); STM benefited from extensive field data
AECOM (2012b)	EFDC, Bed Composition Model (BCM)	See above; BCM primarily focused on arsenic and PCBs, but considered cPAHs and dioxin/furan (only PCBs were modeled for the Food Web Model - FWM)	BCM included bed and accounted for external loads from upstream and CSOs	See above; included different representation of COCs	BCM not predictive, dynamic model

Previous efforts conducted by King County and LDWG have provided a foundation for hydraulic and sediment transport modeling in the LDW using EFDC. Modeling of the fate and transport of toxics in the LDW is less developed. The original King Co. (1999) EFDC model was set up for several pollutants, but, of these, performance could be evaluated only for copper based on the data available at the time. The Superfund RI/FS work by LDWG simulated flow and sediment transport with EFDC, but evaluated toxics only via a mass-balance accounting designed to evaluate how ongoing sources and remediation would affect the concentrations in surface sediment. The 2008 update to the EFDC modeling conducted by King County in support of the LDWG application of the FWM simulated PCBs, but in a simplified manner (as total PCBs using a congener-weighted partitioning coefficient) and with significantly less data than are now available.

Contaminant concentrations in surface sediment were developed by LDWG using estimates of the contaminant concentration in the three major sediment sources (upstream, lateral, and bed), and the output of the STM for these three sediment sources was used in a spreadsheet model called the Bed Composition Model (BCM) as described in the Feasibility Study (AECOM, 2012a). It was assumed that the contaminants were only associated with sediments and that there was no dissolved phase, adsorption/desorption, or degradation. In addition to only considering arsenic, cPAHs, dioxin/furans, and PCBs, there are limitations in this approach for predicting the long-term conditions for water and bed sediments in the LDW as follows:

1. The contaminants calculated were assumed to all be bound to sediment particles,
2. No loss/gain/transformation of contaminants via physical, chemical, or biological degradation mechanisms (desorption, adsorption, diffusion, biotransformation, degradation, dechlorination, volatilization), and
3. No calculation of dissolved and pore water concentrations (except for total PCBs in the 2008 recalibrated EFDC model used in the FWM).

3.2.3 Planned Refinements/Additions to Previous Models

A major component of work to support the PLA will be building on the existing work to develop a full EFDC simulation of the movement and storages of all the project pollutants within both the bed sediment and the water column of the LDW. The previous modeling was focused on the hydrodynamics and sediment transport in the LDW and did not attempt to model and predict water quality.

A new EFDC model will be built on previous modeling and include:

- Original grid with extension upstream to free flowing river.
- Updated hydrodynamic model including flow, velocity, water surface elevation, salinity and temperature modeling and calibration.
- Updated sediment transport modeling and calibration.
- Conventional pollutants of total organic carbon and dissolved organic carbon to support toxics modeling.
- Fate and transport modeling of all the project toxic pollutants within both the bed sediment and the water column using a 2-phase partitioning (freely dissolved and sorbed phase).
- Inclusion of contaminant transport and transformations processes directly in the EFDC model framework, with special emphasis on the pollutants of concern in the water column and the exchange between water column and bed sediments. Details will be further discussed in Section 4.2.4.

These enhancements will allow the use of EFDC in a more rigorous evaluation of source control and water quality improvements to address pollutant loading from various sources and pathways including industrial and other point sources, agricultural runoff, stormwater point and nonpoint sources, natural sources (e.g., forests), atmospheric deposition, and others. The pollutants associated with these sources are varied and will require a comprehensive approach regarding the pathways for pollutant migration to waterways, migration within the waterways, and chemical transformations that affect the long term fate.

3.2.4 Model Representation of Sources and Processes

In estuaries, the transport of particulate and dissolved materials is a process governed by the interaction between freshwater inflows, ocean tidal oscillations, and wind shear over the water surface. Transport in these systems is highly influenced by hydrological regimes. For instance, during periods of high freshwater inflows estuary processes are mostly driven by advective transport and have a higher flushing capacity. Meanwhile, during periods of low freshwater inflows, the estuary processes are more influenced by dispersive transport and have an increasing mixing capacity as a result of the tide dynamics. Transport during average flow conditions is substantially more complex given that estuaries tend to be partially mixed as a result of the vertical gradients of density generated by the confluence of freshwater and ocean water. These density gradients generate internal currents capable of moving matter particles at different rates and heterogeneously through the system.

The major sources and pathways by which pollutants find their way into the LDW and affect water, bed sediments, and biota, include:

- Urban runoff and associated loads of contaminants, COCs and other pollutants (nonpoint stormwater discharges).
- Watershed (non-urban) simulated by LSPC.
- Point source discharges (e.g., CSOs, regulated stormwater outfalls, etc.).
- Spills and/or leaks to the ground, surface water, or directly into the LDW.
- Legacy COCs in bed sediments and exchange with the water column.
- Atmospheric deposition, including spatial variation in deposition rates.
- Vessel discharges.
- Groundwater migration/discharge.
- Advective transport from upstream areas to the LDW.
- Deposition of sediments.
- Transport of resuspended contaminated sediments.
- Release of contaminated sediment porewater.
- Volatilization.
- Dispersion across downstream boundaries.

The toxic pollutants that will be addressed in the EFDC fate and transport model are:

- PCBs (specifics yet to be determined).
- Carcinogenic PAHs as a single group.
- Inorganic arsenic.
- DEHP as a surrogate for other phthalates.
- Copper, dissolved and sorbed inorganic forms.
- Zinc, dissolved and sorbed inorganic forms.

Partitioning of contaminants between the dissolved phase and solids is an important and complex aspect of pollutant transport and bioavailability in the water column, exchanges with the sediment bed, and fractionation between solids and pore water within the sediment bed. Based on the limited amount of available data to characterize the details of partitioning within the LDW, a two-phase equilibrium partitioning approach will be implemented.

For non-polar organics, such as PCBs, EFDC will be implemented with two-phase equilibrium partitioning to particulate organic carbon (POC). POC concentrations will be simulated dynamically in the model. The EFDC code can address either two-phase or three-phase partitioning, with the third phase representing sorption to solids, such as colloids, that effectively behave as dissolved constituents in the water column. In the two-phase representation, the dissolved (C_w) and POC-sorbed (C_{POC}) concentrations can be related to the total concentration (C), expressed as mass per unit volume of the water phase, as:

$$\frac{C_w}{C} = \frac{\varphi}{\varphi + K_{POC}\, POC} \qquad \textbf{Equation 8}$$

$$\frac{C_{POC}}{C} = \frac{K_{POC}\ POC}{\varphi + K_{POC}\ POC}$$ **Equation 9**

Here, the *K* values are partition coefficients (volume per mass) and φ represents porosity. Full derivation is provided in Tetra Tech (2007) and Weston Solutions (2006).

The influence of third-phase partitioning to non-settling or dissolved colloidal organic material will be evaluated as to interpretation of monitoring data, but not directly represented in the model. In the bed sediment, the nature of the carbon present, especially the role of black carbon, will be used to empirically adjust effective partition coefficients and resulting porewater concentrations based on work being conducted for USACE (Gschwend et al., 2015), but will not explicitly simulate black carbon as a state variable.

Ionic metals also sorb to particulate matter, but the process is different from nonpolar organics. Full representation of metals partitioning requires a complete analysis of competing ions in a geochemical model, which is not feasible for this project. The EFDC simulation will use a simplified representation of ionic metal sorption as a function of simulated suspended sediment concentrations using the approach documented in USEPA (1996). In this approach, an approximate partition coefficient to particulate matter (K_P, L/kg) is represented in the following form:

$$K_P = K_{PO} \cdot TSS^{\alpha}$$ **Equation 10**

where TSS is in mg/L and K_{PO} and α are metals-specific coefficients. EPA provides a table of default values, but recommends deriving translators based on site-specific data on dissolved and total metals. Sufficient dissolved metals data appear to be available to do site-specific fitting of the metals partitioning and dissolved fraction parameters. The EFDC and LSPC model codes will be modified to represent ionic metal partitioning using this formulation.

The EFDC model simulation will include chemical transformations of hydrolysis, photolysis, biodegradation, and oxidation. For some PCB congeners these degradation processes are extremely slow and could be ignored; however, for other constituents of concern, such as some PAHs, degradation can be rapid and is a significant part of the mass balance. Exchange of contaminants across the air-water and sediment-water interfaces will be included in the calculations. Their implementation in EFDC is described in detail in Weston Solutions (2006). Transfer of particle-bound contaminants across the sediment-water interface and between bed sediment layers is influenced by bioturbation, diffusion, and other mixing forces such as prop wash. The sediment bed will be modeled as a series of vertical layers in a computationally-active zone and an archive layer. The archive layer provides a record of buried mass that could become uncovered by a substantial erosion event.

3.2.5 Model Configuration

3.2.5.1 Model Boundaries and Boundary Conditions

Tidal influence can reach as far upstream as river mile 17 near Kent, WA under low flow conditions. Given this factor, there is cause to extend the EFDC model domain upstream of the domain used in previous efforts. Figure 10 identifies river mile 17 relative to the model domains of the original King County EFDC model and the EFDC model used for the RI/FS. Both of the prior models stop well short of river mile 17. While it is likely that there is little upstream advective transport at this point, the tidal influence will affect the hydrodynamics (velocity and depth), particularly at a subdaily scale. It is therefore advisable to extend the EFDC model domain to this location. USGS gaging station 12113000 Green River near Auburn, WA is located upstream at approximately river mile 19, and USGS gaging stations 12113390 Duwamish River at Tukwila, WA and 12113350 Green River at Tukwila are both located downstream of River Mile 17. These stations' data, along with LSPC flows, and NOAA's Tide and Currents tidal predictions can be used for hydrodynamic model calibration. USGS Station 12113000 also has daily flows from 1936 to present and 15 minute flow and gage height data from October 2007 to present.

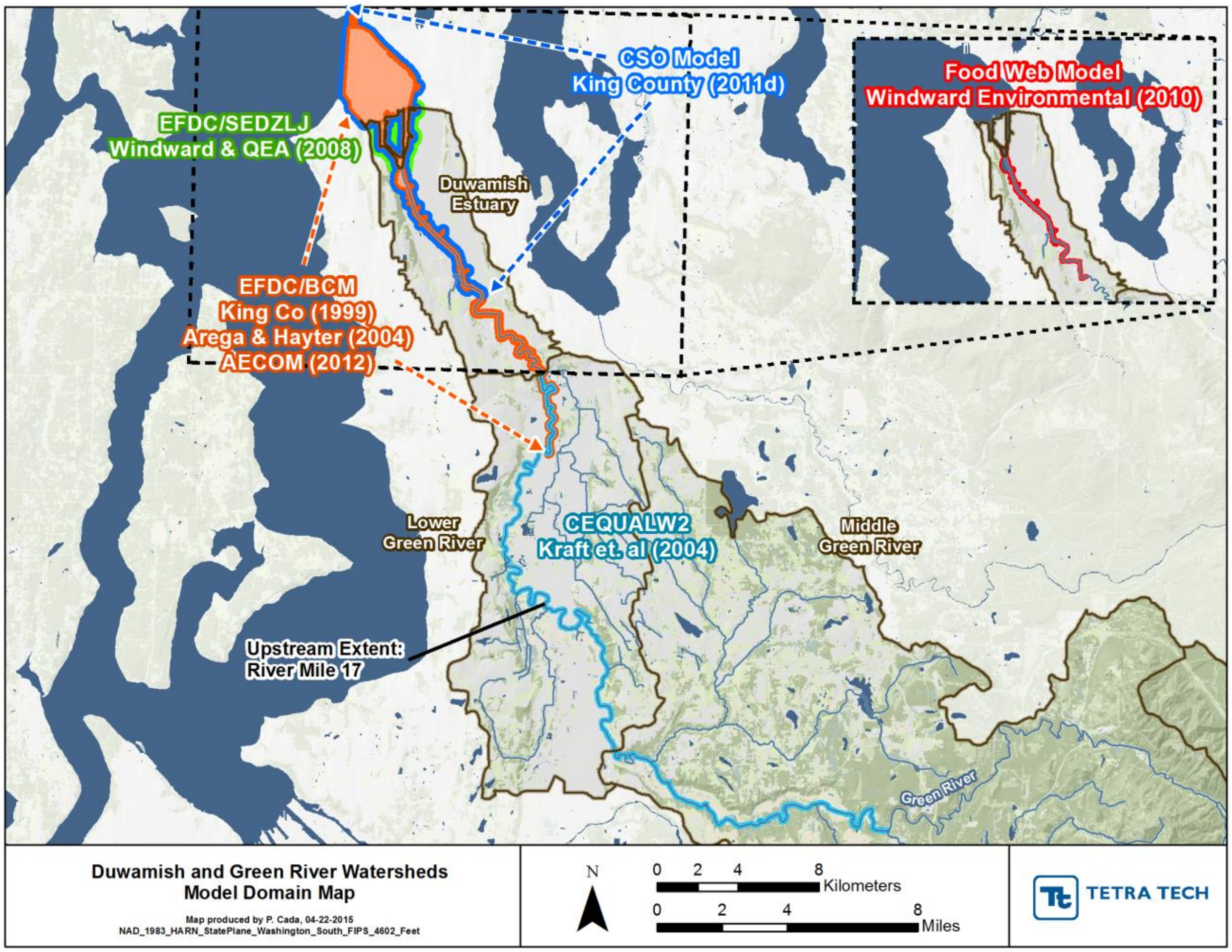

Figure 10. EFDC model domain

As discussed previously the LSPC-predicted flows and pollutant concentrations will be used as boundary conditions for the EFDC fate and transport model. The EFDC hydrodynamic model will be calibrated to USGS flows, gage heights and velocities measurements along with Elliott Bay tidal and salinity boundaries based on NOAA's tidal predictions.

Model Grid and Input File Development

Previous EFDC grids are shown in Figure 11 and Figure 12. A new curvilinear-orthogonal model grid system will be established to represent the expanded EFDC modeling domain guided by previous EFDC applications to the LDW. Enhancements will be implemented to provide linkage to the LSPC watershed model and to extend the grid to approximately river mile 17, but initially the grid resolution should remain basically the same.

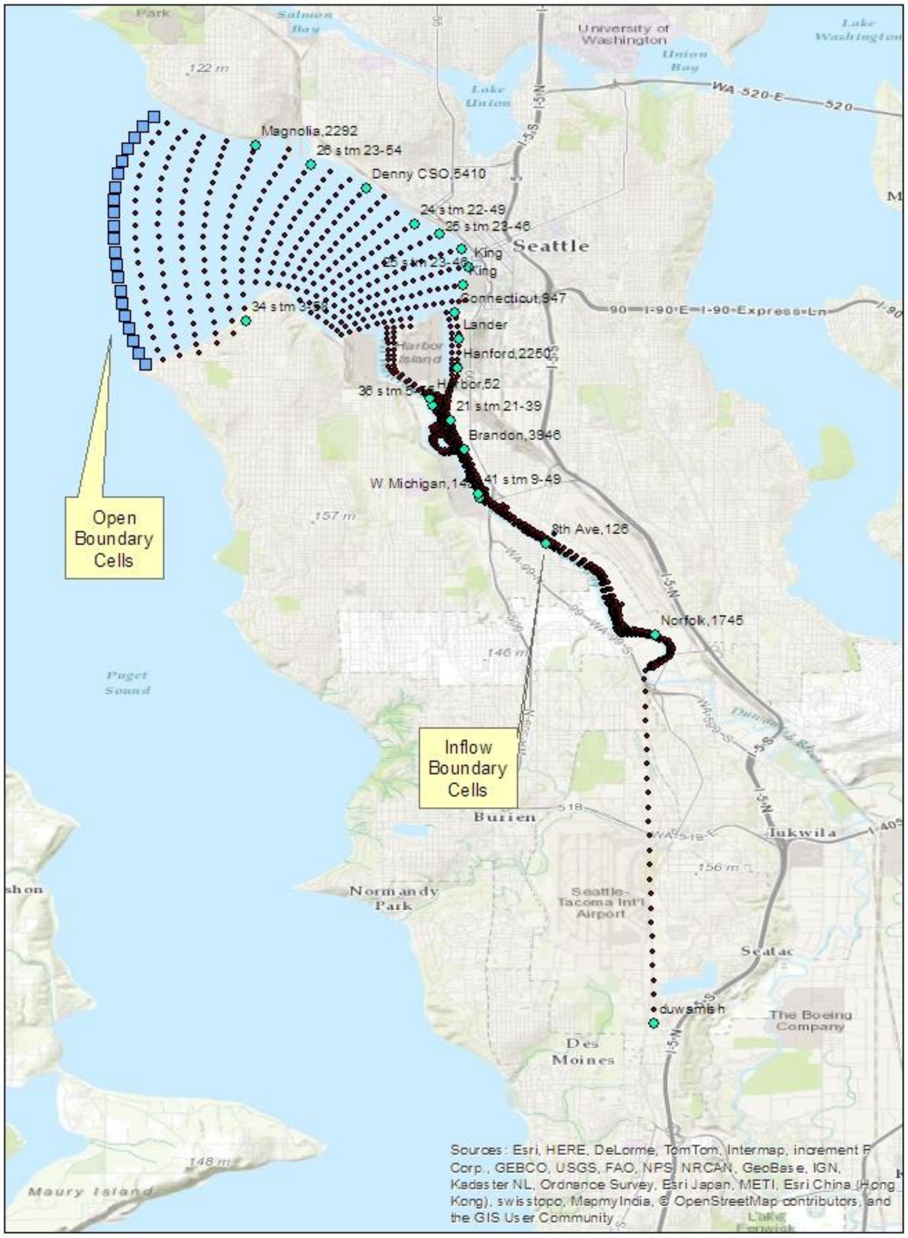

Figure 11. LDWG/QEA EFDC Model - grid centerpoints, open boundary, and upstream inflow cell locations

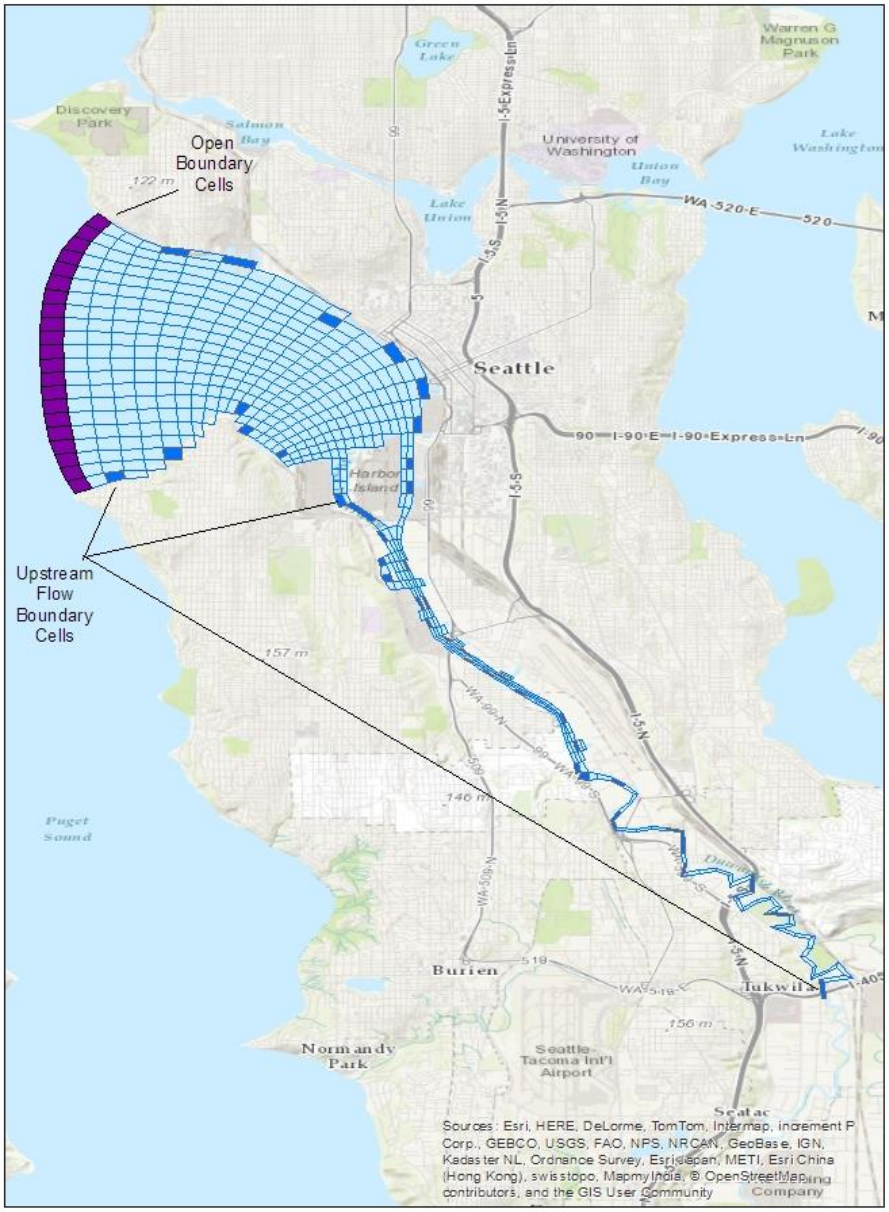

Figure 12. KC EFDC Model - grid centerpoints, open boundary, and upstream inflow cell locations

The EFDC model will be dynamic with at least hourly tidal open water boundaries and will initially start with 10 water layers (based on past models) and up to 8 bed sediment layers with grid dimensions similar to past projects. Final delineations will be based on the available data and model computational requirements to simulate the various chemical processes. Grid resolution adjustments may also need to be made due to the need to run long-term simulations. Other factors such as the computation accuracy and computational costs and model run times will also be considered.

The EFDC model may also have to be broken up in to various multi-year time periods reflecting the change in river's bathymetry due to past dredging activities. The various bathymetric datasets will be interpolated onto the model's grid for a given time period.

Boundary Conditions

Water and sediment quality in the Duwamish Estuary and the lower portion of the Green River are influenced by mainly three types of boundary conditions including upstream boundary conditions, lateral boundary conditions, and downstream open water tidal boundary conditions along with direct air deposition to the water surface.

For the downstream open boundary, tidal predictions at the Elliott Bay boundary NOAA's Duwamish Waterway, Eighth Ave. South station (Station Id: 9447029) and Seattle, WA station (Id: 9447130), will be used for water levels and tidal forcing. Salinity of the incoming water from Elliott Bay will be used as a proxy to estimate the SSC and toxics levels outside of Elliott Bay, along with the conventional pollutant concentrations. Turbidity data are available and can be converted to SSC for the open boundary condition, because SSC is usually a major contributor for turbidity (see Thackston and Palermo, 2006). For toxics, it is planned to use pollutant concentration data from elsewhere in Puget Sound.

The upstream boundary flows will be initially based on the USGS gaging station 12113000 Green River near Auburn, WA. These flows will be combined with estimated inflows for the reach between the gauge and the model boundary to define the upstream boundary condition for the EFDC model.

The lateral boundary conditions will include flow and loadings from tributaries and direct drainage areas, and the stormwater and CSOs from the surrounding areas of the Duwamish Estuary. Similar to the upstream boundary conditions, the watershed model will also provide the lateral boundary conditions for direct stormwater inflows. Existing monitoring and modeling of CSOs by King County will be used to specify CSO contributions. CSO sampling data from King County will be used to specify the COC concentrations and other relevant parameters.

When available, measured data will be used as input to the EFDC model, but measured data will not cover all the inputs required for the EFDC model. Most notably, COC measurements are typically grab samples, whereas the model requires a continuous time series input. For existing condition (calibration) simulations, the continuous watershed model predictions for existing condition can be combined with measured data to provide a composite time series for a particular boundary condition. For those data inputs where no direct measurements are available, the watershed model and the CSO model output data will be used. These simulated data introduce a degree of uncertainty in the EFDC model that will be assessed in the uncertainty analysis.

In addition to the loadings from inflowing water, air deposition can contribute toxics via direct deposition to the water surface. The total mass of air deposition depends on the surface area of the water body. Outside of the water surface, air deposition contribution to loading is through the rainfall-runoff processes and will be included in the watershed model. Air deposition fluxes vary spatially. A number of existing studies provide air deposition data (Tetra Tech, 2015b) over the Duwamish Estuary. No data are available for particulates, organic carbon, and phthalates. For other parameters, limited data are available. New data (based on studies described in the previous watershed model subsection) may provide more information on the range of the air deposition fluxes and will be considered. A sensitivity analysis will also be used to evaluate the model responses to air deposition.

Water Column Initial Conditions

The EFDC model is a dynamic model which requires initial conditions to start the simulation. Initial conditions can also be considered as the net result of historical processes before the beginning time of the simulation. The initial conditions are required for the conventional pollutants, sediment, and toxics in both water column and bed sediment layers of the model. The SSC and toxics concentration in the water column are highly variable in time due to variable freshwater flow and loading, as well as tidal influences in the Duwamish Estuary; however, the initial conditions for the water column are not persistent. A spin-up period (two or three months up to a few years) can usually wash out the effect of initial water column concentrations. In practice, this means that the actual calibration period of the model begins a few months to a year into the simulation.

Bed Sediment Layer Initial Conditions

The sediment and toxics levels in the bed sediment layers change at a much longer time scale than those in the water column in the estuary. As a result, the initial condition of the bed sediments has a much longer memory than the water column. The initial conditions in the sediment layer will rely heavily on monitoring data. Based on the data summary, data on potential toxics of concern in the sediment layer are available for the LDW and will be used as the basic data for determining the initial conditions in the LDW. The results from existing sediment and toxics models from both King County and LDWG will also be used to provide supplementary data to support the determination of initial conditions in areas with limited monitoring or where monitored conditions are expected to have undergone significant changes. A spin-up period is expected to fill the gaps of missing data by running the model for an extended time period of several years to build-up the initial condition for the model simulation.

As previously mentioned, over time various dredging operations have removed bed sediment along with associated toxics from the river. So for each model time period after a dredging operation, the model's bathymetry will need to be adjusted along with the concentration of potential toxics of concern in the sediment layer.

EFDC will be modeling PCB congeners or homologs but most of the data for PCBs in the LDW were reported as Aroclors. In order supply PCB congener or homolog initial conditions to the model, a relationship between Aroclors and PCB congeners or homologs will be explored based on literature information or newly collected PCB data. In general, it is feasible to translate congeners to Aroclors under certain conditions, but it is not exact due to differences in original Aroclor congener composition and subsequent environmental fractionation and decay, as discussed in Leidos (2015).

For the other toxics, available data will be used to generate initial toxic levels in the sediment layer in LDW and the rest of the Duwamish Estuary. Due to the high heterogeneity of the toxics in bed sediment, a series of model sensitivity runs will be needed to test if the initial conditions assigned are reasonable.

The initial sediment layer condition including sediment layer thickness, porosity, and fractions of particle sizes will be based on a combination of the past modeling activities, including the LDWG model, and the available monitoring data.

3.2.6 Model Calibration

3.2.6.1 Objectives

Model calibration consists of the process of adjusting model parameters, within expected ranges, to provide a match to observed conditions. Although these models are formulated from mass balance principles, most of the kinetic descriptions in the models are empirically derived. These empirical derivations contain a number of coefficients that are usually determined by calibration to data collected in the waterbody of interest. Calibration updates the models to represent conditions appropriate to the waterbody and watershed being studied.

3.2.6.2 Time Period and Approach

Calibration for EFDC is approached sequentially beginning with hydrodynamics modeling; then conventional water quality and sediment modeling; and ending with toxic pollutant transport and fate modeling. Details for each sequential component are provided below.

3.2.6.2.1 Linkage of LSPC Watershed Model Results for Input to EFDC Model

The LSPC results will be used to assign the external boundary conditions for input to the EFDC model. The EFDC model requires a continuous time series inputs, and the LSPC model provides continuous estimates of flow, water temperature, suspended sediment, total organic carbon, dissolved organic carbon, and the toxic parameters of interest in dissolved and particulate form. Most water quality measurements, including measured toxics concentrations, are grab samples. LSPC model therefore provides an important capability in providing continuous estimates of concentration over time. If LSPC predictions for a parameter diverge significantly from the measurements at particular locations or times, adjustments to the associated EFDC boundary inputs may be undertaken to achieve better alignment with measurements. If such adjustments are made, they will be documented in the EFDC model development report and considered in the uncertainty analysis.

3.2.6.2.2 Time Period

Calibration of the EFDC models benefits from a long time period that covers a range of tidal, upstream flow and meteorological conditions. Accordingly, the calibration model run period for the EFDC model will initially focus on water years 1996-2007. Additional calibration and model testing using data beyond 2007 will also be conducted.

As discussed earlier, this time period may be broken up in smaller periods to address dredging events.

3.2.6.2.3 Hydrodynamic Calibration and Evaluation

The EFDC hydrodynamic model will be calibrated for water surface elevation, river velocities, salinity and temperature. Hydrodynamic calibration will be based on comparison of model predicted flows, water surface elevation, current velocity, salinity and water temperature to the available data. The main hydrodynamic data source will be the USGS gaging stations previously mentioned. Adjustable parameters and forcing functions for the hydrodynamic model include open boundary water surface elevations and salinities, atmospheric conditions, bottom roughness, and unaccounted fresh water inflow, such as ground water and other flows not accounted for by the watershed model.

Given the complexity of transport in estuaries, one of the most important objectives during the development of water quality models is to calibrate the transport model to ensure that it has the ability to reasonably reproduce the mixing regimes and seasonal variations of temperature and salinity, extent of salinity intrusion, dynamics of water surface elevations, currents during ebb and flood periods, and freshwater flow distribution through the system. The calibration and skill assessment of the hydrodynamic model will based on graphical and statistical tests of goodness-of-fit for different transport variables. For this project in particular, the model will be evaluated to reproduce:

- Water surface elevations.
- Flow distribution.
- Flow and current speed dynamics at different locations within the estuary.
- Temporal variations of salinity at different locations.
- Vertical salinity structure at different locations.
- Temporal variations of temperature.
- Vertical temperature structure at different locations.

The calibration of the hydrodynamic model will be based on graphical and statistical comparisons between the model predictions and the observations. The temporal analyses will be performed creating comparison plots using the model results from the EFDC and available field observations. A graphical comparison will concentrate on various time periods to allow a closer examination of the model versus the observations. The following goodness-of-fit statistics will be presented, where P represent the time series of model predictions and O the time series of observations:

Coefficient of determination: $$R^2 = \frac{\left(n\sum_{i=1}^{n}(P_i \times O_i)\right) - \left(\sum_{i=1}^{n} O_i \times \sum_{i=1}^{n} P_i\right)}{\sqrt{\left[n\sum_{i=1}^{n}(P_i^2) - \sum_{i=1}^{n}(P_i)^2\right]} \times \sqrt{\left[n\sum_{i=1}^{n}(O_i^2) - \sum_{i=1}^{n}(O_i)^2\right]}}$$ **Equation 11**

Mean Absolute Error: $$MAE = \frac{\sum_{i=1}^{n}\left|P_i - O_i\right|}{n}$$ **Equation 12**

Root Mean Squared Error: $$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$ **Equation 13**

Normalized Root Mean Squared Error: $$NRMSE = \frac{RMSE}{\overline{O}} * 100$$ **Equation 14**

Index of Agreement: $$IA = 1.0 - \frac{\sum_{i=1}^{n}\left|P_i - O_i\right|}{\sum_{i=1}^{n}\left[\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right]}$$ **Equation 15**

The coefficient of determination (R^2) is a measure of the variability in the data that is explained by the model (Equation 11). Its square root is the correlation coefficient (*r*), which measures the degree of linear correlation between the trends of two time series, in this case the series of observations and model predictions. It can range from –1 to 1, with negative values indicating that the observed and predicted values tend to vary inversely. It should be recognized that even if the correlation is close to 1, the predicted and observed values may not match each other; they only tend to vary similarly (Stow, 2003).

The mean absolute error (MAE) and the root mean squared error (RMSE) are estimates of the average deviation of the model predictions from the observations (Equations 12 and 13). Meanwhile, the normalized root mean squared error (NRMSE) provides an estimate of the relative importance of the errors with respect to the observations (Equation 14). The MAE, RMSE and NRMSE constitute indicators of model prediction accuracy (Stow, 2003), and the smaller their values, the higher the agreement between the observations and the predictions. Finally, the index of agreement (IA) evaluates the global agreement between the predictions and the observations (Equation 15). It is conveniently bounded between 0 and 1 with the highest value indicating a perfect match between the two time series. A value of zero indicates that the model predicts individual observations no better than the average of the observations.

Final calibration will be determined based on both the graphical evaluation and the goodness-of-fit statistics.

3.2.6.2.4 Sediment Transport Calibration and Evaluation

Sediment transport calibration is based on a comparison of model-predicted and observed suspended sediment concentrations, net flux of suspended sediment, and bed morphology changes at selected locations. Sediment transport calibration parameters include river, watershed, internal and point source sediment and solids loads and their distribution into modeled classes; effective particle diameters or settling velocities for sediment and solids classes; and erosion parameters, including critical stress and mass erosion rates for cohesive sediment. Open boundary suspended sediment concentrations will be determined based on measured data of turbidity and adjusted during the calibration process. Sediment loads will be based on the LSPC-predicted delivery of the sediment to the river, previous compilations and modeling activities and estimations based on the available data.

Initial deposition and erosion parameterizations of the bed will be based on literature values and previous studies. The calibration process will include adjustments to these parameters.

Sediment and solids class settling velocities and the distribution of total loads among the particle size classes may be the primary calibration parameters. To evaluate settling velocities and load distributions, sensitivity analyses will be conducted to assist in developing the final values.

Graphical comparison of model predicted and observed total suspended solids concentrations and net flux will be made of the full time period where suspended solids data are available. If enough solids data are available, a goodness-of-fit statistics analysis will be performed.

3.2.6.2.5 Water Quality and Toxic Pollutant Calibration and Evaluation

Similar to the EFDC hydrodynamic model, the EFDC water quality model calibration will based on graphical and statistical comparisons between the model predictions and the observations. A temporal analyses will be performed creating comparison plots using the model results and available field observations. Goodness-of-fit statistics, where there is sufficient observational data, will be performed. Statistics analyzed included R^2, MAE, RMSE, NRMSE, and IA, as well as the computed mean, median, and 5_{th} and 95_{th} percentiles of the simulations and observations. When measured data available is less than 3 data values, average value of the data will be compared to the average simulated value and visual inspection will be the main approach to determine if calibration is sufficient. A two-stage approach will be used for water quality calibration. In the first stage, the model calibration will be guided by a visual comparison approach aimed at reproducing the trend and overall dynamics of the system. After the model has been calibrated to the trend and overall dynamics, the second stage involves fine tuning the parameters and then calculating various error statistics.

Many of the candidate toxic pollutants (with exception of DEHP, Cu, Zn, arsenic) are strongly sorbed to sediments and thus the ability to simulate sediment - solids transport and settling and resuspension - is important.

3.2.6.3 Calibration Data

Data availability for calibration is discussed in Section 4. Additional relevant hydrodynamic data and information will be downloaded from the USGS and NOAA web sites.

3.3 FOOD WEB MODEL

3.3.1 Objectives

Food web bioaccumulation models are used to describe the relationship between contaminant concentrations in bed sediment, water, and biota. In practice, they are frequently used to estimate fish tissue concentrations resulting from exposure to specified bed sediment and water column contaminant concentrations (Gustavson et al., 2011). The model can be used for direct evaluation of water quality objectives related to fish tissue concentration guidelines, as well as to estimate the consequences of changing exposure concentrations.

3.3.2 Existing FWM Models

The existing Food Web Model (FWM) for the LDW (Windward Environmental, 2007) is an Arnot and Gobas (2004) model of steady-state PCB distribution in biota. Model documentation is included as Appendix D to the LDW RI report. The model represents steady state relationships between exposure concentrations in water and bed sediment external to the food web and internal relationships between organisms at a variety of trophic levels. The simplifying steady state assumption introduces inaccuracies where exposure concentrations change substantially over time frames shorter than are required for an individual's body burden to equilibrate with the exposures; however, a dynamic simulation of bioaccumulation requires a much greater level of effort and support by bioenergetics data that are not believed to be available for the LDW. The steady state approach is widely used for this type of study and is believed to provide a useful approximation in line with the study objectives and available resources.

Model building and calibration focused on averages over the whole LDW and used 190 composite tissue samples collected between 1997 and 2005. Water column data comes from the 2009 update of the 1999 King County EFDC model, documented as Attachment A to Appendix D of the RI report.

The model was calibrated probabilistically through Monte Carlo simulation followed by identification of a best-fit model parameter set. The best-fit set had a mean across species of SPAF = 1.2, where SPAF (species predictive accuracy factor) is the ratio of modeled to observed tissue concentration when the modeled concentration is larger and the inverse of this ratio when the modeled concentration is lower.

Performance of the model was further tested by comparing results for tissue data collected in 2007; note that concurrent inputs for sediment and water column concentrations for 2007 were not available. The 2007 tissue results were lower than those observed in the calibration data and the FWM over-predicted the 2007 results, possibly because there were not matched input data on water and bed sediment concentrations for this year.

The 2007 test highlights the difficulties of applying a steady-state equilibrium model to a dynamic system. Determining whether the model is performing adequately is particularly difficult when concurrent data in tissue, bed sediment, and water are not available.

The FWM has not been developed for other COCs beyond PCBs in the LDW. The basic Arnot-Gobas model is, however, applicable to most hydrophobic/lipophilic organic chemicals that are prioritized parameters for the PLA.

3.3.3 Planned Refinements/Additions to Previous Models

The previous model was developed only for total PCBs, which is sub-optimal due to the wide range of sorption, solubility, and volatility characteristics exhibited across different PCB congeners. The revised model will likely address PCBs in homolog groups that have more similar characteristics; however the decision regarding exact grouping of PCBs will made and documented in a future version of the QAPP, as discussed in Section 1.4.

The structure of the existing FWM is appropriate for other non-polar organics. The model will be expanded to simulate cPAHs. As with PCBs, the grouping/representation of cPAHs will be as discussed in Section 1.4. The FWM may also be used to simulate TCDD bioaccumulation in the future; however, that will not occur until after additional data are collected. The FWM will not be used to simulate DEHP (see earlier discussion of parameter/model selection), arsenic, or inorganic metals.

3.3.4 Model Representation of Sources and Processes

The FWM includes compartments for phytoplankton, zooplankton, filter-feeding benthic invertebrates, other benthic invertebrates (scavenger/predator/detritovore), and fish at several trophic levels. Data from the LDW for target species in many of these compartments were available except for the lowest trophic levels (phytoplankton, zooplankton). Benthic invertebrates were represented by a single scavenger/predator/detritovore compartment. The specific target species used in the FWM for the LDW, in order of declining trophic level, are resident English sole, Pacific staghorn sculpin, shiner surfperch, Dungeness crabs, slender crabs, and large clams. Salmon are not included in the model because of their short residence time in the system during migration to and from the ocean.

The existing FWM considers three-phase partitioning in the water column (but not in the bed sediment), including partitioning to dissolved organic carbon in addition to partitioning to particulate organic carbon and freely dissolved form. Only two-phase partitioning is addressed in bed sediment. The model takes as input total PCB concentrations in the water column then calculates fractions based on partition coefficients, although only a single partition coefficient to organic carbon is entered by the user.

The model requires body weights and lipid content for individuals in each trophic level, and these were based on site data. The model also requires a partitioning coefficient (K_{ow}s) for benthic invertebrate tissue. To address total PCBs, this was calculated as a weighted average over the set of congeners observed in invertebrate tissue samples and using the laboratory K_{ow} values in Hawker and Connell (1988). Diet for each trophic level combined literature information and gut content analysis with sensitivity addressed through multiple scenarios.

3.3.5 Model Configuration

Extensive sensitivity analyses reported in the RI for the existing model found that tissue concentrations in all species are most strongly influenced by the water column concentration, partitioning coefficients (K_{ow}) and the density of lipids. The water column PCB concentration primarily affects species that have food chain pathways that contain 25% or more zooplankton in their diet. Benthic invertebrate-specific parameters of body weight, relative fraction of pore water ventilated, and dietary absorption efficiency also had relatively significant influences on results in many species. Correct assignment of dietary pathways is obviously important to the overall result and was the main factor adjusted as part of the Monte Carlo calibration approach. Additional data to further constrain estimates of dietary sources of individual species would be useful.

The RI Appendix describes two other important sources of uncertainty in model specifications and parameters:

- Observed PCB tissue concentration data for individual species tended to be highly variable. The report cites analytical variability as a potential cause, but dynamic processes related to seasonal changes in feeding, depuration at spawning, and other causes that cannot be well addressed in a steady-state model may also be important.

- The fact that data from different media are not concurrent is a significant contributor to uncertainty. Much of the bed sediment data is from the late 1990s, and the baseline bed sediment distribution is for pre-dredging conditions, whereas the water column data were collected after dredging that occurred in 2003/2004 in the Duwamish/Diagonal area.

The existing model is configured for total PCBs. The previous FWM approach of evaluating bioaccumulation of total PCBs using a wide range of K_{ow} and other kinetic characteristics can be improved by an evaluation based on several homolog groups.

The model will also be implemented for cPAHs and potentially TCDD. Previous efforts with the FWM have not addressed these contaminants, so it is difficult to predict how successful such an effort will be for the Duwamish. Bioaccumulation of these contaminants has, however, been successfully modeled elsewhere with the Arnot-Gobas (2004) framework.

3.3.5.1 Model Boundaries and Boundary Conditions

The domain for the FWM will be a subset of the EFDC model application area (described in Section 3.2.5). The EFDC model includes upstream, transitional freshwater areas that were not included in the existing FWM developed for the RI (Windward Environmental, 2007). These areas include different species and food web pathways; therefore, the FWM domain will be limited to approximately the area used for the RI FWM application and not extended further upstream The FWM is a single, fully mixed computational cell, so model inputs are area-wide averages of water column and bed sediment contaminant concentrations across the relevant part of the EFDC model domain. The model provides a steady-state representation of the relationship between environmental exposure concentrations and tissue concentrations averaged over the entire study area. The environmental exposure concentrations in the water column will be supplied primarily by the EFDC model application. Bed sediment exposure concentrations will be based on the extensive data collection carried out for the RI/FS, which provide a basis for estimating spatially averaged bed sediment exposure concentrations; however, the EFDC model application will be used to help evaluate how these concentrations may have varied over time and in response to interim remedial activities. In- or out-migration of biota to or from the model domain is not addressed in the FWM, consistent with the existing approach (Windward Environmental, 2007).

The EFDC model application will also provide required environmental variables to the FWM, including suspended solids and organic carbon concentrations in the water column.

3.3.6 Model Calibration

3.3.6.1 Objectives

Steady-state food web models incorporate many simplifying assumptions and cannot be expected to predict the tissue concentrations in individual fish as that concentration depends in part on the life history and feeding pattern of that individual. Rather, a model that is well fit and useful for evaluation of response to future changes in exposure concentrations provides a reasonable representation of the statistical distribution of observed tissue concentrations.

3.3.6.2 Approach and Time Period

The existing FWM using a probabilistic calibration approach in which all parameters were varied in a Monte Carlo simulation and a best fit parameter set selected from the results. For the revised model, a more focused approach will be used in which sensitivity analysis is used to select the most important parameters for calibration. Probabilistic calibration methods will then be applied to these parameters to produce a best-fit set that produces estimates most similar to the empirical data as defined by minimizing the mean ratio (SPAF) across all species with empirical data and approximating the interquartile range.

While the model is steady state, it will be applied separately to different time periods. Specifically, Windward Environmental (2007) evaluated the major fish tissue data collection efforts of 2004 and 2007 and concluded that the dredging event that occurred in 2004 had a major effect on tissue concentrations. Therefore, the steady-state model will be applied to conditions representative of 2004, 2007, and more recent fish tissue sampling efforts.

3.3.6.3 Calibration Data

The Arnot and Gobas (2004) model construct is applicable to evaluation of steady-state tissue concentrations of non-polar organic chemicals in the study area; however, the experience of application of the FWM to 2007 fish data suggests limitations to the analysis. A key issue is the lack of concurrent data for different compartments in a system where the bed sediment concentrations and, especially, the water column concentrations are changing over time. While new tissue data will be collected as part of CERCLA action before it is time to develop the food web model, it will be necessary to rely in large part on older bed sediment data within the LDW (collection of new synoptic data in all media would be preferable, but such work is not being pursued at this time due to the large cost of new comprehensive surveys). Some adjustments will be considered to account for both interim remedial actions and dilution of surface sediment concentrations by continued deposition of cleaner sediment from the Green River. Temporal variability (i.e., differences from year to year for a steady-state model application) in water column concentrations will be addressed by the development of an improved water column model (EFDC) that simulates the responses to varying flow and loading conditions over time. Obtaining additional data on dietary sources of individual species would likely improve the model performance.

The food web model accuracy will be evaluated through comparison of modeled and observed tissue concentrations, as well as documentation of the assumptions, sensitivity analysis, data gaps, and limitations of the model.

3.4 Model Linkage and Integration

Model outputs from the LSPC model application will be used as upstream and lateral boundary inputs to the EFDC domain. The LSPC model will provide the EFDC model with inputs for flow, water temperature, sediment, total organic carbon, dissolved organic carbon, and the toxic parameters of interest.

The environmental exposure concentrations in the water column will be supplied to the FWM by the EFDC model application, including dissolved and sorbed toxics in the water column, suspended solids and organic carbon concentrations. Bed sediment exposure concentrations will be based on the extensive data collection carried out for the RI/FS, which provide a basis for estimating spatially averaged bed sediment exposure concentrations. EFDC model predictions will be used to evaluate how these concentrations may have varied over time and may vary in the future.

3.5 MODEL ACCEPTANCE

3.5.1 Model Uncertainty and Sensitivity

Development of water quality models is an inherently uncertain enterprise. Sources of uncertainties in all three models include the following:

- System complexity.
- Simplifying assumptions of the model.
- Uncertainty in process kinetics and rate constants of the model.
- Data Limitations.
- Gaps.
- Limitations in boundary condition and calibration data.
- Measurement error.

Uncertainty and sensitivity analyses are a complementary activity to model calibration, performed as part of an investigation into different sources of error in the predictions. Important findings in this iterative investigation will be documented in the model development report. Key data limitations identified through this process will be summarized for consideration in the planning of any future monitoring.

Depending on project resources and schedule, more advanced analysis of model uncertainty and sensitivity may be undertaken. Options include First Order Variance Analysis (FOVA), which is a formalized method to estimate model sensitivity to specific input variables of interest.

3.5.2 Model Acceptance

The primary model development goals are (1) to minimize the difference between simulated and observed hydrology, water/sediment quality and fish tissue concentration, and (2) to capture the spatial and temporal patterns in the observed environmental conditions. Progress toward achieving these goals is commonly captured in error statistics and graphical plots. However, model quality goes beyond these core evaluations. Several parallel tasks to achieve overall model quality are pursued alongside efforts to reduce model error, including:

1. Incorporation of all available observations of the system (e.g., geometry, flow, boundary inputs/withdrawals, meteorology) for the time period simulated.
2. Reasonable estimation methods and assumptions to fill gaps in the observations.
3. Calibration of model parameters and unmeasured boundary conditions within reasonable bounds to improve agreement between simulated and observed water quality.
4. Identification of key parameters/processes through model calibration and sensitivity analysis.
5. Clear communication of key assumptions during model development with the project team.
6. Clear written documentation of all important elements in the model, including model setup, boundary conditions, assumptions, and known areas of uncertainty.
7. Peer review.

Progress on all of these fronts will factor into the decision to accept a model for use in a decision-making process.

The project team is not establishing quantitative model acceptance criteria in this QAPP based on the following considerations:

1. Overall model quality cannot be fully captured in numeric error statistics.

2. Model error can vary widely depending on the system characteristics and simulated parameters, and the irreducible error cannot be predicted at the outset of the project.
3. It may not be possible to reduce error below numeric acceptance criteria without additional data collection, and this can significantly impact the project schedule, budget, and management goals. A decision to delay model acceptance for additional data collection is a major management decision that should not be pre-judged by criteria in the project planning document.
4. Model acceptance is a policy decision of regulatory agency management and should involve consideration of numerous factors and goals in model quality (described above). The QAPP should ensure good project planning without setting unrealistic goals or constraining management review and decisions.

3.6 Model Application and Scenarios

Once the models are calibrated the project team will have a better understand their limitations based on performance testing. After accepted for use by EPA and Ecology, the models will be used to assess pollutant sources, loadings, fate/transport, and changes in conditions over time (e.g. sediment remediation). This assessment will require the identification of model scenarios, which are specified model runs designed to answer specific questions about the system. The project team will consult with the TAC in developing the priority scenarios to be analyzed. The full set of scenarios cannot be determined prior to the commencement of model development, but the following types of scenarios are likely to be considered:

- Existing Condition (calibrated model predictions for past periods).
- Source Assessment (relative contribution determined by isolating individual sources types, e.g., contaminated sediments, watershed sources, CSOs, air deposition).
- Remediated Sediments (predicted changes due to sediment remediation).
- Land Cover Changes (predicted changes due to changes in impervious cover).
- Water Management Change (changes in Howard Hanson Dam operation).
- Sea Level Rise (higher water levels at the marine boundary).
- Hydrologic Extremes (effects of peak storm events and drought conditions).
- Long Term Change (extended model runs to assess long term change).
- Relationship between water, sediment and tissue targets.

3.7 Model Documentation

Model documentation will be a critical aspect of the project. The objective of model documentation will be to record all actions and assumptions made in developing the models. To meet this objective, a logbook will be kept to document data sources, assumptions, methodology and decisions. As each phase of the model development (e.g., calibration) is completed, a draft chapter documenting the work will be prepared and reviewed. At project team meetings, decisions needed for the project will be reviewed and documented.

A final, complete report documenting all aspects of the model will be prepared for this project once the model is accepted. Model application results (i.e., scenarios) will be documented as well, either as chapters incorporated into the model development report or as separate technical reports.

4 Data Sources

The linked models will be developed with the existing body of data for the Green/Duwamish watershed. The available datasets are sufficient to begin the model development process, but it is unknown if they will be sufficient for final model acceptance for use in evaluating management scenarios. Tetra Tech has identified known limitations and gaps in the data in a prior memo (Tetra Tech, 2015b), but the ramifications of these data gaps on model confidence/uncertainty will not be fully understood until the model calibration process is underway. It is anticipated that the data gaps in sampling of surface water quality will present a more substantial challenge than gaps in flow data.

The model development process will be conducted in phases, beginning with hydrology and hydrodynamic modules of LSPC and EFDC. Once the flow models are complete and water quality data are assembled in a database tool, the project plan includes parallel tasks to develop empirical loading estimates and to calibrate the water quality models. These tasks will bring the key data gaps into greater focus and identify needs for additional data collection and other analyses to improve the models. After calibration is completed with existing data, the project team will evaluate the potential benefits and feasibility of gathering new data and extending the model calibration process to incorporate that data. Any future data collection efforts would be described in a data collection QAPP, and significant adjustments to the model development process would be captured in updates or addenda to this QAPP.

4.1.1 Data Summary

The data summaries produced in Tetra Tech (2014), Tetra Tech (2015a), and Tetra Tech (2015b) are not reproduced for this QAPP. Instead, a high level summary of the primary data to support model development is provided.

Secondary data are data previously collected under an efforts outside the current project that are used for model development and calibration. Table 9 lists the secondary sources that may be used in model development. The sections that follow provide additional details regarding secondary data used for this task.

Table 9. Sources of key secondary data

Data Type	Primary Sources
Watershed Model	
Tributary and mainstem flow	U.S. Geological Survey gaging (National Water Information System); King County Hydrologic Information Center
CSO flows	City of Seattle and King County Combined Sewer Overflow (CSO) monitoring and models
Tributary and mainstem water quality data	King County, USGS, Ecology
Reach hydraulics and subwatersheds	King County HSPF models, City of Seattle (for areas lateral to LDW)
Meteorology	National Climatic Data Center; King County; Washington State University Experimental Field Station, Parameter elevation Regression on Independent Slope Model (PRISM) climate data, North American Land Data Assimilation System (NLDAS)

Data Type	Primary Sources
Point source information (e.g., permits, DMRs)	Discharge Monitoring Reports (via Ecology) for non-stormwater discharges within the watershed
Landcover/land use	King County HSPF model (based on 30-m resolution 2007 satellite-derived dataset with 14 land use categories from the University of Washington)
Soils	USDA Statsgo
Digital Elevation Models	USGS National Elevation Dataset
Atmospheric Deposition	Ecology and King County
EFDC Model	
Model grid	Existing EFDC models developed by LDWG and King County
Meteorology	Seattle-Tacoma International Airport (SEATAC), National Oceanic and Atmospheric Administration (NOAA) tide stations
Tide, water surface elevation, and flow	NOAA tide stations, USGS, output from LSPC, CSO models/monitoring
Salinity and temperature	King County conductivity, temperature, and depth (CTD) sensor monitoring data
Water quality monitoring data	Ecology (Sherlock and EIM), Puget Sound studies, King County
Point source information (e.g., permits, DMRs)	CSO discharge data from City of Seattle and King County
Food Web Model	
Tissue data	Ecology (Sherlock and EIM), Puget Sound studies
Media concentrations	Output from EFDC

The following sections describe the data needed for each of the three models to be developed.

4.1.1.1 Watershed Model

Flow Data

Reliable streamflow data are important to watershed model development and calibration and validation. Flow data at locations within the model domain will be compared against modeled flow to evaluate the model performance. The USGS and King County maintain numerous stations in the Green/Duwamish system. Inflows at Howard Hansen Dam will also be used as a boundary condition. The USGS maintains streamflow gage and data from the gage are readily available through the National Water Information System (NWIS), accompanied by useful QC information. Some additional flow measurements are collected continuously and are available through King County’s Hydrologic Information Center. USGS data are available from the NWIS system at a daily interval and at shorter intervals via the USGS Instantaneous Data Archive, while King County data are available at 15-minute intervals. Figure 13 shows the spatial distribution of flow monitoring stations. Details on station names, period of record and other details are provided in appendices to the Technical Approach (Tetra Tech, 2014). About half of these provide data throughout a proposed modeling period of approximately 1995-2015. The flow data should be sufficient for watershed modeling purposes and to achieve an appropriate representation of system hydrology. When flow data from sources other than USGS and King County gaging and field measurements are used, Tetra Tech will review the relevant QA protocols and document the results in the project report.

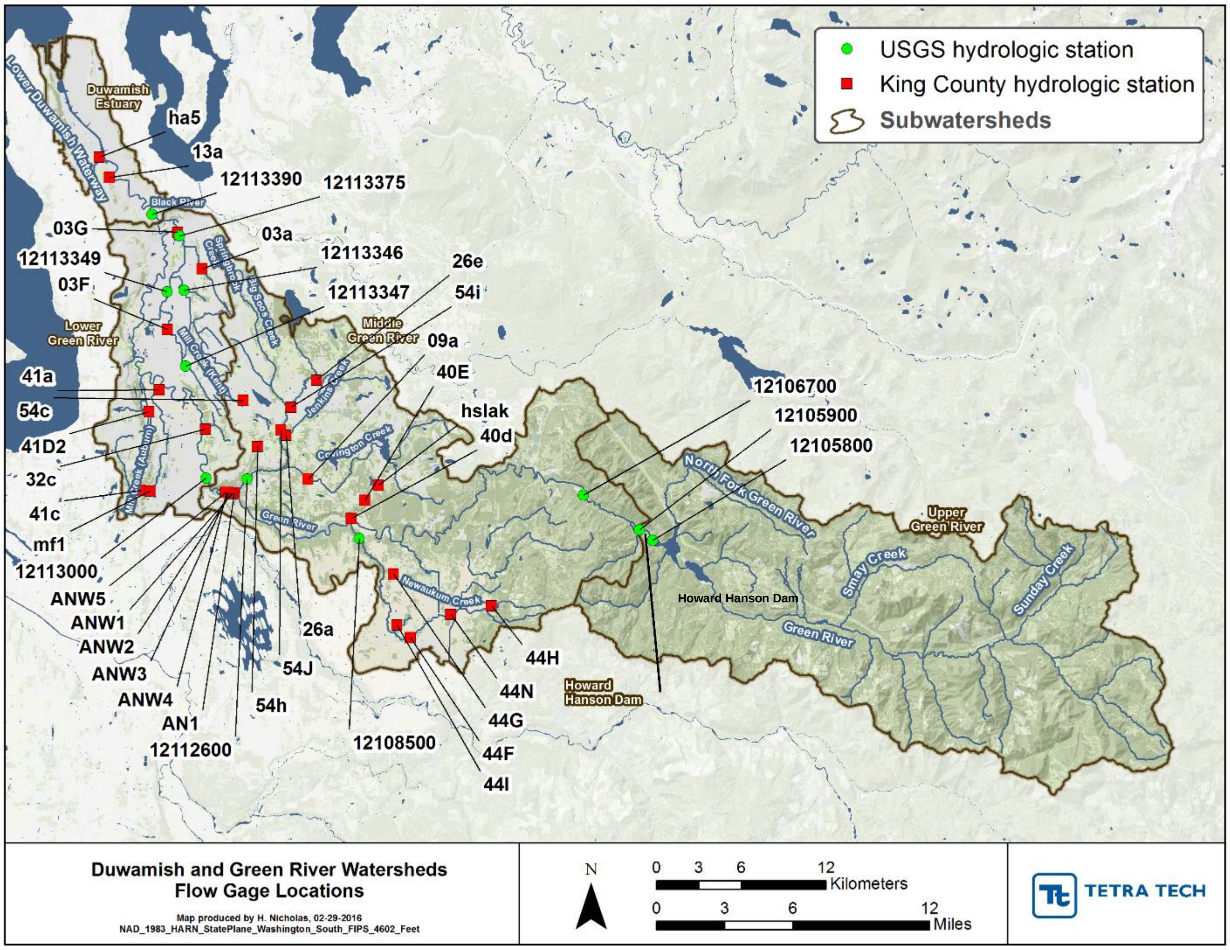

Figure 13. USGS and King County hydrology calibration stations in the study area

Auxiliary information for hydrologic calibration is provided by several sources. Representativeness of selected precipitation gages can be checked against PRISM and other gridded precipitation products that interpolate against topography. Another important check is provided by satellite-derived gridded estimates of actual evapotranspiration. As the largest fraction of incoming precipitation is converted back to evapotranspiration it is crucial to represent this portion of the water budget correctly, both as to total amount and seasonal patterns. The NASA/EOS monthly MOD16 Global Terrestrial Evapotranspiration Data Set will be compared to the LSPC simulated total evapotranspiration.

Meteorological Forcing Data

Meteorological forcing data will primarily include data from the NOAA's NCDC surface airways stations and King County-operated stations. Atmospheric forcing data include precipitation, air temperature, wind speed, dew point, cloud cover, evapotranspiration, and solar radiation.

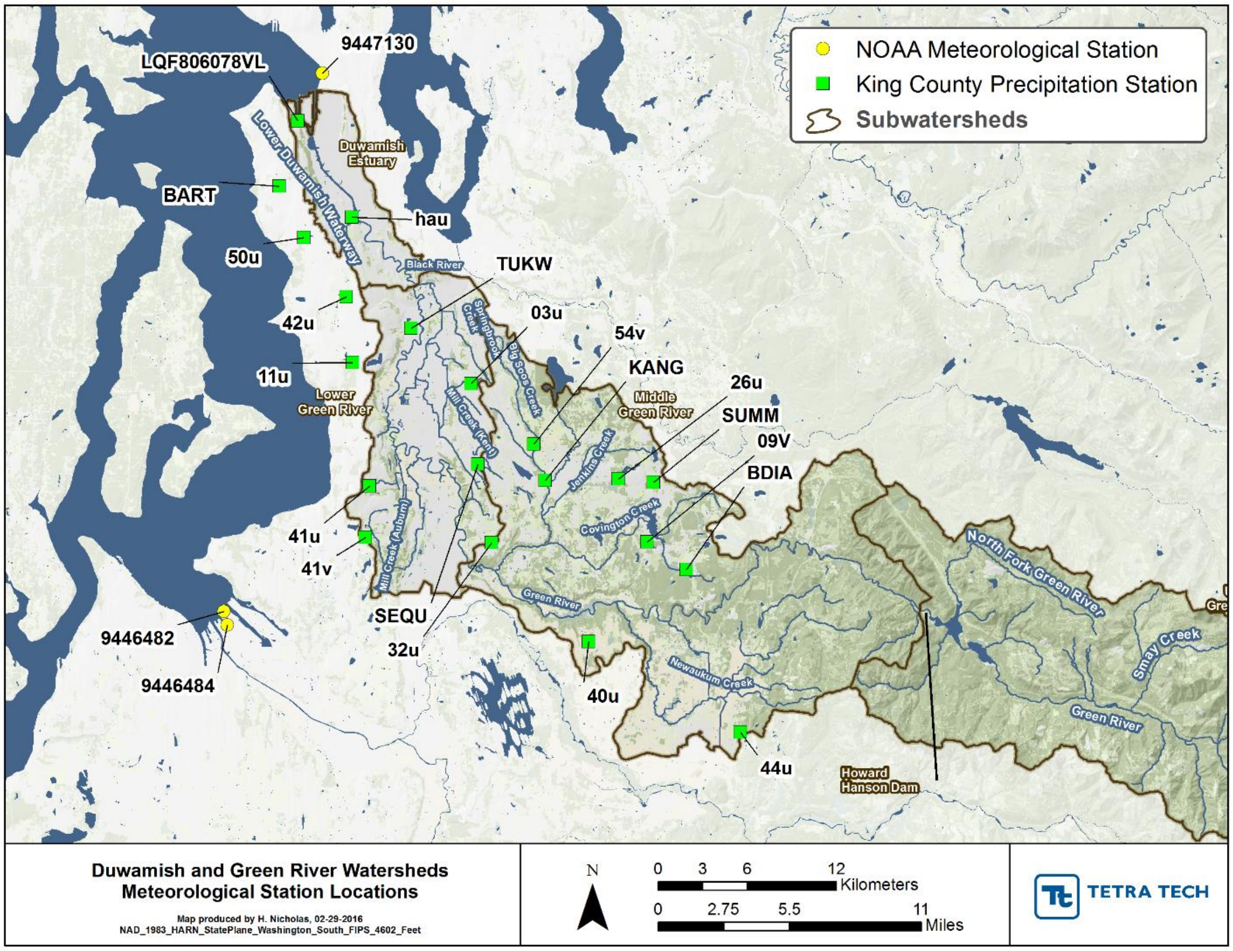

Figure 14. Precipitation and meteorological stations in the Green/Duwamish watershed

The figure above shows the meteorological and precipitation stations identified in the Technical Approach. Details on station names, period of record and other details are provided in appendices to the Technical Approach (Tetra Tech, 2014). Additional stations were identified in the BASINS dataset for the Duwamish/Green watershed that can be used to fill spatial gaps in the meteorological data, especially in the Upper Green watershed. The BASINS data also provide additional precipitation gages throughout the watershed.

Precipitation varies considerably in the greater Seattle region, and the large watershed is subject to a spectrum of precipitation patterns. For example, annual precipitation records from 1971-2000 in the central part of the study area at Landsburg show an annual average precipitation of 56 inches, while data in the upstream portion of the watershed recorded at Cougar Mountain indicate almost double that value, at over 100 inches.

In addition to these point observations, high resolution PRISM climate data are available to fill the gaps of weather data to support the model configurations. These data are grid-based and cover the entire modeling area. The NLDAS also provide grid based climate data. These point observation data and grid based data will be used together, and the spatial and temporal coverage will be sufficient to represent hydrology in the LSPC domain.

Water Quality Observations

Tetra Tech has compiled and reviewed water quality monitoring data for the watershed collected by Ecology, USGS, King County and others. Summaries are provided in Tetra Tech (2014), Tetra Tech (2015a), and Tetra Tech (2015b). It is expected that additional data will be complied in the initial stages of model development.

The water quality simulation will be constrained by comparison to data as well as by auxiliary information on loading rates and pollutant behavior. Because observed concentration data in the water column are relatively sparse and often at or below practical quantitation limits for many COCs, the first step in calibration is to constrain the model to be qualitatively consistent with previous studies on loading rates. Available data sources for loading information are summarized below (Table 10).

Table 10. Summary table of data/study by parameter - land use/land cover-based loading rates

Parameter	Surface Runoff/Shallow Groundwater *	Atmospheric Deposition *
Solids and Suspended Sediment	USGS National Water Quality Assessment (1994-2003) King County (2014) King County (suspended solids study) King County (2015) Herrera (multiple citations)	--
PCBs	Herrera (multiple citations) Ecology (2015)	King County (2013c) Leidos and Newfields (2013)
cPAHs	Herrera (multiple citations) Ecology (2015)	King County (2013c) Leidos and Newfields (2013) Ecology (2010)
DEHP	Herrera (multiple citations) Ecology (2015) King County (2004, 2005a, 2005b)	King County phthalate studies (2004, 2005a, 2005b) Leidos and Newfields (2013)
Arsenic	Herrera (multiple citations) Ecology (2015)	King County (2013c) Leidos and Newfields (2013) Ecology (2010)
Copper	Herrera (multiple citations) Ecology (2015)	King County (2013c) Ecology (2010)
Zinc	Herrera (multiple citations) Ecology (2015)	King County (2013c) Ecology (2010)

* Leidos (2014) provides a compilation that may also provide additional supporting information.

Once land use based-loading rates are estimated and included in the initial model setup, the instream water quality model is calibrated at increasingly larger scales (e.g., by tributary subwatershed and then by the main sections of the mainstem of the Green River (e.g., Upper, Middle, Lower). The table below (Table 11) summarizes data available for instream water quality calibration. The recent data collected by a number of agencies begins to fill keys gaps in the data identified by the remedial investigation / feasibility study (RI/FS) and Leidos (2014). Additional data relevant to this effort are still being collected.

Table 11. Summary table of data/study by parameter and watershed area – instream calibration

Parameter	Upper Green River Watershed	Middle Green River Watershed	Lower Green River Watershed
Solids and Suspended Sediment	King County (2015) USGS National Water Quality Assessment (1994-2003)	King County (2014) USGS National Water Quality Assessment (1994-2003) King County (suspended solids study)	King County (2014) King County (suspended solids study) USGS National Water Quality Assessment (1994-2003) USGS (Tukwila monitoring) Ecology (2009)
PCBs	King County (2015)	King County (2014) King County (suspended solids study)	King County (2014) King County (suspended solids study) USGS (Tukwila monitoring) Ecology (2009)
cPAHs	King County (2015)	King County (2014) King County (suspended solids study)	King County (2014) King County (suspended solids study) USGS (Tukwila monitoring) Ecology (2009)
DEHP		King County (2014) King County (suspended solids study)	King County (2014) King County (suspended solids study) USGS (Tukwila monitoring)
Arsenic	King County (2015)	King County (2014) King County (suspended solids study)	King County (2014) King County (suspended solids study) Ecology (2009)
Copper		King County (suspended solids study)	King County (suspended solids study) USGS (Tukwila monitoring)

Parameter	Upper Green River Watershed	Middle Green River Watershed	Lower Green River Watershed
Zinc		King County (suspended solids study)	King County (suspended solids study) USGS (Tukwila monitoring)

Reach Hydraulics and Subwatersheds

Reach hydraulics and subwatershed delineations will rely primarily on the previous HSPF model by AquaTerra for King County. Refinements will be made as needed. Additional delineation and reach hydraulics will be based on data from City of Seattle and others as available for the areas adjacent to the LDW. Digital elevation model (DEM), local Lidar data, and other data will be used where needed.

Point Source Discharges

The majority of National Pollutant Discharge Elimination System (NPDES) permits in the study area are general permits for stormwater (municipal, industrial and construction) and specific industrial processes (such as Sand & Gravel and Boatyards), which are proposed to be incorporated as upland processes in the watershed model (i.e., not modeled explicitly as a traditional, direct discharge to a stream). There are five individual permits in the Lower Duwamish and Lower Green watersheds. The initial data inventory conducted for the Technical Approach suggested that Discharge Monitoring Report (DMR) data are limited. When available, flow and pollutant concentrations obtained from DMRs and other applicable studies would be used to improve model calibration. When DMR data does not contain the parameters to be modeled, assumptions can be made and documented based on similar monitoring efforts. However, it is likely that most of these will not be included explicitly in the model due to size, nature of the discharge, type of facility, and/or the ability to also be represented as an upland inputs.

Portions of the watershed area adjacent to the LDW have separated and partially separated systems for sewage and stormwater. These will be handled separately, as described in Section 3.1.2. Areas with partially separated storm drainages are generally areas in which street drainage is separated but roof drainages go to the CSS. Existing GIS files that delineate these areas and other information on connectivity will be obtained from Seattle Public Utilities.

Land Cover/Land Use and Soils

Land cover/land use and soils data are typically used to develop hydrologic response units. Since the existing HSPF models for King County already have Hydrologic Response Unit (HRUs) developed based on 2007 land use/land cover, Tetra Tech will begin with these and update only as needed for the initial hydrologic calibration of the PLA watershed model. Development of the water quality model for the watershed, particularly for toxics, may include an update and/or refinement of the HRUs in which case additional land cover/land use data from a combination of local sources (e.g., City of Seattle, King County, and other municipalities) and national data sets (e.g., National Land Cover Dataset or NLCD) will be used. Soils data, if needed, can be obtained from US Department of Agriculture (USDA).

Atmospheric Deposition

Atmospheric deposition of PAHs, PCBs and arsenic are important sources of pollutants that may be considered a boundary condition, as these are external inputs to the watershed and receiving water models. Both wet and dry deposition of these contaminants occur in the watershed, and are spatially and temporally dependent. For example, arsenic deposition occurred near smelter locations prior to their closure. PCBs will have higher concentrations in air in close proximity to PCB sources, such as a building with high PCB concentrations in caulking or paint. PAHs are expected to have higher air concentrations in close proximity to transportation centers.

A number of atmospheric deposition studies in the region provide information to set initial atmospheric deposition rates, and when combined with build-up washoff and sediment/solids potency will form the basis of loading rates from individual land use types. This information can also support direct atmospheric deposition loading to surface water. These studies were summarized in Tetra Tech (2015b).

It is preferable to represent both wet and dry deposition, both of which can be specified in the watershed model, but this will depend on the availability of data. In cases where only total long-term deposition rates are available it would be best to represent this rate as dry deposition; however, if concentrations in rainfall are available both types of sources can be used. Details of the representation of atmospheric deposition of toxics will be described in detail in the model development report.

4.1.1.2 EFDC Model

Model Grid

The proposed EFDC model will be developed using the grid from the existing models with an upstream extension. (See Section 3.2.3) The current LDWG (QEA) and King County EFDC grid extends into Elliott Bay, with an open boundary drawn between Alki Lighthouse and Four Mile Rock. The PLA modeling domain will be extended further upstream on the Green River to capture additional tidally influenced sections.

Meteorology

The receiving water model requires input time series of atmospheric forcing data including precipitation, air temperature, wind speed, dew point, cloud cover, evapotranspiration, and solar radiation. Meteorological data are available from NOAA's surface airway stations and can be used to support hydrodynamic modeling. Meteorological data are available from 1991 to present from other sources including NOAA, King County, and Washington State University.

King County's Hydrologic Information Center also contains rainfall, stream gages, precipitation, air and water temperature, turbidity and other meteorological data for some stations. The available meteorological stations were illustrated in Figure 14. In the meteorological station map below, there are several NOAA meteorological stations with a full suite of atmospheric forcing data. In addition, King County's precipitation gauges provide good spatial and temporal coverage throughout most of the watershed. Wind forcing data from the Seattle Pier 52 ferry terminal are currently used in the QEA and King County EFDC models. This dataset will be applied for the current effort to maintain consistency. These input data are time-variable (hourly) in direction and velocity.

Additional data on evaporation are available from Washington State University. Data sources such as PRISM climate data and NLDAS can be used to supplement these sources if needed. Finally, meteorological data and station selection will be influenced by those used in the King County HSPF models and the LSPC model developed for this work.

Tide, water surface elevation, and flow

Data to support hydrodynamic modeling are available from a variety of sources including USGS, Ecology, EPA, NOAA, King County and associated studies. Important for hydrodynamic receiving water modeling, tidal data are available for 1991-present and are collected at 6 minute, hourly, and monthly intervals at several active stations. Data can also be used from inactive tide stations for calibration purposes, which are also available, if necessary, based on important spatial locations and or time periods. In addition, a single current monitoring station is located in Puget Sound to the north of the study area for

2009-present. Figure 15 shows the location of hydrodynamic monitoring stations in the region. Details on station names, period of record and other details are provided in appendices to the Technical Approach (Tetra Tech, 2014).

Tidal data are available long-term, continuous (i.e., mooring stations), and instantaneous monitoring stations throughout the receiving waters and waterbodies that could be used as external boundary conditions along the open boundary in Elliott Bay. The temporal (1989 to present) and spatial resolutions of the continuous and long-term data provide a strong basis for modeling the LDW and representing its boundary conditions. The instantaneous measurements are less pertinent, but could be used to fill in spatial gaps. LSPC watershed model results will be used to represent tributary inflow boundary conditions.

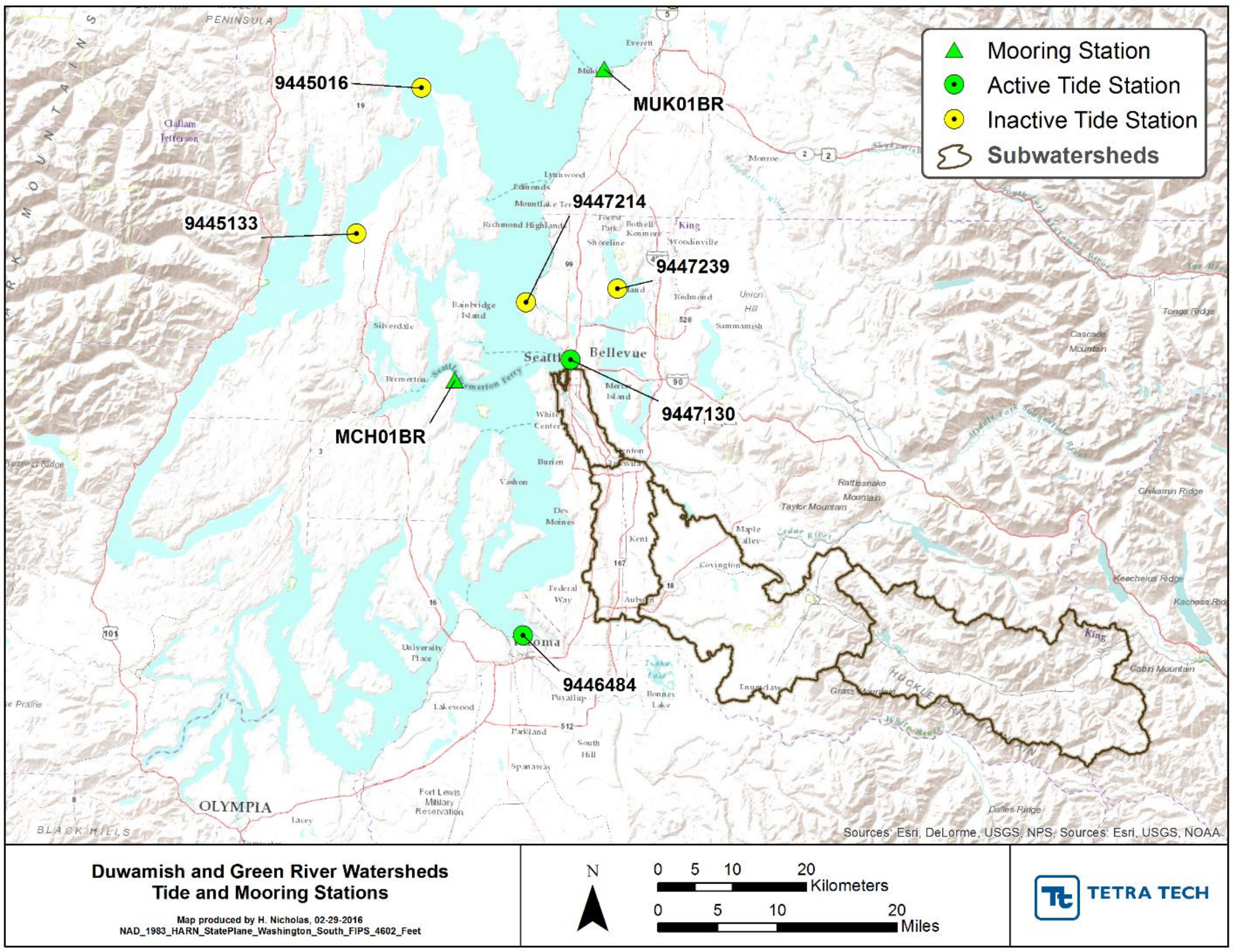

Figure 15. Tide and current stations in the study region

Salinity and temperature

LDW and surrounding waterbodies that would represent boundary conditions are well represented as water temperature and salinity data are available to assist in implementation modeling effort. The upstream water temperature boundary condition will be provided by the LSPC watershed model, and a salinity of 0 will be assigned to flows, consistent with the QEA and King County modeling. Along the open boundary at Elliott Bay, observed salinity and temperature values will be applied that use data sources consistent with the QEA and King County models. Offshore conductivity, temperature, and depth (CTD) sensor monitoring data from the King County's Puget Sound Marine Monitoring Program is available to derive values at the open boundary locations.

Water quality monitoring

Tetra Tech has compiled and reviewed water quality monitoring data for the watershed collected by Ecology, USGS, King County and others. Summaries are provided in Tetra Tech (2014), Tetra Tech (2015a), and Tetra Tech (2015b). Leidos (2015) is in the process of developing a detailed, quality assured database of PCB congener data. It is expected that additional data will be complied in the initial stages of model development.

Point source discharges

Two types of point sources are in the watershed including CSOs, and stormwater runoff (excluding the King County South outfall in Elliott Bay). Most of the point sources are stormwater outfalls and they will be modeled within the LSPC framework. Figure 16 shows existing and historical CSOs in the watershed. For the drainage areas where surface runoff flows into CSO pipes, the CSO monitoring and models from City of Seattle and King County will be used (Tetra Tech will obtain City and County data of flow and concentration for CSOs). For the drainage areas where runoff will enter the stormwater pipes or directly enters the LDW, LSPC will be used. Individual drains will be aggregated so that the total flow and contaminant loading can be allocated to EFDC cells. It will be dependent on subcatchment delineations in the watershed model .

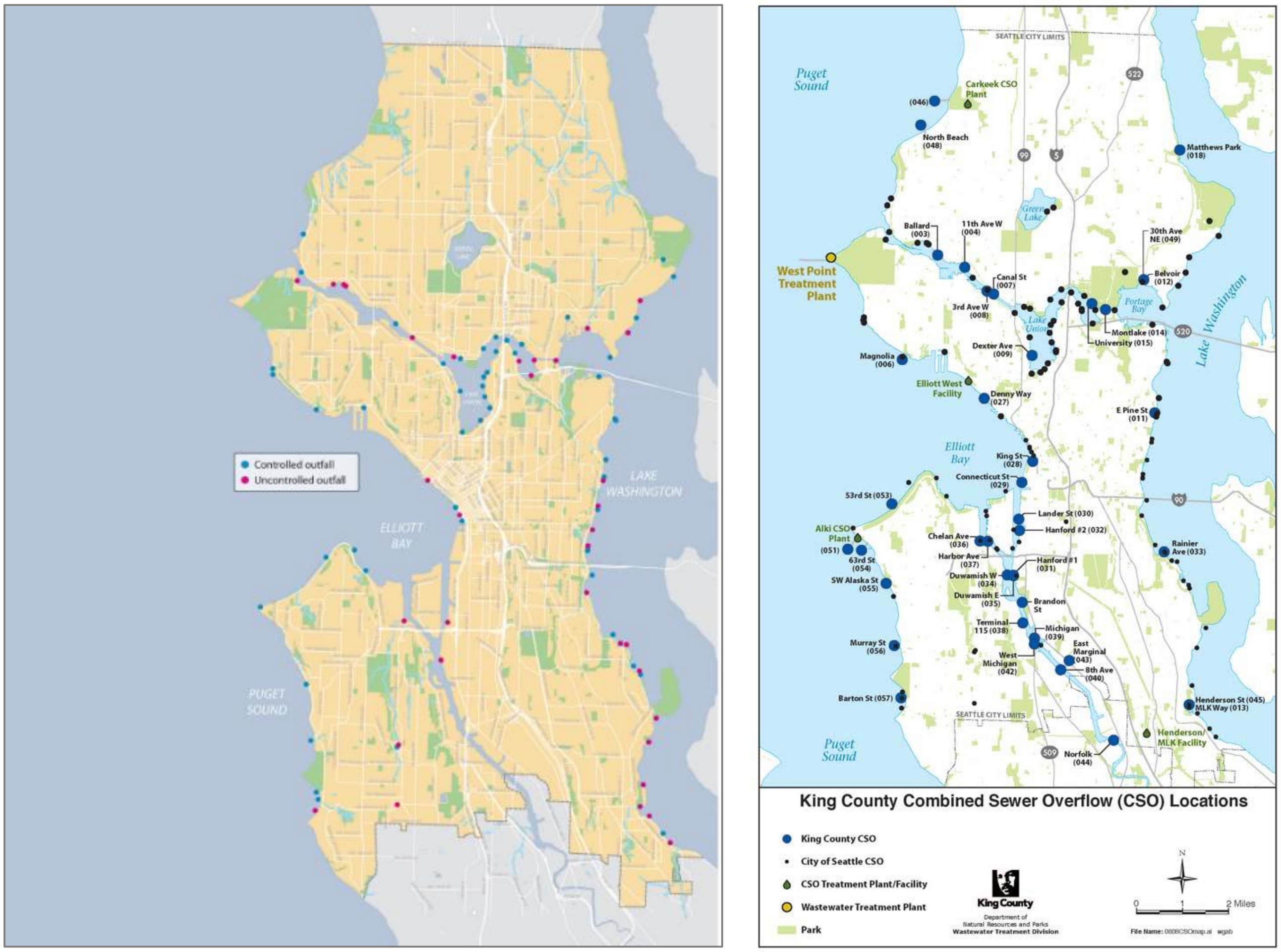

Figure 16. CSO maps for City of Seattle and King County

Left panel from City of Seattle,
http://www.seattle.gov/util/cs/groups/public/@spu/@usm/documents/webcontent/02_008043.pdf.

Right panel from King County, http://www.kingcounty.gov/services/environment/wastewater/cso/library/map.aspx.

4.1.1.3 Food Web Model

A key component of the FWM is the representation of dietary sources of individual species. Information on contaminant depuration rates and the representative mass and lipid content of individual species are also important.

The RI and other existing studies were used to compile tissue data and cover a period of 1984 to 2008 (see summaries in Tetra Tech, 2014). These data will be used for calibration of the food web model. An effort will be made to solicit any additional relevant information from university researchers and state and federal wildlife/fisheries agencies and appropriate modifications will be made and documented if such information is received.

In addition, environmental conditions including toxicant concentration in various media are needed for the food web model. The receiving water model, EFDC, will provide this information. The previous FWM developed for LDW also used the model results from EFDC as the inputs.

EIM currently contains a significant number of tissue samples for PCBs and PAHs (Table 12). Additional data may become available through ongoing data collection efforts.

Table 12. Tissue data in the EIM

Parameters	All Tissue Quality Data	Recent Tissue Quality Data (2003 – 2007)
PAHs	453	296
PCBs	934	466

4.1.2 Use of Data From Other Models

A number of previous modeling efforts in the watershed will inform PLA model development. These were described in Section 3.

4.1.3 Model Data Gaps and Methods to Address Them

Initial parameter-specific data gaps were discussed in Section 1.4. Building on these, model-specific gaps are discussed below.

Watershed Model

A review of the existing data suggested some gaps in the Upper Green River above the dam for instream water quality data, especially for certain parameters (i.e., copper, zinc, DEHP, and 2,3,7,8 TCDD). However, the significance of the gap should be understood relative to the significance of the area as a source of contaminants of concern (COCs). This is a relatively undeveloped and mostly protected area and is unlikely to be a major source of COCs below the dam. Atmospheric deposition is likely a primary source of COCs and these fluxes can likely be well constrained with the existing atmospheric deposition data. Uncertainties will remain but are not considered a barrier to a credible model.

Point sources in the watershed (excepting MS4 stormwater permits) that are monitored and discharge to surface waterbodies directly will be input into the model at a minimum of monthly average or up to daily frequencies according to data availability. Inputs for point sources typically includes Flow Volume and either loads or concentrations. Not all point sources have been monitored for all constituents that are needed for model input. Filling of missing data is conducted in three general ways. First, if there are gaps in the data that are three months or less, an average will be calculated from before and after gap months. Second, if the gaps in the data are larger than three months the long term monthly average will be supplied. Lastly, if no information for a particular constituent that is required for the model exists then a default assumption will be utilized. Default assumptions will be developed in consultation with project team members. Data for these types of point sources, from a modeling perspective is not considered a significant gap at this time.

Development of a watershed model can proceed with all of the prioritized parameters. While data is deemed sufficient for initial model configuration and calibration, the data sets to support instream calibration do not span long periods of time. Therefore, additional data collection to support additional model testing exercises is recommended.

Knowledge gaps and options relative to the watershed model are summarized in Table 13.

Table 13. Summary of knowledge gaps, options, and selected approaches for watershed model

Knowledge Gap	Options and Selected Approach
Limited data for copper, zinc, and DEHP in the Upper Green River	Options: 1. Collect additional data prior to modeling 2. Assume loads are driven by geology and/or atmospheric deposition and proceed with modeling. Selected Approach: Option 2 is selected because loads are expected to be small from this relatively undeveloped area. Sensitivity analyses with the model can be used to determine the value of additional information.
Poor status of existing TSS calibrations in certain subbasins	Options: 1. Use existing calibrated parameters 2. Expend effort to improve calibration Selected Approach: Because movement of sediment is key to the movement of sediment/solids-sorbed pollutants, effort should be expended to improve the existing TSS calibration.

EFDC Model

There is a substantial body of information available with which to construct or revise and calibrate an EFDC model of the Duwamish Estuary, including existing EFDC modeling efforts. Flow and sediment transport model applications are already available and additional data can be used to further refine the modeling. Significant amounts of information on bulk concentrations of COCs are available for the bed sediment. At the same time, significantly less data are available for the water column, and limited or no pore water data are available, depending on the COC. These constitute data gaps for model development, and it may be challenging to fill these gaps. The ideal data set would contain spatially and temporally contemporaneous measurements of concentrations in all media. Additional data sets may be obtainable during the remedial design phase of the CERCLA action on the site. However, synoptic measurement of all parameters of interest in all media (water, sediment, and tissue) will not be available and may be infeasible.

Some of the primary gaps related to the EFDC modeling of toxics in the Duwamish Estuary can be better characterized as knowledge gaps than data gaps. Specifically, data are not generally available for site-specific determination of kinetic parameters that control sorption to sediment and organic carbon, volatilization, mass transfer from the sediment to water and vice versa, and solubility of organic pollutants can be considered as knowledge gaps.

All of these parameters can be estimated from values reported in the literature (e.g., solids partitioning can be estimated from K_{ow}); however, there is plentiful evidence that behavior at specific sites can be quite variable due to factors such as the nature of inorganic carbon in the system, especially the presence of black carbon as a sorbent (Gschwend et al., 2015), non-equilibrium processes, and partitioning to dissolved organic carbon.

Site-specific estimation of kinetic parameters could be pursued through additional field experiments, but this would be time-consuming and costly. Model calibration can also provide evidence as to the adequacy of assumptions based on literature. The approach to be taken for the PLA is to develop the toxics model with available data and then conduct sensitivity analyses to determine the influence of parameter uncertainty on model results that have an impact on management decisions. In this way, the initial model can provide importance guidance as to the need for new data collection. If new data is collected, the model calibration can be fine-tuned.

An additional key challenge is defining the CSO and lateral loads of COCs to the LDW. Tools are or will be available to estimate flows and solids loads from both CSOs and lateral separate storm sewer drainage to the LDW; however, the challenge will be in making appropriate use of the wealth of source information and a determination will need to be made as to the appropriate level of effort.

Table 14 summarizes data and knowledge gaps and options for the EFDC model.

Table 14. Summary of data, knowledge gaps, options, and selected approaches for EFDC model

Data and Knowledge Gap	Options and Selected Approach
In general, data are available but limited in some media. Data gaps and knowledge gaps exist for initial, boundary, and calibration data.	Options: 1. Use all available information including data and previous models to develop a model now of recent historic conditions. 2. Collect additional data and delay modeling to the future. Data collection needs to be coordinated to obtain initial, boundary, and calibration data sets in all media. Selected Approach: Start developing and calibrating the model with available data and use model to guide needs for new data collection.
Limited data for assigning initial conditions in the water column for all toxics	Options: 1. Assign low levels of initial toxics and equilibrate with bed sediment using a model spin-up period. 2. Collect data if the modeling period is in the future. Selected Approach: Use model spin-up combined with existing data; test sensitivity of model results to this assignment. Tetra Tech anticipates low sensitivity to initial conditions in the water column.
Data for bed sediment initial conditions (depending on the modeling period) and need to account for remedial actions over time.	Options: 1. Rely on existing data and use previous model results if modeling a historical period. 2. Collect new data if the modeling period is in the future. Selected Approach: It is unlikely that the massive characterization effort for bed sediment conditions undertaken in the RI can be repeated. The PLA model should thus rely on existing sediment data, but also needs to account for interim remedial actions over time. Applying the model to multiple years can be used to test simulated responses to remedial actions. In addition, use long model spin-up time and conduct multiple model tests where directly measured data are not available. It is anticipated that a new baseline data for LDW (bed sediment, water, porewater, tissue) will be available in next 3-5 years which can be used for calibration/ testing/corroboration purpose.
SSC and toxic loadings from upstream	Options: 1. Use watershed model results for modeling a historical period. 2. Continue collection of comprehensive toxics data from the watershed and develop the model in the future.

Data and Knowledge Gap	Options and Selected Approach
	Selected Approach: Existing HSPF models are calibrated for flow and suspended sediment. Develop the upstream loading with a combination of these models and existing data; continue collection of new data to fill knowledge gaps for LSPC simulation.
SSC and toxics loadings from CSOs	Options: 1. Use existing CSO monitoring data and event volume modeling combined with best estimates of pollutant concentrations. 2. Combine CSO model and monitoring data with watershed model simulations of surface stormwater-derived loads. Selected Approach: Use CSO model to develop time series and estimate CSO concentrations. Confirm model performance relative to CSO outfall monitoring.
Limited toxics data in the water column; lack of information to do site-specific evaluation of some kinetic parameters such as partition coefficients.	Options: 1. Use available data and literature to approximate kinetic parameters. 2. Collect new field data to gain knowledge. 3. Conduct laboratory experiments to fill knowledge gaps. 4. Conduct literature review to fill knowledge gaps. 5. Conduct model sensitivity and uncertainty analyses to fill knowledge gaps. 6. Collect synoptic data for a modeling period in the future and delay model implementation. Selected Approach: Develop model beginning with available data. Options 1 to 5 can all be potentially used to further constrain the data and knowledge gaps the model based on resource availability. Initial model development will greatly assist in determining the cost:benefit ratio of specific types of data collection.

Food Web Model

A FWM was developed in support of the Remedial Investigation to estimate PCB concentrations in tissues and bed sediment, with a goal of using the model to estimate risk-based threshold concentrations in bed sediment for the RI (Windward Environmental, 2010).

The Arnot-Gobas model construct is applicable to evaluation of steady-state tissue concentrations of non-polar organic chemicals in the study area; however, the experience of application of the FWM to 2007 fish data suggests limitations to the analysis. A key issue is the lack of concurrent data for different compartments in a system where the bed sediment concentrations and, especially, the water column concentrations are changing over time. While new tissue data are being collected it will be necessary to rely in large part on older bed sediment data within the LDW. Some adjustments will need to be made to account for both interim remedial actions and possible dilution of surface sediment concentrations by continued deposition of cleaner sediment from the Green River. Temporal variability in water column concentrations can be addressed to some extent by the development of an improved water column model that simulates the responses to varying flow and loading conditions over time. Obtaining additional quantitative data on dietary sources of individual species and pollutant concentrations in prey species would likely improve the model performance.

The previous FWM approach of evaluating bioaccumulation of total PCBs using a wide range of K_{ow} and other kinetic characteristics could be improved by an evaluation based on several homolog groups.

Biomagnification over two or more trophic levels is generally not expected to occur for PAHs, except possibly in species from the lower trophic levels that are not able to effectively metabolize PAHs (Meador et al, 1995). This is because most food webs usually involve a vertebrate, which in most cases can actively biotransform PAHs. The ability to degrade PAHs leads to a short half-life for these compounds in tissue that prevents accumulation. Therefore, the Arnot-Gobas type of bioaccumulation model that will be used for PCBs in this project is not appropriate for PAHs. Instead, we propose to use measured relationships between PAH concentrations in the fish tissue and environmental concentrations in the water and sediment to develop site-specific empirical models (e.g. bioaccumulation factors) for use in estimating the environmental reductions needed to achieve acceptable threshold concentrations in the biota. Predicting tissue accumulation of metals and the metalloid arsenic would require different modeling tools, such as DYMBAM. Arsenic, copper, and/or zinc are best addressed based on water column concentrations and that tissue accumulation models are not needed for these constituents.

In addition, phthalates will not be included in the food web model. They are rapidly metabolized in fish with occasional high tissue concentrations reflective of recent exposure to hotspots.

Table 15 summarizes knowledge gaps and options for the FWM.

Table 15. Summary of knowledge gaps, options, and selected approaches for Food Web Model

Knowledge Gap	Options and Selected Approach
Lack of contemporaneous data in all media and biota	Options: 1. Conduct comprehensive new round of synoptic data in all compartments 2. Use models to estimate temporal changes in stores Selected Approach: Option 2 is selected due to the high cost of new comprehensive surveys.
Limited information on dietary sources of individual species	Options: 1. Conduct gut content surveys

Knowledge Gap	Options and Selected Approach
	2. Rely on existing data Selected Approach: Rely on existing data (2), but supplement prior FWM effort by soliciting additional information from wildlife and university sources.
Limited modeling tools for evaluating bioaccumulation of arsenic, copper, and zinc; limited data on factors controlling bioavailability; phthalates	Options: 1. Do not model bioaccumulation of metals 2. Use DYMBAM model for bioaccumulation of metals Selected Approach: Base analysis for these constituents on ambient water quality standards for protection of aquatic life rather than bioaccumulation models. Do not implement DYMBAM. In addition, phthalates will not be included in the food web model. They are rapidly metabolized in fish with occasional high tissue concentrations reflective of recent exposure to hotspots.

4.1.4 Quality Control for Secondary Data

The majority of the secondary measurements will be obtained from quality assured sources. Tetra Tech will assume that data, documents and databases obtained from EPA, USGS, Ecology, King County, City of Seattle, and others have been screened and meet specified measurement performance criteria. Such criteria might not be reported for the parameters of interest in the documents or databases. During model development, Tetra Tech will identify any data anomalies that warrant analysis of quality assurance information for the particular dataset, and EPA and Ecology will direct any effort to find reports or metadata that might contain that information. Tetra Tech will perform general quality checks on the transfer of data from any source databases to another database, spreadsheet, or document.

Where data are obtained from sources lacking an established data quality program, Tetra Tech will evaluate data quality of such secondary data before using it. Additional methods that might be used to determine the quality of secondary data are the following:

- Verifying values and extracting statements of data quality from the raw data, metadata, or original final report
- Comparing data to a checklist of required factors (e.g., analyzed by an approved laboratory, used a specific method, met specified DQOs, validated)

If it is determined that such searches are not necessary or that no quality requirements exist or can be established, but the data must be used in the task, Tetra Tech will add a disclaimer to the deliverable indicating that the quality of the secondary data is unknown.

4.2 Data Management

Tetra Tech will not conduct sampling (primary data collection) for this project. Secondary data collected as part of this task will be maintained as hardcopy only, both hardcopy and electronic, or electronic only, depending on their nature.

Key secondary data will be compiled from a variety of sources into a common database using a platform such as Microsoft Access or Water Resources Database (WRDB). The database will be used to support model development.

The modeling software to be used for this project consists primarily of the LSPC model, EFDC model, and the Arnot and Gobas (2004) Food Web Model. Code and executables these models are publicly available from EPA or other sources (e.g., Arnot and Gobas [2004) FWM).

Tetra Tech will maintain and provide the final version of the model input, output, and executables (source codes can be made available upon request) to EPA for archiving at the completion of the task. Electronic copies of the data, GIS, and other supporting documentation will be supplied to Region 10 with the final report. Tetra Tech will maintain copies in a task subdirectory (subject to regular system backups) and on disk for a maximum period of 3 years after project termination, unless otherwise directed by EPA.

Most work conducted by Tetra Tech for this task requires the maintenance of computer resources. Tetra Tech's computers are either covered by on-site service agreements or serviced by in-house specialists. When a problem with a microcomputer occurs, in-house computer specialists diagnose the problem and correct it if possible. When outside assistance is necessary, the computer specialists call the appropriate vendor. For other computer equipment requiring outside repair and not covered by a service contract, local computer service companies are used on a time-and-materials basis. Routine maintenance of microcomputers is performed by in-house computer specialists. Electric power to each microcomputer flows through a surge suppressor to protect electronic components from potentially damaging voltage spikes. All computer users have been instructed on the importance of routinely archiving work assignment data files from hard drive to compact disc or server storage. The office network server is backed up on tape nightly during the week. Screening for viruses on electronic files loaded on microcomputers or the network is standard company policy. Automated screening systems have been placed on all Tetra Tech computer systems and are updated regularly to ensure that viruses are identified and destroyed. Annual maintenance of software is performed to keep up with evolutionary changes in computer storage, media, and programs.

5 QA/QC Plan and Assessment

5.1 Assessment and Response Actions

The QA program under which model development will be performed includes surveillance and internal and external testing of the software application. The essential steps in the QA program are as follows:

- Identify and define the problem.
- Assign responsibility for investigating the problem.
- Investigate and determine the cause of the problem.
- Assign and accept responsibility for implementing appropriate corrective action.
- Establish the effectiveness of and implement the corrective action.
- Verify that the corrective action has eliminated the problem.

Many technical problems can be solved on the spot by the staff members involved; for example, by modifying the technical approach, correcting errors in input data, or correcting errors or deficiencies in documentation. Immediate corrective actions are part of normal operating procedures and are noted in records for the task. Problems not solved this way require formalized, long-term corrective action. If quality problems that require attention are identified, Tetra Tech will determine whether attaining acceptable quality requires short- or long-term actions. If a failure in an analytical system occurs (e.g., performance requirements are not met), the appropriate QC officer will be responsible for corrective action and will immediately inform the Tetra Tech Task Order Leader (TOL) or Quality Assurance (QA) officer, as appropriate. Subsequent steps taken will depend on the nature and significance of the problem.

The Tetra Tech TOL (or designee) has primary responsibility for monitoring the activities of this task and identifying or confirming any quality problems. Significant quality problems will also be brought to the attention of the Tetra Tech QA officer, who will initiate the corrective action system described above, document the nature of the problem, and ensure that the recommended corrective action is carried out. The Tetra Tech QA officer has the authority to stop work if problems affecting data quality that will require extensive effort to resolve are identified.

Corrective actions could include the following:

- Reemphasizing to staff the task objectives, the limitations in scope, the need to adhere to the agreed-upon schedule and procedures, and the need to document QC and QA activities.
- Securing additional commitment of staff time to devote to the task.
- Retaining outside consultants to review problems in specialized technical areas.
- Changing procedures.

The assigned QC officer (or designee) will perform or oversee the following qualitative and quantitative assessments of model performance to ensure that models are performing the required tasks while meeting the quality objectives:

- Data acquisition assessments.
- Secondary data quality assessments.
- Model testing studies.
- Model evaluations.

- Internal peer reviews.

5.1.1 Model Development Quality Assessment

This QAPP and other supporting materials will be distributed to all personnel involved in the work assignment. The designated QC officer will ensure that all tasks described in the work plan are carried out in accordance with the QAPP. Tetra Tech will review staff performance throughout each development phase to ensure adherence to task protocols.

Quality assessment is defined as the process by which QC is implemented in the model development task. All modelers will conform to the following guidelines:

- All modeling activities including data interpretation, load calculations, or other related computational activities are subject to audit or peer review. Thus, the modelers are instructed to maintain careful written and electronic records for all aspects of model development.
- If historical data are used, a written record on where the data were obtained and any information on their quality will be documented in the final report. A written record on where this information is on a computer or backup media will be maintained in the task files.
- If new theory is incorporated into the model framework, references for the theory and how it is implemented in any computer code will be documented.
- Any modified computer codes will be documented, including internal documentation (e.g., revision notes in the source code) and external documentation (e.g., user's guides and technical memoranda supplements).

The QC officer will periodically conduct surveillance of each modeler's work. Modelers will be asked to provide verbal status reports of their work at periodic internal modeling work group meetings. The Tetra Tech TOL or his designee will make monthly detailed modeling documentation available to members of the modeling work group.

5.1.2 Software Development Quality Assessment

New software development is not anticipated for this project. If any such development is required, the QC officer (or designee) will conduct surveillance on software development activities to ensure that all tasks are carried out in accordance with the QAPP and satisfy user requirements. Staff performance will be reviewed throughout the project to ensure adherence to task procedures and protocols.

5.1.3 Surveillance of Project Activities

Internal peer reviews will be documented in the project file. Documentation will include the names, titles, and positions of the peer reviewers; their report findings; and the project management's documented responses to their findings.

Performance audits are quantitative checks on different segments of task activities. The Tetra Tech QC officer (or designee) will be responsible for overseeing work as it is performed and for periodically conducting internal assessments during the data entry and analysis phases of the task. The Tetra Tech TOL will perform surveillance activities throughout the duration of the task to ensure that management and technical aspects are being properly implemented according to the schedule and quality requirements specified in the data review and technical approach documentation. These surveillance activities will include assessing how task milestones are achieved and documented; corrective actions are implemented; budgets are adhered to; peer reviews are performed; data are managed; and whether computers, software, and data are acquired in a timely manner.

5.2 Reports to Management

The TOL (or designee) will provide monthly progress reports to EPA. As appropriate, these reports will inform EPA of the following:

- Adherence to project schedule and budget.
- Deviations from approved QAPP, as determined from project assessment and oversight activities.
- The impact of any deviations on model application quality and uncertainty.
- The need for and results of response actions to correct any deviations.
- Potential uncertainties in decisions based on model predictions and data.
- Data quality assessment findings regarding model input data and model outputs.

5.3 Reconciliation with User Requirements

Quality objectives for modeling are addressed in Section 2.4. Specific numeric acceptance criteria are not specified for the model; instead, appropriate uses of the model will be determined by the project team on the basis of an assessment of the types of decisions to be made, the model performance, and the available resources.

If the project team determines that the quality of the model calibration is insufficient to address the principal study questions, Tetra Tech will consult with EPA and other team members, as appropriate, as to whether the levels of uncertainty present in the models can allow user requirements to be met, and, if not, the actions needed to address the issue.

A detailed evaluation of model quality will be provided in the final modeling report.

6 QAPP Implementation

6.1 Project Organization

The organizational aspects of the program provide the framework for conducting the necessary tasks. The organizational structure and function can also facilitate task performance and adherence to QC procedures and quality assurance (QA) requirements. Those who are leading the various technical phases of the project and those who are ultimately responsible for approving and accepting final products and deliverables fill the key task roles. The program organization chart, provided in Figure 17, illustrates the relationships and lines of communication among all participants and data users. The responsibilities of those persons are described below.

Ms. Jayne Carlin, EPA Region 10, is the task order manager (TOM) for the project. Ms. Laurie Mann, EPA Region 10, will serve as project manager providing overall project oversight, and Mr. Ben Cope, EPA Region 10, will provide modeling oversight. They will work with the Tetra Tech task order leader (TOL) to ensure that project objectives are attained. The task order manager, with the assistance of the technical lead, will also have the following responsibilities:

- Providing oversight for model selection, data selection, model calibration, model testing/corroboration, and adherence to project objectives.
- Maintaining the official approved QAPP.
- Coordinating with contractors, reviewers, and others to ensure technical quality and contract adherence.
- Coordinating with Ecology.

The EPA Region 10 QA manager, Mr. Donald Brown, or his designee, will be responsible for reviewing and approving this QAPP. The QA Manager or designee may conduct external performance and system audits and participate in Agency QA review of the study, if necessary.

The Tetra Tech TOL and Project Manager for this project is Mr. J Todd Kennedy. He will provide management oversight for the project. Additional responsibilities of the Tetra Tech TOL include the following:

- Coordinating project assignments, establishing priorities, and scheduling.
- Ensuring completion of high-quality products within established budgets and time schedules.
- Providing guidance, technical advice, and performance evaluations to those assigned to the project, and implementing quality improvements or necessary corrective actions.
- Preparing and reviewing preparation of project deliverables, including the QAPP, draft and final reports, and other materials developed to support the project.
- Providing support to EPA Region 10 in interacting with the project team, technical reviewers, workgroup participants, and others to ensure that technical quality requirements of the study design objectives are met.

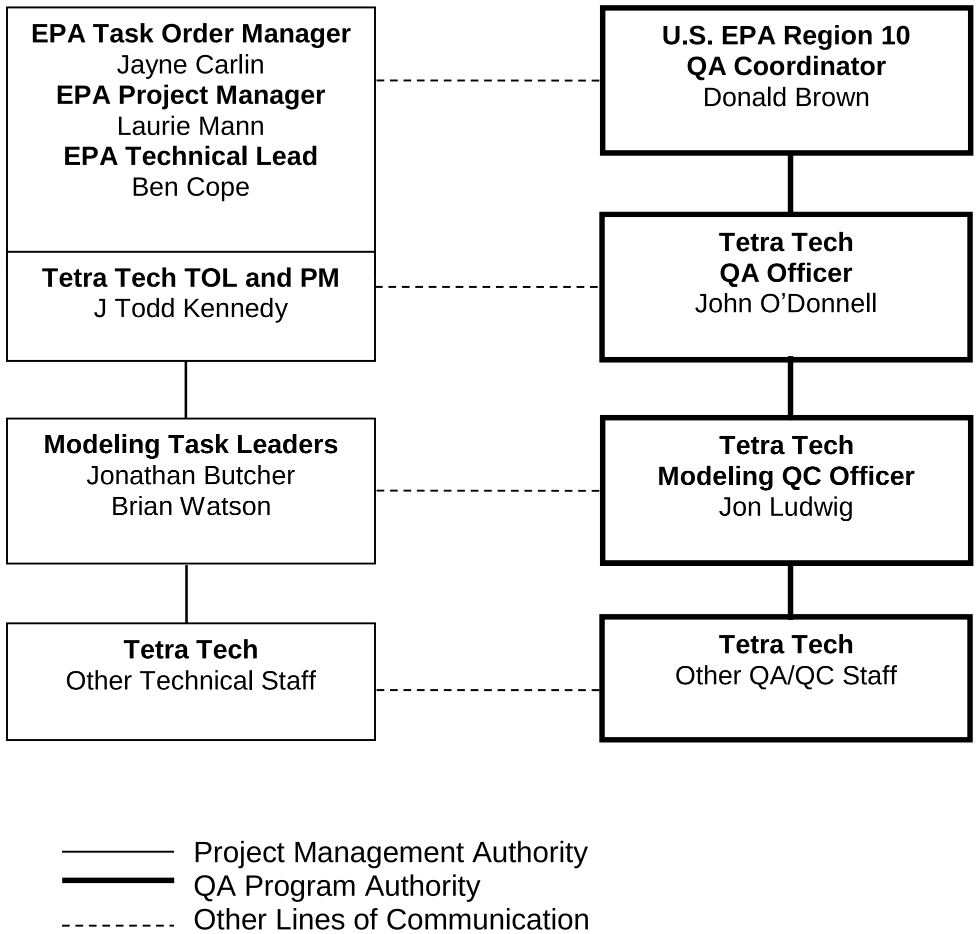

Figure 17. Project organizational structure.

The Tetra Tech QA officer is Mr. John O'Donnell, whose primary responsibilities are the following:

- Providing support to the Tetra Tech TOL in preparing and distributing the QAPP.
- Reviewing and internally approving the QAPP.
- Monitoring QC activities to determine conformance.

Tetra Tech modeling staff will be responsible for developing model input data sets, applying the models, comparing model results to observed data, calibrating the models, and writing documentation. For the purposes of this project, two modeling leads have been identified. Jonathan Butcher will lead the modeling efforts watershed model, and Brian Watson will lead the modeling effort for EFDC and the FWM models. Tetra Tech staff will implement the QA/QC program, complete assigned work on schedule and with strict adherence to the established procedures, and complete required documentation. Other technical staff will perform literature searches; assist in secondary data gathering, compilation, and review; and help complete other deliverables to support the development of the draft and final report.

The modeling QC officer, Jon Ludwig, will provide additional oversight. Mr. Ludwig is familiar with the proposed models and will provide final QC review of the model setup and output. The modeling QC officer or his designees will be responsible for performing evaluations to ensure that QC is maintained throughout the data collection and analysis process. QC evaluations will include reviewing site-specific model equations and codes (when necessary), double-checking work as it is completed, and providing written documentation of those reviews to ensure that the standards set forth in the QAPP and in other planning documents are met or exceeded. Other QA/QC staff, including technical reviewers and technical editors selected as needed, will provide peer review oversight of the content of the work products and ensure that they comply with EPA Region 10's specifications.

6.2 Adaptive Management

Any proposed changes to the project that depart from this QAPP will be documented in a memo sent by the QAO to the TOL, who will then submit the memo and the draft revised plan (plan sections, procedural descriptions, or amendments) to the COR to facilitate review and approval. Minor administrative changes with regard to EPA or Tetra Tech project management teams are generally documented in the form of a technical memorandum, rather than issuing a full plan revision. The TOL and COR will maintain and distribute the memo along with the approved, revised, and amended plans to all project staff as appropriate.

6.3 Record Keeping and Archiving

Thorough documentation of all modeling activities is necessary to be able to effectively interpret the results. All records and documents relevant to the application, including electronic versions of data and input data sets, will be maintained at Tetra Tech's offices in the central file. The central repository for the modeling work will be Tetra Tech's Research Triangle Park, North Carolina, office. Tetra Tech will deliver a copy of the records and documents in the central file to EPA Region 10 at the end of the task. Unless other arrangements are made, records will be maintained at Tetra Tech's offices for a minimum of 3 years after task completion.

The Tetra Tech TOL and designees will maintain files, as appropriate, as repositories for information and data used in models and for preparing reports and documents during the task. Electronic project files are maintained on network computers and are backed up weekly. The Tetra Tech TOL will supervise the use of materials in the central files. The following information will be included in the hard copy or electronic task files in the central file:

- Any reports and documents prepared.
- Contract and task order information.
- QAPP and draft and final versions of requirements and design documents.
- Electronic copies of models.
- Results of technical reviews, internal and external design tests, quality assessments of output data, and audits.
- Documentation of response actions during the task to correct problems.
- Input and test data sets.
- Communications (memoranda; internal notes, telephone conversation records, letters, meeting minutes, and all written correspondence among the task team personnel, suppliers, or others).
- Studies, reports, documents, and newspaper articles pertaining to the task.

- Special data compilations.

Records of receipt with information on source and description of documentation will be filed along with the original data sheets and files to ensure traceability. Records of actions and subsequent findings will be kept during additional data processing.

All data files, source codes, and executable versions of the computer software will be retained for internal peer review, auditing, or post-task reuse in the electronic task files in the administrative record. These materials include the following:

- Versions of the source and executable code used.
- Databases used for model input, as necessary.
- Key assumptions.
- Documentation of the model code and verification testing for newly developed codes or modifications to the existing model.

The Tetra Tech modeling QC officer and other experienced technical staff will review the materials listed above during internal peer review of modified existing models or new codes or models. The designated QC officers will perform QC checks on any modifications to the source code used in the design process. All new input and output files, together with existing files, records, codes, and data sets, will be saved for inspection and possible reuse.

Any changes in this QAPP required during the study will be documented in a memo sent by Tetra Tech's QA officer to each person on the distribution list following approval by the appropriate persons. The memo will be attached to the revised QAPP.

All methods, assumptions, etc. will be documented in a final memorandum detailing the modeling process and conclusions, as required by the task order.

6.4 Resources Needed

6.4.1 Special Training Requirements/Certification

Tetra Tech staff members involved in developing model input data sets and model application have experience in numerical modeling gained through their work on numerous similar projects. The Tetra Tech TOL and Project Manager, J Todd Kennedy, P.H., will provide oversee the project and provide guidance to the modeling leads. He has over 18 years' experience including extensive experience in modeling and managing similar projects. The TOL will ensure strict adherence to the project protocols.

The Tetra Tech TOL will oversee the project team in its execution of key project objectives. Dr. Jonathan Butcher, P.H., modeling co-lead, Brian Watson, P.E., modeling co-lead, and Jon Ludwig, the modeling QC officer will primarily assist the TOL.

Dr. Jonathan Butcher, P.H., is a water quality modeler and Professional Hydrologist with more than 25 years of experience supporting EPA, state, and local governments throughout the United States in complex modeling studies. He is a nationally recognized expert in the application of the watershed and waterbody response models.

Mr. Brian Watson, P.E., P.H., D.WRE is a civil engineer with over 17 years of professional experience, specializing in environmental engineering and water resources engineering, including hydrodynamic and water quality modeling, TMDL development and implementation, and water resources planning.

Mr. Jon Ludwig is a program manager and senior environmental scientist with over 17 years of experience providing technical and management support in the areas of water resources, watershed and water quality assessment, watershed modeling, and TMDL development.

Mr. John O'Donnell is the QA Manager for Tetra Tech's Fairfax Center offices. He has more than 30 years of environmental laboratory and QA experience. He has been QA Officer for several contracts in the past, including EPA Regional support contracts and EPA headquarters contracts with the Office of Research and Development; Office of Wastewater Management; and Office of Wetlands, Oceans, and Watersheds. He has also been project QAO on numerous task orders and work assignments under these contracts, as well as contracts for EPA's Office of Science and Technology, and supporting state and local municipalities.

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