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Green/Duwamish River Watershed Pollutant Loading Assessment

February 2020

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EAP: Environmental Assessment Program

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2.0 Abstract

The Green/Duwamish River watershed is identified on Washington's 303(d) list as being impaired for over 50 different pollutants (including toxic and conventional parameters) under the Clean Water Act (CWA). Portions of the study area are also on the National Priorities List 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.

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.

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.

The purpose of the PLA is to address water, sediment, and tissue quality impairments (i.e., 303(d) listings under the CWA) in the Green/Duwamish River watershed, including the LDW, as appropriate, to attain designated uses. It is a tool for evaluating the effectiveness of sediment cleanup and associated source control efforts in meeting water quality standards. It is also designed to predict bioaccumulation of pollutants in the food web.

This project was initially developed by Tetra Tech under the contract with EPA. Due to the discontinuance of funding from EPA, Ecology has taken over and led the modelling team since 2018. This Quality Assurance Project Plan (QAPP) is built upon the previous PLA QAPP (Tetra Tech, 2016) and model development publications developed by Tetra Tech. This QAPP provides updates to the toxic modeling parameters and the approach for the watershed and the receiving water modeling. The project team expects an update to this QAPP again in the future to specify the management scenarios for the receiving water model and the modeling approach for the food web model.

3.0 Background

3.1 Introduction and problem statement

The Green/Duwamish River watershed provides habitat for wildlife, birds, and fish, including three fish species listed as "threatened" under the Endangered Species Act: Puget Sound Chinook, Puget Sound Steelhead, and Bull Trout. The Green/Duwamish River watershed includes the land surrounding the Green River and the Duwamish River, as well as the land surrounding all of the tributaries that drain to the Green and Duwamish Rivers, including Hamm Creek, Black River, Springbrook Creek, Mill Creek, Soos Creek, Crisp Creek, Newaukum Creek, and Christy Creek and their tributaries.

The lower five miles of the Duwamish River, known as the Lower Duwamish Waterway (LDW), is now largely an engineered channel. Decades of industrial activity in the lower watershed have contaminated portions of the surface water, groundwater, soil, and sediment with a variety of pollutants. Remediation of contaminated groundwater, soil, and sediment is being planned, is under way, or has been completed at numerous locations along the LDW under the supervision of federal and state authorities. A large-scale Superfund in-waterway cleanup, involving sediment dredging, capping, and other remediation techniques, will occur over the next ten years in the lower five miles of the river.

In contrast to the site-specific focus of state and federal cleanup programs, the Clean Water Act (CWA) looks broadly at the cumulative water quality effects of pollutants on impaired watersheds. This CWA requirement is implemented through a series of steps, beginning with development of state water quality standards. Water quality standards establish the "uses" of a waterbody and commonly include fishing, shellfish harvesting, swimming, and the ability to support aquatic life. Each state adopts criteria to protect the designated uses. CWA Section 303(d) requires that states identify those waterbodies where the water quality criteria (and therefore the "uses") are not being met. This list of impaired waters is referred to as the 303(d) list.

Washington Department of Ecology (Ecology) has identified impairments in the water column, fish tissue, and sediment in the Green/Duwamish River watershed. While the in-waterway cleanup and source control efforts will substantially improve the quality of LDW sediments and surface water, and reduce the seafood consumption risk by about 90%, some CWA-based impairments may remain following the LDW cleanup. Both the U.S. Environmental Protection Agency (EPA) and Ecology recognize the need for a scientific approach that can predict short and long-term improvements in water and sediment quality, and can subsequently predict the level of contamination in fish tissue over time, as different cleanup and restoration scenarios are implemented.

State and federal actions to clean up historical contamination and to restore water quality in the Green/Duwamish River watershed are complimentary efforts aimed at a common goal: protecting human health and the environment. Remediation of contaminated sediments, soil, and groundwater in the LDW will help restore water quality, while reduction of pollutant loading throughout the watershed will help protect sediment quality and aquatic habitat in the LDW. Ultimately, successfully integrating state and federal efforts to improve both water and sediment quality will make the most progress toward attaining designated uses, including reducing the bioaccumulation of toxics in the food chain.

The purpose of this report is to outline a proposed comprehensive and quantitative geographically-based pollutant loading assessment (PLA) tool for the Green/Duwamish River watershed, the essential elements of which are described below. A considerable amount of monitoring, modeling, cleanup and restoration work has already been done by local governments, interested parties, and regulatory agencies (e.g., Ecology, 2012b; AECOM, 2012a). This report identifies these previous and ongoing efforts, and is designed to incorporate these efforts into a proposal for future work in a way that best represents the complex dynamics of the Green/Duwamish River watershed.

The PLA modeling approach consists of a linked watershed/receiving water/food web modeling system describing hydrology, hydraulics, hydrodynamics, and pollutant loading in the Green/Duwamish River watershed. The PLA tool will represent sediment transport processes, such as sediment buildup, washoff, resuspension and sedimentation, as well as the dominant processes affecting the pollutant fate and transport throughout the watershed. The original proposed components include a Loading Simulation Program - C++ (LSPC) watershed model, the Environmental Fluid Dynamics Code (EFDC) receiving water model, and the Arnot and Gobas food web model (FWM). The watershed modeling component was changed to the Hydrologic Simulation Program - FORTRAN (HSPF) following recommendations of the project team (details of the model conversion are described in Section 7).

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 required load reductions from various sources in the watershed to address impairments in the receiving waters.~~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), 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.

3.2 Study area and surroundings

The Green/Duwamish River flows for over 90 miles from the Cascade Mountains before discharging into Elliott Bay near the City of Seattle in northwest Washington State. This drainage, which makes up most of Water Resource Inventory Area (WRIA) 9, includes the direct lateral flows to the LDW, and represents the complete study area. Modeling of the watershed and LDW is proposed at two general scales for the PLA: the LDW receiving water and the Green/Duwamish River watershed. The approach is designed to address sources throughout the Green/Duwamish River watershed that affect water, sediment, and tissue quality in the LDW, address the CWA 303(d)-listed impairments throughout the watershed, and minimize post-cleanup recontamination of sediments in the LDW. The geographic scope is discussed and illustrated below for both the LDW and the Green/Duwamish River watershed.

The LDW is of particular interest for this PLA as it is the focus of many source control and sediment cleanup efforts. It is a five-mile, 441-acre waterbody located at the terminus of the Green/Duwamish River watershed. The LDW is defined as the stretch of water between the turning basin near S. 102nd Street Bridge and the southern end of Harbor Island (Figure 1). It is a stratified saltwater wedge estuary affected by both tidally-influenced Puget Sound saltwater and freshwater inflows from the Green/Duwamish River watershed. It is a navigable waterway and supports associated boat traffic and robust industrial commerce. Additionally, the waterway serves as a migratory pathway for numerous fish, including the threatened Puget Sound Chinook salmon and bull trout. Several neighborhoods are also located nearby (South Park and Georgetown), with a mix of residential, commercial, recreational, and industrial activities.

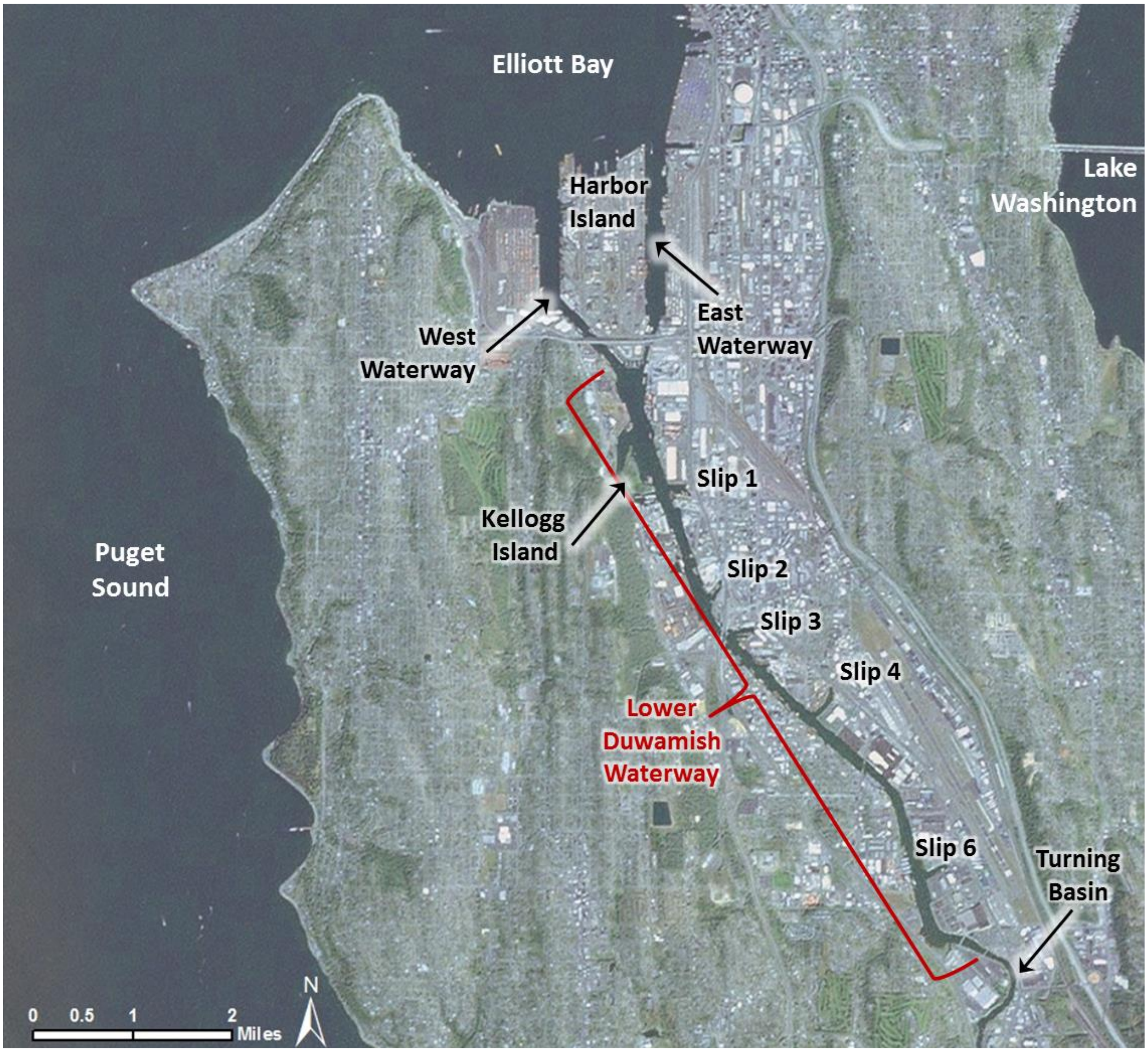

Figure 1. Extent of the Lower Duwamish Waterway

The LDW is at the mouth of the Green/Duwamish River watershed. Consistent with geographic information system (GIS) layers from King County, the Green/Duwamish River watershed area has been divided into four primary subwatersheds for consideration:

- *Duwamish Estuary* from Elliott Bay/Harbor Island to river mile (RM) 11.0 at Tukwila near the confluence with the Black River (22 square miles of industrial and residential areas; includes lateral loading to portion of the Duwamish River downstream of the Black River as well the LDW);
- *Lower Green River* from Tukwila (RM 11.0) to Auburn Narrows (RM 32.0) (nearly 64 square miles of residential, industrial, and commercial land uses);
- *Middle Green River* from Auburn Narrows (RM 32.0) to the Howard Hanson Dam (RM 64.5) (nearly 180 square miles of residential, forest, and agricultural land uses); and
- *Upper Green River* from the Howard Hanson Dam to the headwaters (220 square miles of mostly forested land).

Tributaries in these subwatersheds include the Black River, Mill Creek, Soos Creek, Newaukum Creek, and many other smaller creeks.

The LDW, the receiving waterbody of primary concern, is located within the Duwamish Estuary subwatershed. Direct loading from this subwatershed to the LDW and additional combined sewer overflow (CSO) loading from the sewershed will be considered in this technical approach along with the comprehensive loadings from sources in the three upstream subwatersheds (Lower, Middle, and Upper Green subwatersheds). This watershed-based geographic representation allows for quantification of all sources associated with LDW and other Green/Duwamish River watershed impairments and accounts for the connectivity to Elliott Bay. Loadings from the land or direct discharges to the East and West Waterways will also be included into the technical approach as they impact conditions in the LDW via tidal processes. Ultimately, the connection to downstream receiving waters streamlines expansion of the approach to address impairments in the East and West Waterways as well as Elliott Bay in the future; however, specific details on other cleanup efforts in and around these waterbodies will not be included in this QAPP.

3.2.1 History of study area

The Green/Duwamish River watershed, located partially in Seattle, Washington, has historically provided habitat for fish, birds, and wildlife with its marshes and mudflats, but development has increasingly stressed the lower region of the basin and reduced the natural environment. In the 1890s, raw sewage and stormwater emptied into the Duwamish River, Elliott Bay, and Puget Sound. In the early 1900s, with the expansion of waterway commerce, industrial development and pollutants associated with this waste were also introduced to these waterbodies. During this time the estuary tidelands were filled in and the river was modified to serve the growing industrial and port activities.

The downstream area, known as the Lower Duwamish Waterway (LDW), is now a largely engineered channel. Conditions subsequently deteriorated; however, the 1960s saw increased environmental awareness and action, with treatment plants being required to address industrial effluent and sewage. Contaminated soil, groundwater, and sediment remediation efforts are being conducted along with habitat restoration. Since the turn of the century, regional agencies have emphasized current and future actions, with both sediment investigation and cleanup as well as source control activities. Considerable resources have been utilized to characterize and prioritize these cleanup, restoration, and source control efforts.

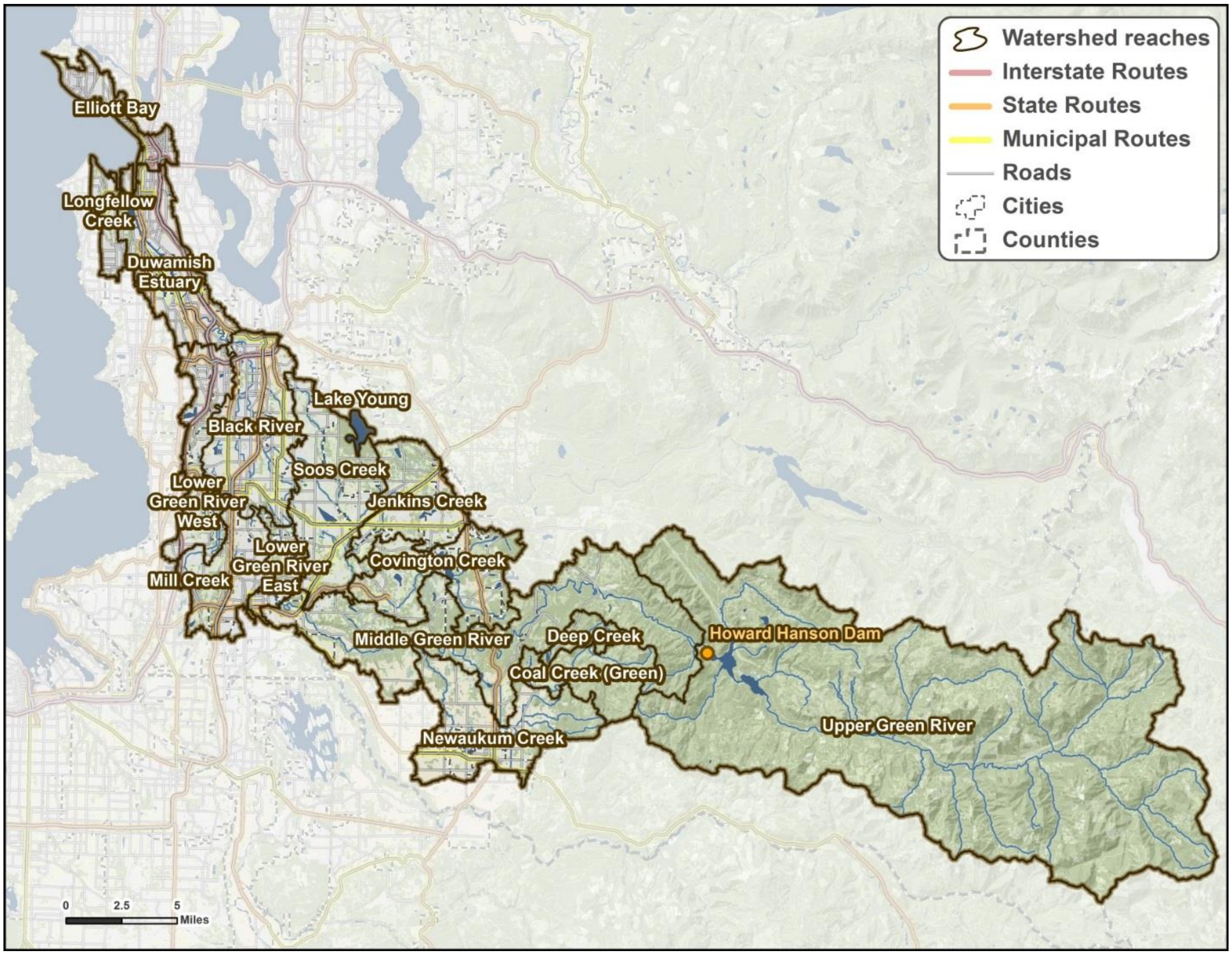

Figure 2. Green/Duwamish River watershed

3.2.2 Summary of previous studies and existing data

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 June 2015, Tetra Tech provided a technical memorandum that documented their findings on Green/Duwamish River Watershed PLA data gaps and pollutant groupings (Tetra Tech, 2015b). In this memo, Tetra Tech provided a discussion on pollutant behavior and grouping recommendations for candidate pollutants and data or knowledge gaps for the PLA model construction and source attribution.

In June 2016, Leidos developed the Green-Duwamish River Watershed PCB Congener Study Phase 1 report for Ecology's Toxics Cleanup Program (Leidos, 2016). The report provided a concise summary of available information on PCB congeners and Aroclors and identified important issues to consider when evaluating historical PCB congener and/or Aroclor data or when collecting new data. In addition, this report compiled available PCB congener data in the Green-Duwamish watershed including any available information on data quality. This provided a basis for the Water Quality Database for the watershed.

In July 2016, Tetra Tech published the first version of the QAPP under contract with EPA (Tetra Tech, 2016). That QAPP provided a general description of the modeling and associated analytical work that Tetra Tech would perform for the project, including following data quality objectives (DQOs) and quality control (QC) procedures to ensure that the final product satisfies EPA requirements. That QAPP also addressed 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.

In February 2017, Tetra Tech documented the development and calibration of hydrologic simulation models for the Green/Duwamish River watershed in a LSPC model development and calibration memo (Tetra Tech, 2017). The memo describes the model setup procedures and data sources, including information on subbasin and reach delineation, development of upland hydrologic response units and calibration of the model for hydrology.

In June 2017, Leidos completed Phase 2 of the PCB congener study, funded by Ecology (Leidos, 2017). This study identified the types of contaminant sources that are contributing to the PCB pollution in the Green/Duwamish River and the LDW using multi-variate statistical techniques. It provided recommendations about which PCBs to model in the PLA and found that the most abundant homologs across water, sediment, and biota compartments are the tetra-, penta-, hexa-, and hepta- homologs.

In March 2018, Tetra Tech converted the LSPF model back to HSPF under the direction of the project team and documented the changes in the Green/Duwamish River Watershed HSPF models memo (Tetra Tech, 2018). The memo includes model platform conversion, temporal extension, delineation and hydraulic refinements, and the addition of the sediment simulation.

In April 2018, Leidos developed a Green/Duwamish Watershed Water Quality Database to support the PLA (Leidos, 2018). The database was created based on an existing database previously developed by Leidos. This task also provided an early look at the spatial/temporal patterns and gaps in the data during the modeled time window.

The PLA is being developed 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.

3.2.3 Parameters of interest and potential sources

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.

Based on the discussion with the project team, all the compliance end points (including the water quality and sediment standards) will be based on total PCBs, which is the sum of all congeners. The modeling team proposed to simulate total PCBs and use the physico-chemical properties from a selected group of homologs, which are groups of PCB congeners with the same number of chlorine atoms in the molecule. The selected groups of PCB homologs considered for modelling included tetra, penta, hexa, and hepta. This is the only change from the original list of candidate chemicals included in the previous QAPP (Table 1).

Table 1. 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.	Simulate Total PCBs and use the physico-chemical properties from the selected group of homologs (tetra-, penta-, hexa-, and hepta-homologs) for modeling.
Carcinogenic PAHs (cPAHs)	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.)
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 and use as a surrogate.
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.

3.2.4 Regulatory criteria or standards

Numerous targets exist for several different media in the LDW and the contributing watershed. Ongoing and future cleanup and source control efforts to address water column, sediment, and tissue contamination can be supported by the technical approach described in this QAPP. A properly designed and applied technical approach provides a source-response linkage and enables estimation of existing and potential future loadings, as well as the distribution of loads among sources and pathways. The estimated loadings will be used as indicators for the attainability of designated uses. The technical approach must enable direct comparison of model results to in-stream water, sediment, and tissue concentrations. Scenarios that simulate reductions associated with sediment cleanup, source control, and regional toxics reduction efforts can be run, evaluated through time, and compared to the various water and sediment targets by changing input values for different model parameters. Food web bioaccumulation modeling will be performed to evaluate the relationship between water and sediment targets with tissue concentrations in aquatic life. For the watershed and receiving water loading analyses and for future implementation activities, it is also important that the framework enables examination of point-source and land use loadings as well as in-stream concentrations.

4.0 Project Description

In this section, both the project goals and objectives will be discussed. The differences between the project goals and the objectives are: the project goals describe the intended use of the tools developed by the project team and what are the goals will be achived through the use of the tools; the project objectives are the what kind of tools will be develop to achieve the goals including the requirement of the tool capability and questions that will be addressed.

As described earlier, the PLA utilizes a group of three linked modeling tools: the watershed model, the receiving water model, and the food web model. This QAPP addresses the detailed modeling objectives and management scenarios for the watershed model and these are provided below. The project team will provide detailed modeling scenarios for the receiving water model, and background and calibration information regarding the food web model in future QAPP revision.

4.1 Project goals

4.1.1 PLA project goals

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

- Address CWA 303(d) listings related to water, bed sediment, and tissue concentrations.
- Protect investment in LDW cleanup (limit 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.

~~As described earlier, the PLA utilizes a group of three linked modeling tools: the watershed model, the receiving water model, and the food web model. This QAPP addresses the detailed modeling objectives and management scenarios for the watershed model and these are provided below. The project team will provide detailed modeling scenarios for the receiving water model, and background and calibration information regarding the food web model.~~

4.1.2 Watershed modeling goals

Watershed modeling will assess the effectiveness of potential mitigation strategies meant to reduce contaminants within the Lower Duwamish Waterway and support clean water and a healthy habitat within the contributing watersheds. The modeling framework will support the needs as presented by stakeholders in the Green/Duwamish River watershed and the LDW. These needs are multifaceted and have evolved over time as the sources of contamination and their impacts on the habitat and aquatic life health are better understood.

The watershed modeling framework is designed using four themes:

(1) Leverage past efforts as appropriate to support a cost-effective process

[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).

(2) Integrate with current complementary modeling efforts (internal and external to the project)

(3) Provide the necessary tools to characterize a highly complex physical landscape in a simpler quantifiable way

(4) Be adaptable to allow for future assessments

The final selection of using a watershed modeling framework based on U.S. EPA's *Hydrologic Simulation Program-FORTRAN* (HSPF) supports all four themes described above.

4.2 Project objectives

4.2.1 PLA project objectives

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 must be capable of assessing the pollutant contribution of a specific point or ~~distributed~~ non-point source to the total pollutant water concentration, which will allow determination of each source's load contribution to the total load. In general, the tool will be used to assess source load reductions needed to reach CWA water, sediment, and tissue quality criteria. For example, the tool could 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; to evaluate and improve the effectiveness of the sediment remedial action; and address and predict CWA water, sediment, and tissue quality impairments in the Green/Duwamish River watershed, including the LDW. The assessment tool can also help identify required load reductions from various sources in the watershed and the receiving waters to address impariments; 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.

4.2.2 Watershed modeling objectives

4.2.2.1 Watershed modeling questions

Objectives are largely driven by the questions being asked. The substance of the questions helps define what types of data are needed, the extent of the data, the spatial and temporal resolutions, as well as the physical processes and mechanisms. These are discussed in the next section.

Below are a series of questions the modeling team will consider, most of which have been developed by stakeholders in the Pollutant Loading Assessment project.

(1) What is the contribution of a contaminant from an identified point source (or sources) in the watershed?

(2) What is the contribution of a contaminant from different land uses that are non-point sources?

(3) What is the contribution of contaminant loadings coming from above Howard Hanson Dam versus downstream sources?

(4) What is the atmospheric contribution of a contaminant to the receiving waterbodies?

(5) What is the contribution of a contaminant from groundwater?

~~(6) What is the contribution of pollutants from bank erosion in the watershed?~~

~~(7)~~(6) What would be the minimum reduction of non-point loadings in the watershed to achieve the stated goals in the LDW?

~~(8)~~(7) Can we model multiple pollutants at once?

~~(9)~~(8) How do lakes/wetlands influence the fate and transport of the pollutants?

~~(10)Will climate change amplify pollutant generation?~~

~~(11)~~(9) What is the rank of pollutant contribution among point sources and non-point sources?

~~(12)~~(10)What are the different methods of treatment that might be modeled?

4.2.2.2 Watershed modeling objectives

The watershed model integrates atmospheric conditions, the physical landscape, and how pollution sources vary over time. The design and development of the watershed modeling will need to achieve three objectives:

(1) Provide boundary conditions for LDW modeling and analyses

(2) Characterize the watershed to estimate loadings from pollutant-generating sources and to identify and quantify the pathways pollutants take ~~the pathways pollutants can take~~

(3) Evaluate the effectiveness of proposed mitigation strategies, such as permitting, CSO control, building materials removal, variety of BMPs and etc..

Specifically, the modeling will fill data gaps in space and time that are not feasible to be filled through monitoring and will support evaluation of outcomes from possible future actions that cannot be measured in the present.

Results from the modeling will also help identify reductions in loading necessary to achieve target conditions for environmental protection in the LDW.

The modeling capabilities and objectives are separated into several categories including pollutants evaluated, study geographic area/spatial scale, characterizing land use/cover impacts, hydrology and hydraulic inputs, atmospheric inputs, pollutant transport and fate features, and boundary conditions. These categories are discussed in more details~~sed~~ below.

4.2.2.2.1 Pollutants to be evaluated

The model will evaluate suspended sediment and sediment-associated contaminants. Suspended sediment is distributed into three fine grained sediment classes—one non-cohesive (sand) and two cohesive (silt and clay). Partition coefficients and sorption rates are adjusted based on characteristics associated with those grain sizes and covalence interactivity with the contaminants of concern. Contaminants of concern to be evaluated in the model include:

- PCBs, using a weighted average coefficient for a set of congeners of interest
- PAHs, simulating a surrogate representative of a set of PAHs of interest
- Arsenic, simulated as a generalized constituent
- Zinc, simulated as dissolved and sorbed forms
- Copper, simulated as dissolved and sorbed forms

Additional simulated constituents to be included:

- Water temperature
- Organic Carbon, simulated as particulate and dissolved forms
- Hardness, simulated as a conservative parameter

4.2.2.2.2 Geographic area and spatial scale of study area

Analyses of model outputs can be readily performed at the catchment scale (i.e., at the outlet of any individual catchment or an aggregate thereof) but can include point sources when sufficient information is known and/or estimated.

The watershed basins to be modeled include the Green and Duwamish River watersheds. The model study area starts just below Howard Hanson Dam (which represents the water conditions leaving the upper watershed above the dam and continues downstream, including lateral areas draining to the Lower Duwamish Waterway.

Defined catchment areas included in the model generally range in size from a couple of hundred acres to several thousand acres. Simulated outputs will be available for each of these catchment areas.

4.2.2.2.3 Characterizing impacts of land cover and land use

Pollutant loadings are affected by land use type. Stormwater runoff and pollutant loadings can be evaluated under various types of land use conditions. The model development will account for watershed areas according to different land use and drainage characteristics. The model will be set up for existing conditions but can be adjusted to evaluate the effects of alternative land cover and land use scenarios, as needed.

Current land cover and land use conditions are derived from satellite imagery collected in 2007. Watershed model categories include ten types of land use. Those categories are then partitioned into pervious and impervious land surfaces. Non-pollutant-generating impervious surfaces (i.e., roofs) are separated from pollutant-generating impervious surfaces (e.g., roads, driveways, hardened surfaces, etc.). In the Lower Duwamish Watershed, the model will reflect the fact that much of the land use is serviced by a combined sewer-stormwater collection system.

Land use inputs will be adjusted for specific geographic areas, because the same land use type may have different loading rates in different basins.

4.2.2.2.4 Hydrology and hydraulics

Measures of water quality that are time-dependent (e.g., established chronic and acute concentration thresholds, etc.) can be applied to simulated flow rates for the contaminants of concern. The model's temporal resolution will support analyses where durations of exposure are relevant.

Simulated hourly continuous flow rates will be available at the outlet of every defined catchment in the watershed model. If other locations become of interest, simulated outputs could be generated (possibly with some limitations) for further analyses.

4.2.2.2.5 Atmospheric inputs

Impacts from atmospheric deposition of pollutants will be evaluated in watershed modeling results. Atmospheric loadings can vary spatially and temporally and will account for specific land use categories.

Atmospheric inputs are specifically defined by the user and assumed to occur continuously at varying rates regardless of rainfall and can be defined for any time scale (e.g., hourly, weekly, monthly, etc.). Background concentrations generated from atmospheric loadings can be compared to land use activity loadings generated during stormwater runoff.

4.2.2.2.6 Pollutant transport

Stormwater runoff and pollutant loadings are simulated to be transported from the source to elsewhere using three possible pathways of transport over the land surface:

(1) Fast response - rain falling on the land surface runoff that flows directly to ditches, streams, stormwater collection systems, etc.

(2) Moderately fast response - rain falling on the land surface that infiltrates into shallow subsurface soils and reemerges in nearby receiving ditches, streams, etc., and

(3) Slow response – infiltration of rain falling on the land into groundwater and taking hours, days, or weeks to reemerge in nearby waterbodies (streams, lakes, rivers).

4.2.2.2.7 Pollutant fate

The fate of pollutants will be simulated according to their charateristics: (1) pollutants that bind to and unbind from sediment in the water column and/or stream bed, (2) pollutants that remain in solution and decay over time, and (3) pollutants that are largely non-reactive, such that mass is conserved as the pollutant is transported downstream.

4.2.2.2.8 Boundary conditions

The watershed model will generate lateral inputs for use in the receiving water body model for waters adjacent to the watershed study area.

As previously mentioned, the upper boundary of the study area starts at the downstream side of the Howard Hanson Dam (HHD). This is thus the upstream boundary of the watershed modeling network. For every simulated watershed parameter to be included in the receiving water body model, there will be a need to develop a corresponding time series input into the watershed model based on HHD outflows.

4.2.2.2.9 Summary of objectives

For the LDW, sources of simulated watershed loading rates into the LDW are from the upstream boundary conditions in the Green River water column and from adjacent lateral inputs that are generated from stormwater runoff and from shallow subsurface and groundwater fluxes.

The stormwater runoff loading rates will be based on a build-up and wash-off method and will be tailored to land use and geographic location. Transport of the pollutants will include instream processes associated with deposition and resuspension of particulates in sediments. Potential source control actions can be applied to stormwater runoff upstream in the watershed and adjacent to the LDW to evaluate the effect on LDW of reductions in pollutant loading rates.

Lateral watershed model subsurface flows into the LDW include fluxes of flow rates and loading rates for contaminants of concern. The two pathways for subsurface flow are shallow subsurface inflows assumed to reemerge along the banks of the LDW and the active groundwater that interacts with the river bed. The loading rates are user specified and can be adjusted to fit observed concentrations within the water column.

Atmospheric loadings will be discretely evaluated to identify the relative contribution of pollutant loading to the LDW.~~Rates of atmospheric loadings of pollutants onto land will likely be applied as two distinct time series: higher loading rates for land within the LDW basin and lower rates for land in the Green River basin. The relative importance of background atmospheric loading rates can be compared to what is generated from stormwater and subsurface contributions.~~

Combined sewer-stormwater systems within the LDW basin are separate from other sources to the LDW and will be evaluated separately.

4.3 Information needed and 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 surface water quality data will present a more substantial challenge than gaps in flow data.

The model development process will be conducted in phases, beginning with the hydrology and hydrodynamic modules of HSPF 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 (from within the period 1996-2017), 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.

4.3.1 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 those data previously collected under efforts outside the current project that are used for model development and calibration. Table 2~~Table 2~~ 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 2. Primary sources of key secondary data

Data Type	Primary Sources
Watershed Model (HSPF)	
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)
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
Receiving Water Model (EFDC)	
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 HSPF CSO models/monitoring

Data Type	Primary Sources
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.

4.3.1.1 Watershed model

4.3.1.1.1 Flow data

Reliable streamflow data are important to watershed model development, 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 gauge data, which 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 3~~Figure 3~~ shows the spatial distribution of the 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, PLA modeling team will review the relevant QA protocols and document the results in the project report.

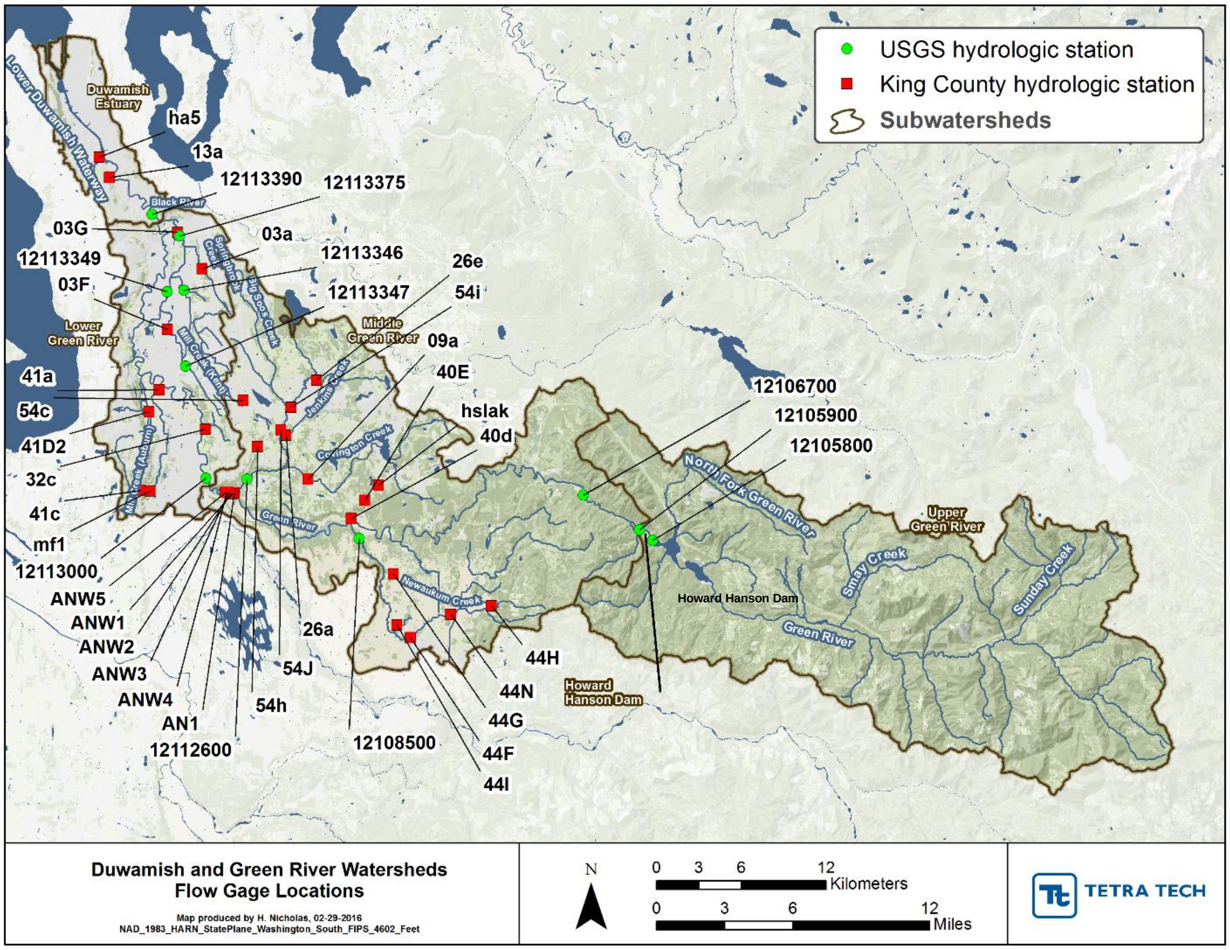

Figure 3. USGS and King County hydrology calibration stations in the study area

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 the total amount and seasonal patterns correctly. The NASA/EOS monthly MOD16 Global Terrestrial Evapotranspiration Data Set will be compared to the HSPF simulated total evapotranspiration.

4.3.1.1.2 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.

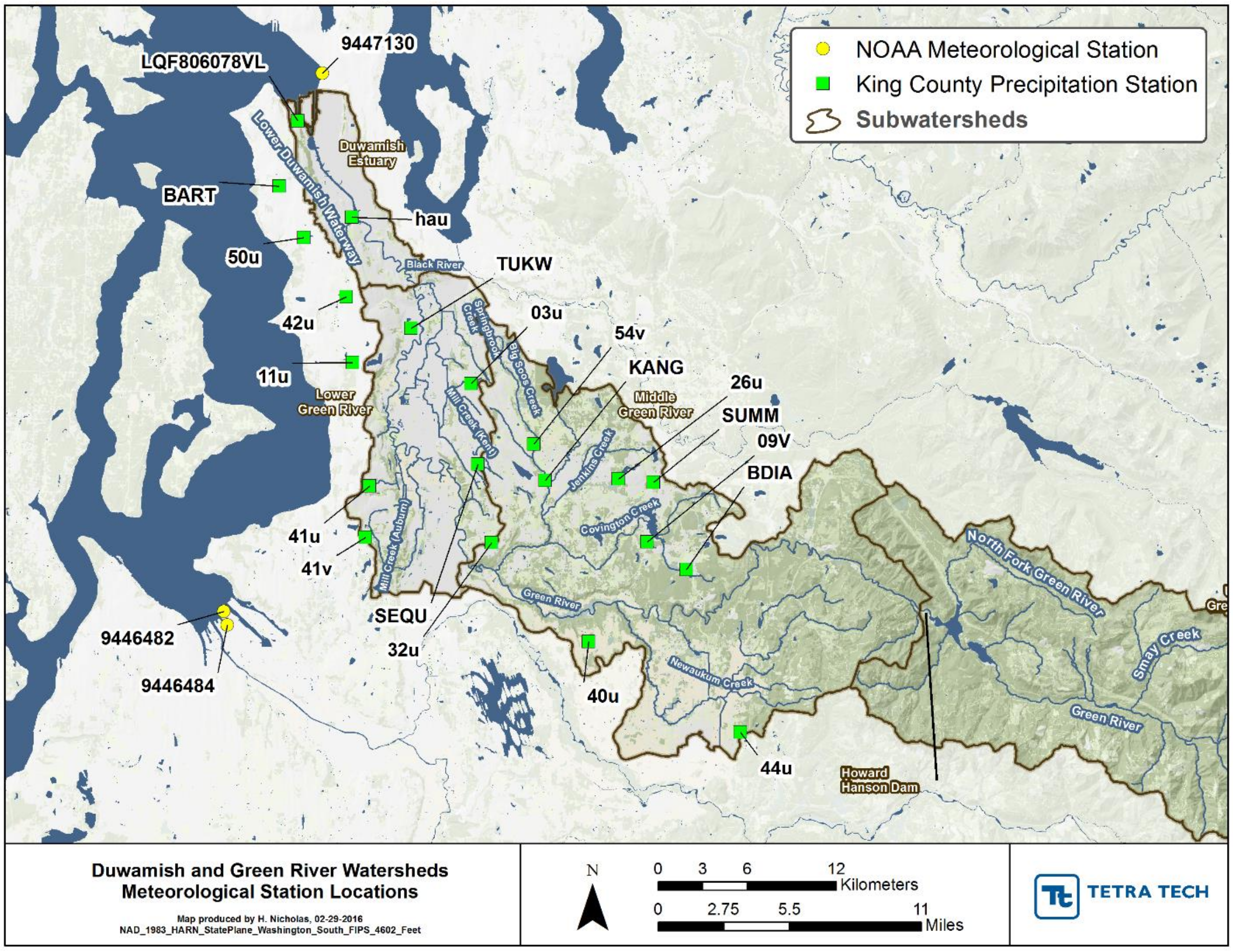

Figure 4. Precipitation and meteorological stations in the Green/Duwamish watershed

Figure 4 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 Green/Duwamish 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 North American Land Data Assimilation System (NLDAS) also provides 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 HSPF domain.

4.3.1.1.3 *Water quality observations*

Tetra Tech 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 in Table 3.

Table 3. Summary table of data sources by parameter

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, 2016) King County (2015) King County (2018) 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)	King County (2013c)

Parameter	Surface Runoff/Shallow Groundwater *	Atmospheric Deposition *
	Ecology (2015)	Ecology (2010)

* Leidos (2014) provides a compilation that contains 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, first by tributary subwatershed and then by the main sections of the mainstem of the Green River (e.g., Upper, Middle, Lower). Table 4~~Table 4~~ 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 4. Summary of data sources by parameter and watershed area used in 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)

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

4.3.1.1.4 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.

4.3.1.1.5 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 NPDES stormwater 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 do 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 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 7.3.2.1.5. 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.

4.3.1.1.6 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 Units (HRUs) developed based on 2007 land use/land cover, the PLA team modelers will begin with these and update them 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 the U.S. Department of Agriculture (USDA).

4.3.1.1.7 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 depositions 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 wet and dry depositions, 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.

4.3.1.2 Receiving Water (EFDC) Model

4.3.1.2.1 Model grid

The proposed EFDC model will be developed using the grids from the existing models with an upstream extension (refer to 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.

4.3.1.2.2 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 4~~Figure 4~~. 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 HSPF model developed for this work.

4.3.1.2.3 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. **Error! Reference source not found.**~~Figure 5~~ 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 from 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. HSPF watershed model results will be used to represent tributary inflow boundary conditions.

4.3.1.2.4 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 the implementation modeling effort. The upstream water temperature boundary condition will be provided by the HSPF 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.

4.3.1.2.5 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) developed a detailed quality assured database of PCB congener data. It is expected that additional data will be collected if there is any need in the initial stages of model development.

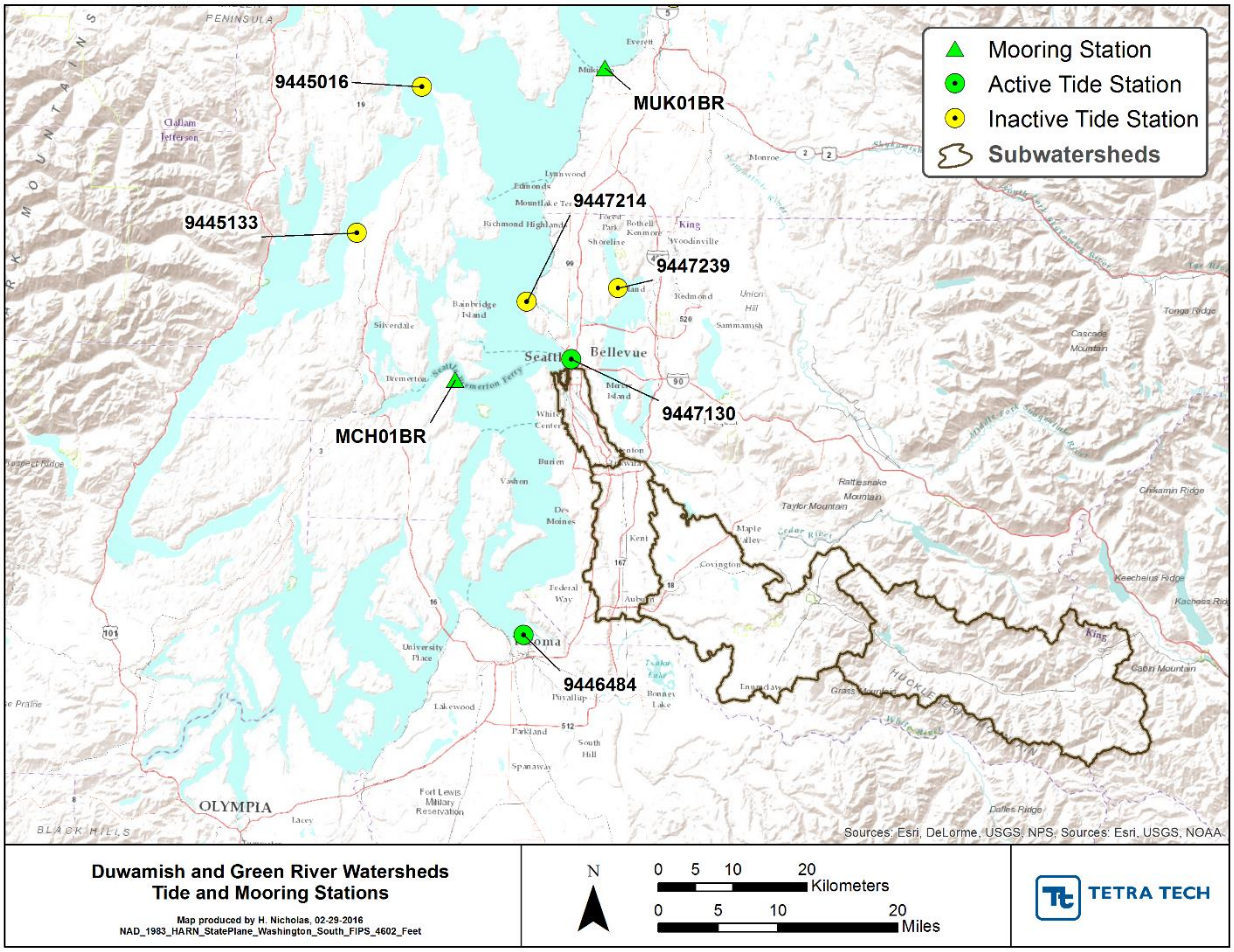

Figure 5. Tide and current stations in the study region

4.3.1.2.6 Point source discharges

There are two types of point sources in the watershed: 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 HSPF framework. Figure 6~~Figure 6~~ 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 (the modeling team will obtain City and County data of flow and concentration for CSOs). For the drainage areas where runoff enters the stormwater pipes or the LDW directly, HSPF 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.

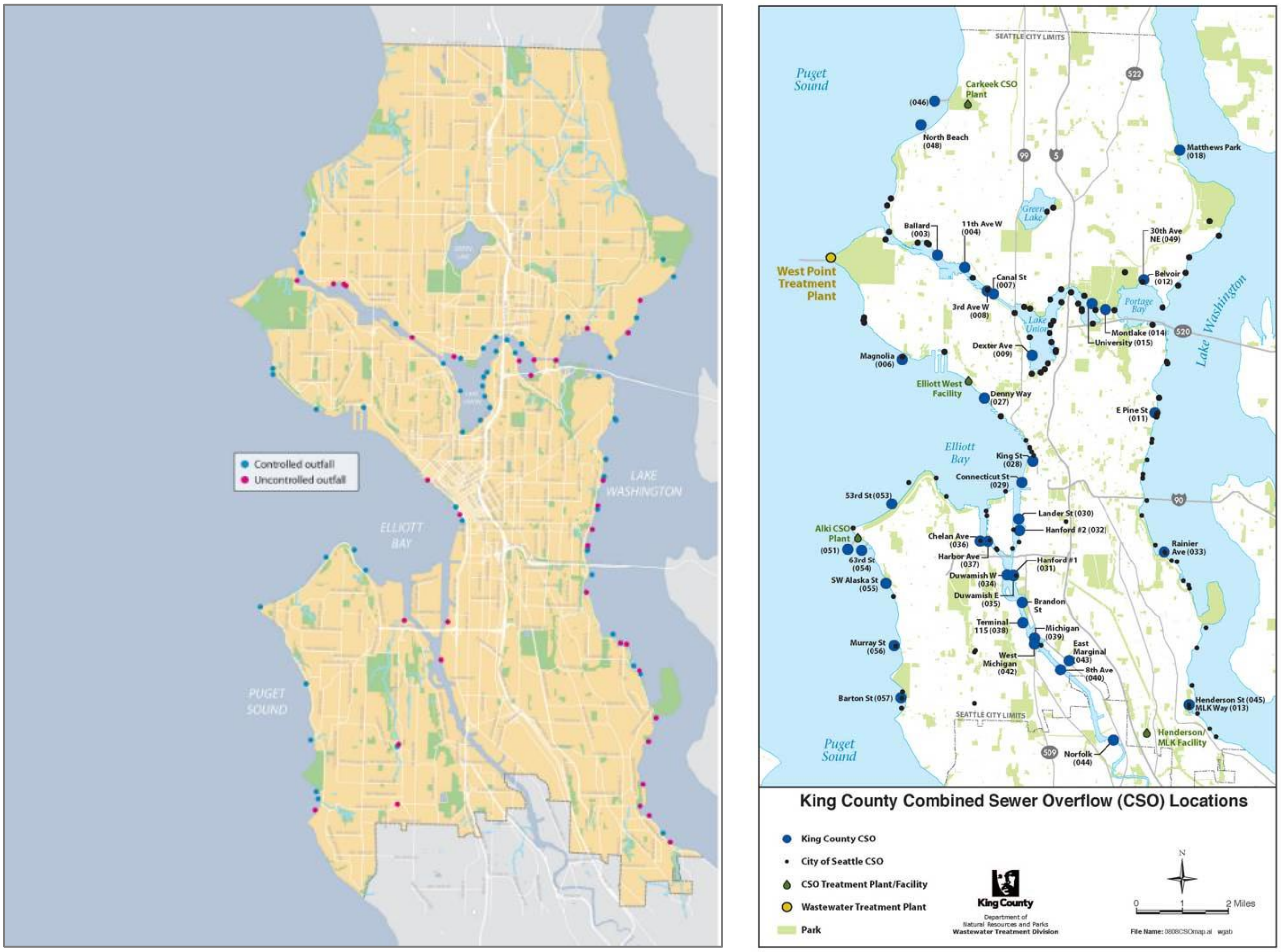

Figure 6. CSO maps for City of Seattle and King County.

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.

4.3.1.3 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 FWM. 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 5~~Table 5~~). Additional data may become available through ongoing data collection efforts.

Table 5. Tissue data in the EIM

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

4.3.2 Model data gaps and methods to address them

Initial parameter-specific data gaps were discussed in PLA data gaps and pollutant groupings memo (Tetra Tech, 2015). Building on these, model-specific gaps are discussed below.

4.3.2.1 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 include 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 the 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, are not considered a significant gap at this time.

Development of a watershed model can proceed with all of the prioritized parameters. While data are 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 6~~Table 6~~.

Table 6. 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

Knowledge Gap	Options and Selected Approach
	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. Expand effort to improve calibration Selected Approach: Option 2 is selected. As movement of sediment is key to the movement of sediment/solids-sorbed pollutants, effort should be expanded to improve the existing TSS calibration.

4.3.2.2 Receiving water 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 fewer 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 filling these gaps may be challenging. The ideal data set would contain spatially and temporally contemporaneous measurements of concentrations in all media. Additional data sets may be obtained 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, bioturbation, 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 guidance as to the need for new data collection. If new data are 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 7. 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. The project team 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 during receiving water modeling 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. Selected Approach: Existing HSPF models are calibrated for flow and suspended sediment. Develop the upstream loading with a combination of these models and

Data and Knowledge Gap	Options and Selected Approach
	existing data; continue collection of new data to fill knowledge gaps for HSPF 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 in the model, based on resource availability. Initial model development will greatly assist in determining the cost benefit ratio of specific types of data collection.

4.3.2.3 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 applying the FWM to 2007 fish data suggests a certain model limitations or EFDC linkage issues 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 sediment resuspension and 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~~updated EFDC model that simulates the responses to varying flow and loading conditions over time, to effectively simplify the processes, a steady-stateassumption can be made to approximately represent long period water column conditions, thus, the long-term water column EFDC averages will be used as the steady-state model concentration inputs. ~~Obtaining additional quantitative data on dietary sources of individual species and pollutant concentrations in prey species would likely improve the model performance.~~As a test case, additional quantitative data on dietary sources of individual species and pollutant concentrations in prey species can be incorporated into the model to evaluate the 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 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 8. 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. 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. 2. Rely on existing data. Selected Approach: Rely on existing data (Option 2), but supplement prior FWM effort by soliciting additional information from wildlife and university sources.

Knowledge Gap	Options and Selected Approach
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.

4.4 Tasks required

The step-by-step tasks for watershed modeling include following:

1. Set up boundary condition.
2. Model input pre-processing including data assessment and analysis.
3. Generate model input.
4. Model calibration.
5. Run model scenarios.
6. Model output post-processing and analysis.

The step-by-step tasks for receiving water modeling include:

1. Set up upstream boundary, downstream open boundary, and initial conditions.
2. Model input pre-processing including data assessment and analysis.
3. Model linkage with watershed and other simulation results.
4. Generate model input.
5. Model calibration and validation.
6. Run model scenarios.
7. Model output post-processing and analysis.

4.5 Systematic planning process used

EPA and Ecology began planning for the Green/Duwamish River PLA in 2013. Initial work was focused on 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. The agency steering committee has regular meetings to discuss tasks and progress.

Also in late 2014, EPA and Ecology established a Technical Advisory Committee (TAC) and an Interested Parties group to help inform the development of the PLA. Both groups include a range of participants (e.g., government, non-government organizations, academic institutions, community, and consultants) and provide a means for key technical stakeholders and the general public to offer input to the Agency Steering Committee on the PLA development. The TAC meets at milestones to review technical issues and to provide input to technical decision points. The Interested Parties group meets less frequently, primarily for updates and general input, and is open to all stakeholders and members of the public.

Like the previous QAPP approved by the EPA, this QAPP reflects input from stakeholders at decision points such as decisions about the contaminants of concern, the type of model to be employed, questions to be addressed by monitoring, and other decisions related to model development.

5.0 Organization and Schedule

5.1 Key individuals and their responsibilities

Table 9 lists the individuals involved in this project. They include Ecology and USEPA Region 10 staff and modelers from King County.

Table 9. Organization of project staff and responsibilities

Staff	Title	Responsibilities
Bo Li Industrial Unit Ecology NWRO Water Quality Section Phone: 425-649-7284	Project Manager	Directs and manages project and modeling team. Helps write and reviews QAPP. Writes the draft project report and final report.
PLA modeling team Yi Xiong, Ecology Kevin Schock, King County Jeff Burkey, King County	Principal Investigators	Write and review QAPP. Conduct QA review of existing data and analyzes and interpret data. Develop model inputs. Assess model performance, conduct sensitivity analyses and calibration runs, and implement modeling scenarios. Post-process model outputs and analyze model results. Write and review technical memos.
PLA project team Cleo Neculae, Ecology Jessica Huybregts, Ecology Laurie Mann, USEPA Office of Water Elly Hale, USEPA CERCLA	Project Team	Clarify scope of the project. Provide internal review of the QAPP and approve the final QAPP.
Jerry Shervy Industrial Unit Ecology NWRO Water Quality Section Phone: 425-649-7293	Unit Supervisor for the Project Manager	Provides internal review of the QAPP, approves the budget, and approves the final QAPP.
Rachel McCrea Ecology NWRO Water Quality Section Phone: 425-649-7033	Section Manager for the Study Area and the Project Manager	Reviews the project scope and budget, tracks progress, reviews the draft QAPP, and approves the final QAPP.
William R. Kammin Ecology Environmental Assessment Program Phone: 360-407-6964	Ecology Quality Assurance Officer	Reviews and approves the draft QAPP and the final QAPP.

QAPP: Quality Assurance Project Plan

5.2 Special training and certifications

PLA modeling team members have previous experience developing and applying watershed and receiving water models. Modelers may need additional training, depending on the selection of the receiving water quality model.

5.3 Organization chart

Table 9 lists the key individuals, their current positions and responsibilities for this project.

5.4 Proposed project schedule

The specific dates of task completion are contingent on funding. Regardless of the pace of funding, PLA development tasks will proceed in the sequence shown in the timeline in Figure 7. 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, data assessment can proceed and inform QAPP updates. Given the timeframe of the project, it is anticipated that QAPP updates or addendum will be periodically needed during the course of the project to make adjustments for development of future components including development of management scenarios.

Since the start of this project in 2014, the hydrodynamic and sediment modules of watershed model have been completed. In this QAPP, the project team focuses on the description of the toxic module of watershed model and the development of the receiving water model over the next three years. The project team expects to update the QAPP again to add more details on the management scenarios for the receiving water model and the development of the food web model.

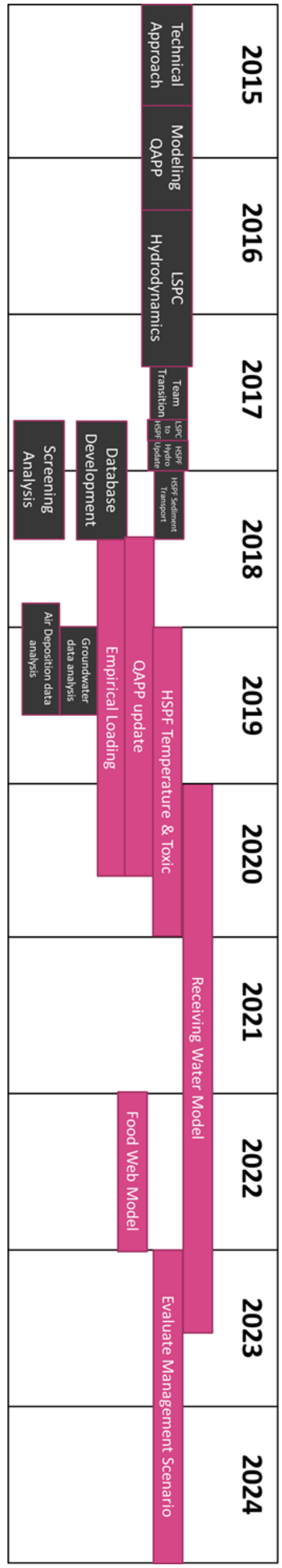

Figure 7. Project timeline

5.5 Budget and funding

This work will be funded through PLA funds from the Water Quality Program in Ecology. The development of the watershed model (HSPF) does not require funding since it will be developed by the Ecology modeler with support from King County. The receiving water modeling may require additional funding, depending on the technical assistance necessary. These will be documented in a future QAPP addendum.

6.0 Quality Objectives

6.1 Data quality objectives (DQO)[2]

The watershed 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 4. Model-specific objectives are described for HSPF (Section 7.3.2.1.1), EFDC (Section 7.3.2.2.1), and the Food Web Model (Section 7.3.2.3.1). Methods for evaluation of model performance are described further in Section 7.3.2.1.6 (HSPF), Section 7.3.2.2.6 (EFDC) and Section 7.3.2.3.6 (Food Web Model).

6.2 Measurement quality objectives

Not applicable; no field sampling is included.

6.3 Acceptance criteria for quality of existing data

The majority of the secondary measurements will be obtained from quality assured sources. The PLA modeling team 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, the PLA modeling team will identify any data anomalies that warrant analysis of quality assurance information for the particular dataset. EPA and Ecology will direct any effort to find reports or metadata that might contain that information. The PLA modeling team 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, the PLA modeling team will evaluate data quality of such secondary data before using them. 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, the PLA modeling team will add a disclaimer to the deliverable indicating that the quality of the secondary data is unknown.

[2] DQO can also refer to Decision Quality Objectives. The need to identify Decision Quality Objectives during the planning phase of a project is less common. For projects that do lead to important decisions, DQOs are often expressed as tolerable limits on the probability or chance (risk) of the collected data leading to an erroneous decision. For projects that intend to estimate present or future conditions, DQOs are often expressed in terms of acceptable uncertainty (e.g., width of an uncertainty band or interval) associated with a point estimate at a desired level of statistical confidence.

6.4 Model quality objectives

The model quality objective is defined by the two model development goals: (1) minimize the difference between simulated and observed hydrology, water/sediment quality, and fish tissue concentration, and (2) 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, and 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. Clearly 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.

7.0 Study Design

7.1 Study boundaries

The modeling boundaries for each model are described in the section below. The boundary for HSPF is described in section 7.3.2.1.5. The boundary and the map for EFDC is listed in section 7.3.2.4.1. The Food Web Model domain will be a subset of the EFDC model application area as described in section 7.3.2.4.1.

7.2 Field data collection

Not applicable; no field data collection is included.

7.3 Modeling and analysis design

7.3.1 Analytical framework

7.3.1.1 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 8, Figure 9, and Figure 10). Additional discussion is provided in Tetra Tech (2014).

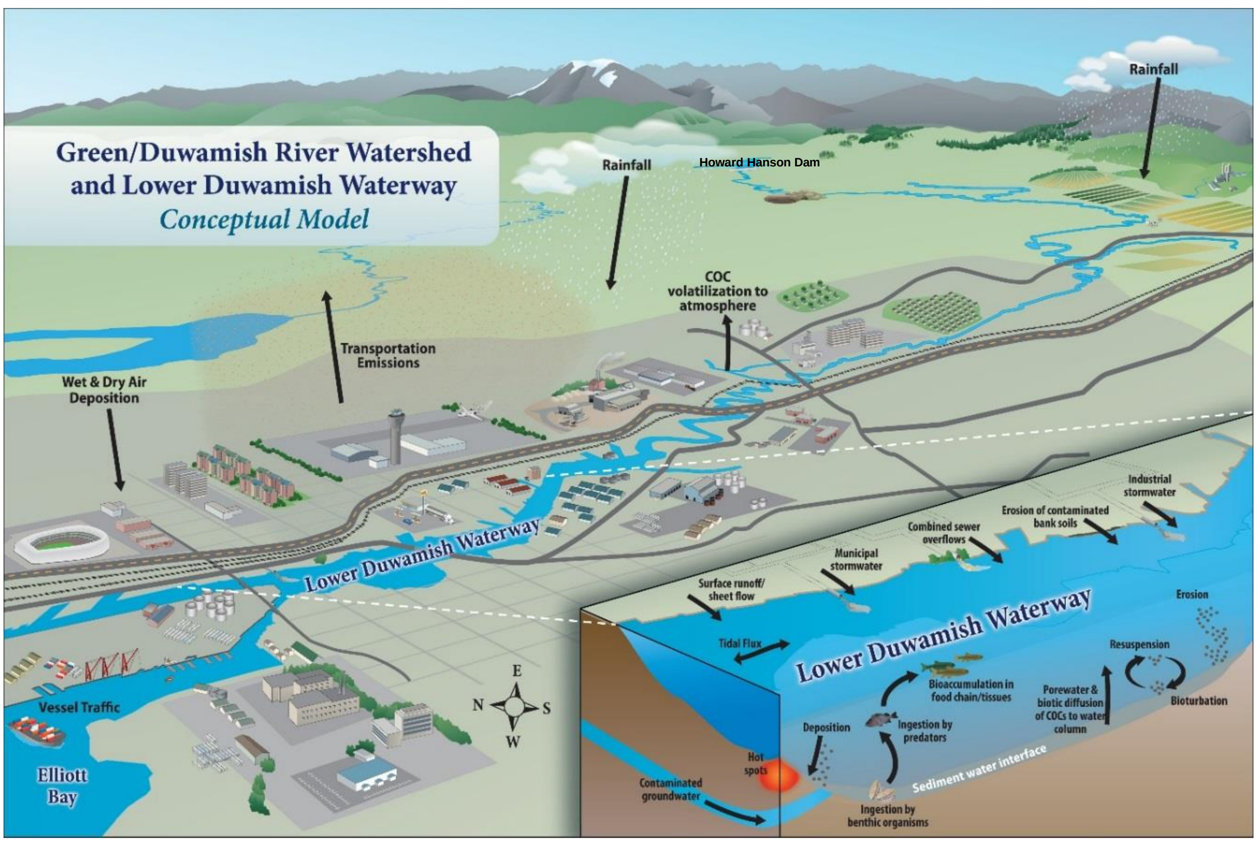

Figure 8. Green/Duwamish River general conceptual model

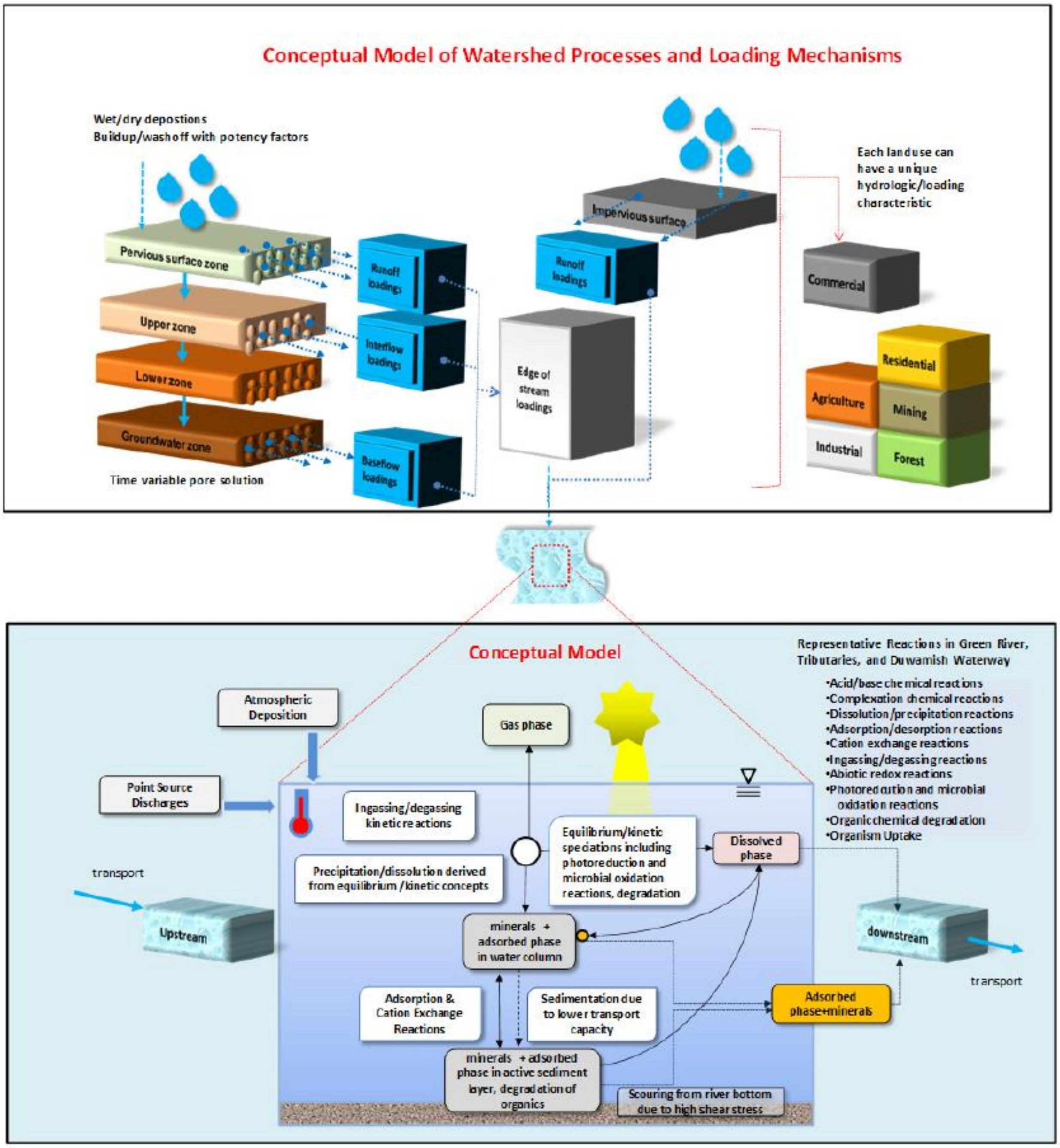

Figure 9. Watershed process and loading mechanisms

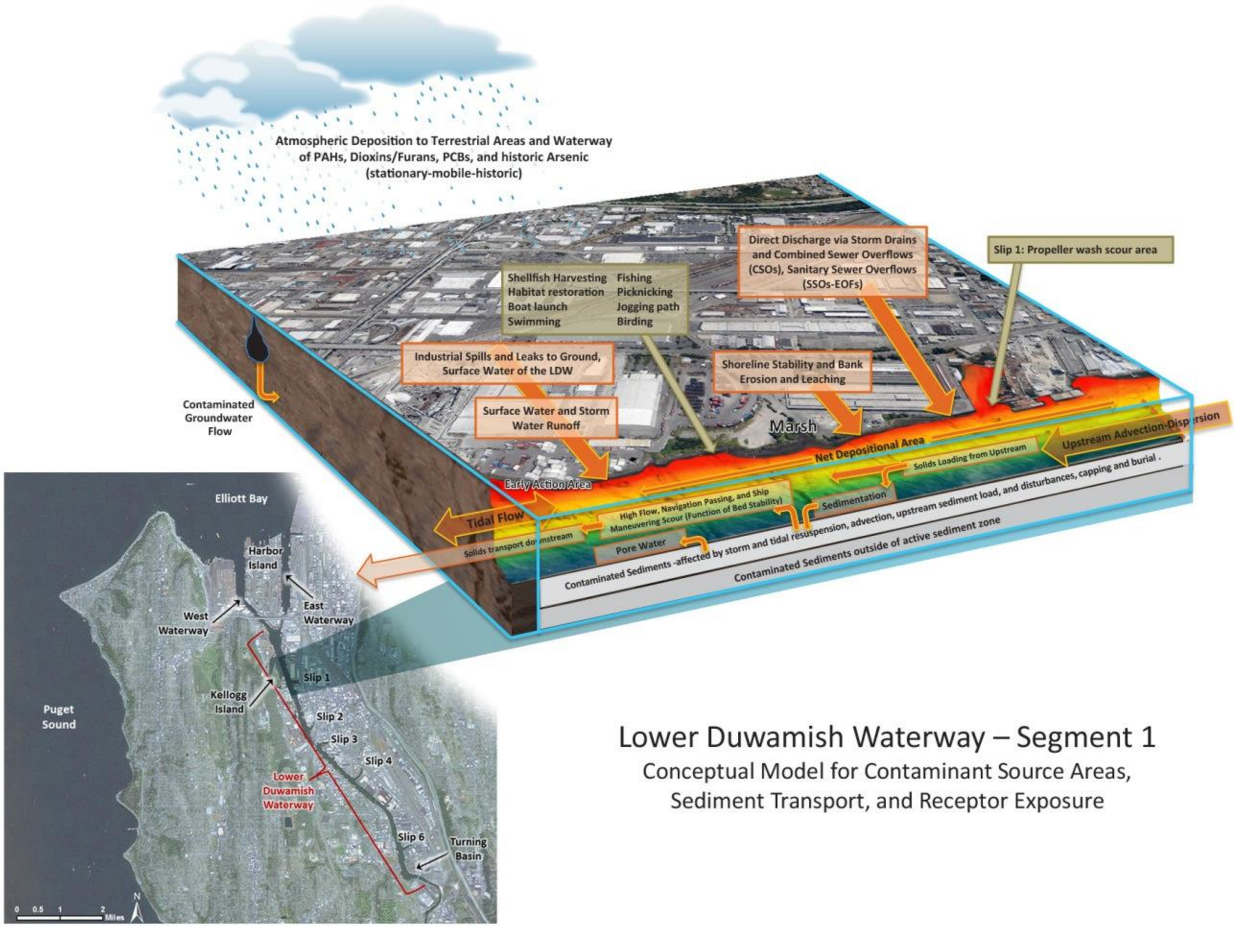

Figure 10. Conceptual model of LDW, segment 1

7.3.1.2 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 HSPF, EFDC, and the Arnot and Gobas FWM. The selection of the modeling framework was described in detail in Tetra Tech (2014); however, there was an added modeling step to convert the original LSPC model (developed by Tetra Tech before the work was assigned to Ecology) back into the public domain HSPF framework for continued development of the watershed model and pollutant loading assessment (Tetra Tech 2018). 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 one-box model, one-dimensional box models to complex three-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.

7.3.1.2.1 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 are 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) was 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 can provide 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). However, LSPC is a proprietary modeling system. Thus, it was uncertain if future modifications and/or applications of the modeling system would require procurement.

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 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.

7.3.1.2.2 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 20 years (see Section 7.3.2.2.2). 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 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 fate and transport 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 LDW Sediment Transport Model (STM) (QEA, 2008) 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 performed 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 through a hydrodynamic linkage file, which can be saved for any subsequent WASP simulations and then eliminates the need to run EFDC hydrodynamics repetitively, but the linkage is cumbersome and requires transfer through enormous binary files. In this one-way EFDC-WASP linkage, EFDC provides hydrodynamic information to WASP and receives no timely feedback from WASP to correct its hydrodynamic simulation. In the case of box models such WASP, while they could provide useful scoping level insights, the complexity of the LDW system limits their use in developing management strategies. The latest EFDC model includes robust sediment transport, contaminant fate and transport, and water quality modules. Its historic use in the LDW makes it highly desirable for model selection and continued use to support the PLA.

The project team and modeling team compared the EFDC version used in previous LDW modeling, the Dynamic Solutions version of EFDC, and the Salish Sea Model (SSM) developed by Pacific Northwest National Lab (PNNL). With an unstructured-grid, Finite-Volume Coastal Ocean Model (FVCOM) framework, SSM is a powerful three-dimensional tool that can simulate hydrodynamic and water quality processes in the Salish Sea. Due to SSM's unstructured grid with triangular elements, increasing horizontal grid resolution and fitting the complex shoreline become much easier than in EFDC. However, the current SSM version has no contaminant fate and transport module. Although SSM toxic module development is under development, the total phased cost to utilize SSM via PNNL's server is high and unpredictable and model development was anticipated to take many years. The Dynamic Solutions version of the EFDC modeling system is being continuously improved and has an efficient post-processor. In addition, selection of Dynamic Solutions EFDC would mean remaining PLA funding could be used to support various projects such as data analysis, sampling, and model review. Furthermore, an advantage of Dynamic Solutions EFDC over other EFDC versions is the addition of a wind-wave submodel. Similar to previous (LDW) EFDC applications, wind-wave will not be modeled, but the wind-wave submodel in Dynamic Solutions EFDC is helpful to evaluate the wind-wave's effect on bottom shear stress.

Additionally, SSM will generate LDW and Elliott Bay organic carbon outputs for contaminant partitioning. Also, SSM-simulated water surface elevation and salinity could be used to verify LDW EFDC modeling.

After considering all evidence in the comparisons discussed above and consulting with the TAC, the project team decided to use the Dynamic Solutions version of EFDC for receiving water representation the In this report, we will use "EFDC" to represent the Dynamic Solutions version of EFDC. If necessary, however, switching from EFDC to SSM to better address the interactions between Puget Sound and the Green/Duwamish River is possible in the future.

7.3.1.2.3 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 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 (https://arnotresearch.com/AQUAWEB/).

7.3.1.2.4 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. 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.

7.3.2 Model setup and data needs

The general project goals and objectives presented in Section 4 are translated into specific model development activities related to characterizing watershed pollutant loading in the Green/Duwamish 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 are 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 (HSPF), the receiving water model focusing on the LDW (EFDC), and the FWM.

7.3.2.1 Watershed model – HSPF

7.3.2.1.1 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 HSPF framework, not only includes the physical and chemical processes within the Green/Duwamish River watershed itself, but also integrates with EFDC 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. The modeling will fill gaps in space and time that otherwise would not be feasible to be obtained through monitoring and to evaluate outcomes from possible future actions that are not present to measure now.

Specifically, the watershed model will address several of the objectives identified in the CMs, 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 7.3.1.2, the LSPC model was converted back into HSPF as the selected framework for the watershed simulations. Prior work with HSPF models in the Green/ Duwamish watershed is available and will facilitate development of the watershed model framework for the PLA.

7.3.2.1.2 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 the 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 and 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 were developed for different land uses and constituents by reviewing literature values for the region and a USGS study of the Puget Sound Basin. Generally, the calibration results suggested a good fit for the constituents with existing 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 on 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 11).

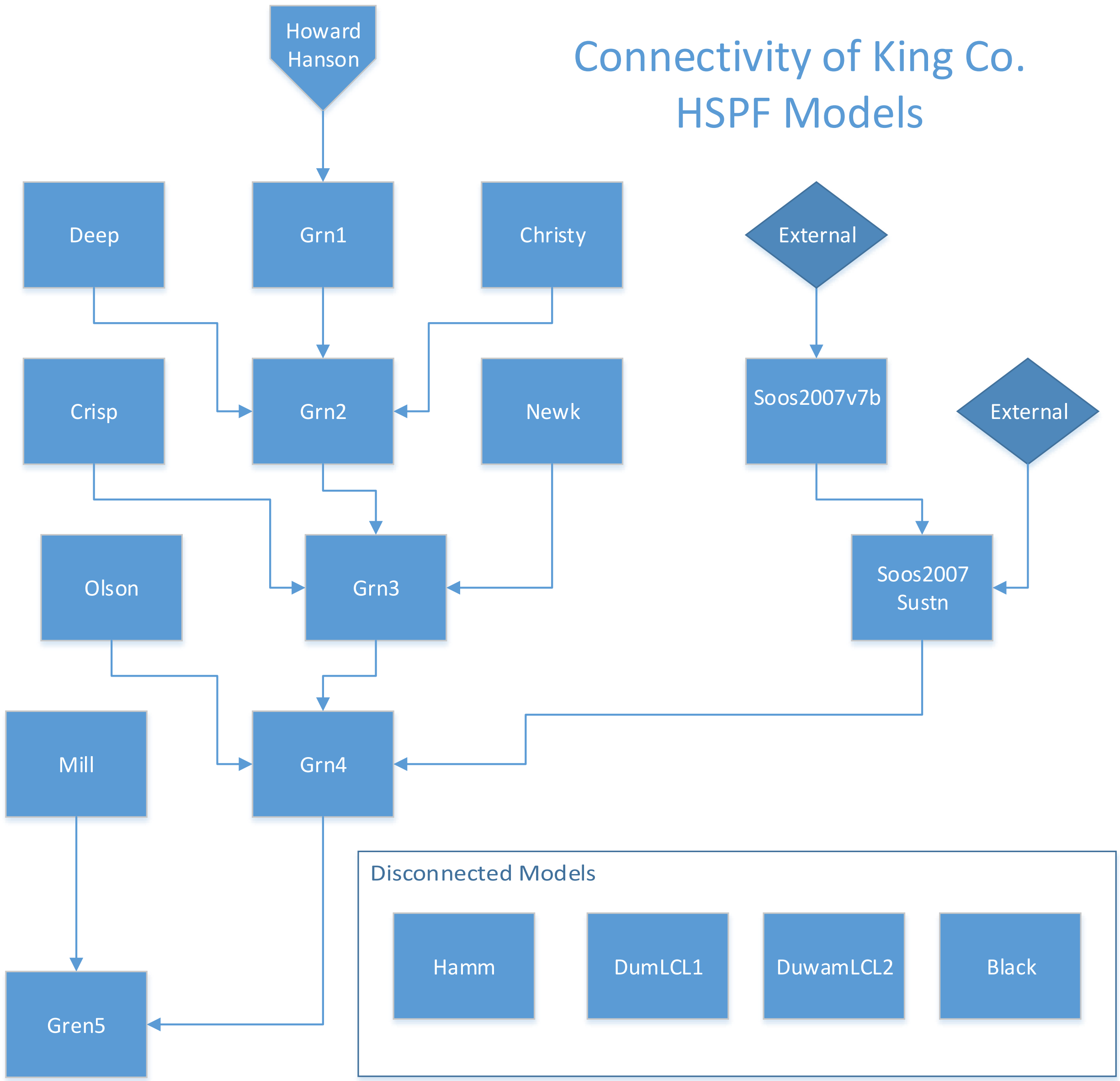

Figure 11. King County WRIA 9 model linkages

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 are 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. As noted earlier, 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 be identified by developing HSPF watershed models that represent and route only those portions of runoff that go directly to the LDW and not to the CSS. Development of HSPF models for areas with partially separated storm sewer systems will be informed by analyses undertaken by King County.

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 County and the City of Seattle.

7.3.2.1.3 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. 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, which were converted to one LSPC model, and convert them into four HSPF models. (Note that any model can have multiple terminal points that provide input to the EFDC model of the LDW). The HSPF models 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 HSPF 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 LSPC model into HSPF modeling framework.
- Process meteorological data to include filling, patching, etc.
- Organize flow data into calibration tool spreadsheets.
- Construct/refine F-tables.

- Configure HSPF models for areas lateral to LDW (note, these are new models where no HSPF models exist).

7.3.2.1.4 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. HSPF provides mechanisms for representing all of these pathways of pollutant delivery.

HSPF 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 HSPF watershed model are:

- Total PCBs
- Carcinogenic PAHs as a single group – Total cPAH toxic equivalents (TEQ)
- Arsenic, dissolved and sorbed forms
- DEHP as a surrogate for other phthalates
- Copper, dissolved and sorbed forms
- Zinc, dissolved and sorbed forms

Hydrology

HSPF provides 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.

Multiple hydrologic components are contained within HSPF 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 (based on the Stanford Watershed Model, but with adaption over the years, Bicknell et al., 2014) 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 HSPF model contains three major flow pathways: surface, interflow, and groundwater outflow.

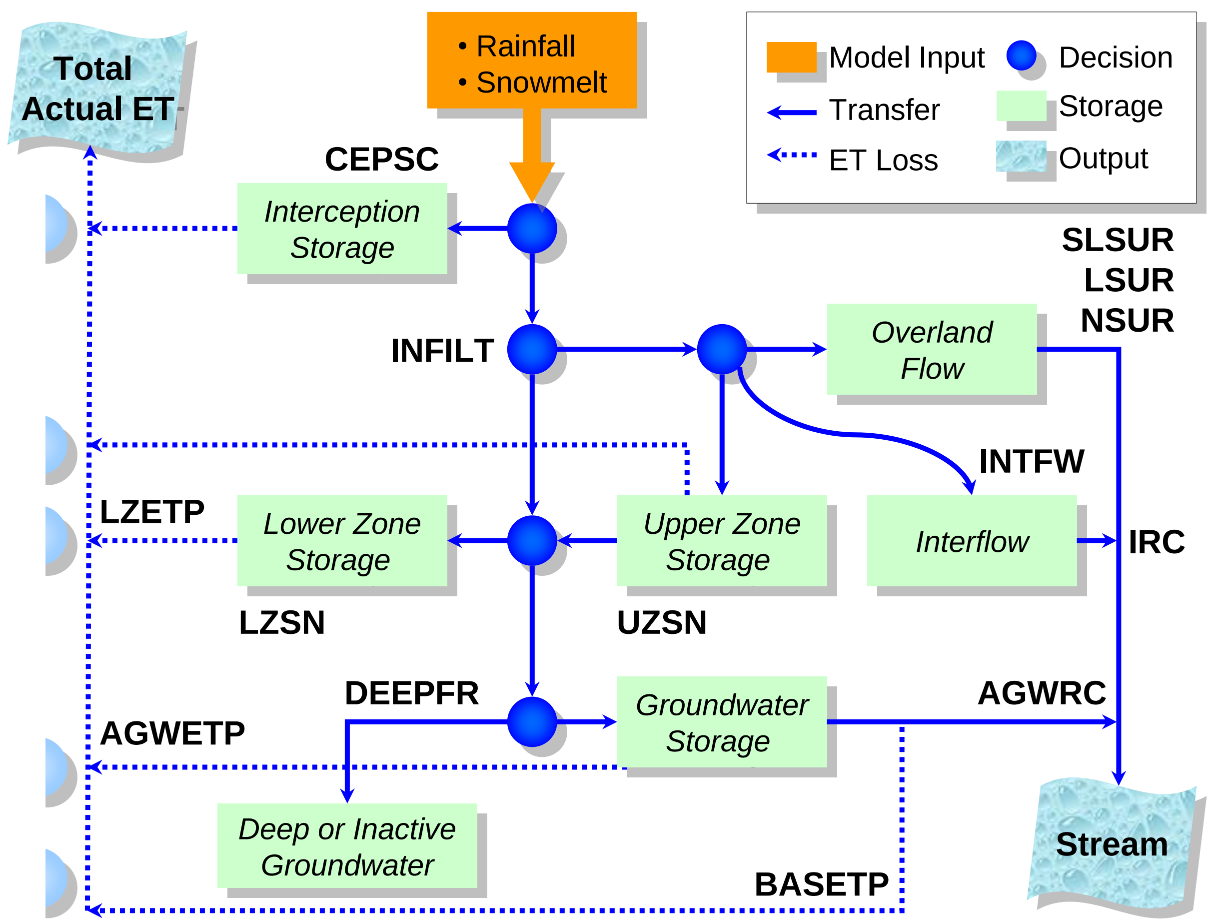

Figure 12. Hydrologic representation in the HSPF model

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

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

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

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:

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

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.

Instream Sediment

HSPF 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.

HSPF 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).

Noncohesive Sediment

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 represented by 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.

Toxics

The HSPF 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 the 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 HSPF 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, phthalates, arsenic, copper, and zinc), the King County models provide a strong hydrologic foundation at the large watershed scale. One limitation is that these models do not include 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.

Hydrologic representation refers to the HSPF modules or algorithms used to simulate hydrologic processes (e.g., surface runoff, ET, and infiltration). PWATER (water budget simulation for pervious land segments) and IWATER (water budget simulation for impervious land segments) modules 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 component on pervious land will also be included in addition to potency as part of the atmospheric deposition (when appropriate) onto saturated surfaces.

The atmospheric deposition time series used in the HSPF models will be derived from a recent analysis completed by King County (2019) that estimates loadings rates within the study area.

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, literature, and recent analyses will inform these rates. These values serve as starting points for water quality calibration. It is anticipated that the atmospheric loading rates will provide a baseline loading condition. Additional buildup/washoff loadings by HRUs will be adjusted to increase generated loads as needed during the calibration process.

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 from a storm 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

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

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

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

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 HSPF, 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 buildup/ 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 4.3.1.1. 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.

<u>Washoff of contaminants to stream</u>

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 (*W*) 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

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

where α (WSQOP in HSPF) 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 HSPF 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 total PCB and cPAHs, 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 HSPF is a two-phase partitioning approach. The partitioning will be based on recorded average concentrations of particulate and dissolved organic carbon in the streams and rivers within the modeling domain.

Sorption-desorption reactions for metals are likely to be of limited importance in flowing reaches, but may be of greater importance in wetlands, lakes, other low gradient areas, and during stormwater runoff events. 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 metal sorption as a function of simulated suspended sediment concentrations using the approach documented in USEPA (1996).

In addition, the methodology described in the Washington State Administrative Code (WAC 173-201A, the Surface Water Quality Standards) will be used to determine exceedances in dissolved copper and zinc concentrations in receiving bodies. This method requires hardness concentrations in the determination. In freshwater bodies, hardness concentrations are generally highest during summer months when stream flows are mostly generated from groundwater inflows. Mean monthly hardness concentrations will be derived from historical observations and used to evaluate acute and chronic conditions for copper and zinc.

7.3.2.1.5 Model configuration

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

- Middle Green River from the confluence of Soos Creek (but not including) to the base of Howard Hanson Dam, covering agriculture, rural residential, pockets of urban development, and forested land. This subwatershed includes Newaukum Creek.
- Soos Creek basin, which includes nearly 60 square miles of urban, residential, forest, and sporadic 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 and includes Mill Creek and Mullen Slough.
- 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.

As discussed in the Technical Approach (Tetra Tech, 2014), 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 (see Figures 2, 3, 4, 8 for the Howard Hansen Dam location).

Model boundaries and boundary conditions

HSPF 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 HSPF 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 HSPF model will be Howard Hanson Dam (HHD), as is also the case for the existing King County HSPF models. The Technical Approach proposes simulating the Lower and Middle Green River up to the Howard Hanson Dam (Tetra Tech, 2014). A USGS gage located just downstream of the HHD provides flow data encompassing the modeling time period of 1993-2013, and will be used as a boundary condition for inflow data. For each simulated pollutant, concentrations associated with those flow rates will be derived from correlations developed using scattered paired observations taken at five monitoring stations located below HHD. The area upstream of Howard Hanson Dam is mostly forested land and is expected to remain static.

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 Lake Youngs and Lake Sawyer (Soos Creek) and groundwater inflows. 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.

The groundwater inflows will be initially assigned pollutant concentrations based on the results of a 2019 USGS study undertaken for the Green/Duwamish River basin. Ideally, these data are consistent with other groundwater concentrations developed during calibration for the tributaries within the watershed.

Hydrologic Response Units

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 County 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 three different soil types, and three 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 County 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 County, 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 County, 2013).

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

Table 10. 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
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	Forest 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	Modeled as medium grass and Impervious surfaces

Land Use	Description	Land Cover
	some roads. For this study the amount of areas are inconsequential and are reassigned to keep permutations to a minimum.	
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 11. HRU numbering scheme from King County (2013b) with associated surficial geology, land cover, and 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
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

HRU Number	Surficial Geology	Land Cover	Slope	Description	Short Descr.
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
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

HRU Number	Surficial Geology	Land Cover	Slope	Description	Short Descr.
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

The PLA team has reviewed the King County HRU definitions and found them to be reasonable, and model performance was good to excellent for hydrology. Two LSPC models were developed to simulate loadings from the landscape and transport through the receiving waters. These two models were then converted into the four HSPF model domains as previously described (Section 7.3.1.2). Detail on the conversion is documented in a technical memorandum (Tetra Tech, 2018). Model development can proceed, at least as it regards to 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 (e.g., using age of development as a basis for differentiating PCB loading parameterization). 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. Unfortunately, the method used by Tetra Tech to convert from LSPC to HSPF utilized nearly the entire range of available IDs to define HRUs in HSPF. This may require some re-structuring of the HRU scheme to accommodate the generation of subset numbering schemes. This will not, however, affect previous calibration efforts.

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 LDW within the City of Seattle, HRUs are 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 will all go to the same storm conveyance.

7.3.2.1.6 Model calibration and evaluation

<u>Objectives</u>

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.

<u>Time period and approach</u>

The watershed model will be calibrated and evaluated through a sequential process, beginning with hydrology, followed by suspended sediment and then water quality.

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 September 2017. The calibration period will be within the period 1996-2017.

The existing hydrologic representation is believed to reflect conditions, 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.

Hydrologic calibration

Hydrologic calibration will use standard operating procedures 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.

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.

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 actual 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. There are two approaches that may be pursued for setting the relevant parameters. One approach 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 20th percentile was used to establish initial values for clay and the 25th 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 90th percentile for clay and the 95th 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.

Water quality calibration

For water quality calibration, we 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 those types of data are 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 inspections coupled with summary statistics of 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. HSPF 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 (ranging in accuracy) 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.

<u>Calibration data</u>

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.

Evaluation metrics

The HSPF models 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.

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:

$$E_{rel} = \frac{\sum |O - P|}{\sum O} X100 \qquad \text{Equation 6}$$

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),

$$NSE = 1 - \frac{\sum(O - P)^2}{\sum(O - \bar{O})^2} \qquad \text{Equation 7}$$

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 HSPF model will be evaluated in terms of relative error for simulation of hydrology measures summarized in Table 12.

Table 12. Model evaluation components for HSPF/LSPC hydrologic simulation

Model Component
1. Error in total volume
2. Error in 50% lowest flow volumes

Model Component
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

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, a potential surrogate for suspended sediment concentration.) Instead, observations typically provide measurements of conditions at a point in time and 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. 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.

7.3.2.2 Receiving water model – EFDC

7.3.2.2.1 Objectives

As previously mentioned, the PLA requires a source-response linkage and the estimation of existing loadings and target loadings to attain water quality goals set forth in the CWA, 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 of the Green and Duwamish Rivers and catchments adjacent to the LDW are described using the HSPF watershed model. The HSPF 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 7.3.1.2), 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 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
- 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. The formulation for its modular sediment process library allows for future options including site-specific parameterizations, such as the SEDZLJ formulation (Jones and Lick, 2001; James et al., 2005).

7.3.2.2.2 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 (see Table 13) (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).

Hydrodynamics, sediment transport, and contaminant fate and transport modeling studies of the LDW began with the King County CSO Water Quality Assessment of the Duwamish River and Elliott Bay in the late 1990s (King County, 1999). EPA (Hayter, 2006; Arega and Hayter, 2004) and the LDWG conducted additional work as part of the RI and subsequent feasibility study (FS) required by Superfund characterization and cleanup efforts (Windward Environmental and QEA, 2008; QEA, 2008; AECOM, 2012b).

Table 13. 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 7.3.2.2.4)	Upstream river flow and loads, CSOs to LDW	Hydrodynamics, sediment transport, and contaminant transport; upstream and internal loading	Served as foundation for subsequent work in the 2000s
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 hydrodynamic 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 County (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 existing 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 fewer data than are now available.

Contaminant concentrations in surface sediment were developed by LDWG using estimates of the contaminant concentrations 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. All calculated contaminants were assumed to be bound to sediment particles,
2. No loss/gain/transformation of contaminants via physical, chemical, or biological degradation mechanisms (desorption, adsorption, diffusion, degradation, 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).

7.3.2.2.3 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:

- Combined 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 (TOC) and dissolved organic carbon (DOC) to support toxics modeling. The complexity and source of the organic carbon inputs, which are time-and spatially-varying for both water column and sediment bed, will be decided for Elliott Bay, the lower five miles (known as the LDW), and upper miles of the Green/Duwamish River (upstream of the LDW). SSM organic carbon simulation results will be used.
- Fate and transport modeling of all the project toxic pollutants within both the bed sediment and the water column using a 3-phase partitioning (freely dissolved, particulate organic carbon sorbed, and dissolved organic carbon complexed phases).
- Inclusion of contaminant fate and transport 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 7.3.2.2.4.

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.

7.3.2.2.4 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, may include:

- Urban runoff and associated loads of contaminants, COCs and other pollutants (nonpoint stormwater discharges).
- Watershed (non-urban) simulated by HSPF
- 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.
- Bioturbation or particle mixing.
- Volatilization.
- Dispersion across downstream boundaries.
- Dredging residuals.

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

- Total PCBs.
- Carcinogenic PAHs as a single group – Total cPAH toxic equivalents (TEQ).
- Arsenic, dissolved and sorbed forms.
- DEHP as a surrogate for other phthalates.
- Copper, dissolved and sorbed forms.
- Zinc, dissolved and sorbed forms.

For non-polar organic toxics, such as Total PCBs, partitioning of contaminants among the freely dissolved (C_d), POC-sorbed (C_{POC}), and DOC-complexed (C_{DOC}) phases 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. In the three-phase representation, the freely dissolved (C_d), POC-sorbed (C_{POC}), and DOC-complexed (C_{DOC}) concentrations can be related to the total concentration (C_t), expressed as mass per unit volume of the water phase, as:

$$\frac{C_d}{C_t} = \frac{\varphi}{\varphi + K_{POC}POC + \varphi K_{DOC}DOC} \qquad \text{Equation 8}$$

$$\frac{C_{POC}}{C_t} = \frac{K_{POC}POC}{\varphi + K_{POC}POC + \varphi K_{DOC}DOC}$$ Equation 9

$$\frac{C_{DOC}}{C_t} = \frac{K_{DOC}DOC}{\varphi + K_{POC}POC + \varphi K_{DOC}DOC}$$ Equation 10

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).

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 expressed 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 model simulation will include chemical degradation. For some PCB congeners and DEHP these degradation processes are extremely slow and could be ignored; however, for other constituents of concern, such as some cPAHs, 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 partitioning of contaminants, deposition/resuspension, bioturbation, diffusion, and other mixing forces such as propeller 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, such as high freshwater flow or high tide.

7.3.2.2.5 Model configuration

Model boundaries and boundary conditions

Tidal influence can reach as far upstream as RM 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 13~~Figure 13~~ identifies RM 17 relative to the model domains of the original King County EFDC model and the EFDC model used for the RI/FS. Both 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 RM 19, and USGS gaging stations 12113390 Duwamish River at Tukwila, WA and 12113350 Green River at Tukwila are both located downstream of RM 17. These stations' data, along with HSPF 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.

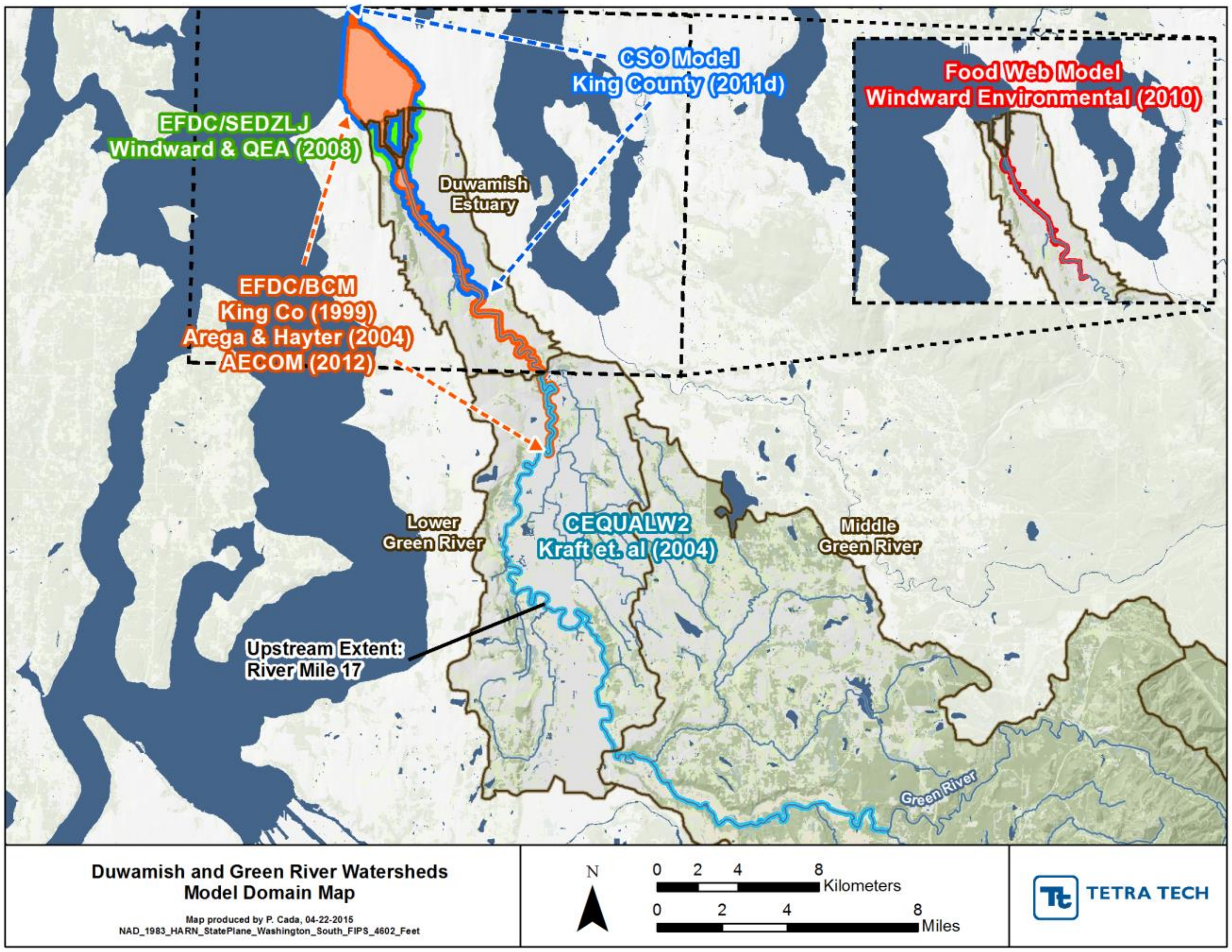

Figure 13. EFDC model domain

As discussed previously, the HSPF-predicted flows and pollutant concentrations will be used as boundary conditions for the EFDC contaminant 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 14 and Figure 15. 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 HSPF watershed model and to extend the grid to approximately RM 17, but initially the grid resolution should remain basically the same.

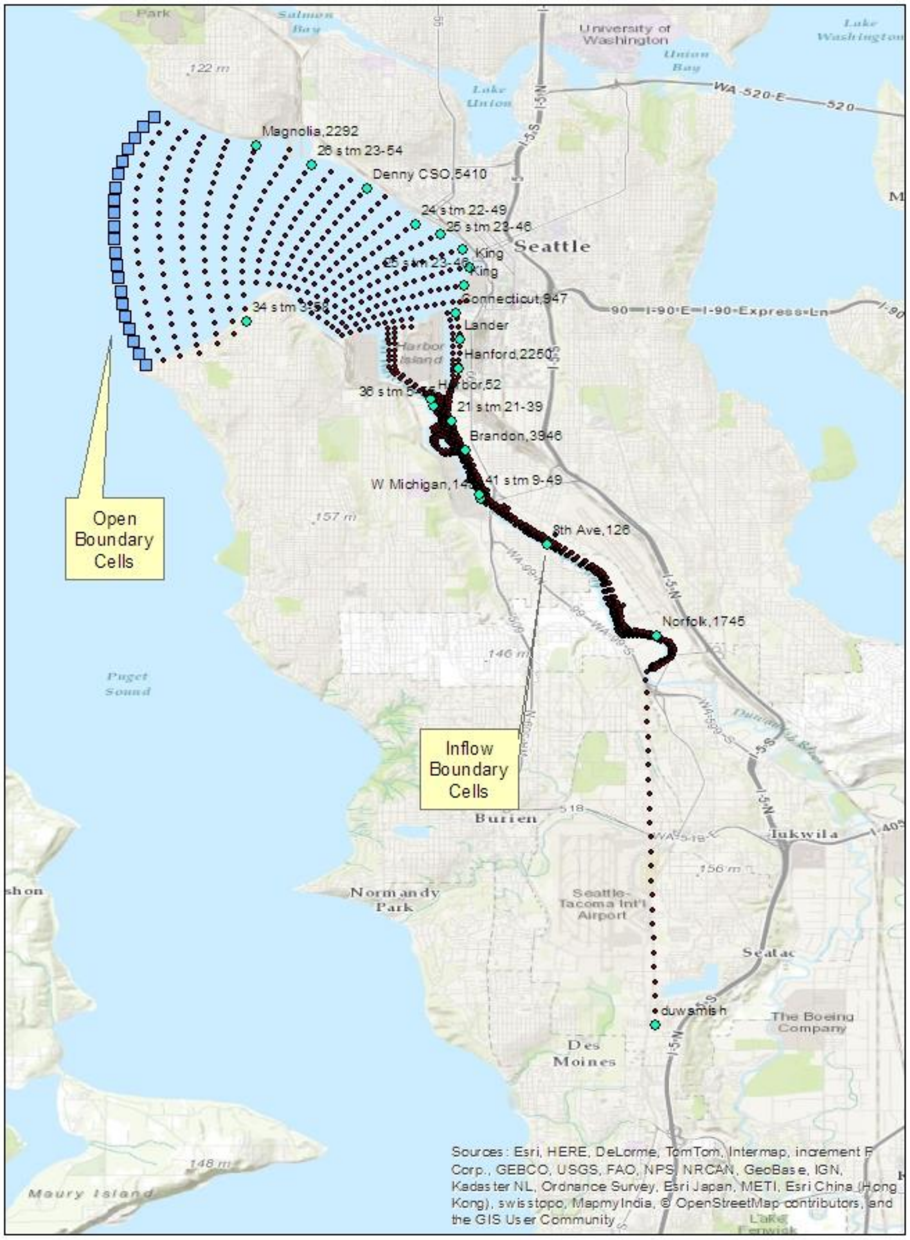

Figure 14. LDWG/QEA EFDC Model - grid centerpoints, open boundary, and upstream inflow cell locations

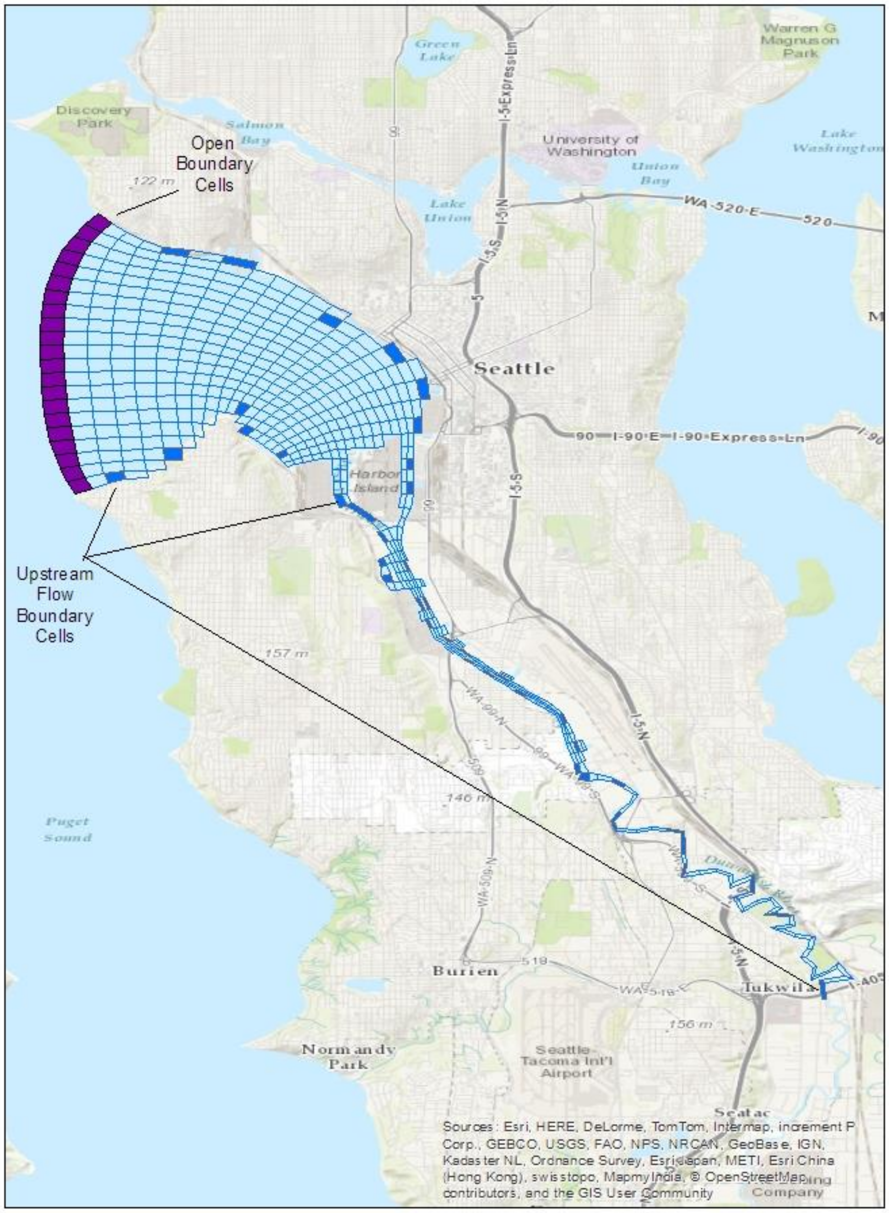

Figure 15. King County EFDC Model - grid centerpoints, open boundary, and upstream inflow cell locations

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 8 sediment bed 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 be made due to the need for long-term simulations. Other factors, such as the computation accuracy, computational costs, and model run times, will also be considered.

The EFDC model may also have to be broken up into various multi-year time periods reflecting the change in river bathymetry, sediment bed characteristics, and constituents' concentrations 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 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 in the Puget Sound from Elliott Bay and Main Basin (Osterberg and Pelletier, 2015).

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 outputs for existing conditions can be combined with measured data to provide a composite time series for a particular boundary condition. For 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 DEHP. For other parameters, limited data are available. New data 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 that 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 concentrations 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. For example, if we will need to see the seasonal pattern for hydrodynamic parameters, we will need about one year for spin-up time.

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. As such, for each model time period following a dredging operation, the model’s bathymetry, and sediment bed characteristics and constituents concentrations will need to be adjusted along with the concentration of potential toxics of concern in the sediment layer.

EFDC will be modeling total PCBs but most of the data for PCBs in the LDW were reported as Aroclors. In order to supply initial Total PCB conditions to the model, a relationship between Aroclors or homologs and PCB congeners will be explored based on literature information or newly-collected PCB data.

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. Spin-up simulation will be conducted to improve the initial sediment bed condition.

7.3.2.2.6 Model calibration

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.

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.

Linkage of HSPF watershed model results for input to EFDC model

The HSPF 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 HSPF 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 forms. Most water quality measurements, including measured toxics concentrations, are grab samples. HSPF model therefore provides an important capability in providing continuous estimates of concentrations over time. If HSPF 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.

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.

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. Ship-induced bottom velocity analysis in Sediment Transport Analysis Report (STAR) (Windward Environmental and QEA, 2008) will be considered. Despite wind-driven shear stress in shallow areas, it will not be included due to its insignificant and limited impact on sediment resuspension in LDW. However, a sensitivity analysis might be performed to evaluate the effects.

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 represents the time series of model predictions and O the time series of observations:

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

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 HSPF-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, sediment core analysis, sedflume data (which characterize the field sediment physical properties including suspendion and resuspension rate) in 2004, 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.

Water quality and toxic pollutant calibration and evaluation

Similar to the EFDC hydrodynamic model, the EFDC water quality model calibration will be based on graphical and statistical comparisons between the model predictions and observations. A temporal analysis will be performed creating comparison plots using the model results and available field observations. Goodness-of-fit statistics, where there are sufficient observational data, will be performed. Statistics analyzed include 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 are fewer than three 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.

Calibration data

Data availability for calibration is discussed in Section 4.3. Additional relevant hydrodynamic data and information will be downloaded from the USGS and NOAA web sites.

7.3.2.3 Food Web Model

7.3.2.3.1 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.

7.3.2.3.2 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 (AECOM, 2012a). 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 organism 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 come from the 2009 update of the 1999 King County EFDC model, documented as Attachment A to Appendix D of the RI report (AECOM, 2012a).

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 than the observed 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.

7.3.2.3.3 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 be made and documented in a future version of the QAPP, as discussed in Section 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 3.2.3. 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 in Section 3.2.3), arsenic, or inorganic metals.

7.3.2.3.4 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.

7.3.2.3.5 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 (AECOM, 2012a). The PCB concentration in the water column 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 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.

Model boundaries and boundary conditions

The domain for the FWM will be a subset of the EFDC model application area (described in Section 7.3.2.4.1). 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.

7.3.2.3.6 Model calibration

Objectives

Steady-state food web models incorporate many simplifying assumptions and cannot be expected to predict the tissue concentrations in individual fish as those concentrations depend 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.

Approach and time period

The existing FWM uses a probabilistic calibration approach in which all parameters were varied in a Monte Carlo simulation and a best fit parameter set was 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 obtain 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.

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.

7.3.2.4 Model linkage and integration

Model outputs from the HSPF model application will be used as upstream and lateral boundary inputs to the EFDC domain. The HSPF models will provide the EFDC model with inputs for flow, water temperature, sediment, total organic carbon, dissolved organic carbon, and the toxic parameters of interest. Refer to Section 7.3.2.2.6 for more details. Moreover, a linkage file based on SSM hourly outputs will be generated to provide the lower five miles and Elliott Bay organic carbon time series for EFDC contaminant modeling, in addition to EFDC internally coupled hydrodynamic and sediment transport information.

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.

7.4 Assumptions in relation to objectives and study area

Modeling work contains inherent assumptions when representing a watershed or water body through a simplified mathematical representation that is not able to fully account for each variable and element influencing the system.

General modeling assumptions for the receiving water model include:

1. Equations that are used in the model are representative of the biological, physical, and chemical processes in the Green/Duwamish River and Elliot Bay.
2. Rates and constants are reasonable and within literature-reported values, when available.
3. Data represent varied spatial and temporal conditions in the environment.
4. Watershed inflow data that are used for model calibration are representative of those sources.
5. Unknown or unidentified sources have a negligible effect on model result.

7.5 Possible challenges and contingencies

7.5.1 Logistical problems

This project is not expecting any logistical problems. The modeling team has access to all appropriate modeling files and software.

7.5.2 Practical constraints

Budget constraints may influence the model runs used for various modeling scenarios and outside technical support. Staff constraints, such as staff change or increase of other workloads, may influence the schedule of model development. The project manager will adjust the workload or seek other funding sources if such issues arise.

7.5.3 Schedule limitations

Any unforeseen limitations, such as change of modeling method due to unforeseen challenges, or additional requirements proposed by project team or outside stakeholders, that would affect the project schedule, will be discussed with the modeling team, project manager, and appropriate management personnel, as needed, and documented.

8.0 Field Procedures

8.1 Invasive species evaluation

Not applicable; no field sampling is included.

8.2 Measurement and sampling procedures

Not applicable; no field sampling is included.

8.3 Containers, preservation methods, holding times

Not applicable; no field sampling is included.

8.4 Equipment decontamination

Not applicable; no field sampling is included.

8.5 Sample ID

Not applicable; no field sampling is included.

8.6 Chain-of-custody

Not applicable; no field sampling is included.

8.7 Field log requirements

Not applicable; no field sampling is included.

8.8 Other activities

Not applicable; no field sampling is included.

9.0 Laboratory Procedures

9.1 Lab procedures table

Not applicable; no lab analysis is included.

9.2 Sample preparation method(s)

Not applicable; no lab analysis is included.

9.3 Special method requirements

Not applicable; no lab analysis is included.

9.4 Laboratories accredited for methods

Not applicable; no lab analysis is included.

10.0 Quality Control Procedures

10.1 Table of field and laboratory quality control

Not applicable; no field sampling or laboratory analysis is included.

10.2 Corrective action processes

The essential steps in the corrective action processes 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 the corrective action and implement it.
- Verify that the corrective action has eliminated the problem.

Many technical challenges can be solved instantaneously by the modeling team by, for example, 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. Issues not solved in this manner require formalized, long-term corrective action, and these will be documented by project staff.

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.

11.0 Data Management Procedures

11.1 Data recording and reporting requirements

The majority of the secondary measurements will be obtained from quality assured sources. The modeling team 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, the modeling team 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. The modeling team 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, the modeling team will evaluate data quality of such secondary data before using them. 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, the modeling team will add a disclaimer to the deliverable indicating that the quality of the secondary data is unknown.

11.2 Laboratory data package requirements

Not applicable; no field sampling or laboratory analysis is included.

11.3 Electronic transfer requirements

Not applicable; no field sampling or laboratory analysis is included.

11.4 EIM/STORET data upload procedures

Not applicable; no field sampling or laboratory analysis is included.

11.5 Model information management

All modeling files (including model source codes, input and output files, modeling reports, etc.) will be stored on an Ecology server. All the technical reports and memos will be distributed to project team and Technical Advisory Committee for review before finalization. The final reports will be posted on Ecology’s PLA website.

12.0 Audits and Reports

12.1 Field, laboratory, and other audits

The modeling team meets weekly to review recent progress, evaluate project needs, and revisit next steps to meet project objectives. The project manager will present modeling updates to project team bi-weekly and will host Technical Advisory Committee meetings at least annually. These meetings provide review and audits on key modeling development before the final report is completed.

12.2 Responsible personnel

Table 9 lists staff responsibilities. The modeling team collaborates on review of data and reports.

12.3 Frequency and distribution of reports

The modeler team will provide bi-weekly update to the project team. The project team will report to the Technical Advisory Committees (TAC) at least annually. As appropriate, these reports will inform the project team and TAC 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.

12.4 Responsibility for reports

Table 9 lists the personnel responsible for drafting and review reports and technical memos.

13.0 Data Verification

All data used in the PLA will be from existing data sources.

13.1 Field data verification, requirements, and responsibilities

Not applicable; no field sampling or laboratory analysis is included.

13.2 Laboratory data verification

Not applicable; no field sampling or laboratory analysis is included.

13.3 Validation requirements, if necessary

Not applicable; no field sampling or laboratory analysis is included.

13.4 Model quality assessment

This QAPP and other supporting materials will be distributed to all personnel involved in the work assignment. PLA project team 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 carefully 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 project manager 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.

13.4.1 Model calibration

The calibration process for each model is discussed in the follow sections: Section 7.3.2.1.6 covers the model calibration process for HSPF; Section 7.3.2.2.6 discusses the model calibration process for EFDC; and, Section 7.3.2.3.6 describes the model calibration process for food web model.

13.4.2 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
- Model structure errors
  - Incomplete or incorrect mathematical representation of the physical, chemical, and biological processes.
- Data quality
  - Instrument errors
- Data quantity
  - Parameter error as a function of data quantity (space and time) used to calibrate model

Uncertainty and sensitivity analyses are complementary activities 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.

14.0 Data Quality (Usability) Assessment

14.1 Process for determining project objectives were met

The processes to ensure the model is effective at reproducing reality ~~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, and 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.~~Identify key or important parameters/processes and then improve the methods to generate a more accurate model inputs for those parameters/processes
4. ~~Identification of key parameters/processes through model calibration and sensitivity analysis.~~ Identify key or important parameters/processes and then improve the methods to generate a more accurate model inputs for those parameters/processes
5. ~~Clear communication of key assumptions during model development with the project team.~~Consult project team, groups and people with variety of backgrounds and experiences to fill the insitu and knowledge gaps that might need to be considered in the model development
6. Clearly written documentation of all important elements in the model, including model setup, boundary conditions, assumptions, and known areas of uncertainty.
7. Development of management scenarios to meet the project goals~~objectives~~.
8. Multiple rounds of peer review during model development.~~Peer review.~~

Progress on all of these fronts will factor into the decision to accept a model for use in a decision-making process. We will develop a separate model report that will include following sections and that report will be public available after the completion of the model development.

1. Executive Summary
2. Background
3. Model Development
4. Model Calibration
5. Model Validation
6. Sensitivity Analysis
7. ~~1.~~ Summary

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.

14.2 Treatment of non-detects

Treatment of non-detects is dependent on data categories and uses, measurement method, modeling phases, spatial and temporal distribution, number of detects, data quantity and cost. Using non-detects in modeling will be treated in several ways depending on goodness-of-fit. Non-detects may be:

1. Replaced with half the detection limit.
2. Treated as an indeterminate value between zero and the detection limit. For example, when comparing model predictions to observed data where the observed data are a non-detect, any predicted value less than the detection limit would be considered a reasonable match.
3. Plotted but not used in the regression analysis if such discard is reasonable and does not affect the overall trend or there is sufficient data for a particular parameter (e.g. TSS).

14.3 Data analysis and presentation methods

Data visualization and analysis will be conducted throughout the modeling processes. The purpose of data analysis includes understanding the system, initial model setup, model input, calibration and validation, model result evaluation. Data analysis might vary with the simulation modules, state variables, model parameters and sampling media.

Specifically, a variety of data analysis methods will be used at different stages throughout this study. These methods will be used during the model application processes, including as a means to analyze existing data for model input and model output results. Some of these data analysis methods may include:

1. Simple interpolation and extrapolation.
2. Regressions to obtain results for specific times and locations with missing data.
3. Descriptive statistics and summary statistics.
4. Graphic and tabular forms to visualize model results against observed values.

5. Compare model results with simplified analytical solutions or other existing simulation results.

6. Additional statistical analyses, as determined necessary by the modeling team.

The data analysis will start from the review of previous data analysis, such as sediment transport analysis report (STAR). Updated data analysis will be considered if there is a growing interest based on new data, for example, data analysis will be used to determine certain rates and constants. An updated data analysis must be performed if significant new data are available, which is expected for contaminant data, sediment bed core, organic carbon, and/or temporal hydrodynamic and sediment transport data. New data analysis will be carried out for any new or unused datasets that will be meaningful to LDW modeling study.

Numerous presentation methods and tools will be used to show model results and related data. These presentation methods may include:

1. Visual representations of data in the form of plane view maps, cross-sections, depth profiles, and three-dimensional projections of different parameters.

2. Time series of model output at a particular locations.

3. Animations to show model simulation over time.

4. Tables with quantitative information, including tables of values specific to various scenarios.

5. Descriptive statistics and summary statistics plots.

6. Mathematical function plots including regressions.

7. Informal, unpublished presentations containing data products.

The above approaches may be used during oral presentations, communication, or published materials including maps, graphics and figures, the modeling scenarios, and technical memos.

14.4 Sampling design evaluation

Not applicable; no field sampling or laboratory analysis is included.

14.5 Documentation of assessment

The PLA modeler team will provide monthly progress reports to project team. As appropriate, these reports will inform project team 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.

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16.0 Appendices

Appendix A. Glossaries, Acronyms, and Abbreviations

Glossary of General Terms

Ambient: Background or away from point sources of contamination. Surrounding environmental condition.

Anthropogenic: Human-caused.

Bankfull stage: Formally defined as the stream level that "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels (Dunne and Leopold, 1978).

Baseflow: The component of total streamflow that originates from direct groundwater discharges to a stream.

Char: Fish of genus *Salvelinus* distinguished from trout and salmon by the absence of teeth in the roof of the mouth, presence of light-colored spots on a dark background, absence of spots on the dorsal fin, small scales, and differences in the structure of their skeleton. (Trout and salmon have dark spots on a lighter background.)

Chronic critical effluent concentration: The maximum concentration of effluent during critical conditions at the boundary of the mixing zone assigned in accordance with WAC 173-201A-100. The boundary may be based on distance or a percentage of flow. Where no mixing zone is allowed, the chronic critical effluent concentration shall be 100% effluent.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Critical condition: When the physical, chemical, and biological characteristics of the receiving water environment interact with the effluent to produce the greatest potential adverse impact on aquatic biota and existing or designated water uses. For steady-state discharges to riverine systems, the critical condition may be assumed to be equal to the 7Q10 flow event unless determined otherwise by the department.

Designated uses: Those uses specified in Chapter 173-201A WAC (Water Quality Standards for Surface Waters of the State of Washington) for each water body or segment, regardless of whether or not the uses are currently attained.

Diel: Of, or pertaining to, a 24-hour period.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Dilution factor: The relative proportion of effluent to stream (receiving water) flows occurring at the edge of a mixing zone during critical discharge conditions as authorized in accordance with the state's mixing zone regulations at WAC 173-201A-100. http://apps.leg.wa.gov/WAC/default.aspx?cite=173-201A-020

Diurnal: Of, or pertaining to, a day or each day; daily. (1) Occurring during the daytime only, as different from nocturnal or crepuscular, or (2) Daily; related to actions which are completed in the course of a calendar day, and which typically recur every calendar day (e.g., diurnal temperature rises during the day, and falls during the night).

Effective shade: The fraction of incoming solar shortwave radiation that is blocked from reaching the surface of a stream or other defined area.

Effluent: An outflowing of water from a natural body of water or from a human-made structure. For example, the treated outflow from a wastewater treatment plant.

Enterococci: A subgroup of the fecal streptococci that includes *S. faecalis*, *S. faecium*, *S. gallinarum,* and *S. avium*. The enterococci are differentiated from other streptococci by their ability to grow in 6.5% sodium chloride, at pH 9.6, and at 10 degrees C and 45 degrees C.

Eutrophic: Nutrient rich and high in productivity resulting from human activities such as fertilizer runoff and leaky septic systems.

Existing uses: Those uses actually attained in fresh and marine waters on or after November 28, 1975, whether or not they are designated uses. Introduced species that are not native to Washington, and put-and-take fisheries comprised of non-self-replicating introduced native species, do not need to receive full support as an existing use.

Extraordinary primary contact: Waters providing extraordinary protection against waterborne disease or that serve as tributaries to extraordinary quality shellfish harvesting areas.

Fecal coliform (FC): That portion of the coliform group of bacteria which is present in intestinal tracts and feces of warm-blooded animals as detected by the product of acid or gas from lactose in a suitable culture medium within 24 hours at 44.5 plus or minus 0.2 degrees Celsius. Fecal coliform bacteria are "indicator" organisms that suggest the possible presence of disease-causing organisms. Concentrations are measured in colony forming units per 100 milliliters of water (cfu/100 mL).

Fish Tissue Equivalent Concentration (FTEC): The FTEC is a tissue contaminant concentration used by Ecology to determine whether the designated uses of fishing and drinking from surface waters are being met. The FTEC is an interpretation of Washington's water quality criterion for a specific chemical for the protection of human health: the National Toxics Rule (40 CFR 131.36). Fish tissue sample concentrations that are lower than the FTEC suggest that the uses of fishing and drinking from surface waters are being met for that specific contaminant. Where an FTEC is not met (i.e., concentration of a chemical in fish tissue is greater than the FTEC), that water body is then placed into Category 5 during Washington's periodic Water Quality Assessment (http://www.ecy.wa.gov/programs/Wq/303d/index.html). Category 5 listings become part of Washington's 303(d) list during the assessment process. The FTEC is calculated by multiplying the contaminant-specific Bio-Concentration Factor (BCF) times the contaminant-specific Water Quality Criterion found in the National Toxics Rule.

Geometric mean: A mathematical expression of the central tendency (an average) of multiple sample values. A geometric mean, unlike an arithmetic mean, tends to dampen the effect of very high or low values, which might bias the mean if a straight average (arithmetic mean) were calculated. This is helpful when analyzing bacteria concentrations, because levels may vary anywhere from 10 to 10,000 fold over a given period. The calculation is performed by either:
(1) taking the nth root of a product of n factors, or (2) taking the antilogarithm of the arithmetic mean of the logarithms of the individual values.

Hyporheic: The area beneath and adjacent to a stream where surface water and groundwater intermix.

Load allocation: The portion of a receiving water's loading capacity attributed to one or more of its existing or future sources of nonpoint pollution or to natural background sources.

Loading capacity: The greatest amount of a substance that a water body can receive and still meet water quality standards.

Margin of safety: Required component of TMDLs that accounts for uncertainty about the relationship between pollutant loads and quality of the receiving water body.

Municipal separate storm sewer systems (MS4): A conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, manmade channels, or storm drains): (1) owned or operated by a state, city, town, borough, county, parish, district, association, or other public body having jurisdiction over disposal of wastes, stormwater, or other wastes and (2) designed or used for collecting or conveying stormwater; (3) which is not a combined sewer; and (4) which is not part of a Publicly Owned Treatment Works (POTW) as defined in the Code of Federal Regulations at 40 CFR 122.2.

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Near-stream disturbance zone (NSDZ): The active channel area without riparian vegetation that includes features such as gravel bars.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Nutrient: Substance such as carbon, nitrogen, and phosphorus used by organisms to live and grow. Too many nutrients in the water can promote algal blooms and rob the water of oxygen vital to aquatic organisms.

Pathogen: Disease-causing microorganisms such as bacteria, protozoa, viruses.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Phase I stormwater permit: The first phase of stormwater regulation required under the federal Clean Water Act. The permit is issued to medium and large municipal separate storm sewer systems (MS4s) and construction sites of five or more acres.

Phase II stormwater permit: The second phase of stormwater regulation required under the federal Clean Water Act. The permit is issued to smaller municipal separate storm sewer systems (MS4s) and construction sites over one acre.

Point source: Source of pollution that discharges at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Primary contact recreation: Activities where a person would have direct contact with water to the point of complete submergence including, but not limited to, skin diving, swimming, and water skiing.

Reach: A specific portion or segment of a stream.

Riparian: Relating to the banks along a natural course of water.

Salmonid: Fish that belong to the family *Salmonidae*. Any species of salmon, trout, or char.

Sediment: Soil and organic matter that is covered with water (for example, river or lake bottom).

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Streamflow: Discharge of water in a surface stream (river or creek).

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

Synoptic survey: Data collected simultaneously or over a short period of time.

System potential: The design condition used for TMDL analysis.

System-potential channel morphology: The more stable configuration that would occur with less human disturbance.

S**ystem-potential mature riparian vegetation:** Vegetation which can grow and reproduce on a site, given climate, elevation, soil properties, plant biology, and hydrologic processes.

System-potential riparian microclimate: The best estimate of air temperature reductions that are expected under mature riparian vegetation. System-potential riparian microclimate can also include expected changes to wind speed and relative humidity.

System-potential temperature: An approximation of the temperatures that would occur under natural conditions. System potential is our best understanding of natural conditions that can be supported by available analytical methods. The simulation of the system-potential condition uses best estimates of *mature riparian vegetation, system-potential channel morphology, and system-potential riparian microclimate* that would occur absent any human alteration.

Thalweg: The deepest and fastest moving portion of a stream.

Total Maximum Daily Load (TMDL): A distribution of a substance in a water body designed to protect it from not meeting (exceeding) water quality standards. A TMDL is equal to the sum of all of the following: (1) individual waste load allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a margin of safety to allow for uncertainty in the waste load determination. A reserve for future growth is also generally provided.

Total suspended solids (TSS): Portion of solids retained by a filter.

Turbidity: A measure of water clarity. High levels of turbidity can have a negative impact on aquatic life.

Waste load allocation: The portion of a receiving water's loading capacity allocated to existing or future point sources of pollution. Waste load allocations constitute one type of water quality-based effluent limitation.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

1-DMax or 1-day maximum temperature: The highest water temperature reached on any given day. This measure can be obtained using calibrated maximum/minimum thermometers or continuous monitoring probes having sampling intervals of thirty minutes or less.

303(d) list: Section 303(d) of the federal Clean Water Act, requiring Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. These are water quality-limited estuaries, lakes, and streams that fall short of state surface water quality standards and are not expected to improve within the next two years.

7-DADMax or 7-day average of the daily maximum temperatures: The arithmetic average of seven consecutive measures of daily maximum temperatures. The 7-DADMax for any individual day is calculated by averaging that day's daily maximum temperature with the daily maximum temperatures of the three days before and the three days after that date.

7Q2 flow: A typical low-flow condition. The 7Q2 is a statistical estimate of the lowest 7-day average flow that can be expected to occur once every other year on average. The 7Q2 flow is commonly used to represent the average low-flow condition in a water body and is typically calculated from long-term flow data collected in each basin. For temperature TMDL work, the 7Q2 is usually calculated for the months of July and August as these typically represent the critical months for temperature in our state.

7Q10 flow: A critical low-flow condition. The 7Q10 is a statistical estimate of the lowest 7-day average flow that can be expected to occur once every ten years on average. The 7Q10 flow is commonly used to represent the critical flow condition in a water body and is typically calculated from long-term flow data collected in each basin. For temperature TMDL work, the 7Q10 is usually calculated for the months of July and August as these typically represent the critical months for temperature in our state.

90th percentile: An estimated portion of a sample population based on a statistical determination of distribution characteristics. The 90th percentile value is a statistically derived estimate of the division between 90% of samples, which should be less than the value, and 10% of samples, which are expected to exceed the value.

Acronyms and Abbreviations

BMP	Best management practice
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	contaminant of concern
cPAH	Carcinogenic Polycyclic Aromatic Hydrocarbons
CSO	Combined sewer ovesrflow
CTD	Conductivity, Temperature, Depth
CM	Conceptual Model
CWA	Clean Water Act
DEM	Digital elevation model
DO	(see Glossary above)
DOC	Dissolved organic carbon
e.g.	For example
EAP	Environmental Assessment Program
Ecology	Washington State Department of Ecology
EFDC	Environmental Fluid Dynamics Code
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency (also USEPA)et al. And others
FC	(see Glossary above)
FWM	Food Web Model
GIS	Geographic Information System software
GPS	Global Positioning System
HHD	Howard Hansen Dam
HHRA	Human Health Risk Assessment
HRU	Hydrologic Response Unit
HSPF	Hydrological Simulation Program - FORTRAN
i.e.	In other words
INTFW	interflow inflow
LDW	Lower Duwamish Waterway
LDWG	Lower Duwamish Waterway Group
LSPC	Loading Simulation Program - C++ model
LZSN	lower zone nominal soil storage capacity

MEL	Manchester Environmental Laboratory
MQO	Measurement quality objective
MTCA	Model Toxics Control Act
NAF	New Approximation Flow
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NPDES	(See Glossary above)
NSDZ	Near-stream disturbance zones
NTR	National Toxics Rule
NWIS	National Water Information System
PAH	Polycyclic Aromatic Hydrocarbons
PBDE	polybrominated diphenyl ethers
PBT	persistent, bioaccumulative, and toxic substance
PCB	polychlorinated biphenyl
PLA	Pollutant Loading Assessment
PP	Proposed Plan
QA	Quality assurance
QAPP	Quality Assurance Project Plan
QC	Quality control
QEA	Quantitative Environmental Analysis, LLC
RI	Remedial Investigation
RM	River mile
RPD	Relative percent difference
RSD	Relative standard deviation
SOP	Standard operating procedure
SRM	Standard reference materials
SSM	Salish Sea Model
STAR	Sediment Transport Analysis Report, by QEA
STM	LDW Sediment Transport Model, by QEA
TEQ	toxic equivalents
TIR	Thermal infrared radiation
TMDL	(See Glossary above)
TOC	Total organic carbon

TSS	(See Glossary above)
USFS	United States Forest Service
USGS	United States Geological Survey
UZSN	upper zone soil storage capacity
WAC	Washington Administrative Code
WDFW	Washington Department of Fish and Wildlife
WQA	Water Quality Assessment
WRIA	Water Resource Inventory Area
WSTMP	Washington State Toxics Monitoring Program
WWTP	Wastewater treatment plant

Units of Measurement

°C	degrees centigrade
cfs	cubic feet per second
cfu	colony forming units
cms	cubic meters per second, a unit of flow
dw	dry weight
ft	feet
g	gram, a unit of mass
kcfs	1000 cubic feet per second
kg	kilograms, a unit of mass equal to 1,000 grams
kg/d	kilograms per day
km	kilometer, a unit of length equal to 1,000 meters
l/s	liters per second (0.03531 cubic foot per second)
m	meter
mm	millimeter
mg	milligram
mgd	million gallons per day
mg/d	milligrams per day
mg/Kg	milligrams per kilogram (parts per million)
mg/L	milligrams per liter (parts per million)
mg/L/hr	milligrams per liter per hour

mL	milliliter
mmol	millimole or one-thousandth of a mole
mole	an International System of Units (IS) unit of matter
ng/g	nanograms per gram (parts per billion)
ng/Kg	nanograms per kilogram (parts per trillion)
ng/L	nanograms per liter (parts per trillion)
NTU	nephelometric turbidity units
pg/g	picograms per gram (parts per trillion)
pg/L	picograms per liter (parts per quadrillion)
psu	practical salinity units
s.u.	standard units
ug/g	micrograms per gram (parts per million)
ug/Kg	micrograms per kilogram (parts per billion)
ug/L	micrograms per liter (parts per billion)
um	micrometer
uM	micromolar (a chemistry unit)
umhos/cm	micromhos per centimeter
uS/cm	microsiemens per centimeter, a unit of conductivity
ww	wet weight

Quality Assurance Glossary

Accreditation: A certification process for laboratories, designed to evaluate and document a lab's ability to perform analytical methods and produce acceptable data. For Ecology, it is "Formal recognition by (Ecology)…that an environmental laboratory is capable of producing accurate analytical data." [WAC 173-50-040] (Kammin, 2010)

Accuracy: The degree to which a measured value agrees with the true value of the measured property. USEPA recommends that this term not be used, and that the terms precision and bias be used to convey the information associated with the term accuracy. (USGS, 1998)

Analyte: An element, ion, compound, or chemical moiety (pH, alkalinity) which is to be determined. The definition can be expanded to include organisms, e.g., fecal coliform, Klebsiella. (Kammin, 2010)

Bias: The difference between the population mean and the true value. Bias usually describes a systematic difference reproducible over time, and is characteristic of both the measurement system, and the analyte(s) being measured. Bias is a commonly used data quality indicator (DQI). (Kammin, 2010; Ecology, 2004)

Blank: A synthetic sample, free of the analyte(s) of interest. For example, in water analysis, pure water is used for the blank. In chemical analysis, a blank is used to estimate the analytical response to all factors other than the analyte in the sample. In general, blanks are used to assess possible contamination or inadvertent introduction of analyte during various stages of the sampling and analytical process. (USGS, 1998)

Calibration: The process of establishing the relationship between the response of a measurement system and the concentration of the parameter being measured. (Ecology, 2004)

Check standard: A substance or reference material obtained from a source independent from the source of the calibration standard; used to assess bias for an analytical method. This is an obsolete term, and its use is highly discouraged. See Calibration Verification Standards, Lab Control Samples (LCS), Certified Reference Materials (CRM), and/or spiked blanks. These are all check standards, but should be referred to by their actual designator, e.g., CRM, LCS. (Kammin, 2010; Ecology, 2004)

Comparability: The degree to which different methods, data sets and/or decisions agree or can be represented as similar; a data quality indicator. (USEPA, 1997)

Completeness: The amount of valid data obtained from a project compared to the planned amount. Usually expressed as a percentage. A data quality indicator. (USEPA, 1997)

Continuing Calibration Verification Standard (CCV): A QC sample analyzed with samples to check for acceptable bias in the measurement system. The CCV is usually a midpoint calibration standard that is re-run at an established frequency during the course of an analytical run. (Kammin, 2010)
Control chart: A graphical representation of quality control results demonstrating the performance of an aspect of a measurement system. (Kammin, 2010; Ecology 2004)

Control limits: Statistical warning and action limits calculated based on control charts. Warning limits are generally set at +/- 2 standard deviations from the mean, action limits at +/- 3 standard deviations from the mean. (Kammin, 2010)

Data integrity: A qualitative DQI that evaluates the extent to which a data set contains data that is misrepresented, falsified, or deliberately misleading. (Kammin, 2010)

Data Quality Indicators (DQI): Commonly used measures of acceptability for environmental data. The principal DQIs are precision, bias, representativeness, comparability, completeness, sensitivity, and integrity. (USEPA, 2006)

Data Quality Objectives (DQO): Qualitative and quantitative statements derived from systematic planning processes that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.(USEPA, 2006)

Data set: A grouping of samples organized by date, time, analyte, etc. (Kammin, 2010)

Data validation: An analyte-specific and sample-specific process that extends the evaluation of data beyond data verification to determine the usability of a specific data set. It involves a detailed examination of the data package, using both professional judgment, and objective criteria, to determine whether the MQOs for precision, bias, and sensitivity have been met. It may also include an assessment of completeness, representativeness, comparability and integrity, as these criteria relate to the usability of the data set. Ecology considers four key criteria to determine if data validation has actually occurred. These are:

- Use of raw or instrument data for evaluation.
- Use of third-party assessors.
- Data set is complex.
- Use of EPA Functional Guidelines or equivalent for review.

Examples of data types commonly validated would be:

- Gas Chromatography (GC).
- Gas Chromatography-Mass Spectrometry (GC-MS).
- Inductively Coupled Plasma (ICP).

The end result of a formal validation process is a determination of usability that assigns qualifiers to indicate usability status for every measurement result. These qualifiers include:

- No qualifier, data is usable for intended purposes.
- J (or a J variant), data is estimated, may be usable, may be biased high or low.
- REJ, data is rejected, cannot be used for intended purposes (Kammin, 2010; Ecology, 2004).

Data verification: Examination of a data set for errors or omissions, and assessment of the Data Quality Indicators related to that data set for compliance with acceptance criteria (MQOs). Verification is a detailed quality review of a data set. (Ecology, 2004)

Detection limit (limit of detection)**:** The concentration or amount of an analyte which can be determined to a specified level of certainty to be greater than zero. (Ecology, 2004)

Duplicate samples: Two samples taken from and representative of the same population, and carried through and steps of the sampling and analytical procedures in an identical manner. Duplicate samples are used to assess variability of all method activities including sampling and analysis. (USEPA, 1997)

Field blank: A blank used to obtain information on contamination introduced during sample collection, storage, and transport. (Ecology, 2004)

Initial Calibration Verification Standard (ICV): A QC sample prepared independently of calibration standards and analyzed along with the samples to check for acceptable bias in the measurement system. The ICV is analyzed prior to the analysis of any samples. (Kammin, 2010)

Laboratory Control Sample (LCS): A sample of known composition prepared using contaminant-free water or an inert solid that is spiked with analytes of interest at the midpoint of the calibration curve or at the level of concern. It is prepared and analyzed in the same batch of regular samples using the same sample preparation method, reagents, and analytical methods employed for regular samples. (USEPA, 1997)

Matrix spike: A QC sample prepared by adding a known amount of the target analyte(s) to an aliquot of a sample to check for bias due to interference or matrix effects. (Ecology, 2004)

Measurement Quality Objectives (MQOs)**:** Performance or acceptance criteria for individual data quality indicators, usually including precision, bias, sensitivity, completeness, comparability, and representativeness. (USEPA, 2006)

Measurement result: A value obtained by performing the procedure described in a method. (Ecology, 2004)

Method: A formalized group of procedures and techniques for performing an activity (e.g., sampling, chemical analysis, data analysis), systematically presented in the order in which they are to be executed. (EPA, 1997)

Method blank: A blank prepared to represent the sample matrix, prepared and analyzed with a batch of samples. A method blank will contain all reagents used in the preparation of a sample, and the same preparation process is used for the method blank and samples. (Ecology, 2004; Kammin, 2010)

Method Detection Limit (MDL): This definition for detection was first formally advanced in 40CFR 136, October 26, 1984 edition. MDL is defined there as the minimum concentration of an analyte that, in a given matrix and with a specific method, has a 99% probability of being identified, and reported to be greater than zero. (Federal Register, October 26, 1984)

Percent Relative Standard Deviation (%RSD): A statistic used to evaluate precision in environmental analysis. It is determined in the following manner:

$$\%RSD = (100 * s)/x$$

where s is the sample standard deviation and x is the mean of results from more than two replicate samples. (Kammin, 2010)

Parameter: A specified characteristic of a population or sample. Also, an analyte or grouping of analytes. Benzene and nitrate + nitrite are all "parameters." (Kammin, 2010; Ecology, 2004)

Population: The hypothetical set of all possible observations of the type being investigated. (Ecology, 2004)

Precision: The extent of random variability among replicate measurements of the same property; a data quality indicator. (USGS, 1998)

Quality assurance (QA): A set of activities designed to establish and document the reliability and usability of measurement data. (Kammin, 2010)

Quality Assurance Project Plan (QAPP): A document that describes the objectives of a project, and the processes and activities necessary to develop data that will support those objectives. (Kammin, 2010; Ecology, 2004)

Quality control (QC): The routine application of measurement and statistical procedures to assess the accuracy of measurement data. (Ecology, 2004)

Relative Percent Difference (RPD): RPD is commonly used to evaluate precision. The following formula is used:

$$[Abs(a-b)/((a + b)/2)] * 100$$

where "Abs()" is absolute value and a and b are results for the two replicate samples. RPD can be used only with 2 values. Percent Relative Standard Deviation is (%RSD) is used if there are results for more than 2 replicate samples (Ecology, 2004).

Replicate samples: Two or more samples taken from the environment at the same time and place, using the same protocols. Replicates are used to estimate the random variability of the material sampled. (USGS, 1998)

Representativeness: The degree to which a sample reflects the population from which it is taken; a data quality indicator. (USGS, 1998)

Sample (field): A portion of a population (environmental entity) that is measured and assumed to represent the entire population. (USGS, 1998)

Sample (statistical): A finite part or subset of a statistical population. (USEPA, 1997)

Sensitivity: In general, denotes the rate at which the analytical response (e.g., absorbance, volume, meter reading) varies with the concentration of the parameter being determined. In a specialized sense, it has the same meaning as the detection limit. (Ecology, 2004)

Spiked blank: A specified amount of reagent blank fortified with a known mass of the target analyte(s); usually used to assess the recovery efficiency of the method. (USEPA, 1997)

Spiked sample: A sample prepared by adding a known mass of target analyte(s) to a specified amount of matrix sample for which an independent estimate of target analyte(s) concentration is available. Spiked samples can be used to determine the effect of the matrix on a method's recovery efficiency. (USEPA, 1997)

Split sample: A discrete sample subdivided into portions, usually duplicates (Kammin, 2010)

Standard Operating Procedure (SOP): A document which describes in detail a reproducible and repeatable organized activity. (Kammin, 2010)

Surrogate: For environmental chemistry, a surrogate is a substance with properties similar to those of the target analyte(s). Surrogates are unlikely to be native to environmental samples. They are added to environmental samples for quality control purposes, to track extraction efficiency and/or measure analyte recovery. Deuterated organic compounds are examples of surrogates commonly used in organic compound analysis. (Kammin, 2010)

Systematic planning: A step-wise process which develops a clear description of the goals and objectives of a project, and produces decisions on the type, quantity, and quality of data that will be needed to meet those goals and objectives. The DQO process is a specialized type of systematic planning. (USEPA, 2006)

References for QA Glossary

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