18912 North Creek Parkway, Suite 101
Bothell, Washington 98011
(425) 482-3329
FAX: (425) 485-5566

TECHNICAL MEMORANDUM

TO: Dan Cargill / Ecology

FROM: John Nakayama / NewFields
Jon Nuwer / NewFields
Glen Vedera / SAIC

DATE: December 14, 2010

SUBJECT: Evaluation of Lateral Loading Models

1.0 Introduction

Science Applications International Corporation (SAIC) is assisting the Washington State Department of Ecology (Ecology) with the development of a study to better understand the potential for sediment recontamination associated with stormwater discharges in the Lower Duwamish Waterway (LDW) (SAIC 2009a; 2009b; 2009c). NewFields provides project support as a subcontractor to SAIC. The Stormwater Lateral Loading Study includes measuring contaminant concentrations associated with stormwater discharges and estimating lateral sediment loadings from significant storm drain outfalls in the LDW. To facilitate this process, Ecology has tasked SAIC with the collection of stormwater, storm drain solids, and continuous flow measurements from four LDW storm drain lines representative of different land use types.

A wide range of contaminants are present in a 5.5-mile reach of the LDW, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and metals. High concentrations of these contaminants have made this portion of the LDW a Federal Superfund and state Model Toxic Control Act (MTCA) site. Ecology supports the Environmental Protection Agency (EPA) efforts on the LDW Remedial Investigation/Feasibility Study (RI/FS) and is leading source control efforts in coordination with local governments. Ecology and EPA are currently implementing a two-phase RI/FS with the potentially responsible parties (PRPs), collectively known as the Lower Duwamish Waterway Group (LDWG). The LDWG members are: City of Seattle, The Boeing Company, Port of Seattle, and King County.

The LDWG has estimated contaminant loading to the LDW through a multi-step process including stormwater runoff modeling, sediment transport modeling, and the application of catch basin and inline solids data. Ecology plans to begin collecting data to help evaluate how well these estimates correlate to actual input of contaminants to the waterway. As part of this evaluation, Ecology plans to measure contaminant concentrations and loadings in stormwater and storm drain solids from significant stormwater outfalls within the LDW study area.

The objectives of the lateral loading study include:

- Collection of data necessary to assess contaminant loading from four significant municipal and industrial stormwater outfalls;
- Identification of stormwater contaminants associated with different land use types;
- Estimation of stormwater contaminant lateral loadings for the studied outfalls; and
- To the extent possible, correlation of in-line sediment trap solids, filtered suspended solids, and catch basin solids data with stormwater data.

The purpose of this Technical Memorandum is to evaluate potential modeling approaches that could be used to estimate contaminant loading and accumulation in LDW sediments in the vicinity of the studied outfalls, and to identify data collection needs to be incorporated into the draft Stormwater Lateral Loading Study Sampling and Analysis Plan (SAP), currently in preparation. Section 2.0 of this Technical Memorandum describes proposed methods for calculation of stormwater contaminant loading to the LDW. Section 3.0 discusses fate and transport models evaluated for possible application to LDW outfalls, and the recommended modeling approach.

2.0 Lateral Loading Calculations

To predict whether localized sediment contamination to levels above the Washington State Sediment Management Standards (SMS) or other approved cleanup standards is likely to occur, estimates of stormwater contaminant loads are needed for input into fate and transport estimation tools and models. Contaminant loading is the product of an outfall's annual discharge volume and the annual mean chemical concentration in the discharge. Loadings will be calculated using the general methods presented in Ecology's *Standard Operating Procedure for Calculating Pollutant Loads for Stormwater Discharges* (Ecology 2009).

2.1 Stormwater Discharge Volume

Annual and event-based stormwater discharge volumes used to calculate chemical loadings will be estimated using modeled rather than measured flow. The surface area of each lateral line sub-basin drainage will be calculated using GIS software. Thiessen polygon analysis of storm drain (SD) structure shapefiles will be used to determine probable drainage boundaries. In order to take into account the large amounts of impervious surface found in these drainages, the surface areas will be adjusted for the ratio of impervious to pervious surface.

Annual and event-based stormwater discharge volumes will be calculated using the following equations, based on Ecology's standard operating procedure (SOP) (Ecology 2009):

$$V = (P/12) * A * RC$$

Where:

V is the discharge volume for the sub-basin in units of cubic feet.

P is precipitation (annual or event) in units of inches.

A is the drainage sub-basin surface area in units of square feet.

RC is the runoff coefficient for the sub-basin.

$RC = 0.009 * IMP + 0.05$

Where:

IMP is the percent impervious surface for the drainage sub-basin.

Measured flow volumes for storm events will not be used to directly calculate stormwater discharge volumes because of the intertidal nature of some of the sampled drain lines. Rising and falling tides influence both water velocity and depth measured by the flow sensor, leading to errors in stormwater volume estimates. Storm event flow data collected during time periods when drain lines are not tidally influenced will be used to assess the accuracy of the runoff coefficient used to estimate runoff volume.

2.2 Annual Mean Contaminant Concentration

Estimation of chemical mass load from stormwater requires an understanding of the chemical concentrations in stormwater. Stormwater chemical concentrations are widely variable depending on factors including (Anchor and Integral 2007):

- Specific chemical sources, which may vary over time and location within a drainage basin;
- Characteristics of the storms and their associated runoff (e.g., dry periods, storm volume, storm intensity and duration, collection system characteristics, and condition of source controls);
- How and where the stormwater is sampled; and
- When the samples are collected during a specific storm (e.g., first flush, rising limb, falling limb).

Stormwater chemical concentrations can be measured in several ways, each of which has advantages and disadvantages. These were discussed by Anchor and Integral (2007), SAIC (2009d), and others, and are summarized in Table 1.

Table 1. Stormwater Sample Types

Sampling Type	Advantages	Disadvantages
Whole-water Grab Samples	Provides a direct measure of chemical concentrations in water that can be converted to a load in one step (multiplying by volume discharged per unit time). Logistically easy and inexpensive to collect.	Captures one small condition in time. Preferentially captures only the fines portion of the particulate load. Samples are filtered prior to analysis. Cannot provide concentrations for the particulate fraction unless a very large sample volume is available. Analytical detection limits may not be adequate to detect chemicals present in stormwater at very low concentrations, particularly for hydrophobic chemicals, unless large volumes are collected and analyzed.

Sampling Type	Advantages	Disadvantages
Whole-water Composite Samples	Provides a direct measure of chemical concentrations in water that can be converted to a load in one step (multiplying by volume discharged per unit time). Samples a large portion of a runoff event. Samples can be composited based on flow to create a sample representative of the entire event.	Preferentially captures only the fines portion of the particulate load. Samples may be filtered prior to analysis. Cannot provide concentrations for the particulate fraction unless a very large sample volume is available. Analytical detection limits may not be adequate to detect chemicals present in stormwater at very low concentrations, particularly for hydrophobic chemicals, unless large volumes are collected. Samples are collected over a relatively short period of time (hours or days). Sample collection is more difficult and therefore more costly.
Sediment Traps	If left in place long enough, can accumulate a large enough sediment sample to reduce the likelihood of analytical limitations. Integrate the particulate-associated chemical loading over a relatively long period of time (4 to 7 months). Provide data for the stormwater particulate load that may recontaminate river sediments. Logistically simple to implement.	Do not measure dissolved load. Preferentially capture only portions of the coarser fraction of the particulate load, depending on trap design. Provide a much less direct measurement of the overall stormwater chemical load, and may not be representative of the actual stormwater discharge. Grain size data would be useful; however, sample volumes are frequently too low to allow for grain size analysis. Samples are collected under somewhat turbulent conditions and therefore are likely to contain a smaller percentage of fine-grained particles (fine silt, clay) than stormwater. Long sampling period is required to collect adequate sample volumes for analysis.
High Volume Water Filtering Techniques (e.g., Filter Bags, Continuous Flow Centrifuge)	Method can be used in locations where sediment traps cannot be installed. Samples will likely contain a higher percentage of fine-grained particles than sediment traps.	Sampling is labor intensive. Sample collection requires pumping that may exclude coarse-grained particles. Samples are collected over a relatively short period of time (hours or days) and therefore have the same time integration limitations as composite stormwater sampling.
Sediment Grab Samples	Logistically easy and inexpensive to collect.	Grab samples from SD structures such as catch basins and manholes tend to contain a smaller percentage of fine-grained particles (fine silt, clay) than stormwater, and thus are not representative of chemical concentrations in stormwater.

For the Lateral Loading Study, whole water samples and filtered solids samples will be separately used to calculate contaminant loadings for each studied outfall. Annual mean concentrations in both whole water and filtered suspended solids will be calculated using a volume-weighted mean approach:

$$AMC = \frac{\sum (C_i * F_i)}{\sum F_i}$$

Where:

AMC is the annual mean contaminant concentration.

C_i *is* the concentration for storm or base flow event *i*.

F_i *is* the average flow for storm or base flow event *i* (total event discharge volume divided by sampling time).

2.3 Contaminant Loading

Whole water loadings will be calculated using the following equation:

$$ML_w = V * AMC$$

Where:

ML_w is the annual contaminant mass loading from stormwater in units of mg/yr.

V is the annual predicted discharge volume in units of liters/yr.

AMC is the annual mean contaminant concentration in whole water in units of mg/liter.

Contaminant loadings from suspended solids will be calculated using the equation:

$$ML_s = V * AMC * TSS$$

Where:

ML_s is the annual contaminant mass loading from solids in units of mg/yr.

V is the annual predicted discharge volume in units of liters/yr.

AMC is the annual mean contaminant concentration in suspended solids in units of mg/kg.

TSS is the measured mean total suspended solids concentration in units of kg/L.

3.0 Fate and Transport Modeling

A model is a simplified description of a system or process that is put forward as a basis for calculations, predictions, or further investigation. Estimates of stormwater contaminant loading will be used as input for a fate and transport model to estimate the maximum allowable concentrations of contaminants in stormwater that will not recontaminate LDW sediments to levels above sediment cleanup standards. Models specifically developed for predicting the fate and transport of chemical pollutants discharged from storm drains into receiving surface water bodies are lacking (Blakley 2004). This is in part due to the complex interface between the storm drain outfalls and the receiving water body. In the case of stormwater discharges to the LDW, such a model would ideally need to encompass such conditions as the intermittent submergence of outfalls at high tidal stages and stormwater discharge to riprap and tidal mudflats. An ideal model would also be able to predict pollutant concentrations in sediment in the immediate vicinity of the outfall (near-field) and larger scale impacts due to longer-range transport of pollutants in the waterway (far-field).

As with any modeling endeavor, there are numerous possible modeling approaches that could be applied to LDW outfalls that vary in both their level of complexity and the level of effort required to construct and operate them. In choosing a specific modeling approach, there is generally a trade-off between cost and uncertainty of the results. The most appropriate modeling approach for the system should stress the aspects of reality that are assumed to be important and omit processes considered to be nonessential. Sensitivity analysis can identify what sources of uncertainty weigh most on the model's conclusions. Demonstrating that model results are insensitive to a particular process allows the model to be simplified through removal of that process.

Different stormwater models, and their associated data requirements, that could be applied to LDW outfalls have been reviewed and summarized by SAIC (2009d). These modeling approaches are listed below in a hierarchical order based on their increasing level of complexity and decreasing degree of uncertainty. Information required for parameterization is listed with each model:

Box Model – Mass balance of particle and contaminant sources and sinks:

- Lateral loading chemical and particle flux,
- Fraction of lateral loading that escapes deposition,
- Upstream loading chemical and particle flux,
- Chemical composition of surface sediments,
- Sedimentation rate, and
- Size of active depositional area.

Sediment Bed Model - Inclusion of processes within the sediment bed and the transfer of particles and contaminants between the overlying water column and sediment bed:

- Water residence time,
- Depth of the mixed layer,
- Chemical composition of sediment below the mixed layer,
- Chemical degradation and diffusion coefficients,
- Bioturbation coefficient,
- Sediment resuspension velocity, and
- Particle settling velocity.

Chemical Partitioning Model – Different chemical components display distinct partitioning behavior:

- Chemical partitioning coefficients.

Near-field Depositional Model – Incorporates hydrodynamic properties of the effluent and the receiving water body:

- Discharge velocity,
- Discharge buoyancy,
- Particle settling velocity,
- Tidal velocity, and
- Bathymetry.

Environmental Fluid Dynamics Code (EFDC) – Can integrate all aspects of the box, sediment bed, chemical partitioning, and near-field models.

3.1 Model Design

The modeling scheme recommended for use in the Lateral Loading Study for the development of threshold stormwater contaminant concentrations is a one-dimensional sedimentation model which is calibrated with results from a higher resolution EFDC model specific to LDW outfalls. This modeling scheme is a combination of methods that have previously been employed by SAIC for the *NBF-GTSP RI/FS Slip 4 Sediment Recontamination Modeling Report* (SAIC 2010a) and the *LDW Industrial Stormwater Monitoring Study* (SAIC 2010b). A one-dimensional sedimentation model will be developed, which takes into account stormwater discharge, transport, and particle deposition in the vicinity of the studied outfalls. This analytical model was initially developed for characterizing both the threshold particle size and horizontal length scale of deposition for suspended solids discharged by storm drains to the LDW's Slip 4 (KCDNR 2009a).

An advantage of this analytical model over more complex models is its ease of setup and implementation. This allows the sedimentation model to be configured for a variety of relevant scenarios that may affect output. A number of different model configurations will be independently run for each outfall in order to assess the uncertainty introduced by variability in both water depth and horizontal velocity caused by tides.

This one-dimensional model is not expected to reproduce the complex depositional patterns observed in the vicinity of outfalls, nor will it predict the temporal evolution of surface sediment concentrations. Instead, application of the analytical model to the individual outfalls provides estimates of the suspended solid mass and particle size distribution that settle as a function of distance from the outfalls. Calibration of the model to LDW Sediment Transport Model (STM) results (QEA 2008) and EFDC modeling of the LDW S Brandon Street combined sewer overflow (CSO) results (KCDNR 2009b) will be used to account for the multiple dynamic processes not directly modeled (dispersion, diffusion, dilution, etc.). These findings will then be extrapolated to the deposition of particle-associated chemicals to the sediment bed using chemical concentrations of SD solids.

Once adequately parameterized to mimic the specific outfall system, the modeling framework can be employed to calculate the independent variables through reverse modeling. By assuming a particle size distribution for discharged SD solids, reverse modeling permits estimation of the maximum allowable SD solids contaminant concentrations that are not expected to cause contamination of LDW surface sediments to concentrations above cleanup criteria.

3.2 Model Parameterization

Parameterization of the LDW sedimentation model to predict the deposition of SD solids and associated contaminants requires the following outfall-specific data:

- Particle settling velocities of SD solids discharged by the outfall,
- LDW flow velocity in the vicinity of the outfall,
- Water depth in the vicinity of the outfall, and
- Chemical concentrations in different particle size classes of SD solids.

Model runs result in the predicted particle size distribution of deposited SD solids as a function of distance from the outfall based on the following equation (KCDNR 2009a):

$$\bar{C}_s = 1 - \exp\left(-\frac{Lw}{UH}\right)$$

Where: $\bar{C}_s$ = Fraction of the depth-averaged suspended solids that settle
L = Distance from outfall (ft)
w = Particle settling velocity (ft/s)
U = Horizontal velocity (ft/s)
H = Average water depth (ft)

The resulting deposited particle size distribution as a function of distance can then be used to calculate predicted sediment chemical concentrations by applying the chemical concentrations of SD solid size fractions.

3.3 Model Calibration

Calibration is the process of modifying model parameters to fit an observed set of data within some acceptable criteria. The one-dimensional sedimentation model results will first be calibrated to the results of a high resolution, multi-dimensional outfall model. Particle deposition estimated by the sedimentation model will be calibrated to EFDC particle modeling results of for the S Brandon Street CSO (KCDNR 2009b). These results suggest that only a small fraction of fine silt and clay particles discharged by the CSO are deposited within a 100-meter radius of the outfall (Table 2).

Table 2. EFDC Model Results for Brandon St. CSO Particle Deposition in the LDW

100m Radius of Outfall	Sand	Coarse Silt	Fine Silt	Clay
Deposition Within	42.5%	17.0%	2.2%	0.1%
Deposition Outside	57.5%	83.0%	97.8%	99.9%

Calibration of the sedimentation model will also take into account the dilution of deposited SD solids by sediments from other sources. Sediment mass loadings for each outfall will be used to determine the local sedimentation rates in the vicinity of the outfalls due only to deposited SD solids. These rates will be calibrated to those predicted by the LDW STM in the vicinity of the outfall (QEA 2008). In order to achieve the full STM-predicted sedimentation rate, the deposition of “background” LDW particles within the outfall’s depositional area will likely be required. A sediment mass balance will be used to determine the degree of SD solids dilution by LDW particles as a function of distance from the outfall. By applying average LDW surface sediment chemical concentrations for the diluting sediment (Integral 2006), surface sediment chemical concentration in the vicinity of the outfall will be estimated. This distribution of surface sediment chemical concentrations will then be used to calculate SD solids maximum compliance concentrations for each of the modeled outfalls.

3.4 Calculating the SD Solids Maximum Compliance Concentrations

Maximum SD solids chemical concentrations expected not to cause sediment contamination in the vicinity of the outfalls will be estimated using the modeling framework outlined above and a technique called “reverse” modeling. During “forward” modeling, independent variables (depth, settling velocity, bulk SD solids chemical concentrations, etc.) will be used to estimate the dependent variable (surface sediment chemical concentrations) as a function of distance. During reverse modeling, the surface sediment chemical concentration is set to the sediment cleanup criteria (dependent variable becomes an independent variable) and the bulk SD solids chemical concentration is solved for (independent variable becomes a dependent variable). The other independent variables remain unchanged. This method has previously been used to calculate maximum SD solids compliance concentrations for the NBF-GTSP stormwater discharge to Slip 4 (SAIC 2010a).

4.0 Summary

A variety of approaches could be used to determine LDW stormwater loadings from outfalls and the maximum allowable concentrations of contaminants in stormwater that will not contaminate LDW sediments to levels above sediment cleanup standards.

The recommended method for determining loadings is through a combination of event-based measurements and drainage basin modeling. This can be accomplished through the measurement of stormwater and SD solids particle size distributions, TSS, and chemical concentrations. Flow data collected during these events can be used to calibrate model-estimated discharge volumes needed for the calculation of loadings.

Particle and chemical loadings can be utilized in a simple one-dimensional sedimentation model to estimate the depositional pattern of stormwater-derived contaminants. Rather than incorporating the complex hydrodynamics of both the LDW and stormwater plumes into a model, EFDC modeling results for an LDW CSO can be used to calibrate the simpler sedimentation model. LDW STM particle deposition results and chemical results for previously-analyzed LDW surface sediments can be used to tailor the model to each of the specific outfalls. A reverse modeling method can be used to calculate maximum SD solids compliance concentrations that would not be expected to cause localized LDW sediment contamination to levels above sediment cleanup standards.

References

Anchor and Integral. 2007. Portland Harbor RI/FS, Round 3A Field Sampling Plan: Stormwater Sampling. Prepared for the Willamette Group by Anchor Environmental, LLC and Integral Consulting Inc. March 1, 2007.

Blakley, N. 2004. Review of models with the potential application for contaminated sediments cleanup and source control in the Lower Duwamish Waterway. Prepared for Washington State Department of Ecology by Nigel Blakley. June 2004.

Ecology. 2009. Standard Operating Procedure for Calculating Pollutant Loads for Stormwater Dsicharges. Washington State Department of Ecology. Version 1.0

Integral. 2006. Lower Duwamish Waterway, Slip 4 Early Action Area. Engineering Evaluation/Cost Analysis. Prepare by Integral Consulting, Inc. for City of Seattle and King County. February 10, 2006.

KCDNR. 2009a. Estimating a Characteristic Length Scale for Particle Deposition at the Head of Slip 4. Prepared for the Washington State Department of Ecology. Prepared by Jeff Stern, King County, as transmitted by Brad Helland, Washington State Department of Ecology, via email on October 7, 2009.

KCDNR. 2009b. Analysis of parameters driving deposition of PCBs loaded from the Brandon CSO in the Duwamish River. Puget Sound Georgia Basin Regional Conference.

QEA. 2008. Lower Duwamish Waterway Sediment Transport Modeling Report. Prepared for U.S. Environmental Protection Agency, Region 10 by Quantitative Environmental Analysis, LLC, Montvale, New Jersey; October 2008.

SAIC. 2009a. Scoping of Lateral Loading Study, Technical Memorandum. Prepared for Washington State Department of Ecology. Prepared by Science Applications International Corporation, Bothell, WA. June 30, 2009.

SAIC. 2009b. Scoping of Lateral Loading Study, Previous Study and Existing Data. Prepared for Washington State Department of Ecology. Prepared by Science Applications International Corporation, Bothell, WA. June 30, 2009.

SAIC. 2009c. Scoping of Lateral Loading Study, Site Reconnaissance Report. Prepared for Washington State Department of Ecology. Prepared by Science Applications International Corporation, Bothell, WA. June 30, 2009.

SAIC. 2009d. North Boeing Field/Georgetown Steam Plant Site Remedial Investigation/Feasibility Study, Evaluation of Loading Models Technical Memorandum. Prepared for Washington State Department of Ecology by SAIC, Bothell, Washington; July 2009.

SAIC. 2010a. North Boeing Field/Georgetown Steam Plant Site Remedial Investigation/Feasibility Study, Slip 4 Sediment Recontamination Modeling Report. Prepared for Washington State Department of Ecology by SAIC, Bothell, Washington; September 2010.

SAIC. 2010b. Lower Duwamish Waterway Industrial Stormwater Monitoring Study, Summary Report. Prepared for Washington State Department of Ecology by SAIC, Bothell, Washington; June 2010.