CSO Sediment Quality Modeling for Lake Washington, Seattle WA.

November 2018

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Prepared for

State of Washington

Department of Ecology

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EXECUTIVE SUMMARY

The NPDES permit for the West Point Wastewater Treatment Plant (No. WA0029181) issued by the Washington State Department of Ecology included a provision for sediment characterization of seven Combined Sewer Overflow (CSO) outfall sites that discharge to Lake Washington. The permit allows sediment monitoring by the collection of field samples or estimated using computer models. This modeling report addresses the required modeling effort to characterize sediments for the seven CSOs.

The model estimated sediment deposition rates and SMS chemical exceedances that would occur under historical discharge conditions. Additional research into historical reporting and modeling was conducted to get the best estimate of historical releases for this modeling effort. There were no predicted exceedances of the CSL at any of the discharge locations although there was the potential for CSL exceedances of silver and di-n-octyl phthalate at the Henderson/Martin Luther King/ (H/MLK) outfall. SCO exceedances for three chemicals are predicted at H/MLK up to 98 feet from the outfall. The potential for an additional four chemicals exceeding the SCO and exceedances farther from the outfall exists. The potential for four chemicals to exceed the SCO at Belvoir/30th Ave PS up to 98 feet from the outfall exists but are not predicted. The remaining five CSOs have no known historical CSO discharges but has a few Emergency discharges; modeling determined that an average of 11MGY would had to have discharged at these sites to have caused a predicted SCO exceedance. There is little likelihood that amount of discharge occurred without notice at any of these sites.

Model uncertainty ranged from $\pm$84% to $\pm$40% for these sites – higher at sites with flatter or restricted geometry. The model met all project objectives and reasonably quantifies sediment deposition rates, which together with the County's solids chemistry dataset, reasonably predicts sediment chemical concentrations.

1.0. INTRODUCTION

The NPDES permit for the West Point Wastewater Treatment Plant (No. WA0029181) issued by the Washington State Department of Ecology (Ecology) and effective on February 15, 2015 includes Special Condition S13.B for sediment characterization of seven CSO outfall sites. The permit allows that characterization of sediment quality can be accomplished by the collection of field samples or estimated using computer models. The County often uses computer models to estimate the potential sediment chemical concentrations that result from County CSOs, particularly when other potential sources are nearby. This modeling report addresses the required modeling effort for seven CSOs defined in the West Point NPDES waste discharge permit consistent with the Post-Construction Monitoring Plan (PCMP; King County, 2012), and with the modeling procedures that have been further defined in the Sediment Management Plan, 2017 Update (King County, 2018a).

1.1 Problem Definition and Background

The NPDES permit condition S13.B requires that the County must model and/or collect sediment samples in the vicinities of seven CSO outfall sites: East Pine Street Pump Station (PS) Emergency Overflow (011), Belvoir (012)/30th Ave NE PS (049), Martin Luther King (013)/Henderson PS (045), Matthews Park PS Emergency Overflow (018), and Rainier Avenue PS Emergency Overflow (033). The seven CSO sites discharge into Lake Washington (Figure 1) at five locations. Belvoir and 30th Ave NE share a discharge location and Martin Luther King and Henderson share a discharge location. The permit also requires submittal of a report containing the results and analysis of the characterization by December 1, 2018.

The County proposed in the sampling and analysis plan required by Ecology to use a simple analytical model to estimate sediment contamination from the County's CSOs (King County 2017). This approach also provides a method for separating different sources at sites shared by multiple outfalls. A physical sample presents information from all sources and without a known and unique signature compound from each source it can be difficult to separate contributions from the different sources. This report provides the modeling results and analysis per condition S13.B.

1.2 Description of Study Area

Lake Washington is the largest of the three major lakes in King County, and the second largest natural lake in the State of Washington. Lake Washington's two major influent streams are the Cedar River at the southern end, which contributes about 57 percent of the annual hydraulic load, and from the north water from Lake Sammamish via the Sammamish River contributes 27 percent of the hydraulic load. The majority of the immediate watershed is highly developed and urban in nature with 63 percent fully developed.

The basin of Lake Washington is a deep, narrow, glacial trough with steeply sloping sides, sculpted by the Vashon ice sheet, the last continental glacier to move through the Seattle area.

The lake is 20.6 feet above mean lower low tide in Puget Sound and is connected to Puget Sound by Lake Union and the Lake Washington Ship Canal, constructed in 1916. The Ship Canal is the only discharge from lakes Sammamish and Washington via the locks and dam at the western end. Mercer Island lies in the southern half of the lake, separated from the east shore by a relatively shallow and narrow channel, and from the west shore by a much wider and deeper channel.

Water quality in the lake has improved substantially since 1967 when Metro (now King County) diverted direct and primary-treated sewage discharges into the lake to the West Point and Renton sewage treatment plants. Today several emergency CSO relief structures remain and occasionally discharge into the lake; King County has seven outfalls at five locations on the western shore of the lake. The sediment quality at these five locations are the subject of this document.

Figure 1. Location of the seven CSOs and five outfall sites (red dots) in Lake Washington. Also shown are other King County CSO sites (green dots).

2.0. MODELING AND ANALYSIS DESIGN

This section defines the modeling goals and objectives, describes the conceptual and analytic framework of the model, and model data and setup needs.

2.1 Modeling Goals and Objectives

The modeling goal is predicting sediment chemical concentrations near King County CSOs that discharge into Lake Washington, and using the predicted concentrations to assess whether CSO discharges are or are not a potential contamination concern. There are two modeling objectives:

1. Simulate the deposition of suspended solids discharged from the CSO to the sediment bed according to the longitudinal distance from the CSO.
2. Estimate the most likely maximum sediment deposition rate and resulting sediment concentration for each chemical with Sediment Management Standards (SMS) deposited into the sediment bed from the CSO.

The model will estimate sediment deposition rates and SMS chemical exceedances that would occur under historical discharge conditions. The model was applied at sites where a King County CSO discharges, but other past and present sources may have also discharged effluent at or adjacent to the same site. These other non-County discharges have the potential to contribute chemicals of concern (COC) to the sediment bed, which could increase concentrations above that predicted from County CSOs. The modeling objective is determining chemical contributions from County CSOs and potential to exceed state SMS.

2.2 Analytical Framework

The modeling methodology comprises two analytical models to predict sediment chemical concentrations near a CSO (near-field). The basis for the simple models came from a study by King County (2011) that reviewed the required geophysical and chemical processes to simulate sediment and sorbed chemical deposition from CSOs in the near-field (area near the outfall). This study developed conceptual models containing known processes that transport CSO solids and processes that determine the fate of the sorbed chemicals. Review of the conceptual models indicated the relevant processes were contained in the governing equations for the Environmental Fluid Dynamics Computer Code (EFDC) model. Starting with these governing equations, a set of scaled equations were derived and analyzed and the relative importance of each process was determined. The relative importance of each process is used to identify those processes that should be included and those that can be omitted for a given model application or purpose. The advection within and settling of suspended solids from the water column was identified as having the greatest influence on the deposition of CSO solids in the near-field with findings summarized below.

1. Horizontal and solids settling velocities were the most significant parameters; solids with settling velocities greater than $2.5\text{x}10^{-4}$ m/s being the most significant within 100 m of the outfall.
2. Solids velocities less than $2.5\text{x}10^{-4}$ m/s carry most of the solids outside of 100 m.
3. Solids velocities less than $2.5\text{x}10^{-4}$ m/s become significant for horizontal velocities near or less than $2.5\text{x}10^{-3}$ m/s, which may occur in a quiescent lake but not in a tidally influenced estuary.

Based on these findings, two linked models were derived:

- The first model determines the longitudinal extent of deposited solids from the CSO outfall. This model describes the transport of suspended solids within the CSO plume and into the sediment bed: sediment deposition model.
- The second model determines the resultant sediment chemical concentration based on the solids deposition determined from the first model. This model describes the mixing of deposited CSO solids and COCs with deposited ambient solids and COCs in the sediment bed: sediment chemical model.

Both models assume steady-state conditions. In Lake Washington, a 10 cm sample represents 30 years of depositing suspended solids from different sources (0.3 cm/yr ambient sedimentation rate (Crecelius,1975)). This process is essentially a steady-state analysis of completely mixing 30 years of loads from different sources into a 10 cm layer. In this report, the sources are from CSO discharges and ambient sediment deposition; the models assume steady-state conditions for a discrete CSO discharge and a constant flux of ambient suspended solids with sorbed COCs into the sediment bed. The steady-state results provide the expected or average sediment chemical concentrations that would result from multiple discharge events over many years.

The models do not account for historic deposition if they differ from the 30 years of loads in the model run. If the historic discharge time series was substantially different than recent discharges used in the model run, these historic discharges will not be reflected in the model results. A portion of a 10 cm sample will contain chemical mass discharged from the historic discharge conditions if the discharge time series changed (i.e. a project was implemented to control the CSO discharge) within the time required to deposit 10 cm of sediment. Even if more than 10 cm of sediment has deposited since the time series change, bioturbation can mix historic deposition into the top 10 cm of sediment. The time series used in this analysis are representative of the previous 20 – 30+ years; discharge records from prior events were not available.

The models also omit chemical decay, absorption, and dispersive effects that would result from short episodic flow conditions such as wind-generated waves, boat prop wash, floods, and other environmental forces. These processes reduce sediment chemical concentrations near the CSO outfall through decay, chemical de-adsorption into the dissolved phase, and dispersal of the deposited sediments to areas away from the outfall; thus, the methodology is conservative in the predicted sediment chemical concentrations.

The models are coded in Microsoft Excel 2013 workbooks. The sediment deposition model was coded for three sediment classes each in a separate worksheet; each type is linked to the same three discharge rates (see Section 2.6.2). The three sediment types are linked in a fourth worksheet to calculate the total sediment deposition.

2.3 Sediment Mass Deposition

A simple analytical model was derived that simulates the transport of suspended solids within the discharge plume and settling from the plume directly to the sediment bed (King County, 2018b). The model emulates a triangular prism where the plume flow area is a function of the radial distance r from the outfall opening (Figure 2). The governing equation was derived by reducing the three-dimensional equations simulated in EFDC to a one-dimensional equation (1.1).

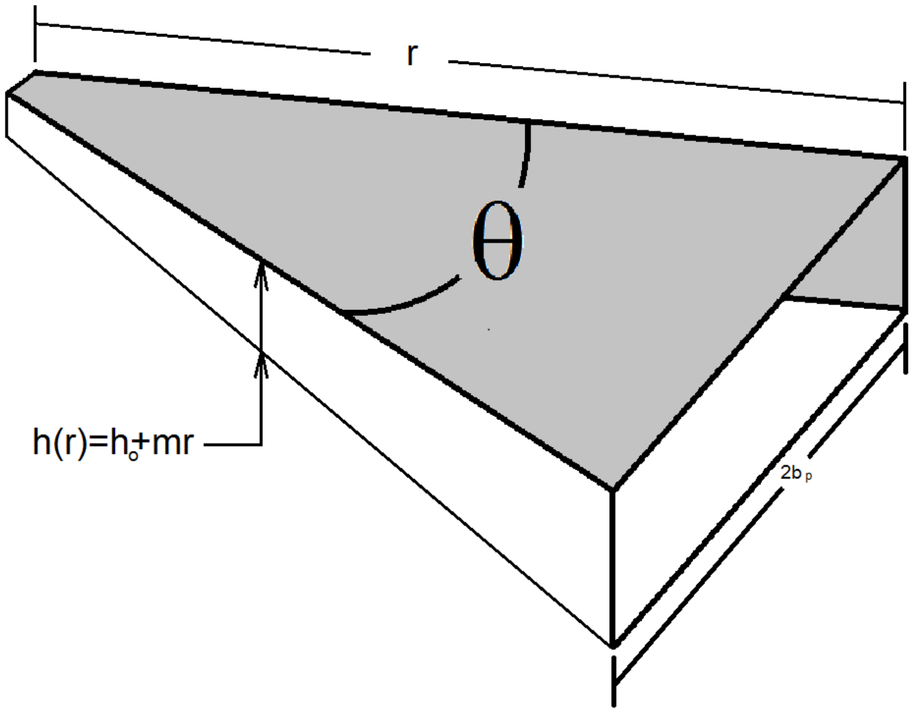

Figure 2. Conceptual rendering of the simple analytical model.

$$s = 1 - \frac{h_0}{h_0 + mr} \exp\left(\frac{-2 l_Q^{\beta} \sin\left(\theta/2\right) w_s r^{2-\beta}}{q_0 \left(2-\beta\right)} \right) \tag{1.1}$$

$$\text{where } l_Q = \sqrt{\pi/4}\, D \text{ and } \beta = \alpha \big/ \sin\left(\theta/2\right)$$

Where s is the percent of total solids mass deposited, h_0 is the pipe diameter, r is the radial distance from the outfall opening, q_0 is the initial flow rate, w_s is the suspended solids settling rate, D is the pipe diameter, and other parameter values are given in Table 1.

Table 1. Values for parameters in equation (1.1). Values were obtained from Fischer et. al. (1979).

Plume parameters	Value	Description
b_w/r	0.107	b_w is the plume width where the axial velocity is one-half maximum plume velocity.
b_p/r	$b_w/2r$	Empirical form that improved axial transport.
α	5.35%	Entrainment coefficient.
Θ	$2\tan^{-1}(b_p/r)$	Angle of plume.
m	bed slope≤*m*≤ $b_w/2r$	Rate of increase in plume depth.

Equation (1.1) provides the fraction of mass deposited in one-dimension, the distance from the discharge. The fraction of mass deposited is converted into a two dimensional sediment depositional rate by transforming the one-dimension radial coordinates into a two-dimensional coordinate system (Figure 3).

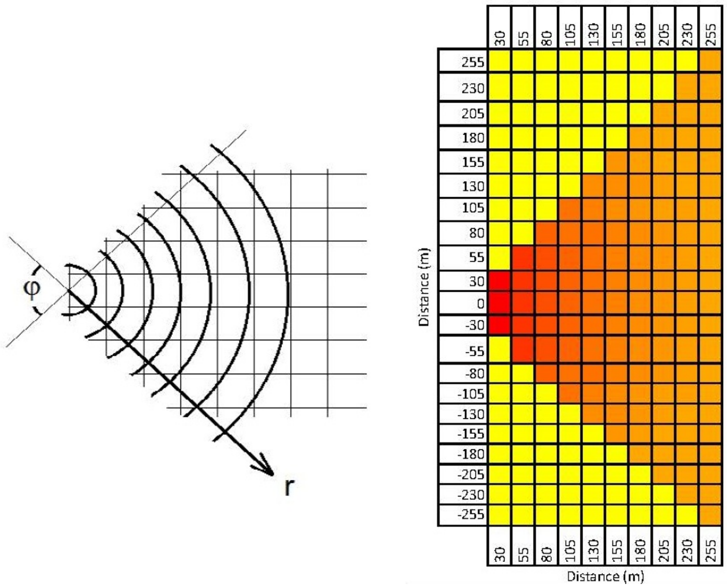

Figure 3. Converting the one-dimensional radial model r into two-dimensions where angle φ determines the effective sweep of the plume over the sediment bed.

The model's predictive capability breaks down very close to the outfall location because the scaling methods assume self-similarity properties (similar concentration and velocity profiles), which require a certain amount of distance to completely develop. This zone of flow establishment occurs within about ten pipe diameters; therefore the model is not applicable for distances less than ten pipe diameters from the outfall. Between 0 and 10 pipe diameters, the sediment deposition rate is assumed to be uniform and sum to the computed mass deposited at 10 pipe diameters.

2.4 Sediment Concentration and Deposition

The CSO sediment deposition rates and COCs are combined with ambient deposition rates and COCs to predict the COC concentration in the sediment bed.

$$COC_{sed} = \frac{COC_{cso} d_{cso} + COC_{amb} d_{amb}}{d_{cso} + d_{amb}} \tag{1.2}$$

Where COC_{sed} is the sediment bed concentration, COC_{cso} is the CSO concentration, d_{cso} is the CSO solids deposition rate, COC_{amb} is the ambient concentration, and d_{amb} is the ambient solids deposition rate. Equation (1.2) provides a conservative concentration estimate because it omits any chemical decay or diffusion processes that would reduce chemical concentrations in the sediment bed. The modeled sediment bed concentration can be compared against the Sediment Management Standards (SMS) sediment chemical thresholds: Sediment Cleanup Objective (SCO) and the Cleanup Screening Level (CSL) sediment chemical concentrations. Instead of assessing deposited sediment chemical concentrations, equation (1.2) was rearranged to calculate an allowable sediment deposition rate for the SCO or CSL threshold (King County, 2018).

$$d_{cso} \le d_{amb} \frac{C_{amb} - 1}{1 - C_{cso}}$$

Where, (1.3)

$$C_{amb} = {COC_{amb}}/{SMS}$$

$$C_{cso} = {COC_{cso}}/{SMS}$$

Where SMS is either the SCO or the SCL. A CSO sediment deposition rate is calculated for this report.

2.5 Modeling Approach

Measured time series discharge hydrographs are not available for the seven CSO sites of interest; however, a characteristic hydrograph was simulated and then scaled to the historic discharges using measured annual discharge volumes. This approach comprised two steps:

1. Determine CSO hydrograph characteristics based on modeled flows that simulated post-controlled sewer conveyance systems.
2. Scale the hydrograph characteristics by the measured average historical annual discharge volumes to obtain characteristic historical hydrograph.

Modeled time series flows are required because historical records contained only volumetric information; the simulated flow hydrograph characteristics are scaled to match historical volumetric discharges.

For the Belvoir[1] CSO, since 2003 hydrologic and hydraulic changes in contributing areas have occurred that increased the CSO frequency such that it no longer meets the performance standard of less than one overflow per year on a 20-year average. These facility changes were replicated in King County's hydrologic basin model and used to estimate recent overflow conditions at the Belvoir site. The second step is not applied to the Belvoir CSO because the applied hydrograph time series represents current hydrologic and hydraulic basin configuration.

2.6 Model Setup

This section identifies the type of data required to operate the model for three characteristic discharge flow rates and three sediment classes. The three characteristics flow rates represent the potential range in flows that are likely to occur through the outfall, and the three characteristic settling velocities represent the suspended solids mostly like to settle within 100 m of the CSO outfall (§2.0).

[1] As first reported in King County Combined Sewer Overflow Control Program 2016 Annual CSO and Consent Decree Report

2.6.1 Data Needs

The model requires information about the CSO and ambient conditions Lake Washington:

1. CSO
   a. discharge flow time series,
   b. historical annual volumes,
   c. suspended solids settling velocity and concentration,
   d. COC concentrations,
   e. pipe diameter.
2. Ambient waterbody
   a. slope of sediment bed,
   b. solids deposition rate,
   c. COC concentrations.

Pump station pipe diameter and plume bottom or sediment bed slope are given in Table 2.

Table 2. Pipe and bed slope for CSO site of interest.

Site	Pipe Diameter (ft)	Sediment Bed Slope (%)
Belvoir/30th Ave NE PS[1]	3.0	0.28
East Pine St PS	2	5.35
Martin Luther King/Henderson PS[1]	7	4.1
Matthews PS	2'x2'	5.35
Rainier Ave PS	3	5.35
1. These facilities share the same outfall pipe.		

2.6.2 Characteristic CSO Discharge Flow Rates

Sediment chemical concentrations at CSO sites include chemical loading from CSO's and Emergency Sewer Overflow (ESO) that occur during conveyance system failures. In this report CSO discharges are characterized from discharge hydrograph time series and ESO discharges are characterized by the total volume discharged.

2.6.2.1 CSO Discharges

Post-control time series hydrographs for characterizing CSO discharge hydrographs were obtained for three sites from previous model studies conducted by King County:

- Martin Luther King and East Pine CSO time series were obtained from County's 2014A No Impact Release Rates (NIRR) modeling study (King County, 2014)
- Belvoir/30th Ave PS time series was obtained from the County's Windermere Flow Characterization and Regional Impacts Technical Memorandum (King County, 2015).

No existing long time series (LTS) flow modeling studies were available for the Rainer Avenue PS, Matthews Park PS, and Henderson PS. Where LTS modeling was unavailable, other information sources were used to assess the potential for overflows.

- After the Matthew Park PS upgrade, PLC's were set at a pump capacity of 85 MGD, but they can be overridden up to 110 MGD. Previous model simulations indicate peak flows never exceed the 85 MGD pump capacity, suggesting no overflows should have occurred.
- After the Henderson PS pump upgrades in 2005, model studies suggest no CSO overflows occurred over a forty-year rainfall time series.
- For East Pine St. PS, Matthew Park PS, and Rainier PS, the 2014 and 2017 CSO Control Program Annual Reports showed that none of the sites overflowed between 1995 and 2017, and they were not overflowing in years 1981-1983 (Table 3).

In summary,

- Belvoir/30th Ave PS has overflowed since it was listed as controlled.
- No reported CSO overflows have occurred for over 30 years at East Pine St. PS, Matthews Park PS, and Rainier PS.
- No reported overflows have occurred at Henderson PS and Martin Luther King since they were controlled in 2005, but overflows were reported in years prior to 2005 with a total annual average discharge rate of 54 MG/yr[1] for Henderson and Martin Luther King.

Table 3. Summary of CSO overflow conditions since control at the seven CSO sites.

CSO site (date controlled)	Overflow status since control	1981-1983 Baseline[1] (MG)
Belvoir/30th Ave NE PS (2005)	Overflows occur[2]	<1
Martin Luther King (1969)	No overflows since control[3,4]	60
Henderson PS (2005)	No overflows since control[3]	15
Matthews Park PS (1983)	No overflows since 1995[3]	<1
East Pine Street PS Emergency Overflow (1976)	No overflows since 1995[3,4]	<1
Rainier Avenue PS Emergency Overflow (1970)	No overflows since 1995[3]	<1

1. Simulated CSO discharge volumes that represent a baseline condition in years 1981 to 1983 before any CSO controls were implemented.
2. King County, 2015. Windermere Flow Characterization and Regional Impacts Technical Memorandum.
3. King County CSO Control Program 2017 Annual Report using historical modeling to estimate the 20-year average whenever monitoring records don't go back far enough.
4. King County 2014, 2014A No Impact Release Rates.

Characteristic hydrographs were generated for the Belvoir/30th Ave NE PS and the Henderson PS and Martin Luther King outfall. Even though Henderson PS and Martin Luther King have not

[1] Compiled data from King County Annual CSO Control Reports from 1992-2006. https://www.kingcounty.gov/services/environment/wastewater/cso/library/annual-reports.aspx

overflowed since control, they have been controlled for only 13 years, which is considered a relatively short time compared to 30 years required to deposit 10cm of sediment. The Henderson PS and Martin Luther King modeling will assess potential SMS exceedances for CSO plus ambient sediment deposition 17 years prior to control and only ambient sediment deposition 13 years after control.

2.6.2.2 ESO Discharges

At five of the seven CSO sites ESO discharges have occurred; total discharge volumes and average annual discharge rates are given in Table 4.

Table 4. Emergency Sewer Overflow volumes and average annual discharge rates that occurred at five CSO sites.

CSO Site	Total Volume Discharged in the Last 30 Years (MG)	Average Annual Discharge Rate Over 30 Years (MG/yr)
30th Ave PS	0.03	0.001
Belvoir PS	4.83	0.16
East Pine PS	0.033	0.0011
Henderson/MLK	2.2	0.073
Matthews Park PS	13	0.43

Average annual discharge rate from Emergency Sewer Overflows are added to CSO discharge rates and the total discharge rate is used to estimate the solids deposition rate.

2.6.2.3 Belvoir/30th Ave NE Hydrograph

Three characteristic flow rates were derived from the Belvoir CSO discharge hydrograph time series. All flows greater than zero were collected and sorted into a histogram, which was then divided into three equal segments between the smallest and largest flow. Within each segment the average flow was calculated and formed a histogram of three characteristic flows; these three flows characterized the CSO discharge time series (King County, 2018b). The flow histogram for Belvoir/30th Ave PS is shown in Figure 4 and numeric values are presented in Table 4. Because the three hydrographs are scaled to a ten-day period, the results are scaled back to yearly rates using values in column four of Table 4 (equivalent years in 10 day simulation).

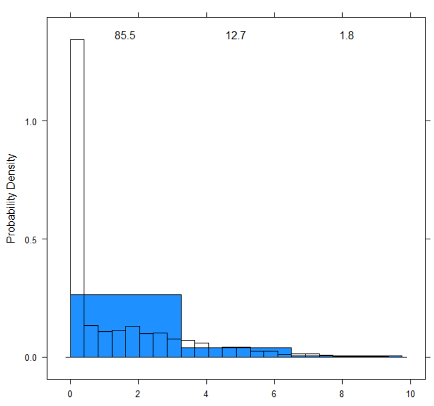

Figure 4. Belvoir/30th Ave PS histogram obtained from the 32-yr Windermere simulation. Group event probabilities are shown at top of chart.

Table 5. Characteristic CSO discharge flows and durations, flows sorted from smallest to largest (lower 1/3 to upper 1/3). Durations sum to ten days and the in the last column (Equivalent years in 10 day simulation), the values are used to normalize sediment deposition rates into depth/yr.

CSO site (date controlled)	Lower 1/3 (MGD)/(days)	Middle 1/3 (MGD)/(days)	Upper 1/3 (MGD)/(days)	Equivalent years in 10 day simulation
Belvoir/30th Ave NE PS	1.62/8.55	4.87/1.27	8.12/0.18	17.8
Henderson/Martin Luther King	28/7.6	84/1.7	141/0.7	3.78

2.6.2.4 Henderson PS/Martin Luther King Hydrograph

A pre-control discharge hydrograph time series is not available for Henderson PS and Martin Luther King (MLK) for years prior to 2005 when the two system where uncontrolled; therefore, three characteristic flow rates will be estimated from the characteristic flow rates from 11 CSO basins. The three characteristic flow rates were scaled to pre-control overflow conditions; characteristic flow rates were estimated in three steps:

1. From the 11 basin flow characteristics, the average probability was calculated for each characteristic flow rate (Figure 5).
2. Using a regression between the 11 average historical discharge rates and middle 1/3 characteristic flows, the Henderson/MLK middle 1/3 characteristic flow was computed for annual average historic discharge rate of 54 MG/yr, which includes ESO discharges (Figure 6).
3. The lower and upper 1/3 characteristic flow were calculated from the middle 1/3 using $Q_{lower1/3} = 0.33 Q_{middle1/3}$ and $Q_{upper1/3} = 1.67 Q_{middle1/3}$.

The Henderson/Martin Luther King characteristic CSO discharge flows are given in Table 4.

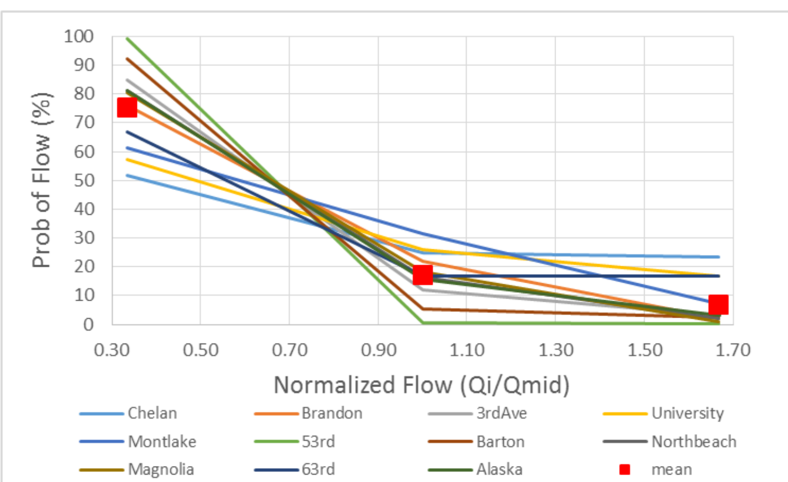

Figure 5. Superposition of the probability for the three characteristic flows for 11 basins and the average probability (red square). The three flows (Qi) where normalized by the middle 1/3 flow (Qmid).

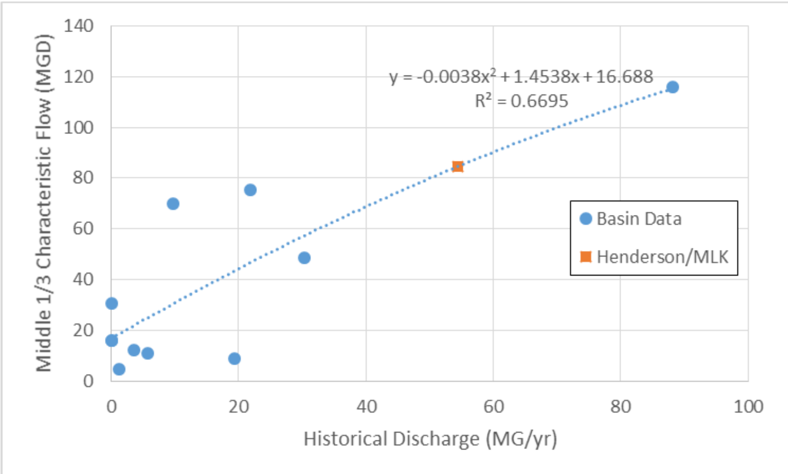

Figure 6. Regression between the 11annual average historical discharge rate and the middle 1/3 characteristic flow (blue dots), the expected Henderson/MLK middle 1/3 characteristic flow is 84 MGD (tan square) based on a historical discharge of 54 (MG/yr).

2.6.3 CSO Sediment Classes

The model as currently configured can use up to three characteristic sediment classes. The sediment class should typify solids that are most likely to settle within 300 meters of the outfall.

Table 6. Three sediment classes that characterize CSO suspended solids (King County, 2011)

Sediment Class	Settling Velocity W_s (m/s)	Percent mass	Conc. (mg/l)
Sand	7.5E-03	33%	41.6
Silt	6.25E-04	34%	43.1
Clay	1.50E-04	34%	43.3

3.0. MODEL RESULTS

The model was configured for the Belvoir/30th Ave PS outfall and the Henderson/MLK outfall and sediment deposition rates were computed. Belvoir/30th Ave results were used directly to estimate chemical exceedances. The Henderson/MLK results need to be corrected because they represent conditions when the CSO was uncontrolled for 17 years; corrections account for years when the CSO was controlled when only ambient sediment deposition occurred.

$$d_{effcso} = d_{cso}\left(\frac{10 - d_{amb}T_{post}}{10 + d_{cso}T_{post}}\right) \tag{1.4}$$

Where d_{effcso} is the effective CSO sediment deposition rate that accounts for the deposition of clean sediment since the outfall was controlled, 10 is ten centimeters of sediment, T_{post} is the time since the CSO was controlled. The other CSO sites were not modeled because no discharges were recorded, anecdotal modeling efforts suggested no overflows would occur, and the 1981-

1983 baseline conditions suggest the sites did not discharge 35 years ago. While the current information suggests these other sites are not a concern, a generic outfall model was configured to determine when a generic discharge condition would cause concern in Lake Washington. The generic model provides an estimate of how much volume would need to be released at one of these sites before the possibility of a sediment quality concern would exist. This section presents the results for the Belvoir/30th Ave PS, Henderson/MLK, and the generic outfall.

3.1 Sediment Deposition Thresholds

Modeled sediment deposition rates were compared against threshold deposition rates computed from equation (1.3). Two threshold deposition rates were calculated for the SCO and CSL; one threshold calculation used the 25th percentile CSO chemical concentration, the other calculation used the 75th percentile CSO chemical concentration (King County, 2018). The 25th percentile chemical concentration characterizes a CSO basins with lower chemical concentrations (Predicted Exceedance), and the 75th percentile chemical concentration characterizes CSO basins with higher chemical concentrations (Potential Exceedance). These threshold rates are given in Table 6 and Table 7. Note that in mainly residential basins, the chemical concentrations are more likely to be represented by the 25th percentiles, meaning the potential exceedances are less likely to occur.

Table 7. Freshwater Sediment CSL Threshold Deposition Rates

CSO Deposition Rate (cm/yr)			Potential Exceedance	Predicted Exceedance
0	to	0.046	None	None
0.046	to	0.73	Silver	None
0.73	to	0.86	Silver, di-n-octyl phthalate	None
0.86	to	1.5	Silver, di-n-octyl phthalate, mercury	None
1.5	to	6.9	Silver, di-n-octyl phthalate, mercury	Silver
6.9	and above		Additional analytes	Silver

Table 8. Freshwater Sediment SCO Threshold Deposition Rates

CSO Deposition Rate (cm/yr)			Potential Exceedance	Predicted Exceedance
0	to	0.0024	Nickel, silver	Nickel
0.0024	to	0.0052	Nickel, silver, di-n-octyl phthalate	Nickel
0.0052	to	0.027	Nickel, silver, di-n-octyl phthalate, BEHP	Nickel
0.027	to	0.033	Nickel, silver, di-n-octyl phthalate, BEHP, PCBs	Nickel
0.033	to	0.069	Nickel, silver, di-n-octyl phthalate, BEHP, PCBs	Nickel, BEHP
0.069	to	0.14	Nickel, silver, di-n-octyl phthalate, BEHP, PCBs	Nickel, BEHP, silver
0.14	to	0.27	Nickel, silver, di-n-octyl phthalate, BEHP, PCBs, cadmium	Nickel, BEHP, silver
0.27	to	0.45	Nickel, silver, di-n-octyl phthalate, BEHP, PCBs, cadmium, mercury	Nickel, BEHP, silver

CSO Deposition Rate (cm/yr)			Potential Exceedance	Predicted Exceedance
0.45	to	4.3	Nickel, silver, di-n-octyl phthalate, BEHP, PCBs, cadmium, mercury	Nickel, BEHP, silver, PCBs
4.3	and above		Additional analytes	Nickel, BEHP, silver, PCBs
Note: 4-Methylphenol (p-Cresol) exceedances are not found in sediment because contaminant degrades rapidly and not included				

3.2 Belvoir/30th Ave PS

Sediment deposition was simulated for the Belvoir/30th Ave PS site and the predicted solids deposition rate are shown in Figure 7, and deposition rates of concern are given in Table 8. Potential sediment chemical concentration exceedances were determined by comparing the tabulated solids deposition rate against the Threshold Deposition Rates for SMS screening criteria CSL Table 6 and SCO Table 7 (King County, 2018a).

Comparing the modeled solids deposition rates and tabulated deposition thresholds, Belvoir/30th Ave PS (0.009 cm/yr) has no potential to exceed the CSL. At the SCO level, sediment deposition between 0 ft to 98 ft has potential to exceed nickel, silver, di-n-octyl phthalate and BEHP. The sediment deposition rate between 98 ft and 180 ft (0.0024 cm/yr) has the potential to exceed the SCO for nickel, silver, di-n-octyl phthalate. There are no predicted exceedances of the SCO at any distance except for nickel, which already exceeds the SCO at ambient concentrations.

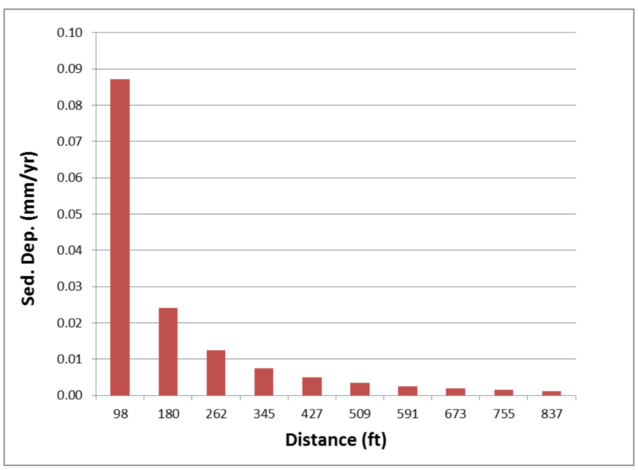

Figure 7. Predicted sediment deposition rates near the Belvoir/30th Ave CSO outfall.

Table 9. Predicted Belvoir CSO solids deposition rates have the potential to exceed the SCO or CSL, the annual discharge rate was 1.4 MG/yr.

Longitudinal Range of Exceedance (ft)	Solids Deposition Rate (cm/yr)	Potential to Exceed SCO	Potential to Exceed CSL	Predicted to Exceed SCO	Predicted to Exceed CSL
0 to 98	0.0098	Yes	No	No[1]	No
98 to 180	0.0027	Yes	No	No[1]	No
1. Nickel already exceeds SCO at Lake Washington ambient concentrations.					

Since the recent changes in the basin and associated modeled increase of overflow frequency at Belvoir, the modeled CSO sediment concentrations are expected to be higher than CSO sediment concentrations that would have occurred when the CSO outfall was controlled, because CSO discharge volumes would have been less when the outfall was controlled. The Belvoir model provides a conservative estimate of the sediment chemical concentration.

3.3 Henderson PS/Martin Luther King

Since control at Henderson PS and Martin Luther King was relatively recent; the historical discharges would have much more effect on the deposition rate that is incorporated into the top 10 cm. As Henderson PS and Martin Luther King both discharge out the same outfall, they were modeled as one release. The predicted effective solids deposition rate are shown in Figure 8, and deposition rates of concern are given in Table 9, the effective solids deposition rate is used to estimate chemical exceedances.

Comparing the modeled solids deposition rates and tabulated deposition thresholds, the Henderson/MLK outfall (0.265 cm/yr) has the potential to exceed the CSL for silver between 0 ft and 98 ft and could extend to 180 ft. There is no predicted exceedance of the CSL. At the SCO level, the discharges have the potential to exceed nickel, silver, di-n-octyl phthalate, BEHP, PCBs, and cadmium and are predicted to exceed nickel, BEHP, and silver between 0 ft and 98 ft. Potential SCO exceedances for some chemicals could extend to 755 ft from the outfall.

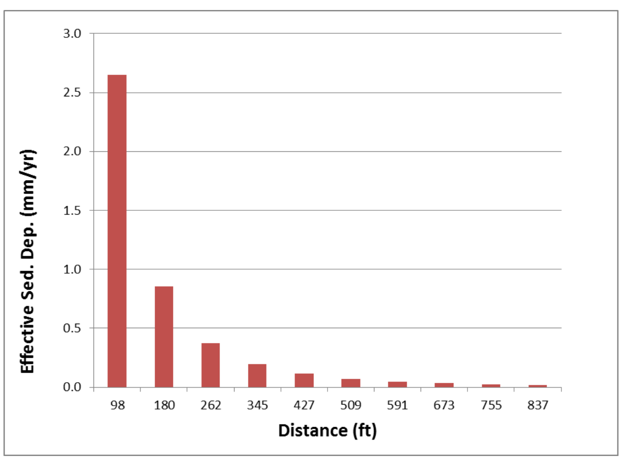

Figure 8. Predicted effective sediment deposition rates near the Henderson/MLK CSO outfall.

Table 10. Predicted Henderson/MLK CSO effective solids deposition rates that have the potential to exceed the SCO or CSL, the annual discharge rate was 54 MG/yr.

Longitudinal Range of Exceedance (ft)	Effective Solids Deposition Rate (cm/yr)	Potential to Exceed SCO	Potential to Exceed CSL	Predicted to Exceed SCO	Predicted to Exceed CSL
0 to 98	0.27	Yes	Yes	Yes	No
98 to 180	0.09	Yes	Yes	Yes	No
180 to 262	0.04	Yes	No	Yes	No
262 to 755	≥0.0024	Yes	No	No[1]	No
1. Nickel already exceeds SCO at Lake Washington ambient concentrations.					

3.4 Generic outfall

The generic outfall simulation determines what annual discharge volume is required to cause a predicted exceedance of the SCO for BEHP[2], or a CSO deposition rate of 0.033 (cm/yr). The generic outfall replicated the Belvoir/30th Ave PS outfall characteristic except the rate-of-increase in the plume width was 4.8% (average *m* in Table 2) and the hydrographs were scaled until the CSO deposition rate was 0.033 (cm/yr). A generic outfall must discharge about 11 (MG/yr) to cause a predicted exceedance of the SCO for BEHP (Table 10) and would not have a possible exceedance of the CSL for any chemical (Table 6).

Table 11. Annual discharge volume for a generic outfall that deposits 0.033 (cm/yr) within 0 ft to 100 ft of the outfall.

Solids Deposition Rate (cm/yr)	Annual Discharge Volume (MG/yr)
0.033	11

The East Pine PS, Matthews Park PS, and Rainier PS facilities appear controlled and that they have never discharged under normal operations in the last 30 years. If the CSO overflow records are incorrect and the facilities have been discharging enough to cause a predicted exceedance, then the generic model suggests the annual discharge rate needs to be 11 MG/yr, which can typically be detected in our conveyance monitoring.

Average annual discharge rate from Emergency Sewer Overflows (Table 4) were added to CSO discharge rates and the total discharge rate is used to estimate the solids deposition rate. Effects from ESO's are included in the Belvoir/30th Ave PS and Henderson/MLK results. The two remaining CSO sites have no record of CSO discharges in the last 30 years, so only the ESO discharges contribute to sediment chemical deposition near the outfalls. Average annual

[2] Nickel is already exceeding the SCO at ambient concentrations and is therefore not used in this assessment.

discharge rates for East Pine PS (0.001 MG/yr) and Matthews Park PS (0.43 MG/yr) are substantially smaller than the generic model rate (11 MG/yr) and the Belvoir/30th Ave PS rate (0.16 MG/yr added to CSO volumes totals 1.4 MG/yr), which suggests no predicted exceedances.

4.0. UNCERTAINTY ANALYSIS

Model sensitivity and uncertainty was addressed using two methods: 1) upper and lower bound analysis using the 75th and 25th percentile values of the COC concentration data set, 2) and error propagation methods (Dieck, 1997).

Uncertainty in the COC concentration data set is reflected in the “Potential Exceedance” and “Predicted Exceedance” columns in Table 6 and Table 7. The Predicted Exceedance deposition rate represents the 25th percentile COC concentration in the CSO, and the Potential Exceedance deposition rate represents 75th percentile COC concentration.

Equation (1.1) provides the percent of total mass deposited between the discharge and radius r; the mass deposited between two radial points is defined by equation (1.5).

$$M_D = M_T\left(s(r_2) - s(r_1)\right) \tag{1.5}$$

Where M_D is the mass deposited between radial points r_2 and r_1, and M_T is the total mass discharged. The total mass discharged is,

$$M_T = cQt_d \qquad (1.6).$$

Where c is the total suspended solids concentration, Q is the average flow rate that occurred over duration t_d; t_d represents only non-zero flow conditions. Equations (1.5) and (1.6) are combined and used to calculate sediment deposition rates given in equation (1.7).

$$d_{cso} = \frac{cQt_d S_{r_2,r_1}}{A_{rea}\rho_{specific}\left(1-\eta\right)\left(t_d + t_z\right)} \qquad (1.7).$$

Where d_{cso} is the CSO sediment deposition rate, $S_{r2,r1}=s(r_2)-s(r_1)$ is percent of sediment mass deposited between radial points r_2 and r_1, A_{rea} is the depositional area, $\rho_{specific}$ is the specific sediment density, and η is porosity. The term t_d+t_z is the duration of the CSO discharge time series used to estimate the characteristic CSO discharge flow rates (§2.6.2), t_z is the accumulated period of time of zero discharges. Uncertainty in sediment deposition rates is estimated by equation (1.8).

$$\left(\frac{2\Delta d_{cso}}{d_{cso}}\right)^2 = \left(\frac{2\Delta c}{c}\right)^2 + \left(\frac{2\Delta Q}{Q}\right)^2 + \left(\frac{2\Delta S_{r_2,r_1}}{S_{r_2,r_1}}\right)^2 + \left(\frac{2\Delta \eta}{1-\eta}\right)^2 \tag{1.8}$$

Where all Δ terms represent the standard deviation, uncertainty is defined as twice the standard deviation. For the third term on the right of the equal sign, uncertainty was determined by equation (1.9).

$$\left.\frac{2\Delta S_{r_2,r_1}}{S_{r_2,r_1}}\right|_{\pi_i} = \frac{2\Delta\pi_i \frac{\partial}{\partial \pi_i}\left\{\left(\frac{h_0}{h_0+mr_1}\exp\left(\frac{-2l_Q^{\beta}\sin\left(\theta/2\right)w_s r_1^{2-\beta}}{q_0\left(2-\beta\right)}\right)\right)-\left(\frac{h_0}{h_0+mr_2}\exp\left(\frac{-2l_Q^{\beta}\sin\left(\theta/2\right)w_s r_2^{2-\beta}}{q_0\left(2-\beta\right)}\right)\right)\right\}}{\frac{h_0}{h_0+mr_1}\exp\left(\frac{-2l_Q^{\beta}\sin\left(\theta/2\right)w_s r_1^{2-\beta}}{q_0\left(2-\beta\right)}\right)-\frac{h_0}{h_0+mr_2}\exp\left(\frac{-2l_Q^{\beta}\sin\left(\theta/2\right)w_s r_2^{2-\beta}}{q_0\left(2-\beta\right)}\right)} \quad (1.9)$$

Where $\Delta S_{r2,r1}$ is the uncertainty in the percent of total solids mass deposited when the parameter value π_i is changed from its expected value π_0 by $\Delta\pi = \pi - \pi_0$, $\Delta\pi$ is the standard deviation of π.

Parameter uncertainty values used in equation (1.8) are given in Table 11. Parameter uncertainty values were determined from different sources:

- Fisher et. al. (1979) for b_w/r and alpha,
- King County's
  - CSO particle settling studies for the settling velocities,
  - CSO database for total suspended solids concentrations,
  - Basin model statistical measures of fit and flow meter uncertainty analyses for flow rates, and
- Published literature for porosity (Geotechdata.info, 2013).

Table 12. Parameter values and uncertainty values used for estimating uncertainty in sediment deposition rate for each outfall site.

Parameter	Name	Belvoir	Henderson MLK	Uncertainty
b_w/r	Rate of change in plume width	0.107	0.107	±0.003
α	Entrainment coefficient	0.0535	0.0535	±0.0025
β	α/sin(Θ/2)	1.001	1.001	±0.054
m	Rate of increase in plume depth	0.0028	0.04	±0.0028
w_s (fine sand)	Settling velocity	7.5e-3	7.5e-3	±0.163
w_s (silt)	Settling velocity	6.25e-4	6.25e-4	±0.038
w_s (clay)	Settling velocity	1.5e-4	1.5e-4	±0.024
q_0	Flow in plume	0.09[1]	2.0[1]	±28%
c	Total suspended solids concentration	42.6[2]	42.6[2]	±6%
Q	Used to calculate sediment mass	0.09[1]	2.0[1]	±28%
η	Porosity	0.45	0.45	±0.15

1. The duration weighted average of the three characteristic flows.
2. Average suspended solids concentration.

4.1 Uncertainty Results

Model uncertainty in the sediment deposition rate was ±84% (0 ft to 100 ft of outfall) for the Belvoir PS outfall and ±40% (0 ft to 100 ft of outfall) for the Henderson/MLK outfall (Table 12). Results for the two outfall sites are presented separately.

4.1.1 Belvoir/30th Ave PS

At the Belvoir site, the total relative uncertainty in sediment deposition rate is ± 84% within 100 ft of the outfall and it decreases with increasing distance from the outfall (Figure 9). The deposition rate is most affected by the uncertainty in the rate-of-increase in the plume depth (m); the propagated error from m is ±56% (Table 12). The value is high because m=0.28% infers the plume depth is essentially constant and the plume velocity will not decrease as fast with distance from the outfall; there will be higher plume velocities farther from the outfall. The higher plume velocities will carry suspended solids with smaller settling velocities farther from the outfall. Thus decreasing the sediment mas deposited near the outfall.

The next largest propagated uncertainty is the plume flow q_0, which has a propagated uncertainty of ±39%; the plume flow affects the plume velocity and how far suspended solids will be transported away from the outfall and dispersed over the sediment bed. After the plume flow, parameters beta, the average flow (Q), and porosity (η) are the next largest propagated uncertainties with values of 28%, 28%, and 27%. Beta affects the width of the plume and entrainment of ambient water into the plume; both conditions affect the plume velocity. The average flow Q affects the total mass of suspend solids that could settle and porosity affects the depth of any solids deposited on the sediment bed. The settling velocities (w_s) and total suspended solids concentration (c) have a relatively small effect on the uncertainty in the sediment deposition rate.

Table 13. Uncertainty in the percent of total mass deposited (equation (1.9)) contributed by parameter and the total propagated. Uncertainties are for sediment deposition from 0 ft to 100 ft of the outfall.

Parameter	Belvoir/30th Ave PS (%)	Henderson/MLK (%)
β	28	1
m	56	4
w_s	11	1
q_0	39	1
c	6	6
Q	28	28
η	27	27
Total	84	40

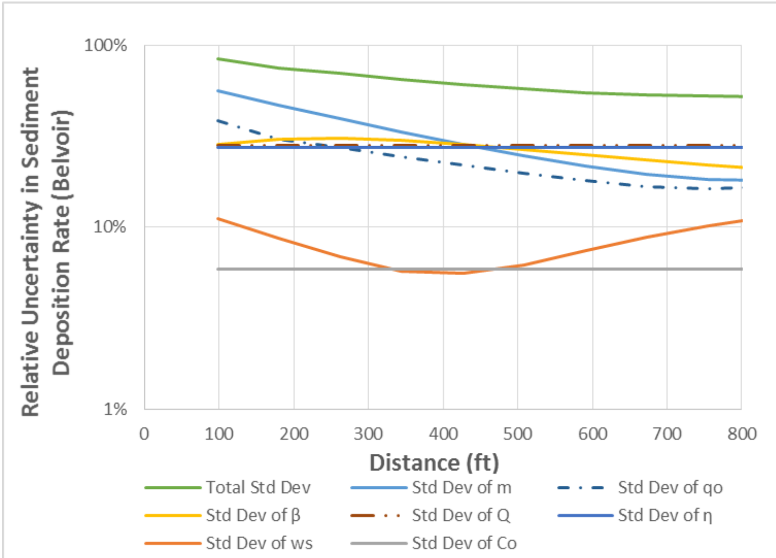

Figure 9. Relative uncertainty in the predicted sediment deposition rate at the Belvoir PS outfall for total and component uncertainties. At Belvoir, *m*=0.28%.

4.1.2 Henderson/MLK Outfall

The Henderson/MLK sediment deposition uncertainty is ±40% within 100 ft of the outfall and was essentially constant with distance from the outfall (Figure 10). The deposition rate is most affected by the uncertainty in the average flow (Q), the propagated error from Q is ±28% (Table 12). Next largest contribution was the porosity (η), the propagated error from η is 27%. The remaining four parameters propagated a very small amount of uncertainty in sediment deposition rate.

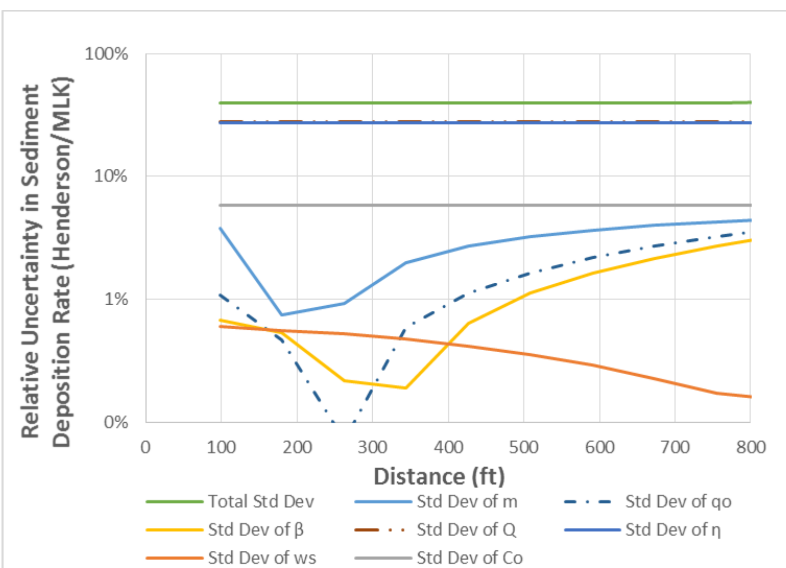

Figure 10. Relative uncertainty in the predicted sediment deposition rate at the Henderson/MLK outfall for total and component uncertainties. At Henderson/MLK, *m*=4%.

4.2 Assessing very small rate-of-increase in plume depth

The uncertainty in sediment deposition at Belvoir was much larger than that computed at Henderson/MLK, yet between the two sites the only differences in parameter values was the average flow (Q) and the rate-of-increase in plume depth (Table 11). Average flow affects the total mass of suspended solids discharged through the outfall; a value that is independent of what happens within the plume. Because Q does not affect conditions within the plume, the difference in sediment deposition rate uncertainties can only be ascribed to the different values for the rate-of-increase in plume depth. This difference results from the mathematical form given by equation (1.9), the equation becomes very sensitive for certain conditions on the rate-of-increase in plume depth (m) and suspended solids settling velocities (w_s). This sensitivity results from the denominator in equation (1.9) becoming small relative to the numerator. When m is very small, the denominator is essentially just the percent solids mass that has deposited between radius r_2 and r_1; the percent mass deposited is small for a suspended solid that is unlikely to settle from the plume i.e., it has a very small settling velocity. As a result, the model is increasingly more sensitive to suspended solids with smaller and smaller settling velocities because they are less likely to settle from the plume near the outfall. Suspended solids with very small settling velocities are dispersed farther away from the outfall and contribute less to the accumulation of sediment chemical concentrations near the CSO outfall. This section will contrast model uncertainty and sediment mass accumulations at the Belvoir and Henderson/MLK CSO sites, and it will show that the Belvoir CSO site is most sensitive (higher uncertainty) to the silt and clay suspended solids and that deposited silt and clay sediments are much smaller near the CSO.

For the Belvoir site, the percent mass deposited for the fine sand ranges from 24% to 2%, but the silt and clay are much less and nearly equivalent from 9% to 3% (Figure 11). The corresponding relative uncertainties range from 18% to 17% for the fine sand, 36% to 0% for the silt, and 39% to 6% for the clay. In general, fine sand has a lower uncertainty and higher deposition rate (24% and 24%) compared to the silt (36% and 9%) and clay (39% and 8%) near the outfall. The uncertainty in the clay and silt sediment deposition rate essentially determine the uncertainty in the propagated sediment deposition rate from the rate-of-increase in plume depth (m).

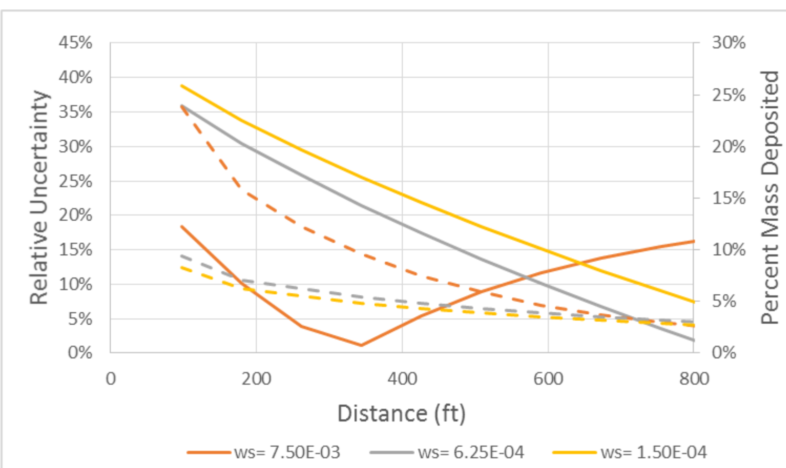

Figure 11. Relative uncertainties (solid lines) and percent mass deposited (dashed lines) for fine sands (w_s=6.25e-4), silts (w_s=1.5e-4), and clays (w_s=7.5e-3) for the Belvoir CSO site.

At the Henderson/MLK CSO site, the fine sand, silt, and clay have very similar relative uncertainties and are much smaller than those computed at Belvoir. For all three suspended solids, the percent mass deposited range between 30% to 2% and relative uncertainty ranged from 2% to 3% (Figure 12). All three suspended solids had the same quantitative form between the relative uncertainty and percent mass deposited near the outfall.

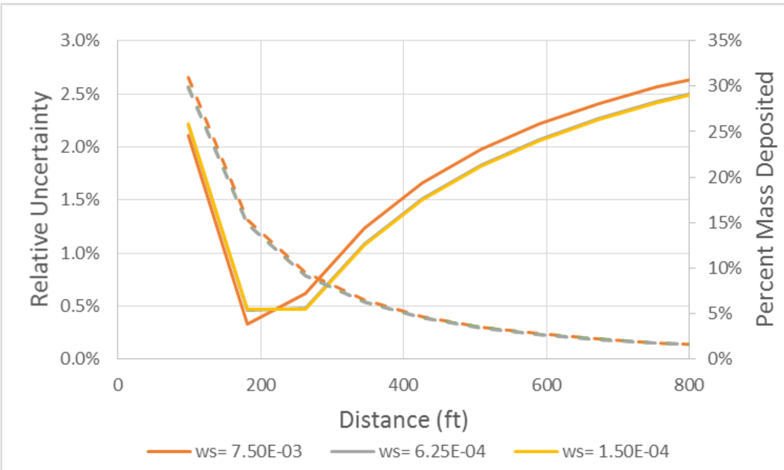

Figure 12. Relative uncertainties (solid lines) and percent mass deposited (dashed lines) for fine sands (w_s=6.25e-4), silts (w_s=1.5e-4), and clays (w_s=7.5e-3) for the Henderson/MLK CSO site.

Both outfall locations have the same level of uncertainty in the rate-of-increase in plume depth (m); the parameter value m is equally well understood at both sites. However, the relative uncertainty in sediment deposition rate at the Belvoir CSO site is substantially higher because the rate-of-increase in plume depth is much smaller, which produces a relatively constant plume depth. The nearly constant plume depth increases the plume velocity enough that silts and clays travel farther from the outfall before depositing into the sediment, which results in a lower sediment deposition rate. The fine sand deposition is not as affected by the increased plume velocity because the percent mass deposited was between 24% to 2%, which is very similar to the fine sand deposited by the Henderson/MLK CSO site (30% to 2%). These results suggest that when the rate-of-increase in plume depth approaches zero, the model will become more sensitive to suspended solids with small settling velocities because they will be less likely to deposit in significant amounts near the outfall. These findings and conclusion are very similar to those discussed in section 2.2, where it discusses a threshold settling velocity where a suspended solid is carried past some boundary of interest.

This analysis suggest that for an outfall where the growth of the plume depth is restricted by the local geography, the sediment deposition rate uncertainty will be relative high for some particle near or below a threshold settling velocity. The high uncertainty is not because the rate-of-increase in plume depth is poorly known, but because it is not likely much particle mass will settle in the area.

5.0. MODEL OUTPUT QUALITY (USABILITY) ASSESSMENT

Sufficient model output quality must meet the two objectives outlined in section 2.1 and discuss three topics outline in the QAPP for CSO Sediment Quality Modeling (King County, 2018d). The modeling objectives were:

1. Simulate the deposition of suspended solids discharged from the CSO to the sediment bed according to the longitudinal distance from the CSO.
2. Estimate the most likely maximum sediment deposition rate for each chemical with Sediment Management Standards (SMS) deposited into the sediment bed from the CSO.

The QAPP for CSO Sediment Quality Modeling (King County, 2018d) identified three topics that would be addressed in the final modeling report, the topics were:

1. Model outcomes are consistent with the processes embed in the equations and sedimentation and chemical reaction processes in Lake Washington.
2. Whether the outcomes reasonably quantify the concentration of COCs from CSOs.
3. Identifying any data limitations discovered during the project.

5.1 Outcome Consistency With Equations

The simple model was derived from a simplified set of partial differential equations that describe the transport of a constituent as it travels through the water column. These equations were based on the complete partial differential equations used in the Environmental Fluid Dynamics Computer Code (EFDC). In order to test that the simple model equations were correctly coded in the spreadsheet, model results were compared against a set of sediment deposition patterns modeled by EFDC. EFDC was configured for three different freshwater discharge configurations to simulate sediment deposition from a CSO outfall, sites were for the University CSO, Montlake CSO, and the 3rd Avenue CSO. The simple model was configured to replicate EFDC's geophysical boundaries and forcing functions. This task was done to replicate geophysical approximations made within EFDC and allow a more direct comparison between EFDC results and the simple model. When the results were compared, the following conclusion were made (EFDC, King County, 2018c):

- The simple model replicated EFDC's freshwater deposition of suspended solids discharged from the CSO to the sediment bed according to the longitudinal distance from the CSO.
- Both models produced an exponential change in sediment deposition with increasing distance from the outfall.
- The simple model over-predicted the peak EFDC sediment deposition for the University CSO by 85%, the Montlake CSO by 371%, and the 3rd Avenue CSO by 32%.

The simple model produced an exponential change in sediment deposition with increasing distance, which was consistent with the embedded exponential equations. And it replicated the sediment deposition patterns predicted by EFDC model, which infers the derived equations are functionally representative of the sediment deposition relations used in EFDC. Thus, the simple model outcomes functionally represent the equations used to express sediment deposition in a quiescent freshwater system.

While the simple model replicated the longitudinal sediment deposition predicted by EFDC, it over-estimated peak sediment deposition predicted by EFDC. Compared to EFDC, the simple model could be considered to produce a more conservative estimate of the potential sediment deposition rates near CSOs. Neither the simple model nor the EFDC simulations included any geo-chemical processes that may occur in some freshwater systems.

5.2 Reasonableness of COC Sediment Concentrations

Without measures of comparable sediment chemical deposition rates from all possible sources, one cannot verify if the model reasonably quantifies concentration of COCs from CSOs. But a single sediment chemistry sample is available at the Belvoir site and may be used to assess how much the modeled deposition would contribute to the measured sediment chemistry. The sediment concentration of BEHP was 2020 ug/kg dry wt. The modeled sediment concentrations are substantially less with Belvoir as the only source (252 ug/kg dry wt using the 25th percentile of CSO concentrations and 746 ug/kg dry wt using the 75th percentile of CSO concentrations, Table 13). For the model to match the observed sediment concentration with Belvoir CSO as the only source, the required deposition rate must be substantially larger than that modeled. The deposition rate needs to be 3800% larger at the 25th percentile and 335% larger at the 75th percentile. These increases substantially exceed the expected error range of the model; model uncertainty is ±84%, and the simple model over-estimates deposition rates compared to EFDC simulations (32% to 370%). The needed increase in sediment deposition rate to match the measured BEHP seems unreasonable for the Belvoir PS model; these results may be an artifact of nearby non-CSO discharges. There are nearby pathways and potential sources. A storm drain and CSO (which share the same outfall) discharges 10 ft to the north of Belvoir/30th outfall.

What does seem reasonable is the predicted sediment deposition rate obtained from reasonable estimates of CSO flow rates and suspended solids concentrations used in the model. CSO flows were obtained from a model that was calibrated against metered inflows to the Belvoir PS with reasonably low uncertainty. Expected suspended solids concentrations were estimated from 726 samples collected from King County CSO sites. The model reasonably estimates sediment deposition rates from CSO outfalls.

Table 14. Expected BEHP sediment concentration near the Belvoir CSO considering only Lake Washington and Belvoir sources; BEHP CSO concentrations used were the 25^{th} and 75^{th} percentile.

Source	Source BEHP Concentration (ug/kg)	Sediment Deposition Rate (cm/yr)	Model Predicted BEHP Sediment Concentration (ug/kg)	Required CSO Deposition Rate to Achieve Measured BEHP Sediment Concentration of 2020 ug/kg (cm/yr)
Lake Washington	150[1]	0.3[1]	--	--
Belvoir CSO$_{25th}$	3640[1]	0.009[2]	252	0.34
Belvoir CSO$_{75th}$	20600[1]		746	0.03

1. Data obtained from the King County Sediment Management Plan 2018 Update.
2. Modeled sediment deposition rate §3.2.

5.3 Data Limitations

Two data use types are assessed for their completeness: data used to configure the model, and data used to verify the model. Data that limits configuring the model would be that which produces the most uncertainty in model outcomes. Finally, data that limits verifying the model would be data sets that do not allow assessing a detectable difference. Model uncertainty and detectable differences are products of statistical analyses.

5.3.1 Model Configuration Data

For the Belvoir model, parameters that contributed the largest to model uncertainty were the rate-of-increase in plume depth (m), plume flow (q_0), average flow (Q), and porosity (η). Model uncertainty is decreased by reducing uncertainty in the parameter; however, it is unlikely that uncertainty in parameters m, q_0, and Q can be reduced. Uncertainty values for m were based on an allowable surveying error of 0.01 ft, which would be difficult to improve for bathymetric surveys. CSO flows were obtained from a model that was calibrated against metered inflows to the Belvoir PS with reasonably low uncertainty. Uncertainty values for q_0 and Q are unlikely to change unless more accurate flow monitoring equipment is developed and better hydrologic models are available. For these three parameters, the applied values and uncertainties are as good as they can be.

In the model, porosity values were assumed to be 0.45 because sediment porosity was not measured; therefore, porosity uncertainty was determined from published ranges in sediment porosity. This approach very likely over estimated uncertainty in porosity. Porosity uncertainty could be reduced if measured sediment samples were collected.

5.3.2 Verification Data

In order to determine where solids from an outfall discharge will settle onto the sediment bed, one must either measure or model the discharged solids deposition. When a model is used, the model is verified by comparing model results against measured solids deposition either in the field or in the laboratory. The measured data must be accurate enough to allow detecting solids deposition from the outfall and the ambient environment. Relations between chemical concentration uncertainty and deposition rates can be derived by rearranging equation (1.2).

$$\frac{d_{cso}}{d_{amb}} \geq \frac{-2U_{COC_{amb}}}{1+2U_{COC_{amb}}-\gamma}, \quad \text{for } \gamma = \frac{COC_{cso}}{COC_{amb}} \tag{1.10}$$

Where $U_{COC_{amb}}$ is uncertainty in the measured ambient COC concentration. From equation (1.10), one could detect CSO solids deposition rates if two conditions are met:

$$\begin{gathered} COC_{cso} \geq \left(1+2U_{COC_{amb}}\right) COC_{amb} \quad (a) \\ \text{and} \\ d_{cso} \geq d_{amb} \frac{-2U_{COC_{amb}}}{1+2U_{COC_{amb}}-\gamma} \quad (b) \end{gathered} \tag{1.11}$$

If these conditions are not met, then the uncertainty in the data can overwhelm the ability to detect an effect from the CSO. If the modeled sediment deposition is less than that required by equation (1.11)(b), then the simulated sediment deposition pattern would be difficult to discern from the noise in the measured data. Thus, verification data will be of limited use if the CSO signal is not statistically different from the ambient noise.

Uncertainty in the analytical results of chemistry measurements varies by analyte but is typically ±35% for BNAs and PCBs. The first condition is met because the conditional CSO BEHP (3640 ug/kg) concentration is greater than the ambient BEHP concentration in Lake Washington (150 ug/kg). The second condition requires the CSO sediment deposition rate is equal to or greater than that determined by equation (1.11)(b). The largest required deposition rate is obtained for the smallest CSO BEHP concentration, the 25th percentile value. The second condition is met because the modeled sediment deposition rate (0.009 cm/yr, Table 8) is equal to the conditional sediment deposition rate (0.009 cm/yr, Table 14).

Table 15. Conditional CSO sediment deposition rate for BEHP with ±35 % measurement uncertainty and a Lake Washington sediment deposition rate of 0.3 cm/yr.

Source	BEHP Concentration (ug/kg)	Conditional Sediment Deposition Rate (cm/yr)
Lake Washington	150	0.009
CSO (25th percentile)	3640	

5.4 Model Output Quality Summary

Discussions in this section show that the model meets the projects objectives and reasonably:

1. Simulates the deposition of suspended solids discharged from a CSO outfall to the sediment bed according to the longitudinal distance from the CSO outfall.
2. Estimates the most likely maximum sediment deposition rate for each chemical (with Sediment Management Standards) deposited into the sediment from a CSO outfall.

Model outcomes are consistent with an exponential solution to the differential equations and the equations coded in the model. The model is considered to reasonably quantify sediment deposition rates based on the reasonableness of the applied CSO flow rates and suspended solids concentrations. Adequate data is not available to verify the modeled chemical sediment deposition rates.

6.0. REFERENCES

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