East Waterway Operable Unit

Supplemental Remedial Investigation/ Feasibility Study

Final Sediment Transport Evaluation Report

For submittal to

The U.S. Environmental Protection Agency
Region 10
Seattle, WA

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LIST OF ACRONYMS AND ABBREVIATIONS

1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
ADCP	Acoustic Doppler Current Profiler
Anchor QEA	Anchor QEA, LLC
ASAOC	Administrative Settlement Agreement and Order on Consent
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
cfs	cubic feet per second
City	City of Seattle
cm	centimeter
cm/s	centimeters per second
cm/yr	centimeters per year
County	King County
Cs-137	cesium-137
CSM	Conceptual Site Model
CSO	combined sewer outfall
CTD	conductivity/temperature/depth
DWT	deadweight tonnage
EFDC	Environmental Fluid Dynamics Code
EHI	Evans Hamilton, Inc.
EISR	Existing Information Summary Report (Anchor and Windward 2008a)
ENR	enhanced natural recovery
EPA	U.S. Environmental Protection Agency
EW	East Waterway
EWG	East Waterway Group (Port of Seattle, City of Seattle, and King County)
FS	Feasibility Study
ft/s	feet per second
kg/s	kilograms per second
lb/ft^2	pounds per square foot
LDW	Lower Duwamish Waterway

m	meters
MHHW	mean higher high water
MLLW	mean lower low water
MNR	monitored natural recovery
MSL	mean sea level
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
OU	Operable Unit
Pa	Pascals
Pb-210	lead-210
Port	Port of Seattle
psu	practical salinity unit
PTM	particle tracking model
QAPP	Quality Assurance Project Plan
RI	remedial investigation
RM	River Mile
RMS	root mean square
Rn-222	radon-222
ROD	Record of Decision
SCE	Source Control Evaluation
SCEAM	Source Control Evaluation Approach Memorandum (Anchor and Windward 2008b)
Sea Engineering	Sea Engineering, Inc.
SEDGM	Initial Source Evaluation and Data Gaps Memorandum (Anchor and Windward 2009)
SOW	Statement of Work
SPU	Seattle Public Utilities
SRI/FS	Supplemental Remedial Investigation/Feasibility Study
STAR	Sediment Transport Analysis Report (Windward and QEA 2008)
STE	Sediment Transport Evaluation
STER	Sediment Transport Evaluation Report

STEAM	Sediment Transport Evaluation Approach Memorandum (Anchor and Battelle 2008a)
STM Report	Lower Duwamish Waterway Sediment Transport Modeling Report (QEA 2008)
TEU	twenty-foot equivalent units
TSS	total suspended solids
U-238	uranium-238
U&A	Usual and Accustomed
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
Workplan	SRI/FS Workplan (Anchor and Windward 2007)
WW	West Waterway

1 INTRODUCTION

The Sediment Transport Evaluation Report (STER) presents the data and modeling outcomes that will be used to characterize sediment transport dynamics within the East Waterway (EW). The EW is one of seven operable units (OU) of the Harbor Island Superfund site, which was added to the US Environmental Protection Agency's (EPA's) National Priorities List (NPL) in September 1983 under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund. As described in EPA's Superfund regulations (1988), EPA requires that a remedial investigation and feasibility study be conducted for each site listed on the NPL, and thus EPA has ordered the Port of Seattle (Port) to conduct a Supplemental Remedial Investigation/Feasibility Study (SRI/FS) for the EW OU. Under the oversight of EPA, the EW SRI/FS is being conducted by the East Waterway Group (EWG), which consists of the Port, the City of Seattle (City), and King County (County). The Port signed the Administrative Settlement Agreement and Order on Consent (ASAOC) with EPA in October 2006, and subsequently signed a Memorandum of Agreement with the City and County to conduct the SRI/FS. The SRI/FS will ultimately lead to an EPA Record of Decision (ROD) outlining cleanup actions to address threats to human health and the environment in the EW.

The STER is a required deliverable set forth in the SRI/FS Workplan (Workplan; Anchor and Windward 2007), prepared in response to the ASAOC and Statement of Work (SOW; EPA 2006).

1.1 Report Organization

This report is organized into eight main sections, as follows:

- Introduction and study objectives (Section 1)
- Description of data collection efforts (Section 2)
- Evaluation of net sedimentation rate in the EW (Section 3)
- Development, calibration, and results from the hydrodynamic model (Section 4)
- Propwash modeling and description of vessel operations in the EW (Section 5)
- Evaluation of erosion potential due to natural processes and vessel operations within the EW (Section 6)

- Evaluation of mass contribution from lateral sources in the EW, and Particle Tracking Model (PTM) (Section 7)
- Preliminary reassessment of Physical Processes Conceptual Site Model (CSM) (Section 8)

The main body of the report is supported by the following appendices:

- Appendix A – Bathymetry Data
- Appendix B – Velocity and Salinity Data
- Appendix C – Geochronological Core Data
- Appendix D – Sedflume Core Data
- Appendix E – Hydrodynamic Model Calibration
- Appendix F – Lateral Flow and Solids Data, PTM Model Input Data
- Appendix G – PTM Model Sensitivity Analysis

1.2 Sediment Transport Evaluation Objectives

The primary purpose of the Sediment Transport Evaluation (STE) is to develop datasets and complete modeling and analytical evaluations that will be used to characterize sediment transport dynamics and assess sediment stability within the EW. The information provided in the STER will be used to refine the preliminary Physical Processes CSM within the SRI Report; the preliminary Physical Processes CSM was presented in the CSM and Data Gaps Analysis Report (Anchor, Windward and Battelle 2008).

The Workplan (Anchor and Windward 2007) provides the guidelines and objectives for conducting the STE. As stated in the Workplan, the objectives of the STE are to address the following topics:

1. Identify and evaluate the primary sources of sediment to the EW
2. Identify temporal and spatial patterns of sediment erosion and deposition (if applicable)
3. Identify the physical processes driving sediment transport
4. Identify likely routes or pathways for sediment movement

5. Assess how sediment transport pathways may affect the feasibility of remedial alternatives, including monitored natural recovery (MNR), enhanced natural recovery (ENR), dredging, and isolation capping
6. Assess potential for physical processes to contribute to recontamination

The STER will address STE objectives 1 through 4, while objectives 5 and 6 will be addressed in the SRI Report. Much of the information required to address objectives 5 and 6 is provided in the STER; however, interpretation of the data will occur in the SRI Report. The specific topics addressed in the STER include an outline of the methodology for the STE, descriptions of data collected as part of the STE, and results of proposed evaluations. The STER only describes the physical measurements and processes associated with transport of sediment and stability of the sediment bed. A preliminary verification of the Physical Processes CSM based on the information developed through the STE process is provided in Section 8 of this report. Updates to the preliminary Physical Processes CSM will be completed as part of the SRI.

The sediment transport evaluation was developed using information described in the Existing Information Summary Report (EISR; Anchor and Windward 2008a) and methodology outlined in the Sediment Transport Evaluation Approach Memorandum (STEAM; Anchor and Battelle 2008a) and the STE Workshop Summary Memorandum (Anchor and Battelle 2008b). The information presented in the STEAM is closely linked to, and relies in part on, the preliminary Physical Processes CSM presented in the CSM and Data Gaps Analysis Report (Anchor, Windward and Battelle 2008). In that report, the preliminary Physical Processes CSM description synthesized the EWG's understanding about important hydrodynamic and physical processes within the EW, focusing specifically on the processes that govern sediment transport within the waterway. Data and information presented in the EISR (Anchor and Windward 2008a) was used to develop the preliminary Physical Processes CSM. Data and information developed as part of the STE process will be used to update the preliminary Physical Processes CSM in the SRI/FS process, including investigation of the nature and extent of contamination, recontamination potential, and feasibility of remedial alternatives.

1.3 Review of Sediment Transport Evaluation Process

The development of the STER was an iterative process between the EWG and EPA. This process consisted of several evaluation and coordination steps, which are listed below:

- **Establish STE Workgroup.** This Workgroup consisted of sediment transport and modeling experts from the EWG and EPA, and provided technical input to the modeling approach and other STE methodologies. The Workgroup met at regular intervals during development of the STER to discuss key milestones and solicit input on technical issues and inform the Workgroup on results of preliminary evaluations. Workgroup recommendations (e.g., recommendations for key modeling parameters and assumptions) were documented and provided to EPA.
- **Develop field sampling program to fill the data needs.** The STEAM (Anchor and Battelle 2008a) identified key data needs to complete the STE. A Quality Assurance Project Plan (QAPP) was prepared to address STE data needs with input from the STE Workgroup and included details of how the sediment transport data needs were to be filled (Anchor QEA 2009).
- **Conduct field-sampling investigations.** Data collection included bathymetry within the EW, vertical current profiles, salinity and temperature profiles, geochronological cores (lead-210 [Pb-210] and cesium-137 [Cs-137]), and Sedflume cores.
- **Develop and run the STE models based on an approach developed with the STE Workgroup.** The approved STE modeling methodology was documented in the STEAM (Anchor and Battelle 2008a) and meeting minutes from the STE Workshop (Anchor and Battelle 2008b).
- **Prepare STER.** This report provides the results of related data collection efforts, the sediment transport modeling efforts and an assessment of sediment stability.

1.4 Physical Setting of the East Waterway

This section presents an overview of the physical site characteristics pertinent to the development of the STE. Additional detailed information on the environmental setting of the EW is presented in Section 2 of the EISR (Anchor and Windward 2008a). Section 1 of the EISR also presents a detailed site history of the EW and surrounding areas.

The EW is located approximately 1 mile southwest of downtown Seattle, in King County, Washington. It is part of the greater Duwamish River estuary, which includes the freshwater/saltwater interface extending as far as 10 miles upstream from the mouth at Elliott Bay. The Duwamish River drains approximately 362,000 acres, flowing northward to its terminus in Puget Sound at Elliott Bay. Near the mouth of the Duwamish River at River Mile (RM) 1.5, the northward flowing river splits into the EW and the West Waterway (WW), surrounding Harbor Island. The EW and WW extend from the southern end of Harbor Island to the island's north end at Elliott Bay (Figure 1-1). The EW runs along the eastern shore of Harbor Island. The EW OU is immediately downstream from the Lower Duwamish Waterway (LDW) Superfund Site. The northern and southern study area boundaries for the EW OU are shown in Figure 1-1. The east and west boundaries of the EW OU are defined by mean higher high water (MHHW), as shown in Figure 1-2.

The EW is approximately 7,100 feet long and 750 feet wide (for most of its length). It is channelized and has a south-to-north orientation. The southern 1,700-foot section of the EW varies in width from 250 feet north of the Spokane Street corridor and beneath the bridges to approximately 150 feet south of the bridges (see Figure 1-2). The mudline elevation of the EW varies from approximately -40 to -60 feet mean lower low water (MLLW) in the 750-foot-wide portion of the waterway (Figures 1-3A and 1-3B). Mudline elevations increase to between -13 and -6 feet MLLW in the vicinity of Spokane Street and the West Seattle Bridge (DEA 2010). The shallow water depths associated with this "sill" along the Spokane Street corridor form a physical constriction that generally causes a larger fraction of the total riverine flow to pass through the WW. The presence of the bridges along the Spokane Street corridor also prohibits any type of boat passage, except at low tide by small, shallow-draft boats (e.g., kayaks and skiffs).

The highly developed shoreline within the EW is primarily composed of piers, riprap, constructed seawalls, and bulkheads for industrial and commercial use (Anchor and Windward 2008a). In addition, three combined sewer outfalls (CSOs) and 39 storm drains are present along the EW that contribute freshwater and solids to the waterway (Figures 1-4A and 1-4B).

The EW, north of the Spokane Street corridor, experiences regular vessel traffic of various sizes and types. Container ships call at Terminals 18 (T-18), 25 (T-25), and 30 (T-30). U.S. Coast Guard (USCG) vessels are based at Pier 36. The EW also has significant tug and barge traffic. The EW is part of the Tribal Usual and Accustomed (U&A) fishing areas for the Muckleshoot and Suquamish Tribes and is extensively utilized for gill net fishing for salmon. South of the Spokane Street corridor, a 750-foot dock along Harbor Island is used for commercial moorage.

1.5 Preliminary Physical Processes Conceptual Site Model of the East Waterway

The current understanding of sediment transport in the EW is described in the CSM and Data Gaps Analysis Report (Anchor, Windward and Battelle 2008). Information available prior to completion of the STE was reviewed and used as the basis for conceptualizing the processes that influence sediment transport in the EW. Section 2 in the CSM and Data Gaps Analysis Report (Anchor, Windward and Battelle 2008) summarizes sediment transport processes due to natural and anthropogenic processes within the EW study area. The results of the STE (as provided in this report) will be used to update the preliminary Physical Processes CSM in the SRI Report.

In the preliminary Physical Processes CSM, three reaches of the EW were identified: the Junction Reach (south of the Spokane Street corridor to the southern boundary of the EW), the Sill Reach (the shallow area in the Spokane Street corridor), and the Main Body Reach (north of the Spokane Street corridor) (Figure 1-5). These three reaches are characterized by different sediment transport and hydrodynamic processes, and are used to refer to particular areas within the EW throughout the STER.

1.6 Overview of Sediment Transport Evaluation Technical Approach

The STE Workgroup revised and developed a preferred approach during a series of meeting from March to July 2008. This approach and rationale is described in the STEAM (Anchor and Battelle 2008a).

The STE for the EW utilized the Environmental Fluid Dynamics Code (EFDC) model previously developed for the LDW sediment transport study (Windward and QEA 2008). The first phase of the LDW modeling study began during 2004. That phase of the study involved the development, calibration, and application of the LDW hydrodynamic model. The model was used to evaluate bed stability during high-flow events. The modeling work was documented in the Sediment Transport Analysis Report (STAR; Windward and QEA 2008), which was approved by EPA and finalized in January 2008. The second phase of the modeling study began during 2006, and focused on the development, calibration, and application of the LDW sediment transport model. The sediment transport model was documented in the Sediment Transport Modeling (STM) Report, which was approved by EPA and finalized in October 2008 (QEA 2008).

The EW STE approach used a modified LDW hydrodynamics model (with increased resolution and updated bathymetry in the EW), together with empirical measurements of net sedimentation rates (geochronological cores) and critical shear stresses (Sedflume cores), to evaluate hydrodynamics and erosion potential in the EW. The LDW hydrodynamic model was then combined with a localized PTM to assess recontamination potential from lateral sources (Anchor and Battelle 2008a).

An outline of the STE approach steps is summarized below:

1. Collect bathymetry within the EW, including under-bridge and under-pier areas. Update the existing hydrodynamic model developed for the LDW (Windward and QEA 2008) for the EW study area using the new bathymetry data.
2. Calibrate the updated hydrodynamic model with site-specific velocity and salinity profile data collected as part of the STE. Specific attention will be paid to calibration of bottom velocities.
3. Collect and analyze geochronological cores collected as part of the STE.
4. Collect and analyze Sedflume cores collected as part of the STE.
5. Run the updated hydrodynamic model consistently with hydrodynamic forcing utilized in the LDW (Windward and QEA 2008); spring tide with mean annual, 2-year, 10-year, and 100-year upstream flow.

6. Use a Lagrangian PTM (developed by the U.S. Army Corps of Engineers [USACE; McDonald et al. 2006]) to estimate the contribution and distribution of lateral sediment loads to the EW.
7. Use results from the EW hydrodynamic model to:
   a. Determine erosion potential (i.e., bottom shear stresses) within the EW
   b. Estimate inflows (including the flow split) from LDW and the residence time of EW
   c. Provide input to the PTM model
8. Utilize data provided from erosion potential and geochronological cores to determine potential depositional areas and net deposition rates within the EW (where propwash is not a significant factor). Erosion areas will also be identified using these data. The hydrodynamic model will be used to confirm/refine the preliminary Physical Processes CSM in the SRI Report. Sediment load from the LDW will be estimated from geochronological cores located in the southern portion of the EW.
9. Sedimentation within the EW due to upstream sources will be estimated from geochronological core data located south of Slip 27 and the results of the PTM model. These estimates will be compared to existing estimates of incoming sediment load (Windward and QEA 2008). Use a "box model approach" to evaluate the mass balance of sediment load from lateral sources (PTM model) and upstream sources (Steps 6 and 7 above).
10. Use the results of all above analyses to validate, and refine as necessary, the preliminary Physical Processes CSM for the EW.

Steps 1 through 6 represent data collection and modeling tasks, which have been completed and are summarized in this report. Steps 7 through 11 involve interpretation of the data and modeling efforts. These analyses will be completed as part of the SRI process, and the results will be provided in the SRI Report.

2 OVERVIEW OF DATA COLLECTION

Data gaps associated with the STE approach were identified in Table 3-4 of the STEAM (Anchor and Battelle 2008a). These data gaps included bathymetry within the Sill and Junction Reaches of the EW, updated bathymetry within the Main Body Reach of the EW, synoptic vertical current and salinity profiles within the EW, and site specific empirical surface and subsurface sediment data to inform an evaluation of net sedimentation rate (geochronological cores) and critical shear stress at the bed (Sedflume cores). These data were collected as part of the STE. Details regarding field collection and laboratory methods are provided in the Sediment Transport Characterization QAPP (Anchor QEA 2009).

An overview of the data collected is provided in Sections 2.1 through 2.4. Sampling locations and durations, field data collection methods, laboratory methods (where applicable), and field deviations from the Sediment Transport Characterization QAPP (Anchor QEA 2009) are described in detail in Appendices A through D of this report. Discharge flows and total suspended solids (TSS) values from lateral sources (CSOs and storm drains) were also identified as data gaps for the STE approach as required input for the PTM. These data are being developed through the Source Control Evaluation (SCE), and will be discussed in detail the SRI Report. A summary of these data are provided in Section 7.2 of this report, and additional detail regarding development of these data is provided in Appendix F.

2.1 Bathymetry

Bathymetry data were collected as part of the EW STE on January 13 through January 15, 2010. David Evans and Associates collected multi-beam bathymetry data within the EW, including under-pier areas (DEA 2010). Lead-line depth information was collected under the Spokane Street Bridge, where depths were too shallow and overhead freeboard was too limited to use conventional multi-beam equipment (DEA 2010). The datasets were merged together to form a contiguous surface of bathymetric elevations with the EW. The horizontal datum for the survey was Washington State Plane North Zone, North American Datum of 1983 (NAD83), and the vertical survey datum was North American Vertical Datum of 1988 (NAVD88). Tidal datum information for the EW was used to convert NAVD88 to MLLW and mean sea level (MSL) for use in the hydrodynamic model. The tidal benchmark used to convert between NAVD88 and various tidal datums was Seattle National Oceanic and

Atmospheric Administration (NOAA) Station #9447130. Tidal datum information is provided in Table 2-1.

Table 2-1
Tidal Datums for the East Waterway

Tidal Datum	Relative to MLLW (feet)	Relative to NAVD88 (feet)
MHHW	11.4	9.1
MHW	10.5	8.2
MSL	6.6	4.3
MLW	3.7	1.4
NAVD88	2.3	0
MLLW	0	-2.3

The updated bathymetric surface developed for the EW is shown in Figures 1-3A and 1-3B. Appendix A provides a more detailed description of the bathymetry data collection.

2.2 Current and Salinity Data

Site-specific empirical measurements of velocity and salinity profiles and water levels within the EW were identified as a data gap (Table 3-4; Anchor and Battelle 2008a) and are discussed in detail in the STE Workshop Summary Memorandum (Anchor and Battelle 2008b). Velocity and salinity profile data and velocity transects were collected by Evans Hamilton, Inc. (EHI), within the EW study area. In addition, a tide gage was also installed by EHI south of the bridges in the Junction Reach of the EW and surveyed into NAVD88. Figure 2-1 shows the locations of the moored Acoustic Doppler Current Profilers (ADCPs), tide gage, and the current transects. These data facilitated calibration of the existing LDW hydrodynamic model for the EW. The original LDW hydrodynamic model calibration did not include any data collected in the EW (Windward and QEA 2008). The data collection efforts for velocity and salinity were targeted to allow examination of the proposed hydrodynamic characteristics of the EW study area and calibration of the hydrodynamic model within the study area.

Velocity data collected consisted of four moored (bottom-mounted) upward-looking ADCPs, which collected velocity profile data from May 7 through August 18, 2009. Each ADCP provided velocity measurements at discrete vertical intervals. Sites 3 and 4 (shown in Figure 2-1) provide velocity measurements every 0.5 meter (m) in the vertical; Sites 1 and 2 (shown in Figure 2-1) were recorded at a 1.0-m vertical interval (due to deeper water depths at these sites). Measured velocities ranged from near-bed to near-surface based on the height of the instrument off the bed, the blanking distance above each current meter, and the distance below the water surface where viable backscatter measurements can be taken. The blanking distance is a function of the frequency of the instrument, as well as other factors. Taking into account these issues, velocity measurements are available from approximately 1 m above the bed and 1.5 m below the water surface for Sites 3 and 4. For Sites 1 and 2, velocity measurements are available from approximately 2 m above the bed to 2 m below the water surface. In addition, velocity measurements may not be available at particular locations or times if the velocity in the water column was very small (due to limitations of the ADCPs to measure and record small current velocities).

In addition, 16 velocity transects were collected over a complete tidal cycle from May 13 to 14, 2009. Salinity profiles were taken using conductivity/temperature/depth (CTD) casts at the same time that the velocity transects were being completed. Sixteen salinity profiles were measured at Site 3, Site 2, and Site 1 (shown in Figure 2-1), and coincided temporally with the velocity transects. Data reports provided by EHI (EHI 2009a, 2009b, and 2009c), as well as digital copies of the raw velocity and salinity data, are provided in Appendix B.

2.3 Geochronological Cores

Geochronological cores were collected as part of the EW STE to provide empirical site-specific estimates of net sedimentation rate within the EW. Geochronological cores were collected and processed between January 25 and February 1, 2010. Twenty-two sediment cores were proposed for collection. Of the 22 proposed cores, 18 were collected. Four cores were not collected due to the presence of dense substrate near the surface in those proposed locations, which prevented penetration and sampling. The locations of the 18 collected geochronological cores, as well as locations of the four cores that were not collected, are shown in Figure 2-2.

The cores were collected to a maximum length of 90 centimeters (cm) (or to refusal) and sliced into 2-cm sections. The top 2-cm sample from each 6-cm increment was tested and all others were archived. Samples were tested for radiochemistry (Cs-137 and Pb-210), as well as grain size distribution, bulk density, percent solids, and total organic carbon (TOC). Additional information regarding the geochronological core data collection is provided in Appendix C.

2.4 Sedflume Cores

Sedflume cores were collected as part of the EW STE to provide empirical site-specific estimates of critical shear stress within the EW. Sedflume cores were collected and analyzed on site by Sea Engineering, Inc. (Sea Engineering) between April 19 and April 21, 2010. A total of eight cores were collected throughout the EW, as shown in Figure 2-3. Critical shear stress, grain size distribution, and bulk density were evaluated at various vertical intervals in the core down to approximately 20 cm below mudline. Additional information regarding the Sedflume data collection, including data reports provided by Sea Engineering, are provided in Appendix D.

3 EVALUATION OF NET SEDIMENTATION RATE IN THE EAST WATERWAY

The purpose of collecting geochronology cores was to evaluate net sedimentation rates within various portions of the EW and the occurrence of significant mixing of deposited sediment by physical processes. These data provide a key line of evidence in the evaluation of net sedimentation rates throughout the study area. Variation observed among the different cores provides information on the potential variability of net sedimentation rates and potential mixing within the EW.

3.1 Geochronology Core Sampling and Analysis

Geochronology core sampling included field collection of subsurface sediment cores from 18 locations located throughout the EW, and testing for Cs-137 (Figure 3-1) and Pb-210 (Figure 3-2). The geochronology core collection effort originally included 22 core locations; however, four cores had no recovery due to surface sediment conditions (i.e., gravel) at those locations (GC-4, GC-17, GC-21, and GC-22), and one core (GC-20) had low recovery. The locations of the cores included the Main Body, Junction, and Sill Reaches of the EW (Figure 1-5). This spatial coverage was intended to encompass a wide range of depositional conditions within the EW. Sampling locations did not include known dredge areas since using geochronology analysis to estimate net sedimentation rates may be problematic due to the disturbance of the sediment profile. Details of the sampling methodology and deviations from the approved Sediment Transport Characterization QAPP (Anchor QEA 2009) are presented in Appendix C.

Selection of cores for geochronology (age-dating) analysis followed a tiered approach. This approach determined the order in which core samples underwent radioisotope analysis in the laboratory and subsequent results made available. Tier 1 samples included all cores located in areas within the EW where influence from propwash was expected to be low (generally south of Slip 27), and a selection of cores in areas where propwash was expected to have some impact on evaluation of core data.

Radiochemistry results from the Tier 1 samples showed that cores located north of Slip 27 all appeared to be influenced by vessel operations in that area and were not viable for evaluation of net sedimentation rates. Therefore, archived samples from the remaining cores in the Main Body Reach north of Slip 27 (Cores GC-06, -07, -03, and-01) were not analyzed.

Detailed information regarding the collection and processing methodology, tier rationale, field logs, archiving procedures, and summaries of results and observations for the geochronology cores is in Appendix C. Table C-1 presents a summary of the subsurface sediment collection including recovery percentage, major lithologic units, and general sampling scheme.

3.2 Sediment Dating

The geochronology analysis was conducted by evaluating the vertical profiles of Cs-137 and Pb-210 activities, which are used to age-date sediments and estimate net sedimentation rates in estuarine and freshwater systems (Olsen et al. 1978; Orson et al. 1990). Additional information regarding specific core intervals and sampling methods is provided in Section 2.3 and Appendix C.

3.2.1 Cs-137 Data Evaluation

The ages and sedimentation characteristics of the sediment cores were analyzed using Cs-137 activity data consistent with the method described in Jeter (2000). The first occurrence of detectable Cs-137 in sediments generally marks the year 1954 (i.e., start of atmospheric testing of nuclear bombs), while peak activities correspond to 1963 (Simpson et al. 1976). Based on these dates, the best estimate of the long-term average net sedimentation rate for a particular core is computed by dividing the depth of sediment between the sediment surface and the buried Cs-137 peak by the number of years between 1963 and the time of core collection (e.g., 47 years for a core collected in 2010). Significant compaction of the sediments was not observed during the geochronology study; therefore, recovered and sediment horizon depths were not altered from field measurements. This approach was successfully used to date sediment cores in the LDW (Windward and QEA 2008).

Uncertainty in the exact location of the true Cs-137 peak exists for the following reasons: 1) the laboratory reports 95% confidence intervals around the best estimate of the Cs-137 activity for each sample (to reflect measurement uncertainty); and 2) the true Cs-137 peak could exist within un-analyzed sediment segments located immediately above and below the observed Cs-137 peak. Therefore, to account for this uncertainty, a range of net sedimentation rates was computed for each core. A lower-bound net sedimentation rate was computed by dividing the depth (in cm) between the sediment surface and the lower edge of the analyzed segment immediately above the observed Cs-137 peak by 47 years. An upper-bound net sedimentation rate was computed by dividing the depth (in cm) between the sediment surface and the upper edge of the analyzed segment immediately below the observed Cs-137 peak by 47 years. Net sedimentation rates for each core, as estimated using these two approaches, are presented in Table 3-1 and Figure 3-1.

Table 3-1
Estimated Net Sedimentation Rates based on Cs-137 Data

Sediment Core ID	Depth of Cs-137 Peak (cm)	Estimated Net Sedimentation Rate (cm/yr)	
		Via Cs-137 Peak	Estimated Range
GC-02	--	--[a]	--[a]
GC-05	--	--[a]	--[a]
GC-08	--	--[a]	--[a]
GC-09	--	--[a]	--[a]
GC-10	62	1.3	1.2 - 1.4
GC-11	80	Greater or equal to 1.7 [b]	1.6 - 1.8
GC-12	90	Greater or equal to 1.9 [b]	1.8 - 2.0
GC-13	--	--[a]	--[a]
GC-14	56	1.2	1.1 - 1.3
GC-15	62	1.3	1.2 - 1.4
GC-16	74	1.6	1.5 - 1.7
GC-18	90	Greater or equal to 1.9 [b]	1.8 - 2.0
GC-19A	56	1.2	1.1 - 1.3
GC-20	--	--[c]	--[c]

Notes:
GC-01, -03, -06, and -07 were archived.
a. No peak observed.

b. Cs-137 peak was at the bottom of the core; therefore, the actual peak may be below the recovered depth of the core.
c. Low recovery.

Eight of the 15 sediment cores analyzed contained distinct Cs-137 activity that allowed the calculation of an estimated net sedimentation range. For cores GC-11, GC-12, and GC-18, it is expected that the maximum Cs-137 peak is below the recovered depth of the core. This expectation was based on the increasing trend in Cs-137 activity at the bottom of the core and comparison of Cs-137 profiles at nearby cores (GC-14, GC-15, and GC-19A) that exhibit similar trends. Deep vertical mixing is not expected to produce the results seen at core locations GC-11, GC-12, and GC-18 due to review of vessel operations in these areas and comparison of cesium profiles in areas where deep vertical mixing is expected (GC-05 and GC-08) that show different trends over the vertical. Therefore, a minimum net sedimentation rate for these cores was assigned based on the deepest sampled interval in the core. As shown in Figures 3-3A and 3-3B and in Table 3-1, the depth of the Cs-137 activity peak varied between 56 and 90 cm in these eight cores, which corresponds to a net sedimentation rate range of 1.2 to 1.9 centimeters per year (cm/yr). These net sedimentation rates are similar in magnitude to previous geochronological cores collected in the EW, which ranged between 1.0 and 1.5 cm/yr (Table 4-2 of the EISR; Anchor and Windward 2008a). Due to a lack of recovery in the Junction Reach (south of the bridges) and lack of discernable Cs-137 peaks in cores located in the northern portion of the EW, net sedimentation rates cannot be compared throughout the waterway. Within the Main Body Reach, there was no consistent variation in estimated net sedimentation rates between analyzed cores.

3.2.2 Pb-210 Data Evaluation

Pb-210, which is a decay product of volatilized atmospheric radon-222 (Rn-222), is present in sediments primarily as a result of atmospheric deposition. Rn-222 is a volatile, short-lived, intermediate daughter of uranium-238 (U-238), a naturally occurring radioisotope found in the earth's crust. The Pb-210 activity in a sediment sample represents the total Pb-210 activity, which is measured indirectly by analysis of its radioactive decay products bismuth-210 or polonium-210. Total Pb-210 activity consists of two components: 1) unsupported Pb-210, which represents Pb-210 that is deposited on the earth's surface at an approximately constant rate via atmospheric deposition; and 2) supported Pb-210, which is the background Pb-210 activity in the sediment. In aquatic environments, the approximately constant atmospheric flux of Pb-210 and its decay half-life of 22.3 years results in relatively homogeneous Pb-210 activities within the biologically-active surface layer of the sediments and activities that decay exponentially below this depth (see Figure 3-4). For this reason, Pb-210 serves as a useful tracer for estimating net sedimentation rates in aquatic systems.

Estimation of net sedimentation rates using Pb-210 data relies on determination of the unsupported fraction of the total Pb-210 activity, also referred to as excess Pb-210. The unsupported fraction (Pb_u-210) is estimated as follows:

$$Pb_u\text{-}210 = Pb_T\text{-}210 - Pb_S\text{-}210 \tag{3-1}$$

Where:

Pb_T-210	=	total Pb-210 activity reported by the laboratory in the sediment samples
Pb_S-210	=	supported Pb-210 activity derived from natural decay in sediments

Unsupported Pb_u-210 activities are computed by subtracting the average supported Pb_S-210 activity from the total Pb_T-210 activities throughout the core, as per Equation 3-1. Based on the affinity of Pb-210 for silts and clays, the unsupported Pb_u-210 values were fines normalized (Ab Razak et al. 1996). The natural log of the unsupported Pb_u-210 (i.e., ln [Pb_u-210]) was plotted as a function of core depth, and a linear regression was performed. The slope of this line (m) was used to estimate the average net sedimentation rate (Pb_R with units of cm/yr):

$$Pb_R = -\ 0.0311/m \tag{3-2}$$

The supported (Pb_S-210) activity in the sediments was estimated for this study. Therefore, to account for this uncertainty in values of the supported Pb-210 activity, an analysis was performed to determine the best estimate of the net sedimentation rate for each core based on varying assumptions regarding unsupported Pb-210 activities in the EW sediments. This analysis was performed independently for each of the cores with interpretable Pb-210 profiles.

This approach yields best estimates of the average net sedimentation rates for each core in consideration of the uncertainty associated with the actual supported Pb_S-210 activities in the sediments. However, these best estimates are subject to other sources of uncertainty (see Section 3.4). Therefore, in addition to the best estimate, a range of average net sedimentation rates was determined for each core to account for these additional sources of uncertainty. The lower-bound ($Pb_{R\ lcl}$) and upper-bound ($Pb_{R\ ucl}$) estimates were computed for each core using the confidence limits around the slope of the best-fit lines and Equations 3-3 and 3-4, respectively:

$$Pb_{R\ lcl} = -\ 0.0311/(m-m_{cl}) \qquad (3\text{-}3)$$

$$Pb_{R\ ucl} = -\ 0.0311/(m+m_{cl}) \qquad (3\text{-}4)$$

Where:

m_{cl} = 95% confidence interval around the mean slope of the best-fit line

The best estimate and range of average net sedimentation rates for each of the cores with interpretable Pb-210 profiles are presented in Table 3-2 and shown in Figures 3-5A and 3-5B.

Table 3-2

Estimated Net Sedimentation Rates based on Pb-210 Data

Sediment Core ID	R^2 value for Best-fit Line	Estimated Net Sedimentation Rates (cm/yr)	
		Estimate Based on Best-fit Line	Range
GC-02	0.17	--[a]	--[a]
GC-05	0.78	0.67	0.26 - 0.67
GC-08	0.92	0.28	0.20 - 0.48
GC-09	0.78	0.56	0.35 - 1.4
GC-10	0.63	0.61	0.30 - 0.61
GC-11	0.70	0.47	0.27 - 1.8
GC-12	0.71	0.46	0.27 - 1.8
GC-13	0.63	0.69	0.34 - 0.69
GC-14	0.003	--[a]	--[a]
GC-15	0.45	--[a]	--[a]

Sediment Core ID	R^2 value for Best-fit Line	Estimated Net Sedimentation Rates (cm/yr)	
		Estimate Based on Best-fit Line	Range
GC-16	0.91	0.18	0.09 - 4.2
GC-18	0.48	--[a]	--[a]
GC-19A	--[b]	--[b]	--[b]
GC-20	--	--[c]	--[c]

Notes:
GC-01, -03, -06, and -07 were archived.
a. Net sedimentation rate not estimated due to low correlation ($R^2 < 0.50$).
b. Core contains un-interpretable Pb-210 profile.
c. Low recovery.

The correlation coefficient (R^2) values for the best-fit lines determined during the Pb-210 analysis range from 0.003 to 0.92. Eight of 13 cores produced correlations in the Pb-210 profile with R^2 values greater than 0.50; net sedimentation rates for cores with R^2 values less than 0.50 are considered to be unreliable estimates and, therefore, were not calculated. Cores with R^2 values less than 0.50 are GC-02, GC-14, GC-15, and GC-18. GC-15 and GC-18 had R^2 values that were close to 0.50 (0.45 and 0.48, respectively) and exhibited reasonable Cs-137 peaks. Therefore, the slightly lower than threshold (0.50) R^2 values for these cores are likely due to uncertainties/variability in the evaluation (see Section 3.4). Cores GC-02 and GC-14 had significantly lower R^2 values (0.17 and 0.003, respectively). The lower correlation values for these cores are due to variability in the Pb-210 values primarily at one depth interval; approximately 14 cm below mudline for both cores (see Figures 3-5A and 3-5B). This variability could be due to the presence of a sand layer at that depth interval for Core GC-02 (see Figures 3-3A and 3-3B), or could be due to mixing of the surface sediments in either core.

Some of the uncertainties discussed in this section and Section 3.4 with respect to the Pb-210 analysis may also contribute to the low R^2 values computed for some cores. However, consistent relationships between R^2 values and core characteristics (e.g., core recovery) were not observed. Best-estimate net sedimentation rates for the eight cores with R^2 values greater than 0.50 ranged from 0.18 to 0.69 cm/yr as provided in Table 3-2 and shown graphically in Figure 3-2.

3.3 Summary of Results – Net Sedimentation Rates in the East Waterway

Net sedimentation rates were calculated for each of the eight cores with interpretable Cs-137 activity profiles and eight cores with high correlation Pb-210 activity profiles. The estimated rates are shown in Table 3-3.

Table 3-3
Comparison of Net Sedimentation Rates

Sediment Core ID	Estimated Net Sedimentation Rates from Cs-137 Analysis (cm/yr)		Estimated Net Sedimentation Rate from Pb-210 Analysis (cm/yr)	
	Via Cs-137 Peak	Peak Range	Estimate Based on Best-fit Line	Range
GC-02	--[a]	--[a]	--[b]	--[b]
GC-05	--[a]	--[a]	0.67	0.26 - 0.67
GC-08	--[a]	--[a]	0.28	0.20 - 0.48
GC-09	--[a]	--[a]	0.56	0.35 - 1.4
GC-10	1.3	1.2 - 1.4	0.61	0.30 - 0.61
GC-11	>1.7	1.6 - 1.8	0.47	0.27 - 1.8
GC-12	>1.9	1.8 - 2.0	0.46	0.27 - 1.8
GC-13	--[a]	--[a]	0.69	0.34 - 0.69
GC-14	1.2	1.1 - 1.3	--[b]	--[b]
GC-15	1.3	1.2 - 1.4	--[b]	--[b]
GC-16	1.6	1.5 - 1.7	0.18	0.09 - 4.2
GC-18	>1.9	1.8 - 2.0	--[b]	--[b]
GC-19A	1.2	1.1 - 1.3	--[c]	--[c]
GC-20	--[d]	--[d]	--[d]	--[d]

Notes:
GC-01, -03, -06, and -07 were archived.
a. No Cs-137 peak observed.
b. Net sedimentation rate not estimated due to low correlation ($R^2 < 0.50$).
c. Core contains un-interpretable Pb-210 profile.
d. Low recovery.

Direct comparisons of the two methodologies are possible for four cores: GC-10, GC-11, GC-12, and GC-16. At two of the four locations (GC-11 and GC-16), the net sedimentation rate based on the Cs-137 profile analysis fell within the range of the net sedimentation rate based on the Pb-210 profile analysis. In the other two cores (GC-10 and GC-12), net sedimentation rates determined from the Pb-210 profile analysis were lower than those estimated using the Cs-137 profile analysis.

Analyses of Cs-137 and Pb-210 profiles in the cores for which net sedimentation rates can be reliably estimated indicated that net sedimentation rates range from 0.2 to greater than 2.0 cm/yr. These net sedimentation rates are consistent with the results of earlier studies in the EW and WW for Cs-137 (1.0 to 2.4 cm/yr) and Pb-210 (0.5 to 0.8 cm/yr) (EVS and Hart Crowser 1995).

The majority of cores analyzed for radioisotopes during this investigation exhibited relatively uniform, interpretable profiles with depth, suggesting that, overall, these areas are net depositional. However, vertical profiles of physical and chemical properties in the sediments also provide a means of identifying evidence of episodic disturbances. For some of the EW cores, the absence of discernable peaks of Cs-137 and variations in the vertical distributions of Cs-137 activity, Pb-210 activity, TOC, grain size distribution, and total solids content indicate that episodic disturbances may be occurring on a local scale. These episodic erosion/deposition events may be the result of several phenomena (e.g., dredging activities, slumping of nearby sediments, high-flow events, or ship-induced bed scour), although the exact nature of these events is not known.

3.4 Uncertainty Discussion

Several physical, chemical, and biological factors introduce uncertainty into net sedimentation rates estimated from the radioisotope profiles. Some of these factors include:

1. Temporal variability of the net sedimentation rate
2. Natural variability in radioisotope measurements
3. Variations in sediment characteristics
4. Spatial variability of depths to which benthic invertebrates burrow into the EW sediments (e.g., mixing or bioturbation depth)
5. Spatial variability of physical disturbances of the sediments in the EW (e.g., erosion, dredging, or ship-induced vertical mixing)
6. Compaction and/or mixing of sediments during core collection/extrusion
7. Poor sediment recovery rates in core samples

Some of these sources of uncertainty are documented by NOAA and Battelle in a Pb-210 study that was conducted in Puget Sound (Lavelle et al. 1985). The first five factors are likely the greatest contributors to uncertainty in net sedimentation rates estimated during this study, primarily due to the variability in the extent and magnitude that these processes occur in the EW.

The final two factors were mitigated through careful sample collection methodology. Core collection and processing are not believed to be significant contributors to uncertainty in estimated net sedimentation rates. Core compaction and/or mixing of sediments during core collection/extrusion can result in the smearing of Cs-137 and Pb-210 activity gradients throughout the sediment column. However, significant compaction and/or mixing of the sediments was not observed during the geochronology study; therefore, cores were not corrected for compaction and sediment was not sampled from the core side walls where smearing occurs. Sediment recovery rates ranged from 73% to 96%. If core compaction did occur to any significant extent, then actual net sedimentation rates would be greater than those presented in this report.

4 HYDRODYNAMIC MODEL

4.1 Overview of Technical Approach

The hydrodynamic model utilized in the STE was developed through modification of an existing model used to evaluate hydrodynamics in the LDW (Windward and QEA 2008). The model utilizes the three-dimensional (3-D) EFDC computer code to represent hydrodynamic processes. It is a physics-based model in that it includes the important physical processes and algorithms to describe the hydrodynamic processes in the system. The model domain extends from the Duwamish River at the south to a boundary between Puget Sound and Elliott Bay that is located between Alki Point and West Point.

The LDW hydrodynamic model was updated to increase the grid resolution within the EW. Data collected as part of the STE were used to update the bathymetry within the EW and calibrate the model within the EW (current and salinity data). In particular, there was a need to update bathymetry in the vicinity of the shallow water Sill Reach, the Junction Reach of the EW with the LDW, and under-pier areas. In addition, Slips 27 and 36 were included in the model domain.

The updated hydrodynamic model was used to evaluate hydrodynamics (current velocities, salinity distribution, water surface elevations) within the EW due to tidal forcing and various upstream inflow conditions in the Green River and LDW (annual average, mean wet season, 2-year, 10-year, and 100-year flow events). The updated model was also used to evaluate erosion potential (by determining bottom shear stresses) within the EW for these events. These model results will be used to help refine and validate the preliminary EW Physical Processes CSM during the SRI process.

4.2 Development of Numerical Grid

Modifications to the original numerical grid included updated bathymetry based on data collected for the STE and increased grid resolution within the EW. The modified numerical grid included approximately 375 horizontal cells within the EW study area, with ten layers in the vertical direction. Specific changes to model resolution within the EW included the following (see Figure 4-1):

- In the Main Body Reach of the EW (see Figure 1-5), eleven grid cells were used across the EW (east to west), which resulted in an average grid cell width of approximately 75 feet.
- Along the channel of the EW, grid cells are approximately 200 feet long (north to south), which produced approximately 250 horizontal grid cells within the Main Body Reach of the EW (approximately 27 cells along the channel and 9 cells perpendicular to the channel).
- In the Sill Reach (see Figure 1-5), three grid cells were used across the EW, expanding to four and five grid cells in the area north of the bridges.
- In Slip 27, six grid cells (approximately 400 feet by 200 feet) were used; three cells along the slip and two cells across the slip.
- In Slip 36, 12 grid cells (approximately 300 feet by 200 feet) were used; six cells along the slip and two cells across the slip.
- Additional increases to grid resolution at the confluence of the EW and LDW were required to blend the upstream grid cells from the original LDW model into the higher resolution grid cells in the EW. This change was required to ensure model stability.
- Additional increases to grid resolution within Elliott Bay were required to better represent the confluence of Elliott Bay and the EW and to ensure model stability.

Bathymetry values were assigned to each grid cell as the average elevation within the extent of a specific grid cell. The input bathymetry was converted from feet, NAVD88, to MSL based on the tidal datums provided in Table 2-1. Figure 4 shows the updated numerical grid within the EW.

4.3 Boundary Conditions

In all calibration and production simulations, the model was driven by two boundary conditions: 1) inflow rate at the upstream boundary in the Green River; and 2) spatially-uniform water surface elevation at the Elliott Bay open boundary. The upstream boundary condition was specified using measured daily-average flow rates obtained at the U.S. Geological Survey (USGS) gage near Auburn, Washington. The tidal boundary condition was established using verified, 6-minute water level data collected at the NOAA tidal gage station in Elliott Bay (#9447130). The tidal elevation data were referenced to the MSL datum, consistent with the input bathymetry datum. In addition, upstream and downstream boundary conditions for salinity were also included in the model. The upstream inflow at the Green River was set to a constant salinity of 0 practical salinity unit (psu) (freshwater) and the downstream boundary at Elliott Bay was set to a constant salinity of 31 psu. Each model simulation included 45 days of simulation time before the time period of interest in order to fully develop the salinity distribution within the model domain. The boundary conditions for the model calibration simulations were designed to temporally coincide with current velocity and water level data collected between March 1 and August 31, 2009. Temporal variations in tidal elevation at the open boundary and upstream inflow rate during this time period are shown in Figures 4-2 and 4-3.

The production simulations focused on a 2-month time period (June 1 to July 31, 2009) in order to facilitate integration with the PTM discussed in subsequent sections of this report. There were five different production simulations, each with the same tidal boundary condition (Figure 4-4) and time-independent upstream inflow representing the mean annual, wet mean annual, 2-year, 10-year, and 100-year flows. The second two weeks of June 2009 exhibited tidal fluctuations consistent with a typical spring tide event in the area, with a maximum range of 16 feet between consecutive high and low water levels.

Five upstream inflow boundary conditions were used for the production simulations, based on extreme return period flow events developed previously for the LDW: 1) mean annual discharge; 2) mean 'wet season' discharge (defined here as November through May); 3) 2-year high-flow event; 4) 10-year high-flow event; and 5) 100-year high-flow event. Figure 4-5 illustrates variations in the monthly-average flow rate; it is evident that the period of November through May experiences significantly higher flow rates than June through September. The 2-, 10-, and 100-year high-flow events were taken from the LDW Sediment Transport Modeling Report (Windward and QEA 2008). Mean annual flow rate was estimated as the average monthly flow rate over all 12 months of the year and mean 'wet season' flow rate was taken as the average monthly flow rate for the months of November through May (see Figure 4-5). Table 4-1 lists the flow rates corresponding to the five production simulations.

Table 4-1
Upstream Flow Rates for Production Simulations

Flow Condition	Flow Rate (cfs)
Mean annual	1,330
Mean 'wet season'	1,875
2-year high-flow event	8,400
10-year high-flow event	10,800
100-year high-flow event	12,000

Notes:
cfs = cubic feet per second

4.4 Calibration Strategy

The hydrodynamic model calibration effort optimized the agreement between measured and predicted current velocities, water surface elevations, and salinity in the EW using data collected during the 4-month period of May 2009 through August 2009. Calibration metrics included the root mean square (RMS) error between the measured and predicted time series of water surface elevation and depth-averaged salinity and current velocity, along with qualitative assessments of the vertical profiles of predicted and observed salinity and current velocity. The primary parameters/inputs adjusted during model calibration were: 1) bottom roughness height in the EW, particularly in the vicinity of the West Seattle Bridge; and 2) bathymetry of the WW. The numerical grid in the WW was not modified from the original LDW model and the resolution of the numerical grid within the WW was relatively coarse (two grid cells across the WW). Therefore, representation of WW geometry within the model was assumed to be uncertain (compared to the updated model geometry within the EW) and the bathymetry within the WW was treated as a calibration parameter during the calibration process for the hydrodynamic model.

Model predictions of vertical distribution of salinity showed good agreement with measurements prior to the calibration effort. Figures E-1 through E-48 show comparisons of measured and predicted values of salinity for each of the 16 salinity profiles measured at locations 1, 2, and 3 (see Figure 2-1 for locations). Measurements of water surface elevation were also well predicted by the model prior to model calibration; RMS errors ranged between 6 and 10 cm. Figure 4-6 shows a comparison of predicted and measured water surface elevation at the tide gage installed by EHI just south of the bridges in the Junction Reach (see Figure 2-1 for location). As illustrated in Figure 4-6, the model is able to accurately predict tidal elevations over a wide range of tidal forcing and freshwater inflow conditions.

The calibration effort focused on the comparison of measured near-bed current velocities (1 to 2 m above the bed) and measured vertical distribution of current velocities at Sites 1, 3, and 4, (as shown in Figure 2-1) with corresponding model predictions. Current measurements at Site 2 were very small, and together with the high signal-to-noise ratio, could not be quantified accurately by the instrument. Therefore, current velocities at this location were not used in the calibration effort (see Section 2.2). During calibration, the bottom roughness height in the section of the EW adjacent to the West Seattle Bridge was increased to 50 cm, tapering to 5 cm away from the narrowest section to account for interaction of the flow with the bridge pilings and shallower water in those areas. The bottom roughness for the remainder of the numerical grid was left at the original value assigned for the majority of the areas in the LDW model: 0.2 cm. In addition, the depth in the WW was increased by 25% (relative to the bathymetry in the WW in the original LDW model), and the transitions into Elliott Bay and the LDW were smoothed to ensure numerical stability in those areas. These changes in bottom roughness and WW bathymetry made the modeled vertical current profiles align more closely with the measured data.

After the above adjustments, the predicted water surface elevations and salinity and current velocity profiles matched reasonably well with measurements. Table 4-2 provides a comparison of RMS error for the initial model simulations and the final calibrated model for depth-averaged current velocity and salinity.

Table 4-2
Summary of RMS Error for Model Calibration

Calibration Simulation	Calibration Parameter		RMS Error in Depth Averaged Current (cm/s) 1-month Simulation Time - May 2009			
	West Waterway Bathymetry	Bottom Roughness in Junction Reach (m)	Site 1	Site 2	Site 3	Site 4
1	no changes	0.05	1.7	1.7	3.3	8.0
2	no changes	varies from 0.05 to 0.1	1.7	1.7	3.1	8.0

Calibration Simulation	Calibration Parameter		RMS Error in Depth Averaged Current (cm/s) 1-month Simulation Time - May 2009			
	West Waterway Bathymetry	Bottom Roughness in Junction Reach (m)	Site 1	Site 2	Site 3	Site 4
3	no changes	varies from 0.05 to 0.25	1.7	1.7	2.9	7.8
4	no changes	varies from 0.05 to 0.5	1.7	1.7	2.8	7.8
5	25% deeper and blended upstream into LDW	0.002	1.7	1.7	3.2	8.2
6 (final calibrated model)	25% deeper and blended upstream into LDW	varies from 0.05 to 0.5	1.7	1.7	2.5	7.9
7	50% deeper and blended upstream into LDW	varies from 0.05 to 0.5	1.7	1.7	2.5	8.5

Notes:
cm/s = centimeters per second
m = meters
LDW = Lower Duwamish Waterway

Comparisons of predicted and measured current velocity profiles for the calibrated model are provided in Appendix E. These comparisons are provided in Adobe PDF format for locations 1, 3, and 4 (see Figure 2-1 for site locations). Each PDF file contains current velocity profiles plotted in 15-minute intervals from May 7 to May 31, 2009.

Figures 4-7, 4-8, and 4-9 show typical examples of agreement between predicted and measured current velocity profiles at Sites 4, 3, and 1, respectively (see Figure 2-1 for site locations). Overall, model predictions of the vertical current velocity distribution were in close agreement with measurements over a majority of the tidal cycle for Sites 3 and 4, which were located in the southern portion of the EW where the width is constricted and the water depth is shallow compared to the EW basin. The vertical current velocity profiles at Site 1 (as well as Site 2) were not as accurately predicted by the model because the magnitudes of the current velocities were relatively small and the vertical profile had minimal structure. The current velocity magnitudes predicted by the model at Sites 1 and 2 were within acceptable errors compared to measurements.

An additional evaluation of model performance was conducted by analyzing the distribution of flow rate between the EW and WW as a function of upstream inflow. This analysis was done to ensure that deepening the WW (in order to calibrate the model to current velocities measured within the EW) did not unrealistically affect the split in flow rate during high-flow events. The modeled relationship between flow rate through the EW and total upstream flow rate indicates that:

- For low to moderate flow conditions, there is approximately a 50% - 50% split between flow in the EW and WW
- As the LDW flow rates increases and shifts to high-flow conditions (i.e., 2-year flood), the East:West flow split is about 30% to 70%, and this ratio is approximately constant as flow rate increases above the 2-year flood
- The reduction in the percentage of flow within the EW (compared to the WW) can be explained by the relatively constricted entrance to the EW. Therefore, changes to the WW bathymetry during calibration do not appear to have a significant effect on the split in flow between the EW and WW in the calibrated hydrodynamic model.

Model predictions of flow rate within the EW (just north of the bridges) were compared to flow rates estimated from three cross-channel ADCP transects taken as part of the data collection effort (see Figure 2-1 for locations). Figure 4-10 illustrates this comparison. Variability in flow rates estimated from ADCP transects shown in Figure 4-10 is due to overall low current velocities, higher signal-to-noise ratios (and thus higher error in the measurements), and lack of distinct flow patterns within the transect data. The flow rate in the EW predicted by the model appears to be the slightly higher than measured values on ebb tide and slightly lower than measured values on flood tide. However, flow rates estimated from the ADCP transect data did not include flow in the surface (top 2 m) and near bottom (variable, but generally equal to or less than 0.5 m above the bottom) due to limitations of the instrument (blanking distance). Based on ADCP transect data (see Appendix B), approximately 20% of the total flow cross-sectional area was excluded from the ADCP measurements due to blanking distances for the instrument. This may account for some of the differences noted between predicted and measured flow rates in the EW. Within the variability of the data, measured and predicted flow rates within the EW appear to be within the same order of magnitude and follow similar temporal patterns.

Overall, calibration of the hydrodynamic model was successful based on agreement between measurements and model predictions of salinity, current velocity, and water surface elevation. The results of the calibration effort indicate that the model is sufficiently accurate and reliable to meet the stated STE objectives in Section 1.

4.5 Hydrodynamics Model Results

Results of the hydrodynamic model runs are described in Sections 4.5.1 through 4.5.3, and are broken down by EW Reach. The hydrodynamic model results are used in this report to describe hydrodynamics within the EW and to estimate bottom shear stress throughout the EW under various flow conditions. The evaluation of bottom shear stress is discussed in Section 6.

The hydrodynamics within the EW were evaluated overall and within each defined reach (i.e., Sill, Junction, and Main Body Reaches) (see Figure 1-5). General discussion of the hydrodynamics within the EW is included in this section of the report. Discussion of hydrodynamics specific to each reach is provided in Sections 4.5.1 through 4.5.3.

Histograms of modeled velocity magnitudes within the entire EW at the surface, mid-depth, and near-bottom layers are provided in Figures 4-11 through 4-13 for mean annual flow, Figures 4-14 through 4-16 for the 2-year flood, and Figures 4-17 through 4-19 for the 100-year flood. These figures show that higher current velocities with greater spread in the velocity magnitude are present in the surface layer, compared to mid-depth and near-bottom layers. Current velocities in all layers increase with increasing river flow rate. Velocity magnitudes in the surface layer range from 0 to 70 centimeters per second (cm/s), with a mean near 10 cm/s for mean annual inflow. These current velocities increase in range from 0 to 100 cm/s, with a mean near 30 cm/s for the 100-year high-flow event. Velocity magnitudes in the near-bottom layer range from 0 to 20 cm/s, with a mean near 5 cm/s for mean annual inflow. These velocities increase slightly under 100-year flood conditions, with maximum values of about 30 cm/s, but the mean remains near 5 cm/s.

Maximum ebb (downstream) and flood (upstream) current velocities within the EW are plotted as a function of upstream flow rate in Figure 4-20. Maximum ebb velocities in the surface layer are greater than at mid-depth, which are greater than at near-bottom. These current velocities all increase as upstream flow increases. This pattern is expected, as increased flow rate in the river should increase downstream velocities within the EW. Maximum flood velocities, on the other hand, decrease in the surface and mid-depth layers with increases in upstream flow rate. This pattern is also expected, as increased flows in the river reduce the influence of the incoming tide in the upper water column. Near-bottom flood velocities show a slight increase in magnitude with increased river flow rate.

Vertical salinity distribution and 3-D current structure was examined for each model simulation. Figures 4-21 through 4-23 show vertical distributions of salinity and along-channel velocities within the EW (RMs in the EW shown on Figure 1-5) for all three reaches for typical flood tide conditions for the mean annual, 2-year, and 100-year high-flow events, respectively. Figures 4-24 through 4-26 show the same information for typical ebb tide conditions for the mean annual, 2-year, and 100-year high-flow events, respectively. These figures illustrate typical extremes of current velocities and salinities within the EW over the tidal cycle with increased river flow rates. Figures 4-27 through 4-29 show residual (tidally averaged) current velocities and average salinities over several tidal cycles for the mean annual, 2-year, and 100-year high-flow events, respectively. These figures illustrate the net current magnitude and direction and average salinities within the EW. In all events, there is a net outflow of lower salinity (fresher) water in the upper layers of the EW, and a net inflow of high-salinity water in the bottom layers. Higher outgoing (downstream) current velocities are located in the surface layer in the Junction and Sill Reaches, and higher incoming (upstream) current velocity is found in the bottom layers near the mouth of the EW. The magnitude of the surface current velocity decreases moving downstream from the Junction Reach into the Main Body Reach, while the magnitude of the bottom current velocity increases from the mouth of the EW upstream toward the Sill and Junction Reaches. Salinity is highest in the bottom layers near the mouth of the EW and lowest in the surface layers in the Junction Reach.

As the upstream inflow rate increases, so does the magnitude of the net current velocities. During the 2-year and 100-year high-flow events, there is no net incoming (upstream) flow in the Sill and Junction Reaches; all vertical layers have a net outgoing flow. At any given location, average salinity decreases as upstream inflow increases.

4.5.1 Main Body Reach

The Main Body Reach is characterized by relatively low current velocities and a distinct distribution of top to bottom salinity. Velocity magnitudes at the surface range from approximately 0 to 40 (cm/s), with higher current velocities occurring during ebb tide during higher upstream flow events. Surface current velocities tended to be higher in the southern portion of the Reach and were lower toward the mouth of the EW. Surface water flows towards the LDW during flood tide during low upstream flows; however, these current velocities are very low. Maximum near bottom velocities within this reach ranged from approximately 0 to 18 cm/s, with current velocity increasing as upstream flow increases. Near bottom current velocities were higher near the mouth of the EW and were lower to the south. The increase in near bottom velocity at the mouth of the EW, and subsequent reduction in current velocities moving upstream (and with increasing upstream flow), is due to the two-layer density-driven circulation within the EW. During incoming tide, higher salinity water flows from Elliott Bay into the relatively constricted opening of the EW at depth, which produces relatively high near bottom velocities at the mouth of the EW. As this flow moves upstream, density-driven circulation and vertical mixing of the incoming tidal waters with the lower salinity surface waters (from upstream flows) causes a reduction in near bottom velocities between the mouth and the Sill Reach in the EW (see Figures 4-27 through 4-29).

A layer of fresher water ranging in depth from about 5 to 20 feet (depending on tide and upstream flow conditions) is found at the top of the water column, with a nearly constant vertical distribution of high salinity water found from the bottom of the fresher water layer to the sediment bed. Over the tidal cycle, surface salinities range from 22 to 26 psu for mean annual flow and 14 to 18 psu for 100-year high-flow event. Bottom salinities range from 30 to 31 psu for mean annual and 100-year high-flow event (see Figures 4-21 through 4-29).

4.5.2 The Junction Reach

The Junction Reach is characterized by high surface current velocities (compared to the Main Body Reach) with a distinct top to bottom salinity stratification during most flow conditions. Current velocity magnitudes at the surface range from approximately 0 to 90 cm/s, with higher velocities occurring during ebb tide at higher upstream flows. Surface water does flow upstream into the LDW during low flow conditions at flood tide; however, these current velocities are quite low. Maximum near bottom velocities range from 0 to 10 cm/s and are generally consistent throughout the reach. Near bottom velocities are highest during ebb tide, increase with increasing upstream flow rate, and are affected by the pervasive two-layer flow that exists in this reach, as well as the majority of the EW (see Figures 4-27 to 4-29). Upstream flow of higher salinity water in the bottom layers (compared to surface layer salinities) confine high downstream current velocities (due to upstream freshwater input) to the surface layers. This results in lower near bottom current velocities in the Junction Reach than would be expected if the system had single-layer flow (no flow reversal at depth) (see Section 4.5).

A layer of fresher water is found at the top of the water column with a nearly constant vertical distribution of higher salinity water found at the bottom of the water column. The thickness of the freshwater layer, and top to bottom salinity differences, vary with upstream flow conditions. During periods of high flow, lower salinity water can encompass most of the water column. Top to bottom salinity ranges from 0 to 22 psu for mean annual flow and 0 to 14 psu for 100-year high-flow events (see Figures 4-21 through 4-29).

4.5.3 The Sill Reach

The Sill Reach is similar to the Junction Reach in both current velocity structure and salinity distribution. The Sill Reach is characterized by shallow water (approximately 6 feet MSL at its most shallow) with no defined deeper channel, which is present in the Junction Reach. Surface current velocities have similar magnitudes to the Junction Reach and react similarly to increases in upstream flow and tidal conditions. Maximum near bottom velocities within the Sill Reach are slightly lower than in the Junction Reach and range from 0 cm/s to approximately 7 cm/s. This difference between the two reaches is caused by the increased width of the Sill Reach. Salinity distribution within the Sill Reach is also similar to the Junction Reach; however, bottom salinities remain slightly higher than in the Junction Reach for all flow conditions. Top to bottom salinity ranges from 0 to 22 psu for mean annual flow and 0 to 18 psu for 100-year high-flow event (see Figures 4-21 through 4-29). Near bottom current velocities within the Sill Reach are similar to the Junction Reach, in that they are also affected by the pervasive two-layer flow that is characteristic of the EW (see Figures 4-27 to 4-29). Therefore, near bottom current velocities in this reach are lower than would be expected if the system were riverine (as opposed to estuarine).

5 PROPWASH MODELING AND VESSEL OPERATIONS IN THE EAST WATERWAY

Major vessel hydrodynamic characteristics that can have an impact on the mobility of bottom and slope sediment include propwash, vessel wakes, and pressure fields. Impact analysis from vessel hydrodynamics on bottom sediment was limited herein to propwash and pressure fields only. Due to low vessel speeds, impacts from ship wakes are expected to be minimal except along armored side slopes in the Main Body Reach of the EW and in the Sill and Junction Reaches where water depths are shallow. Estimates of ship wakes are provided in this section of the report; however, an analysis of their effect on sediment mobility will be completed as part of the FS.

5.1 Propwash Modeling

5.1.1 Overview of Technical Approach

The first step in estimating the magnitude and location of bottom scour due to ship propulsion (e.g., ship propellers) is to simulate the current velocity pattern created by the propulsion source installed on the ship, incorporating the channel depth at separate locations in the waterway. The second step is to apply the maximum near-bed velocity in each location to determine the bed shear stress and sediment size at threshold of motion.

The modeling tool applied to determine near-bed velocities is the two-dimensional (2-D) model JETWASH (CHE 2003). The JETWASH model simulates the velocity field created by propulsion systems and accounts for the interaction of the velocity jet with the sediment bed. The model and data requirements were briefly summarized in the STEAM (Anchor and Battelle 2008a). The JETWASH model is based on a well-established and empirically verified theory of flow produced by a momentum jet. The JETWASH model has been implemented by EPA Region 8 and USACE for the analysis of sediment stability under impact from propwash of vessels ranging in size from small recreational boats to large ships (CHE 2007). JETWASH has also been successfully applied to studies of ships equipped with thrusters.

The velocity distribution through the water column (due to propwash) in JETWASH is modeled by a Gaussian distribution, as described by Albertson et al. (1948), which is used in most other propwash models, including that developed by the USACE (Maynord 2000). The vertical distribution of velocity is calculated from the water surface to a height of 26 cm off the seabed (CHE 2003). The logarithmic distribution assumption is then applied in JETWASH to extrapolate velocities below 26 cm (USACE 2002). The height above bottom of 26 cm for the model output was selected because at this distance (26 cm), JETWASH was calibrated in a number of field experiments and proved to be a reliable predictor for propwash velocity (CHE 2003).

The JETWASH model assumes a fully developed boundary layer (steady-state conditions) for prediction of bed velocities, and does not explicitly account for velocities produced within a developing boundary layer. This assumption may reduce the computed shear stresses at the bottom layer, depending on local site conditions. However, it should be noted that at present, no methods exist for assessing boundary layer development for conditions such as propeller wash impinging on the sediment bed. Analytical (computational) tests conducted previously with JETWASH concluded that the conservative assumptions built into the model compensate for the deficiency of not accounting for a developing boundary layer. The test was conducted assuming that shear stress at the bottom is proportional to bottom flow velocity at a small distance above the bed. The test consisted of computing velocities with JETWASH for cases with a near bottom boundary and with no bottom boundary (bottom was lowered to indefinite depth). The computational test description and results are provided in Appendix H, Attachment 1.

Shear stresses developed in the near-bed propwash velocity field were calculated using the assumptions of rough, turbulent flow and logarithmic velocity profile. Sediment stability (or threshold of initiation of motion) is assumed to be related to sediment critical shear stress (threshold) through the Shields parameter (Vanoni 2006). The bottom roughness was estimated as described in Section 6.2.1.1 and shown in Equation 6-9, and is thus consistent with bottom roughness values used to estimate bed shear stress due to tidal and riverine currents. More detailed discussion on shear stress computation procedure, including input parameters, is presented in a technical memorandum produced by Coast and Harbor Engineering (July 14, 2011; provided in Appendix H, Attachment 2).

5.1.2 Development of Propwash Operational Areas (Segmentation)

Typical and extreme vessel operations within the EW were developed through interviews and personal conversations with various organizations, agencies, and companies that operate vessels within the EW. Table 5-1 provides a list of these information sources and dates of communication.

Table 5-1
Information Sources used to Develop Vessel Operation Areas

Type of Information	Organizational Source	Individual Source	Communication Date(s)
Ship and Tug Operations	Puget Sound Pilots Association	Captain Jonathan Ward and Captain Eric VonBrandenfels	January 2011/February 2011
USCG Operations	USCG	Bobbie Battaglia (Environmental Branch Chief) and Randy Sommerville, (Port Services Division Officer)	February 2011
Barge and Tug Operations	Harley Marine (formerly Olympic Tug and Barge)	Don Meberg	February 7, 2011
General Vessel Operations and Future Vessel Operations	Port of Seattle	Eric Hanson and Doug Hotchkiss	January 2011 through March 2011
Vessel Operations in Junction Reach	Harbor Island Marina	Kathy Goodman	February 2011

Information on vessel types and typical and extreme vessel operations during berthing and navigation with the EW were compiled from the various sources shown in Table 5-1. This information was used to develop operational areas within the EW where vessel operations were similar. Figure 5-1 provides a map of the operational areas developed for the EW through this process.

Within each of these operational areas, anticipated extreme vessel operation scenarios (with respect to potential for erosion due to propwash) were chosen as representative of that operational area. These vessel operations do not represent typical fair weather operating procedures; instead they represent berthing and navigation operations in high winds, high currents, or other atypical environmental conditions within the EW. These propwash scenarios are adequate to meet the purpose of the STER, which is to evaluate the overall feasibility of the project. They do not represent “worst case” or emergency operations that could result in deep vertical mixing of bed sediments, such as vessel maneuvers required to avoid collision, vessel grounding, or similar. Additional evaluation will be conducted during the remedial design phase of the project to address impacts on bed sediments of these types of extreme events on design.

This process resulted in a list of extreme vessel operations by operational area (shown in Figure 5-1), which were used to develop site-specific propwash modeling scenarios for the purpose of evaluating erosion potential due to vessel operations in the EW. This list is provided in Table 5-2, and includes type of vessel, vessel characteristics, vessel maneuvers, representative water depths, and anticipated operational power during maneuvers.

Table 5-2
Vessel Operations within each Operational Area in the East Waterway

Propwash Area	Terminals	EW Station		Bathy Range (feet MLLW)[a]		Type of Ship(s)[b]	Types of Tugs[c]	Tug Operations		Ship Operations	
		Start	End	low end	high end			Description	Max. Power (operational)	Description	Max. Power (operational)
1A (berthing)	18, 30	0	4800	-54	-50	Large and small container vessels	4,000 to 5,500 HP	Ships are brought in bow first along Terminal 18. Two tugs use lines fore and aft of the ship. Ships are turned in Elliott Bay (outside of the EW) and brought in stern first for Terminal 30. Two tugs use lines fore and aft of the ship. Bow thrusters of ship are used as "rudder" to help steer ship as it is brought in.	50% or more	Bow thrusters are used 15-35% of time coming into the waterway, and 50% of time leaving the waterway for "short bursts" of power. During "pinning," bow thrusters are sometimes used; hard to quantify frequency and power. Main props are used 60-80% of the time while in waterway at "dead slow" (10% power)	100% (bow thrusters) 10% (main prop)
1B (in channel operation)	18, 30	0	4800	-54	-50	Large and small container vessels	4,000 to 5,500 HP	Ships are brought in bow first along Terminal 18. Two tugs use lines fore and aft of the ship. Ships are turned in Elliott Bay (outside of the EW) and brought in stern first for Terminal 30. Two tugs use lines fore and aft of the ship.	30-50%	(none)	(none)
1C (no berthing)	n/a	0	1500	-54	-50	No berthing in this area	No berthing in this area	Potential for some overlap with in-waterway maneuvers in Area 1B and from berthing operations in Area 1A	Potential for some overlap with in-waterway maneuvers in Area 1B and from berthing operations in Area 1A	Potential for some overlap with in-waterway maneuvers in Area 1B and from berthing operations in Area 1A	Potential for some overlap with in-waterway maneuvers in Area 1B and from berthing operations in Area 1A
2 (berthing)	Slip 36	0E	200E	-40	-40	USGC 378-foot High Performance Cutter and *Polar* Class Icebreaker (~400 feet). Other smaller vessels down to ~87 feet in length. Berthing may be tug–assisted.	Similar types used in other areas of the EW—11 different tugs (1,350 to 4,400 HP).	Some vessels use one tug; others use two tugs.	Used similar operating criteria as Area 6. Within the waterway, 30%; while docking, 50% (based on conversations with USCG).	Based on discussions with USGC, come in at very slow speed under their own power (or tug-assisted). Can be placed anywhere in the slip depending on availability.	Used upper limit as 25% for both the High Performance Cutter and *Polar* Class Icebreaker (based on conversations with USCG).

Propwash Area	Terminals	EW Station		Bathy Range (feet MLLW)[a]		Type of Ship(s)[b]	Types of Tugs[c]	Tug Operations		Ship Operations	
		Start	End	low end	high end			Description	Max. Power (operational)	Description	Max. Power (operational)
3 (berthing)	Slip 27	3600	4200	-40	-30	North edge: Tugs and empty barges; may be used for vessel storage in the future South edge: Barge for Boeing plane parts (travels to Everett)	(Estimate operational criteria from Area 4)	(Estimate berthing operational criteria from Area 6)	(Estimate berthing operational criteria from Area 6)	(Estimate berthing operational criteria from Area 6)	(Estimate berthing operational criteria from Area 6)
4A (berthing) - current operations	25 (now called south T30)	3600	5700	-40	-40	Far south end of Area used to be Olympic Tug and Barge (now Harley Marine Services) Tugs and barges	11 different tugs (1,350 to 4,400 HP)	Typically use two tugs to move barges down the waterway.	Within the waterway, 30%; while making up lines, briefly 50%	n/a	n/a
4A (berthing) - future operations)	25 (now called south T30)	3600	5700	-46	-46	Small Container vessels	4,000 to 5,500 HP	Ships are brought in bow first along Terminal 18. Two tugs use lines fore and aft of the ship. Ships are turned in Elliott Bay (outside of the EW) and brought in stern first for Terminal 30. Two tugs use lines fore and aft of the ship. Bow thrusters of ship are used as "rudder" to help steer ship as it is brought in.	While operating within the waterway, 30-50% power; while docking, 50% or more	Bow thrusters are used 15-35% of time coming into the waterway, and 50% of time leaving the waterway for "short bursts" of power. During "pinning," bow thrusters are sometimes used; hard to quantify frequency and power. Main props are used 60-80% of the time while in waterway at "dead slow" (10% power)	30-50% (bow thrusters) 10% (main prop)
4B (in channel operation)	25 (now called south T30)	3600	5700	-40	-40	In channel operations from vessels that berth in Areas 4A, 5, and 6 Tugs and barges	In channel operations from vessels that berth in Areas 4A, 5, and 6 Tugs and barges	In channel operations from vessels that berth in Areas 4A, 5, and 6 Tugs and barges	In channel operations from vessels that berth in Areas 4A, 5, and 6 Tugs and barges	In channel operations from vessels that berth in Areas 4A, 5, and 6 Tugs and barges	In channel operations from vessels that berth in Areas 4A, 5, and 6 Tugs and barges
5 (berthing)	n/a	4900 (west)	5800 (west)	-40	-40	~600-foot ships (bulk carriers) docking under tug power only; turn around within the EW. Four times per year - molasses bulk.	4,000 to 5,500 HP	Two tugs are used; ships are turned within the EW.	Within the waterway, 30-50% power; while docking, 50% or more	~600-foot ships - bulk carrier	30-50% (bow thrusters) 10% (main prop)
6 (berthing)	n/a	6150 (west)	7050 (west)	-40	-20	Leased by Olympic Tug and Barge (now Harley Marine Services) Tugs and barges	11 different tugs (1,350 to 4,400 HP)	Typically use two tugs to move barges down the waterway.	Within the waterway, 30%; while making up lines, briefly 50%	n/a	n/a

Propwash Area	Terminals	EW Station		Bathy Range (feet MLLW)[a]		Type of Ship(s)[b]	Types of Tugs[c]	Tug Operations		Ship Operations	
		Start	End	low end	high end			Description	Max. Power (operational)	Description	Max. Power (operational)
7 (no berthing)	n/a	6150 (east)	7050 (east)	-40	-30	No berthing in this area	No berthing in this area	Potential for some overlap from operations in Area 6	Potential for some overlap from operations in Area 6	Potential for some overlap from operations in Area 6	Potential for some overlap from operations in Area 6
8 (berthing)	Harbor Island Marina - Lateral dock in EW	7200 (west)	7600 (west)	-30	-15	Tugs, barges, and towboats 94 to 110 feet (complete list available)	Prudhoe Bay tug	Moorage	Minimal (assumed to be less than 25%)	n/a	n/a

Notes:

a. Excluding underdock areas because slopes are all armored. Representative of most of the propwash area.
b. Ship inventory available
c. Tug inventory available

5.1.3 Test Matrix and List of Scenarios

Fifteen scenarios were developed for analyzing propwash effects based on the list of vessel operations provided in Table 5-2. The scenarios consist of maneuvers for: 1) docking, undocking, and navigating the waterway; 2) using a ship's main power and thrusters; and 3) using various types of tugs. Additional specifics regarding vessel characteristics (e.g., length, depth, and draft) and propulsion were collected from public information obtained from the shipping line, tug companies, and Coast and Harbor Engineering archives.

All simulations assumed a tidal elevation of MLLW. This will result in conservatively high estimates of near-bed velocity and bed shear stress due to propwash because it represents the case where the ship's propulsion system is closest to the bed. Simulations of all vessels, including tugs, in the docking and undocking maneuvers assumed that the source of propwash was stationary. Tugs transiting the waterway were assumed to have a speed of 4 knots, which represents safe operating speeds within the EW based on interviews with tug pilots. The 15 simulation scenarios and pertinent model input parameters are listed in Table 5-3.

Table 5-3
Propwash Modeling Scenarios for East Waterway

Scenario Number	Propwash Area/Terminal	Depth at MLLW (feet)	Vessel Type/Name	Maneuver	Propulsion Type	Available Power (%)
1	Area 1A Berths 1 and 2 Terminal 18	50	Container *Xin Mei Zhou*	Docking	Ship's main power	10
2	Area 1A Berths 1 and 2 Terminal 18	50	Container *Xin Mei Zhou*	Undocking	Bow thruster	100
3	Areas 1A and 1B All Berths Terminal 18	50	Tractor Tug *Garth Foss*	Docking a container ship	Voith-Schneider	75
4	Area 1A Berths 3 and 4 Terminal 30	50	Container *Margrit Rickmers*	Docking	Ship's main power	10

Scenario Number	Propwash Area/Terminal	Depth at MLLW (feet)	Vessel Type/Name	Maneuver	Propulsion Type	Available Power (%)
5	Area 1A Berths 3 and 4 Terminal 30	50	Container *Margrit Rickmers*	Undocking	Bow thruster	100
6	Area 2 Slip 36	40	USCG Icebreaker *Polar Star*	Docking	3 controllable pitch props	50
7	Area 2 Slip 36	40	USCG Cutter *Hamilton* Class	Docking	2 controllable pitch props	50
8	Area 3 Slip 27	30	Tug *Hunter D*	Docking a barge	2 standard props	50
9	Areas 4, 4A, 4B, and 5 South Terminal 30	40	Tug *Eagle*	Docking a barge	Twin ducted props	75
10	Area 6	20	Tug *Eagle*	Docking a barge	Twin ducted props	50
11	Area 7	30	Tug *Eagle*	Maneuvering with Barge	Twin ducted props	50
12	Area 8	20	Tug *Alaska Mariner*	Docking	Twin props	50
13	Areas 1B and 1C Terminals 18 and 30	50	Tractor Tug *Garth Foss*	Navigation through EW	Voith-Schneider	50
14	Area 4A (future condition)	46	Container *Margrit Rickmers*	Docking	Ship's main power	10
15	Area 4A (future condition)	46	Container *Margrit Rickmers*	Undocking	Bow thruster	100

5.1.4 Results

Near-bed propwash velocity and associated shear stresses were evaluated for each scenario listed in Table 5-3. These results are summarized in the following sections. Velocities and shear stresses estimated for each scenario were applied to the entire operational area in which that scenario occurs.

The JETWASH model was used to estimate near-bed velocity, and bottom roughness values provided in Table 6-4 were used to evaluate bed shear stress associated with predicted near-bed velocities. A detailed description of this methodology is provided in Section 6.2.1.1 and a technical memorandum produced by Coast and Harbor Engineering (July 14, 2011; provided in Appendix H).

5.1.4.1 Scenario 1 – Area 1A, Terminal 18 Berths 1 and 2 (Main Ship Propulsion)

The largest container ships that utilize the EW call at Terminal 18, Berths 1 and 2, and were represented by the *Xin Mei Zhou*, a 102,500 deadweight tonnage (DWT) vessel with a capacity of 8,530 twenty-foot equivalent units (TEU). Propwash generated by the ship's main propulsion was simulated for Scenario 1. The area of propwash modeling was Berths 1 and 2 of Terminal 18, as shown in Figure 5-2. In simulating propwash, the *Xin Mei Zhou* was assumed to be drafted to 46 feet, corresponding to a minimum under-keel clearance of 4 feet. Predicted propwash velocity generated by the ship's main propulsion during docking is shown in Figure 5-2, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity predicted by the model is 9.3 feet per second (ft/s). The bed shear stress corresponding to this velocity is 0.32 pounds per square foot (lb/ft^2) (15 Pa).

5.1.4.2 Scenario 2 – Area 1A, Terminal 18 Berths 1 and 2 (Bow Thruster)

For this scenario, the *Xin Mei Zhou* was assumed to undock using the bow thruster at full power. All container ships operating in the waterway were assumed to be fitted with a bow thruster, and the *Xin Mei Zhou* represents the most powerful thruster located closest to the sediment bed. For conservatively examining near-bed velocity, the vessel draft upon departing was assumed to be 46 feet. A diagram illustrating the size and location of a bow thruster on a container ship is shown in Figure 5-3. Thruster wash generated by the bow thruster was simulated in Scenario 2. Predicted velocity generated by the ship's thruster during undocking is shown in Figure 5-4, which shows the horizontal plane of the pattern of near-bed velocity toward the berth. The maximum near-bed velocity is 11.4 ft/s. The bed shear stress corresponding to this velocity is 0.48 lb/ft^2 (23 Pa).

5.1.4.3 Scenario 3 – Areas 1A and 1B, Terminal 18 Berths 1 and 2 (Tug Operations)

Tugs assisting container ships during docking, undocking, and navigating in the waterway are represented by the *Garth Foss*. This tug is powered by Voith-Schneider propulsors and can output 5,000 horsepower. Propwash generated by the two propulsors is simulated in Scenario 3. Predicted near-bed velocity generated by the tug during application of 50% power is shown in Figure 5-5, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 3.6 ft/s. The bed shear stress corresponding to this velocity is 0.05 lb/ft^2 (2 Pa).

5.1.4.4 Scenario 4 – Area 1A, Terminal 18 Berths 3 and 4; Terminal 30 (Main Ship Propulsion)

A container ship representing vessels calling at Terminal 18, Berths 3 and 4, and at Terminal 30 is the *Margrit Rickmers*, a 67,600 DWT vessel. This ship has a capacity of 5,080 TEU. The maximum draft is 39 feet. Propwash generated by this ship's main propulsion was simulated for Scenario 4. The area of propwash modeling was Terminal 18, Berths 3 and 4, and Terminal 30 in Area 1, as shown in Figure 5-6. Predicted propwash velocity generated by the ship's main propulsion during docking is shown in Figure 5-6, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 6.3 ft/s. The bed shear stress corresponding to this velocity is 0.15 lb/ft^2 (7 Pa).

5.1.4.5 Scenario 5 – Area 1A, Terminal 18 Berths 3 and 4; Terminal 30 (Bow Thruster)

The vessel *Margrit Rickmers* is assumed to undock using the bow thruster at full power. The position and dimensions of the bow thruster are shown in Figure 5-3. Thruster wash generated by the bow thruster was simulated in Scenario 5. For conservatively examining propwash-generated near-bed velocity, the vessel draft upon departing was assumed to be the same as when arriving (39 feet). The area of propwash modeling was Berths 3 and 4 of Terminal 18 and all of Terminal 30 in Area 1, as shown in Figure 5-7. Predicted velocity generated by the ship's thruster during undocking is shown in Figure 5-7, which shows the horizontal plane of the pattern of near-bed velocity toward the berth. The maximum near-bed velocity is 7.1 ft/s. The bed shear stress corresponding to this velocity is 0.19 lb/ft^2 (9 Pa).

5.1.4.6 *Scenario 6 – Area 2, Slip 36 (*Polar *Class Icebreaker)*

USCG vessels identified as sources of propwash that may have the potential for initiating bed sediment movement in Area 2 are the *Polar* class icebreakers and the *Hamilton* class high-endurance cutters. The icebreakers have a loaded draft of 32 feet, and have three controllable pitch propellers. The area of propwash modeling is Slip 36, as shown in Figure 5-8. Predicted propwash velocity generated by the main propulsion of the *Polar* class icebreaker during docking is shown in Figure 5-8, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 6.5 ft/s. The bed shear stress corresponding to this velocity is 0.16 lb/ft^2 (8 Pa).

5.1.4.7 *Scenario 7 – Area 2, Slip 36 (*Hamilton *Class USCG Cutter)*

The *Hamilton* class USCG cutter has a draft of 20 feet and has twin controllable pitch propellers, which was simulated to determine the potential for initiating bed sediment movement in Area 2. These cutters are fitted with retractable thrusters that are capable of outputting 350 horsepower, which were not simulated because the power is small relative to the main propulsion. The area of propwash modeling is Slip 36, as shown in Figure 5-9. Predicted propwash velocity generated by the main propulsion of the *Hamilton* class cutter during docking is shown in Figure 5-9, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 4.5 ft/s. The bed shear stress corresponding to this velocity is 0.08 lb/ft^2 (4 Pa).

5.1.4.8 *Scenario 8 – Area 3, Slip 27 (Tug Operations)*

Vessel activity at Area 3 consists of tugs, represented by the *Hunter D,* moving barges to and from the slip. This tug has a draft of 14 feet and is powered by two engines that can develop 3,420 horsepower each. The area of propwash modeling is Slip 27, as shown in Figure 5-10. Predicted propwash velocity generated by the *Hunter D* during maneuvering is shown in Figure 5-10, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 3.0 ft/s. The bed shear stress corresponding to this velocity is 0.03 lb/ft^2 (2 Pa).

5.1.4.9 Scenario 9 – Areas 4, 4A, 4B, and 5 (Tug Operations)

The *Eagle* represents tugs that maneuver barges at South Terminal 30 (Area 4), and that assist bulk carriers that call at the south end of Terminal 18 (Area 5). The *Eagle* has a draft of 17 feet and is powered by two engines that can develop 3,000 horsepower each. The tug is assumed to apply 75% of available power in these two areas. Areas 4 and 5 for propwash modeling are shown in Figure 5-11. Sediment bed elevation in both areas is -40 feet MLLW. Predicted propwash velocity generated by the *Eagle* during maneuvering is shown in Figure 5-11, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 3.0 ft/s. The bed shear stress corresponding to this velocity is 0.03 lb/ft^2 (2 Pa).

5.1.4.10 Scenario 10 – Area 6 (Tug Operations)

The *Eagle* represents tugs that maneuver at the west side of the EW north of the West Seattle Bridge (Area 6). The *Eagle* is assumed to apply 50% of available power in this area. Sediment bed elevation in this area is -20 feet MLLW. Predicted propwash velocity generated by the *Eagle* during maneuvering is shown in Figure 5-12, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 11 ft/s. The bed shear stress corresponding to this velocity is 0.45 lb/ft^2 (22 Pa).

5.1.4.11 Scenario 11 – Area 7 (Tug Operations)

The *Eagle* represents tugs that transit the eastern part of the EW north of the bridges (Area 7). The *Eagle* is assumed to apply 50% of available power in this area. Bed elevation in this area is -30 feet MLLW. Area 7 for propwash modeling is shown in Figure 5-13. Predicted propwash velocity generated by the *Eagle* during maneuvering is shown in Figure 5-13, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 4.7 ft/s. The bed shear stress corresponding to this velocity is 0.08 lb/ft^2 (4 Pa).

5.1.4.12 Scenario 12 – Area 8 (Tug Operations)

The tug *Alaska Mariner* represents the largest of the Western Towboat fleet that moors in Area 8. This tug has a draft of 14 feet and is powered by twin engines, each producing 2,260 horsepower. The area of propwash modeling is shown in Figure 5-14. Sediment bed elevation in this area is -20 feet MLLW. Predicted propwash velocity generated by the *Alaska Mariner* during maneuvering in Area 8 is shown in Figure 5-14, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 4.2 ft/s. The bed shear stress corresponding to this velocity is 0.07 lb/ft^2 (3 Pa).

5.1.4.13 Scenario 13 – Areas 1B and 1C, Navigating in East Waterway (Tug Operations)

Container ships mooring at Terminal 18 and 30 are moved into the EW bow-first by at least two tugs. Tugs are at the bow and stern, and the ship's thruster aids in steering the ship in the waterway. Container ships mooring at Terminal 30 enter the EW stern-first, under the assistance of at least two tugs. The *Garth Foss* represents tugs that assist ships in the EW. Tug speed is assumed to be 4 knots, and the maximum power applied while moving a ship into or out of the EW is assumed to be 50% of available power. Predicted propwash velocity generated by the *Garth Foss* during assisting in Area 1 (bed elevation in this area is -50 feet MLLW) is shown in Figure 5-15, which shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 3.0 ft/s. The bed shear stress corresponding to this velocity is 0.03 lb/ft^2 (2 Pa).

5.1.4.14 Scenario 14 – Area 4A, Future Condition of Small Container Ship (Main Propulsion)

Scenario 14 was developed to represent future conditions at South Terminal 30. It is assumed that the berthing area at the terminal would have a minimum depth of 46 feet (at MLLW) to accommodate a container ship such as the *Margrit Rickmers*, a 67,550 DWT and 5,080 TEU capacity vessel. The maximum draft of the ship for this scenario is assumed to be 39 feet.

Predicted propwash velocity generated by the ship's main propulsion during docking is shown in Figure 5-16. The figure shows the horizontal plane of the pattern of near-bed velocity. The maximum near-bed velocity is 7.0 ft/s. The bed shear stress corresponding to this velocity is 0.18 lb/ft^2 (9 Pa).

5.1.4.15 Scenario 15 – Future Condition of Small Container Ship in Area 4A (Bow Thruster)

Scenario 15, similar to Scenario 14, was also developed to represent future conditions at South Terminal 30 with a representative depth of 46 feet. The container vessel *Margrit Rickmers* is assumed to undock using the bow thruster at full power. For conservatively examining propwash-generated bed velocity, the vessel draft upon departing was assumed to be the same as when arriving.

Predicted velocity generated by the ship's thruster during undocking is shown in Figure 5-17. The figure shows the horizontal plane of the pattern of near-bed velocity toward the berth. The maximum near-bed velocity is 9.0 ft/s. The bed shear stress corresponding to this velocity is 0.30 lb/ft^2 (14 Pa).

5.2 Summary of Results

Maximum near-bed velocities and bed shear stresses within each of the operating areas shown in Figure 5-1 were evaluated by choosing the maximum values from the 15 different scenarios described in Section 5.1. Table 5-4 provides a summary of these values for each operating area. It is important to note that the boundary between operational Area 1B (navigational area) and the berthing areas adjacent to Terminals 18 and 30 (Area 1A) is an approximation based on our current understanding of vessel operations within the EW. The estimated shear stress value of 2 Pa in Area 1B (navigation area) is representative of typical transiting maneuvers in the navigation channel; however, the navigation channel is expected to experience a range of shear stresses due to adjacent berthing maneuvers. Therefore, it is possible that portions of the navigation channel (Area 1B) along this boundary may experience higher bed shear stress than estimated in Table 5-4 (2 Pa).

Area 4 has values associated with current operations (Scenario 9) and future planned operations (Scenario 15). Figure 5-18 provides maximum near-bed velocities based on current and future operating conditions (Area 4). Figure 5-19 provides maximum bed shear stresses for the same conditions. Evaluation of erosion potential due to propwash is discussed in Section 6.3.

Table 5-4
Summary of Maximum Near-Bed Velocities and Bed Shear Stresses Due to Propwash

Operating Area (see Figure 5-1)	Scenario in Area Resulting in Maximum Near-Bed Velocity (see Table 5-3)	Maximum Near-Bed Velocity ft/s	Maximum Bed Shear Stress lb/ft^2(Pa)
Terminal 18, Berths 1 and 2 Area 1A	Scenario 2	11.4	0.48 (23 Pa)
Terminal 18, Berths 3 and 4 Area 1A	Scenario 5	7.1	0.19 (9 Pa)
Area 1B	Scenario 13	3.0	0.03 (2.0 Pa)
Area 1C	Scenario 13	3.0	0.03 (2.0 Pa)
Slip 36 Area 2	Scenario 6	6.5	0.16 (8.0 Pa)
Slip 27 Area 3	Scenario 8	3.0	0.03 (2.0 Pa)
South Terminal 30 Area 4A [a]	Scenario 9 (Future Conditions - Scenario 15)	3.0 (Future Conditions - 9.0)	0.03 (2.0 Pa) (Future conditions - 0.30 [14 Pa])
South Terminal 30 Area 4	Scenario 9	3.0	0.03 (2.0 Pa)
Area 4B	Scenario 9	3.0	0.03 (2.0 Pa)
Area 5	Scenario 9	3.0	0.03 (2.0 Pa)
Area 6	Scenario 10	10.6	0.45 (22 Pa)
Area 7	Scenario 11	4.7	0.08 (4 Pa)
Area 8	Scenario 12	4.2	0.07 (3 Pa)

Note:
a Operational Conditions in Area 4A may change in the future. These future conditions are described in Scenario 15.

5.3 Pressure Field Evaluation

As a vessel moves through a waterway it produces a depression in the water surface and generates return currents around the vessel. Near-bed currents generated beneath a moving vessel can be an agent for mobilizing sediment on the sediment bed if the velocity is of sufficient magnitude. Within the EW, these velocities are expected to be small compared to velocities produced by propwash, as described in Section 5.1. In addition, velocities generated by the pressure fields are directed along the direction of ship movement, which is opposite the direction of bed velocities due to propwash. (In addition, velocities due to pressure fields are spatially separate from those produced by propwash.) In order to validate this assumption, near-bed velocities generated by a ship being assisted by a tug are discussed in this section.

5.3.1 Overview of Technical Approach

Hydrodynamic forces generated by the pressure field of a vessel were calculated using the Vessel Hydrodynamics Longwave Unsteady (VH-LU) model (Shepsis et al. 2001). The VH-LU model predicts water level and velocity fluctuations surrounding a moving ship and the resulting velocity beneath the hull. The main factors that determine the magnitude of the pressure wave generated by the moving vessel are the ship's length, beam, draft, shape, and speed at which it moves relative to the water.

A container ship representative of those calling at Berths 3 and 4 of Terminal 18 and the assisting tug were the vessels selected for pressure field analysis. Results of the analysis include near-bed velocity as the vessel passes above. Channel depth and dimensions are nearly uniform along the length of the EW. Therefore, the vessel-induced near-bed velocity at one location along the sailing line is similar to that at other locations, and a single snapshot of velocity pattern is sufficient to characterize conditions in the waterway. Figures 1-3A and 1-3B show the bathymetry within the navigation channel alongside Terminal 18. Vessel speed while moving in the EW is assumed to be 4 knots or less.

5.3.2 Evaluation and Results

Figure 5-20 shows the predicted velocity from the pressure-field modeling at a single location for a container ship moving inbound along the channel centerline at 4 knots. For this container ship simulation, the maximum near-bed velocity relative to the stationary bed was 1.3 ft/s, averaged in the 13-foot vertical distance between the hull and the bottom. Bed shear stress associated with this velocity is 0.30 Pa (0.0063 lb/ft^2). This value falls within the range of estimated critical shear stress values for bed sediments in the EW (0.20 to 0.37 Pa); therefore, velocities due to pressure fields are not expected to cause significant movement of surface sediments in the EW. In addition, bed shear stress due to pressure fields are 85% lower than the lowest estimated value of bed shear stress due to propwash (2 Pa).

Figure 5-21 shows the predicted water velocity induced by tug movement that would assist the ship in the EW. The assumed tug characteristics are those listed in Tables 5-3 for Area 1. For this simulation, the maximum near-bed velocity relative to the stationary bed was less than 1.3 ft/s, averaged in the 36-foot vertical distance between the tug hull and the sediment bed.

For all cases, the near-bed velocity due to pressure fields (1.3 ft/s) was less than the near-bed velocities predicted due to propwash throughout the EW (3.0 ft/s and greater). While these are significant velocities compared to riverine and tidal current velocities (see Section 4), they are smaller than velocities produced by propwash activities. Therefore, pressure fields due to ship movement are of secondary importance for sediment mobility in the EW when compared to propwash activities.

5.4 Vessel Wake Evaluation

Impacts to the sediment bed due to ship wakes are expected to be minimal in the navigation areas within the EW. However, at lower tidal elevations, wakes from faster-moving tugs may impact sediments overlying armored side slopes and non-armored slopes in the Main Body Reach and the sediment bed within shallow areas of the Sill and Junction Reaches. Wake heights over a range of tug operating conditions were evaluated and are provided in this section of the report. Impacts to sediment mobility in areas of concern for wakes will be completed as part of the FS.

5.4.1 Overview of Technical Approach

Wave height and steepness were estimated for wakes produced by the tug *Garth Foss* (see Table 5-3, Area 1, for tug characteristics). The *Garth Foss* has a length of 94 feet, a beam of 36 feet, a draft of 17 feet, and a gross tonnage of 194 tons. This information was input into a ship wave prediction model based on methodology developed by Weggel and Sorensen (1986).

5.4.2 Evaluation and Results

Since operating conditions of tugs within the EW are variable (especially when not assisting other larger ships) wakes were estimated using a range of reasonable expected vessel speeds and locations within the navigation channel. There is no documented speed limit within the EW; therefore, ranges of tug speed were chosen based on discussion with pilots and tug operators within the EW. Sail distances (distance from the moving tug to the shoreline of the EW) between 100 and 365 feet represent the tug operating in the wider (north) section of the EW. Sail distances of 50 to 75 feet represent operation in the narrower section (south). Wakes are affected by water depths; therefore, a range of water depths over the tidal cycle were used to evaluate wake heights. Table 5-5 lists predicted wave heights for the different scenarios.

Table 5-5
Wake Heights Estimated in the East Waterway

Water Depth (feet)	Speed (knots)	Distance to Sail Line (feet)	Wave Height (feet)
54	6.0	365	1.2
54	6.0	100	2.4
54	5.5	365	0.9
54	5.5	100	2.0
54	5.0	365	0.7
54	5.0	100	1.6
50	6.0	365	1.1
50	6.0	100	2.1
50	5.5	365	0.8

Water Depth (feet)	Speed (knots)	Distance to Sail Line (feet)	Wave Height (feet)
50	5.5	100	1.7
50	5.0	365	0.6
50	5.0	100	1.3
40	6.0	365	0.8
40	6.0	50	2.2
40	5.5	365	0.6
40	5.5	50	1.7
40	5.0	365	0.4
40	5.0	50	1.3
30	6.0	75	1.4
30	6.0	50	1.7
30	5.5	75	1.0
30	5.5	50	1.3
30	5.0	75	0.7
30	5.0	50	0.9
15	6.0	75	1.1
15	6.0	50	1.3
15	5.5	75	0.7
15	5.5	50	0.9
15	5.0	75	0.4
15	5.0	50	0.6

5.4.3 Uncertainty Discussion

Vessel operations information has been collected through conversations with various individuals that work within the EW including pilots, operations managers, USCG officials, Port planners, and others (Table 5-1). Therefore, uncertainty in the evaluation of erosion potential due to propwash is primarily dependent on the reliability of this information. In the case of USCG operations, conservative assumptions were made regarding power of main propulsion and bow thrusters used during berthing based on past project experience. Modeling scenarios developed for the analysis took this uncertainty into account by using conservative operational criteria for the propwash simulations based on an understanding of vessel operations. However, there is still some uncertainty in the definitions of specific vessel operation parameters for each scenario (e.g., percent power used for bow thrusters and actual tug operations). Extreme handling situations due to emergencies and unforeseen circumstances (such as berthing of larger vessels than anticipated in locations within the EW due to an emergency, maneuvers required to avoid collision, ship grounding, or other situations) are difficult to define and quantify. Therefore, modeled scenarios have been chosen to represent extreme conditions, as defined in Section 5.1.2. These scenarios are anticipated to drive sediment mobilization in the EW (due to propwash) to a larger extent than a single emergency maneuver or event. However, additional evaluation will be conducted during the remedial design phase of the project to address impacts on bed sediments due to emergency situations, which were not included in this analysis.

Additional uncertainties include defining transitions between operational areas, understanding the duration of each operation (e.g., how long the vessel uses its bow thruster at 100% power), and choice of representative water depths for the simulations. As with uncertainties in operational information, conservative assumptions were used when developing the simulations to offset these additional uncertainties as much as possible. Simulations assumed steady state conditions for vessels transiting the EW (i.e., infinite duration of operations in one location), and water depths chosen for the simulations in each of the operational areas were conservatively low (i.e., shallower depths at MLLW within each operational area).

The JETWASH model assumes steady state conditions (i.e., fully developed boundary) that may not be a conservative assumption for berthing vessels. Boundary layer development may influence bottom shear stress and stability of bed material. The logarithmic profile of velocity, assumed by JETWASH, is appropriate for a developed boundary layer and may differ from that of the profile for a developing boundary layer. However, estimates of velocities within developing boundary layers due to propwash are still an active area of research and a subject for future fundamental studies. To account for the potential effect of a developing boundary layer, the JETWASH model uses several conservative parameters to develop velocity predictions, which are discussed in detail in Appendix H.

6 EVALUATION OF EROSION POTENTIAL WITHIN THE EAST WATERWAY

Mechanisms for erosion of bed sediments within the EW include currents due to tidal fluctuations and upstream freshwater flows and vessel operations, including propwash, pressured fields, and wakes. The potential for erosion within the EW from these various sources was estimated through a combination of hydrodynamic modeling, propwash and pressure field modeling, and evaluation of Sedflume core data collected within the EW.

Sedflume cores were collected within the EW (Section 2.4) to evaluate in situ critical shear stress of bed sediments. This evaluation is discussed in Section 6.1. Near bottom current velocities provided by the hydrodynamic model (Section 4) were used to estimate bed shear stresses within the EW due to tidal and riverine currents as described in Section 6.2. Near bottom velocities due to vessel operations (Section 5) were utilized to estimate bed shear stresses due to propwash and pressure fields as described in Section 6.3. Estimates of bed shear stresses due to tidal/riverine currents and vessel operations were compared to critical shear stresses from Sedflume cores to evaluate erosion potential within the EW.

6.1 Analysis of Sedflume Erosion Rate Data

6.1.1 Overview of Sedflume Testing

Eight Sedflume cores were collected within the EW to provide empirical estimates of critical shear stress. The discrete values of critical shear stress from the Sedflume core data were used to estimate a representative range.

Locations of the Sedflume cores are shown in Figure 2-3. Table 6-1 lists the EW station, approximate bed elevation, and water depth at each Sedflume core location. A summary of the core data collection (including any deviations from the QAPP), reports produced by Sea Engineering, and laboratory forms are provided in Appendix D. Detailed summaries outlining collection, observations, and testing of each Sedflume core are provided in the Executive Summary of the Sea Engineering report provided in Appendix D, Attachment 2.

Table 6-1
East Waterway Station and Bed Elevation at Sedflume Core Locations

Core ID	EW Station	Approximate Bed Elevation (feet MLLW)	Approximate Water Depth (feet)
SF_1	6000	-38	45
SF_2	5300	-44	47
SF_3	6500	-30	32
SF_4	7100	-6	7
SF_5	6800	-10	17
SF_6	3800	-52	52
SF_7	550	-56	57
SF_8	2000	-54	59

6.1.2 Results of Sedflume Testing (Critical Shear Stress)

Sedflume cores were tested in a mobile laboratory facility set up near the EW to measure erosion rates as a function of shear stress and depth in the core. Sedflume erosion rate data were analyzed to estimate the critical shear stress for initiation of erosion. This analysis was conducted using three different regression methods: 1) power law; 2) linear; and 3) log-linear. The power law and linear regression analyses were completed by Sea Engineering and described in their report in Appendix D), and a log-linear regression was completed by Anchor QEA and described in detail below.

The critical shear stress is defined as the shear stress needed to produce an erosion rate of 0.0001 cm/s. For each interpolation method, an equation is developed that relates erosion rate to shear stress. The value of critical shear stress can then be computed from the developed relationship by inserting an erosion rate of 0.0001 cm/s into the equation.

The log-linear regression analysis was conducted as follows. Erosion rate data obtained from Sedflume testing were analyzed to develop a relationship between erosion rate and shear stress (Jones 2000):

$$\begin{aligned} E &= A\tau^n \quad \text{for } \tau > \tau_{cr} \\ &= 0 \qquad \text{for } \tau \le \tau_{cr} \end{aligned} \tag{6-1}$$

Where:

E	=	erosion rate (cm/s)
τ	=	shear stress (Pascals [Pa])
τ_{cr}	=	critical shear stress (Pa)

The parameters, A and n, are site-specific and may be spatially variable, both horizontally and vertically. The site-specific parameters, A and n, were determined using the erosion rate data collected during the Sedflume study as follows:

- Each core was divided into 5-cm-thick layers (in the vertical)
- Erosion data within each 5-cm layer of a core were analyzed using a log-linear regression analysis between erosion rate and shear stress.
- The regression analysis produced values of A and n for each 5-cm layer in a core.

Critical shear stress for each 5-cm layer was calculated using:

$$\tau_{cr} = (E_{cr} / A)^{1/n} \qquad (6\text{-}2)$$

Where:

E_{cr}	=	0.0001 cm/s

Figures 6-1 through 6-8 show the results of the log-linear regression analyses for each 5-cm layer within all of the Sedflume cores. The site-specific parameters (A and n) developed from the log-linear analyses were used to estimate critical shear stress based on Equation 6-2 and are provided in Figures 6-1 through 6-8. The critical shear stress results for each core interval are listed in Table 6-2 and graphically shown in Figure 6-9.

Table 6-2
Critical Shear Stress Based on Log-Linear Regression Analysis

Vertical Interval (cm)	Critical Shear Stress (Pa)							
	Core SF_1	Core SF_2	Core SF_3	Core SF_4	Core SF_5	Core SF_6	Core SF_7	Core SF_8
0-5	0.33	0.35	0.41	0.08	0.27	0.42	0.04	0.35
5-10	0.64	0.73	0.38	0.22	0.39	0.32	0.23	0.31
10-15	0.36	0.82	0.44	NA	0.60	0.61	0.35	1.15
15-20	0.36	1.23	0.49	NA	NA	2.17	NA	NA
20-25	0.32	0.56	0.26	NA	NA	1.52	NA	NA

Note:
NA = not available due to shallow core recovery

6.1.3 *Surface Critical Shear Stress Estimates for the East Waterway*

In order to evaluate erosion potential within the EW, an average critical shear stress for surface sediments in the EW was developed through comparison of three estimates of critical shear stress of surface sediments developed from the results of the Sedflume evaluation as defined below:

- τ_{cr1} = Estimates of critical shear stress from power law, linear, and log-linear regression analysis using 0.0001 cm/s criteria (the erosion rate that corresponds to critical shear stress). (These values are shown in columns 2 through 4 of Table 6-3.)
- τ_{cr2} = The lowest shear stress applied during the Sedflume test for the surface interval (0 to 5 cm). (This value is shown in column 5 of Table 6-3.)
- τ_{cr3} = The lowest shear stress for which erosion occurred in the surface interval (0 to 5 cm). (This value is shown in column 6 of Table 6-3.)

Critical shear stress for surface sediments for each Sedflume core (τ_{cr}) were adjusted using the following comparison criteria (values shown in column 7 of Table 6-3):

$$\text{If } \tau_{cr2} < \tau_{cr1} < \tau_{cr3} \;\rightarrow\; \text{Then } \tau_{cr} = \tau_{ct1} \tag{6-3}$$

$$\text{If } \tau_{cr1} < \tau_{cr2} \;\rightarrow\; \text{Then } \tau_{cr} = \tau_{ct2} \tag{6-4}$$

$$\text{If } \tau_{cr1} > \tau_{cr3} \;\rightarrow\; \text{Then } \tau_{cr} = \tau_{ct3} \tag{6-5}$$

These comparisons also help define uncertainty in estimates of critical shear stress due to differences in the regression analyses.

Surface critical shear stresses for each core estimated using the three regression methods and the comparison criteria described above are summarized in Table 6-3. To develop an average representative value and 95% confidence interval for critical shear stress of surface sediments within the EW, estimates of critical shear stress were averaged within each method and the standard deviation and 95% confidence interval were calculated, as shown in Table 6-3. The range of critical shear stress within the EW is 0.20 to 0.37 Pa.

Table 6-3
Comparisons of Surface Critical Shear Stress Estimated by Multiple Methods

Core	Critical Shear Stress in Surface Sediments (Pa)			Lowest Applied Shear Stress (Pa)[c]	Lowest Shear Stress Resulting in Erosion[d] (0 to 5 cm layer) (Pa)	Adjusted Critical Shear Stress in Surface Sediments (Pa)[e]
	Power Law Regression	Linear Regression	Log-Linear Regression			
SF_01	0.38	0.32	0.33	0.10	0.40	**0.33**
SF_02	0.42	0.26	0.35	0.10	0.40	**0.35**
SF_03	0.45	0.32	0.41	0.10	0.40	**0.40**
SF_04	n/a[a]	0.24[b]	0.08	0.10	0.20	**0.10**
SF_05	0.43	0.26	0.27	0.10	0.40	**0.27**
SF_06	0.49	0.32	0.42	0.10	0.40	**0.40**
SF_07	0.34	0.24	0.04	0.10	0.40	**0.10**
SF_08	0.34	0.24	0.35	0.10	0.40	**0.35**
Average	0.41	0.27	0.28	n/a	n/a	**0.29**
Standard Deviation	0.049	0.072	0.14	n/a	n/a	**0.12**
95% Confidence Interval	0.37 to 0.45	0.22 to 0.32	0.19 to 0.37	n/a	n/a	**0.20 to 0.37**

Notes:
a. Shell hash and organic material in surface layer of core. Erosion occurred in clumps in surface layer. Power law was not a good fit to the data.
b. Due to uneven erosion in the core, the average critical shear stress over the depth of the core was used (see Note a).
c. This value is the lowest shear stress applied during the Sedflume test (see Appendix D).
d. This value is the lowest shear stress applied to the 0 to 5 cm layer during the Sedflume test (see Appendix D) that resulted in sediment erosion.
e. This value is the adjusted critical shear stress determined by Equations 6-3 through 6-5.

Particle size (median diameter) and wet bulk density were also estimated within each vertical interval in the core as described in Sea Engineering's report in Appendix D. Figures 6-10 and 6-11 show the vertical distribution of both median diameter and wet bulk density for all eight Sedflume cores (laboratory forms are provided in Appendix D, Attachment 3). Observations and general trends from estimates of critical shear stress and vertical distribution of median grain size diameter and wet bulk density are summarized below:

- Based on the range of critical shear stresses estimated by the three regression methods, reasonable lower- and upper-bound values for critical shear stress of surface sediments in the EW are 0.20 and 0.37 Pa.
- The adjusted critical shear stress in the 0 to 5 cm layer ranges from 0.10 to 0.40 Pa (based on log-linear regression) for six of the eight cores. Cores SF_4 and SF_7 have relatively low critical shear stress values in the 0 to 5 cm layer (approximately 0.1 Pa). Both of these cores were difficult to extract due to consolidated sediments just under the surface, which resulted in a retrieved core that was relatively shallow due to less penetration. The surface sediments (0 to 5 cm interval) of these two cores were characterized by fine silty sands, which were easier to erode than the 5 to 10 cm interval in these same cores (see Appendix D for more information).
- Generally, critical shear stress increases, or is approximately constant, with depth. Core SF_2 exhibited uneven erosion during Sedflume testing, which may have contributed to some of the variability in the vertical distribution of critical shear stress for that core. Core SF_6 exhibited a consolidated layer around 15 cm below mudline that was difficult to erode (Appendix D, Attachment 1).
- Mean particle diameter (Figure 6-10) ranges from 20 to 40 microns for six of eight cores. Cores SF_06 and SF_07 exhibit larger mean diameters in the upper portions of the core (from 0 to approximately 10 cm) with sizes ranging between approximately 50 to 106 microns. Below 10 cm, mean particle diameters return to the range of 20 to 40 microns found in the other six cores. For core SF_06, this is evidence of the sand cap that was placed in this area. In the case of core SF_07, there is no known anthropogenic explanation for the variation in surface sediments in this area compared to other cores. Trends in the vertical distribution of wet bulk density (Figure 6-11) generally follow the trends in critical shear stress, with the exception of Cores SF_05 and SF_06. Comparison of trends in wet bulk density and mean particle diameter exhibit variability from core to core.

6.2 Erosion Potential Due to Tidal and Riverine Currents

Results from the hydrodynamic model simulations described in Section 4 were used to evaluate bed shear stress within the EW. These estimates of bed shear stress were compared to critical shear stress estimates of in situ sediments obtained from Sedflume cores (Section 6.1) to evaluate erosion potential within the EW due to tidal and riverine currents.

6.2.1 Bed Shear Stress due to Tidal and Riverine Currents

6.2.1.1 Estimates of Bed Shear Stress

Bed shear stresses were estimated from the results of five hydrodynamic model simulations (see Section 4), which included mean annual, mean wet-season, 2-year, 10-year, and 100-year flood inflow rates with spring tide conditions. Bed shear stresses were calculated using near-bed velocity (velocity in the lowest sigma layer of the model) for each hydrodynamic model grid cell within the EW (see Figures 4-1A and 4-1B) and for each time step in the simulation (42 days).

Erosion rate is dependent on bed shear stress, which is calculated using near-bed current velocity predicted by the hydrodynamic model. The bed shear stress calculated within the hydrodynamic model is the total bed shear stress, which represents the total drag on the water column by the sediment bed. The total bed shear stress (τ_{tot}) is the sum of shear stresses associated with skin friction (τ_{sf}) and form drag (τ_{fd}):

$$\tau_{tot} = \tau_{sf} + \tau_{fd} \tag{6-6}$$

Skin friction represents the shear stress generated by sediment particles (i.e., small-scale physical features), whereas form drag corresponds to the drag generated by bedforms (e.g., ripples, dunes) and other large-scale physical features. When simulating the erosion of a cohesive bed, as is present in the EW, skin friction is considered the dominant component of the bed shear stress for most applications. The natural (e.g., tidal and riverine current velocities) hydrodynamic and sediment bed conditions in the EW are likely not favorable for developing physical features (e.g., wavy beds) that induce form drag. This assumption was corroborated through collection and evaluation of bathymetry data within the EW (Figures 1-3A and 1-3B and Section 2.1). Bed features may exist in the areas where propwash is significant. However, in those areas, bed shear stress due to propwash will dominate and it is calculated using a different methodology (see Section 5). Thus, for estimates of bed shear stress due to tidal and riverine currents, it is a reasonable approximation and a standard approach to use the skin friction component and neglect form drag for calculating bed shear stress for a cohesive bed. This approach is consistent with accepted sediment transport theory (Parker 2004). Skin friction shear stress is calculated using the quadratic stress law:

$$\tau_{sf} = \rho_w \, C_f \, u^2 \tag{6-7}$$

Where:

ρ_w	=	density of water
C_f	=	bottom friction coefficient
u	=	near-bed current velocity (i.e., predicted velocity in the bottom layer of the numerical grid)

Use of the near-bed current velocity is standard practice for calculating bed shear stress in a 3-D model. The bottom friction coefficient is determined using (Parker 2004):

$$C_f = \kappa^2 \ln^{-2}(11\, z_{ref} / k_s) \tag{6-8}$$

Where:

z_{ref}	=	a reference height above the sediment bed
k_s	=	effective bed roughness
κ	=	von Karman's constant (0.4)

The reference height (z_{ref}) is spatially and temporally variable because it is equal to half of the thickness of the bottom layer of the numerical grid. Because a stretched (sigma-layer) grid with ten layers is used in the vertical direction, the thickness of the bottom layer of the vertical grid is equal to 10% of the local water depth, which varies due to changes in tidal elevation and river flow rate. Thus, the reference height properly incorporates temporal and spatial variations in water depth into the calculation of the bottom friction coefficient. The effective bed roughness is assumed to be proportional to the D_{90} (diameter where 90% of the particles by weight in the sediment sample are smaller) of the surface sediment layer (Parker 2004; Wright and Parker 2004):

$$k_s = 2D_{90} \tag{6-9}$$

Grain size distribution data from the geochronology cores were used to specify the value of D_{90} for the surface layer of EW sediments (0 to 2 cm below mudline). Based on these D_{90} values, three representative areas within the EW were designated and assigned a representative upper-bound value for D_{90} (Table 6-4). No viable geochronology cores are available for the Junction and Sill Reaches (see Section 3). Therefore, the D_{90} value for these two reaches was assumed to be equivalent to Area 3 as shown in Table 6-4 (3,000 microns). These upper-bound D_{90} values were used to determine the effective bed roughness throughout the EW. Since bed shear stress increases with increasing effective bed roughness, using upper-bound D_{90} values produces conservatively high estimates of bed shear stress throughout the EW.

Grain size information for surface sediment samples collected in the Junction and Sill Reaches, as well as Slip 27 within the EW (Figure 4-1 of the Final Surface Sediment Data Report; Windward 2010) were compared to the upper-bound values for D_{90} obtained from the geochronology core data. Values of D_{90} based on these cores were consistent with values shown in Table 6-4. In the Junction Reach and Area 3, surface sediment cores SS-003 and SS-005 have values of D_{90} greater than 2,000 microns. In the interior of Slip 27, cores SS-104 and SS-106 also have D_{90} values greater than 2,000 microns.

Table 6-4

Area-Specific Upper-Bound D_{90} Values

Area	Upper-Bound D_{90} (microns)
Area 1: Main Body Reach between EW Stations 0 and 6200	370
Area 2: Interior of Slip 27	8,000
Area 3: Main Body Reach between EW Stations 6200 and 6800	3,000

6.2.1.2 Comparison of Bed Shear Stress to Critical Shear Stress

The maximum bed shear stress within each hydrodynamic model grid cell during each of the five 42-day simulations was determined using the methodology outlined in Section 6.2.1.1. Spatial distributions of maximum bed shear stresses for the mean annual, mean wet-season, 2-year, 10-year, and 100-year flood simulations are shown in Figures 6-12 through 6-16.

As discussed in Section 6.1, Sedflume data indicate that the representative range in critical shear stress for surface sediments (0 to 5cm) within the EW (95% confidence interval about the average) is 0.20 to 0.37 Pa (2.0 to 3.7 dyne/cm^2). Maximum bed shear stress predicted by the model ranges from 0.05 Pa during mean annual flow to 0.12 Pa during the 100-year high-flow event. As shown in Table 6-2, shear stress at each Sedflume core location generally increases with depth below the surface (below 5 cm).

Figures 6-17 through 6-21 show the spatial distributions of maximum bed shear stresses normalized by the lower bound of critical shear stress estimated for the EW (0.20 Pa) for the mean annual, mean wet-season, 2-year, 10-year, and 100-year flood simulations. Figures 6-22 through 6-26 show the cumulative probability distribution of maximum bed shear stress within the EW for the mean annual, mean wet-season, 2-year, 10-year, and 100-year flood simulations, as summarized in Table 6-5. These figures show that even with 100-year flows, the maximum predicted bed shear stress due to tidal/riverine currents (0.12 Pa) is approximately 35% less than the critical shear stress for EW bed sediments. In addition, the 99th percentile bed shear stress (on average) is 54% less and the 50th percentile bed shear stress (on average) is 94% less than the estimated lower bound of critical shear stress for EW bed sediments (0.20 Pa).

Table 6-5

Cumulative Probability Distribution of Maximum Predicted Bed Shear Stresses in the East Waterway

Upstream Flow	Maximum Value of Bed Shear Stress (Pa)	50th Percentile (Pa)	99th Percentile (Pa)
Mean Annual	0.046	0.007	0.045
Mean Wet Season	0.053	0.007	0.051
2-year	0.097	0.011	0.095

Upstream Flow	Maximum Value of Bed Shear Stress (Pa)	50th Percentile (Pa)	99th Percentile (Pa)
10-year	0.113	0.013	0.106
100-year	0.120	0.013	0.114

Because the maximum bed shear stress predicted by the model for all flow events is at least 35% below the lower confidence bound value for critical shear stress (0.20 Pa) as estimated from the Sedflume core data, it is anticipated that significant bed scour or erosion of in situ bed sediments within the EW will not occur as a result of tidal or riverine currents.

6.2.1.3 Discussion of Spatial Distribution of Bed Shear Stress in the East Waterway

The spatial distribution of bed shear stress within the EW is characterized by the highest bed shear stresses at the mouth of the EW, becoming lower in value moving upstream (to the south). Higher near bottom current velocities (and corresponding higher bed shear stress) at the mouth are due to the two-layer flow structure within the EW. During incoming tide, higher salinity water flows from Elliott Bay into the relatively constricted opening of the EW at depth producing relatively high near bottom velocities at the mouth. As this flow moves upstream, density-driven circulation and vertical mixing of the incoming tidal waters with the lower salinity surface waters (from upstream flows) causes a reduction in near bottom current velocities between the mouth and the Sill Reach in the EW (see Section 4.5).

Maximum bed shear stresses within the Sill Reach are affected by pervasive two-layer flow that exists in this reach (as well as the majority of the EW). Upstream flow of higher salinity water in the bottom layers (compared to surface layer salinities) confine downstream current velocities (due to upstream freshwater input) to the surface layers. This circulation pattern results in lower bed shear stress in the Sill Reach than would be expected if the system had single-layer flow (i.e., no flow reversal at depth) (see Section 4.5).

Relatively high bed shear stresses (associated with relatively high current velocities) are predicted along the southern half (shallower) of Slip 27. The higher current velocities may be due to the geometry and resolution of the numerical grid in that location. However, bed shear stresses predicted throughout Slip 27 are still at least 20% lower than critical shear stress values for surface sediments in the EW.

Grain size information for surface sediment samples collected in Slip 27 (Figure 4-1 of the Final Surface Sediment Data Report; Windward 2010) were reviewed to provide an additional line of evidence for comparison with these results. Surface sediments along the southern (shallow) portions of Slip 27 (cores SS-104 and SS-106) have a median diameter of approximately 200 microns and a D_{90} of greater than 2,000 microns. Surface sediments along the northern (deeper) portions of Slip 27 (cores SS-109 and SS-112) have a median diameter of 15 microns and a D_{90} of 250 microns. This information implies that southern (shallower) portions of Slip 27 may be impacted by higher near bottom current velocities than northern (deeper) portions of Slip 27. This observation is consistent with the results of the hydrodynamic model evaluation.

6.2.2 Uncertainty Discussion

The purpose of this analysis is to evaluate the effect of uncertainty in estimates of critical shear stress (from Sedflume core data) and estimates of bed shear stress (from hydrodynamic model results) on the evaluation of erosion potential due to tidal and riverine flows. Uncertainties in estimates of critical shear stress, as evaluated from Sedflume data, include collection effects on sediment properties, experimental error during testing, methodology used to estimate critical shear stress, and spatial variability in erosion properties. Collection effects and experimental errors are difficult to quantify. However, it is important to note that while Sedflume testing is a standard accepted methodology, there is uncertainty associated with the laboratory measurements. Variability due to differences in the method for calculating critical shear stress was discussed in Section 6.1. While spatial variability in critical shear stress does exist, the representative range in critical shear stress for surface sediments was estimated to be about 0.20 to 0.37 Pa.

6.3 Erosion Potential Due to Vessel Operations

Near-bed velocities in the EW due to vessel operations, including propwash and pressure field velocities, were calculated and this analysis was discussed in Section 5. Near-bed velocities were estimated assuming extreme vessel operations (e.g., vessels operating under extreme weather versus emergency vessel operations as defined in Section 5.1.2) as opposed to operations during typical fair weather conditions. Maximum near-bed velocities and bed shear stresses are discussed in Section 5.2. Table 5-4 provides a summary of these values for each operating area. The maximum near-bed velocity and bed shear stress in each operational area (shown in Figure 5-1) were taken as the maximum result due to all vessel operations considered within each area. Maximum bed shear stresses due to propwash were estimated for all operational areas and range from 2 to 23 Pa within the EW (based on estimates of extreme vessel operations, as defined in Section 5.1.2, while navigating and berthing). Figures 5-18 and 5-19 show the spatial variation of maximum near-bed velocities and bed shear stress due to propwash throughout the EW.

The 95th percentile confidence interval of critical bed shear stress for surface sediments in the EW ranges between 0.20 and 0.37 Pa (Section 6.1). Based on this analysis, surface sediments within the waterway have the potential to be eroded due to extreme vessel operations (as defined in Section 5.1.2) throughout the EW.

Geochronology cores collected as part of the STE and surface sediment samples collected for sediment characterization were used to provide additional lines of evidence for comparison with propwash results. In general, results of the geochronology evaluation coincide with the results of the propwash evaluation. Cs-137 results from the geochronology core analysis (Figure 3-1) suggest that areas within Slip 27 and south of Slip 27 (between EW Stations 4000 and 5200) are net depositional and have not been impacted by mixing events below the surface sediments (since Cs-137 peaks were documented for most of those cores). This area coincides with propwash operational Areas 3, 4A, 4B, 4C, and 5 where maximum bed shear stress due to propwash (for existing conditions at extreme vessel operations) is estimated at 2 Pa. Bed shear stress values of 2 Pa may be large enough to disturb surface sediments, but are less likely to disturb sediments below the surface. The area north of Slip 27 (where Cs-137 peaks were not found in tested cores) appears to be impacted by vertical mixing of both surface and subsurface sediments. This area coincides with propwash operational areas 1A and 1B, where maximum bed shear stress due to propwash is estimated at 9 to 23 Pa.

Grain size information for surface sediment samples collected along the front of Terminal 25 (South Terminal 30) and Terminal 18 (Figure 4-1 of the Final Surface Sediment Data Report;

Windward 2010) was reviewed to see if surface grain size (median diameter and D_{90}) is related to bed shear stress due to propwash. Areas impacted by higher bed shear stress are expected to have higher surface sediment grain sizes. Surface sediments along the face of Terminal 25 (South Terminal 30) (cores SS-040, SS-031, SS-034, SS-038, and SS-103) and south Terminal 18 (cores SS-028 and SS-035) have a median diameter of approximately 15 microns and a D_{90} of 125 microns. These areas coincide with propwash operational areas 4A, and 5 where maximum bed shear stress due to propwash (for existing conditions) is estimated at 2 Pa. Surface sediments along Terminal 18, Berths 1, 2, and 3 (cores SS-122, SS-126, SS-205, SS-207, and SS-112) have a median diameter of 125 microns and a D_{90} of 500 to greater than 2,000 microns. This area coincides with propwash operational area 1A where maximum bed shear stress due to propwash (for existing conditions) is estimated to be between 9 and 23 Pa. This information suggests that areas predicted to have high bed shear stress due to propwash have larger grain sizes in the surface sediments (on average) compared to areas predicted to have lower bed shear stress due to propwash.

6.3.1 Uncertainty Discussion

The evaluation of erosion potential with the EW due to vessel operations involves comparison of estimates of bed critical shear stress (from Sedflume data) with estimates of bed shear stress due to vessel operations (propwash and pressure field modeling). Therefore, uncertainties in this evaluation are dependent on the uncertainty in the estimates of those parameters, as described in Sections 5.4.3 (bed shear stress due to vessel operations) and Section 6.2.2 (critical bed shear stress from Sedflume data).

7 SPATIAL DISTRIBUTION OF SEDIMENTS ORIGINATING FROM LATERAL SOURCES

The spatial distribution of sediments deposited within the EW from lateral sources was estimated using the PTM developed by USACE. The purpose of the PTM modeling effort was to provide information that can be used to evaluate the potential for recontamination due to sediment loads from identified lateral sources, as well as estimate the relative contribution of solids loads from lateral sources to sedimentation in the EW. Net sedimentation for the EW as a whole was estimated through evaluation of geochronological cores described in Section 3.

7.1 Overview of Technical Approach

The PTM model uses a Lagrangian method to simulate the transport of discrete particles within the modeling domain (McDonald et. al 2006). The PTM model uses the hydrodynamic model results (e.g., current velocities) to simulate the transport of suspended particles within the EW. The hydrodynamic model (see Section 4) is run independently of the PTM model. The PTM model tracks the path particles may travel in the water column from the time of particle release at the source location until the particle is deposited on the sediment bed. Particles are released into the flow field at their discharge location with no incoming plume velocity; therefore, the initial velocity of the particle within the model is solely dictated by the hydrodynamic model results at the discharge location. Results of the PTM model will be combined with empirical estimates of net sedimentation rate developed from the evaluation of geochronological cores (which includes contribution from all sediment sources to the EW as described in Section 3) to evaluate the relative contribution of solids loads from lateral sources to sedimentation in the EW.

The PTM model is best suited for simulating relatively short-term sediment transport events such as resuspension due to dredging or other activities. Conducting a long-term, multi-year PTM simulation can be impractical due to exceedingly long runtimes as increasing numbers of particles are created within the model. Thus, a base-case PTM simulation, with an acceptable simulation time, was developed that is assumed to be representative of long-term average conditions. Results from the base-case simulation are used to estimate long-term sedimentation rates from lateral sources based on extrapolation from a shorter simulation period. The inputs and boundary conditions for the base-case simulation are discussed in Section 7.3. Bounding simulations (based on results of the sensitivity analysis discussed in Section 7.3.4) were conducted to define reasonable upper- and lower-bound estimates of sedimentation rates due to lateral sources.

7.2 Lateral Sources of Sediment Within the East Waterway

Sediment loads to the EW are from three types of sources: 1) upstream solids from the Green/Duwamish River; 2) solids from Elliott Bay; and 3) solids from lateral sources (Anchor and Windward 2009). Lateral sources include both stormwater discharges and CSOs. Data from lateral sources are used as inputs to the PTM; specifically, discharge volumes, TSS, and particles size distributions associated with those discharges.

Lateral sources of sediment to the EW were identified through the SCE and are presented in the Final Initial Source Evaluation and Data Gaps Memorandum (SEDGM; Anchor and Windward 2009). Sediment loading from these sources was developed using existing information (i.e., overflow volumes and TSS measurements for CSOs and modeling and literature values for TSS for the storm drains).

Currently, 39 outfalls (36 storm drains, one CSO, and two CSO/SDs) to the EW have been identified. Two of the outfalls (at S Hinds Street and S Lander Street) are shared by the separated storm drain and combined sewer service systems. These outfalls are referred to as CSO/SD outfalls. Loading for the stormwater component of these discharges is discussed in Section 7.2.1.1. Loading for the CSO component is discussed in Section 7.2.1.2. Locations and ownership information for each of these storm drains and CSOs, and associated drainage basins, is shown in Figures 1-4A and 1-4B. Drainage basins are identified with a number that matches the City's National Pollutant Discharge Elimination System (NPDES) number for the outfall that the basin discharges through into the EW. Bridges and port aprons are identified with a number that corresponds to the closest storm drain. Additional information regarding the routing of stormwater discharges is provided in Appendix F.

7.2.1 Sediment Mass Loading from Lateral Sources

7.2.1.1 Stormwater Discharge

Stormwater discharges to the EW are described in detail in Section 4 of the SEDGM (Anchor and Windward 2009). Drainage basin boundaries and stormwater discharge volumes have been revised since publication of the SEDGM. Because of these changes, estimates of annual stormwater discharges and solids loading for drainage basins, bridges, and port aprons that discharge to the EW have also been updated. These updates are described in a report produced by Seattle Public Utilities (SPU) dated June 2011 provided in Appendix F, Attachment 1.

Sediment loads from stormwater discharges were developed based on the estimated runoff for an average water year (1986). Runoff estimates were developed using a simplified Hydrologic Simulation Program-Fortran (HSPF) model that calculated runoff volumes per unit area for individual land use, soil type, and slope based on regional Puget Sound input parameters and local rainfall data. Sediment loads were calculated by multiplying the annual stormwater volume by a representative TSS concentration. Representative TSS values were estimated based on land use using stormwater data compiled from studies conducted in western Washington and Oregon. TSS values from parking lots and other paved areas were used to characterize runoff quality for the largely paved Port terminal areas. For all other areas, TSS values were based on available stormwater data for the various land use categories within each drainage basin (e.g., industrial, commercial, single-family residential, multi-family residential, roadway/right-of-way). Table 7-1 provides 25th percentile, 50th percentile (median), and 75th percentile TSS values, which were used to develop stormwater solids loading for the STE.

Table 7-1
TSS Values for Stormwater

Land Use	Low (25th percentile)	Base-Case (10% trimmed mean)	High (75th percentile)
Single-family residential	24	48	70
Multi-family residential	39	68	101
Commercial	31	58	84
Industrial[a]	34	74	117

Land Use	Low (25th percentile)	Base-Case (10% trimmed mean)	High (75th percentile)
Industrial (Port terminals)[b]	20	43	60
Open/Vacant/Park	8	13	18
Right-of-way	34	71	86

Notes

a. Used for industrial land use in all Seattle Public Utilities (SPU) drainage basins except B-21, plus Port of Seattle (Port) basin B-34, and all private basins.
b. Used for all Port terminals that are mostly paved except B-34 plus SPU basin B-21.

Tables 7, 8, and 9 in Appendix F, Attachment 1, provide summary information on basin size, stormwater discharge, and sediment loading for all stormwater basins shown in Figures 1-4A and 1-4B for the 25th percentile, 50th percentile, and 75th percentile TSS values, respectively.

Sediment load was partitioned into four sediment size fractions consistent with the sediment transport evaluation completed for the LDW (Windward and QEA 2008). The particle size distribution of the four sediment classes for stormwater discharge was developed through evaluation of site-specific data, as described in Appendix F, Attachment 1. The particle size distribution used to develop sediment load for the PTM model was taken from EW sediment trap samples rather than available stormwater samples that were used in the LDW study (see Appendix F, Figure F-1). Compared to the LDW, particle size distribution used for stormwater discharges in the EW contained a larger percentage of sands, compared to clay and silt fractions. This will provide a conservative estimate of sedimentation at lateral source discharge locations; as sands will settle out quickly compared to silts and clays, which could be dispersed more broadly throughout the EW. This will not necessarily provide a conservative estimate of sedimentation for locations in the EW that are farther away from the discharge location. A sensitivity run was completed using the particle size distribution for stormwater used in the LDW study (Windward and QEA 2008) to validate this assumption. Characteristic diameters used for stormwater inputs in the PTM model were defined in the LDW Sediment Transport Modeling Report (Windward and QEA 2008) and are provided in Table 7-2; see Section 7.3.3 for their usage in the PTM model runs.

Table 7-2
Characteristic Diameter and Particle Size Distribution for Stormwater

Sediment Size Class	Effective Diameter (microns)	Effective Diameter (mm)	Percent of Each Sediment Class in Stormwater	
			From Site-specific Sediment Trap Data	Assumptions Used in LDW Study[a]
1A: clay and fine silt	5	0.005	15%	55%
1B: medium/coarse silt	20	0.02	23%	18%
2: fine sand	130	0.13	26%	23%
3: medium/coarse sand	540	0.54	35%	4%

Notes:
a Windward and QEA (2008)
LDW = Lower Duwamish Waterway

Annual solids load for stormwater drainage basins for the average water year (1986) and for CSO discharges (10-year average) for each basin (Tables F-1 through F-3 in Appendix F) were converted to a mass flux (kilograms per second [kg/s]) and partitioned by grain size (based on values provided in Table 7-2) for input into the PTM model. Tables 7-3, 7-4, and 7-5 provide mass flux used as input to the PTM model for base-case (50th percentile), 25th percentile, and 75th percentile TSS values, respectively.

Table 7-3
Solids Input to PTM Model by Outfall for Base-Case (50th Percentile TSS Values)

Seattle Public Utilities-owned Outfalls/Basins (and Bridges BR-39, 34, 4, 5, and 6)

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Hinds[d]	1.525E+04	6.920E+03	2.19E-04	0.00003377	0.00005066	0.00005723	0.00007763
Lander[d,e]	7.041E+04	3.194E+04	1.01E-03	0.00015587	0.00023380	0.00026417	0.00035830
21	3105	1408	4.46E-05	0.00000687	0.00001031	0.00001165	0.00001580
25	1449	657	2.08E-05	0.00000321	0.00000481	0.00000544	0.00000737
36	2340	1061	3.36E-05	0.00000518	0.00000777	0.00000878	0.00001191
4	3236	1468	4.65E-05	0.00000716	0.00001074	0.00001214	0.00001647
5	1417	643	2.04E-05	0.00000314	0.00000470	0.00000532	0.00000721
39	515	234	7.40E-06	0.00000114	0.00000171	0.00000193	0.00000262

Port of Seattle-owned Basins (and Bridges BR-2 and BR-27)

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
1	378	171	5.43E-06	0.00000084	0.00000126	0.00000142	0.00000192
7	3598	1632	5.17E-05	0.00000796	0.00001195	0.00001350	0.00001831
10	2276	1032	3.27E-05	0.00000504	0.00000756	0.00000854	0.00001158
11	11514	5223	1.65E-04	0.00002549	0.00003823	0.00004320	0.00005859
12	2034	923	2.92E-05	0.00000450	0.00000675	0.00000763	0.00001035
13	1599	725	2.30E-05	0.00000354	0.00000531	0.00000600	0.00000814
14	609	276	8.75E-06	0.00000135	0.00000202	0.00000228	0.00000310
16	1212	550	1.74E-05	0.00000268	0.00000402	0.00000455	0.00000617
17	674	306	9.69E-06	0.00000149	0.00000224	0.00000253	0.00000343
18	2058	933	2.96E-05	0.00000456	0.00000683	0.00000772	0.00001047
19	1657	752	2.38E-05	0.00000367	0.00000550	0.00000622	0.00000843
22	3348	1519	4.81E-05	0.00000741	0.00001112	0.00001256	0.00001704
23	3108	1410	4.47E-05	0.00000688	0.00001032	0.00001166	0.00001581
24	2665	1209	3.83E-05	0.00000590	0.00000885	0.00001000	0.00001356
26	3349	1519	4.81E-05	0.00000741	0.00001112	0.00001256	0.00001704
27	2162	981	3.11E-05	0.00000479	0.00000718	0.00000811	0.00001100
28	1218	552	1.75E-05	0.00000270	0.00000404	0.00000457	0.00000620
29	2365	1073	3.40E-05	0.00000524	0.00000785	0.00000887	0.00001203
30	1910	866	2.75E-05	0.00000423	0.00000634	0.00000717	0.00000972

31	2529	1147	3.64E-05	0.00000560	0.00000840	0.00000949	0.00001287
32	1083	491	1.56E-05	0.00000240	0.00000360	0.00000406	0.00000551
33	3415	1549	4.91E-05	0.00000756	0.00001134	0.00001281	0.00001738
34	5416	2457	7.78E-05	0.00001199	0.00001798	0.00002032	0.00002756
37	1519	689	2.18E-05	0.00000336	0.00000504	0.00000570	0.00000773
39	496	225	7.13E-06	0.00000110	0.00000165	0.00000186	0.00000252
2	63	29	9.06E-07	0.00000014	0.00000021	0.00000024	0.00000032

Privately-owned Basins

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
6	1300	590	1.87E-05	0.00000288	0.00000432	0.00000488	0.00000661
40	989	449	1.42E-05	0.00000219	0.00000328	0.00000371	0.00000503
41	1890	857	2.72E-05	0.00000418	0.00000628	0.00000709	0.00000962
42	190	86	2.73E-06	0.00000042	0.00000063	0.00000071	0.00000097
43	2362	1071	3.40E-05	0.00000523	0.00000784	0.00000886	0.00001202

Seattle Public Utilities CSOs

Outfall	Average TSS in kg/L[c]	Average Flow in million gal/yr[c]	Average Flow in liters/yr	Average Solids in kg per year	Mass Flux - Total Solids TSS in kg/s	Mass Flux (kg/s) - By Size Class[b]			
						1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Hinds	0.000086	1	3.785E+06	3.255E+02	1.03E-05	0.00000433	0.00000423	0.00000175	0.00000000

King County CSOs

Outfall	Average TSS in kg/L[c]	Average Flow in million gal/yr[c]	Average Flow in liters/yr	Average Solids in kg per year	Mass Flux - Total Solids TSS in kg/s	Mass Flux (kg/s) - By Size Class[b]			
						1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Lander	0.000086	39.8	1.507E+08	1.296E+04	4.11E-04	0.00017244	0.00016834	0.00006980	0.00000000
Hanford	0.000086	74.3	2.813E+08	2.419E+04	7.66E-04	0.00032193	0.00031426	0.00013030	0.00000000

Notes:
a. Sediment load taken from runoff modeling completed by Seattle Public Utilities as described in Appendix F, Attachment 1.
b. Characteristic particle sizes and particle size distributions provided in Table 7-2.
c. TSS and flow rates for Lander and Hanford CSOs developed by King County; Hinds developed by SPU. Described in Appendix F, Attachment 2.
d. Lander drainage basin discharges to the Lander Street outfall, which is shared with the Lander CSO. Hinds drainage basin discharges to the Hinds outfall, which is shared with the Hinds CSO.
e. Low runoff assumption.
N/A - Not applicable

Table 7-4
Solids Input to PTM Model by Outfall for 25th Percentile TSS Values

Seattle Public Utilities-owned Outfalls/Basins (and Bridges BR-39, 34, 4, 5, and 6)

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Hinds[d]	7.087E+03	3.215E+03	1.02E-04	0.00001569	0.00002353	0.00002659	0.00003607
Lander[d,e]	3.322E+04	1.507E+04	4.77E-04	0.00007353	0.00011029	0.00012462	0.00016902
21	1444	655	2.08E-05	0.00000320	0.00000479	0.00000542	0.00000735
25	723	328	1.04E-05	0.00000160	0.00000240	0.00000271	0.00000368
36	1106	502	1.59E-05	0.00000245	0.00000367	0.00000415	0.00000563
4	1518	689	2.18E-05	0.00000336	0.00000504	0.00000569	0.00000772
5	672	305	9.66E-06	0.00000149	0.00000223	0.00000252	0.00000342
39	236	107	3.39E-06	0.00000052	0.00000078	0.00000089	0.00000120

Port of Seattle-owned Basins (and Bridges BR-2 and BR-27)

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
1	175	79	2.52E-06	0.00000039	0.00000058	0.00000066	0.00000089
7	1677	761	2.41E-05	0.00000371	0.00000557	0.00000629	0.00000853
10	1058	480	1.52E-05	0.00000234	0.00000351	0.00000397	0.00000538
11	5355	2429	7.70E-05	0.00001185	0.00001778	0.00002009	0.00002725
12	946	429	1.36E-05	0.00000209	0.00000314	0.00000355	0.00000481
13	744	337	1.07E-05	0.00000165	0.00000247	0.00000279	0.00000379
14	283	128	4.07E-06	0.00000063	0.00000094	0.00000106	0.00000144
16	563	255	8.09E-06	0.00000125	0.00000187	0.00000211	0.00000286
17	314	142	4.51E-06	0.00000070	0.00000104	0.00000118	0.00000160
18	957	434	1.38E-05	0.00000212	0.00000318	0.00000359	0.00000487
19	770	349	1.11E-05	0.00000170	0.00000256	0.00000289	0.00000392
22	1556	706	2.24E-05	0.00000344	0.00000517	0.00000584	0.00000792
23	1444	655	2.08E-05	0.00000320	0.00000479	0.00000542	0.00000735
24	1239	562	1.78E-05	0.00000274	0.00000411	0.00000465	0.00000630
26	1557	706	2.24E-05	0.00000345	0.00000517	0.00000584	0.00000792
27	1005	456	1.44E-05	0.00000222	0.00000334	0.00000377	0.00000511
28	566	257	8.14E-06	0.00000125	0.00000188	0.00000212	0.00000288
29	1099	498	1.58E-05	0.00000243	0.00000365	0.00000412	0.00000559
30	889	403	1.28E-05	0.00000197	0.00000295	0.00000334	0.00000452

31	1175	533	1.69E-05	0.00000260	0.00000390	0.00000441	0.00000598
32	503	228	7.23E-06	0.00000111	0.00000167	0.00000189	0.00000256
33	1588	720	2.28E-05	0.00000352	0.00000527	0.00000596	0.00000808
34	2488	1129	3.58E-05	0.00000551	0.00000826	0.00000933	0.00001266
37	706	320	1.01E-05	0.00000156	0.00000234	0.00000265	0.00000359
39	231	105	3.32E-06	0.00000051	0.00000077	0.00000087	0.00000118
2	29	13	4.17E-07	0.00000006	0.00000010	0.00000011	0.00000015

Privately-owned Basins

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
6	597	271	8.58E-06	0.00000132	0.00000198	0.00000224	0.00000304
40	528	239	7.59E-06	0.00000117	0.00000175	0.00000198	0.00000269
41	869	394	1.25E-05	0.00000192	0.00000289	0.00000326	0.00000442
42	87	39	1.25E-06	0.00000019	0.00000029	0.00000033	0.00000044
43	1085	492	1.56E-05	0.00000240	0.00000360	0.00000407	0.00000552

Seattle Public Utilities CSOs

Outfall	Average TSS in kg/L[c]	Average Flow in million gal/yr[c]	Average Flow in liters/yr	Average Solids in kg per year	Mass Flux - Total Solids TSS in kg/s	Mass Flux (kg/s) - By Size Class[b]			
						1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Hinds	0.0000653	1	3.785E+06	2.472E+02	7.83E-06	0.00000329	0.00000321	0.00000133	0.00000000

King County CSOs

Outfall	Average TSS in kg/L[c]	Average Flow in million gal/yr[c]	Average Flow in liters/yr	Average Solids in kg per year	Mass Flux - Total Solids TSS in kg/s	Mass Flux (kg/s) - By Size Class[b]			
						1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Lander	0.0000653	39.8	1.507E+08	9.838E+03	3.12E-04	0.00013094	0.00012782	0.00005300	0.00000000
Hanford	0.0000653	74.3	2.813E+08	1.837E+04	5.82E-04	0.00024444	0.00023862	0.00009894	0.00000000

Notes:
a. Sediment load taken from runoff modeling completed by Seattle Public Utilities as described in Appendix F, Attachment 1.
b. Characteristic particle sizes and particle size distributions provided in Table 7-2.
c. TSS and flow rates for Lander and Hanford CSOs developed by King County; Hinds developed by SPU. Described in Appendix F, Attachment 2.
d. Lander drainage basin discharges to the Lander Street outfall, which is shared with the Lander CSO. Hinds drainage basin discharges to the Hinds outfall, which is shared with the Hinds CSO.
e. Low runoff assumption.
N/A - Not applicable

Table 7-5
Solids Input to PTM Model by Outfall for 75th Percentile TSS Values

Seattle Public Utilities-owned Outfalls/Basins (and Bridges BR-39, 34, 4, 5, and 6)

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Hinds[d]	2.255E+04	1.023E+04	3.24E-04	0.00004993	0.00007489	0.00008462	0.00011477
Lander[d,e]	9.321E+04	4.228E+04	1.34E-03	0.00020632	0.00030949	0.00034968	0.00047428
21	4332	1965	6.23E-05	0.00000959	0.00001438	0.00001625	0.00002204
25	2176	987	3.13E-05	0.00000482	0.00000723	0.00000816	0.00001107
36	3084	1399	4.43E-05	0.00000683	0.00001024	0.00001157	0.00001569
4	4584	2079	6.59E-05	0.00001015	0.00001522	0.00001720	0.00002332
5	1834	832	2.64E-05	0.00000406	0.00000609	0.00000688	0.00000933
39	813	369	1.17E-05	0.00000180	0.00000270	0.00000305	0.00000414

Port of Seattle-owned Basins (and Bridges BR-2 and BR-27)

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
1	527	239	7.57E-06	0.00000117	0.00000175	0.00000198	0.00000268
7	5035	2284	7.24E-05	0.00001115	0.00001672	0.00001889	0.00002562
10	3175	1440	4.56E-05	0.00000703	0.00001054	0.00001191	0.00001616
11	16066	7287	2.31E-04	0.00003556	0.00005334	0.00006027	0.00008175
12	2839	1288	4.08E-05	0.00000628	0.00000943	0.00001065	0.00001445
13	2232	1012	3.21E-05	0.00000494	0.00000741	0.00000837	0.00001136
14	851	386	1.22E-05	0.00000188	0.00000283	0.00000319	0.00000433
16	1691	767	2.43E-05	0.00000374	0.00000561	0.00000634	0.00000860
17	942	427	1.35E-05	0.00000209	0.00000313	0.00000353	0.00000479
18	2873	1303	4.13E-05	0.00000636	0.00000954	0.00001078	0.00001462
19	2312	1049	3.32E-05	0.00000512	0.00000768	0.00000867	0.00001176
22	4671	2119	6.71E-05	0.00001034	0.00001551	0.00001752	0.00002377
23	4336	1967	6.23E-05	0.00000960	0.00001440	0.00001627	0.00002206
24	3719	1687	5.35E-05	0.00000823	0.00001235	0.00001395	0.00001892
26	4673	2120	6.72E-05	0.00001034	0.00001552	0.00001753	0.00002378
27	3017	1368	4.34E-05	0.00000668	0.00001002	0.00001132	0.00001535
28	1700	771	2.44E-05	0.00000376	0.00000564	0.00000638	0.00000865
29	3300	1497	4.74E-05	0.00000730	0.00001096	0.00001238	0.00001679
30	2667	1210	3.83E-05	0.00000590	0.00000886	0.00001001	0.00001357

31	3529	1601	5.07E-05	0.00000781	0.00001172	0.00001324	0.00001796
32	1511	685	2.17E-05	0.00000334	0.00000502	0.00000567	0.00000769
33	4766	2162	6.85E-05	0.00001055	0.00001582	0.00001788	0.00002425
34	8563	3884	1.23E-04	0.00001895	0.00002843	0.00003212	0.00004357
37	2120	962	3.05E-05	0.00000469	0.00000704	0.00000795	0.00001079
39	693	314	9.96E-06	0.00000153	0.00000230	0.00000260	0.00000353
2	89	40	1.28E-06	0.00000020	0.00000030	0.00000033	0.00000045

Privately-owned Basins

Outfall	Annual Average Sediment Load in lbs[a]	Annual Average Sediment Load in kg	Annual Avg. Mass Flux Total Solids in kg/s	Mass Flux (kg/s) - By Size Class[b]			
				1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
6	2055	932	2.95E-05	0.00000455	0.00000682	0.00000771	0.00001046
40	1434	650	2.06E-05	0.00000317	0.00000476	0.00000538	0.00000730
41	2984	1354	4.29E-05	0.00000661	0.00000991	0.00001119	0.00001518
42	300	136	4.31E-06	0.00000066	0.00000100	0.00000113	0.00000153
43	3735	1694	5.37E-05	0.00000827	0.00001240	0.00001401	0.00001900

Seattle Public Utilities CSOs

Outfall	Average TSS in kg/L[c]	Average Flow in million gal/yr[c]	Average Flow in liters/yr	Average Solids in kg per year	Mass Flux - Total Solids TSS in kg/s	Mass Flux (kg/s) - By Size Class[b]			
						1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Hinds	0.000106	1	3.785E+06	4.013E+02	1.27E-05	0.00000534	0.00000521	0.00000216	0.00000000

King County CSOs

Outfall	Average TSS in kg/L[c]	Average Flow in million gal/yr[c]	Average Flow in liters/yr	Average Solids in kg per year	Mass Flux - Total Solids TSS in kg/s	Mass Flux (kg/s) - By Size Class[b]			
						1A (0.005 mm)	1B (0.02 mm)	2 (0.13 mm)	3 (0.54 mm)
Lander	0.000106	39.8	1.507E+08	1.597E+04	5.06E-04	0.00021255	0.00020749	0.00008603	0.00000000
Hanford	0.000106	74.3	2.813E+08	2.981E+04	9.45E-04	0.00039679	0.00038734	0.00016061	0.00000000

Notes:

a. Sediment load taken from runoff modeling completed by Seattle Public Utilities as described in Appendix F, Attachment 1.

b. Characteristic particle sizes and particle size distributions provided in Table 7-2.

c. TSS and flow rates for Lander and Hanford CSOs developed by King County; Hinds developed by SPU. Described in Appendix F, Attachment 2.

d. Lander drainage basin discharges to the Lander Street outfall, which is shared with the Lander CSO. Hinds drainage basin discharges to the Hinds outfall, which is shared with the Hinds CSO.

e. Low runoff assumption.

N/A - Not applicable

7.2.1.2 CSOs

Three CSOs discharge into the EW, as shown in Figures 1-4A and 1-4B. Detailed information regarding these CSOs is provided in Section 5 of the SEDGM (Anchor and Windward 2009). The County and City routinely monitor CSO discharges as part of their CSO control programs. The County collected CSO TSS data as part of ongoing source control activities. CSO volume and discharge frequencies are recorded by the County and SPU as part of their permit reporting requirements for CSOs. Flow information for Lander and Hanford #2 CSOs and TSS information for these two CSOs are summarized in a memorandum produced by the County dated May 13, 2011, provided in Appendix F, Attachment 2. Flow data for the Hinds CSO is summarized in a report produced by SPU dated June 2011, provided in Appendix F, Attachment 1. CSO discharge volumes and frequencies were based on annual averages from the 2000-2009 reporting period. TSS values, based on samples collected between 1995 and 2009 (with the majority collected between 2007 and 2009), were developed for all CSOs and are provided below:

- 25th Percentile = 65.3 milligrams per liter (mg/L)
- 50th Percentile (average) = 86 mg/L
- 75th Percentile = 106 mg/L

Table 7-6 provides CSO flow and particle size distribution used to develop CSO solids loads for the PTM model. The particle size distribution of the four sediment classes for CSOs was developed through evaluation of data from four King County CSOs, as described in Section 5.1.3.2 of the SEDGM (Anchor and Windward 2009). Effective diameters of the four size classes for CSOs are the same as used for stormwater provided in Table 7-2.

Table 7-6
Flow and Particle Size Distribution for CSOs

CSO	Average Annual Flow (million gallons per year)	Percent of each Sediment Size Class in CSO Flow[a]			
		1A	1B	2	3
Hanford #2	74.3	42%	41%	17%	0%
Lander	39.8	42%	41%	17%	0%
Hinds	1.0	42%	41%	17%	0%

Note:
a Characteristic diameters for each size class shown in Table 7-2.

The mean annual solids load for each CSO is based on the average TSS values and the average annual flows for each CSO. These annual mass loads were then converted to a mass flux (kg/s) and partitioned by grain size (based on values provided in Table 7-6) for input into the PTM model. This information is provided in Tables 7-3 through 7-5.

7.3 Particle Tracking Model

7.3.1 Input From the Hydrodynamic Model

Section 4.3 describes boundary conditions for the five hydrodynamic model simulations that provided input to the PTM model. Each hydrodynamic model simulation was 42 days in duration (4 weeks of particle input plus 2 weeks of spindown/settling). Tidal elevations at the open boundary in Elliott Bay were specified using measured water surface elevations during June and July 2009. The incoming flow rate at the upstream boundary (i.e., Green River inflow) was temporally constant during each hydrodynamic simulation, as described in Section 4. While this results in high flow events that last much longer than in reality, it serves to estimate the potential range of particle dispersion within the EW and beyond due to tidal and river flow. Incoming flow rates for the five hydrodynamic simulations were as follows:

- Annual average (1,300 cubic feet per second [cfs])
- 'Wet-season' (November through May) average (1,875 cfs)
- 2-year high-flow event (8,400 cfs)
- 10-year high-flow event (10,800 cfs)
- 100-year high-flow event (12,000 cfs)

Once the hydrodynamic simulations were completed using EFDC, the output files were converted to 3-D ADCIRC format (Luettich and Westerink 2004) using a command-line utility program developed by USACE personnel. This utility program converted the hydrodynamic model output at each rectangular grid cell (with ten layers in the vertical) into two triangular grid cells (also with ten layers in the vertical). This conversion process did not change the resolution of the hydrodynamic model output. A comparison of EFDC and ADCIRC grid cells within the EW is shown in Figure 7-1.

7.3.2 Model Output Post-Processing

The PTM directly uses ADCIRC-format output files; there is no need to create a separate numerical grid for the PTM. The output of the PTM consists of location coordinates, source information, and path of travel data for each particle released into the model at each recorded time step of the simulation. The location coordinates provided by the PTM output are not directly linked to a particular hydrodynamic grid cell. Therefore, the particle location information output by the PTM can be post-processed in numerous ways. For the purposes of the STE, positions of particles deposited within the EW during the simulation period were extracted from the PTM output file and imported into ArcGIS. The points were then post-processed to create a raster representation of mass accumulation in the EW with a 50-foot by 50-foot resolution. Mass accumulation within each 50-foot by 50-foot cell in the raster was calculated by adding up all of the particles that had been deposited within that area. This cell size was chosen to provide an appropriate level of resolution for predicting sediment deposition patterns within the EW and to inform recontamination potential within the EW as part of the SRI process.

The effect of raster cell size on the representation of mass accumulation was evaluated by varying the resolution of the raster cells for the base-case simulation (simulation 1) and simulation 5 (75% TSS sediment loading), and comparing mass accumulation in kilograms deposited per square foot of area between the different resolution raster maps. Resolutions of 50- and 100-feet square were used. The resulting figures are provided as Figures G-1 through G-4 in Appendix G. From this evaluation, it was concluded that the resolution of the raster does not have a significant impact on the representation of deposition patterns within the EW. However, in portions of the EW where deposition is very high (large numbers of points deposited in a small area), increasing the size of the raster tends to smooth out the peak in mass accumulation.

7.3.3 Lateral Source Inputs

The lateral source sediment loading information (described in Section 7.2) was used to develop a total of ten sediment source files to be used as input for the PTM simulations. These ten variations in sediment loading were used as input to the base run, bounding runs and a variety of sensitivity runs to test model sensitivity to changes in sediment load and model parameters. These input files are used to specify the following for each sediment input:

- Parcel mass (the mass of each 'parcel' representing individual sediment particles)
- Mass loading rate
- Representative particle diameter
- Standard deviation of particle diameter (assuming Gaussian distribution)

Resuspension processes in the PTM were not included in the simulations, as the objective of the PTM model was to evaluate initial sediment deposition patterns from lateral sources (since resuspension of deposited material is expected to be dominated by propwash). This was accomplished by setting the critical shear stress for initiation of motion to a very high value (100 Pa), which resulted in no resuspension of particles due to currents. Table 7-7 outlines the characteristics of the ten lateral source sediment input files. These sediment source files are used in conjunction with the hydrodynamic model input to develop PTM model scenarios. Source S1 was used for the base-case, while sources S4 and S5 were used for bounding runs and sensitivity runs. All others were used for sensitivity analysis only. The PTM model tracks the movement of parcels of sediment with a set mass, as opposed to individual particles. The parcel size was set to 0.5 kg for all simulations (except for Simulation 3, where it was changed as a sensitivity parameter) and standard deviation of the particle size distribution was set to 0.8 φ. These values are commonly accepted values for this application (McDonald et. al 2006). Increasing the standard deviation of the particle size distribution within the PTM model does not change the median diameter of each sediment size class, but results in a larger percentage of particles both smaller and larger than the median diameter to be input into the model.

Table 7-7
Lateral Source Load Characteristics for PTM Simulations

Source File No.	Parcel Mass (kg)	Standard Deviation of Particle Diameter	Characteristic Particle Diameter, by Size Class (microns)				Particle Size Distribution in Storm Drain Flows (%)				TSS Loading Rate (percentile)
			1A	1B	2	3	1A	1B	2	3	
S1	0.5	0.8	5	20	130	540	15	23	26	35	50th
S2	0.25	0.8	5	20	130	540	15	23	26	35	50th
S3	0.5	1.0	5	20	130	540	15	23	26	35	50th

Source File No.	Parcel Mass (kg)	Standard Deviation of Particle Diameter	Characteristic Particle Diameter, by Size Class (microns)				Particle Size Distribution in Storm Drain Flows (%)				TSS Loading Rate (percentile)
			1A	1B	2	3	1A	1B	2	3	
S4	0.5	0.8	3.5	14	130	540	15	23	26	35	50th
S5	0.5	0.8	7	28	130	540	15	23	26	35	50th
S6	0.5	0.8	5	20	130	540	15	23	26	35	75th
S7	0.5	0.8	5	20	130	540	15	23	26	35	25th
S8	0.5	0.0	5	20	130	540	15	23	26	35	50th
S9	0.5	0.8	5	20	130	540	15	23	26	35	50th, higher Lander[a]
S10	0.5	0.8	5	20	130	540	55	18	23	4	50th

Note:
a Higher estimate of flow in the Lander separated storm basin based on its operation

7.3.4 Base-Case Simulation

The PTM simulations were conducted using the hydrodynamic input described in Section 7.3.1. Sediment loads from the lateral sources were active during the first 28 days of a simulation (June 3 through June 30, 2009 of the tidal boundary condition), with the lateral source loads set to zero for the last 14 days of a simulation. The result is an estimate of average lateral sediment loads and initial sediment deposition within the EW over a 4-week period.

The base-case simulation, which was considered to be representative of average long-term conditions within the EW, was specified as follows:

- Hydrodynamic boundary conditions
  - Annual average flow in the Green River (1,300 cfs)
  - 28-day tidal cycle (includes spring and neap tides)
- Lateral source load input (sediment source file S1, Table 7-7)
  - Annual average stormwater runoff and CSO flows
  - Median (50%) TSS concentration developed for stormwater and CSO discharges
  - Particle size distribution of CSO flows (see Table 7-6)
  - Particle size distribution of stormwater flows based on sediment trap data (see Table 7-2)

- PTM input parameters
  - Standard deviation set to 0.8 (default model parameter)
  - Parcel size set to 0.5 kg (considered an appropriate parcel size for this application)
  - Critical bed shear stress set to 100 Pa

The predicted spatial distribution of sediment mass accumulation for the base-case simulation is presented in Figure 7-2.

7.3.5 Sensitivity Simulations

The effects of hydrodynamic boundary conditions and various model inputs on PTM predictions were evaluated during a sensitivity analysis. A total of 13 sensitivity simulations were conducted and compared to the base-case simulation. Table 7-8 outlines the characteristics of the sensitivity simulations. These sensitivity simulations were developed in cooperation with EPA prior to completing the evaluation.

The sensitivity evaluations were divided into two tiers for consideration of model performance:

- Tier 1 included simulations that evaluated the response to the model to changes in sediment loads and particles size distributions, which have recognized uncertainties based on evaluation of existing datasets (see Section 7.2). The results of these simulations were ultimately used as representative bounding runs for the base-case simulation. Tier 1 simulations included 4, 5, 7, and 8, as described in Table 7-8. Results of these simulations are provided in Figures 7-3 through 7-6.
- Tier 2 included simulations that were evaluated to better understand the behavior of the model in response to either internal model parameters or hydrodynamic input. The results of these simulations were used to evaluate model sensitivity only, and were not used directly to evaluate deposition patterns from lateral sources within the EW. Tier 2 simulations included 2, 3, 6, and 9 through 14, as shown in Table 7-8. Results of these simulations are provided in Appendix G.

The PTM sensitivity simulations utilized the same tidal boundary condition and run duration as the base-case simulation. Sediment loads from the lateral sources were active during the first 28 days of a simulation (June 3 through June 30, 2009), with the lateral source loads set to zero for the last 14 days of a simulation. The result is an estimate of lateral sediment loads and spatial distribution of initial sediment deposition within the EW over a 4-week period.

Table 7-8
PTM Sensitivity Simulations

Simulation	Type of Simulation	Description of Simulation	Inflow Condition	Sediment Source File (from Table 7-7)
1	Base-case	Base-case	Mean annual	S1
2	Tier 2 Sensitivity	Repeat base-case	Mean annual	S1
3	Tier 2 Sensitivity	Base-case with 0.25-kg parcel size for Class 1A/1B particles	Mean annual	S2
4	Tier 1 Sensitivity (bounding run)	Base-case with 25% TSS values	Mean annual	S7
5	Tier 1 Sensitivity (bounding run)	Base-case with 75% TSS values	Mean annual	S6
6	Tier 2 Sensitivity	Base-case with Standard Deviation set to 1	Mean annual	S3
7	Tier 1 Sensitivity (bounding run)	Base-case with smaller Class 1A/1B particle diameters	Mean annual	S4
8	Tier 1 Sensitivity (bounding run)	Base-case with larger Class 1A/1B particle diameters	Mean annual	S5
9	Tier 2 Sensitivity	Simulation 5 with 2-year flow	2-year	S6
10	Tier 2 Sensitivity	Simulation 5 with 10-year flow	10-year	S6
11	Tier 2 Sensitivity	Simulation 5 with 100-year flow	100-year	S6
12	Tier 2 Sensitivity	Base-case with Standard Deviation set to 0	Mean annual	S8
13	Tier 2 Sensitivity	Base-case with higher median flow at Lander SD	Mean annual	S9
14	Tier 2 Sensitivity	Base-case with different particle size distribution in stormwater	Mean annual	S10

In order to assist in the comparison of the results of the PTM base-case and sensitivity simulations, sediment mass accumulations within discrete areas of the EW were tallied for each simulation and then compared using the following procedure:

- Define five discrete areas within the EW that were used to compare sediment mass accumulation from the different runs. These areas each represent an area that is two hydrodynamic model grid cells wide by two hydrodynamic model grid cells long (see Figure 7-7). Each of these areas represents a different location in the EW both hydrodynamically and by the magnitude of sedimentation expected.

- Calculate total mass deposited within each of the defined areas for each PTM simulation. This was done by calculating the sum of all mass parcels that were deposited in the area at the end of the simulation.
- Normalize the mass deposited in each area for Tier 1 sensitivity simulations (4, 5, 7, and 8) by the mass deposited in the base-case simulation. Comparison of these normalized values and the mass deposited in each area for the base-case simulation are shown in Figure 7-8.
- Normalize the mass deposited in each area for Tier 1 and Tier 2 sensitivity simulations that used annual average upstream flow conditions (2 to 8 and 12 to 14) by the mass deposited in the base-case simulation. Comparison of these normalized values and the mass deposited in each area for the base-case simulation are shown in Figure 7-9.
- Normalize the mass deposited in each area for Tier 2 sensitivity simulations that used extreme upstream flow conditions and 75% TSS loading (9, 10, and 11) by the mass deposited in sensitivity simulation 5 (which used annual average flow and 75% TSS loading). This comparison provides an evaluation of the model response to increases in riverine flow (see Figure 7-10).

Based on the comparisons illustrated in Figures 7-8 and 7-10, the following observations regarding sensitivity of the PTM to model inputs and parameters are developed:

- Decreasing (increasing) the TSS concentration for lateral sources causes deposition decreases (increases) in deposition that are proportional to changes in sediment loading.
- Based on comparisons of deposition patterns and amounts between simulations 1 and 2, PTM predictions are repeatable (i.e., stochastic component of the model does not have significant effect on predictions) in areas where deposition is significant. Caution must be taken when comparing results between model runs in areas of low deposition, as a small change in the number of deposited packets will make the differences between the runs appear exaggerated.

- Based on comparisons of deposition patterns and amounts between simulations 1 and 3, increasing the number of particles (reducing the parcel size) released during a simulation does not have a significant effect on results.
- Increasing the standard deviation of the particle size distribution (which introduces increased numbers of larger, faster settling particles into the model) has similar effects as increasing Class 1A and 1B particle sizes (i.e., increased deposition). This is because an increase in the standard deviation for the larger particles causes a wider range of particle sizes to be input into the model; as a result, there is a greater number of 'larger' particles introduced into the model as standard deviation increases, and these larger particles settle out faster than smaller particles.
- Decreasing Class 1A and 1B particle sizes produces less deposition.
- No significant change in deposition occurs during the 2-year high-flow event, when compared to average-flow conditions.
- Generally, less deposition occurs during 10- and 100-year high-flow events, when compared to average-flow conditions, due to higher current velocities in the EW, which tend to transport suspended particles in the surface layer out of the EW prior to deposition. These model runs were performed to verify expected particle transport behavior and were not used for a detailed analysis of deposition in the EW.
- Simulation 13, which increased the sediment load for Lander (storm only) showed increased deposition just outside the Lander outfall (Area 4), but little change in other high-deposition areas.
- Simulation 14, which increased the percentage of fines in stormwater flow, reduced deposition at outfall locations and increased deposition in areas farther away from outfalls.

7.3.6 Deposition Patterns Due to Lateral Source Sediment Loads

The results of the sensitivity analysis were used to evaluate reasonable lower- and upper-bound simulations for the PTM. The base-case simulation represents the best estimate of model inputs and parameters. However, uncertainty exists in the model inputs and parameters. These uncertainties were taken into account through bounding run simulations, which both increase and decrease the sediment load from lateral sources and the particle size diameter for clay and silt fraction based on evaluation of lateral load data (Section 7.2).

These bounding runs are represented by the Tier 1 sensitivity simulations (Table 7-8). These reasonable lower- and upper-bound simulations correspond to the realistic range of model predictions, with the base-case results corresponding to the best estimate within that range.

The results of the base-case and bounding PTM simulations were used to provide a reasonable range of values for initial sediment mass accumulation in the EW from lateral sources (excluding resuspension due to vessel operations). The results of the base-case simulation (Figure 7-2) define a representative average mass accumulation. Minimum and maximum values of mass accumulation were estimated through the sensitivity analysis (Tier 1 sensitivity simulations) discussed in Section 7.3.4 (Table 7-8), as shown in Figure 7-8. Based on review of Figures 7-8 and 7-9, simulations 4 and 5 produce consistent low and high predictions of sediment mass accumulation and encompass the range of variation seen in other sensitivity runs. One exception is Area 4, which exhibited the highest deposition during Run 8, where particle sizes for smaller size fraction particles were increased. This resulted in higher deposition adjacent to the outfall location in Area 4. However, particle size distributions used for the base-case and Tier 1 sensitivity runs already assume a high percentage of coarser particles; which results in a conservative estimate of deposition adjacent to outfall locations. Therefore, for the purpose of evaluating the contribution of lateral sources to sedimentation in the EW, sensitivity simulations 4 and 5 were selected to represent reasonable lower- and upper-bound inputs and parameters for the PTM, respectively.

7.3.7 Uncertainty Discussion

Uncertainty in the PTM model results arises from several sources. Some inherent randomness exists within the model related to the standard deviation of the characteristic particle size and "random walk" in the particle paths. This randomness is evident in the differences between the results of simulations 1 and 2, which have identical input files but exhibit differences in final particle positions predicted by the PTM. These uncertainties are not significant in areas where there is relatively high deposition; the total amount deposited in these areas is nearly identical between simulations 1 and 2. Since the purpose of the STE is to identify areas where mass contribution from lateral sources is significant enough (relative to other potential sources) to present recontamination potential, the uncertainty in estimates within low deposition areas is not a serious concern for this application. The model does not account for the initial momentum of particles as they enter the system; this could have an influence on their final deposition location, the effect being similar to spreading the PTM discharge location along the plume trajectory. However, the scale of the hydrodynamic model (which drives the PTM model simulation) is not appropriate for resolving flow fields from individual outfalls. In addition, resuspension and redeposition of sediments by ship operations is not included in the PTM model simulations.

Additional uncertainties exist within the lateral source input data developed for the PTM including particle size distributions, stormwater and CSO flows, and TSS concentrations. These uncertainties have been integrated (to the extent practical) into the STE through the development of lower- and upper-bound simulations, which provide a range of model results based on variations in the input data. Uncertainties may also arise from the hydrodynamic model due to limitations in grid resolution (both horizontally and vertically).

As discussed, shorter-term simulations were performed to provide data that can be used to evaluate long-term conditions. This involved using a representative tidal condition and temporally-constant mean annual average riverine inflow and sediment source input rates. This information, while not representative of any particular storm event, provides average deposition rates and patterns that can be utilized to evaluate recontamination potential from lateral sources over the long term.

8 PRELIMINARY REASSESSMENT OF PHYSICAL PROCESSES CONCEPTUAL SITE MODEL

The preliminary Physical Processes CSM for the EW, which was developed prior to completion of the STE, was presented in the CSM and Data Gaps Analysis Report (Anchor, Windward and Battelle 2008). This CSM will be updated in the SRI Report based on results of the STE, as provided in this report. However, a brief summary of the STE results and a screening-level comparison of those results to the preliminary Physical Processes CSM is provided in this section. In general, the results of the STE support and validate the preliminary Physical Processes CSM for the EW.

8.1 East Waterway Hydrodynamics

Hydrodynamic modeling results confirmed the validity of the preliminary Physical Processes CSM. Modeled current velocities within the EW due to tidal and riverine currents are confirmed to be relatively low during periods of low upstream inflow. As upstream inflow increases, surface velocities within the EW increase. Surface velocities are highest in the Junction and Sill Reaches (maximum 90 cm/s), and are lower in the Main Body Reach (maximum 40 cm/s). Near-bed velocities are highest in the Main Body Reach near the mouth of the EW (maximum 18 cm/s) and lowest in the area south of Slip 27 (maximum 2 cm/s). The presence of distinct two-layer flow (inflow of higher density saline water at depth with outflow of fresher water at the surface) becomes more prevalent as upstream inflow increases. During low flow events, vertical gradients in salinity are consistent throughout the EW. During high flow events, vertical gradients in salinity are more pronounced in the Main Body Reach, where a layer of freshwater overlies high salinity water. During high flow events in the Sill and Junction Reaches, freshwater may be present throughout the water column.

Freshwater input to the EW and WW from upstream sources is split equally during periods of lower flow (i.e., less than 2-year flood). During flood events greater than the 2-year flow, the EW:WW flow split is consistently about 30% to 70% (from 2- to 100-year flood flows).

8.2 Erosion Potential

The 95th percentile confidence interval of critical bed shear stress for surface sediments in the EW ranges between 0.20 and 0.37 Pa. The maximum predicted bed shear stress for a 100-year high-flow event (0.12 Pa) is below the lower confidence bound value for critical shear stress (0.20 Pa) as estimated from the Sedflume data. Therefore, it is not anticipated that significant bed scour or erosion of in situ bed sediments will occur as a result of tidal or riverine currents.

Near-bed velocities generated by episodes of propwash are confirmed to be significantly higher than those due to tidal and riverine currents in areas of the EW that are subjected to large vessel operations (generally north of Slip 27). Consequently, bed shear stress due to vessel operations is significantly greater than bed shear stress due to natural forces for all areas experiencing vessel operations. Erosion potential due to propwash is anticipated to be more significant north of Slip 27 (compared to areas south of Slip 27) due to concentrated large container ship activity in those areas. This assumption is consistent with geochronological core data (see Section 3). Estimates of bed shear stress due to propwash range from 2 to 23 Pa within the EW based on estimates of vessel operations while navigating and berthing. Based on the propwash evaluation, surface sediments within the waterway have the potential to be eroded due to extreme vessel operations (as defined in Section 5.1.2) throughout the EW. This observation is not necessarily consistent with the results of geochronological core data (Section 3); which imply that areas south of Slip 27 (between EW Stations 4000 and 5200) are not subject to significant mixing at depth below the mudline. However, it is possible for this area to be net depositional over time (as shown by the geochronological core data) but subject to occasional suspension of surface sediments due to propwash/vessel activity in those areas. Since the propwash evaluation focused on extreme standard vessel operations, and there is vessel activity south of Slip 27, it is likely that potential erosional events are not as frequent in that area compared to areas north of Slip 27 possibly associated with smaller vessel size.

8.3 Net Sedimentation in the East Waterway

An evaluation of 17 geochronology cores suggests that portions of the EW south of Slip 27 and portions of the EW north of Station 6200 are net depositional with minimal mixing of sediments in these areas. An evaluation of the one geochronology core collected within the interior of Slip 27 suggests that portions of the slip may also be net depositional. Areas north of Slip 27 (including at the mouth of Slip 36) appear to be heavily influenced by episodic erosion events, as radiochemistry results for cores located in those areas indicate the presence of a well-mixed sediment bed. No geochronology cores were collected within the interior of Slip 36.

Although areas in the Main Body Reach south of Station 6200 and north of Station 6800 (north of the bridges), as well as the southern portion (shallower areas) within the interior of Slip 27, appear to be net depositional, grain size distribution data for those cores shows that surface sediments in those areas are significantly coarser than in the deeper areas of the Main Body Reach. This may imply that finer sediments tend to settle in the deeper areas within the EW north of Station 6800 (where the EW becomes both wider and deeper and current velocities are relatively low). In addition, bed sediments in the western side of the Main Body Reach between Station 6200 to 6800 (propwash operation Area 6) are likely impacted by propwash due to tug and barge operations in that area.

Geochronology cores were not retrieved in the Sill and Junction Reaches due to consolidated gravel surface sediments in those areas. This suggests that these areas are likely not net depositional due to relatively high tidal and riverine currents in this portion of the EW.

8.4 Contribution of Solids from Lateral Sources

Preliminary PTM model results, which predict initial sediment mass accumulation within the EW from lateral sources, imply that the solids mass contribution to the EW from lateral sources is greatest close to the outfall locations. The mass accumulation predicted by the PTM model does not account for resuspension and transport of material due to vessel operations.

The contribution of solids from lateral sources declines quickly with increasing distance from the outfall location with relatively little deposition occurring in much of the deeper areas of the Main Body Reach. Coarser sediment size fractions (sands) tend to settle quite close to outfall locations, whereas silts and clays tend to settle farther away from their source, as would be expected.

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FIGURES

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