Lower Duwamish Waterway Group

Port of Seattle / City of Seattle / King County / The Boeing Company

Lower Duwamish Waterway

SEDIMENT TRANSPORT ANALYSIS REPORT
FINAL

For submittal to

US Environmental Protection Agency
Region 10
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Acronyms

Acronym	Definition
ADCP	acoustic Doppler current profiler
CI	confidence interval
CFS	cubic feet per second
CSM	conceptual site model
EFDC	Environmental Fluid Dynamics Code
EPA	US Environmental Protection Agency
FS	feasibility study
LDW	Lower Duwamish Waterway
LDWG	Lower Duwamish Waterway Group
MHW	mean high water
MLLW	mean lower low water
MSL	mean sea level
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priority List
Pa	pascal
PCB	polychlorinated biphenyl
pCi	picocurie
QAPP	quality assurance project plan
QEA	Quantitative Environmental Analysis, LLC
RI	remedial investigation
RM	river mile
RMS	root mean square
SSC	suspended sediment concentration
STM	sediment transport modeling
TOC	total organic carbon
USACE	US Army Corps of Engineers
USCS	Unified Soil Classification System
USGS	US Geological Survey
Windward	Windward Environmental LLC

Executive Summary

ES.1 INTRODUCTION

This report presents an analysis of data collected during the Phase 2 remedial investigation (RI) for the purpose of characterizing sediment transport in the Lower Duwamish Waterway (LDW). These data, combined with historical data and information documented in the Phase I RI (Windward 2003), have been used to refine the preliminary conceptual site model (CSM), which was also presented in the Phase 1 RI. Though the Phase 1 RI yielded a basic understanding of the stability of bed sediments and sediment transport in the LDW, the CSM was considered to be preliminary because sufficient site-specific information and data were not available at that time. Based on the data available during Phase 1, the preliminary CSM postulated:

- The LDW is net depositional on a site-wide scale
- On a local scale (i.e., in some channel or bed segments), the sediment bed is either aggrading (i.e., sediment bed elevation is increasing as a result of sediment deposition) or in dynamic equilibrium (i.e., sediment bed elevation is neither increasing nor decreasing)
- Bed erosion occurs only episodically and over small spatial scales

A primary goal of this sediment transport analysis was to further assess and test the Phase 1 CSM by gathering additional site-specific data to describe sediment transport processes in the LDW. The results have been used to develop a revised sediment transport CSM that will support future remedial design activities. Through an improved understanding of LDW sediment transport processes, potential remedial alternatives can be evaluated with increased confidence. The results of this study will be used in subsequent investigations aimed specifically at assessing the effectiveness of various remedial alternatives. Specifically, additional evaluation of the erosion properties of sediments, and the erosion potential during storm events and long term events will be further evaluated in the Sediment Transport Model (STM). These analyses will then be used with other lines of evidence to evaluate remedial alternatives in the feasibility study (FS).

As described in the Phase 2 RI work plan (Windward 2004) and the sediment transport data report (Windward and QEA 2005), additional data were collected in 2004 and 2005, consistent with US Environmental Protection Agency (EPA) guidance (EPA 2005), to support development of a concise description of LDW sediment transport processes. A range of empirical analyses and modeling was conducted during this effort, with each analysis focusing on a specific component of sediment transport and bed stability in the LDW.

This report presents the synthesis of information collected during Phase 1 and Phase 2 and has four main objectives:

- Analyze additional net sedimentation data collected from bench areas during Phase 2 to supplement the Phase 1 net sedimentation data available for the navigation channel
- Analyze Phase 2 data to evaluate the importance and effects of natural (e.g., hydrodynamic) and anthropogenic (e.g., ship propeller wash and ship wake) forces on bed scour in the LDW
- Evaluate data collected during Phase 2, in conjunction with existing Phase 1 data, to refine the Phase 1 CSM
- Determine if additional field data or modeling are needed to further refine the CSM for sediment transport processes and the stability of bedded sediments in the LDW

Factors that affect the stability of sediments include both man-made features and natural forces. Particularly significant factors include the channel geomorphology and the presence of a saltwater wedge. In its present form, the LDW is an excavated navigation channel located at the downstream end of a highly modified drainage basin. The current configuration, past construction, and ongoing maintenance of the LDW have constrained and continue to limit the geomorphic processes that shape the river channel. The navigation channel is substantially deeper than the natural channel that would exist in the absence of continued dredging activities. As a result, the LDW experiences deposition and requires periodic dredging to maintain the channel for navigation. The channel will continue to be dominated by sediment deposition as long as it is maintained to be larger than the channel that would naturally form in this setting.

In addition, the LDW acts as a stratified, saltwater wedge estuary. The saltwater wedge, which has its source in Elliott Bay, oscillates upstream and downstream with the tide and river flow. During periods of low freshwater inflow and high tide, the saltwater wedge can extend as far upstream as the Foster Bridge, 8.7 miles from the southern end of Harbor Island.[1] At moderate freshwater inflows (i.e., greater than 1,000 cfs), the saltwater wedge generally does not extend upstream beyond the East Marginal Way Bridge (River Mile [RM] 6.3), regardless of the tide height. Under freshwater high-flow conditions, the saltwater wedge is estimated to extend upstream only as far as RM 3.0, with the area between RM 2.0 and RM 3.0 acting as a transitional region between saltwater (downstream) and freshwater (upstream). Overall, the presence of the saltwater wedge dampens the potential bed scour that might otherwise result from high natural flow conditions.

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[1] All river miles in this report are referenced from the southern end of Harbor Island, which is considered to be river mile 0.0.

ES.2 EVALUATION OF LDW DEPOSITIONAL ENVIRONMENT

The depositional environment of the LDW was evaluated based on sediment core samples collected as part of Phase 2 and historical data documented in the Phase 1 RI. Core samples were used to age-date sediments (i.e., geochronology cores) in order to better understand net sedimentation rates in the bench areas as compared to the rates previously estimated in the navigation channel. Other sediment core samples were collected and analyzed in Phase 2 to determine the erosion properties of LDW sediments (i.e., Sedflume measurements).

Results from both types of sediment core analyses include:

- Net sedimentation rates in the bench areas were estimated to range from 0.2 to > 2.0 cm/yr. The cores with lower estimated net sedimentation rates were generally collected from areas with shallower water depths (i.e., above +0.4 ft mean lower low water [MLLW]), suggesting that these areas may be subject to relatively low deposition.
- Evidence of potential disturbances (e.g., episodic erosion and deposition, dredging, slumping) was observed in some of the cores
- Gross erosion rate was strongly dependent on near-bed current velocity (i.e., shear stress)
- Erosion properties of LDW sediments were relatively uniform throughout the system

Analysis of the various lines of evidence yields several conclusions. The age-dating and bulk bed property profiles provide no evidence of widespread, episodic erosion. The geochronology cores suggest that the bench areas of the LDW are net depositional system-wide. However, some cores suggest possible localized effects from erosion/deposition events.

A net sedimentation rate analysis was conducted that used a range of site data, including: chemistry and stratigraphy data from subsurface sediment cores collected during 2006; geochronology cores; historical subsurface cores; grain size distribution data; dredging records, chemical spill, industrial, and regional discharge records; and bathymetric data. These data were used to estimate the spatial distribution of net sedimentation rates and develop a large-scale view of LDW net sedimentation. Two primary conclusions from this work are:

- Based on empirical data, the bench areas are net depositional on annual timescales. Net sedimentation rates are spatially variable, with the highest rates in the navigation channel (greater than 2 cm/yr), moderate in the subtidal bench areas (less than 2 cm/yr), and lowest in the intertidal bench areas (less than 0.5 cm/yr).

- The reliability of these results is relatively high based on the consistency between net sedimentation rates estimated using different approaches (i.e., physical and chemical time markers, radioisotope analysis).

ES.3 ANALYSIS OF EROSION POTENTIAL

An analysis of erosion potential was conducted using hydrodynamic modeling and ship-induced bed scour analysis. The objectives of these analyses were to: 1) analyze erosion property (i.e. Sedflume) data collected in 2004, 2) quantify the effects of hydrodynamics on the spatial distribution of bed shear stress in the LDW for various flow conditions, 3) determine areas where sediment bed scour may occur during episodic high-flow events, and 4) quantify the effects of anthropogenic forces (e.g., ship propeller wash and ship wake) on sediment bed erosion.

Results of the hydrodynamic modeling of the LDW include:

- The potential for erosion was higher in the navigation channel than in the bench areas due to higher bed shear stresses in the navigation channel
- During high-flow events (i.e., discharge greater than or equal to the 2-yr high-flow event), the potential for erosion was limited to areas of the navigation channel within the area of the waterway occupied by the saltwater wedge and throughout much of the waterway (including bench areas) upstream of the saltwater wedge
- During average-flow conditions, only a few isolated areas in the Upper Turning Basin (near RM 4.6) showed a potential for erosion
- Within the portions of the bench areas where erosion was predicted to occur, the potential for erosion tended to be highest near the navigation channel and tended to decrease toward the shoreline

The potential for gross bed scour from ship traffic along particular LDW transects was also analyzed. The goal of this analysis was to assess the potential effects of upstream and downstream movement of ships within the navigation channel on bed stability in the LDW. These bed scour results are considered to be upper-bound estimates. Actual bed erosion due to ship traffic is expected to be less than these estimates. The effects of ship-induced bed scour are incorporated into the present structure of the LDW sediment bed because ship movement has been occurring for at least the past 40 years, which is the primary period of concern related to chemical fate and transport in the LDW.

This analysis found that:

- Ship-induced bed scour tends to act like a mixing process for surficial bed sediment in the LDW. It is possible that ship-induced bed scour results in net erosion at some locations near the banks of the LDW. Within the bench areas of the LDW, the average thickness of the reworked surface layer ranges from about 1 to 2 cm downstream of RM 2.0 and less than 1 cm upstream of RM 2.0.

The average thickness of the reworked surface layer is less than 1 cm in the navigation channel.

- Higher ship-induced bed scour may occur in shallow, nearshore areas or adjacent to berthing areas as a result of ships maneuvering, accelerating, decelerating, or berthing in these areas. Evaluation of these localized conditions was beyond the scope of this analysis.

ES.4 SUMMARY AND RESULTS

The results of the Phase 2 field studies and modeling efforts have been integrated and synthesized with the historical site data (as documented during the Phase 1 RI) using multiple lines of evidence. Results of the modeling efforts indicate that the LDW can be separated into three broad reaches during high-flow conditions. Examining these three reaches separately allows for an improved understanding of sediment transport and bed stability in the LDW. The three reaches are:

- **Reach 1 -- Downstream of RM 2.0:** Reach 1 is occupied by the saltwater wedge for all flow and tidal conditions.
- **Reach 2 – RM 2.0 to RM 3.0:** Reach 2 is a transition region that contains the toe of the saltwater wedge under high-flow conditions.
- **Reach 3 – Upstream of RM 3.0:** Reach 3 has flow that is characteristic of a freshwater tidal river under high-flow conditions; under low and moderate flow conditions the saltwater wedge may be present in this reach.

ES.4.1 Refinement of preliminary conceptual site model

The primary goal of this analysis was to allow for an improved understanding of sediment transport processes in the LDW, with a focus on issues related to bed stability. The results of the empirical analyses and modeling have been used to refine the Phase 1 preliminary CSM. The revised CSM is based on the following:

- The LDW is net depositional site-wide over annual time scales, with the rate of net sediment deposition (i.e., net sedimentation rate) being spatially variable. This component of the CSM has been expanded by separating net depositional areas into three categories:
    - **Lower net depositional:** Net sedimentation rates less than 0.5 cm/yr. In small, isolated areas within this category, the net sedimentation rate is minimal (e.g., less than 0.1 cm/yr), and the bed may approach a state of dynamic equilibrium (i.e., minimal changes in bed elevation over annual time scales).
    - **Intermediate net depositional:** Net sedimentation rates ranging from 0.5 to 2.0 cm/yr.
    - **Higher net depositional:** Net sedimentation rates greater than 2.0 cm/yr.

- Net sedimentation rates are generally higher in the navigation channel than in the bench areas. For the navigation channel, the net sedimentation rate decreases when moving from the Upper Turning Basin (near RM 4.8) to downstream areas. For the bench areas, no trends in net sedimentation rate are apparent in the upstream-to-downstream direction, but net sedimentation tends to be lower in the intertidal areas than in the subtidal areas.
- Bed erosion is an episodic process that may be most pronounced during high-flow events. Episodic bed scour is predicted to occur to the greatest extent in Reach 3, is lower in Reach 2 (relative to Reach 3), and is minimal in Reach 1. The potential for erosion during high-flow events is generally greater in the navigation channel than in the bench areas. Within the portions of the bench areas where erosion is predicted to occur, erosion tends to be highest near the navigation channel and tends to decrease toward the shoreline.
- Ship-induced bed scour tends to act as a mixing process for surficial sediments. The reworked surficial layer has an upper-bound average thickness of less than about 1 cm in the navigation channel and less than about 1-2 cm in the bench areas, with the frequency of such mixing about 100 to 250 events per year.

The revised CSM detailed above has been extended to the three broad reaches of the LDW. Examining the three reaches separately allows for a more comprehensive understanding of sediment dynamics and bed stability within the LDW. Findings for each reach are discussed below. Graphical representations of the benches and navigation channel for Reaches 1, 2, and 3 under the revised CSM are presented as Figures ES-1, ES-2, and ES-3, respectively. These figures include qualitative illustrations of sediment bed dynamics, which show the approximate relative contributions of deposition, episodic erosion due to high-flow events, depth of mixing due to ship-induced scour, and net deposition. These figures also provide a qualitative means for comparing the effects of various processes on sediment dynamics and bed stability in the three identified reaches of the LDW. Quantitative estimates of net sedimentation rates were developed from data collected within the LDW. The assessment of potential bed scour during high-flow events was achieved using the hydrodynamic modeling results. However, quantitative estimates of bed scour depth cannot be derived from LDW sediment core data. These estimates were achieved through sediment transport modeling, and the details of the estimates are presented in the STM report.

Reach 1: Downstream of RM 2.0

This reach is net depositional on annual time scales in both the navigation channel and the adjacent bench areas. Based on net sedimentation rate estimates, the navigation channel is classified as intermediate and higher net depositional. The benches range from lower to higher net depositional. With respect to episodic erosion, the saltwater wedge is always present within this reach, even during a 100-yr high-flow event. The permanent presence of the saltwater wedge serves as a protective barrier for the bed within this reach. Consequently, bed shear stresses (i.e., near-bed current velocities) are dominated by tidally driven flows (relatively low for all flow conditions), which results in minimal bed scour. The potential for re-exposing chemicals that are buried at depth in the bed due to scour during high-flow events is minimal in this reach. Ship-induced mixing of the surficial bed layer potentially extends to average depths of about 1 to 2 cm in the bench areas and less than 1 cm in the navigation channel.

Reach 2: RM 2.0 to 3.0

Overall, Reach 2 is net depositional on annual time scales. The navigation channel is classified as higher net depositional. The benches range from lower to higher net depositional. The effects of high-flow events on bed scour are significantly less in this reach than in Reach 3, with less total area subject to scour and lower predicted potential scour depths during high-flow events. This reach serves as a transition reach between Reaches 1 and 3. The extent and magnitude of episodic erosion in Reach 2 is intermediate between the minimal bed scour in Reach 1 and the relatively high potential bed scour in Reach 3. The benches of Reach 2 experience lower potential bed scour during high-flow events than the navigation channel. Ship-induced mixing of the surficial bed layer potentially extends to average depths of less than 1 cm in the bench areas and less than 0.1 cm in the navigation channel.

Reach 3: Upstream of RM 3.0

Overall, this reach is net depositional on annual time scales. The relatively high net sedimentation rates in the navigation channel indicate that this area should be classified as higher net depositional. Similar to Reaches 1 and 2, the bench areas range from lower to higher net depositional. Modeling results indicate that higher episodic erosion during high-flow events may occur in Reach 3 than in the two downstream reaches. Generally, there is a relatively high potential for bed scour in a few isolated areas in the navigation channel and benches, with greater potential erosion expected to occur in the navigation channel than in the benches during high-flow events. Within the benches, the potential for erosion tends to be highest near the navigation channel and lowest in the nearshore/intertidal areas. Ship-induced mixing of the surficial bed layer potentially extends to average depths of less than 1 cm in the bench areas and less than 0.1 cm in the navigation channel.

ES.4.2 Recommendations for decision point regarding project status

The empirical and modeling analyses, and associated field studies, conducted during this investigation provide a significant amount of new information and insight into sediment transport processes in the LDW. A clearer picture of LDW sediment transport emerges from this work, particularly with respect to sediment stability. In addition, the refined CSM for sediment transport is well supported by various lines of evidence.

From a qualitative viewpoint, sediment transport processes in the LDW are more completely understood and supported by available information. However, the CSM for sediment transport requires further refinement through the application of a sediment transport model to the LDW. Development and application of this type of model will provide quantitative information on sediment transport processes (e.g., deposition and erosion) over a range of spatial and temporal scales and allow for better quantification of sediment transport effects. The data and information contained within this report provide a solid foundation for developing, calibrating, and applying a sediment transport model.

1.0 Introduction

The Lower Duwamish Waterway (LDW) was added to the US Environmental Protection Agency's (EPA's) National Priority List (NPL, also known as Superfund) on September 13, 2001. Under Superfund regulations, EPA requires that a remedial investigation and feasibility study (RI/FS) be conducted for listed sites. The first phase of the RI was completed in July 2003 (Windward 2003). Additional investigations were recommended in the Phase 1 RI and further defined in the Phase 2 RI work plan (Windward 2004) to address data gaps. This report presents an analysis of the Phase 2 RI data, previously presented in the data report (Windward and QEA 2005), regarding sediment transport characteristics of the LDW.

In the LDW, the transport and fate of particle-associated chemicals (e.g., polychlorinated biphenyls [PCBs]) are affected by a range of physical and chemical processes. With respect to physical processes, the stability of the existing sediment deposits and sediment transport processes has been shown to be of importance at other sites (e.g., Hudson River in New York, Lavaca Bay in Texas). Consequently, a credible analysis of particle-associated chemical transport and fate in the LDW cannot be accomplished without first understanding sediment transport processes (i.e., net sedimentation, erosion, bed stability).

1.1 OVERVIEW OF LDW CONFIGURATION AND HYDROLOGY

The confluence of the Black and Green Rivers forms the Duwamish River 10.5 miles upstream from the southern end of Harbor Island. The LDW consists of the downstream portion of the Duwamish River, excluding the East and West Waterways around Harbor Island, and extends from RM 0.0 at the southern tip of Harbor Island to the upstream end of the Upper Turning Basin located near RM 4.8. The LDW is tidally influenced over its entire length, with the degree of tidal influence varying depending on stream flow and on tide stage at the mouth of the LDW.

The US Army Corps of Engineers (USACE) maintains the LDW as a navigable waterway through dredging (Dexter et al. 1981). The USACE is authorized[2] to maintain and operate the Federal Navigation channel on the LDW to the Upper Turning Basin near RM 4.8.

The typical cross section of the LDW includes a deeper, maintained navigation channel at the middle of the waterway, with intermittent shallow benches along the margins of the channel. The navigation channel is maintained throughout the study area, with typical depths ranging from greater than -30 ft MLLW downstream of RM 2.0 to less than -15 ft MLLW near the Upper Turning Basin. Although bathymetric data upstream of the Upper Turning Basin are not available, typical depths at the

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[2] 71st Congress, House of Representatives, Document No. 126, 1929 and adopted in Public Law, PL 71-520

Oxbow Bridge (RM 4.8) range from -6 ft MLLW to 4 ft MLLW. Shallower bench areas exist in the nearshore, intertidal, and shallow subtidal zones outside of the navigation channel, with variable dimensions and elevations (with minimum depths of less than -3 ft MLLW). The width of the LDW is relatively uniform, ranging between about 500 and 700 ft. The navigation channel is approximately 200 ft wide.

The banks of the LDW are predominantly occupied by structures, including piers and buildings. Where they are not occupied by structures, the banks are typically armored with a combination of riprap, concrete debris, and other forms of bank stabilization. An exception to this is the area around Kellogg Island (approximately RM 0.8), which is partially formed by a remnant meander of the natural Duwamish River channel. Industrial land use dominates on the east bank in the immediate vicinity of the waterway. The west bank includes industrial, commercial, and mixed residential land uses in the vicinity of the waterway.

The LDW is a stratified saltwater wedge estuary (Stoner 1972). The circulation of water within a stratified estuary is composed of a net upstream movement of water within a bottom-layer saltwater wedge, and a net downstream movement of freshwater in the layer overriding the wedge. The saltwater wedge, which has its source in Elliott Bay, oscillates upstream and downstream with the tide and stream flow. During periods of low freshwater inflow and high-tide stage, the saltwater wedge has extended as far upstream as the Foster Bridge at RM 8.7. At freshwater inflow greater than 1,000 cfs, the saltwater wedge does not extend upstream beyond the East Marginal Way Bridge (RM 6.3), regardless of the tide height (Stoner 1967).

Saline water is entrained within the interface between the overriding layer of freshwater and the saltwater wedge. There is little or no downward movement of water from the upper layer into the saltwater wedge; studies using fluorescent dye have shown that downward mixing in the stratified estuary is negligible (Santos and Stoner 1972). Also, at any given time and location along the estuary, the salinity at a given depth is nearly the same from one side of the channel to the other (Stoner 1972).

Freshwater flow into the LDW from the Upper Duwamish and Green Rivers affects the hydrodynamic circulation in the study area. Daily-average discharge data collected at the US Geological Survey (USGS) gauging station on the Green River in Auburn are available for the period from 1961 through 2004; data at this gauging station provide the best estimate of freshwater discharge from the river into the LDW. Flow rate data prior to 1961 were not included in this analysis because construction of the Howard Hansen Dam at that time altered the hydrologic characteristics of the river. The long-term mean flow rate in the river from 1961 to 2004 is 1,340 cfs.

Because of their circulation, estuaries naturally act as sediment traps for incoming sediment. Sediment from freshwater sources is transported into the estuary at the upstream end, while sediment from coastal waters is transported into the estuary via the saltwater wedge. The spatial distribution and rate of sediment deposition in an estuary is dependent on the physical characteristics of the estuary, including configuration, tidal range, freshwater inflow, and incoming sediment loading. It is difficult to develop general statements about sedimentation in an estuary, but enhanced deposition often occurs in man-made channels that are maintained to be deeper and wider than the natural channel of the estuary. The creation of a man-made channel causes the cross-sectional area of the estuary to increase, relative to natural conditions, which results in a decrease in current velocities and an increase in deposition.

Sediment deposition within the LDW drives the need for maintenance dredging to maintain vessel passage in the navigation channel. USACE effectively uses the Upper Turning Basin as a sediment trap. This practice forces most of the deposition of sediments entering the LDW from upriver to occur within a limited zone, thereby reducing the amount and frequency of dredging necessary to maintain the navigation channel downstream of the Upper Turning Basin. The navigation channel downstream of RM 3.35 has not been subjected to maintenance dredging since 1984, and that was only for a small portion of the navigation channel near Kellogg Island. At the Upper Turning Basin, the river channel cross section sharply expands from a somewhat natural section to an engineered channel maintained to be significantly larger than its natural analog. The sharp transition and enlarged channel results in greatly reduced flow velocities, which promotes sediment deposition.

Downstream of the Upper Turning Basin, the saltwater wedge forms another hydrodynamic transition that affects sediment deposition. As freshwater encounters the toe of the saltwater wedge, it is forced to separate from the river bed and flow over the saltwater. During high-flow events that deliver sediment from upstream, the sharp velocity gradient between the freshwater lens and the saltwater wedge forces deposition of the bed load. The saltwater wedge migrates up and down the river with the tides. Its range and upstream extent are determined by the volume of freshwater delivered from upstream. The result is a migrating zone of rapid sediment deposition during high-flow events.

Erosion in an estuary may be separated into two main categories. First, tidal currents may cause a thin surficial layer of fluff to be resuspended into the water column during peak flow conditions for ebb and flood tides. Fluff refers to a surficial layer of flocculent material that is primarily composed of organic detritus, clay, and fine silt. The resuspended fluff is subsequently redeposited onto the bed during slack water conditions between ebb and flood tides. Generally, the fluff layer is relatively thin (i.e., less than 1 cm) and is not part of the consolidated sediment bed. Second, rare storm events may increase current velocities (e.g., flood on an incoming river), cause a tidal surge (e.g., hurricane), or generate wind waves. These rare storm events may increase near-bed velocities sufficiently to cause erosion of the consolidated bed. The eroded sediment may be transported to other areas in the estuary and be redeposited, or it may be transported out of the estuary and into the adjacent coastal waters. Detailed technical discussions of estuarine sediment transport are provided in Dyer (1973) and Perillo (1995).

1.2 HISTORICAL STUDIES

Sediment transport in the LDW has been studied for several decades, both across the entire LDW and at specific sites within the LDW (Table 1-1). The Phase 1 RI (Windward 2003) summarized the information from these historical sediment transport studies, some of which included modeling efforts, and included additional analyses of some of the historical data. Analyses conducted during the Phase 1 RI included temporal comparisons of bathymetric and sediment morphology data to evaluate sediment stability, a comparison of measured current velocities within the LDW to estimated critical velocities for scour from other studies outside the LDW (Striplin et al. 1985), an estimation of total suspended and bedload sediment loading from upstream sources, and a review of previous sediment transport studies.

Table 1-1. Studies related to sediment transport processes within the LDW

AUTHOR AND DATE	PORTION OF LDW	TYPE OF SEDIMENT TRANSPORT INFORMATION
Santos and Stoner (1972)	saltwater wedge extent (approximately RM 4.5)	suspended sediment load, sediment bedload
Stevens, Thompson & Runyan (1972)	navigation channel	suspended sediment load, sediment bedload, areas of deposition, sediment accumulation rates
Harper-Owes (1981)	entire LDW	suspended sediment load, relative suspended sediment inputs
Harper-Owes (1983)	entire LDW	suspended sediment load, relative suspended sediment inputs, sediment accumulation rates
Weston (1993)	south of Harbor Island to approximately RM 1.0	net sedimentation rates based on sediment traps and radioisotope dating of sediment cores
McLaren and Ren (1994)	navigation channel bottom	net sediment transport direction, areas of erosion, deposition, or dynamic equilibrium
King County (1999b)	entire LDW	sediment erosion potential; deposition rates for grid areas within the LDW calculated from sediment mass balance/hydrodynamics
Pentec et al. (2001)	RM 2.9 to 3.7 (east bank)	sediment erosion and recontamination potential
King County (2001)	RM 0.3 to 1.0 (east bank)	sediment natural recovery, erosion, and recontamination potential

LDW – Lower Duwamish Waterway
RM – river mile

Previous studies have examined net sedimentation rates and patterns in the LDW (Harper-Owes 1983; Windward 2003). Those studies focused on net sedimentation in the navigation channel (Figure 4-7 and Table 4-17 of the Phase 1 RI (Windward 2003)). Estimated net sedimentation rates in the navigation channel range from 1 to 110 cm/yr (with the higher end of that range only in the Upper Turning Basin).

However, only very limited data are available on sediment bed elevation changes in the shallower bench[3] areas of the LDW.

Prior to this study, no site-specific data were available to describe sediment bed erosion in the LDW. Estimates of LDW current velocities and bed shear stresses, which exert hydrodynamic forces on the surface of the sediment bed, were made using current velocity data and modeling during the Phase 1 RI (Windward 2003). However, the results of those analyses were not sufficient to develop a comprehensive evaluation of hydrodynamic effects on sediment bed erosion within the LDW. A preliminary analysis of anthropogenic effects (e.g., ship propeller forces) on sediment bed scour was also discussed in the Phase 1 RI. This analysis was conducted for the berthing areas of the Duwamish/Diagonal site (King County et al. 2003) and for the area offshore of Boeing Plant 2 (Pentec et al. 2001).

Other results from the Phase 1 RI that may be useful in evaluating sediment transport processes include:

- Estimate of total suspended solids loading from upstream sources (Section 4.4.2.2 of Phase 1 RI; (Windward 2003)
- Analysis of bathymetric survey data collected in various portions of the LDW during 1998, 2000, and 2001 (Section 4.4.2.5 of the Phase 1 RI; (Windward 2003)

1.3 CONCEPTUAL SITE MODEL

Sediment transport and stability information from this study and historical studies are important in the formulation of a conceptual site model (CSM) for the LDW estuarine system. A CSM is a useful tool for understanding fate and transport processes. In general, a CSM is a narrative or graphical representation of processes that influence the transport and fate of physical media (e.g., water, soil, sediment) within a study area of interest. CSMs may incorporate both spatial and temporal elements.

The Phase 1 RI summarized existing information in the LDW on sediment processes and yielded a basic understanding of the stability of bedded sediments and sediment transport in the system, which was used to develop the Phase 1 CSM. This CSM was considered to be preliminary because sufficient site-specific information and data were not available during the Phase 1 RI to confirm it. Based on the data available for that study, the Phase 1 CSM consists of three components:

- The LDW is net depositional on a site-wide scale
- On a local scale, the sediment bed is either aggrading (i.e., sediment bed elevation increasing as a result of sediment deposition) or in dynamic equilibrium (i.e., sediment bed elevation is neither increasing nor decreasing)

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[3] The sediment bench refers to the shallow subtidal (i.e., sediment elevation < -5 ft to ≧ -20 ft MLLW) or intertidal (i.e., sediment elevation ≥ -5 ft MLLW) sediment bed between the deeper navigation channel in the center of the LDW and the banks on either side of the LDW.

- Bed erosion occurs only episodically and over small spatial scales

For convenience, brief definitions of these terms are provided here:

- **Annual time scales:** Refers to time periods of one to ten years, with average or 'typical' conditions being the focus of the sediment transport processes that are examined or discussed. Temporal variability in the processes exists but conclusions or observations generally relate to long-term average conditions.
- **Depositional environment:** An area in which the sediment bed is net depositional (i.e., bed elevation increasing) over annual time scales. The bed may experience episodic erosion due to high-flow events or ship-induced bed scour.
- **Erosional environment:** An area in which the sediment bed is net erosional (i.e., bed elevation decreasing) over annual time scales. The bed may experience net deposition over time scales of less than a year.
- **Dynamic equilibrium:** The condition in which the sediment bed is neither net erosional nor net depositional, with minimal changes in bed elevation occurring over annual time scales. The bed may experience episodic erosion due to high-flow events or ship-induced bed scour, or net deposition over short time scales.
- **Episodic erosion:** Bed scour that occurs during an episodic high-flow event or due to ship movement. The occurrence of episodic erosion at a particular location does not necessarily mean that an erosional environment exists at that location; a depositional environment can experience episodic erosion. During these events current velocities are sufficiently fast to erode the bed at some locations. Generally, episodic erosion occurs over periods of hours to days.
- **Net depositional:** The condition in which a portion of the sediment bed, or a reach of the river or waterway, experiences more deposition (i.e., settling of sediment from the water column onto the bed) than erosion (i.e., scour from the bed to the water column) over periods of about one year or longer (i.e., annual time scales). The net sedimentation rate is the rate at which net deposition occurs.

Net deposition and episodic erosion can be interrelated. For example, a net depositional area may experience episodic erosion, but more sediment is deposited on the bed over one or more years than is eroded during the small number of high-flow events during that same period. The relationship between net depositional and episodic erosion is illustrated in Figure 1-1. In this example, it is assumed that the bed is net depositional, which results in a net accumulation of sediment (i.e., increase in bed elevation) over a period of years. However, bed elevation may not increase at a constant rate due to year-to-year variations in conditions in the LDW, such as changes in river inflow and sediment loading. In addition, the occurrence of a high-flow event during a particular year may cause the bed elevation to decrease due to bed scour, but additional deposition after the high-flow event will increase bed elevation. Over a period of years, net deposition occurs due to more sediment accumulation during depositional periods than removal of sediments during episodic high-flow events.

1.4 STUDY OBJECTIVES

The primary goal of this sediment transport characterization study is to test and refine the Phase 1 CSM by gathering additional site-specific data to describe sediment transport processes in the LDW. The results are used to develop a revised CSM for sediment transport processes that supports future remedial design activities. Through an improved understanding of LDW sediment transport processes, the transport and fate of chemicals bound to sediment particles and remedial alternatives that may be applicable to the system can be evaluated with increased confidence. The results of this study can be used in subsequent investigations that are aimed specifically at assessing the effectiveness of various remedial alternatives.

As described in the Phase 2 RI work plan (Windward 2004), additional data are needed to develop a concise description of the LDW sediment transport processes that affect sediment stability in the system, consistent with EPA guidance. This report presents the results of that work, which has four main objectives to address the primary goal:

- Analyze additional geochronology data collected from bench areas during Phase 2 to supplement existing Phase 1 net sedimentation data available for the navigation channel. These data are used to evaluate sediment dynamics in the bench areas of the LDW.
- Analyze Phase 2 data to describe erosion potential as a function of shear stress, sediment characteristics (i.e., grain size), and depth in the bed. This analysis supports an evaluation of the importance and effects of natural (e.g., hydrodynamic) and anthropogenic (e.g., ship propeller wash and ship wake) forces on bed scour in the LDW
- Evaluate data collected during Phase 2 on sediment dynamics, in conjunction with existing Phase 1 data and analyses, to refine the Phase 1 CSM
- Determine if additional field data or modeling are needed to refine the CSM for sediment transport in the LDW

This updated CSM will describe in general terms the degree of sediment stability resulting from the critical sediment transport processes in the LDW. Information and insights about LDW sediment transport gained from the present study will be used in subsequent investigations that are aimed at assessing the effectiveness of various remedial alternatives. Specifically, the information obtained during this sediment transport characterization study may be used in other studies to:

- Identify areas for subsequent subsurface sediment sampling and analyses

- Identify areas potentially suitable for monitored natural recovery, *in-situ* capping, confined aquatic disposal, or near-water confined disposal facilities (EPA 2002)
- Evaluate capping construction requirements (i.e., armoring)
- Evaluate chemical transport and the potential for recontamination to support source control decisions

1.5 OVERVIEW OF TECHNICAL APPROACH

The objectives discussed above are achieved using a combination of empirical data and modeling analyses. Sedimentation processes in the LDW were evaluated based on two primary types of empirical data: 1) geochronology, using radioisotope profiles; and 2) bed elevation changes, using bathymetric data collected between 2000 and 2003. These site-specific data, in conjunction with hydrologic and bed property data, were used to evaluate sediment transport processes in the LDW, with a focus on bench areas. In addition, the geochronology analysis provided an estimate of net sedimentation rates at different locations in the LDW bench areas.

Erosion potential was evaluated using a hydrodynamic model to investigate potential bed scour in the LDW for a range of high-flow events and tidal conditions. Spatial distributions of bed shear stress were predicted by the hydrodynamic model. Insights concerning potential bed scour due to high-flow events were developed from these model results. Potential effects of ship-induced bed scour were also evaluated using a screening-level analysis that produces order-of-magnitude estimates of scour depths. Site-specific erosion rate data collected using a device called Sedflume were obtained from the LDW and used in the bed scour analyses.

In summary, the following empirical and modeling analyses were used to evaluate sediment transport processes and bed stability in the LDW:

- Empirical analyses of sedimentation processes
  - Hydrology and bulk bed properties (Section 2.1)
  - Geochronology (age-dating) cores (Section 2.2)
  - Bed elevation changes (Section 2.3)
- Modeling analyses to evaluate erosion potential
  - Erosion properties of LDW sediments (Section 3.1)
  - Potential effects of high-flow events (Section 3.2)
  - Potential effects of ship-induced scour (Section 3.3)

These analyses were used to evaluate the validity of the three components of the Phase 1 CSM as follows:

- The LDW is net depositional on a site-wide scale: empirical analyses of sedimentation processes (Section 2.0).
- On a local scale, the sediment bed is either aggrading (i.e., sediment bed elevation increasing as a result of sediment deposition) or in dynamic equilibrium (i.e., sediment bed elevation is neither increasing nor decreasing): combination of empirical analyses of sedimentation processes (Section 2.0) and modeling analyses to evaluate erosion potential (Section 3.0).
- Bed erosion occurs only episodically and over small spatial scales: modeling analyses to evaluate erosion potential (Section 3.0).

1.6 REPORT ORGANIZATION

This report is organized into six main sections:

- Executive Summary
- Section 1.0: Introduction
- Section 2.0: Evaluation of LDW Depositional Environment
- Section 3.0: Analysis of Erosion Potential
- Section 4.0: Summary and Synthesis of Results
- Section 5.0: References

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

- Appendix A: Presentation and Analysis of Sedflume Data
- Appendix B: Hydrodynamic Model Calibration and Validation Results
- Appendix C: Diagnostic Results for High-Flow Event Simulations
- Appendix D: Propeller Wash and Ship Wake Bed Scour Model
- Appendix E: Supporting Analyses for Section 2.0
- Appendix F: Estimation of Net Sedimentation Rates Using Empirical Lines of Evidence for the Lower Duwamish Waterway

2.0 Evaluation of LDW Depositional Environment

The depositional environment of the LDW was evaluated using the results of a geochronology study and an evaluation of the existing bathymetric information. The geochronology study (Windward 2004; Windward and QEA 2006) provided an analysis of the age-dating of sediment cores collected from the LDW in December 2004. The objective of this analysis was to quantify net sedimentation rates in the bench areas and provide a better understanding of how net sedimentation rates in these areas compare to rates previously estimated for the navigation channel. The bathymetric analysis consisted of an evaluation of existing bathymetric information collected from portions of the LDW to provide a qualitative assessment of potential scour and deposition in the bench areas.

The results of the geochronology analysis (see Section 2.2) were used in the analysis presented in Appendix F, in conjunction with additional data and information, to evaluate sedimentation processes in the LDW. The primary objective of that analysis was to estimate net sedimentation rates in the LDW using several empirical lines-of-evidence, which included: sediment core profiles (chemical, physical, and radioisotope); historical review to age-date sediments; and LDW geomorphology, grain size distribution, and bathymetry. For convenience, conclusions from Appendix F are presented in Section 2.4.

A high-flow event frequency analysis of daily-average flow rate data collected at the Green River gauging station was conducted to support the bed scour analysis. Daily-average flow data, instead of instantaneous measurements, are used in this analysis for two reasons. First, instantaneous data are not available for the entire period of record. Second, the saltwater wedge location is more strongly affected by daily-average flow rate than instantaneous discharge, and the location of the saltwater wedge in the LDW during a high-flow event is an important component of the bed scour analysis (Section 3.2). The issue of flow variability within a high-flow event is discussed in Appendix E of the LDW STM report (QEA 2007). The maximum daily-average flow rate during each year of the 44-yr period of record (i.e., 1961 through 2004) was used as input to the high-flow event frequency analysis. A description of this analysis is provided in Appendix E.1.

The results of this analysis indicate that high-flow event discharges range from 8,400 cfs for a 2-yr high-flow event to 12,000 cfs for a 100-yr high-flow event (Figure 2-1). The relatively low range in river discharge is caused by flow control at the Howard Hansen Dam, which is located approximately 65 miles upstream of the LDW. The numbers of high-flow events with return periods ranging from 2 to 10 years and from 10 to 100 years between 1961 and 2004 are presented in Table 2-1. During this period, there were 34 high-flow events with return periods of 2 to 10 years and four higher flow events with return periods from 10 to 100 years. Note that the return periods (i.e., 2, 10 and 100 years) for high-flow events do not necessarily mean that one event is expected to occur in a certain time period. The flow frequency analysis provides estimates of flow rates for events with a specific probability of occurrence in any given year. For example, 2-yr, 10-yr, and 100-yr events have 50, 10, and 1%, respectively, probabilities of occurring in any given year.

Table 2-1. Summary of high-flow events in the Green River (1961-2004)

Calendar Year	Number of Events		Maximum Flow Rate (cfs)
	2-to-10-Yr High-Flow Event	10-to-100-Yr High-Flow Event	
1961	1	0	9,850

Calendar Year	Number of Events		Maximum Flow Rate (cfs)
	2-to-10-Yr High-Flow Event	10-to-100-Yr High-Flow Event	
1962	2	0	9.140
1964	1	0	8,600
1965	0	1	10,900
1968	1	0	8,700
1969	1	0	9,100
1972	4	0	8,780
1974	2	0	9,080
1975	1	1	11,600
1976	1	0	9,050
1977	1	0	9,750
1979	1	0	8,620
1982	2	0	10,400
1983	1	0	8,790
1984	2	0	10,500
1986	1	1	11,500
1989	1	0	8,580
1990	4	0	10,400
1991	1	0	9,990
1995	2	0	10,800
1996	0	1	11,100
1997	1	0	8,970
1998	1	0	9,090
1999	2	0	8,940
2000	0	0	3,010
2001	0	0	6,790
2002	0	0	7,020
2003	0	0	8,180
2004	0	0	7,440
Total	**34**	**4**	**11,600**

Freshwater discharge from the Green River varies over the course of a year due to seasonal changes in precipitation and runoff. Variation in the long-term monthly-average flow rate in the Green River is shown in Figure 2-2. Discharge peaks in January and tends to decline to a minimum in August, after which flow increases through December. For comparison, monthly-average discharge values during 2004 (the year in which the field work for this study was conducted) are included in this figure. This comparison shows that 2004 was a relatively typical year, with monthly-average flow following the general long-term seasonal trend. Discharge during December 2004, when the Phase 2 field studies were conducted, was lower than the long-term average flow for that month.

2.1 ANALYSIS OF BULK BED PROPERTY DATA

2.1.1 Grain size distribution and dry density data

2.1.1.1 Historical data

Sediment grain size distribution data have been collected in the surface layer sediments in several previous field studies between 1990 and 2005 (Appendix F, Figure 1) (Windward 2003, 2005a, b). These data provide information on the clay, silt, and sand content in the bed. Combining the data into 0.2-mile segments and displaying the average sediment-class content in each segment provides insight into possible spatial trends in the west bench area (Figure 2-3), navigation channel (Figure 2-4), and east bench area (Figure 2-5).

Generally, no distinct trend in the longitudinal direction is evident in the data. The data are variable in the bench areas and navigation channel, with no apparent spatial structure (e.g., downstream fining). Sediment in the navigation channel tends to have higher clay-silt content than sediment in the bench areas. Typical clay-silt content in the navigation channel ranges from about 60 to 80%. Clay-silt content is more variable in the bench areas, ranging from about 30 to 80%. Note that these ranges refer to average values (Figures 2-3 through 2-5).

2.1.1.2 Sedflume core data

As described in Section 3.1, a field study was conducted in December 2004 to obtain erosion rate data for LDW sediments. A device called a Sedflume was used to test 19 cores collected within the LDW for erodibility (Windward and QEA 2004). Core locations are shown in Figure 3-1. The Sedflume device is used to measure gross erosion rates over a range of shear stresses at various depths in a sediment core. In addition to supporting erosion rate data estimates, the Sedflume cores were segmented and analyzed for grain size distribution and wet (bulk) density. Laboratory methods used to measure grain size distribution and wet density are presented in the quality assurance project plan (QAPP) (Windward and QEA 2004) and in the data report and data report addendum for this study (Windward and QEA 2005, 2006).

The particle size distribution in the surface layer (i.e., approximately top 5 cm) of the 19 Sedflume cores is summarized in Table 2-2. Additional results for the deeper portions of the cores are presented in Appendix A. Eighteen cores were classified as sandy silt, and one core (Sf-5) was classified as silty sand (with median particle diameter [D_{50}] of 329 μm and sand content of 79%). A statistical analysis of the 18 sandy silt cores indicates that the average characteristics of these cores are: D_{50} = 30 μm, 6% clay, 69% silt, and 25% sand (Table 2-3). Cumulative frequency distributions of D_{10}, D_{50}, and D_{90} values[4] for the surface layer are shown in Figure 2-6. Generally, variability in particle size in the Sedflume cores is relatively low. For example, about 90% of the D_{50} values for individual samples vary between 10 and 50 μm (silt). In

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[4] D_{10}, D_{50}, and D_{90} are the 10th, 50th (i.e., median), and 90th percentile grain size diameters, respectively.

general, the 18 sandy silt cores had more silt and less sand than the average surface sediment sample from throughout the LDW, which had approximately 41% silt and 41% sand (Phase 2 RI (Windward 2007)). These differences reflect the design of the Sedflume sampling, which was primarily focused on bench areas with fine-grained sediment. The larger LDW-wide sediment grain size dataset will be used for the sediment transport modeling.

Table 2-2. Particle size data for surface layer of Sedflume cores

SEDIMENT CORE ID	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	CLAY CONTENT (%)	SILT CONTENT (%)	SAND CONTENT (%)
Sf-1	2	12	60	9	82	9
Sf-2	3	24	115	6	72	22
Sf-3	3	19	117	7	75	18
Sf-4	3	19	223	7	71	22
Sf-5	11	329	739	2	19	79
Sf-6-R1	3	21	122	7	73	20
Sf-6-R2	4	39	184	5	60	35
Sf-7	4	41	1,112	5	55	40
Sf-8	3	28	235	6	68	26
Sf-9	5	79	402	4	43	53
Sf-10	3	23	89	6	78	16
Sf-11	4	94	653	5	41	54
Sf-12	4	24	139	5	73	22
Sf-13	3	21	97	7	76	17
Sf-14	3	22	161	7	70	23
Sf-15	2	16	73	8	81	11
Sf-16-R1	3	20	93	7	76	17
Sf-16-R2	2	18	82	8	78	14
Sf-17	3	19	88	7	78	15

Table 2-3. Statistical analysis of particle size data for surface layer (0 to 5 cm) of 18 sandy silt cores collected during Sedflume study

STATISTICAL QUANTITY	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	CLAY CONTENT (%)	SILT CONTENT (%)	SAND CONTENT (%)
Average	3	30	225	6	69	25
Standard deviation	0.8	22	265	1.3	12	13
95% CI	2 – 4	19 – 41	93 – 357	5 – 7	63 – 75	17 – 31
Minimum	2	12	60	4	43	9
Maximum	5	94	112	9	82	54

Note: Core Sf-5 was excluded from statistical analysis because it contained sandy sediment.

CI – confidence interval

Wet densities of the 18 sandy silt cores (excluding Sf-5) ranged from about 1.2 to 1.7 g/cm^3. The single silty sand core (Sf-5) had higher wet density (1.8 to 1.9 g/cm^3). The cumulative frequency distribution of wet density in the Sedflume cores is shown in Figure 2-7. Generally, wet density increases with depth because of consolidation effects. Similar to particle size distributions, wet densities in the Sedflume cores are relatively uniform throughout the LDW.

A correlation analysis was conducted between wet density and particle size. Figure 2-8 shows the relationship between D_{50} and wet density in surface layer sediment. This analysis indicates that minimal correlation exists between these two bulk bed properties for the 18 sandy silt cores. The cores with sandy sediment (i.e., core Sf-5) had higher wet density than the sandy silt sediments.

2.1.2 Total organic carbon contents

2.1.2.1 Historical data

Total organic carbon (TOC) content in the surface sediments was analyzed during earlier studies. Spatial distributions of TOC content in the bench areas and navigation channel are shown in Figure 2-9. Although a few isolated areas with elevated TOC content are noted (e.g., western bench area near RM 0.5 and eastern bench area near RM 3.5), the data are variable, and no consistent longitudinal trend is evident. Frequency distributions of TOC content in the bench areas and navigation channel are presented in Figure 2-10. The distribution of TOC content in surface sediment is similar throughout the LDW, with a median value of about 1.8% and a range of about 0.1 to 6%.

2.1.2.2 Data from this study

TOC and total solids were analyzed in every fifth 1-cm increment within cores collected during the geochronology study (geochronology core sampling locations are presented in Figure 2-12; see Section 2.2.1 and Figures 2-13 through 2-26 for a description of core increments). Although some variability is evident, TOC contents are generally low in the geochronology cores (i.e., 1 to 3%), with the variability within a particular core typically being only a factor of 2 or 3. Total solids contents are relatively uniform, generally varying by 10 to 20% in each core.

TOC data for the surface interval (0 to 10 cm) of the geochronology cores are presented in Figure 2-11. Comparison of the TOC contents in these cores with the historical surface sediment data (Figure 2-9) indicates that TOC in the geochronology cores is within the range of variability observed in the larger historical data set. No consistent spatial trend is apparent in the total solids data.

2.2 GEOCHRONOLOGY ANALYSIS

The focus of the geochronology study was to estimate long-term net sedimentation rates in the bench areas of the LDW through the collection and analysis of sediment cores for two radioisotopes, cesium-137 (^{137}Cs) and lead-210 (^{210}Pb). The navigation channel was not a focus of this study because information useful for calculating net sedimentation rates already exists for that portion of the LDW (Harper-Owes 1981, 1983). In addition, the navigation channel has been disturbed by maintenance dredging and is therefore less amenable to this type of analysis (Windward 2003). Cesium-137 and ^{210}Pb were selected because they are commonly used to age-date sediments and establish net sedimentation rates in estuarine and freshwater systems (Olsen et al. 1978; Orson et al. 1990). The radioisotope data are presented in the sediment transport data report (Windward and QEA 2005) and the data report addendum (Windward and QEA 2006). The report and addendum do not include any data interpretation. The study design and data are summarized below, followed by an interpretation of the data.

In general, net sedimentation rates are affected by several environmental factors, including seasonal variations in river discharges, vessel traffic, biological activities, and long-term changes in land use patterns/practices. The potentially confounding effects of these factors on estimates of net sedimentation rates are minimized in this study through the collection and analysis of multiple cores from the LDW and the use of two independent tracers. In addition, the physical composition of the sediment bed, which serves as a qualitative indication of the sediment transport regime (e.g., depositional, episodic erosion) at each core location, is examined. For this analysis, vertical profiles of sediment type, as characterized using the Unified Soil Classification System (USCS), TOC, and total solids content are used to evaluate the physical composition of the sediment cores.

2.2.1 Description of field study

Sediment cores for the geochronology study were collected from the LDW during December 2004. Monthly-average discharge in the LDW during December 2004 was 1,840 cfs, which is about 12% lower than the long-term monthly-average flow of 2,100 cfs for December. The geochronology study consisted of the collection and laboratory analysis of 14 sediment cores obtained from bench areas within the LDW (Figure 2-12). Originally, each core was to be photographed and visually inspected prior to processing (Windward and QEA 2004). However, the 3-inch coring apparatus that was originally intended for the study was replaced with a 4-inch coring apparatus so that adequate sample volumes could be collected for the various laboratory analyses. Because the 4-inch coring apparatus used opaque core liners, photographs of the geochronology cores could not be taken. The 3-inch coring device used clear liners, which would have allowed the cores to be photographed. The decision to switch from the smaller to the larger coring device was made during the initial phase of the December 2004 study and obtaining a 4-inch coring device with a clear liner was not possible.

After collection, each core was segmented in 1-cm intervals and every fifth segment within the top 81 cm (i.e., 0-1 cm, 5-6 cm, etc. to 80-81 cm) was submitted for ^{137}Cs, ^{210}Pb, TOC, and total solids content analyses. Samples were also visually characterized using the USCS. Details on the rationale used for the selection of the sediment core sampling locations and sample collection techniques employed during this field effort are presented in the QAPP (Windward and QEA 2004). Sample collection information for each geochronology core is provided in Table 2-4.

Table 2-4. Sample collection information for geochronology sediment cores

LOCATION	COLLECTION DATE	TIME (PST)	ELEVATION (ft MLLW)	PENETRATION DEPTH (cm)[a]	CORE RECOVERY (cm)[b]	PERCENT RECOVERY[c]
Sg-1a	12.17.2004	1512	-17.7	165	127	77
Sg-2	12.17.2004	1424	-3.5	122	87	71
Sg-3	12.16.2004	1406	-21.4	175	136	78
Sg-4	12.16.2004	1225	-12.8	170	117	69
Sg-5a	12.17.2004	0954	-16.5	162	138	85
Sg-6	12.16.2004	1147	-17.9	205	140	68
Sg-7	12.16.2004	0802	-16.1	150	118	79
Sg-8	12.16.2004	1043	-10.3	165	133	81
Sg-9	12.16.2004	1027	+0.4	165	96	58
Sg-10	12.16.2004	0934	-11.0	132	101	78
Sg-11c	12.17.2004	1244	-1.3	116	36	31
Sg-11b	12.17.2004	1157	+0.6	83	43	52
Sg-12	12.16.2004	0854	-11.1	182	123	68
Sg-13	12.16.2004	0834	-8.3	180	130	72

[a] Penetration depth estimated in the field by measuring the distance from the top of the core catcher insert (estimated from outside the gravity corer) to the highest level sediment reached along the outside of the gravity corer.

[b] Core recovery was calculated in the field by measuring from the top of the core catcher insert (estimated from outside the gravity corer) to the top of the core tube and subtracting the distance from the top of the core tube to the sediment surface layer inside the tube.

[c] Percent recovery was calculated as core recovery/penetration depth x 100.

MLLW – mean lower low water

PST – Pacific Standard Time

Analytical results for the radioisotope and physical characterization measurements obtained during the geochronology study are presented in the sediment transport data report (Windward and QEA 2006). After the initial evaluation of the radioisotope data was completed, an additional 29 archived 1-cm samples from select cores were submitted for ^{137}Cs and/or ^{210}Pb, TOC, and total solids content analyses. Specifically, the following archived samples were analyzed:

- Core Sg-2: 18-19, 19-20, 22-23, and 23-24 cm
- Core Sg-3: 85-86, 90-91, 95-96, 100-101, and 105-106 cm
- Core Sg-6: 85-86, 90-91, 95-96, 100-101, 105-106, and 110-111 cm
- Core Sg-7: 85-86, 90-91, 95-96, and 100-101 cm

- Core Sg-10: 68-69 and 72-73 cm
- Core Sg-11b: 23-24 and 27-28 cm
- Core Sg-13: 85-86, 90-91, 95-96, 100-101, 105-106, and 110-111 cm

These archived samples were analyzed to obtain additional data to assist in the interpretation of these cores. Results are presented in an addendum to the sediment transport data report (Windward and QEA 2006).

Vertical profiles of the ^{137}Cs, ^{210}Pb, TOC, and total solids content for each core are presented in Figures 2-13 through 2-26. In these figures, data collected during the original study are presented as circles, while results for the archived samples are presented as squares.

2.2.2 Analysis of radioisotope data

Cesium-137 and ^{210}Pb profiles were analyzed to better understand net sedimentation rates within the bench areas of the LDW. The approach for and results of this evaluation are presented in the subsections below. Several physical, chemical, and biological factors affect these radioisotope profiles to various extents and, thus, introduce uncertainty into the net sedimentation rates estimated from these data. Potential factors affecting the estimated net sedimentation rates are discussed in Section 2.2.2.4. To account for these uncertainties, best estimates (where possible) and ranges of estimated net sedimentation rates are reported. Additional analyses of net sedimentation rates using other lines of evidence are presented in Appendix F.

2.2.2.1 Average net sedimentation rates via Cesium-137 analysis

The first occurrence of detectable ^{137}Cs in sediments generally marks the year 1954, 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 ^{137}Cs peak by the number of years between 1963 and the time of core collection (e.g., 41 years for a core collected in 2004). This approach was successfully used to date sediment cores in the East and West Waterways downstream of the LDW (EVS and Hart Crowser 1995).

However, uncertainty in the exact location of the true ^{137}Cs peak exists because: 1) the laboratory reports 95% confidence intervals around the best estimate of the ^{137}Cs activity for each sample (to reflect measurement uncertainty); and 2) the true ^{137}Cs peak could exist anywhere within the unanalyzed sediment segments located immediately above and below the observed ^{137}Cs 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 ^{137}Cs peak by 41 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 ^{137}Cs peak by 41 years. For example, in core Sg-1a, an observed ^{137}Cs peak of 0.43 picocuries per gram dry weight (pCi/g dw) was reported in the 40- to 41-cm segment. The two sample intervals with ^{137}Cs measurements above and below this observed ^{137}Cs value were at 35-37 cm and 45-46 cm, respectively. Therefore, lower- and upper-bound net sedimentation rates for this core were computed by dividing 37 cm (i.e., lower edge of sample interval above the observed ^{137}Cs peak) and 45 cm (i.e., upper edge of sample interval below the observed ^{137}Cs peak) by 41 years, respectively.

The cores were also examined to identify the first detectable presence of ^{137}Cs (typical detection limits were 0.1 pCi/g dw or below), which generally signifies the year 1954, to corroborate, where possible, the net sedimentation rates estimated from the locations of the ^{137}Cs peaks. For this evaluation, the net sedimentation rate for a particular core was computed by dividing the depth of sediment between the sediment surface and the first detectable presence of ^{137}Cs (found deeper in the core) by the number of years between 1954 and the time of core collection (e.g., 50 years for a core collected in 2004). Similar to the ^{137}Cs peak analysis, upper- and lower-bound estimates of net sedimentation rate were computed using the upper edge of the first detectable presence of ^{137}Cs and the lower edge of the analyzed segment above the segment containing the first detectable presence of ^{137}Cs, respectively, to account for uncertainties associated with the exact location within the sediment column where ^{137}Cs actually exists.

Net sedimentation rates for each core, as estimated using these two approaches, are presented in Table 2-5. The estimated rates include ranges that represent the uncertainty in data analyses. Nine of the 14 sediment cores collected from the bench areas of the LDW contained distinct ^{137}Cs peaks at depth (Figures 2-13 through 2-26). Cesium-137 activities in cores Sg-3, Sg-4, Sg-5a, Sg-7, and Sg-10 peaked between 60 and 80 cm below the sediment-water interface, while ^{137}Cs activities in cores Sg-3 and Sg-13 peak between 100 and 105 cm. Cesium-137 activities in cores Sg-1a and Sg-9 were much shallower, peaking at depths of about 40 and 15 cm, respectively. Below these peaks, which typically ranged from 0.3 to 0.5 pCi/g dw, ^{137}Cs activities generally declined and, in some cases, are nearly undetectable. Peak ^{137}Cs activities in the LDW cores were lower than those in sediments from Puget Sound (Lefkovitz et al. 1997), presumably due to compositional differences (e.g., mineralogy, TOC content) between the sediments in the two systems. Overall, cores with interpretable ^{137}Cs profiles indicated long-term average deposition rates of 0.9 to 2.7 centimeters per year (cm/yr) in the LDW subtidal bench areas. Lower net sedimentation rate estimates (0.3 to 0.9 cm/yr) were generally collected from areas with shallower water depths (i.e., above +0.4 ft MLLW) relative to the other geochronology cores.

Table 2-5. Estimated net sedimentation rates based on ^{137}Cs data

SEDIMENT CORE ID	ELEVATION (ft MLLW)	ESTIMATED NET SEDIMENTATION RATES (cm/yr)	
		VIA ^{137}CS PEAK	VIA FIRST PRESENCE OF DETECTABLE ^{137}CS
Sg-1a	-17.7	0.9 – 1.1	1.2 – 1.3
Sg-2	-3.5	---[a]	0.5 – 0.6
Sg-3	-21.4	1.9 – 2.1	---[b]
Sg-4	-12.8	1.6 – 2.0	---[b]
Sg-5a	-16.5	1.4 – 1.6	---[b]
Sg-6	-17.9	2.5 – 2.7	---[b]
Sg-7	-16.1	1.9 – 2.1	---[b]
Sg-8	-10.3	---[a]	---[c]
Sg-9	+0.4	0.3 – 0.5	0.8 – 0.9
Sg-10	-11.0	1.6 – 1.8	---[b]
Sg-11c	-1.3	---[a]	---[c]
Sg-11b	+0.6	---[a]	0.6 – 0.7
Sg-12	-11.1	> 2.0[d]	---[b]
Sg-13	-8.3	2.3 – 2.6	---[b]

[a] No peak observed.

[b] No detectable marker of 1954 observed, but likely located below 81 cm.

[c] No detectable marker of 1954 observed.

[d] No peak observed, but likely located below 81 cm.

ID – identification

MLLW – mean lower low water

The first presence of detectable ^{137}Cs (signifying 1954) was observed in only four of the 14 sediment cores collected from the bench areas of the LDW: Sg-1a, Sg-2, Sg-9, and Sg-11b. Of these four cores, two contained a distinct ^{137}Cs peak, allowing for a direct comparison of estimated net sedimentation rates from both methods. In Sg-1a, both methodologies yielded similar estimates of net sedimentation rates (1.2 to 1.3 cm/yr versus 0.9 to 1.1 cm/yr). In Sg-9, net sedimentation rates determined using the first detectable presence of ^{137}Cs were about a factor of 2 higher than those determined from the ^{137}Cs peak. In cores Sg-2 and Sg-11b, the first presence of detectable ^{137}Cs yielded net sedimentation rates of about 0.5 to 0.6 and 0.6 to 0.7 cm/yr, respectively. The absence of ^{137}Cs peaks in these two cores suggests that these sediments have been subject to erosion or some other disturbance that resulted in the loss of deeper, older sediments (containing higher ^{137}Cs activities). This technique could not be applied to the remaining 10 cores either due to un-interpretable ^{137}Cs profiles (Sg-8 and Sg-11c) or to the fact that the 1954 ^{137}Cs marker may be located below the depth of analyzed sediments (Sg-3, Sg-4, Sg-5a, Sg-6, Sg-7, Sg-10, Sg-12, and Sg-13).

Although a ^{137}Cs peak was not evident in core Sg-12 (adjacent to the Upper Turning Basin dredged area), ^{137}Cs activities in this core were relatively constant with depth (0.1 to 0.2 pCi/g dw) at activities similar to those in the post-1970 sections of sediment cores with distinct ^{137}Cs peaks, suggesting that only post-1970 sediments were collected. If this is the case, the net sedimentation rate in this area is greater than 2 cm/yr. The collection of only post-1970 sediments in these cores could also indicate that the area where this core was collected was disturbed (e.g., directly during dredging or by post-dredging slumping of sediments in this area).

2.2.2.2 Average net sedimentation rates via lead-210 analysis

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

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

$$^{210}Pb_u = {}^{210}Pb_T - {}^{210}Pb_s \qquad \text{(Equation 2-1)}$$

where $^{210}Pb_T$ is the total ^{210}Pb activity reported by the laboratory in the sediment samples, and $^{210}Pb_s$ is the supported ^{210}Pb activity derived from natural decay in sediments. Unsupported $^{210}Pb_u$ activities are computed by subtracting the average supported $^{210}Pb_s$ activity from the total $^{210}Pb_T$ activities throughout the sediment column, as per Equation 2-1. The unsupported $^{210}Pb_u$ activities are transformed to natural log space (i.e., ln [$^{210}Pb_u$]) and plotted as a function of core depth. A linear regression of ln($^{210}Pb_u$) versus core depth is performed, and the slope of this line (m) is used to estimate the average net sedimentation rate (^{Pb}R with units of cm/yr):

$$^{Pb}R = -\, 0.0311/m \qquad \text{(Equation 2-2)}$$

This approach, however, requires knowledge of the supported ($^{210}Pb_s$) activity in the sediments, which is not available for this study. Therefore, to account for this uncertainty in the supported ($^{210}Pb_s$) activity, an analysis was performed to determine the best estimate of the net sedimentation rate for each core based on varying assumptions regarding unsupported $^{210}Pb_u$ activities in the LDW sediments. This analysis was performed independently for each of the cores with interpretable $^{210}Pb_T$ profiles (see Appendix E).

This approach yields best estimates of the average net sedimentation rates for each core in consideration of the uncertainty associated with the actual supported $^{210}Pb_s$ activities in the sediments. However, these best estimates are subject to other sources of uncertainty (see Section 2.2.2.4). 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 (as determined in Step 4, described in Appendix E) and Equations 2-3 and 2-4, respectively:

$$^{Pb}R_{lcl} = -\ 0.0311/(m-m_{cl}) \qquad \text{(Equation 2-3)}$$

$$^{Pb}R_{ucl} = -\ 0.0311/(m+m_{cl}) \qquad \text{(Equation 2-4)}$$

where m_{cl} is the 95% confidence interval (CI) 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 $^{210}Pb_T$ profiles are presented in Table 2-6.

Table 2-6. Estimated net sedimentation rates based on ^{210}Pb data

SEDIMENT CORE ID	ELEVATION (ft MLLW)	R^2 VALUE FOR BEST-FIT LINE	ESTIMATED NET SEDIMENTATION RATES (cm/yr)	
			BEST ESTIMATE	RANGE
Sg-1a	-17.7	0.22	---[a]	---[a]
Sg-2	-3.5	0.97	0.5	0.4 – 1.1
Sg-3	-21.4	---[b]	---[b]	---[b]
Sg-4	-12.8	---[b]	---[b]	---[b]
Sg-5a	-16.5	0.52	1.3	0.7 – 9.3
Sg-6	-17.9	0.28	---[a]	---[a]
Sg-7	-16.1	0.84	0.7	0.5 – 1.1
Sg-8	-10.3	---[b]	---[b]	---[b]
Sg-9	+0.4	0.32	---[a]	---[a]
Sg-10	-11.0	0.92	0.3	0.2 – 1.0
Sg-11c	-1.3	---[b]	---[b]	---[b]
Sg-11b	+0.6	---[b]	---[b]	---[b]
Sg-12	-11.1	---[b]	---[b]	---[b]
Sg-13	-8.3	0.19	---[a]	---[a]

[a] Net sedimentation rate not estimated due to low correlation (i.e., $R^2 < 0.50$).

[b] Core contained un-interpretable ^{210}Pb profile.

ID – identification

MLLW – mean lower low water

The R^2 values for the best-fit lines determined during the ^{210}Pb analysis range from 0.19 to 0.97, with low correlations or un-interpretable ^{210}Pb profiles dominating the data set. Only four of fourteen cores produced correlations in the ^{210}Pb 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. Some of the uncertainties discussed in this section with respect to ^{210}Pb analysis may 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 average net sedimentation rates for the four cores with R^2 values greater than 0.50 ranged from 0.3 to 1.3 cm/yr (Table 2-6).

2.2.2.3 Comparison of net sedimentation rates from cesium-137 and lead-210 analyses

Net sedimentation rates estimated from the ^{137}Cs and ^{210}Pb analyses are compared in Table 2-7. Direct comparisons of the two methodologies are possible for four cores: Sg-2, Sg-5a, Sg-7, and Sg-10. At two of the four locations (Sg-2 and Sg-5a), the ^{137}Cs net sedimentation rate fell within the range of the ^{210}Pb net sedimentation rate. In the other two cores (Sg-7 and Sg-10), net sedimentation rates determined from the ^{210}Pb measurements were lower than those estimated using the ^{137}Cs data. Generally, net sedimentation rates were greater than 1 cm/yr in the subtidal bench areas and less than 1 cm/yr in the intertidal areas. Thus, net sedimentation rates in the subtidal bench and intertidal areas are lower than those previously estimated for the LDW navigation channel (i.e., 1 to 15 cm/yr between RM 0 and RM 1.7, 10 to 25 cm/yr between RM 1.7 and RM 3.4, and 20 to 110 cm/yr between RM 3.4 and RM 4.7) (Windward 2003).

Table 2-7. Comparison of net sedimentation rates from ^{137}Cs and ^{210}Pb analyses

Sediment Core ID	Elevation (ft MLLW)	Range of Estimated Net Sedimentation Rates from ^{137}Cs Analysis (cm/yr)		Range of Estimated Net Sedimentation Rates from ^{210}Pb Analysis (cm/yr)
		Via ^{137}Cs Peak	Via First Presence of Detectable ^{137}Cs	
Sg-1a	-17.7	0.9 – 1.1	1.2 – 1.3	---[a]
Sg-2	-3.5	---[a]	0.5 – 0.6	0.4 – 1.1
Sg-3	-21.4	1.9 – 2.1	---[b]	---[a]
Sg-4	-12.8	1.6 – 2.0	---[b]	---[a]
Sg-5a[c]	-16.5	1.4 – 1.6	---[b]	0.7 – 9.3
Sg-6	-17.9	2.5 – 2.7	---[b]	---[a]
Sg-7[c]	-16.1	1.9 – 2.1	---[b]	0.5 – 1.1
Sg-8	-10.3	---[a]	---[a]	---[a]
Sg-9	+0.4	0.3 – 0.5	0.8 – 0.9	---[a]
Sg-10	-11.0	1.6 – 1.8	---[b]	0.2 – 1.0
Sg-11c	-1.3	---[a]	---[a]	---[a]
Sg-11b	+0.6	---[a]	0.6 – 0.7	---[a]
Sg-12	-11.1	> 2.0	---[b]	---[a]
Sg-13	-8.3	2.3 – 2.6	---[b]	---[a]

[a] Rate not estimated.

[b] No detectable marker of 1954 observed, but likely located below 81 cm.

[c] These cores were located relatively close to areas subject to maintenance dredging in the 1990s. Consequently, the uncertainty around estimated net sedimentation rates for these cores is greater than the uncertainty around estimated net sedimentation rates for cores not located near historical dredged areas.

2.2.2.4 Sources of uncertainty in radioisotope analyses

Several physical, chemical and biological factors introduce uncertainty into the net sedimentation rates estimated from the radioisotope profiles. Some of these factors include: 1) natural variability in the radioisotope measurements, 2) variations in sediment characteristics, 3) depths to which benthic invertebrates burrow into the LDW sediments (e.g., mixing), 4) physical disturbances of the sediments (e.g., erosion, dredging), 5) compression and/or mixing of sediments during core collection/extrusion, and 6) poor sediment recovery rates in core samples. Some of these sources of uncertainty are documented by the National Oceanic and Atmospheric Administration (NOAA) and Battelle in a ^{210}Pb study that was conducted in Puget Sound (Lavelle et al. 1985). The first four factors are likely the greatest contributors to uncertainty in net sedimentation rates estimated during this study, primarily due to uncertainty in the extent and magnitude that these processes occur in the LDW.

Core collection and processing are not believed to be significant contributors to uncertainty in the estimated net sedimentation rates. Core compression and/or mixing of sediments during core collection/extrusion can result in the smearing of ^{137}Cs and ^{210}Pb activity gradients throughout the sediment column. However, the field crew that conducted this study indicated that significant compression and/or mixing of the sediments was not observed during the geochronology study. If core compression did occur to any significant extent, then actual net sedimentation rates would be greater than those presented in this report. Sediment recovery rates (i.e., depth of sediments recovered divided by the depth of sediments penetrated, multiplied by 100) for most cores ranged between 52 and 85%. One exception was core Sg-11b, where only 31% of the sediments penetrated were recovered. However, greater sediment recovery rates would not change the interpretation of most geochronology cores because: 1) analysis of the ^{210}Pb data focused solely on sediments located in the upper portions of the sediment column; and 2) ^{137}Cs peaks were observed in many of the cores.

2.2.3 Implications for sediment transport

Examination of radionuclide activities in geochronology core samples provides a means for estimating long-term average net sedimentation rates in the LDW. Most cores collected from the bench areas of the LDW exhibited relatively uniform, interpretable ^{137}Cs profiles with depth, suggesting that, overall, these areas are net depositional on annual or decadal time scales. However, vertical profiles of physical and chemical properties in the sediments also provide a means of identifying evidence of episodic disturbances (e.g., erosion and deposition from natural and/or anthropogenic activities, dredging, slumping). For some of the LDW cores, the presence of non-detectable activities of ^{137}Cs and variations in the vertical distribution of ^{137}Cs activities, ^{210}Pb activities, TOC and/or total solids content indicate that episodic disturbances may be occurring on a local scale.

Physical and chemical properties in the sediments were investigated further in an attempt to interpret the sediment dynamics at each core location. A core-by-core discussion is provided in Appendix E.4. In some instances, the cause of the disturbance is hypothesized based on the general location where the core was collected, correlations between physical and chemical measurements from the core, information about historic activities within the LDW, and the results of other analyses conducted as part of this study. However, it is possible that alternative interpretations could be developed that may more accurately explain the cause of the episodic disturbances observed in these cores.

2.3 BATHYMETRIC ANALYSIS

Numerous bathymetric surveys have been conducted within the LDW by the USACE during the past 40 years. More recent USACE bathymetric surveys have been conducted in the upper portion of the LDW, primarily between Slip 4 (RM 2.8) and the Upper Turning Basin (approximately RM 4.7) (Windward 2003). These single-beam bathymetry surveys were conducted along transect lines perpendicular to the navigation channel, spaced approximately 200 feet apart, and were limited to the navigation channel and areas immediately adjacent to the navigation channel. These surveys provide little information in the bench areas outside of the navigation channel. To supplement the data gathered by the USACE and to provide bathymetric information in the bench areas, The Boeing Company conducted a bank-to-bank single-beam bathymetric survey in the vicinity of the Boeing Plant 2 site (between RM 2.9 and 3.5) during 2000. Also, a high-resolution multi-beam bathymetric survey was conducted by David Evans and Associates on behalf of the Lower Duwamish Waterway Group (LDWG) in 2003. This survey provided detailed bathymetric information for the entire LDW between the Upper Turning Basin and Harbor Island (Windward and DEA 2004).

Comparisons of many of these surveys were presented in the Phase 1 RI (Windward 2003). However, the comparisons were primarily limited to the navigation channel because of data limitations. Therefore, bathymetric data from the USACE and Boeing surveys conducted during 2000 and the 2003 multi-beam bathymetric study, which included the bench areas adjacent to the navigation channel, were compared to provide an assessment of potential erosion and deposition in the bench areas. This comparison was limited to the portion of the LDW immediately upstream of Slip 4 (about RM 2.6) to approximately the upstream end of the Upper Turning Basin (RM 4.8); this portion of the LDW is unique because data were collected from the bench areas during both 2000 and 2003.

Baseline sediment surface elevations in 2000 were defined using a combination of bathymetric measurements from both the USACE and Boeing surveys. Sediment surface elevations in 2003 were defined using the acoustic multi-beam bathymetric data. Because of the higher density of measurements in 2003 (relative to 2000), each 2000 measurement was paired with the nearest 2003 measurement and a change in sediment elevation at each paired location was computed. Linear interpolation was performed between measurement locations to estimate areas of scour and deposition. This approach is identical to the approach used to investigate areas that experienced scour and deposition during the ice jam that occurred in the lower Grasse River (New York) in spring 2003 (Alcoa 2004).

In the bathymetric analysis performed for the lower Grasse River, sediment elevation changes in excess of 6 in. (15 cm) were considered measurable. This measurable change criterion was selected based on the fact that the Grasse River data were collected and processed by the same contractor and that the single-beam sediment elevation measurements used to define baseline conditions were collected at relatively closely-spaced intervals (i.e., transects were spaced approximately 50 feet apart). For the LDW, several positioning and measurement inaccuracies associated with the LDW surveys have been noted (Windward 2003). Specifically, potential errors resulting from positioning inaccuracies have the most significant effect on the steep sloped areas of the LDW or at the outermost limits of the surveyed transects. These inaccuracies are further compounded by the fact that the three surveys were performed by different contractors, using different equipment and different methods. Finally, sediment elevation measurements from the USACE and Boeing surveys in 2000, which were used to define baseline conditions in the LDW, were collected along transects spaced at approximately 200-foot intervals. Although an accurate estimate of the measurement uncertainty associated with the bathymetric comparisons for the LDW is not known, it is believed that, for the reasons stated above, a measurable change criterion of about 12 in. (30 cm) or more is appropriate.

Results of this comparison are presented graphically in Figures 2-27 and 2-28. Note that bathymetric comparisons were not performed for the portion of the navigation channel between the Upper Turning Basin and Slip 6 (green shading in Figure 2-28) because approximately 96,500 cy of sediment was removed from this reach during maintenance dredging that the USACE conducted in 2002 (USACE 2003).

The comparisons show that sediment elevation changes in excess of 12 in. were observed in less than 20% of this portion of the LDW (i.e., RM 2.6 to 4.7) between 2000 and 2003. Between RM 2.6 and 4.0, areas of scour and deposition (in excess of 12 in.) were generally located along the edges of the navigation channel or at the outermost limits of the transects surveyed in 2000 (Figure 2-27). In the uppermost portion of the LDW (i.e., RM 4.0 to 4.7), an area of deposition is noted in the navigation channel in the vicinity of Slip 6, while areas with estimated scour were primarily located in the bench areas along the edge of the navigation channel (Figure 2-28). Because the areas of scour and deposition (in excess of 12 in. [30 cm]) were primarily located along the edges of the navigation channel or at the outermost limits of the transects surveyed in 2000, it is unclear whether these areas: 1) truly experienced scour/deposition, 2) were affected by other factors (e.g., sloughing of the bench areas after dredging, dredging outside of the targeted navigation channel area), 3) were subject to greater measurement error as described above, particularly positioning error across a transect because most of the estimated scour is along the west bench and most of the estimated deposition is along the east bench adjacent to the navigation channel, or 4) were influenced by some combination of these factors. For this reason, reliable conclusions regarding areas of sediment bed deposition and erosion in the LDW were not developed from this analysis. An additional factor that contributed to the inability to derive reliable conclusions is the relatively short period between the 2000 and 2003 bathymetric surveys; a longer time period between surveys may be required to develop more reliable results.

2.4 SUMMARY

A sediment geochronology analysis and an evaluation of existing bathymetric information were performed to provide a better understanding of the sedimentation and erosion processes of the bench areas within the LDW. The physical and chemical properties of the high-resolution geochronology cores were examined to: 1) estimate long-term average net sedimentation rates in the LDW and 2) identify evidence of episodic erosion and deposition events. The bathymetric information was evaluated to identify areas of the LDW, if any, that may have experienced recent short-term changes in bathymetry. Ultimately, this combined information was used to refine the CSM for sediment transport in the LDW.

Analyses of ^{137}Cs and ^{210}Pb profiles in the cores for which net sedimentation rates can be reliably estimated indicated that net sedimentation rates at those locations on the benches range from 0.2 to > 2.0 cm/yr. These net sedimentation rates are lower than rates estimated for the LDW navigation channel (Windward 2003). No consistent spatial trend was apparent in the estimated net sedimentation rates calculated from radioisotope age-dating methods, likely because the data were too sparse to develop spatial relationships. By expanding the geochronology analysis to include chemical and physical markers, thereby providing greater spatial coverage, spatial trends emerged (see Appendix F). Stations were grouped into areas based on similar net sedimentation rates, water depth, grain size, and location along the LDW. The geochronology cores with lower estimated net sedimentation rates were generally collected from areas with shallower water depths (i.e., above +0.4 ft MLLW) relative to other cores.

Evidence of potential episodic erosion and deposition was noted in some of the geochronology cores. The coincidence of medium sand and non-detectable levels of ^{137}Cs was observed in the surface sediments of three geochronology cores. The coarser material was only observed in the surface sediments and was absent from the deeper sediments in these cores, suggesting that these areas may have been subject to a recent erosion/deposition event. In addition, some cores exhibited variations in ^{137}Cs activities with depth that are consistent with an episodic disturbance in these areas. These episodic erosion/deposition events could be the result of several phenomena (e.g., dredging activities, slumping of nearby sediments, high-flow events, ship-induced bed scour), although the exact nature of these events is not known. Overall, the radioisotope and bulk bed property profiles provided no evidence of widespread, episodic erosion and deposition.

An independent verification of net sedimentation rates estimated from the geochronology cores discussed above is presented in Appendix F, which uses several empirical lines-of-evidence (chemical, physical, and radioisotope) from the LDW. The available site data used in that analysis includes: chemistry and stratigraphy data from 56 subsurface sediment cores collected during 2006; historical subsurface cores; grain size distribution data; dredging records; chemical spill, industrial, and regional discharge records; and bathymetric data. These data provided a set of time markers that are apparent at different depths in the sediment bed at various locations in the LDW. After assigning a date or time period for a particular marker and then establishing the presence of the marker at a specific depth, the net sedimentation rate was estimated. This estimate represents the average rate of net deposition for the time period between the time marker and core collection. Two primary conclusions from the analyses presented in Appendix F are:

- Based on empirical data, the bench areas are net depositional on annual timescales. Net sedimentation rates are spatially variable, with the highest rates in the navigation channel (greater than 2 cm/yr), moderate in the subtidal bench areas (less than 2 cm/yr), and lowest in the intertidal bench areas (less than 0.5 cm/yr).
- The reliability of these results is relatively high based on the consistency between net sedimentation rates estimated using different approaches (i.e., physical and chemical time markers, geochronology analysis).

Because of the consistency between the different approaches, the net sedimentation rates determined from the time marker and geochronology analyses were combined to develop a large-scale view of LDW net sedimentation. A primary result of the analysis presented in Appendix F is a map showing the spatial distribution of estimated net sedimentation rates in the LDW within specific “sedimentation areas” (see Figure 5 in Appendix F). That map delineates sedimentation areas with the LDW using five categories of net sedimentation rate: less than 0.5 cm/yr; 0.5 to 1.0 cm/yr; 1.0 to 1.5 cm/yr; 1.5 to 2.0 cm/yr; and greater than 2 cm/yr. Even though spatial variability on local scales exists within the areas shown in Figure 5, the results of the analysis presented in Appendix F provide a consistent picture of large-scale net sedimentation processes in the LDW. Use of different lines-of-evidence in Appendix F reduces uncertainty in and increases the reliability of the results of that analysis.

Evaluation of bathymetric information collected from the upstream portion of the LDW in 2000 and 2003 indicated that measurement inaccuracies and other confounding factors reduce the value of bathymetric information in development of conclusions regarding sediment transport in the LDW. For example, areas of scour and deposition in excess of 12 in. (30 cm) were noted in these comparisons, but most of these areas are located along the edge of the navigation channel (which has been routinely dredged) or at the outermost limits of the survey data. These areas are subject to measurement errors in excess of the acceptability criterion applicable to these data (i.e., 12 in. [30 cm]).

3.0 Analysis of Erosion Potential

Refinement of the Phase 1 CSM, as discussed in Section 1.0, requires evaluation of the potential effects of natural and anthropogenic forces on bed stability in the LDW. Evaluating the potential for sediment bed scour within the LDW requires information on: 1) erosion properties of the sediment bed and 2) natural and anthropogenic hydrodynamic forces exerted on the sediment bed. A field study was conducted to obtain erosion property data within the LDW. Sediment bed scour resulting from both natural and anthropogenic causes was investigated to assess whether sediment bed erosion occurs episodically and, if so, over which areas of the navigation channel and benches. In addition to the field study, an analysis of natural erosion events was performed, which focused on bed stability during 2-, 10- and 100-yr high-flow events. These events were selected to evaluate bed stability during episodic high-flow conditions in the LDW. The 2-, 10-, and 100-yr high-flow events correspond to flows of 8,400, 10,800, and 12,000 cfs, respectively, whereas average flows are estimated to be only 1,350 cfs.

This section describes: 1) collection and analysis of data on the potential for sediment bed erosion, 2) quantification of the effects of hydrodynamics on the spatial distribution of bed shear stress in the LDW for various flow conditions, 3) determination of areas of potential sediment bed scour during episodic high-flow events, and 4) quantification of the effects of anthropogenic forces (e.g., ship propeller scour and wake) on sediment bed erosion.

3.1 SITE-SPECIFIC EROSION PROPERTIES

3.1.1 Description of field and laboratory study

A study was conducted to obtain data on the erosion properties of LDW sediments. Nineteen cores were collected in December 2004 from 17 locations in the LDW (Figure 3-1). Fourteen cores were obtained from bench areas, and five cores were collected in the navigation channel. Many of the cores collected from the bench areas for erosion property analysis were located relatively close to the geochronology cores discussed in Section 2.2. Duplicate cores were collected at two locations, one each in the bench area and navigation channel. Details concerning the core collection are described in the QAPP (Windward and QEA 2004) and in the sediment transport data report (Windward and QEA 2005).

Erosion rates as a function of depth in the bed and shear stress were measured in the laboratory over the top 30 cm of each core using Sedflume (Windward and QEA 2004).

Sediment samples were also obtained at 5-cm intervals from each core and analyzed for particle size distribution and dry density.

3.1.2 Analysis of erosion rate data

Erosion of a sediment bed depends on a number of factors, including, but not limited to: shear stress, grain size distribution, dry (bulk) density, TOC content, and gas content (Jepsen et al. 1997; Roberts et al. 1998). A simple illustration of the erosion process is presented in Figure 3-2. The rate at which sediment is removed from the consolidated sediment bed and transported to a thin near-bed layer that exists between the consolidated sediment bed and the water column is termed the gross erosion rate (E_{gross}). Some of the eroded sediment in the near-bed layer is re-deposited to the consolidated bed; the rate of re-deposition is referred to as the gross deposition rate (D_{gross}). The remainder of the eroded material in the near-bed layer is transported to the water column; this rate is referred to as the net erosion rate (E_{net}).

Erosion rate data obtained from Sedflume testing were analyzed to develop an understanding of the erosion properties of LDW sediments. The goal of this analysis was to develop a functional relationship between E_{gross} and other parameters that affect erosion rate. Two parameters that affect E_{gross} are shear stress (τ) and bulk density (ρ) (Jepsen et al. 1997). An evaluation of Sedflume data indicated that minimal correlation exists system-wide between bulk density and erosion rate for LDW sediment. Thus, it is assumed in this study that erosion rate is dependent on shear stress (Jones 2000):

$$\begin{aligned} E_{gross} &= A\,\tau^{n} && \text{for } \tau > \tau_{cr} \\ &= 0 && \text{for } \tau \le \tau_{cr} \end{aligned} \qquad \text{(Equation 3-1)}$$

where E_{gross} is gross erosion rate (cm/s), τ is shear stress (Pa), and τ_{cr} is critical shear stress (Pa), which is the shear stress at which a small, but measurable, rate of erosion occurs. The erosion parameters, A and n, are site-specific and may be spatially variable, both horizontally and vertically.

The site-specific parameters, A and n, are determined using the erosion rate data collected during the Sedflume field study. One (Sf-5) of the 19 cores collected in December 2004 contained sandy sediment and was excluded from this analysis. The erosion rate properties of the remaining 18 cores, which consisted of cohesive sediment, were analyzed using the following procedure. Each core was divided into 5-cm thick layers (i.e., 0-5, 5-10, 10-15, 15-20, 20-25 cm depth intervals). These depth intervals were chosen because the shear stress series used in the Sedflume tests, where shear stress was increased from low to high values, were cycled over approximately 5-cm thick layers. The erosion rate data within each layer of a particular core were analyzed through application of a log-linear regression analysis between erosion rate and shear stress. The log-linear regression analysis produced values of A and n (see Equation 3-1) for each 5-cm layer in a particular core. The results of this analysis for the Sedflume cores with cohesive sediment are presented in Appendix A.

While the results of the individual core analysis provide useful information, these data can also be used to develop an understanding of the spatial variability (i.e., horizontal and vertical) of the erosion rate parameters in Equation 3-1 (i.e., A, n and τ_{cr}). An examination of graphical displays of the Sedflume data analyses for the individual cores (see Figures A-1 through A-18 in Appendix A) indicates that the erosion rate relationship (i.e., Equation 3-1) is similar between various cores within a specific 5-cm depth layer. This similarity suggests that the cores may be separated into different groups for a given depth layer. The log-linear regression lines for all of the cores within a specific 5-cm layer were compared, and cores were grouped according to similarities in erosion properties. The resulting groups of cores are presented in Table 3-1. Outliers are noted in the 10-15, 15-20, 20-25 cm layers, which refer to cores for which erosion rate relationships differ from the rest of the groups within a specific depth layer.

Table 3-1. Sedflume core groups

DEPTH LAYER (CM)	GROUP NUMBER	SEDFLUME CORES IN GROUP	NUMBER OF CORES IN GROUP
0-5	1-A	Sf-2, 7, 8, 9, 10, 11, 13, 15	8
0-5	1-B	Sf-3, 4, 6-R1, 6-R2, 14, 16-R1, 16-R2, 17	8
0-5	1-C	Sf-1, 12	2
5-10	2-A	Sf-6-R1, 6-R2, 8, 10, 11, 12, 15, 16-R1, 16-R2	9
5-10	2-B	Sf-2, 4, 7, 14	4
5-10	2-C	Sf-3, 17	2
5-10	2-D	Sf-1, 9, 13	3
10-15	3-A	Sf-2, 6-R1, 6-R2, 13, 16-R1, 16-R2	6
10-15	3-B	Sf-3, 8, 10, 11, 14, 17	6
10-15	3-C	Sf-7, 12, 15	3
10-15	Outlier	Sf-1	1
15-20	4-A	Sf-4, 6-R1, 8, 10, 13, 14, 16-R2	7
15-20	4-B	Sf-2, 6-R2, 7, 11	4
15-20	4-C	Sf-3, 12, 17	3
15-20	Outlier	Sf-9	1
20-25	5-A	Sf-2, 4, 6-R1, 6-R2, 7, 17	6
20-25	5-B	Sf-1, 8, 10, 11, 13	5
20-25	5-C	Sf-14, 16-R1, 16-R2	3
20-25	Outlier	Sf-3, 9, 12, 15	4

Results of the graphical grouping of cores for the five depth layers are presented in Figures 3-3 through 3-7. These results demonstrate and confirm that, generally, significant similarity exists in the erosion properties of cores within a specific group. Thus, the log-linear regression results for the individual cores within a group may be combined to determine average erosion parameter values for that group. The average exponent (n) value for a group is simply the arithmetic average of the n values for the cores within the group. The average proportionality constant (A_{ave}) is determined by calculating the log-average value:

$$\log(A_{ave}) = (1/K) \sum \log(A_k) \qquad \text{(Equation 3-2)}$$

where K is the total number of cores in the group. The average A and n values for each group are listed in Table 3-2. Note that the A and n values correspond to erosion rate (E_{gross}) in cm/s and shear stress (τ) in Pa.

Table 3-2. Average erosion rate parameters for Sedflume core groups

DEPTH LAYER (CM)	GROUP NUMBER	AVERAGE A ($x\ 10^{-4}$)	AVERAGE N	CRITICAL SHEAR STRESS (PA)
0-5	1-A	14	1.5	0.16
0-5	1-B	37	2.5	0.24
0-5	1-C	4.9	3.4	0.63
5-10	2-A	5.1	2.8	0.56
5-10	2-B	4.1	2.0	0.49
5-10	2-C	24	2.9	0.34
5-10	2-D	0.22	3.3	1.6
10-15	3-A	0.35	3.2	1.4
10-15	3-B	12	2.3	0.35
10-15	3-C	2.5	4.0	0.79
15-20	4-A	0.42	2.8	1.4
15-20	4-B	2.6	2.4	0.67
15-20	4-C	8.6	3.1	0.49
20-25	5-A	0.49	3.3	1.3
20-25	5-B	0.047	3.6	2.4
20-25	5-C	0.53	2.5	1.3

The critical shear stress (τ_{cr}), defined as the shear stress at which a small but measurable rate of erosion is observed, is estimated from Sedflume erosion rate data. For Sedflume studies performed at other sites (Jones 2000; McNeil et al. 1996; Jepsen et al. 2001), the critical erosion rate was set at 10^{-4} cm/s, a value that consistently corresponds to initiation of erosion. Thus, a critical erosion rate of 10^{-4} cm/s is used in this study. The critical shear stress is calculated rearranging Equation 3-1:

$$\tau_{cr} = (E_{gross}/A)^{1/n} \qquad \text{(Equation 3-3)}$$

where E_{gross} is equal to 10^{-4} cm/s. Critical shear stress values for each core group are listed in Table 3-2. The vertical distribution of τ_{cr} values for all of the core groups is shown in Figure 3-8. Generally, critical shear stress increases with increasing depth in sediment bed, which is expected as a result of bed consolidation.

The group-average A, n and τ_{cr} values that were determined from this analysis will be useful for developing horizontal and vertical spatial distributions of these parameters for input to a sediment transport model of the LDW. Developing these spatial distributions is not necessary for the analyses described in this report, but those distributions may be generated during the development of a sediment transport model.

3.1.3 Implications for sediment transport

The primary use of Sedflume data is to estimate erosion properties of sediments throughout the LDW. These data provide information on measured erosion rates as a function of shear stress and depth in the sediment bed at specific locations. While these data are useful for quantifying erosion rates and the parameters used to calculate erosion rate in a sediment transport model, using the Sedflume erosion rate to develop inferences about sediment transport processes at a particular location is difficult and has limitations. The limited ability to develop these types of inferences from erosion rate data is due to limited knowledge about the correlation between erosion rates, or gradients in erosion rates, and present and past sediment transport processes (e.g., erosion and deposition) at a particular location. In contrast, a large knowledge base exists for developing inferences about sediment transport processes from stratigraphy or geomorphology data. Thus, it may be possible to develop inferences, or insights, about sediment transport processes from the bulk bed property data (i.e., wet density, grain size distribution) that were obtained from the Sedflume cores. This type of evaluation, which is similar to analysis of the geochronology cores in Appendix E.4, is presented in Appendix A.3.

3.1.4 Summary

Analysis of the Sedflume erosion rate data yields the following observations:

- High correlation exists between gross erosion rate and shear stress (i.e., gross erosion rate is strongly dependent on the shear stress)
- Minimal correlation could be developed between Sedflume measured erosion rates and bulk density
- Significant similarity in the erosion properties of various cores within 5-cm depth layers was observed, allowing for the creation of groups of cores with similar properties. Average erosion parameter and critical shear stress values can be determined for each core group. The results of this analysis are useful for developing spatial distributions of erosion rate parameters for use in a sediment transport model.

3.2 POTENTIAL EFFECTS OF NATURAL EVENTS

Different time scales need to be considered when evaluating the potential effects of natural events (e.g., episodic high-flow events) on bed stability in the LDW. High-flow events in this estuary are episodic in nature, with typical event durations having time scales of hours to days. These episodic events may cause bed scour or deposition to occur at specific locations in the LDW, with erosion or deposition occurring over a relatively short time scale (i.e., a portion of the event). While it is possible that a particular high-flow event may cause measurable effects on bed elevation (i.e., either net deposition or erosion) at some locations, the long-term effects of this event on the depositional or erosional environment at those locations may be relatively minor. Thus, observed (or predicted) effects during high-flow events should not be assumed to be indicative of the depositional/erosional environment over annual time scales.

Sediment transport during an episodic high-flow event in the LDW is affected by a range of processes, including: hydrodynamic circulation patterns; spatial and temporal variations in bed shear stress; deposition; erosion, including bed armoring and consolidation effects; and sediment loads from upstream sources (magnitude and composition). These processes are the primary determinants of the effects of a high-flow event on bed stability and sediment transport in the LDW. Thus, a quantitative evaluation of sediment transport during a high-flow event requires application of hydrodynamic and sediment transport models that incorporate all of the processes discussed above.

3.2.1 Overview of technical approach

The potential effects of an episodic high-flow event on bed stability in the LDW were evaluated through use of a hydrodynamic model. This approach is not as comprehensive as application of a sediment transport model, but it does provide useful insights about LDW bed stability. In addition, results of the hydrodynamic modeling analysis are used as lines of evidence when evaluating various CSM hypotheses.

The hydrodynamic model was used to simulate circulation in the LDW for a range of high-flow events (e.g., events with return periods of 2, 10, and 100 years) and tidal conditions. Results of the hydrodynamic simulations were used to develop inferences and hypotheses about bed scour in the LDW during high-flow events. Two analyses were used to develop hypotheses about: 1) areas where bed shear stress exceeds the critical shear stress and 2) spatial distribution of excess shear stress. Explanations of each analysis are provided below.

The first approach uses the critical shear stress criterion (i.e., $\tau > \tau_{cr}$) to determine locations where bed shear stress is large enough to cause an initial erosion rate of 10^{-4} cm/s. Use of this criterion to make inferences about potential bed scour at a particular location is difficult because erosion of a cohesive bed is a complex process. Measurable bed scour may not occur simply because $\tau > \tau_{cr}$, where measurable scour corresponds to scour depths of about 0.1 to 1 cm. The cohesive nature of LDW sediments, coupled with the non-linear relationship between erosion rate and shear stress, makes it possible to use the critical shear stress criterion only as an indicator that the initial gross erosion rate is greater than 10^{-4} cm/s. The amount of potential bed scour cannot be determined through application of this criterion. Thus, the objective of performing hydrodynamic simulations is to identify areas of potential bed scour. Based on analysis of Sedflume erosion rate data, τ_{cr} values of core groups 1-A, 1-B, and 1-C for surface layer (0-5 cm depth) sediment are 0.16, 0.24, and 0.64 Pa, respectively. Core groups 1-A and 1-B represent 89% of the Sedflume samples, indicating that a critical shear stress range of 0.16 to 0.24 Pa is applicable to a large portion of surface sediments in the LDW. As a first-approximation, which produces conservative results, a critical shear stress value of 0.16 Pa is assumed for surface-layer (0-5 cm) sediment in the shear stress analyses discussed in this report.

The second analysis examines the spatial distribution of excess shear stress (i.e., $\tau_{ex} = \tau - \tau_{cr}$) in the LDW during high-flow events. This analysis provides more information about potential bed scour than the critical shear stress analysis because relative differences in excess shear stress between different locations are an indication of relative differences in potential bed scour. Generally, erosion depth is expected to increase as excess shear stress increases. However, similar to the critical shear stress criterion, scour depths cannot be determined through evaluation of excess shear stress. Thus, the main objective of this analysis is to identify areas of relatively low and high bed scour.

This approach provides two lines of evidence that are used to evaluate potential bed scour in the LDW. By examining the results of each analysis, a consistent picture of the effects of natural events on bed scour may be developed. The critical shear stress analysis provides estimates of areas where bed scour may occur. The excess shear stress analysis yields a refined view of potential erosion areas through delineation of areas of relatively low and high potential bed scour.

Erosion rate is dependent on the bed shear stress, which is calculated using the 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 due to skin friction (τ_{sf}) and form drag (τ_{fd}):

$$\tau_{tot} = \tau_{sf} + \tau_{fd} \qquad \text{(Equation 3-4)}$$

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 in the LDW, skin friction is the appropriate component of the bed shear stress for use in Equation 3-1 and, also, for use in the critical and excess shear stress analyses described above. This approach is consistent with accepted sediment transport theory (Parker 2004).

Skin friction shear stress is calculated using the quadratic stress law:

$$\tau_{sf} = \rho_w C_f u^2 \qquad \text{(Equation 3-5)}$$

where ρ_w is the density of water, C_f is the bottom friction coefficient, and u is the near-bed current velocity (i.e., predicted velocity in the bottom layer of the numerical grid). The bottom friction coefficient is determined using Parker (2004):

$$C_f = \kappa^2 \ln^{-2}(11\ z_{ref}\ / k_s) \qquad \text{(Equation 3-6)}$$

where z_{ref} is a reference height above the sediment bed (e.g., thickness of bottom layer of numerical grid), k_s is the effective bed roughness, and κ is von Karman's constant (0.4). The effective bed roughness is assumed to be proportional to the D_{90} (i.e., 90th percentile particle diameter) of the surface sediment layer:

$$k_s = \alpha\ D_{90} \qquad \text{(Equation 3-7)}$$

where the proportionality constant (α) typically ranges between 2 and 3 (Parker 2004; Wright and Parker 2004). For this analysis, α is set at a value of two.

Grain size distribution data collected from the LDW were used to specify D_{90} values for use in Equation 3-7. Spatial distributions of D values within the east bench, navigation channel, and west bench areas are shown in Figure 3-9. While longitudinal variability in D_{90} exists, that refinement is not necessary for this analysis. However, longitudinal variability in D_{90} may be accounted for during development of a sediment transport model. Lateral variations in D_{90} exist, with average values in the east bench, navigation channel, and west bench areas being 740, 270, and 750 μm, respectively. These values of D_{90} were used to calculate skin friction shear stress in the analyses discussed below.

3.2.2 Description of hydrodynamic model

A three-dimensional hydrodynamic model of the LDW and Elliott Bay was developed during a water quality study of Elliott Bay, the East and West Waterways, and the LDW (King County 1999b). This model was created using the Environmental Fluid Dynamics Code (EFDC). Calibration and validation results indicate that the model (referred to as the King County model) simulates hydrodynamic processes in the LDW and Elliott Bay with reasonable accuracy. However, relatively low grid resolution was used in the LDW, with three grid cells typically being used to represent lateral variations in bathymetry. Thus, the King County version of the model may not simulate hydrodynamics in the LDW with sufficient spatial resolution for analyzing sediment bed scour during episodic high-flow events.

Dr. Earl Hayter (EPA) modified the King County model by adapting the grid structure and resolution specifically for the LDW (Arega and Hayter 2004). The refined numerical grid developed by Arega and Hayter, which is used in this study, increased grid resolution in both the lateral and longitudinal directions, with seven lateral grid cells at most locations in the LDW and lateral grid resolution ranging from 20 to 150 m (Figure 3-10). A total of 1,995 horizontal grid cells were used, with 10 layers in the vertical direction. Bathymetric data collected during 2003 (Windward and DEA 2004) were used to specify bathymetric inputs for the model.

The basic structure of the original hydrodynamic model developed by King County was not altered for this application. However, evaluations were conducted to ensure that the modified model predictions were consistent with the King County modeling results. This process involved re-calibration of the modified model, which was achieved by adjusting the amplitude of the tidal components for the open boundary in Elliott Bay. In addition, a model validation exercise was conducted. Results of the model calibration and validation efforts are presented in Appendix B. In summary, model calibration and validation results indicated that the modified model used in this study was consistent with the King County model and the two models had similar levels of accuracy and reliability. Note that the wetting-drying option in EFDC was activated for these simulations to account for the wetting and drying of shallow areas resulting from variable tidal and flow conditions. Use of this option made it possible to simulate flow in the intertidal areas of the LDW.

3.2.3 Boundary conditions

The hydrodynamic model requires three types of boundary conditions: 1) water surface (tidal) elevation and salinity along the open boundary in Elliott Bay, 2) surface wind velocity and direction, and 3) freshwater inflow from the Upper Duwamish River at the upstream boundary. At the Elliott Bay boundary, the tidal forcing consists of six tidal harmonic constituents (i.e., M2, S2, N2, K1, O1, P1), as discussed in (King County 1999a) and in Appendix B. Salinity of the incoming water from Elliott Bay was held constant at 31 ppt at this boundary. Wind forcing was assumed to be spatially uniform and was based on NOAA observations at the Seattle Pier 52 ferry terminal (Arega and Hayter 2004).

3.2.4 Evaluation of erosion potential during high-flow events

Potential effects of high-flow events on bed stability in the LDW were evaluated using the methods described in Section 3.2.1. The potential effects of three high-flow events were investigated: 1) 2-yr high-flow event (8,400 cfs), 2) 10-yr high-flow event (10,800 cfs), and 3) 100-yr high-flow event (12,000 cfs). The 10-yr peak discharge is forecast to last 3.5 days, and the 100-yr peak discharge is forecast to last 8 days (USACE 1989). The forecast 100-year peak discharge duration of 8 days corresponds to the period of time during which the discharge is expected to remain between 11,000 and 12,200 cfs. Discharges would remain above average flow conditions (1,350 cfs) for longer than 8 days (Eriksen 2007). In addition, circulation during average-flow conditions was simulated; average-flow results were compared to predictions for high-flow events. The results of the 100-yr high flow event during spring tide conditions are presented below. This combination of river flow and tidal conditions produces the maximum skin friction shear stresses in the LDW for all of the simulations conducted during this analysis. For convenience, results of the other high-flow and average-flow simulations are presented in Appendix C. Note that in the discussions presented below, and in Appendix C, the term “bed shear stress” refers to skin friction shear stress.

Simulation of an actual high-flow event, and sediment transport during the event, requires specification of a time-variable hydrograph for the freshwater inflow. However, specifying time-variable inflow was not needed for this analysis because sediment transport was not being simulated; the focus was on the spatial distributions of bed shear stress for the specified high-flow condition. Thus, the freshwater inflow from the Upper Duwamish River was held constant at a specific flow rate (e.g., 10,800 cfs for a 10-yr high-flow event) for the entire simulation period of 14 days. This assumption is appropriate for the analyses considered during this study because it provides estimates of maximum shear stresses during various tidal periods. The effects of time-variable inflow on sediment transport during a high-flow event needs to be considered during the application of a sediment transport model.

As mentioned above, temporal variations resulting from tidal effects were incorporated into the high-flow event simulations. Tidal amplitude in the LDW varies over an approximately 14-day period, which corresponds to the spring-neap tidal cycle. As Figure 3-11 shows, significant changes in tidal amplitude exist between the spring and neap tidal cycles. The effects of these differences in tidal forcing on LDW hydrodynamics were investigated by analyzing time-variable bed shear stress over a 48-hr period during peak spring and neap tidal periods (Figure 3-11).

The effects of time-variable tidal conditions on bed erosion are difficult to diagnose simply through the application of a hydrodynamic model (i.e., critical and excess shear stress analyses). The proper metric for time-variable bed shear stress is unclear for tidal peaks that last only a few hours. For the shear stress analyses, two snapshots of bed shear stress were used: 1) maximum value during ebb tide for the 48-hr period; and 2) maximum value during flood tide for the 48-hr period. Use of these two metrics provided qualitative insight into the level of variability associated with the shear stress analyses over tidal cycles.

3.2.4.1 General features of LDW hydrodynamics and circulation

Prior to presenting the results of high-flow simulations, it is useful to discuss the general effects of episodic high-flow events on circulation patterns in the LDW. The LDW is a saltwater wedge estuary and its hydrography has been studied by various investigators (Santos and Stoner 1972; Harper-Owes 1981). For convenience, brief descriptions of circulation patterns within the estuary during average-flow and high-flow conditions are presented.

During average-flow conditions, the toe of the saltwater wedge extends upstream to approximately the southern end of the Upper Turning Basin (about RM 4.8). The predicted circulation pattern and salinity distribution for average-flow conditions (i.e., river inflow of 1,340 cfs) in a vertical plane along the longitudinal axis of the LDW are shown in Figures 3-12a and 3-12b. During this period, the toe of the saltwater wedge extends from approximately RM 4.3 at the end of an ebb tide cycle (Figure 3-12a) to about RM 5.5 at the end of a flood tide cycle (Figure 3-12b). For average-flow conditions, density-driven, two-layer flow is evident within that portion of the LDW occupied by the saltwater wedge, with denser, saline water moving upstream as a saltwater wedge in the bottom layer and less dense, fresher water moving downstream in the surface layer. Relatively strong vertical salinity gradients exist in the LDW, with differences between surface and bottom salinities typically ranging between about 20 and 30 ppt. Generally, near-bed current velocities are relatively low under average-flow conditions.

As freshwater inflow increases during a high-flow event, the toe of the saltwater wedge moves downstream of the Upper Turning Basin, with the translation distance increasing as freshwater discharge increases. This effect is shown in Figures 3-13a and 3-13b, which present the predicted circulation pattern and salinity distribution for a 100-yr high-flow event discharge (i.e., river inflow of 1,340 cfs). During this period, the toe of the saltwater wedge extends from approximately RM 1.8 at the end of an ebb tide cycle (Figure 3-13a) to about RM 3.1 at the end of a flood tide cycle (Figure 3-13b). For this flow condition, single-layer flow exists in the freshwater region upstream of the saltwater wedge; density-driven circulation does not occur upstream of the saltwater wedge toe. In this region, the LDW behaves like a tidal-freshwater river. Circulation patterns in the saltwater wedge region of the LDW are similar during high-flow and more typical conditions, with the primary difference between the two conditions being the upstream extent of the saltwater wedge. During a high-flow event, the thickness of the fresher surface layer increases, which causes bottom-layer velocities to increase in comparison to average-flow conditions.

As discussed in the following subsections, the location of the saltwater wedge not only affects circulation in the LDW, but its location also has an effect on bed shear stress distributions and bed scour during high-flow events. Results from hydrodynamic simulations of various high-flow events were used to estimate the location of the upstream extent of the saltwater wedge, which is affected by LDW tidal conditions. Variation in the location of the upstream extent of the saltwater wedge (i.e., location of the toe of the saltwater wedge) for 2-, 10-, and 100-yr high-flow events is presented in Table 3-3, with the range in location due to tidal effects.

Table 3-3. Location of saltwater wedge toe during various high-flow events

HIGH-FLOW EVENT RETURN PERIOD (yrs)	RANGE OF LOCATION OF SALTWATER WEDGE TOE DURING EBB TIDE	RANGE OF LOCATION OF SALTWATER WEDGE TOE DURING FLOOD TIDE
2	RM 2.1 – 2.7	RM 3.6 – 3.8
10	RM 1.9 – 2.3	RM 3.1 – 3.3
100	RM 1.8 – 2.2	RM 3.0 – 3.1

These results suggest that the LDW may be broadly separated into three hydrodynamic reaches during high-flow conditions: 1) Reach 1 is downstream of RM 2.0 and is occupied by the saltwater wedge during all flow and tidal conditions, 2) Reach 2 extends from RM 2.0 to 3.0 and includes the saltwater wedge toe, and 3) Reach 3 is upstream of RM 3.0, with flow in portions of this reach corresponding to a freshwater tidal river. The boundaries between the three reaches are uncertain, with the boundary between Reaches 1 and 2 ranging between RM 1.8 and 2.2, and the

Reach 2-3 boundary located approximately between RM 3.0 and 3.1. However, establishing the boundaries between the reaches at RM 2.0 and 3.0 provides an effective method for delineating the LDW when discussing the potential effects of high-flow events on bed scour.

3.2.4.2 Bed shear stress distributions during high-flow events

The spatial distribution of bed shear stress (i.e., skin friction shear stress, τ_{sf}) during high-flow conditions is the primary focus of this analysis. Diagnostic analyses of hydrodynamic model results were conducted to gain an understanding of those spatial distributions. These analyses were focused on the area between RM 0.0 and RM 4.8, which encompasses the LDW between Harbor Island and the upstream extent of the Upper Turning Basin.

A summary of the important findings from the diagnostic evaluations is presented here. First, bed shear stress tends to be higher in the navigation channel than in the bench areas. Second, bed shear stress did not increase significantly in LDW areas occupied by the saltwater wedge during a high-flow event. Generally, bed shear stresses are about an order of magnitude, or more, higher in the tidal-freshwater reach than in the saltwater wedge reach during a high-flow event. Third, high-flow events occurring during the spring tidal cycle generate higher bed shear stresses in the tidal-freshwater reach than high-flow events during the neap tidal cycle.

Results of simulations for the 100-yr high-flow event during spring tide conditions are presented below. Appendix C contains results for the following flow conditions: average flow, neap and spring tide; 2-yr high-flow, neap and spring; 10-yr high-flow, neap and spring; and 100-yr high-flow, neap and spring.

3.2.4.3 Critical shear stress analysis

Areas at which the critical shear stress was exceeded (i.e., initial erosion rate of 10^{-4} cm/s or greater) for a range of high-flow and tidal conditions were estimated by comparing predicted bed shear stress distributions to surface-layer τ_{cr}, which is assumed to be 0.16 Pa for this analysis. Predicted areas of τ_{cr} exceedance, using the maximum shear stresses during the ebb and flood tide portions of the 48-hr evaluation period as a metric, for a 100-yr high-flow event during spring tide are shown in Figures 3-14 and 3-15.

Generally, these results indicate that in Reach 1, τ_{cr} exceedance conditions occur between RM 1.8 to 2.0 and in relatively small areas downstream of RM 1.8. Upstream of the saltwater wedge toe (i.e., Reaches 2 and 3), the critical shear stress is exceeded throughout the entire navigation channel. In the bench areas of Reaches 2 and 3, τ_{cr} exceedance conditions occur in areas nearer the navigation channel, with portions of the bench areas nearer the shore being non-erosional. For the reach upstream of the saltwater wedge during high-flow events, the following general observations are suggested by these results: 1) areas where the critical shear stress is exceeded are larger during spring tide than during neap tide and 2) minor differences exist between ebb and flood tide conditions with respect to τ_{cr} exceedance.

3.2.4.4 Excess shear stress analysis

Excess shear stress (τ_{ex}) represents the difference between bed shear stress and critical shear stress (i.e., $\tau_{ex} = \tau - \tau_{cr}$ for τ greater than τ_{cr} and $\tau_{ex} = 0$ for τ less then or equal to τ_{cr}). When excess shear stress is equal to zero, then negligible bed scour occurs. This quantity provides a measure of the potential for bed scour, with erosion rate increasing as excess shear stress increases. Analyzing the spatial distributions of τ_{ex} aids in refining the critical shear stress analysis, discussed above, by identifying areas of low and high excess shear stress. This information is used to develop inferences concerning potential bed scour in various reaches of the LDW; areas of relatively low bed scour can be differentiated from areas of relatively high bed scour.

Predicted spatial distributions of excess shear stress for a 100-yr high-flow event during spring tide are shown in Figures 3-16 and 3-17, using the maximum shear stresses during the ebb and flood tide portions of the 48-hr evaluation period as a metric. In Reach 1 (i.e., within the saltwater wedge), the excess shear stress analysis shows that τ_{ex} values of 0.4 Pa or less occur between RM 1.8 and 2.0. Downstream of RM 1.8, τ_{ex} values of 0.2 Pa or less occur in the relatively small areas of critical shear stress exceedance. Upstream of the saltwater wedge (i.e., Reaches 2 and 3), the simulation results indicate the following: 1) minor differences exist in the general spatial distributions of τ_{ex} during ebb and flood tides, and 2) higher τ_{ex} values occur in the navigation channel than in the bench areas.

Cumulative frequency distributions of excess shear stress in Reaches 1, 2, and 3 for a 100-yr high-flow event during spring tide conditions are shown in Figures 3-18 through 3-21. These results show that relatively low τ_{ex} values exist in Reach 1, which is the location of the saltwater wedge. The highest excess shear stresses occur in Reach 3, which corresponds to the freshwater tidal portion of the LDW during a high-flow event. Generally, τ_{ex} values are higher in the navigation channel than in the bench areas. However, about 3% of the bench area grid cells experience τ_{ex} values greater than the maximum τ_{ex} value in the navigation channel (i.e., approximately 1.4 Pa). A summary of median and maximum τ_{ex} values for the 100-yr high-flow event during spring tide conditions is presented in Table 3-4.

Table 3-4. Median excess shear stress values for 100-yr event during spring tide

REACH	TIDAL CONDITION	MEDIAN EXCESS SHEAR STRESS: BENCH AREAS (Pa)	MEDIAN EXCESS SHEAR STRESS: NAVIGATION CHANNEL (Pa)	MAXIMUM EXCESS SHEAR STRESS: BENCH AREAS (Pa)	MAXIMUM EXCESS SHEAR STRESS: NAVIGATION CHANNEL (Pa)
1	Ebb	< 0.1	< 0.1	0.18	0.24
1	Flood	< 0.1	< 0.1	0.10	0.20
2	Ebb	< 0.1	0.30	1.1	1.1
2	Flood	< 0.1	0.30	1.1	1.1

REACH	TIDAL CONDITION	MEDIAN EXCESS SHEAR STRESS: BENCH AREAS (Pa)	MEDIAN EXCESS SHEAR STRESS: NAVIGATION CHANNEL (Pa)	MAXIMUM EXCESS SHEAR STRESS: BENCH AREAS (Pa)	MAXIMUM EXCESS SHEAR STRESS: NAVIGATION CHANNEL (Pa)
3	Ebb	< 0.1	0.75	2.7	1.4
3	Flood	< 0.1	0.75	2.9	1.4

Pa – pascal

3.2.4.5 Conditions at geochronology-Sedflume core locations

The simulation results for excess shear stress were used to evaluate conditions at the locations of the geochronology and Sedflume cores. An understanding of these conditions may provide insights about the sediment transport regime at the core locations.

The basic approach of this analysis was to search for correlations, or qualitative patterns, between core structure/properties and the transport conditions at the location of the core. For this analysis, transport conditions were represented by excess shear stress during spring tide conditions for 2-, 10-, and 100-yr high-flow events. Each geochronology and Sedflume core was located within a grid cell of the model and the results queried from model output. Excess shear stresses at each core location are listed in Tables 3-5 and 3-6. For comparative purposes, the Sedflume cores located in the navigation channel (i.e., Sf-14 through Sf-17) were excluded from this analysis. This analysis is focused on cores located in the bench areas.

Table 3-5. Excess shear stress at geochronology core locations (spring tide)

SEDIMENT CORE ID	RIVER MILE	EXCESS SHEAR STRESS		
		2-YR HIGH-FLOW EVENT (Pa)	10-YR HIGH-FLOW EVENT (Pa)	100-YR HIGH-FLOW EVENT (Pa)
Sg-1a	0.23	0.00	0.00	0.00
Sg-2	0.66	0.00	0.00	0.00
Sg-3	1.17	0.00	0.00	0.00
Sg-4	1.43	0.00	0.00	0.00
Sg-5a	1.91	0.00	0.09	0.12
Sg-6	2.31	0.12	0.24	0.30
Sg-7	2.72	0.33	0.58	0.72
Sg-8	3.55	0.14	0.28	0.36
Sg-9	3.59	0.07	0.17	0.22
Sg-10	3.64	0.09	0.19	0.25
Sg-11c	3.81	0.00	0.00	0.00
Sg-11b	3.93	0.00	0.00	0.01
Sg-12	4.31	0.25	0.44	0.54
Sg-13	4.44	0.21	0.39	0.47

ID – identification
Pa – pascal

Table 3-6. Excess shear stress at Sedflume core locations (spring tide)

SEDIMENT CORE ID	RIVER MILE	EXCESS SHEAR STRESS		
		2-YR HIGH-FLOW EVENT (Pa)	10-YR HIGH-FLOW EVENT (Pa)	100-YR HIGH-FLOW EVENT (Pa)
Sf-1	0.45	0.00	0.00	0.00
Sf-2	0.66	0.00	0.00	0.00
Sf-3	1.17	0.00	0.00	0.00
Sf-4	1.43	0.00	0.00	0.00
Sf-5	1.98	0.00	0.01	0.03
Sf-6-R1	2.31	0.12	0.24	0.30
Sf-6-R2	2.31	0.12	0.24	0.30
Sf-7	2.72	0.33	0.58	0.72
Sf-8	3.55	0.14	0.28	0.36
Sf-9	3.59	0.07	0.17	0.22
Sf-10	3.64	0.09	0.19	0.25
Sf-11	3.93	0.00	0.00	0.01
Sf-12	4.31	0.25	0.44	0.54
Sf-13	4.44	0.21	0.39	0.47

ID – identification
Pa – pascal

A review of these results indicates that the cores may be separated into two broad categories based on excess shear stress: 1) less than 0.1 Pa and 2) 0.1 to 1.0 Pa. These categories are generally described as corresponding to: 1) minimally erosional (< 0.1 Pa) and 2) potentially erosional (0.1 to 1.0 Pa). The geochronology and Sedflume cores that fall within these two categories are listed in Table 3-7.

Table 3-7. Excess shear stress categories

EXCESS SHEAR STRESS RANGE (Pa)	DESCRIPTIVE CATEGORY	GEOCHRONOLOGY CORES	SEDFLUME CORES
< 0.1	Minimally erosional	Sg- 1a, 2, 3, 4, 11b, 11c	Sf-1, 2, 3, 4, 5, 11
0.1 – 1.0	Potentially erosional	Sg- 5a, 6, 7, 8, 9, 10, 12, 13	Sf-6-R1, 6-R2, 7, 8, 9, 10, 12, 13

The two groups of geochronology and Sedflume cores were examined to determine if any common characteristics or patterns were evident within the various groups, or if significant differences existed between the cores in the different groups. For the Sedflume cores, the following data sets were reviewed: 1) erosion rate (Figures A-1 through A-18), 2) erosion rate groups (Figures 3-3 through 3-7), 2) wet density (Figures A-19 through A-23), and 3) particle size distribution (Figures A-24 through A-28). For the geochronology cores, the vertical profiles of radioisotope and bulk bed property data presented in Figures 2-13 through 2-26 were examined.

Minimal distinguishing characteristics appeared to exist for the two groups of Sedflume cores. Separating the erosion rate data into two groups did not reveal any commonalities or differentiating characteristics. Nor did grouping the wet density and particle size distribution data for the Sedflume cores provide any additional insights about transport conditions within the LDW. Similarly, the geochronology data did not exhibit any differentiating characteristics or common attributes when the radioisotope profiles were separated into two groups. In addition, no correlation is apparent between excess shear stress values and radioisotope profiles that exhibit evidence of past episodic disturbance (i.e., deposition or erosion).

This analysis indicates that the hydrodynamic energy regime (represented by excess shear stress), during high-flow events did not have a significant effect on the erosion rate properties or geochronology at a particular location within the bench areas of the LDW. No correlation was apparent between the structure of either a Sedflume core or a geochronology core and the hydrodynamic energy regime at the core location.

3.2.5 Summary

The hydrodynamic model developed for the LDW was used to simulate the potential effects of average-flow conditions and high-flow events (e.g., 2-, 10-, and 100-yr high-flow events) on LDW bed stability. Modeling results suggested that the LDW may be broadly separated into three reaches during high-flow conditions:

- **Reach 1:** located downstream of RM 2.0 and is occupied by the saltwater wedge during all flow and tidal conditions
- **Reach 2:** extends from RM 2.0 to 3.0 and includes the saltwater wedge toe
- **Reach 3:** located upstream of RM 3.0, with flow in portions of this reach corresponding to a freshwater tidal river

The boundaries between the three reaches are indistinct, with the boundary between Reaches 1 and 2 ranging between RM 1.8 and 2.2, and the Reach 2-3 boundary located between approximately RM 3.0 and 3.1. However, establishing the boundaries between the reaches at RM 2.0 and 3.0 effectively delineates the LDW for discussion of the potential effects of high-flow events on bed scour.

Several analyses were conducted to evaluate spatial distributions of bed shear stress in the LDW. With respect to bed shear stress during high-flow events, the following general insights were developed from this work:

- Bed shear stress tended to be higher in the navigation channel than in the bench areas
- During high-flow events in Reaches 2 and 3 (i.e., upstream of the saltwater wedge), higher bed shear stresses occurred during spring tide than during neap tide

Two different metrics of the erosional environment were estimated to evaluate the potential effects of high-flow events on bed scour in the LDW: critical shear stress and excess shear stress. The critical shear stress (τ_{cr}) analysis yielded the following general results:

- For Reach 1 (i.e., occupied by the saltwater wedge):
  - τ_{cr} exceedance occurs between RM 1.8 and 2.0 and in relatively small areas downstream of RM 1.8
- For Reaches 2 and 3 (i.e., upstream of the saltwater wedge):
  - Areas where τ_{cr} is exceeded were larger during spring tide than during neap tide
  - Minor differences exist between ebb and flood tide conditions with respect to τ_{cr} exceedance

The following insights were developed from the excess shear stress (τ_{ex}) analysis:

- For Reach 1 (i.e., occupied at all times by the saltwater wedge):
  - Between RM 1.8 and 2.0, τ_{ex} values of 0.4 Pa or less occur
  - Downstream of RM 1.8, τ_{ex} values of 0.2 Pa or less occur in relatively small areas
- For Reaches 2 and 3 (i.e., upstream of the saltwater wedge):
  - Minor differences exist in the general spatial distributions of τ_{ex} during ebb and flood tides
  - Generally, lower τ_{ex} values occurred in the bench areas than in the navigation channel for a given high-flow event and tidal condition
  - Within the portions of the bench areas where erosion was predicted to occur (i.e., τ_{ex} greater than zero), the potential for erosion tended to be higher near the navigation channel and tended to decrease toward the shoreline
  - Reach 3 tends to have higher τ_{ex} values than Reach 2
- The hydrodynamic energy regime (represented by excess shear stress) during high-flow events does not appear to have a significant effect on the erosion rate properties or geochronology at a particular location within the bench areas of the LDW. No correlation was apparent between the structure of either a Sedflume core or a geochronology core and the hydrodynamic energy regime at the core location.

These results indicate that the hydrodynamic model is a useful tool for evaluating the potential effects of a high-flow event on LDW bed stability. Various insights concerning the potential for bed scour were developed from this analysis. However, limitations of this approach are acknowledged. While areas of potential erosion were identified through an analysis of spatial distributions of bed shear stress, the depth of bed scour in those areas during a specific high-flow event cannot be reliably estimated without the application of a sediment transport model.

3.3 POTENTIAL EFFECTS OF SHIP-INDUCED BED SCOUR

The primary objective of this analysis was to evaluate the potential for ship-induced bed scour within the LDW. A more general goal was to incorporate the ship-induced bed scour evaluation into the development of a CSM for sediment transport in the LDW. A corollary goal was to evaluate the relative importance of anthropogenic and natural events on bed stability.

3.3.1 Overview of technical approach

An outline of the technical approach for evaluating the potential effects of ships on bed stability in the LDW is presented here. A detailed presentation of the model used to estimate bed scour due to ship movement in the LDW is provided in Appendix D. The propeller wash and ship wake model used in this analysis is based on the approach developed by Maynord (2000). Included in Appendix D is a detailed description of the calculation of bed shear stress due to propeller wash and ship wake. That approach incorporates the effects of variable bathymetry so that bed shear stress can be calculated in both the navigation channel and bench areas.

The first step in the analysis was to calculate the spatial distribution of total bottom velocity generated by a moving ship. The total bottom velocity (V_b) is the sum of two components: 1) bottom velocity due to the ship's wake (V_{wake}) and 2) bottom velocity due to propeller wash (V_{prop}). Using a coordinate system that is fixed to the moving ship (i.e., the X_p – Y_{cl} coordinate system, Figures D-1 and D-3 in Appendix D), the wake velocity varies with longitudinal distance (in the X_p direction) behind the ship's bow. Bottom velocity due to propeller wash varies both longitudinally and laterally (cross-channel) behind the ship propeller. Thus, a two-dimensional distribution of the total bottom velocity extends from the ship's bow to a certain distance behind the ship.

Of particular interest in this analysis was the potential erosion at a specific LDW transect as a ship passes. Bottom velocity due to ship wake and propeller wash was time variable at a particular transect, with the bottom velocity increasing from zero as the ship's bow passes the transect to a maximum value and then decreasing to zero after the ship passes. This process occurs over a period of approximately one to three minutes, depending on ship speed and length. To quantitatively evaluate the time-variable bottom velocity, the spatial distribution of total bottom velocity due to ship movement (with respect to the X_p – Y_{cl} coordinate system that is fixed to the moving ship) was converted to a time-variable bottom velocity that varied spatially along an LDW transect (i.e., in the Y_{cl} direction).

Once total bottom velocity was determined, time-variable bed shear stress (τ) due to ship movement, caused by propeller wash and ship wake, was calculated at each transect. If bed shear stress exceeded a critical value (τ_{cr}), then particle motion may be initiated, potentially resulting in erosion. The extent of bed scour due to the passage of a single ship at a particular LDW transect was estimated using Sedflume data, which relates gross erosion rate (E_{gross}) to bed shear stress using Equation 3-1. Site-specific values of the erosion rate parameters (i.e., τ_{cr}, A, and n) are discussed in Section 3.1. Near-bed propeller wash velocities were assumed to reach steady-state during the passage of a ship to provide a conservative erosion analysis for this assessment. The more likely propeller wash condition in the LDW may be characterized as relatively short-duration velocity increases that may only achieve the predicted peak velocities for short intervals of time. Since the magnitude and duration of near-bed velocity are important determinants of particle movement and bed scour, the assumption that near-bed velocities due to propeller wash reach steady-state during the passage of a ship provides an additional level of conservatism to the analysis.

Effects of ship movement on bed stability were incorporated into the CSM for sediment transport to provide a context for evaluating the relative importance of bed scour due to propeller wash and ship wake. Inherent uncertainty in the analysis, due to a combination of modeling simplifications and site-specific data limitations, limited the quantitative accuracy of the results. Thus, this analysis is considered to be a screening-level evaluation, with order-of-magnitude accuracy at best, that provides a qualitative assessment of the effects of ship movement on bed stability in the LDW.

The methodology outlined above provides an objective method, using an empirical model that approaches the state-of-the-science, to evaluate the effects of ship movement on bed stability. However, this methodology does have limitations, as does any empirical approach. These limitations need to be acknowledged so that the reliability and applicability of analysis results are fully recognized. The Maynord (2000) model, which calculates bottom velocity and shear stress due to propeller wash and ship wake, is the main quantitative tool used to estimate bed scour due to ship traffic in the LDW. This model has various limitations, including:

- It is a simplification of a highly turbulent, chaotic process
- The model equations were developed from results of a physical model study and have undergone little or no field verification
- The physical model used to develop the algorithm focused on barge tows typical of the upper Mississippi River and Illinois Waterway system, which are generally much larger than LDW ships
- Bank effects (i.e., due to confined channels) are not incorporated into the model. This limitation is not significant because ships in the LDW generally occupy a relatively minor portion of the channel width.
- The model only considers helicoidal propellers; it does not account for Voith-Schneider (cycloidal) propellers that are commonly used on large tugboats

- The model was developed for unidirectional flow in rivers, not for bi-directional, density-driven flow in a saltwater wedge estuary, such as the LDW. The impact of this limitation is uncertain but it is probably not significant because the primary component of ship-induced bed shear stress is propeller wash. It is unlikely that the highly turbulent flow generated by propeller wash is substantially affected by estuarine circulation.

In addition to the limitations of the basic model framework, application of the model to the LDW has the following uncertainties:

- Few site-specific data are available for model calibration and validation. This limitation is common because obtaining data is difficult. Relatively few studies have been conducted to obtain data for calibration and validation of this type of model. However, the limited field studies that have been performed to date suggest that the model in its current form provides a reasonably accurate method to predict propeller wash and ship wake velocities associated with passing ships (Shaw and Anchor 2006).
- Estimation of propeller thrust, and its relationship to ship speed, for various LDW ships is problematic. Propeller thrust is difficult to measure directly, so it is estimated from other ship operating parameters.
- Uncertainty exists in LDW ship operations (e.g., ship speed, movement patterns and frequency). Similar to cars moving on a highway, ship movement in the LDW is variable and somewhat episodic. Observations and data on LDW ship operations are limited, which introduces uncertainty into the model predictions.
- This analysis focuses on the effects due to typical ship movement within the LDW (i.e., ship traffic moving upstream and downstream in the navigation channel). Localized effects caused by more complex ship movements (e.g., maneuvering, stopping and starting, berthing) are not evaluated in this analysis because of the large uncertainty associated with this type of movement. Specification of model input parameters is poorly constrained for complex ship movements and, hence, model predictions would be highly uncertain.

Even though the above limitations are considered when assessing the reliability of analysis results, this methodology produces order-of-magnitude estimates of potential effects on bed scour associated with ship traffic in the LDW. These results are used to develop qualitative conclusions about the relative importance of ship-induced scour on bed stability in the LDW.

3.3.2 Method for estimating potential effects on bed stability

The objective of this technical analysis is to estimate potential gross bed scour due to ship traffic at a particular LDW transect, where the focus is on upstream and downstream ship movements within the navigation channel. This analysis is limited to estimating gross bed scour because sediment transport and deposition processes are not accounted for here. Thus, the bed scour results are considered to be upper-bound estimates, with actual bed erosion due to ship traffic being less than these estimates (potentially substantially less).

As discussed above, uncertainty exists in both the model algorithm/theory and model inputs. Thus, a bounding-estimate approach is used so that the effects of parameter variation (or uncertainty) are incorporated into the results, thereby increasing the reliability of conclusions developed from model predictions. Bed scour effects at an LDW transect associated with a single-ship passage are estimated from the distribution of predicted scour depths resulting from a range of model parameter combinations. Uncertainty in input parameters is represented using bounding estimates of various parameters. Model calculations are conducted using the bounding input parameters, which produces model results that are expressed as ranges that provide a measure of the uncertainty in model accuracy.

The basic approach of this analysis is to predict bed scour in the navigation channel and bench areas at eight transects between RM 0.0 and 4.0, which is the portion of the LDW that experiences significant ship traffic. Bounding estimates are developed by separating model parameters into three broad areas: 1) ship operation, 2) LDW hydrodynamics and configuration, and 3) LDW bed erosion properties. Details of the model input parameters are listed in Table 3-8 and discussed below.

Table 3-8. Model input parameters for ship-induced bed scour analysis

DATA TYPE	SYMBOL	DESCRIPTION
Ship operation	L_{tb}	length of ship
	d_s	ship draft
	L_{set}	distance from ship stern to propeller
	W_p	distance between twin propellers
	D_p	propeller diameter
	δ_p	propeller axis depth
	none	type of propeller
	V_g	ship speed relative to ground
	P_{hp}	applied ship power
	none	location of ship in navigation channel
LDW configuration/ hydrodynamics	h	water depth
	H_p	cross section bathymetry relative to ship centerline
	V_a	average current velocity
	k_s	effective bottom roughness
LDW bed erosion properties	τ_{cr}	critical shear stress
	A	erosion rate parameter
	n	erosion rate exponent

3.3.3 Estimation of model inputs

General information on ship traffic in the LDW is presented in Riley (2006) and Takasaki (2006). Based on information contained in those two memorandums, ship traffic in the LDW may be summarized as follows:

- Ocean-going ships are always under tug assistance in the LDW, although those ships may also be self-propelled. Ocean-going ships do not travel further upstream than the 1st Avenue Bridge (approximately RM 2.0). These ships typically travel at a speed of 2 to 3 knots, with a maximum speed of 5 knots. This type of ship is unable to turn around in the LDW, so these ships are towed into Elliott Bay when out-bound.
- The Pilot's Association indicated that two large ships travel up to the James Hardie and Glacier docking areas, which are located at approximately RM 1.6. These ships are 85 ft wide and 600 ft long, and have drafts of 20 ft (unloaded) and 30 ft (loaded).
- Yachts travel to and from Delta Marine, which is located near RM 4.2. These vessels range in length from 100 to 160 ft, and have drafts of 5.5 to 10 ft.
- A range of barges are used in the LDW. Barges with dimensions of 100-ft width, 400-ft length, and 14-ft draft are used to just upstream of the 1st Avenue Bridge (approximately RM 2.0). Barges with dimensions of 76-ft width, 286-ft length, and 12-ft draft travel no further upstream of the South Park Bridge (approximately RM 3.3). General Construction has a barge storage area upstream of the South Park Bridge, but otherwise there is relatively minimal ship traffic upstream of RM 3.3. Barges typically travel at a speed of 2 to 3 knots, with a maximum speed of 5 knots.
- Captain Steve Kimmel, Port Captain for Foss Maritime, said that ship wakes are minimal in the LDW because ships and barges move too slowly to generate a significant hull effect on the water surface.

A survey of ships operating in the LDW indicates that two representative tugboats are *J.T. Quigg* and *Sea Valiant*. The physical characteristics of these tugboats are listed in Table 3-9. Determination of propeller thrust, which is used to calculate propeller jet velocity, is based on an estimate of the applied ship power. For this analysis, it was assumed that the applied ship power is equal to 10% of total ship power (see Appendix D). The sensitivity of model predictions to applied ship power is discussed in Section 3.3.4. A 5-knot speed limit is imposed on ships in the LDW, so this value was used for ship speed (V_g) in all calculations. Note that using the 5-knot velocity in this analysis produces conservative results because the typical vessel speed is 2 to 3 knots.

Table 3-9. LDW ship physical characteristics

PARAMETER	SHIP	
	J.T. QUIGG	*SEA VALIANT*
Length of ship (L_{tb})	100 ft	128 ft
Ship draft (d_s)	12.3 ft	19.9 ft
Distance from stern to propeller (L_{set})	10 ft	13 ft
Distance between twin propellers (W_p)	15 ft	19 ft
Propeller diameter (D_p)	6.3 ft	9.3 ft
Propeller axis depth (δ_p)	8 ft	8.5 ft
Type of propeller	open wheel	open wheel
Total ship power	3,000 hp	5,750 hp

The above information on LDW ships was used to construct the following scenarios for simulating the effects of propeller wash and ship wake on bed scour:

- For areas downstream of RM 1.6, the *Sea Valiant* pushes/pulls the large ships that travel to the James Hardie and Glacier docking areas. It is assumed that the ships are loaded, resulting in a 30-ft draft.
- Between RM 1.6 and the 1st Avenue S Bridge (approximately RM 2.0), the *Sea Valiant* pushes/pulls barges with dimensions of 100-ft width, 400-ft length, and 14-ft draft.
- Upstream of the 1st Avenue Bridge (approximately RM 2.0), the *J.T. Quigg* pushes/pulls barges with dimensions of 76-ft width, 286-ft length, and 12-ft draft.

Based on the LDW ship information presented above, these scenarios are representative and generally correspond to conservative, upper-bound estimates.

Hydrodynamic parameters that are input to the Maynord model are current velocity and water depth (i.e., tidal stage). Circulation in the LDW is complicated due to density-driven, two-layer flow within the saltwater wedge region, which typically extends upstream to just above the Upper Turning Basin (to approximately RM 4.7) during average-flow conditions. The effects of bi-directional, estuarine flow on propeller wash and ship wake have not been studied; the Maynord model assumes unidirectional flow, which typically occurs in rivers. This limitation introduces uncertainty into the modeling results. As a first approximation, the effects of ambient current velocity are neglected and set to zero in the analysis.

Bed scour at eight LDW transects was estimated for a range of conditions for both ships. The eight transects are separated by 0.5 mile, from RM 0.5 to RM 4.0. Cross sections at each transect is based on the 2003 multi-beam bathymetric data (Figure 3-22). The location of the navigation channel within each of the transects is shown as a shaded region on that figure. The bench areas are the unshaded regions to the right and left of the navigation channel. Bed shear stresses, due to propeller wash and ship wake, were calculated in both the navigation channel and bench areas, with the effects of variable bathymetry incorporated into the analysis. The ship input parameters used in the Maynord model at each transect are presented in Table 3-10. The ship length is the sum of the tug and barge lengths.

Table 3-10. Ship input parameters used in Maynord model

TRANSECT LOCATION (RM)	TOTAL LENGTH (FT)	DRAFT (FT)	TUG
0.5	728	30	*Sea Valiant*
1.0	728	30	*Sea Valiant*
1.5	528	20	*Sea Valiant*
2.0	528	20	*Sea Valiant*
2.5	386	12	*J.T. Quigg*
3.0	386	12	*J.T. Quigg*
3.5	386	12	*J.T. Quigg*
4.0	386	12	*J.T. Quigg*

Ship captains tend to avoid moving their ships during low-water conditions in the LDW due to safety concerns. Thus, these lower- and upper-bound estimates of tidal stage height were used to specify water depth at each transect: 1) tidal stage at mean sea level (MSL), which is 2.02 m above MLLW (lower-bound) and 2) tidal stage at mean high water (MHW), which is 3.19 m above MLLW (upper-bound).

The lateral location of the ship in the navigation channel may affect bed scour due to spatial variations in ship-induced bed shear stress. The effect of ship location on bed scour was estimated by performing calculations with the ship at three lateral positions in the navigation channel: 1) center of channel, 2) toward the east shore, 40% of channel width from centerline, and 3) toward the west shore, 40% of channel width from centerline.

A simplified bed model was used to simulate bed scour. As a conservative, upper-bound estimate, it was assumed that bed scour induced by propeller wash and ship wake is approximated using the gross erosion rate calculated by Equation 3-1. The effects of bed armoring and gross deposition are not included in this simulation. This approach, which conservatively over-predicts ship-induced bed scour, was sufficient for the purposes of this analysis. A more refined analysis was not warranted given the limitations of the model framework that are discussed in Section 3.3.1.

The bed model used a 5-cm thick layer, with the erosion properties of this surface-layer (0-5 cm) sediment being determined from an analysis of Sedflume data (see Section 3.1). The results of that analysis indicated that the erosion properties of surface-layer sediments may be separated into three groups (i.e., groups 1-A, 1-B, 1-C). Groups 1-A and 1-B represent 88% of the Sedflume cores, with the erosion properties of group 1-C falling between the group 1-A and 1-B properties. Thus, groups 1-A and 1-B represent the lower- and upper-bound values, respectively, of erosion properties of surface-layer (0-5 cm) sediment in the LDW. The lower-bound (group 1-A) parameters are: A = 0.0014, n = 1.5, and τ_{cr} = 0.16 Pa. Upper-bound erosion rate parameters (group 1-B) are: A = 0.0037, n = 2.5, and τ_{cr} = 0.24 Pa.

3.3.4 Model predictions

As a ship passes a cross-sectional transect within the LDW, bottom velocities associated with propeller wash and ship wake affect the bed for approximately one to three minutes, depending on ship speed and water depth. This process is illustrated in Figures 3-23 through 3-25, which show time-histories of cumulative bed scour within the east bench, navigation channel, and west bench, respectively, at an LDW transect located at RM 4.0. While the magnitudes of these quantities vary with location along the transect, the general structure of the time history is similar at all three locations. Generally, the bow of the ship passes the transect at time equal zero, with the initiation of the ship wake. About 20 to 50 seconds after the ship wake is initiated, bed scour begins. Most of the erosion occurs during a period of 60 to 120 seconds as the propeller wash and ship wake impacts the bed. About three minutes after the ship's bow initially passed the transect, propeller wash and ship wake have dissipated as the ship moves downstream and bed scour ceases.

Bottom velocities are generated by ship wake and propeller wash, with the wake velocity being initiated before propeller wash velocity begins. For the ship-induced bed scour simulation, wake velocity is greater than propeller wash velocity; however, the reverse situation may occur for some simulations. Bed shear stress increases rapidly after the ship's bow passes the transect, and then a relatively slow decline in shear stress occurs after the ship's propeller passes the transect. Peak erosion rate occurs during peak shear stress, with declining scour rate as shear stress decreases with time.

As discussed above, combining the permutations for ship operation, hydrodynamic and erosion property parameters yields a total of 12 simulations to estimate bed scour due to passage of a single ship at each of the eight transects. Model input parameters for the 12 simulations were set at these bounding values:

- **Tidal stage height:** lower-bound at MSL and upper-bound at MHW
- **Lateral location of ship in navigation channel:** center of channel, eastern portion of channel, and western portion of channel
- **Erosion rate parameters:** lower-bound of A = 0.0014, n = 1.5, and τ_{cr} = 0.16 Pa; upper-bound of A = 0.0037, n = 2.5, and τ_{cr} = 0.24 Pa

These bounding values produce 12 sets of input parameters at a particular transect.

Representative measures of the effects of ship movement on bed scour are the average and maximum scour depths due to a single ship passage within the three areas of interest: west bench, navigation channel, and east bench. Note that the average scour depth represents the average value for a particular area (e.g., west bench). Cumulative frequency distributions of average and maximum scour depths at the eight LDW transects are presented in Figures 3-26 through 3-28. The results in these figures are distributions of predicted scour depths in the three areas across the LDW channel, represented as average or maximum predicted values, corresponding to the 12 sets of input parameters applied at a specific transect. Ship input parameters applied at each transect location are listed in Table 3-10.

The results of the 12 simulations that were conducted for each of the three areas at a transect, due to variability and uncertainty in model input parameters, are represented as: 1) mean value of the 12 simulations and 2) range of the predicted scour depths. The mean value is the most appropriate quantity for comparing relative differences in bed scour between the ship parameters (Table 3-9) and spatial location (i.e., river mile, navigation channel, bench area). The range of predicted scour depths is useful for evaluating the variability of predicted scour depths. A summary of the bed scour calculations at each transect is presented in Tables 3-11 through 3-13. Due to the use of a simplified bed model (as discussed above), bed scour simulations that resulted in the 5-cm thick layer used in the model being completely eroded are reported as bed scour depth that is greater than or equal to 5 cm.

Table 3-11. Results of ship-induced bed scour simulations: navigation channel

Transect Location (RM)	Average Bed Scour (cm)	Range of Average Bed Scour (cm)	Mean of Maximum Bed Scour (cm)	Range of Maximum Bed Scour (cm)
0.5	0.3	0.1 – 0.8	0.5	0.1 – 1.3
1.0	0.6	0.1 – 1.8	0.7	0.2 – 2.7
1.5	<0.1	<0.1	<0.1	<0.1
2.0	0.5	<0.1 – 2.5	1.0	<0.1 – ≥5
2.5	<0.1	<0.1	<0.1	<0.1
3.0	<0.1	<0.1	<0.1	<0.1
3.5	<0.1	<0.1 – 0.3	0.3	<0.1 – 1.4
4.0	<0.1	<0.1 – 0.2	0.2	<0.1 – 0.6

Table 3-12. Results of ship-induced bed scour simulations: west bench area

Transect Location (RM)	Average Bed Scour (cm)	Range of Average Bed Scour (cm)	Mean of Maximum Bed Scour (cm)	Range of Maximum Bed Scour (cm)
0.5	1.8	0.6 – 3.6	4.9	4.3 – ≥5
1.0	2.4	0.6 – 4.4	3.7	1.0 – ≥5
1.5	NB	NB	NB	NB
2.0	1.4	0.2 – 5.0	2.1	0.2 – ≥5
2.5	<0.1	<0.1	<0.1	<0.1
3.0	0.5	<0.1 – 1.9	1.3	<0.1 – ≥5
3.5	NB	NB	NB	NB
4.0	0.4	<0.1 – 1.1	1.6	0.1 – ≥5

RM – river mile
NB – no west bench area

Table 3-13. Results of ship-induced bed scour simulations: east bench area

Transect Location (RM)	Average Bed Scour (cm)	Range of Average Bed Scour (cm)	Mean of Maximum Bed Scour (cm)	Range of Maximum Bed Scour (cm)
0.5	1.8	0.5 – 3.9	4.7	3.3 – ≥5
1.0	1.8	0.4	4.6	2.2 – ≥5
1.5	1.1	0.2 – 2.3	3.9	0.8 – ≥5
2.0	NB	NB	NB	NB
2.5	<0.1	<0.1	<0.1	<0.1
3.0	0.4	<0.1 – 1.3	1.4	0.1 – ≥5
3.5	0.7	<0.1 – 2.9	1.3	<0.1 – ≥5
4.0	0.7	<0.1 – 2.1	1.9	0.2 – ≥5

RM – river mile
NB – no east bench area

These results show that, generally, less than 1 cm of bed scour occurs in the navigation channel due to the passage of a single ship. In the bench areas downstream of the 1st Avenue Bridge (approximately RM 2.0), bed scour typically ranges between 1 and 2 cm due to the passage of a single ship. Generally, bed scour in the bench areas upstream of the 1st Avenue Bridge is 1 cm or less due to a single ship passage. Higher bed scour occurs in the bench areas than in the navigation channel due to the effects of ship wake traveling into the shallower nearshore areas. Downstream of the 1st Avenue Bridge, bed scour increases in the bench areas due to the larger ships used in that region. Variability in model predictions indicates that the uncertainty in these results may be as large as a factor of 2 to 3. As discussed above, these bed scour values are upper-bound estimates because of the simplified bed model used in the simulations.

Uncertainty exists in the estimates of ship-induced bed scour due to various factors. In addition, the reliability of the predictions is unknown because calibration and validation of the bed scour model were not conducted in the absence of site-specific data. Thus, the predicted scour depths are viewed as order-of-magnitude, upper-bound estimates.

In addition to the bounding-estimate approach discussed above, which considers the effects of a range of input parameters on model predictions, the sensitivity of the model to ship speed and applied ship power was investigated, with ship speed decreased by a factor of 2 (i.e., from 5 knots to 2.5 knots) and ship power increased by a factor of 2 (i.e., from 10% of applied ship power to 20% of applied ship power). For the sensitivity analysis, the simulations at RM 0.5, 1.0, 1.5 and 2.0 were repeated and the sensitivity results were compared to the original results. These locations were chosen because bed scour tended to be greatest in the region downstream of the 1st Avenue Bridge.

Comparisons of average bed scour for ship speeds of 2.5 and 5 knots in the west bench area, navigation channel, and east bench area are shown in Figures 3-29 through 3-31. These results show that ship speed has a significant effect on bed scour in the bench areas. As ship speed is decreased from the maximum value of 5 knots (i.e., LDW speed limit) to a 'typical' value of 2.5 knots, bed scour decreases to 0.5 cm or less.

The results of the applied ship power sensitivity analysis are presented in Figures 3-32 through 3-34. The model is relatively insensitive to the applied ship power, with minimal changes caused by increased the applied power by a factor of two. Overall, doubling ship power increased bed shear stress generally less than 5%. The maximum increase in bed shear stress was about 10 to 20%. The primary reason that model results are relatively insensitive to the applied ship power is that, generally, the effects of propeller wash on bed scour are less than the effects of ship wake. This result reduces uncertainty in the model predictions because the applied ship power is difficult to determine and it is one of the most uncertain parameters used in the model.

The above results represent the effect of a single ship passage at various locations in the LDW. Of course, multiple ship passages occur on an annual time scale. The frequency of ship movement within the LDW was investigated, as shown in Figure 3-35. In the region between RM 0.0 and 4.0, about two to five ship passages occur per week, which translates to approximately 100 to 250 ship passages per year.

The long-term effects of multiple ship passages at a particular transect location should not be estimated by simply multiplying the estimated bed scour depth by the number of ship passages and producing a "cumulative" scour depth due to ships. Bed scour due to a single ship passage occurs over about one minute at any particular transect. This short scour period is viewed as an impulse event for both the bed and water column. The impulse-load of sediment to the water column is re-deposited on the sediment bed, probably within a relatively short time after the scour event (i.e., within a few minutes to a few hours), depending on location and flow conditions.

This erosion-deposition process is different from sediment transport during a high-flow event, when complex erosion and deposition processes may cause significant transport of sediment within the LDW. Thus, ship-induced bed scour tends to behave like a mixing process for bed sediment, with the impulsive erosion-deposition process reworking the surface layer. It is possible that ship-induced bed scour results in net erosion at some locations near the banks of the LDW, as indicated by the simulated scour depths provided in Tables 3-12 and 3-13, and Figures 3-29 and 3-31. Upper-bound estimates of the thickness of this reworked surface layer range from less than 1 cm in the navigation channel and the bench areas upstream of the 1st Avenue Bridge (approximately RM 2.0) to 1-2 cm in the bench areas downstream of the 1st Avenue Bridge. The frequency of surface layer mixing is about 100 to 250 events per year.

3.3.5 Conditions at geochronology-Sedflume core locations

Results of the above simulations were used to estimate potential effects of ship-induced bed scour in the vicinity of the geochronology and Sedflume cores. Similar to the evaluation discussed in Section 3.2.5.6 for the hydrodynamic modeling results, an understanding of ship-induced bed scour at the core locations may provide insights about conditions at those locations.

The Maynord model was applied at specific transect locations between RM 0.0 and 4.0; the model was not applied at the locations of each core. Thus, model predictions at the transect closest to each core were used to estimate potential effects at that location. Given the order-of-magnitude accuracy of the Maynord model, this approximation was appropriate for this analysis. In addition, several cores were excluded from the analysis for the following reasons. Cores Sg-2 and Sf-2 are negligibly affected by ship traffic because of their location in the shallow channel to the west of Kellogg Island. Cores Sg-12, Sg-13, Sf-12, Sf-13, and Sf-17 are upstream of Slip 6 (RM 4.2), which is a region with minimal ship traffic.

Predicted ranges of average and maximum bed scour in the vicinity of the geochronology and Sedflume core locations are listed in Tables 3-14 and 3-15. The cores are separated into three broad categories based on average bed scour: 1) <0.1 cm, 2) 0.1 - 1 cm, and 3) 1 - 2 cm. The cores that are grouped into these three categories are presented in Table 3-16.

Table 3-14. Ship-induced bed scour at geochronology core locations

Sediment Core ID	Core Location (RM)	Average Bed Scour (cm)	Range of Average Bed Scour (cm)	Mean of Maximum Bed Scour (cm)	Range of Maximum Bed Scour (cm)
Sg-1a	0.23	1.8	0.6 – 3.6	4.9	4.3 – ≥5
Sg-3	1.17	1.8	0.4	4.6	2.2 – ≥5
Sg-4	1.43	1.1	0.2 – 2.3	3.9	0.8 – ≥5
Sg-5a	1.91	1.4	0.2 – 5.0	2.1	0.2 – ≥5
Sg-6	2.31	<0.1	<0.1	<0.1	<0.1
Sg-7	2.72	0.5	<0.1 – 1.9	1.3	<0.1 – ≥5
Sg-8	3.55	0.7	<0.1 – 2.9	1.3	<0.1 – ≥5
Sg-9	3.59	0.5	<0.1 – 1.9	1.3	<0.1 – ≥5
Sg-10	3.64	0.7	<0.1 – 2.9	1.3	<0.1 – ≥5
Sg-11c	3.81	0.7	<0.1 – 2.1	1.9	0.2 – ≥5
Sg-11b	3.93	0.7	<0.1 – 2.1	1.9	0.2 – ≥5

ID – identification
RM – river mile

Table 3-15. Ship-induced bed scour at Sedflume core locations

Sediment Core ID	Core Location (RM)	Average Bed Scour (cm)	Range of Average Bed Scour (cm)	Mean of Maximum Bed Scour (cm)	Range of Maximum Bed Scour (cm)
Sf-1	0.45	1.8	0.6 – 3.6	4.9	4.3 – ≥5
Sf-3	1.17	1.8	0.4	4.6	2.2 – ≥5
Sf-4	1.43	1.1	0.2 – 2.3	3.9	0.8 – ≥5
Sf-5	1.98	1.4	0.2 – 5.0	2.1	0.2 – ≥5

SEDIMENT CORE ID	CORE LOCATION (RM)	AVERAGE BED SCOUR (cm)	RANGE OF AVERAGE BED SCOUR (cm)	MEAN OF MAXIMUM BED SCOUR (cm)	RANGE OF MAXIMUM BED SCOUR (cm)
Sf-6-R1	2.31	<0.1	<0.1	<0.1	<0.1
Sf-6-R2	2.31	<0.1	<0.1	<0.1	<0.1
Sf-7	2.72	<0.1	<0.1	<0.1	<0.1
Sf-14	2.99	<0.1	<0.1	<0.1	<0.1
Sf-8	3.55	0.7	<0.1 – 2.1	1.9	0.2 – ≥5
Sf-15	3.55	<0.1	<0.1	<0.1	<0.1
Sf-9	3.59	0.5	<0.1 – 1.9	1.3	<0.1 – ≥5
Sf-10	3.64	0.7	<0.1 – 2.9	1.3	<0.1 – ≥5
Sf-11	3.93	0.7	<0.1 – 2.1	1.9	0.2 – ≥5
Sf-16-R1	3.93	<0.1	<0.1	<0.1	<0.1
Sf-16-R2	3.93	<0.1	<0.1	<0.1	<0.1

ID – identification
RM – river mile

Table 3-16. Ship-induced bed scour categories

AVERAGE BED SCOUR (cm)	DESCRIPTIVE CATEGORY OF BED SCOUR	GEOCHRONOLOGY CORES	SEDFLUME CORES
< 0.1	Relatively low	Sg- 6	Sf- 6-R1, 6-R2, 7, 14, 15, 16-R1, 16-R2
0.1 – 1	Intermediate	Sg- 7, 8, 9, 10, 11c, 11b	Sf- 8, 9, 10, 11
1 - 2	Relatively high	Sg- 1a, 3, 4, 5a	Sf- 1, 3, 4, 5

The three groups of cores were examined to determine if any common characteristics or patterns were evident within the various groups. For the Sedflume cores, the following data were reviewed: 1) erosion rate (Figures A-1 through A-18), 2) erosion rate groups (Figures 3-3 through 3-7), 2) wet density (Figures A-19 through A-23), and 3) particle size distribution (Figures A-24 through A-28). For the geochronology cores, the vertical profiles of radioisotope and bulk bed property data presented in Figures 2-13 through 2-26 were examined, as well as net sedimentation rates listed in Table 2-7.

A review of these data sets indicated that minimal distinguishing characteristics were apparent for the three groups. No differentiating characteristics or common attributes were evident for the three groups of cores, which is similar to the results in Section 3.2.5.6. These results suggest that ship-induced bed scour does not have a significant effect on the erosion rate properties or geochronology at a particular location in the bench areas or navigation channel of the LDW. No correlation is apparent between the structure of a geochronology or Sedflume core and the level of ship-induced bed scour at the core location.

3.3.6 Summary

The Maynord model was used to predict time-variable bed shear stress at an LDW transect due to the passage of a single ship. Upper-bound estimates of bed scour within the navigation channel and bench areas were calculated using the results of the Maynord model. An analysis of the bed scour results, at eight LDW transects and for a range of input parameters, yields the following conclusions about the potential effects of ship-induced bed scour:

- Within the navigation channel, ship movement causes average bed scour of less than 1 cm per ship passage in Reach 1, and less than 0.1 cm per ship passage in Reaches 2 and 3. Within the bench areas, average bed scour of about 1-2 cm per ship passage occurs in Reach 3, and less than 1 cm per ship passage in Reaches 2 and 3. Variability in model predictions indicates that the uncertainty in these results may be as large as a factor of 2 to 3. These bed scour values are upper-bound estimates.
- A sensitivity analysis indicates that reducing ship speed from the LDW speed limit (5 knots) to a typical ship speed (2.5 knots) significantly reduces bed scour, with predicted bed scour of less than 1 cm throughout the LDW for all conditions. Doubling the applied ship power had minimal effect on predicted scour depth, with changes in bed shear stress generally less than 5%. The maximum increase in bed shear stress was about 10 to 20%.
- Ship-induced bed scour is viewed as an impulsive erosion-deposition process that tends to behave like a mixing process for surficial bed sediment. In this view, the reworked sediment layer is equated to the depth of gross bed scour. It is possible that ship-induced bed scour results in net erosion at some locations near the banks of the LDW. The reworked surface layer in Reach 1 had an upper-bound average thickness of less than about 1 cm in the navigation channel and about 1-2 cm in bench areas. In Reaches 2 and 3, the reworked surface layer had an upper-bound average thickness of less than 0.1 cm in the navigation channel and less than 1 cm in bench areas. The frequency of mixing is about 100 to 250 events per year.
- Ship-induced bed scour does not have a significant effect on the erosion rate properties or geochronology at a particular location in the bench areas or navigation channel of the LDW. No correlation was apparent between the structure of a geochronology or Sedflume core and the level of ship-induced bed scour at the core location.

The effects of ship-induced bed scour are incorporated into the present structure of the LDW sediment bed because ship movement has been occurring for at least the past 40 years, which is the primary period of concern related to chemical transport and fate in the LDW. This fact suggests that the cumulative effect of ship-induced bed scour has expressed itself in the chemical distributions within the sediment bed that are found in the LDW today.

This analysis focused on the effects of typical ship movement on bed stability within the navigation channel and bench areas. In addition to typical ship traffic moving upstream and downstream in the navigation channel, more complex ship movements occur in the LDW, including: maneuvering, starting/stopping, and berthing. Analyzing the effects of these complex movements, which tend to occur over localized areas, on bed stability is difficult and quantitative predictions would be highly uncertain. The frequency of such events may change over time, depending on site, tenant, and economy, making it difficult to predict which locations in the future may be subject to more frequent scour from these activities. This type of analysis is beyond the scope of the present study.

General qualitative comments about potential effects of complex ship movements are possible. First, bed stability effects are typically confined to a relatively limited spatial area within the immediate vicinity of the ship movement. Second, potentially large scour depths (e.g., greater than 1 ft) may occur during complex movements, but this magnitude of scour depth is probably limited to a small spatial area. In a net depositional environment, such scour areas are likely to fill-in over time, suggesting that these scour events would have a transitory effect on the sediment bed. Finally, detailed analysis of this type of ship movement should be restricted to site-specific analyses at localized sites in the LDW. An example of a site-specific analysis is presented in King County et al. (King County et al. 2003), which examines anthropogenic effects on bed scour for berthing areas at the Duwamish/Diagonal site.

4.0 Summary and Synthesis of Results

The Phase 1 RI summarized existing information on sediment processes in the LDW and yielded a basic understanding of the stability of bedded sediments and sediment transport in the system, which was used to develop a preliminary CSM. This CSM was considered to be preliminary because sufficient site-specific information and data were not available during the Phase 1 RI to confirm it. Based on the data available for that study, the Phase 1 CSM postulated:

- The LDW is net depositional on a site-wide scale
- On a local scale, the sediment bed is either aggrading (i.e., sediment bed elevation is increasing as a result of sediment deposition) or in dynamic equilibrium (i.e., sediment bed elevation is neither increasing nor decreasing)
- Bed erosion occurs only episodically and over small spatial scales

As described in the Phase 2 RI work plan (Windward 2004) and the Sediment Transport Data Report (Windward and QEA 2005), additional data were collected in 2004 and 2005, consistent with EPA guidance (EPA 2005), to support development of a concise description of LDW sediment transport processes that affect sediment stability in the system. This report presents a synthesis of information collected during Phases 1 and 2, and has four main objectives:

- Analyze the additional net sedimentation data collected from bench areas during Phase 2 to supplement the Phase 1 net sedimentation data available for the navigation channel. These data were used to evaluate sediment dynamics in the bench areas of the LDW.
- Analyze Phase 2 data to describe erosion potential in the LDW as a function of shear stress, sediment characteristics (i.e., grain size), and depth in the bed. This analysis supports evaluation of the importance and effects of natural (e.g., hydrodynamic) and anthropogenic (e.g., ship propeller wash) forces on bed scour in the LDW.
- Evaluate data collected during Phase 2 on sediment dynamics, in conjunction with existing Phase 1 data and analyses, to refine the Phase 1 CSM.
- Determine if additional field data or modeling are needed to further refine the CSM for sediment transport processes and the stability of bedded sediments in the LDW.

The final CSM for sediment transport processes may support future remedial design activities. Through an improved understanding of LDW sediment transport processes, remedial alternatives that may be applicable to the system can be evaluated with increased confidence. The results of this study will be used in subsequent investigations that are aimed specifically at assessing the effectiveness of various remedial alternatives in the FS.

4.1 SUMMARY OF LDW DEPOSITIONAL ENVIRONMENT EVALUATION

The depositional environment of the LDW was characterized using the results of a geochronology study and an evaluation of the existing bathymetric information. The geochronology study consisted of the collection and radioisotope age-dating of sediment cores collected in 2004 from the LDW. These data provide an improved understanding of net sedimentation in the bench areas relative to net sedimentation rates estimated for the navigation channel in previous studies. The bathymetric analysis consisted of a comparison of two existing bathymetric data sets collected from portions of the LDW in 2000 and the entire LDW in 2003 to provide a qualitative assessment of potential scour and deposition areas.

Results of the geochronology analysis are summarized as follows:

- Net sedimentation rates in the bench and sideslope areas were estimated to range from 0.2 to >2.0 cm/yr. The cores with lower estimated net sedimentation rates were generally collected from areas with shallower water depths (i.e., above +0.4 ft MLLW) relative to the other geochronology cores, suggesting that these areas may be subject to relatively low deposition. No other consistent spatial trend was apparent in the estimated net sedimentation rates calculated from radioisotope age-dating methods, likely because the data were too sparse to develop spatial relationships. By expanding the geochronology analysis to include chemical and physical markers, thereby providing greater spatial coverage, some spatial trends emerged. Stations were grouped into areas with similar net sedimentation rates, water depth, grain size, and location along the LDW.

- Evidence of potential disturbances (e.g., episodic erosion and deposition, dredging, slumping) was observed in some of the geochronology cores.
- The lines of evidence taken together indicate that the radioisotope and bulk bed property profiles provide no evidence of widespread, episodic erosion; the cores suggest that the bench areas of the LDW are net depositional system-wide. However, some cores suggest possible localized effects from erosion/deposition events.

The bathymetric evaluation is summarized as follows: measurement inaccuracies and other confounding factors made conclusions regarding sediment transport in the LDW unreliable. Areas of scour and deposition in excess of 12 in. (30 cm) were noted in these comparisons. However, most of these areas are located along the edge of the navigation channel (which has been routinely dredged) or at the outermost limits of the survey data; these areas are likely subject to measurement errors that are in excess of the criterion used in this analysis (i.e., 12 in. [30 cm]).

An independent verification of net sedimentation rates estimated from the geochronology cores discussed above is presented in Appendix F, which uses several empirical lines-of-evidence (physical, chemical, and radioisotope) from the LDW. Two primary conclusions from the analyses presented in Appendix F are:

- Based on empirical data, the bench areas are net depositional on annual timescales. Net sedimentation rates are spatially variable, with the highest rates in the navigation channel (greater than 2 cm/yr), moderate in the subtidal bench areas (less than 2 cm/yr), and lowest in the intertidal bench areas (less than 0.5 cm/yr).
- The reliability of these results is relatively high due to the consistency between net sedimentation rates estimated using different approaches (i.e., physical and chemical time markers, radioisotope analysis).

Because of the consistency between the different approaches, the net sedimentation rates determined from the time marker and radioisotope analyses were combined to develop a large-scale view of LDW net sedimentation. A primary result of the analysis presented in Appendix F is a map showing the spatial distribution of estimated net sedimentation rates in the LDW within specific “sedimentation areas” (see Figure 5 in Appendix F). That map delineates sedimentation areas with the LDW using five categories of net sedimentation rate: less than 0.5 cm/yr; 0.5 to 1.0 cm/yr; 1.0 to 1.5 cm/yr; 1.5 to 2.0 cm/yr; and greater than 2 cm/yr. Even though spatial variability on local scales exists within the areas shown in Figure 5, the results of the analysis presented in Appendix F provide a consistent picture of large-scale net sedimentation processes in the LDW. Use of different lines-of-evidence in Appendix F reduces uncertainty in and increases the reliability of the results of that analysis.

4.2 SUMMARY OF EROSION POTENTIAL ANALYSES

Sediment bed scour resulting from both natural and anthropogenic causes was investigated to assess whether sediment bed erosion occurs episodically and, if so, over what spatial scales. Evaluating the potential for sediment bed scour within the LDW requires information on: 1) erosion properties of the sediment bed and 2) natural and anthropogenic hydrodynamic forces exerted on the sediment bed.

The objectives of these analyses were to: 1) analyze data collected in 2004 on the potential for sediment bed erosion, 2) quantify the effects of hydrodynamics on the spatial distribution of bed shear stress in the LDW for various flow conditions, 3) determine areas where sediment bed scour may occur during episodic high-flow events, and 4) quantify the effects of anthropogenic forces (e.g., bed scour due to ship propeller wash and ship wake) on sediment bed erosion.

Erosion rates as a function of shear stress and depth in the sediment bed were measured experimentally using sediment cores collected from the LDW. The erosion rate tests were conducted using Sedflume. A hydrodynamic model developed for the LDW was used to predict bed shear stress in the LDW for various flow conditions. The relationship between shear stress and erosion rate, which was developed using site-specific data, was used to identify areas in the LDW that could potentially experience erosion for freshwater discharge conditions ranging from average flow to the 100-yr high-flow event.

Analysis of the Sedflume erosion rate data led to the following conclusions:

- High correlation exists between gross erosion rate and shear stress (i.e., gross erosion rate is strongly dependent on the shear stress).
- Minimal correlation exists between erosion rate and bulk density.
- Significant similarity in the erosion properties of various cores within 5-cm depth layers was observed, allowing for the creation of groups of cores with similar properties. Average erosion parameter and critical shear stress values can be determined for each core group. The results of this analysis are useful for developing spatial distributions of erosion rate parameters for use in a sediment transport model.

Results of the hydrodynamic modeling indicate that LDW may be broadly separated into three reaches during high-flow conditions, which are useful when discussing the potential effects of high-flow events on bed scour:

- **Reach 1:** located downstream of approximately RM 2.0 and is occupied by the saltwater wedge during all flow and tidal conditions.

- **Reach 2:** extends from approximately RM 2.0 to 3.0 and includes the saltwater wedge toe during high-flow events; the saltwater wedge extends even farther upstream during average-flow conditions.
- **Reach 3:** located upstream of approximately RM 3.0, with flow in portions of this reach being characteristic of a freshwater tidal river during high-flow events.

Various modeling analyses were conducted to evaluate potential bed scour in the LDW during average-flow conditions and high-flow events (i.e., discharge greater than or equal to the 2-yr high-flow event). These analyses are summarized as follows:

- During average-flow conditions, the bed shear stress exceeds the critical shear stress (i.e., shear stress great enough to potentially initiate erosion) in only a relatively small area in the Upper Turning Basin (i.e., upstream of RM 4.6). Thus, negligible erosion, relative to a high-flow event, is predicted to occur in the LDW during average-flow conditions.
- Bed shear stress tended to be higher in the navigation channel than in the bench areas.
- During high-flow events in Reach 1 (i.e., occupied by the saltwater wedge), negligible bed scour occurs in most of the area downstream of RM 1.8. Between RM 1.8 and 2.0, excess shear stress values of 0.4 Pa or less occur during high-flow events.
- During high-flow events in Reaches 2 and 3 (i.e., upstream of the saltwater wedge):
  - Minor differences exist in the general spatial pattern of excess shear stress during ebb and flood tides.
  - Higher bed shear stresses occur during spring tide than during neap tide.
  - Generally, lower excess shear stresses occurred in the bench areas than in the navigation channel for a given high-flow event and tidal condition.
  - Within the portions of the bench areas where erosion was predicted to occur, the potential for erosion tended to be highest near the navigation channel and tended to decrease toward the shoreline.
  - Reach 3 tends to have higher excess shear stress values than Reach 2.
- The hydrodynamic energy regime (represented by the excess shear stress) during high-flow events does not appear to have a significant effect on the erosion rate properties or geochronology at a particular location within the bench areas of the LDW. No correlation was apparent between the structure of either a Sedflume core or a geochronology core and the hydrodynamic energy regime at the core location.

These results indicate that the hydrodynamic model is a useful tool for evaluating the potential effects of a high-flow event on LDW bed stability. Various insights concerning the potential for bed scour were developed from this analysis. However, there are limitations in this approach. While areas of potential erosion were identified through an analysis of spatial distributions of bed shear stress, the depth of bed scour in those areas during a specific high-flow event cannot be reliably estimated without the application of a sediment transport model.

Gross bed scour potentially resulting from ship traffic along particular LDW transects was also analyzed, as summarized below. The focus was on upstream and downstream movements of ships within the navigation channel to assess the effects of ship movement on bed stability in the LDW. This analysis was necessarily limited to estimating gross bed scour because sediment transport and deposition processes are not explicitly accounted for here. Results of this analysis indicated that:

- The bed scour results were considered to be upper-bound estimates, with actual bed erosion due to ship traffic being less than these estimates, and this analysis was considered to be a screening-level evaluation, with order-of-magnitude accuracy at best.
- Within the navigation channel, ship movement causes average bed scour of less than 1 cm per ship passage in Reach 1, and less than 0.1 cm per ship passage in Reaches 2 and 3. Within the bench areas, average bed scour of about 1-2 cm per ship passage occurs in Reach 3, and less than 1 cm per ship passage in Reaches 2 and 3.
- A sensitivity analysis indicates that reducing ship speed from the LDW speed limit (5 knots) to a typical ship speed (2.5 knots) significantly reduces bed scour, with predicted bed scour of less than 1 cm throughout the LDW for all conditions. Doubling the applied ship power had minimal effect on predicted scour depth.
- Ship-induced bed scour is viewed as an impulsive erosion-deposition process that tends to behave like a mixing process for surficial bed sediment. In this view, the reworked sediment layer is equated to the depth of gross bed scour. It is possible that ship-induced bed scour results in net erosion at some locations near the banks of the LDW. The reworked surface layer in Reach 1 had an upper-bound average thickness of less than about 1 cm in the navigation channel and about 1-2 cm in bench areas. In Reaches 2 and 3, the reworked surface layer had an upper-bound average thickness of less than 0.1 cm in the navigation channel and less than 1 cm in bench areas. The frequency of mixing is about 100 to 250 events per year.
- Ship-induced bed scour does not have a significant effect on the erosion rate properties or geochronology at a particular location in the bench areas or navigation channel of the LDW. No correlation was apparent between the

structure of a geochronology or Sedflume core and the level of ship-induced bed scour at the core location.

- The effects of ship-induced bed scour are incorporated into the present structure of the LDW sediment bed because ship movement has been occurring for at least the past 40 years, which is the primary period of concern related to chemical transport and fate in the LDW.

4.3 INTEGRATION AND SYNTHESIS OF RESULTS

A range of empirical and modeling analyses was conducted during this study, with each analysis focusing on a specific component of sediment transport and bed stability in the LDW. The results of this study were integrated and synthesized with the historical site data using multiple lines of evidence to provide a better understanding of sediment transport and bed stability within the LDW, which is used to refine the Phase 1 CSM.

The results and conclusions concerning the evaluation of potential bed scour are largely based on modeling analyses. While the models used in this study provide reliable results, the uncertainty associated with the results, and limitations in the models, must be acknowledged. The qualitative conclusions derived from these analyses have a relatively low level of uncertainty, whereas the quantitative results of the bed scour modeling, for both natural and anthropogenic events, have a higher level of uncertainty. Generally, uncertainty associated with the quantitative modeling results ranges between a factor of 2 and 10; this estimated range of uncertainty is based on past experience from modeling studies conducted at other sites.

Furthermore, the models used in this study considered only the potential for scour associated with high-flow events and not the potential for deposition that would also occur during those events. Thus, potential scour during high-flow events was generally overestimated in this analysis because inclusion of deposition would decrease the amount of net erosion during high-flow events. Consequently, the model results provide a qualitative understanding of bed stability and erosion potential, but do not provide a quantitative measure of overall bed dynamics and sediment transport.

4.3.1 Conceptual site model for sediment transport

The primary goal of this study was to develop an improved understanding of sediment transport processes in the LDW, with a focus on issues related to bed stability. The starting point of this investigation was the Phase 1 CSM for sediment stability and transport, which was developed from the results of previous studies and information available prior to the start of the present study. Results of the empirical and modeling analyses presented in this report were used to refine the Phase 1 CSM, which produced a better understanding of sediment transport and bed stability in the LDW. Additional refinement of the CSM will occur based on the results of ongoing and future studies. The revised CSM for sediment transport is:

- The LDW is net depositional site-wide over annual time scales.
- Net sedimentation rates are generally higher in the navigation channel than in the bench areas. For the navigation channel, the net sedimentation rate decreased when moving from the Upper Turning Basin (near RM 4.8) to downstream areas. For the bench areas, no trends in net sedimentation rate were apparent in the upstream-to-downstream direction, but net sedimentation tended to be lower in the intertidal areas than in the subtidal areas.
- Bed erosion is an episodic process that may be most pronounced during high-flow events. Episodic bed scour was predicted to occur to the greatest extent in Reach 3, was lower in Reach 2 (relative to Reach 3), and was minimal in Reach 1. The potential for erosion during high-flow events was generally greater in the navigation channel than in the bench areas. Within the portions of the bench areas where erosion was predicted to occur, erosion tended to be highest near the navigation channel and tended to decrease toward the shoreline.
- Ship-induced bed scour tends to behave as a mixing process for surficial sediment. The reworked surficial layer had an upper-bound average thickness of less than about 1 cm in the navigation channel and less than about 1-2 cm in the bench areas, with the frequency of such mixing being about 100 to 250 events per year.

The first component of the revised CSM states that the LDW is net depositional over annual time scales, with the rate of net deposition (i.e., net sedimentation rate) being spatially variable. The best estimate of the spatial distribution of net sedimentation rates in the LDW that is presently available is presented in Appendix F (i.e., Figure 5). The spatial distribution in that figure suggests that this CSM component may be expanded through separation of net depositional areas into three categories:

- **Lower net depositional:** net sedimentation rates are less than 0.5 cm/yr. In small, isolated areas within this category, the net sedimentation rate is minimal (e.g., less than 0.1 cm/yr) and the bed may approach a state of dynamic equilibrium (i.e., minimal changes in bed elevation over annual time scales).
- **Intermediate net depositional:** net sedimentation rates range from 0.5 to 2.0 cm/yr.
- **Higher net depositional:** net sedimentation rates are greater than 2.0 cm/yr.

Quantitative estimates of net sedimentation rates were developed from data collected within the LDW. Only a qualitative evaluation of potential bed scour during high-flow events could be achieved using the hydrodynamic modeling results. Quantitative estimates of bed scour depths cannot be derived from LDW core data but are achieved through STM (see the STM report (QEA 2007)).

The revised CSM is extended to the three broad reaches of the LDW that are discussed in Section 4.3. Viewing these three reaches separately provides a more comprehensive understanding of sediment dynamics and bed stability within the LDW. Findings for each reach, moving from downstream to upstream, are discussed below.

Reach 1: Downstream of RM 2.0

This reach is net depositional on annual time scales, in both the navigation channel and the adjacent bench areas. Based on net sedimentation rate estimates (i.e., Figure 5 in Appendix F), the navigation channel is classified as intermediate and higher net depositional. The bench areas range from lower to higher net depositional. With respect to episodic erosion, this reach is always occupied by the saltwater wedge, even during a 100-yr high-flow event. The permanent presence of the saltwater wedge serves as a protective barrier for the bed within this reach. Consequently, bed shear stresses (i.e., near-bed current velocities) are dominated by tidally driven flows, which are relatively low for all flow conditions, which results in minimal bed scour. The potential for re-exposing chemical concentrations that are buried at depth in the bed due to scour during high-flow events is minimal in this reach. Ship-induced mixing of the surficial bed layer potentially extends to average depths of about 1 to 2 cm in the bench areas and less than 1 cm in the navigation channel.

Reach 2: RM 2.0 to 3.0

Overall, Reach 2 is net depositional on annual time scales. The navigation channel is classified as higher net depositional. The benches range from lower to higher net depositional. The effects of high-flow events on bed scour are significantly less in this reach than in Reach 3, as discussed below, with less total area subject to scour and lower predicted excess shear stress (i.e., bed scour) during a high-flow event. This reach may be viewed as a transition region between Reaches 1 and 3; the extent and magnitude of episodic erosion in Reach 2 is between the minimal bed scour in Reach 1 and the relatively high potential bed scour in Reach 3. The benches of Reach 2 experience lower potential bed scour during high-flow events than the navigation channel in this reach. Ship-induced mixing of the surficial bed layer potentially extends to average depths of less than 1 cm in the bench areas and less than 0.1 cm in the navigation channel.

Reach 3: Upstream of RM 3.0

Overall, this reach is net depositional on annual time scales. The relatively high net sedimentation rates in the navigation channel indicate that this area is classified as higher net depositional. Similar to Reaches 1 and 2, the bench areas range from lower to higher net depositional. Modeling results indicate that higher episodic erosion may occur during high-flow events in Reach 3 than in the two downstream reaches. Generally, there is a relatively high potential for bed scour in a few isolated areas in the navigation channel and benches, with greater erosion potential expected to occur in the navigation channel than in the benches during high-flow events. Within the benches, the potential for erosion tends to be highest near the navigation channel and lowest in the nearshore/intertidal areas. Ship-induced mixing of the surficial bed layer potentially extends to average depths of less than 1 cm in the bench areas and less than 0.1 cm in the navigation channel.

A summary of the results for the three reaches, discussed above, is presented in Table 4-1. As a convenient method to present and discuss study conclusions, graphical representations of the CSM in the bench areas and navigation channel of Reaches 1, 2 and 3 have been developed (see Figures 4-1 through 4-3). In addition, these figures include qualitative illustrations of sediment bed dynamics, which show the approximate relative contributions of deposition, bed scour due to high-flow events, depth of mixing due to ship-induced scour, and net deposition. These illustrations provide a means for comparing the effects of various processes, in a qualitative sense, on sediment dynamics and bed stability in different reaches of the LDW. The lengths of the arrows representing deposition, episodic erosion, and net deposition on the illustrations are an approximate representation of the relative magnitude of each process. The effects of ship-induced scour are represented as a mixing process, indicated by the curling arrow, in the surface layer of the bed, with the relative thickness of the mixing depth shown in an approximate manner.

Table 4-1. Summary of sediment stability characteristics within the LDW

REACH	AREA WITHIN REACH	NET DEPOSITIONAL CATEGORY	RELATIVE LEVEL OF POTENTIAL EPISODIC EROSION	PREDICTED AVERAGE DEPTH OF SHIP-INDUCED MIXING (cm)
1	Bench areas	lower, intermediate and higher	minimal	1 – 2
	Navigation channel	lower, intermediate and higher	minimal	< 1
2	Bench areas	lower, intermediate and higher	intermediate	< 1
	Navigation channel	higher	intermediate	< 0.1
3	Bench areas	lower, intermediate and higher	higher	< 1
	Navigation channel	higher	higher	< 0.1

Table 4-1 illustrates the spatial variability of estimated sediment dynamics throughout the LDW, which is captured by the revised CSM. For example, locations in the navigation channel with the greatest scour potential also experience the greatest sediment deposition. Similarly, diminished scour potential within the navigation channel tends to correspond with decreased sediment deposition. The balance of scour and deposition tends to scale with the level of sediment dynamics throughout the LDW, further supporting the conclusions of the revised CSM. This observation is consistent with anticipated geomorphic processes that occur during high-flow events. For example, at a particular location in the LDW, scour may occur during the rising limb of the high-flow hydrograph, with the sediment dynamics shifting toward deposition during the falling limb of the hydrograph.

The above results and discussion indicate that the sediment transport characterization study provides sufficient information to confirm the various components of the revised CSM. Thus, the revised CSM should be accepted and considered to be representative of sediment dynamics and bed stability in the LDW.

4.3.2 Recommendations for decision point regarding project status

The empirical and modeling analyses, and associated field studies, conducted during this investigation provide a significant amount of new information and insights about sediment transport processes in the LDW. A clearer picture of LDW sediment transport emerges from this work, particularly with respect to sediment stability. In addition, the refined CSM for sediment transport is well-supported by various lines of evidence.

A significant amount of knowledge about sediment stability and large-scale sediment transport processes has been gained during this study. From a qualitative viewpoint, our understanding of sediment transport in the LDW is well supported. However, the CSM for sediment transport will be refined through application of a sediment transport model to the LDW. Development and application of this model will provide quantitative information on sediment transport processes (e.g., deposition and erosion) over a range of spatial and temporal scales. The data and information contained within this report provide a good foundation for developing, calibrating, and applying the sediment transport model.

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