Lower Duwamish Waterway Group
Port of Seattle / City of Seattle / King County / The Boeing Company

Lower Duwamish Waterway
Sediment Transport Modeling Report
Final

Prepared for:

U.S. Environmental Protection Agency

Region 10

Seattle, WA

Washington State Department of Ecology

Northwest Regional Office

Bellevue, WA

Prepared by:

Quantitative Environmental Analysis, LLC

Montvale, NJ

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List of Acronyms

CI	Confidence Interval
CFS	Cubic Feet Per Second
CSM	Conceptual Site Model
CSO	Combined Sewer Overflow
EAA	Early Action Area
EFDC	Environmental Fluid Dynamics Code
EPA	U.S. Environmental Protection Agency
FS	Feasibility Study
GSD	Grain Size Distribution
LAE	Linear Attribution Estimate
LDW	Lower Duwamish Waterway
LDWG	Lower Duwamish Waterway Group
MLLW	Mean Lower Low Water
MNR	Monitored Natural Recovery
MT	Metric Ton
MTCA	Model Toxics Control Act
NOAA	National Oceanic and Atmospheric Administration

NPL	National Priority List
NSR	Net Sedimentation Rate
Pa	Pascal
PCB	Polychlorinated Biphenyl
QEA	Quantitative Environmental Analysis, LLC
RI	Remedial Investigation
RM	River Mile
SSC	Suspended Sediment Concentration
STAR	Sediment Transport Analysis Report
STM	Sediment Transport Model
TE	Trapping Efficiency
TSS	Total Suspended Solids
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
Windward	Windward Environmental, LLC

EXECUTIVE SUMMARY

ES.1 SEDIMENT TRANSPORT MODELING STUDY

The evaluation of various remedial alternatives in the Lower Duwamish Waterway (LDW), including Monitored Natural Recovery (MNR), during the Feasibility Study (FS) requires an understanding of sediment transport within the study area. The Sediment Transport Analysis Report (STAR) study (Windward and QEA 2007) produced a significant amount of information on LDW sediment transport. However, a limitation of those analyses is the inability to predict erosion, deposition, and net sedimentation throughout the LDW during high-flow events and over multi-year periods. It was recognized by the Lower Duwamish Waterway Group (LDWG), the Washington Department of Ecology (Ecology), and the U.S. Environmental Protection Agency (EPA) that development of a sediment transport model may enhance the efficacy of various analyses during the FS process. This study is strictly focused on analyzing the physical transport of sediment in the LDW. The FS will use the results of these analyses, along with relevant chemical information, to examine the importance of sediment transport processes as they relate to remedial alternatives for the LDW. The FS will include an evaluation of natural recovery potential, and estimated natural recovery rates, using the results of the sediment transport modeling.

For convenience, brief definitions of the following terms related to sediment transport processes 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 as a result of 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 as a result of 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 as a result of 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 or dynamic equilibrium 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 1 year or longer (i.e., annual time scales). The net sedimentation rate is the rate at which net deposition occurs.

Discussions and meetings between LDWG, Ecology, and EPA, during July and August, 2006, concerning a sediment transport model resulted in the formation of a sediment transport model (STM) group that worked collaboratively and provided advice on the development, calibration, and application of the model. The members of this group have included: Shane Cherry (Cherry Creek Environmental, Inc.), Karl Eriksen (USACE), Joe Gailani (USACE), Earl Hayter (USACE), Brad Helland (Ecology), Bruce Nairn (King County), Mike Riley (S.S. Papadopulos & Associates), Peter Rude (City of Seattle), Beth Schmoyer (City of Seattle), David Schuchardt (City of Seattle), Jeff Stern (King County), Kym Takasaki (USACE), and Kirk Ziegler (QEA). The STM group held meetings, conference calls, and informal discussions among members at various times between August 2006 and April 2008 to review model status and discuss the next steps to be taken in model development, calibration, and application.

Generally, the STM group attempted to reach consensus on decisions about STM development, calibration and application, but consensus was not a requirement for moving forward with the modeling work. This collaborative effort was instrumental in producing the modeling framework presented in this report, and in achieving the following overall study objectives:

- develop a quantitative tool to evaluate short-term and long-term sediment transport processes in the LDW;
- refine the Conceptual Site Model (CSM) for the LDW; and
- provide information to support FS analyses and inform remedial decision making.

Only sediment transport modeling was conducted during this study; a chemical transport and fate model was not developed.

Both short-term (episodic) and long-term sediment transport phenomena were examined through application of the sediment transport model. Multi-year simulations were conducted to predict long-term changes in bed elevation (i.e., net sedimentation rate), as well as changes in surface-layer sediment composition. These results will be used in the FS to estimate the rate of natural recovery in the LDW attributable to sediment transport processes. Specific questions that are addressed using the sediment transport model for long-term, multi-year periods (e.g., 30 years) include:

- What areas in the LDW are net depositional, net erosional, or in dynamic equilibrium?
- How does the composition of the surface-layer sediment change over time as external sediment loads (from upstream and lateral sources, such as storm drains) become incorporated into the sediment bed?
- What is the effect of high-flow events on episodic scour in otherwise net depositional areas?
- What is the potential depth of scour during high-flow events in areas that are net depositional, net erosional, or in dynamic equilibrium?

In addition, the effects of high-flow events on bed scour, and the potential for re-exposing buried sediments, were evaluated with the model. The FS will examine whether the predicted scour depths have the potential for re-exposing buried sediments with chemical concentrations at levels of concern, and whether specific remedial actions are warranted to address bed scour during high-flow events. For episodic high-flow events, questions of interest include:

- What areas in the LDW are depositional and what areas experience erosion during a high-flow event?
- In the areas that experience erosion during high-flow events, what is the potential depth of scour?
- What is the potential for re-exposing buried sediments?

ES.2 MODEL CAPABILITIES AND LIMITATIONS

The sediment transport model used in this study, referred to as SEDZLJ, has been developed over the past 20 years and is capable of simulating erosion and deposition of sediment within cohesive (i.e., muddy) and non-cohesive (i.e., sandy) bed areas (Ziegler et al. 2000; Jones and Lick 2001). The sediment transport model has the following characteristics and capabilities: 1) three-dimensional transport of suspended sediment in the water column; 2) use of Sedflume core data to specify erosion rate parameters; 3) spatially variable bed properties; 4) sediment bed model that tracks temporal changes in bed composition (i.e., sediment particle size, sediment source); and 5) bedload transport of sand.

The sediment transport model is incorporated into the Environmental Fluid Dynamic Code (EFDC). The hydrodynamic model within EFDC is linked to the sediment transport model via a coupling file, which transfers hydrodynamic transport information (e.g., current velocity, water depth) from the hydrodynamic model to the sediment transport model. The coupling file is used as input to the model during a sediment transport simulation. This process significantly reduces the time required to complete a sediment transport simulation because: 1) a larger timestep can be used than if the hydrodynamic and sediment transport models are running in parallel; and 2) the computational burden is lower because the hydrodynamic calculations do not have to be repeated every time a sediment transport simulation is repeated for a specific time period. Long-term, multi-year simulations are only practical using the coupling-file approach.

The coupling between the hydrodynamic and sediment transport models produces a limitation on the predictive capabilities of the modeling framework. This coupling is one-way with no feedback between the two models; output from the hydrodynamic model feeds into the sediment transport model. Changes in bed elevation predicted by the sediment transport model are not incorporated into the hydrodynamic model (i.e., bathymetry in the hydrodynamic model is assumed to remain constant with time). This limitation may have the most impact on model predictions in the region of the upper turning basin (i.e., near RM 4.5), where high net sedimentation rates may cause substantial changes in channel morphology over relatively short periods of time and, subsequently, affect hydrodynamic circulation in that region. However, since this area is routinely dredged to maintain navigation depths, the effect in this area is reduced. While this limitation may appear to reduce the reliability of the model predications, successful calibration and validation of the model, along with the results of the spatial-scale and uncertainty analyses, indicate that this limitation in the modeling framework does not have a significant effect on the predictive capabilities of the model in most of the LDW.

ES.3 MODEL CALIBRATION AND VALIDATION

The mathematical modeling framework that was applied to the LDW consists of hydrodynamic and sediment transport models that are linked together. The hydrodynamic model simulates the movement of water in the LDW. This model includes the effects of the following factors on water movement: freshwater inflow from the Green River; tides in Elliott Bay; and estuarine circulation (i.e., saltwater wedge) resulting from density differences between seawater and freshwater. The hydrodynamic model is used to simulate temporal and spatial changes in water depth, current velocity, and bed shear stress. This information is transferred from the hydrodynamic model to the sediment transport model, where it is used to simulate the erosion, deposition, and transport of sediment in the LDW. The sediment transport model is used to simulate temporal and spatial changes in: suspended sediment concentrations in the water column; bed elevation changes (i.e., bed scour depth, net sedimentation rate); and changes in sediment bed composition (i.e., relative amounts of clay, silt, and sand from different sources).

The hydrodynamic model originally developed and calibrated during the STAR study was re-calibrated because modifications were made to the numerical grid. Modifications to the numerical grid used in the STAR study were necessary so that long-term, multi-year simulations could be accomplished during the STM study. The numerical grid upstream of RM 5.7 was modified such that the river channel is now represented by a single grid cell in the cross-channel direction. In addition, the original grid was modified so that slips located along the eastern shore of the LDW are included in the numerical grid. The re-calibration results show that the hydrodynamic model realistically simulates all of the major characteristics of estuarine circulation in the LDW. The vertical structure of tidal current velocity is realistically simulated, with the model able to reproduce two-layer flow in the region occupied by the saltwater wedge. Overall, re-calibration of the hydrodynamic model demonstrates that the model is sufficiently accurate and reliable for the objectives of this study.

The sediment transport model is built on a foundation of mechanistic formulations that are used to simulate erosion and deposition of cohesive (muddy) and non-cohesive (sandy) sediment. The erosion and deposition formulations used in the model are based on results from a large number of laboratory and field studies. Site-specific data were used to determine model inputs, including sediment loading from the Green River and erosion properties of LDW sediments, which are two important model inputs. The significant amount of site-specific data, in conjunction with the mechanistic nature of the model formulations, provided an opportunity to develop and calibrate a reliable sediment transport model that is well constrained.

ES.4 MODEL PREDICTIVE CAPABILITY AND RELIABILITY

Calibration and validation of the sediment transport model, in conjunction with the spatial-scale and uncertainty analyses, were used to evaluate the accuracy and reliability of the model. The objective of the spatial-scale analysis was to determine the relationship between model predictive capability and spatial scale. The following general conclusions were derived from the spatial-scale analysis: 1) average absolute difference between predicted and empirically estimated net sedimentation rate (NSR) values is less than ± 0.25 cm/year for spatial scales ranging from about 0.5 to 300 acres, which indicates that the predicted NSR values are not biased low or high over this range of spatial scales; 2) 95% confidence interval about the average absolute difference is about ± 0.5 cm/year for areas less than about 8 acres, about ± 0.38 cm/year for areas between about 8 and 20 acres, and less than ± 0.38 cm/year for areas between about 20 and 300 acres; and 3) variation (standard deviation) in absolute differences increases with decreasing spatial area, which is an expected characteristic.

The objective of the uncertainty analysis was to evaluate the effect of uncertainty in model inputs on model predictions. The uncertainty analysis demonstrated that two model inputs (upstream sediment load and class 1A/1B settling speed) are the primary controlling factors of predicted NSR over multi-year periods in the LDW. The upstream sediment load was specified using the results of two U.S. Geological Survey (USGS) studies that provide estimates of the magnitude of the Green River load. Class 1A/1B settling speeds were treated as adjustable parameters during model calibration, with the model being relatively sensitive to these parameters. Therefore, the two primary model inputs controlling predicted NSR over multi-year periods were reliably defined by site-specific data (i.e., USGS studies) and model calibration (i.e., class 1A/1B settling speeds). The results of the uncertainty analysis were used to generate realistic lower- and upper-bound uncertainty limits on the model calibration results. The uncertainty analysis results demonstrate that uncertainty in model inputs does not change the overall STM conclusions or the CSM.

The 21-year simulation period used to calibrate and validate the model was a strong test of the model's capabilities because of the wide range of tidal and river flow conditions during that period. Results of the calibration and validation exercises, as well as the spatial-scale and uncertainty analyses, demonstrate that the sediment transport model is able to adequately predict NSRs and bed composition in the navigation channel and bench areas. These results indicate that the model adequately simulates sediment transport processes in the LDW for the purposes and applications specified in this report. Based on these results, the following conclusions concerning model reliability were developed:

- The STM may be used to refine, confirm and validate the CSM.
- The analysis provides quantitative uncertainty estimates for STM predictions and CSM components.
- The STM provides a framework to support evaluation of physical processes and the effects of potential actions in the LDW.
- Over small spatial-scales (i.e., areas corresponding to approximately one or two grid cells in size), the STM will typically demonstrate trends that may be used as one line-of-evidence, along with other information and data, to guide decision making.
- The STM is a reliable framework for supporting extrapolation to conditions where no erosion and/or NSR data are available.

The STM group collaborated and provided guidance during the calibration and validation process, with important contributions being made by various group members. The group reviewed the results of the calibration and validation simulations, as well as the spatial-scale and uncertainty analyses, during April 2008. After discussion among the members of the STM group, concurrence was reached on the five conclusions presented above.

Acceptable reliability of the STM makes it possible to use model results to support FS analyses. The model provides a reliable framework for use as a diagnostic and prognostic tool to extrapolate information to areas in the LDW where either no data or minimal data are available for FS evaluations. However, it is emphasized that the STM provides only one line-of-evidence for the FS analyses, which will typically rely on multiple lines-of-evidence to reach conclusions about the efficacy of a range of remedial alternatives.

ES.5 INTEGRATION AND SYNTHESIS OF RESULTS

The modeling analyses conducted during this study, in conjunction with empirical analyses (e.g., estimation of net sedimentation rates in the bench areas) and ship-induced bed scour analyses from the STAR study, have produced an improved understanding of sediment transport processes in the LDW. A large amount of information on LDW hydrodynamics and sediment transport is presented in this report, and in the STAR (Windward and QEA 2007). Results and findings from the major components of the study were integrated and synthesized to produce a clear and concise picture of sediment transport in the LDW.

The LDW was separated into three reaches as a convenient aid for understanding and describing hydrodynamic and sediment transport processes in the study area: Reach 1 (RM 0.0 – 2.2); Reach 2 (RM 2.2 – 4.0); and Reach 3 (RM 4.0 – 4.8). Separation of the study area into these three reaches was based on the hydrodynamic and sediment transport characteristics of the LDW during high-flow events.

The first step in understanding sediment transport in the LDW is to understand the hydrodynamics of this saltwater-wedge estuary. During low-flow conditions in the Green River, the saltwater wedge extends to or beyond the upstream portion of Reach 3 (i.e., RM 4.5 to 4.8), see Figure ES-1. The saltwater wedge is dominated by two-layer estuarine circulation, with saltier and denser water transported upstream in the lower-layer of the water column and fresher water transported downstream in the upper-layer. Near-bed velocities, and bed shear stresses, within the saltwater wedge are tidally driven and relatively low, which results in minimal bed scour within the saltwater wedge during low-flow conditions. During a high-flow event (which in the discussion presented in this sub-section is defined as a discharge equivalent to a 2-year high-flow event or greater) in the Green River, with durations ranging between about 3 and 30 days, the toe of the saltwater wedge is pushed downstream to the vicinity of the boundary between Reaches 1 and 2 (i.e., RM 2.0 to 2.5). Two-layer estuarine circulation exists within the saltwater wedge (Reach 1) during a high-flow event (Figure ES-2). High freshwater inflow causes the hydrodynamic characteristics of Reaches 2 and 3 to change from two-layer estuarine circulation (low-flow conditions) to a freshwater tidal river. This change in the hydrodynamic characteristics of these two reaches results in significant increases in near-bed current velocities and bed shear stresses in Reaches 2 and 3 during a high-flow event.

Overall, Reaches 1, 2, and 3 have different sediment transport characteristics, primarily as a result of differences in the hydrodynamic characteristics of each reach during high-flow events and the sediment load from upstream sources. Reach 1 has relatively high net sedimentation rates, but these rates are generally lower than the rates in Reach 3 because less sand is transported into this portion of the LDW than into the upstream reach. Reach 2 has net sedimentation rates that are spatially variable, with areas of relatively low net sedimentation. This reach experiences the most erosion during a high-flow event as a result of relatively high bed shear stresses caused by changes in hydrodynamics during an event (i.e., transition from estuarine circulation with a saltwater wedge during low-flow conditions to a tidal freshwater river during high-flow conditions). Reach 3 has the highest net sedimentation rates in the LDW, because of the presence of the upper turning basin, which acts as a sediment "sink" and captures a large portion of the load of sand from the Green River.

During a high-flow event, most of the bed scour occurs in Reach 2, with Reach 1 having minimal erosion except in a small area near RM 0.8-0.9. Limited net erosion occurs in Reach 3. During a high-flow event with a return period of 100 years, model predictions indicate that about 18% of the total bed area in the LDW (i.e., about 70 acres) is net erosional, with most of the bed scour occurring in Reach 2. The remaining 82% of the total bed area in the LDW experiences net deposition during a 100-year high-flow event (Figure ES-3). A large majority of the predicted net erosion is limited to the surface layer (i.e., 0 to 10 cm) of the bed, with about 6% of the total bed area (about 22 acres) having net erosion greater than about 10 cm. The maximum depth of bed scour (i.e., net erosion) during a 100-year high-flow event is about 21 cm, with the effects of bed armoring limiting the depth of bed scour. Approximately 78% of the sediment mass eroded from the bed is re-deposited within the LDW, with the remaining 22% transported out of the LDW. Areas that are predicted to be net erosional during a 100-year event are typically net depositional over long-term, multi-year periods which include high-flow events that are similar in magnitude to a 100-year event.

Reaches 1, 2, and 3, and thus the entire LDW, are net depositional on annual timescales. The general effect of erosion during high-flow events is to reduce the net sedimentation rate in locations where bed scour occurs. Net sedimentation rates, on a reach-average basis, vary from about 2 cm/yr in Reaches 1 and 2 to over 15 cm/yr in Reach 3 (excluding the upper turning basin). Reach 2 was separated into two sub-reaches based on differences in net sedimentation rate, with the spatially-averaged rate in Reach 2A (RM 2.2-2.6) being about 50% higher than the average rate in Reach 2B (RM 2.6-4.0), see Figure ES-4. Within Reach 3, the upper turning basin, which is designed to be an effective sediment trap, has an average net sedimentation rate of over 40 cm/yr. Generally, spatially-averaged net sedimentation rates are similar in the navigation channel and bench areas, with differences between the zones being less than a factor-of-two in a particular reach.

Three sources of sediment are transported within the LDW: upstream source (Green River); lateral source (streams, stormwater runoff, combined sewer overflows [CSOs]); and original bed source. The annual average sediment load from lateral sources is estimated to be approximately 0.6% of the annual average sediment load from the Green River. Approximately 49% of the external sediment load, from upstream and lateral sources, is deposited (or trapped) in the LDW (Figure ES-4). Trapping efficiency (i.e., portion of incoming sediment load deposited within a reach) varies between the three reaches as a result of differences in the hydrodynamic and sediment transport characteristics of these reaches.

The transport of suspended sediment within the water column is dominated by the upstream source (on an annual average basis), with that source component composing over 99% of the total suspended sediment load (Figure ES-4). Among the sediment transported downstream of the LDW (i.e., past RM 0.0), sediment originating from the upstream source represents over 99% of the total suspended load, with sediment originating from lateral and bed sources composing about 0.5% and less than 0.2% of the total load past RM 0.0, respectively. The contribution from lateral sources to the total suspended sediment load exiting the LDW at RM 0.0 is about two to three times greater than the contribution from the bed-source sediment.

The bed-source content of the surface (0-10 cm) layer decreases with time at an approximately exponential rate, primarily because of the deposition of upstream-source sediment. The rate of decrease is spatially variable within the LDW as a result of variations in net sedimentation rate. Half-time (i.e., time needed for 50% of material in the initial surface layer [0-10 cm] of the sediment bed to be replaced with depositing sediments) is a convenient measure of the rate of decrease of bed-source content. Approximately 94% of the total bed area in the LDW has a half-time of 10 years or less. About 6% of the LDW bed area has a half-time of 30 years or more; net sedimentation rates in these areas are less than about 0.3 cm/yr. Predicted decreases in reach-average bed-source content, and corresponding half-times, over a 30-year period are shown in Figure ES-5.

Comparison of the reach-average NSR values on Figure ES-4 to the reach-average half-time values on Figure ES-5 demonstrates the complex relationship between NSR and half-time caused by erosion and deposition processes in the LDW. For example, Reaches 1 and 3 have the same reach-average half-time, but the reach-average NSRs for Reaches 1 and 3 are 1.8 and 15 cm/yr, respectively. With respect to the half-time estimates, one of the primary simplifying assumptions in the idealized analysis is that deposition is continuous and occurs at a constant rate. As deposition and erosion processes at a specific location deviate from this simplifying assumption, the agreement between model predictions of the rate of bed-source content decline and the exponential model will degrade. However, the degradation in agreement between the STM predictions and the exponential model does not affect the reliability of the STM because this comparison is for illustrative purposes only.

Generally, the effects of sediment loads from lateral sources are greatest in the immediate vicinity of the discharge point of a storm drain, CSO, or stream. In Reaches 2 and 3, elevated lateral-source content (i.e., greater than 1%) in surface-layer sediment generally occurs in the slips near the storm drain/CSO/stream discharge points. The effects of lateral sources on surface-layer composition are more widely distributed in Reach 1, with elevated lateral-source content values (greater than 1%) occurring over approximately 88% of the bed area of this reach.

At the end of a 30-year period, reach-average values of lateral-source content in the surface layer of the bed are about 1% to 2% (Figure ES-6).

An analysis of gross bed scour potentially resulting from upstream and downstream movements of ships within the navigation channel was used to assess the effects of ship movement on bed stability in the LDW. Important findings from that analysis are as follows. Ship-induced bed scour is viewed as an impulsive erosion-deposition process (i.e., bed sediment is eroded during a 1-3 minute period as a ship passes and is then re-deposited) that tends to behave like a mixing process for surficial bed sediment. In this view, the reworked surface layer is equated to the depth of gross bed scour. 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 Reach 2, 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 such mixing is about 100 to 250 events per year in the lower reaches of the LDW (i.e., downstream of RM 4.0), with a lower frequency farther downstream. 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. In summary, an analysis of ship-induced bed scour was conducted independently of the sediment transport model. The results indicate that ship-induced bed scour behaves as a mixing process for surficial bed sediment and it does not affect the insights and conclusions developed from the sediment transport modeling.

ES.6 REVISED CONCEPTUAL SITE MODEL FOR SEDIMENT TRANSPORT

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 CSM developed during the STAR study. The revised CSM for sediment transport is:

- Reaches 1, 2, and 3, and thus the entire LDW, are net depositional 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 4.5) to downstream areas. For the bench areas, net sedimentation rates are higher in Reaches 1, 2A, and 3 than in Reach 2B. Net sedimentation rates tended to be lower in the inter-tidal areas than in the sub-tidal 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 2, was lower in Reach 3 than in Reach 2, and was minimal in Reach 1. Net erosion occurs over about 18% or less of the LDW bed area during high-flow events with return periods of 2 years or greater (i.e., erosional area increases with increasing return period); most of the bed scour is less than 10 cm deep and maximum net erosion depths are 21 cm or less.
- Ship-induced bed scour tends to behave as a mixing process for surficial sediment for typical ship traffic within the navigation channel. The effects of berthing operations may cause net erosion at small, localized areas. 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 is presented in Section 4.3 (i.e., Figure 4-2). 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.

The revised CSM is extended to the three reaches of the LDW separately. 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: RM 0.0 to 2.2

This reach is net depositional on annual time scales, in both the navigation channel and the adjacent bench areas. Based on net sedimentation rates predicted by the model, the navigation channel is classified as intermediate and higher net depositional, with a small area near RM 0.8-0.9 being lower net depositional. The bench areas range from intermediate to higher net depositional, with two small areas classified as lower net depositional. With respect to episodic erosion, this reach is always within the saltwater wedge, even during a 100-year 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, resulting in relatively low bed scour (less than 2 cm) within only a small area near RM 0.8-0.9. The potential for re-exposing buried sediments as a result of 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 2.2 to 4.0

Reach 2 is net depositional on annual time scales. Net sedimentation is spatially variable in this reach, with classification in the navigation channel and bench area ranging from lower to higher net depositional. This reach experiences significantly more net erosion during high-flow events than Reaches 1 and 3, but erosion is generally limited to the upper 10 cm of the sediment bed and maximum net erosion depths are 21 cm or less. The primary cause of relatively high net erosion during high-flow events (i.e., return period of 2 years or greater) in Reach 2 is the hydrodynamic characteristics of this reach, which experiences relatively high bed shear stresses during high-flow events. 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: RM 4.0 to 4.8

This reach is net depositional on annual time scales. The relatively high net sedimentation rates in this reach indicate that the navigation channel and bench areas are classified as higher net depositional. Modeling results indicate that episodic erosion may occur during high-flow events in Reach 3, but the areal extent of net erosion is significantly less than the areal extent of net erosion in Reach 2. Bed scour during high-flow events (i.e., 2-year event or greater) is generally limited to the upper 15 cm of the sediment bed, with maximum scour depths of 20 cm. 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.

SECTION 1
INTRODUCTION

The Lower Duwamish Waterway (LDW) was added to the U.S. Environmental Protection Agency's (EPA's) National Priority List (NPL, also known as Superfund) on September 13, 2001. The LDW Superfund study area extends from the southern tip of Harbor Island, located at river mile (RM) 0.0, to the vicinity of the Norfolk storm drain and combined sewer overflow (CSO), located near RM 4.9 (see Figure 1-1). In addition, the LDW is a Model Toxics Control Act (MTCA) site and it was added to Ecology's Hazardous Site List on February 6, 2002. Under Superfund regulations, EPA requires that a remedial investigation (RI) and feasibility study (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.

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. Generally, sediment transport processes (i.e., net sedimentation, erosion, bed stability) have a significant effect on the transport and fate of these types of chemicals. Accordingly, this study is focused on a quantitative evaluation of the physical transport of sediment. The FS will use the results of these analyses, along with relevant chemical information, to examine the importance of sediment transport processes relative to potential remedial alternatives for the LDW. The FS will include an evaluation of natural recovery potential, and estimated natural recovery rates, using the results of the sediment transport modeling.

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 near the southern tip of Harbor Island to RM 4.9, which is upstream of the upper turning basin. 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. A large-scale view of the LDW and the upstream watershed, including the location of the Howard Hansen Dam, is provided in Figure 1-2.

The U.S. Army Corps of Engineers (USACE) maintains the LDW as a navigable waterway through periodic dredging (Dexter et al. 1981). The USACE is authorized to maintain and operate the Federal Navigation channel on the LDW according to dimensions described in the 71st Congress, House of Representatives, Document No. 126, 1929 and adopted in Public Law, PL 71-520. Maintenance dredging by the USACE extends upstream to the upper turning basin, which is located at approximately RM 4.6.

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 deeper than -30 ft. mean lower low water (MLLW) downstream of RM 2.0 to shallower than the authorized depth (i.e., -15 ft. MLLW) near the upper turning basin. Shallower bench areas exist in the nearshore, inter-tidal, and shallow sub-tidal zones outside of the navigation channel, with variable dimensions and elevations (with minimum depths shallower 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 occupied predominantly 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 fresher water 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 fresher water 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 length of 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 (located at RM 22.6) 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. Before construction of the dam, flow rates in the river during high-flow events could exceed 20,000 cubic feet per second (cfs). After dam construction, maximum flow rates in the river are limited to approximately 12,000 cfs, which corresponds to the discharge for a 100-year high-flow event. 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 sediment 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 sediment 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 result in greatly reduced flow velocities, which promote 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 bedload. 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, as well as the tidal conditions (i.e., neap and spring tide conditions). 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 re-deposited 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), contains a relatively small amount of sediment (i.e., has a low bulk density), and is not part of the consolidated sediment bed. Second, rare storm events may increase current velocities or generate wind waves, which 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 re-deposited, or it may be transported out of the estuary and into the adjacent coastal waters. A detailed technical discussion of estuarine sediment transport processes is provided in Dyer (1986).

1.2 PREVIOUS STUDIES RELATED TO LDW SEDIMENT TRANSPORT

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 critical velocities for scour estimated 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 (1999)	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]), and estimated that net sedimentation rates there range from 1 to 110 cm/yr (with the higher end of that range only in the upper turning basin). However, only limited data are available on sediment bed elevation changes in the shallower bench[1] 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). A preliminary analysis of anthropogenic effects (e.g., ship propeller forces) on sediment bed scour was also discussed in the Phase 1 RI.

[1] 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.

This analysis was conducted for the berthing areas of the Duwamish/Diagonal area (King County et al. 2003) and for the area offshore of Boeing Plant 2 (Pentec et al. 2001).

The initial phase of the sediment transport study discussed in this report focused on the depositional environment in the LDW and the effects of natural and anthropogenic events on bed stability. The results of that phase of the sediment transport study are presented in the Sediment Transport Analysis Report (STAR) prepared by Windward and QEA (2007). The results of data and modeling analyses presented in the STAR have been used in developing, calibrating, and applying the sediment transport model discussed in this report.

1.3 CONCEPTUAL SITE MODEL DEVELOPMENT

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 transport and fate 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. Conceptual site models 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 initial 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 initial CSM consisted 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).

- Bed erosion occurs only episodically and over small spatial scales.

The primary goal of the STAR study was to develop 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 were used to refine the initial CSM as follows (Windward and QEA 2007):

- 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 inter-tidal areas than in the sub-tidal 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 than in 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 CSM will continue to be revised as the RI/FS for the LDW is developed. Section 5.8 of this report presents revisions to the CSM based on the results of this modeling effort.

1.4 DEFINITIONS OF SEDIMENT TRANSPORT TERMS

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 as a result of 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 as a result of 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 as a result of 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 or dynamic equilibrium 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 1 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.

This process is illustrated by some of the modeling results presented in this report. In the above definitions, high-flow event refers to a river discharge with a return period of 2 years or greater.

1.5 SEDIMENT TRANSPORT MODELING STUDY

The evaluation of various remedial alternatives in the LDW, including Monitored Natural Recovery (MNR), during the FS requires an understanding of sediment transport within the study area. The STAR study produced a significant amount of information on LDW sediment transport. However, a limitation of those analyses is the inability to predict erosion, deposition, and net sedimentation throughout the LDW during high-flow events and over multi-year periods. It was recognized by the Lower Duwamish Waterway Group (LDWG), the Washington Department of Ecology (Ecology), and EPA that development of a sediment transport model may enhance the efficacy of various analyses during the FS process, as well as refine and validate the CSM.

Discussions and meetings between LDWG, Ecology, and EPA, during July and August, 2006, concerning a sediment transport model resulted in the formation of a sediment transport model (STM) group that worked collaboratively and provided advice on the development, calibration, and application of the model. The members of this group have included: Shane Cherry (Cherry Creek Environmental, Inc.), Karl Eriksen (USACE), Joe Gailani (USACE), Earl Hayter (USACE), Brad Helland (Ecology), Bruce Nairn (King County), Mike Riley (S.S. Papadopulos & Associates), Peter Rude (City of Seattle), Beth Schmoyer (City of Seattle), David Schuchardt (City of Seattle), Jeff Stern (King County), Kym Takasaki (USACE), and Kirk Ziegler (QEA). The STM group held meetings, conference calls, and informal discussions at various times between August 2006 and April 2008 to review model status and discuss the next steps to be taken in model development, calibration, and application. This collaborative effort was instrumental in producing the modeling framework presented in this report, and in achieving the study objectives that are discussed below.

1.6 STUDY OBJECTIVES

The overall objectives of the sediment transport modeling study are to:

- develop a quantitative tool to evaluate short-term and long-term sediment transport processes in the LDW;
- refine the CSM for the LDW; and
- provide information to support FS analyses and inform remedial decision-making.

Only sediment transport modeling was conducted during this study; a chemical transport and fate model was not developed. However, several issues concerning the potential effects of sediment transport on chemical transport and fate were addressed through application of the sediment transport model. Multi-year simulations were conducted to predict long-term changes in bed elevation (i.e., net sedimentation rate), as well as changes in surface-layer sediment composition. These results will be used in the FS to estimate the rate of natural recovery in the LDW attributable to sediment transport processes. Specific questions that are addressed using the sediment transport model for long-term, multi-year periods (e.g., 30 years) include:

- What areas in the LDW are net depositional, net erosional, or in dynamic equilibrium?
- How does the composition of the surface-layer sediment change over time as external sediment loads (from upstream and lateral sources, such as storm drains) become incorporated into the sediment bed?
- What is the effect of high-flow events on episodic scour in otherwise net depositional areas?
- What is the potential depth of scour during high-flow events in areas that are net depositional, net erosional, or in dynamic equilibrium?

In addition, the effects of high-flow events on bed scour, and the potential for re-exposing buried sediments, were evaluated with the model. The FS will examine whether the predicted scour depths have the potential for re-exposing buried sediments with chemical concentrations at levels of concern, and whether specific remedial actions are warranted to address bed scour during high-flow events. For episodic high-flow events, questions of interest include:

- What areas in the LDW are depositional and what areas experience erosion during a high-flow event?
- In the areas that experience erosion during high-flow events, what is the potential depth of scour?
- What is the potential for re-exposing buried sediments?

The following model output was used to achieve the goals of this study and address various questions related to both the RI and FS:

- areas of net deposition and net erosion, areas that experience erosion during a high-flow event, and areas that are in dynamic equilibrium;
- spatial and temporal changes in bed elevation and composition;
- water-column concentrations of suspended sediment (temporally and spatially variable);
- changes in composition of existing surface-layer sediment as a result of external sediment loads; and
- resuspension and fate of sediment from the bed.

1.7 GENERAL DESCRIPTION OF MODELING FRAMEWORK

The mathematical modeling framework that was applied to the LDW consists of hydrodynamic and sediment transport models that are linked together. The hydrodynamic model simulates the movement of water in the LDW. This model includes the effects of the following factors on water movement: freshwater inflow from the Green River; tides in Elliott Bay; and estuarine circulation (i.e., saltwater wedge) resulting from density differences between seawater and freshwater. The hydrodynamic model is used to simulate temporal and spatial changes in water depth, current velocity, and bed shear stress. This information is transferred from the hydrodynamic model to the sediment transport model, where it is used to simulate the erosion, deposition, and transport of sediment in the LDW. The sediment transport model is used to simulate temporal and spatial changes in: suspended sediment concentrations in the water column; bed elevation changes (i.e., bed scour depth, net sedimentation rate); and changes in sediment bed composition (i.e., relative amounts of clay, silt, and sand from different sources).

The modeling framework provides a deterministic approach for simulating sediment transport within the LDW. The sediment transport model simulates the movement of sediment by suspended load (i.e., primarily clay, silt, fine sand) and bedload (i.e., primarily medium, coarse sand) modes of transport. The hydrodynamic and sediment transport models are constrained by governing equations that are based on the conservation of mass and momentum. Mechanistic formulations and algorithms are used in the sediment transport model to simulate deposition and erosion of cohesive and non-cohesive sediment. The formulations and algorithms used to simulate deposition and erosion are based on empirical information and data from a wide range of laboratory and field studies. In addition, site-specific data are used to determine various parameters used in the sediment transport model, which provides additional constraints on the model.

1.8 OVERVIEW OF TECHNICAL APPROACH

The development and application of a sediment transport model for the LDW involves the following basic steps:

- development, calibration and validation of the hydrodynamic model;
- collection, compilation, and analysis of data related to sediment transport;
- preparation of inputs for the sediment transport model;
- calibration and validation of the sediment transport model; and
- application of the calibrated model as a tool to address study questions related to sediment transport.

An overview of the technical approach used to implement these five steps is provided below.

The first step in developing a modeling framework for the LDW was the development and calibration of a hydrodynamic model because of the dependence of the sediment transport model on hydrodynamic information (i.e., current velocity, bed shear stress). A hydrodynamic model for the LDW was developed and calibrated during the STAR study (Windward and QEA 2007). As discussed in Section 2 of this report, modifications to the numerical grid used in the STAR study were necessary so that long-term, multi-year simulations could be accomplished during the STM study. Therefore, the hydrodynamic model needed to be re-calibrated using the modified numerical grid.

Sediment transport data were collected, compiled, and analyzed during the STAR study (Windward and QEA 2007). Sediment cores were collected from the LDW and erosion rate data obtained using a device called Sedflume. The Sedflume core data were analyzed and used to quantify the erosion properties of LDW sediments. Additional analysis of the Sedflume core data was conducted during this study to evaluate the spatial variability of erosion properties within the LDW. Net sedimentation rates in the bench areas of the LDW were estimated using time-markers based on physical, chemical, and radioisotope data from sediment cores collected throughout the LDW. Bulk bed property data (e.g., grain size distribution, dry density) were also compiled and analyzed during the STAR study.

The preparation of inputs for the sediment transport model used the data collected, compiled, and analyzed during the STAR study, as well as data and information from other sources. Inputs for the sediment transport model are separated into three broad categories: 1) sediment properties; 2) bed properties; and 3) boundary conditions.

Sediment properties are the physical properties of sediment particles. The model simulates the movement of sediment particles separated into different size classes, with each size class representing sediment within a specific range of particle diameters. Four sediment size classes are used in this study, with the size classes representing these types of sediment: 1) clay and fine silt (less than 10 μm); 2) medium and coarse silt (10 to 62 μm); 3) fine sand (62 to 250 μm); and 4) medium and coarse sand (250 to 2,000 μm). The effective diameter of each size class, which determines the settling speed of that sediment class, was determined either from analysis of site-specific data or during model calibration.

Specification of bed properties within the LDW begins with separating the sediment bed into two distinct types of sediment: cohesive and non-cohesive. Cohesive sediment is described as a muddy bed that is composed of a mixture of clay, silt, sand, and organic matter. Non-cohesive sediment corresponds to a sandy bed that has a relatively low amount of clay, silt, and organic matter. Once the spatial (horizontal) distribution of cohesive and non-cohesive sediment in the LDW is determined, model inputs related to bulk bed and erosion properties within each bed type must be specified. The bulk bed properties include: grain size distribution, composition (i.e., relative amounts of clay, silt, sand), and dry (bulk) density. For the bed within cohesive sediment areas, parameters related to erosion rate are determined from the Sedflume core data.

Determining boundary conditions for the model corresponds to the specification of sediment loads at different inflow locations. Both the magnitude and composition of the incoming sediment loads must be specified for model input. The largest source of sediment to the LDW is the Green River. Sediment loading from lateral sources (e.g., storm drains, streams, and CSOs) is relatively small compared to the Green River load, but lateral sediment loads are of importance when considering chemical mass balances in the LDW because differences in chemical concentrations on sediment particles may exist between the lateral-source and Green River loads.

Calibration of the sediment transport model involves adjusting model inputs over reasonable ranges such that the agreement between model results and data is optimized. For this study, the calibration targets were net sedimentation rates in the navigation channel and bench areas of the LDW. The calibration period was a 21-year period extending from 1960 through 1980. Spatial distributions of net sedimentation rate predicted by the model were compared to empirically-derived estimates of net sedimentation rate within the navigation channel and bench areas.

Successful calibration produces a model that can be used as a reliable tool to answer the study questions posed in Section 1.6. The model was used to simulate sediment transport during high-flow events, including an event with a return period of 100 years. A primary result of this analysis was the location and depth of bed scour after a high-flow event. The effect of external sediment loads on the composition of surface-layer bed sediment was evaluated using the results of a 30-year simulation. Two external sediment loads were included in this simulation: 1) upstream (Green River) source; and 2) lateral (storm drains, CSOs, streams) sources. To evaluate uncertainty in model predictions associated with uncertainty in model inputs, sensitivity analyses were conducted as part of the high-flow event and external sediment load analyses.

1.9 REPORT ORGANIZATION

The main body of this report presents an overview and general description of the modeling framework and technical approach. The report focuses on presenting and interpreting model results, and synthesizing those results with other studies and empirical evidence from the LDW. The primary goal of the main body of this report is to address the questions posed in Section 1.6 and to present a refined version of the CSM discussed in Section 1.3. Most of the technical details associated with model theory, development, calibration, and application are provided in the appendices to this report. This report is organized into seven main sections:

- Executive Summary
- Section 1: Introduction
- Section 2: Development, Calibration, and Validation of the Sediment Transport Model
- Section 3: Effects of High-Flow Events on Sediment Bed Stability
- Section 4: Effects of External Sediment Loads on Surface-Layer Bed Composition over Multi-Year Periods

- Section 5: Summary and Synthesis of Results
- Section 6: References

The main body of this report is supported by these appendices:

- Appendix A: Details of Sediment Transport Theory and Formulation
- Appendix B: Development of Sediment Transport Model Inputs
- Appendix C: Re-Calibration and Validation of Hydrodynamic Model
- Appendix D: Details of Sediment Transport Model Calibration and Validation
- Appendix E: Details of Sediment Bed Stability Analysis
- Appendix F: Details of External Sediment Load Analysis

SECTION 2 DEVELOPMENT, CALIBRATION, AND VALIDATION OF THE SEDIMENT TRANSPORT MODEL

The sediment transport model was calibrated to a 21-year period that extended from 1960 through 1980. Prior to calibrating this model, the hydrodynamic model, which was developed during the STAR study, was re-calibrated because of modifications to the numerical grid. An overview of the structure and capabilities of the sediment transport model, along with a discussion of the development of model inputs, is presented below. Summaries of model calibration and validation results are provided, along with results of the spatial-scale and uncertainty analyses. Finally, conclusions regarding the reliability of the sediment transport model are presented.

2.1 NUMERICAL GRID

The hydrodynamic model developed during the STAR study used a numerical grid that contained approximately 2,000 grid cells in the horizontal plane (Windward and QEA 2007). Ten layers, or grid cells, are used in the vertical direction. That numerical grid included about 700 horizontal grid cells in the Green River upstream of RM 5.7, with three grid cells being used in the cross-channel direction. This level of grid resolution in the region upstream of RM 5.7 was not needed to achieve the objectives of this study. In addition, initial testing of the sediment transport model indicated that long-term, multi-year simulations could not be completed in a practical amount of time using the original numerical grid (i.e., approximately 12 hours of computer time to complete a 1-year simulation). Thus, the numerical grid upstream of RM 5.7 was modified. In that region, the river channel is now represented by a single grid cell in the cross-channel direction. In addition, the original grid was modified so that slips located along the eastern shore of the LDW are included in the numerical grid. Downstream of the LDW (i.e., downstream of RM 0.0), the numerical grid extends past Harbor Island and includes Elliott Bay. Placing the downstream boundary of the model at the outer limit of Elliott Bay makes it possible to adequately simulate tidal and estuarine circulation in the LDW because of the relatively large distance between this boundary and the study area. The modified grid has about 1,000 grid cells in the horizontal plane and 10 layers in the vertical direction (see Figures 2-1 through 2-5).

The LDW, extending from RM 0.0 to 4.8, is delineated using 727 grid cells in the horizontal plane. The total area of the LDW represented by the model is 398 acres. The areal sizes of the grid cells in this region range from about 0.1 to 4 acres. The median area of a grid cell is 0.5 acre, with 94% of the grid cells having an areal size of one acre or less. Note that the numerical grid encompasses the entire Superfund study area (see Figure 1-1).

2.2 RE-CALIBRATION OF HYDRODYNAMIC MODEL

Modifying the numerical grid made it necessary to re-calibrate the hydrodynamic model that was originally calibrated during the STAR study (Windward and QEA 2007). The original calibration approach was repeated, except that the modified numerical grid was used. Re-calibration of the hydrodynamic model focused on comparisons between predicted and observed values of tidal elevation, current velocity, and salinity at various locations within the LDW and Elliott Bay. Detailed descriptions of the re-calibration process and results are presented in Appendix C.

The results of the re-calibration exercise indicate that the hydrodynamic model realistically simulates all of the major characteristics of estuarine circulation in the LDW. The model is able to accurately predict tidal elevations over a wide range of tidal forcing and freshwater inflow conditions. The vertical structure of tidal current velocity is realistically simulated, with the model able to reproduce two-layer flow in the region occupied by the saltwater wedge. Strong vertical stratification of salinity is observed within the saltwater wedge and the model is able to simulate that stratification with acceptable accuracy. In addition, the model realistically simulates the dynamic nature of the saltwater wedge and the location of the toe of the saltwater wedge as it varies over the course of a tidal cycle, as well as variations that result from changes in freshwater inflow and phase of the tidal cycle (i.e., spring and neap tide conditions). Overall, re-calibration of the hydrodynamic model was successful, indicating that the model is sufficiently accurate and reliable for the objectives of this study.

2.3 SEDIMENT TRANSPORT MODEL STRUCTURE AND CAPABILITIES

Different sediment particle sizes, ranging from clay to coarse sand, are transported throughout the LDW via either suspended load or bedload transport. Suspended load transport corresponds to the movement of sediment, primarily clay, silt, and fine sand, suspended in the water column. Bedload transport is the movement of sand and gravel in a thin layer (i.e., about 1 mm to 1 cm thick) located just above the sediment bed. Mathematical formulations, based on laboratory and field studies, have been developed to predict suspended load and bedload transport (e.g., van Rijn 1993).

The sediment transport model used in this study, referred to as SEDZLJ, has been developed over the past 20 years and is capable of simulating erosion and deposition of sediment within cohesive (i.e., muddy) and non-cohesive (i.e., sandy) bed areas (Ziegler et al. 2000, Jones and Lick 2001). The sediment transport model has the following characteristics and capabilities: 1) three-dimensional transport of suspended sediment in the water column; 2) use of Sedflume core data to specify erosion rate parameters; 3) spatially variable bed properties; 4) sediment bed model that tracks temporal changes in bed composition (i.e., sediment particle size, sediment source); and 5) bedload transport of sand. A detailed description of the formulations used in and structure of the sediment transport model is provided in Appendix A.

The sediment transport model is incorporated into the Environmental Fluid Dynamic Code (EFDC). The hydrodynamic model within EFDC is linked to the sediment transport model via a coupling file, which transfers hydrodynamic transport information (e.g., current velocity, water depth) from the hydrodynamic model to the sediment transport model. For a particular period, such as the 21-year period used for model calibration, the hydrodynamic model is used to simulate circulation within the study area. During the hydrodynamic simulation, the relevant transport information is output to the coupling file every 15 minutes during the simulation. This frequency of output is necessary to accurately represent the effects of tidal estuarine circulation on sediment transport. The coupling file is used as input to the model during a sediment transport simulation. This process significantly reduces the time required to complete a sediment transport simulation because: 1) a larger timestep can be used than if the hydrodynamic and sediment transport models are running in parallel; and 2) the computational burden is lower because the hydrodynamic calculations do not have to be repeated every time a sediment transport simulation is repeated for a specific time period. For example, the timesteps used in the hydrodynamic and sediment transport models are 2 to 4 seconds and 5 to 15 seconds, respectively. Use of the coupling-file approach reduces the simulation times by nearly a factor-of-ten, with respect to a simulation that has the hydrodynamic and sediment transport models running in parallel. Thus, long-term, multi-year simulations (e.g., 30-year simulation discussed in Section 4) are only possible using the coupling-file approach.

The coupling between the hydrodynamic and sediment transport models produces a limitation on the predictive capabilities of the modeling framework. This coupling is one-way with no feedback between the two models; output from the hydrodynamic model feeds into the sediment transport model. Changes in bed elevation predicted by the sediment transport model are not incorporated into the hydrodynamic model (i.e., bathymetry in the hydrodynamic model is assumed to remain constant with time). This limitation may have the most impact on model predictions in the region of the upper turning basin (i.e., near RM 4.5), where high net sedimentation rates may cause substantial changes in channel morphology over relatively short periods of time and, subsequently, affect hydrodynamic circulation in that region. The primary effect of using the coupling-file approach (i.e., no feedback between the two models) is an under-prediction of the amount of sediment transported downstream of the upper turning basin and into the region between RM 0 and 4.3. If feedback between the two models was incorporated into the modeling framework, then less sediment would be deposited in the upper turning basin as the basin filled up and that sediment would be transported further downstream, where it could be deposited. While this limitation may appear to reduce the reliability of the model predications, successful calibration and validation of the model, along with the results of the spatial-scale and uncertainty analyses, indicate that this limitation in the modeling framework does not have a significant effect on the predictive capabilities of the model in most of the LDW. In addition, maintenance dredging in the upper turning basin offsets this limitation (i.e., no feedback between the hydrodynamic and sediment transport models) because dredging is a mechanism that periodically returns the morphology of the upper turning basin region to conditions represented in the model.

A summary of the primary assumptions and approximations used in the hydrodynamic and sediment transport models is presented in Table 2-1. Justification for each assumption and approximation is also given in that table.

Table 2-1. Approximations and assumptions used in hydrodynamic and sediment transport models.

Model	Approximation or Assumption	Justification
Hydrodynamic	Effect of temperature gradients on water density is assumed to be negligible	Unlike lakes and reservoirs, significant thermal stratification does not occur in a high-energy tidal system like the LDW.
Hydrodynamic	Effect of wind on currents is assumed to be negligible	The channel-like geometry, with relatively small open fetches, minimizes the effects of wind-driven currents in the LDW, which are small compared to the tidal currents.
Hydrodynamic	Freshwater flow from Duwamish/Green River is assumed to be only significant inflow to the LDW in terms of water volume	Freshwater inflows from CSOs and storm drains, in total, are only about 1.3% of the annual average Green River flow.
Hydrodynamic	Vertical variations in water column variables are approximated using 10 layers	Simulating estuarine hydrodynamics using 10 vertical layers has been demonstrated to produce satisfactory results in numerous modeling studies (e.g., Blumberg et al. 1999).
Sediment transport	Effect of form drag on bed shear stress is negligible in cohesive bed areas	Generally, bed forms are not a significant feature of cohesive sediment beds.
Sediment transport	Sediment bed in the LDW is assumed to be cohesive except in the upper turning basin region	Sediment samples collected in the LDW are primarily composed of cohesive sediment, with isolated, localized areas of non-cohesive sediment also being present. Insufficient data are available (e.g., side-scan-sonar data) to develop a detailed bed map of the LDW.
Sediment transport	Sediment bed is assumed to be hard bottom downstream of RM 0.0 and upstream of RM 4.8	Erosion rate data are not available downstream of RM 0.0, and neither are bed-type data. Thus, specifying bed property parameters for that area is highly uncertain. Upstream of RM 4.8, minimal bed property data are available. Attempts to simulate non-cohesive bed transport in that area were unsuccessful, primarily due to data limitations.

Model	Approximation or Assumption	Justification
Sediment transport	Predicted spatial distribution of bed composition (i.e., evolved bed) is assumed to be best estimate of initial conditions	Available bed composition data in the LDW are insufficient for development of a reliable spatial distribution based only on data. Based on extensive model testing and diagnostic simulations, it was determined that the model was the most reliable method for specifying initial conditions.
Sediment transport	Lateral-source loads are assumed to be aggregated and input at 21 locations	Limited or no data are available for many of the point sources that contribute to the lateral-source loading. Thus, attempting to specify lateral loads at numerous point sources will not significantly improve the accuracy of the model predictions based on the aggregated loads.
Sediment transport	Distribution of sediment particle sizes is assumed to be represented by 4 size classes	Sufficient composition data for external sediment loads are not available to warrant use of additional size classes. Previous studies have developed reliable models using 2 or 3 size classes.
Sediment transport	Vertical variations in erosion properties are represented using 5 layers, with 0-20 cm represented by four 5-cm layers	Vertical variations in erosion properties were specified based on the vertical distribution of Sedflume data.
Sediment transport	Bed properties below 25-cm depth are assumed to be equal to 20-25 cm layer values	Erosion rate data are not available below 25-cm depth, so data collected in the 20-25 cm layer are the best estimate for values below 25 cm. Typically, consolidation effects cause erosion rates to decrease with depth in the bed. Thus, this assumption produces conservative model predictions.
Sediment transport	Effects of flocculation on cohesive settling speed are not explicitly simulated	During initial model testing, different flocculation models (i.e., Ziegler et al. 2000; Lick 2007) were evaluated. Numerical testing demonstrated that these flocculation models were unable to reproduce, either quantitatively or qualitatively, observed sedimentation patterns in the LDW. Thus, the explicit inclusion of flocculation effects on settling speed would not have improved the predictive capability of the model.
Sediment transport	Effects of consolidation on the erosion properties of deposited cohesive sediment are not explicitly simulated	The effects of consolidation on cohesive erosion properties are implicitly incorporated into the Sedflume data (i.e., erosion rates generally decrease with increasing depth in the bed). An explicit consolidation model primarily addresses the issue of the erosion properties of freshly deposited material (i.e., fluff layer). The objectives of the STM study are focused on the evolution of the consolidated bed, so inclusion of the fluff layer in the model was not needed to meet study objectives.

Model	Approximation or Assumption	Justification
Sediment transport	Spatial (horizontal) distribution of erosion properties is approximated through separation of Sedflume cores into groups	Sufficient Sedflume data were not available to use standard interpolation methods to develop a horizontal distribution of erosion properties. Separating the Sedflume cores into groups provided a reliable method for accounting for large-scale horizontal variations in erosion properties. The potential effect of this approximation on model predictions was evaluated during a sensitivity analysis.
Sediment transport	Erosion rates measured by Sedflume are assumed to be representative of in-situ bed erosion	Use of Sedflume data in other modeling studies has been shown to produce reliable results.
Sediment transport	Dry density is assumed to be spatially constant within cohesive and non-cohesive bed areas	Sufficient data are not available to reliably develop spatial distributions of dry density in the cohesive and non-cohesive bed areas (which have different dry density values).
Hydrodynamic and sediment transport	No feedback between hydrodynamic and sediment transport models (i.e., changes in bed elevation due to erosion and deposition are not incorporated into the hydrodynamic model)	Direct coupling of the models (i.e., incorporation of feedback) would make conducting long-term, multi-year simulations infeasible. Assuming no feedback is consistent with assuming that the upper turning basin is continuously dredged, which maximizes the amount of sediment that the model predicts is deposited in the upper turning basin. Thus, this assumption produces conservative results (i.e., lower sedimentation rates) in the area downstream of the upper turning basin.

2.4 DEVELOPMENT OF SEDIMENT TRANSPORT MODEL INPUTS

Inputs for the sediment transport model are separated into three broad categories: 1) sediment properties; 2) bed properties; and 3) boundary conditions. Sediment properties correspond to the physical properties of sediment particles (i.e., effective particle diameter, settling speed). Bed properties range from bulk bed characteristics (e.g., dry density, grain size distribution) to erosion rates. Determining boundary conditions for the model corresponds to the specification of sediment loads at different inflow locations. A summary of model inputs is presented in Table 2-2, which includes the data sources and an estimate of the level of uncertainty for each input.

Table 2-2. Model inputs and data sources.

Model Input	Data Source	Level of Uncertainty
Bathymetry and geometry	2003 David Evans multi-beam survey (LDW); NOAA and USGS bathymetry data	Measurement uncertainty in vertical bed elevation is: ± 0.5 ft. in LDW; ± 2 ft. upstream of RM 4.7; ± 1 ft. downstream of RM 0
Green River flow rate	USGS gauging station at Auburn	USGS rates discharge data at this station as good (i.e., ± 10% accuracy).
Tidal elevation in Elliott Bay	NOAA gauging station at Seattle Ferry	Accuracy of tidal elevation measurements is ± 0.3 cm
Sediment bed: erosion parameters	Sedflume study conducted during December 2006; 18 cores	Level of uncertainty of Sedflume data for a specific core cannot be assessed. Potential uncertainties due to spatial variability were addressed through a sensitivity analysis.
Sediment bed: dry density	16 samples, 2006 sub-surface core data	95% confidence interval, with respect to average value, is 0.14 g/cm^3. The 95% confidence interval values for the navigation channel, east bench, and west bench are 0.13, 0.22, and 0.14 g/cm^3, respectively. The number of samples in the turning basin is too low to calculate the 95% confidence interval.
Sediment bed: non-cohesive bed D_{50}	58 samples, 1991-2006 core data	95% confidence interval, with respect to average value, is 90 µm
Sediment bed: effective bed roughness (D_{90})	875 samples, 1991-2006 core data	95% confidence interval, with respect to average value, is 60 µm
Upstream sediment load: magnitude	USGS sediment load studies conducted during 1965-66 and 1996-97	Annual sediment load estimates have approximately factor-of-two level of uncertainty.
Upstream sediment load: composition	USGS sediment load studies conducted during 1965-66 and 1996-97; composition was adjusted during calibration	Available data were used to constrain the calibration value to a realistic range.
Lateral source sediment load: magnitude	<u>CSOs</u> Approximately 100 samples collected during 1995 to 1997 from 5 major outfalls (Brandon, Chelan, Hanford, Connecticut, and King). Monthly CSO discharge volumes for nine locations summarized for June 1999 to May 2006 period and obtained from annual CSO reports. Period was wet seasons from 1999-2000 and 2005-2006. <u>Storm Drains</u> Data from over 500 storm water	95% confidence interval, with respect to average value, is 20 mg/L

Model Input	Data Source	Level of Uncertainty
	samples collected at 24 different locations to determine representative TSS concentrations in urban storm water. Precipitation data (1986-2005) collected at East Marginal Way S pump station were used in watershed model to estimate monthly-average volume discharge at each storm drain location.	
Lateral source sediment load: composition	CSOs Grain size distribution (GSD) estimated using settling analysis results at four CSOs: Denny, Henderson, M.L. King, and Norfolk Storm Drains GSD data collected at 16 sites across the U.S.	Available data were used to constrain the calibration value to a realistic range.

2.4.1 Sediment Properties

For estuaries like the LDW, suspended sediment particles typically have a range of sizes, with particle diameters ranging from less than 1 µm clays to coarse sands on the order of 1,000 µm (van Rijn 1993). Simulation of the entire particle size spectrum is impractical for several reasons: simulation times and array-storage requirements increase with each particle-size class that is added; limitations in grain size distribution data for the sediment bed make it difficult to specify initial conditions for the entire spectrum; and sparse data for the composition of the upstream sediment load (i.e., Green River load) make it problematic for specifying this boundary condition for the entire spectrum. Therefore, particles were separated into four classes: 1) clay and fine silt with particle diameters less than 10 µm; 2) medium and coarse silt (10 to 62 µm); 3) fine sand (62 to 250 µm); and 4) medium and coarse sand (250 to 2,000 µm). Use of these four size classes provides an adequate approximation of the grain size distribution of bed sediment observed in the LDW for achieving the objectives of this study; each class represents a major component of the LDW sediment bed. The four size classes used in the LDW simulations provide a realistic range of sediment particle sizes (from clay to coarse sand) that are present in the graded bed of the LDW. Inclusion of this wide range of particle sizes in the model is necessary for simulation of bed armoring processes during an erosion event. From a practical point of view, simulating the transport of four sediment size classes makes it possible to conduct long-term, multi-year simulations in a practical amount of time. Finally, the results of the model calibration and validation exercises (discussed below) indicate that use of four sediment size classes is sufficient for producing a modeling framework with adequate accuracy and reliability for the application and use of the STM as specified in this report.

For convenience, the four sediment classes have been labeled as noted in Table 2-3. Each sediment size class is represented as an effective particle diameter. Effective particle diameters for classes 1A and 1B were treated as adjustable calibration parameters, see Section 2.5. Specification of effective particle diameters for classes 2 and 3 is discussed in Appendix B.

Table 2-3. Characteristics of sediment particle size classes.

Sediment Size Class	Particle Size Range (μm)	Effective Particle Diameter (μm)	Effective Settling Speed (m/day)
1A: clay, fine silt	< 10	5	1.3
1B: medium, coarse silt	10 – 62	20	21
2: fine sand	62 – 250	130	770
3: medium, coarse sand	250 – 2,000	540	5,500

The settling speeds of sediment particles are related to the effective particle diameter, with settling speed increasing as effective diameter increases. The effective settling speeds for the four sediment size classes have a large range, from about 1 m/day for class 1A to about 5,500 m/day for class 3 (Table 2-1). This wide range (i.e., factor of 5,000) has a significant effect on the transport characteristics of the different sediment classes.

2.4.2 Bed Properties

Specification of bed properties within the LDW begins with separating the sediment bed into two distinct types of sediment: cohesive and non-cohesive. Cohesive sediment is described as a muddy bed that is composed of a mixture of clay, silt, sand, and organic matter. Non-cohesive sediment corresponds to a sandy bed that has a relatively low amount of clay, silt, and organic matter. The sediment transport model requires specification of the following bed property inputs within the cohesive and non-cohesive bed areas: 1) dry (bulk) density; 2) initial sediment bed composition (i.e., relative amounts of classes 1A, 1B, 2, 3); 3) effective bed roughness (based on D_{90} values); and 4) median particle diameter (D_{50} values). Values of D_{50} and D_{90} values are determined from site-specific grain size distribution data and input to the model. The spatial distribution of erosion rate parameters, both horizontally and vertically, must be determined in the cohesive bed areas. An initial analysis of the erosion properties of LDW sediments, based on Sedflume core data, is presented in the STAR (Windward and QEA 2007). The results of that analysis were extended and a spatial distribution of erosion rate parameters was determined. A detailed discussion of the specification of bed property inputs is presented in Appendix B.

2.4.3 Boundary Conditions

Sediment loads from upstream (i.e., Green River) and lateral (e.g., storm drains, CSOs, streams) sources need to be determined for use as boundary conditions for the sediment transport model. Both the magnitude and composition (i.e., relative amounts of classes 1A, 1B, 2, 3) of the sediment loads are important model inputs, but loads from the lateral sources were not included during the calibration period simulation because the total load from lateral sources is 0.6% of the upstream load on an annual average basis. Thus, excluding lateral-source loads had a negligible effect on calibration results. The lateral-source loads were included in the long-term, multi-year simulations. Specification of lateral-source loads is discussed in Section 4.2 and Section B.3. The incoming sediment load at the open boundary in Elliott Bay is assumed to be negligible; water-column sediment load associated with incoming flow (i.e., flood tide) is set to zero at the open boundary

The methodology for estimating the magnitude and composition of sediment loads in the Green River is presented in Section B.2. The results of that analysis are summarized here. Variation in the total annual sediment load (i.e., total mass of all sediment size classes, representing both suspended and bedload) during the 21-year calibration period, which extends from 1960 through 1980, is shown in Figure 2-6. The average total annual load over this 21-year period is 221,000 metric tons/year (MT/yr). The average annual values for suspended and bedload for the calibration period are 167,000 and 54,000 MT/yr, respectively; bedload composes 24% of the total sediment load, on average, at the upstream boundary in the Green River. Year-to-year variation in sediment load occurs because of variability in river flow, with sediment load increasing during years with relatively high flows. During the 21-year calibration, the lowest and highest total annual sediment loads differ by about a factor-of-ten.

2.5 SEDIMENT TRANSPORT MODEL CALIBRATION

The sediment transport model was calibrated to a 21-year period that extended from 1960 through 1980. A wide range of tidal and flow conditions occurred during that 21-year period. Maximum flow rates in the Green River during each year of the calibration period are presented in Figure 2-7. A number of high-flow events occurred during this period, including a high-flow event with a return period of approximately 50 years in 1975. The maximum flow rate during the 1975 high-flow event was 11,600 cfs, which is only 3% lower than the flow rate for a 100-year high-flow event (12,000 cfs). Additional details on Green River flow rates and tidal conditions during the calibration period are provided in Appendix D.

Calibration of the sediment transport model involved adjusting model inputs such that the agreement between model results and data is optimized. For this study, the calibration targets were net sedimentation rates (NSR, with units of cm/yr) in the navigation channel and bench areas of the LDW. Discussion of the data and methods used to estimate NSRs in the navigation channel and bench areas is included in Appendix D, along with more details about the calibration process.

Four model parameters were adjusted to achieve the optimum agreement between predicted and empirically-derived estimates of NSR in the navigation channel and bench areas. The parameters adjusted during calibration, and the calibration values, are summarized in Table 2-4. In addition to the parameters listed in Table 2-4, two additional adjustments were made to the sediment transport model during calibration. First, a particle-shielding factor was incorporated into the calculation of bed erosion flux. This factor is used to reduce the erosion flux of smaller particles within a graded bed (i.e., bed with wide range of particle sizes) that are sheltered by larger particles. Grain size distribution data indicate that a graded bed exists in most areas of the LDW, so particle-shielding is a process that occurs in this estuarine system. This process was not included in the original version of SEDZLJ (Jones and Lick 2001) because particle-shielding can be a process of secondary importance in other aquatic systems. However, this process was incorporated in SEDZLJ for the LDW application because it is of primary importance in some regions of the LDW. Inclusion of the particle-shielding factor improved representation of bed dynamics in the model, which was demonstrated by better agreement between predicted and empirically-derived estimates of net sedimentation rate in Reach 2. The mathematical formulation used in the sediment transport model to simulate the particle-shielding effect is presented in Appendix A.

The second adjustment to the model was specifying that the sediment bed upstream of RM 4.8 be treated as a "hard-bottom", which means that the bed in that region (i.e., in the river upstream of the upper turning basin) experiences no erosion or deposition. Bedload transport of sediment is allowed in that region. This adjustment was made because unrealistic bed scour was predicted in portions of the region upstream of RM 4.8, which resulted in an unrealistic increase in the sediment load transported from the river into Reach 3. Additional explanation of and justification for the decision to make this adjustment to the model are presented in Appendix D.

Table 2-4. Calibration parameter values.

Adjusted Parameter	Calibration Value
Effective particle diameters of class 1A and 1B sediment	Class 1A: 5 μm Class 1B: 20 μm
Average composition of class 1A and 1B sediment in incoming suspended load	Class 1A: 70% Class 1B: 18%

Comparisons of predicted NSRs in the navigation channel to empirically-derived estimates are shown in Figures 2-8 and 2-9. The empirically-derived estimates were determined from bathymetric soundings collected over the calibration period and more recent times (i.e., last 20 years), with soundings averaged over cross-sectional transects for the navigation channel. The scale of the vertical axis in Figure 2-9 is adjusted to show greater resolution for the area downstream of RM 4.0. Model results presented on these two figures represent the cross-channel average of predicted values in grid cells located within the navigation channel. The predicted NSR is the time-averaged value for the 21-year simulation period. These results show that the model is able to reproduce the large-scale spatial changes in NSR between relatively high values in the upper turning basin region upstream of RM 4.0 (Figure 2-8) and relatively low values in the region downstream of RM 4.0 (Figure 2-9). Upstream of RM 4.0 (i.e., upper turning basin region), the model over-predicted NSRs in the navigation channel. In the region downstream of RM 4.0, spatial variability is evident in the empirically-derived estimates, with NSRs ranging between about 0.5 and 6 cm/yr. The model tends to under-predict NSRs in the areas between RM 2.6 – 3.9 and RM 1.4 – 2.0. In addition, the model does not predict the areas of empirically-derived net erosion at RM 1.0 and 2.4. While there are discrepancies between the observed and predicted values, the model is able to adequately simulate the observed variability in NSR in the navigation channel.

Predicted net sedimentation rates in the east and west bench areas are compared to empirically-derived estimates in Figure 2-10. The empirically-derived estimates were determined from an interpretation of time markers from LDW sediment cores and associated NSR estimates (Windward and QEA 2007). Estimation of a NSR value was not possible at 10 of the LDW sediment cores examined during the analysis presented in Windward and QEA (2007). Thus, those sediment cores are not represented in Figure 2-10. The model results shown on this figure represent spatially-averaged values, in the cross-channel direction, in the east (upper panel) and west (lower panel) bench areas. Model predictions were spatially averaged along a row of grid cells in the cross-channel direction within the east and west bench areas, with two or three points typically used to calculate the average value at a specific longitudinal location in the LDW. The predicted NSRs in the bench areas correspond to time-averaged values for the 21-year calibration period. The model is able to adequately simulate the observed spatial variability in estimated NSRs in both bench areas. The model over-predicted NSRs in the region upstream of RM 4.0, but this over-prediction may be due to uncertainty in the estimated bedload input at the upstream model boundary in the river (see Section F.4). Between RM 2.0 – 4.0, model results are generally within the range of the empirically-derived estimates in the east bench area, with a tendency to over-predict NSRs near RM 2.5 – 2.8. Within the west bench area between RM 2.0 – 4.0, the model tends to over-predict NSRs. Downstream of RM 2.0 in both bench areas, the model results are less variable than the empirically-derived estimates, but the predicted NSRs are in good agreement with the general trend of the empirically-derived estimates. Discrepancies between predicted and observed values occur at some locations but, overall, the model satisfactorily captures spatial trends in the data.

2.6 SEDIMENT TRANSPORT MODEL VALIDATION

Model validation involves comparison of model predictions to an independent dataset (i.e., data not used to calibrate the model) with no adjustment of calibration inputs. The first step in model validation was achieved through comparison of the predicted composition of sediment deposited in the LDW to the observed composition of surface-layer sediment. The relative amounts of the four size classes (i.e., classes 1A, 1B, 2, 3) in the sediment predicted to be deposited between RM 0 and 4.3 (i.e., region downstream of the upper turning basin) during the 21-year calibration period are shown in Figure 2-11. The model results shown in the upper-left panel of this figure represent average values for the entire region downstream of the upper turning basin. The other three panels in this figure show model results in the west bench, navigation channel, and east bench areas between RM 0 and 4.3. These model results were compared to the relative amounts of the four sediment size classes in the Sedflume cores, which represent the upper 30 cm of the sediment bed. The values for the Sedflume cores shown on this figure represent the average values for 18 cores. No model inputs were adjusted to optimize the agreement between observed and predicted composition shown in Figure 2-11.

On Figure 2-11, the “fines” class (i.e., clay/silt or class 1) corresponds to the summation of classes 1A and 1B. For the cohesive bed area in the LDW (noted as “All Areas” on Figure 2-11), predicted class 1 composition on average is 26% greater than observed composition in the Sedflume cores. Predicted class 1 composition on average is 47%, 1% and 20% greater than observed average class 1 composition in the west bench, navigation channel and east bench, respectively. Thus, the model over-predicts class 1 composition in the east and west bench areas, but it produces an excellent agreement with data in the navigation channel. This over-prediction of class 1 composition indicates that the model tends to under-predict the amount of class 2 and 3 (i.e, fine, medium and coarse sand) transported into the bench areas downstream of RM 4.3. The exact reasons for the cause of this over-prediction of class 1 deposition in the bench areas are unclear because bed composition predictions are the result of a number of complex and non-linear processes. It is also possible that processes not incorporated into the STM (e.g., boat-induced bed scour) may contribute to differences between observed and predicted bed composition. However, generally, the model satisfactorily predicts the composition of surface-layer sediment in the RM 0 to 4.3 region, and adequately simulates spatial differences between the bench areas and navigation channel.

The second step in validation was additional evaluation of the predictive capabilities of the model with respect to NSR. This evaluation was accomplished using one-to-one comparisons of predicted and estimated NSR values, which provides a quantitative analysis of predictive capability at the grid-cell scale. Note that this analysis was conducted after the model was calibrated and it did not affect or guide the calibration process. The estimated NSR values used in this analysis were determined using various time-horizon markers in sediment cores (see Appendix F in the STAR [Windward and QEA 2007] for details). A one-to-one comparison consists of locating a sediment core within a specific grid cell and calculating the absolute difference between the predicted value for that grid cell and the estimated value for the core. For a sediment core with multiple NSR estimates, resulting from different time-horizon markers, the average value of all NSR estimates for that core was used as the "estimated" value in calculating the absolute difference.

This analysis focused on the region between RM 0 and 4.0 because of the importance of the predictive capabilities of the model within this region. The locations of the 58 cores used in the one-to-one analysis are shown in Figure 2-12. This figure also provides visual comparisons of predicted and estimated NSR values at the core locations. As noted in Section 2.5, estimation of a NSR value was not possible at 10 of the LDW sediment cores examined during the sedimentation analysis presented in Windward and QEA (2007). The locations of those cores are shown in Figure 2-12. Additional figures and discussion of the one-to-one comparisons are presented in Appendix D. The general conclusions from this analysis are: 1) absolute difference (or error) has an average value of approximately 0 cm/year, which means that the NSR values predicted by the model are not biased low or high at the grid-cell scale; 2) absolute difference values are normally distributed with a median value of about 0 cm/year; and 3) 95% confidence interval about the average absolute difference is ± 0.5 cm/year.

2.7 SPATIAL-SCALE ANALYSIS

The objective of this analysis was to determine the relationship between model predictive capability and spatial scale. Absolute differences between predicted and estimated NSR values were calculated for zones located in the RM 0 to 4.0 region, with zonal areas ranging from about 5 acres (i.e., 7 grid-cell zone) to about 300 acres (entire RM 0-4 region). The spatial-scale analysis focused on the RM 0-4 region (i.e., Reaches 1 and 2) because this region of the LDW is of importance when evaluating the efficacy of different remedial alternatives during the FS. Because STM results will be used as one line-of-evidence during the FS analyses of remedial alternatives, an understanding of the relationship between model predictive capability and spatial scale in the RM 0-4 region needed to be developed. Details of the approach used in this analysis, along with additional results, are included in Appendix D.

The primary results of the spatial-scale analysis are shown in Figure 2-13. This figure presents the absolute difference for zonal spatial-scales ranging from about 5 to 300 acres. For reference, the results of the one-to-one comparison (see Section 2.6) are also included in this figure (i.e., result plotted at 0.8 acre). The solid dots in Figure 2-13 represent the average absolute difference, with the 95% confidence interval about the average shown as error bars. The following general conclusions were derived from the spatial-scale analysis: 1) average absolute difference is less than ± 0.25 cm/year for spatial scales ranging from about 0.5 to 300 acres, which indicates that the predicted NSR values are not biased low or high over this range of spatial scales; 2) 95% confidence interval about the average absolute difference is about ± 0.5

cm/year for areas less than about 8 acres, about ± 0.38 cm/year for areas between about 8 and 20 acres, and less than ± 0.38 cm/year for areas between about 20 and 300 acres; and 3) variation (standard deviation) in absolute differences increases with decreasing spatial area, which is an expected characteristic because the number of data points included in a zone tends to decrease with decreasing area and, statistically, this causes the variation and 95% confidence to increase.

2.8 UNCERTAINTY ANALYSIS

The objective of this analysis was to evaluate the effect of uncertainty in model inputs on model predictions. Based on sensitivity analysis results (see Sections 3.4 and 4.4), the effects of the following five model inputs on model uncertainty were examined: 1) upstream sediment load; 2) settling speeds of class 1A/1B sediment; 3) erosion rate parameters; 4) effective bed roughness; and 5) class 2/3 particle diameter. Lower- and upper-bound limits of these five inputs were determined and a factorial analysis was then conducted, which resulted in 32 simulations to account for all of the possible combinations of the bounding limits of the five inputs. The spatial-scale analysis discussed in Section 2.7 was applied to the 32 bounding simulations so that realistic lower- and upper-bound parameter sets could be determined using an objective and quantitative procedure. Details of the technical approach used in this analysis, along with additional results, are included in Appendix D.

The uncertainty analysis demonstrated that two model inputs (upstream sediment load and class 1A/1B settling speed) are the primary controlling factors of predicted NSR over multi-year periods in the LDW. The other three inputs (i.e., erosion rate parameters, effective bed roughness, class 2/3 particle diameter) have only a minor effect on multi-year model predictions. The upstream sediment load was specified using the results of two USGS studies (i.e., 1965-66 and 1996-97 studies) that provide good estimates of the magnitude of the Green River load. Class 1A/1B settling speeds were treated as adjustable parameters during model calibration, with the model being relatively sensitive to these parameters. Thus, the values of the class 1A/1B settling speeds were determined with relatively high precision during the calibration process.

Therefore, the two primary model inputs controlling predicted NSR over multi-year periods were reliably defined by site-specific data and model calibration.

The results of the uncertainty analysis were used to generate realistic lower- and upper-bound uncertainty limits on the model calibration results. Comparisons of the realistic bounding limits to the original calibration results for the navigation channel, east bench, and west bench are shown in Figures 2-14, 2-15 and 2-16, respectively. The uncertainty analysis results demonstrate that uncertainty in model inputs does not change the overall STM conclusions or the CSM.

2.9 CONCLUSIONS REGARDING STM RELIABILITY

The results of the model calibration and validation, spatial-scale analysis, and uncertainty analysis indicate that the predictive capability and reliability of the sediment transport model are sufficient for achieving the following overall objectives of this study (see Section 1.6):

- develop a quantitative tool to evaluate short-term and long-term sediment transport processes in the LDW;
- refine the CSM for the LDW; and
- provide information to support FS analyses and inform remedial decision-making.

Additionally, the following conclusions concerning model reliability are supported by the results presented in this section and Appendix D:

- The STM may be used to refine, confirm and validate the CSM.
- The analysis provides quantitative uncertainty estimates for STM predictions and CSM components.
- The STM provides a framework to support physical process evaluation and the effects of potential actions in the LDW.

- Over small spatial-scales (i.e., areas corresponding to approximately one or two grid cells in size), the STM will typically demonstrate trends that may be used as one line-of-evidence, along with other information and data, to guide decision making.
- The STM is a reliable framework for supporting extrapolation to conditions where no erosion and/or NSR data are available.

The STM group collaborated and provided guidance during the calibration and validation process, with important contributions being made by various group members. The group reviewed the results of the calibration and validation simulations, as well as the spatial-scale and uncertainty analyses, during April 2008. After discussion among the members of the STM group, concurrence was reached on the five conclusions presented above.

SECTION 3
EFFECTS OF HIGH-FLOW EVENTS ON SEDIMENT BED STABILITY

A preliminary evaluation of bed stability during high-flow events was conducted during the STAR study (Windward and QEA 2007). That analysis used a hydrodynamic model to investigate the spatial distribution of bed shear stress within the LDW during high-flow events. The locations of potential bed scour, and the relative amounts of potential bed scour within those areas, were predicted during that study. Inferences about potential bed scour in the LDW during high-flow events were used to develop a provisional CSM for sediment transport (Windward and QEA 2007).

The sediment transport model was used in this study to extend the initial bed stability analysis and simulate erosion and deposition in the LDW during high-flow events. Simulations of high-flow events were conducted with the calibrated hydrodynamic and sediment transport models. The results of these simulations were used to address specific questions about the effects of high-flow events on bed stability. Uncertainty in model predictions associated with uncertainty in model inputs was evaluated through a sensitivity analysis.

3.1 OBJECTIVES OF SEDIMENT BED STABILITY ANALYSIS

This analysis focused on the effects of high-flow events on sediment bed stability in the LDW. A range of high-flow conditions in the Green River, from 2-year to 100-year high-flow events, were investigated, with the objective being to answer the following questions:

- What areas in the LDW are depositional and what areas experience erosion during a high-flow event?
- In the areas that experience erosion during high-flow events, what is the potential depth of scour?
- What is the potential for re-exposing buried sediments?

Issues related to chemical concentrations in the sediment bed were not addressed in this study. However, the sediment transport results for high-flow events may be used in future analyses related to bed chemical concentrations.

3.2 DEVELOPMENT OF HIGH-FLOW EVENT SIMULATIONS

Three high-flow events, with return periods of 2, 10, and 100 years, were evaluated during the bed stability analysis (see Table 3-1). The flow rates listed in Table 3-1 represent the peak flow rate during each high-flow event. Simulating sediment transport in the LDW during high-flow events requires specifying time-variable flow in the Green River; the time history of river flow during an event is referred to as a hydrograph. This analysis used the hydrograph for an actual high-flow event that occurred in the Green River and linearly scaled this hydrograph to match the desired peak flow rate (e.g., 100-year high-flow event), while maintaining the overall shape of the actual hydrograph. For this analysis, the hydrograph of a high-flow event that occurred during November-December 1975 was chosen to be representative of rare events in the Green River and LDW. The peak flow rate during the 1975 high-flow event was 11,600 cfs, which has a return period of about 50 years; this flow rate is only 3% lower than that of a 100-year high-flow event.

Table 3-1. Return periods and flow rates for high-flow events in the Green River.

Return Period of High-Flow Event (years)	Peak Flow Rate (cfs)
2	8,400
10	10,800
100	12,000

Hydrographs for high-flow events evaluated in this analysis were developed by linearly adjusting the measured flow rates during the 1975 event so that the peak flow rate corresponded to the appropriate values for the 2-, 10-, and 100-year high-flow events. The resulting hydrographs for these three events are shown in Figure 3-1 (top panel). A 26-day period was simulated for each of the high-flow events investigated in this analysis. The peak flow rate during each event coincides with spring tide conditions (see bottom panel of Figure 3-1). This characteristic of the high-flow event simulations (i.e., peak discharge during spring tide) produces the maximum bed shear stresses for a specific river discharge condition (Windward and QEA 2007), which will yield conservative results for the bed stability analysis discussed below (i.e., maximum bed scour depths). The sensitivity simulation for neap tide conditions presented in Section 3.4 supports this statement.

Temporal variations in tidal elevation at the model boundary in Elliott Bay were specified for the high-flow event simulations. Data collected at the National Oceanic and Atmospheric Administration (NOAA) Seattle Ferry Pier tide gauge station during the high-flow period in November-December 1975 were used to specify boundary condition inputs (see bottom panel of Figure 3-1). During the rising limb of the hydrograph and at peak flow conditions (i.e., days 3 to 6 in Figure 3-1), spring tide conditions occurred in Elliott Bay and the LDW. The maximum tidal range during ebb tide over this 3-day period of the high-flow event was approximately 15 ft. During high-flow events, the bed shear stress analysis conducted during the STAR study showed that significantly higher bed shear stresses occur for spring tide conditions than for neap tide conditions in the region upstream of RM 2.0. Thus, the high-flow event simulations discussed below produced conservative results because bed shear stress and, consequently, bed scour are maximized as a result of the combination of tidal and flow boundary conditions used in the hydrodynamic model. Additional discussion about model inputs and boundary conditions for the sediment transport model is presented in Appendix E.

3.3 RESULTS OF SEDIMENT BED STABILITY ANALYSIS

The sediment transport model was used to simulate erosion, deposition, and transport of sediment in the LDW during high-flow events with return periods of 2, 10, and 100 years. Model results of primary interest for the sediment bed stability analysis are the locations and depth of bed scour. Two quantities related to bed scour are derived from the results of the simulations. First, net erosion at a specific location is the total decrease in bed elevation over the course of the high-flow event (i.e., difference in bed elevation between start and end of the 26-day simulation), which incorporates the effects of erosion and deposition during the entire event.

Second, maximum bed scour is the maximum depth of erosion that occurred at a specific location at any time during the high-flow event. Typically, at a location that experiences net erosion during an event, maximum bed scour occurs near the time of the peak flow rate, with deposition occurring during the falling limb of the hydrograph (i.e., after the peak flow rate, as river discharge declines). At locations that experience net deposition during an event, deposition may occur at any time during the event and the rate may also vary in magnitude.

Spatial distributions of predicted net erosion at the end of high-flow events with return periods of 2, 10, and 100 years are presented in Figures 3-2, 3-3, and 3-4, respectively. The spatial distribution of maximum bed scour during the 100-year high-flow event is shown in Figure 3-5. The locations of the maximum depth of bed scour in cohesive and non-cohesive bed areas are denoted on these figures. Maximum net erosion depths in the non-cohesive bed area, which is located in the vicinity of the upper turning basin, range from about 9 to 20 cm during high-flow events with return periods between 2 and 100 years. Net erosion occurs over approximately 18% (about 70 acres) of the LDW sediment bed, on an areal basis, during a 100-year high-flow event. Net erosion of 10 cm or greater occurs over about 6% (about 22 acres) of the bed area in the LDW during the 100-year high-flow event. Net deposition is predicted to occur over large portions of the LDW during a high-flow event (i.e., return periods of 2 years or greater), which is not surprising because the upstream sediment load is relatively high during these events, as compared to low-flow conditions. Maximum net deposition of 10 cm or more is predicted at specific locations within the LDW. Additional results for the bed stability analysis are presented in Appendix E.

The model results show that net erosion primarily occurs between RM 2.2 and 4.0 during high-flow events, including the 100-year high-flow event, in the LDW. Most of the net erosion occurs in this reach of the LDW because most of the region upstream of approximately RM 2.2 behaves as a tidal freshwater river during high-flow events, with the saltwater wedge being located downstream of approximately RM 2.2. An earlier investigation of bed shear stress distribution during high-flow events showed that relatively high bed shear stresses occur upstream of the saltwater wedge (Windward and QEA 2007), which is consistent with the predicted distributions of net erosion. Less net erosion occurs in the reach upstream of RM 4.0 than in the reach from RM 2.2 to 4.0 for two reasons. First, bed shear stresses are generally lower upstream of RM 4.0 than in the reach from RM 2.2 to 4.0, which is mainly because of differences in cross-sectional area between the two reaches (i.e., larger cross-sectional area upstream of RM 4.0). Second, more deposition, and less net erosion, occurs upstream of RM 4.0 because a large of portion of sand (i.e., sediment classes 2 and 3) transported from the Green River to the LDW is deposited in this reach; the upper turning basin was designed to be an effective sediment trap.

Net erosion occurs in only a few relatively small areas in the reach downstream of RM 2.2, even during a 100-year high-flow event, with typical net erosion depths of 2 cm or less. The cause for the significant difference in erosional environment between the reaches upstream and downstream of RM 2.2 is the presence of the saltwater wedge downstream of RM 2.2 during high-flow events, which results in relatively low bed shear stresses and a small amount of erosion in that reach.

The effects of deposition on net erosion during the receding limb of the hydrograph are illustrated through comparison of the spatial distributions shown in Figures 3-4 and 3-5. These two figures show that: 1) the areal extent of maximum bed scour is larger than the areal extent of net erosion at the end of the 100-year high-flow event; 2) net erosion is less than maximum bed scour at most locations; and 3) net deposition over the course of the event can occur at locations that experienced bed scour during the event. Additional analysis of model results for the 100-year high-flow event (see Appendix E) shows that at locations where net erosion occurred, about 1 cm or less of deposition occurred after the maximum bed scour depth was achieved (i.e., between the peak flow period and the end of the 26-day event).

The relative amounts of sediment eroded from surface (0 to 10 cm) and sub-surface (deeper than 10 cm) layers during the 100-year high-flow event were evaluated by "tagging" sediments within those two layers at the start of the simulation and tracking the sediment from those two bed sources separately. Results of a mass balance analysis (see Appendix E) for the

100-year high-flow event indicate that 20% of the mass of sediment eroded from the sediment bed in the LDW was from the sub-surface layer (i.e., deeper than 10 cm), with the remaining 80% of eroded sediment originating from the surface layer (0 to 10 cm). The mass balance analysis also showed that about 4% and 2% of the total sediment transported downstream of RM 0.0 during the 100-year high-flow event was eroded from the surface and sub-surface layers of the LDW sediment bed, respectively.

Finally, the results of the high-flow event simulations indicate that the LDW may be separated into three reaches, with each reach having different erosional and depositional characteristics during high-flow events:

- *Reach 1 (RM 0.0 to 2.2)*: This reach is primarily net depositional during high-flow events, with relatively small areas of net erosion. Net erosion depths are generally 2 cm or less, even during the 100-year high-flow event.
- *Reach 2 (RM 2.2 to 4.0)*: Net erosion occurs over a large portion of this reach during high-flow events, with relatively small areas of net deposition. Net erosion depths are typically less than 10 cm, with maximum net erosion depths of 14 and 21 cm predicted in the cohesive bed during high-flow events with return periods between 2 and 100 years, respectively.
- *Reach 3 (RM 4.0 to 4.8)*: This reach is primarily net depositional during high-flow events, with a few areas of net erosion. Net erosion depths are typically less than 10 cm, with maximum erosion depths of 9 and 20 cm occurring in the non-cohesive bed during high-flow events with return periods between 2 and 100 years, respectively.

3.4 SENSITIVITY ANALYSIS

The calibrated sediment transport model is a reliable tool for evaluating sediment stability during high-flow events. However, uncertainty exists in the results of the high-flow event simulations because of uncertainty in model inputs. The effects of input uncertainty on model predictions were evaluated through a sensitivity analysis.

The 100-year high-flow event was used to evaluate the effects of varying the following model inputs: 1) erosion rate parameters; 2) upstream sediment load; 3) effective bed roughness; 4) settling speed of class 1A and 1B sediment; 5) particle-shielding factor; 6) neap tide occurs during peak flow rate; and 7) duration of peak flow rate. For the first four components of this list, the input values were varied between upper- and lower-bound limits. The particle-shielding factor affects the erosion flux calculation and it tends to reduce the amount of erosion during a high-flow event. The base-case simulation has the peak flow rate occurring during spring tide, so the sensitivity of the simulation to tidal conditions was evaluated by adjusting the timing of the high-flow hydrograph such that the peak flow rate occurred during neap tide. USACE operating guidelines for Howard Hansen dam allow continuous peak discharge to occur for up to 8 days (K. Eriksen, personal communication, March 2008). Even though this controlled high-flow event is unlikely to occur in the future, and has not occurred since the dam was constructed, the potential effects of continuous peak discharge for an 8-day period were evaluated. For the sensitivity analysis, the effect of the particle-shielding factor was turned off. Descriptions of the adjustments to these parameters for the sensitivity analysis are presented in Appendix E.

Eleven sensitivity simulations were conducted, with the 100-year high-flow event simulation being repeated with the appropriate changes to model inputs. The effects of each sensitivity simulation were evaluated through comparison to results for the base-case simulation (i.e., 100-year high-flow event simulation presented in Section 3.3). A summary of the results of the sensitivity analysis is presented here. More detailed discussion of the sensitivity simulation results is provided in Appendix E.

The overall effects of the sensitivity analysis are captured in the lower- and upper-bound values of the erosion rate parameters, with the spatial distributions of net erosion for the two sensitivity simulations shown in Figures 3-6 and 3-7. Net erosion distributions for the other sensitivity simulations fall between the results shown on these two figures. The lower-bound erosion parameters produce less erosion than the base-case simulation, with net erosion of 2 cm or less in most areas in the reach between RM 2.2 and 4.0 and maximum net erosion of 11 cm in the cohesive bed area. Increased net erosion occurs for the upper-bound erosion parameters, with maximum net erosion of 35 cm near RM 3.6.

Quantitative comparisons of the sensitivity simulations are presented in Figures 3-8 and 3-9, which show comparisons of the relative area of net erosion and total mass of eroded sediment for the eleven sensitivity simulations. On these two figures, the area of net erosion and mass of eroded sediment for the sensitivity simulations were normalized with respect to the values for the base-case simulation (i.e., 65 acres and 51,300 metric tons). The uncertainty ranges for the lower- and upper-bound erosion parameter simulations, relative to the base-case 100-year event simulation, for the RM 0–4.3 region, and the three zones within that region, are listed in Table 3-2. The sensitivity analysis for the 100-year high-flow event focused on the RM 0-4.3 region because the sediment bed within this region is entirely cohesive, and sensitivity results were dominated by the erosion rate parameters for cohesive sediment. Upstream of RM 4.3, the bed is a mixture of cohesive and non-cohesive sediment, and the non-cohesive bed is not affected by changes in the erosion rate parameters. Thus, RM 0-4.3 was the most appropriate region for the sensitivity analysis.

These results indicate that uncertainty in predicted erosion area due to model input uncertainty is less than ± 50%, with respect to the base-case simulation, within the RM 0-4.3 region, including the three primary zones. Uncertainty in predicted sediment mass ranges from about -50% to +75% within the RM 0-4.3 region, as well as in the east bench and navigation channel. More uncertainty exists in the west bench zone for predicted sediment mass; the uncertainty range in the west bench is about -40% to +130%.

Table 3-2. Uncertainty ranges for erosion parameter simulations.

Normalization Metric	RM 0–4.3: Entire Region (%)	RM 0–4.3: East Bench (%)	RM 0–4.3: West Bench (%)	RM 0–4.3: Navigation Channel (%)
Erosion Area	-33 → +45	-28 → +45	-46 → +40	-29 → +42
Erosion Mass	-47 → +76	-48 → +73	-36 → +130	-51 → +57

SECTION 4
EFFECTS OF EXTERNAL SEDIMENT LOADS ON SURFACE-LAYER BED COMPOSITION OVER MULTI-YEAR PERIODS

The effects of external sediment loads on the composition of surface-layer sediment were evaluated over a 30-year period. A 30-year simulation was selected because of its usefulness for FS analyses. External sediment loads were specified from two sources: 1) upstream loads (i.e., Green River); and 2) lateral loads (i.e., storm drains, CSOs, streams). Original bed sediment (i.e., sediment at the beginning of the 30-year simulation) was treated as a third source of sediment. The effects of the external loads on the relative amounts of sediment from the three sources (i.e., bed, upstream, lateral) in the surface layer of the sediment bed over the 30-year period were predicted by the sediment transport model. In addition, the 30-year simulation provides an evaluation of long-term changes in bed elevation caused by erosion and deposition over multi-year periods.

4.1 OBJECTIVES OF EXTERNAL SEDIMENT LOAD ANALYSIS

This analysis was conducted so that the effects of external sediment loads on surface-layer bed composition over long-term, multi-year periods could be evaluated. Specific questions that were addressed using the sediment transport model for long-term, multi-year periods include:

- What areas in the LDW are net depositional, net erosional, or in dynamic equilibrium?
- How does the composition of the surface-layer sediment change over time as external sediment loads (from upstream and lateral sources, such as storm drains) become incorporated into the sediment bed?
- What is the effect of high-flow events on episodic scour in otherwise net depositional areas?
- In areas that are net depositional, what is the potential depth of scour during high-flow events?

Issues related to chemical concentrations in the sediment bed were not addressed in this study. However, the results of this analysis may be used in future analyses related to bed chemical concentrations.

4.2 DEVELOPMENT OF EXTERNAL SEDIMENT LOAD SIMULATION

The 30-year simulation was achieved by extending the 21-year period used for model calibration by nine years. This approach assumed that these historical flow rates (i.e., 1960 through 1989) are representative of the 30-year period from the present into the future. Boundary conditions for the model were specified using river flow rate and tidal elevation data collected during the 30-year period from 1960 through 1989 (see Appendix F). The river discharge characteristics during the 1960-89 period are similar to the characteristics for the 30-year period from 1977 through 2006 (see Table 4-1). Thus, the 30-year period chosen for the simulation (i.e., 1960-89) is representative of discharge conditions in the Green River since construction of the Howard Hansen dam and this period may be used as a surrogate for making prognostic simulations.

Table 4-1. Comparison of river discharge characteristics during different 30-year periods.

30-Year Period	Number of Years With No 2-Year or Greater High-Flow Events	Number of 2-Year to 10-Year Events During Period	Number of 11-Year to 100-Year Events During Period
1960 through 1989	13	23	3
1977 through 2006	14	21	3

External sediment loads were specified from two sources: 1) upstream loads (i.e., Green River); and 2) lateral loads (e.g., storm drains, CSOs, streams). Original bed sediment (i.e., sediment at the beginning of the 30-year simulation) was treated as a third source of sediment. The effects of the external loads on the relative amounts of sediment from the three sources (i.e., bed, upstream, lateral) in the surface layer of the sediment bed over the 30-year period were predicted by the sediment transport model. The surface layer is defined as the top 10 cm of the bed.

Sediment from each of the three sources was separated into four size classes (i.e., classes 1A, 1B, 2, 3), with the sediment transport characteristics of the four size classes being the same for all three sediment sources. For example, the erosion, deposition, and transport of class 1A sediment is treated the same way for sediment originating from the bed, upstream, and lateral sources. Thus, the model simulates the erosion, deposition, and transport of 12 sediment classes during the 30-year period.

As discussed in Appendix B, initial conditions for bed composition (i.e., proportional amounts of classes 1A, 1B, 2, and 3 sediment in the bed) were specified based on the predicted spatial distribution of bed composition at the end of a 21-year simulation. The initial conditions used in the 30-year simulation were the same as those used for the model calibration and bed stability simulations discussed in Sections 2 and 3, respectively. These initial conditions are assumed to be representative of present conditions in the LDW because of the results of the model validation (see Section 2.6 and Figure 2-11). The model validation results demonstrate that the predicted composition of the bed compares favorably to the observed composition of surface-layer sediment, which supports the approach used to specify initial conditions for the 30-year simulation.

Changes in the composition of the 10-cm layer at the surface of the sediment bed are of particular importance in this analysis. At the beginning of the 30-year simulation, the composition of the 10-cm surface layer is 100% bed-source sediment, with no sediment from upstream and lateral sources. As the 30-year simulation progresses, upstream- and lateral-source sediment is transported in the LDW and is deposited into the 10-cm surface layer, which reduces the relative amount of bed-source sediment in that layer. The model tracks spatial and temporal changes in the relative amounts of sediment from the three sources over the course of the 30-year period that result from erosion, deposition, and transport processes in the LDW.

The 30-year simulation used the same approach for estimating the magnitude and composition of the upstream (river) sediment load as was used for the 21-year calibration simulation (see Appendix B). The average annual total sediment load from the Green River for the 30-year period was 207,000 MT/yr, with 76% and 24% of the total load being composed of suspended and bedload, respectively. The average annual sediment load during the 30-year period (207,000 MT/yr) is lower than the average load during the 21-year calibration period (217,000 MT/yr) because the annual upstream sediment loads are relatively low during the last nine years of the 30-year period. More details on specification of the upstream sediment load for the 30-year simulation are provided in Appendix F.

Sediment loads from lateral sources (i.e., storm drains, CSOs, streams) were estimated using an approach developed by the City of Seattle (Schmoyer 2007) and King County (Nairn 2007). A summary of the results of that analysis is presented here, with details of the approach provided in Section B.3. Storm drains, streams, and CSOs discharge sediment into the LDW at over 200 locations and incorporating each individual discharge location into the model is not practical. Thus, the lateral sources were aggregated and represented by 21 point sources that discharged into the LDW at 16 representative locations (Figure 4-1). This simplification of input locations has certain implications for interpretation of the predicted spatial distribution of sediment from lateral sources, as discussed in Section 4.3. Estimation of sediment loads from lateral sources required determination of two basic quantities for each lateral source: flow rate and suspended sediment concentration. A watershed model, which predicts runoff during precipitation events, was used to estimate flow rate. Suspended sediment concentration data collected from various storm drains and CSOs were used to estimate values used in the lateral load calculations.

The total average annual load from lateral sources is approximately 1,200 MT/yr, with 76%, 3%, and 21% of the total load from storm drains, CSOs, and streams, respectively. The total annual load from lateral sources is about 0.6% of the average annual total load from the upstream (river) source. The lateral loads are composed of 73% clay/silt and 27% sand for storm drains and streams, and 84% clay/silt and 16% sand for CSOs.

4.3 RESULTS OF EXTERNAL SEDIMENT LOAD ANALYSIS

4.3.1 Net Sedimentation Rates

The spatial distribution of the average net sedimentation rate predicted for the 30-year period is presented in Figure 4-2. These model results illustrate several characteristics of sediment transport processes in the LDW. First, similar to the bed stability results presented in Section 3, the LDW may be separated into three reaches with distinct sedimentation characteristics: Reach 1: RM 0.0 to 2.2; Reach 2: RM 2.2 to 4.0; and Reach 3: RM 4.0 to 4.8. Reach 1 is net depositional over multi-year periods with net sedimentation occurring everywhere. Within Reach 1, relatively high net sedimentation rates (i.e., greater than 2 cm/yr) are predicted between RM 1.4 and 2.2, with lower rates (i.e., typically 0.5 to 2 cm/yr) downstream of RM 1.4. The model predicts a relatively low net sedimentation rate (i.e., less than 0.1 cm/yr) in a small area near RM 0.8-0.9 over the 30-year period; this location experiences net erosion during high-flow events (see Section 3). Within Reach 2 (RM 2.2 to 4.0), spatial variability in net sedimentation rates is greater in this reach than in Reaches 1 and 3, with three small areas (i.e., three grid cells) of low net erosion being predicted for the 30-year period. These small areas of net erosion over the 30-year period are considered to represent a state of dynamic equilibrium at those locations because the predicted net erosion is less than 1 cm over the 30-year period. Relatively high variability in net sedimentation rates, from less than 0.5 cm/yr to greater than 3 cm/yr, in Reach 2 reflects the dynamic nature of this reach, which experiences episodic bed scour during high-flow events (see Section 3 for more discussion). Reach 3 is net depositional and experiences the highest net sedimentation rates within the LDW, which is not surprising because the upper turning basin, which is designed to function as a sediment trap, is located within this reach.

Large-scale comparisons of net sedimentation rates between the three reaches were made by calculating reach-average values (Table 4-2). Reach 2 was separated into two sub-reaches to reflect significant spatial variations in net sedimentation rate within that reach. Reach 2A extends from RM 2.2 to 2.6 and Reach 2B is from RM 2.6 to 4.0. The value for Reach 3 corresponds to the average in the area excluding the upper turning basin; average net sedimentation in the upper turning basin region is over 40 cm/yr.

Table 4-2. Reach-average sedimentation and composition values at end of 30-year period.

Reach	Net Sedimentation Rate (cm/yr)	Bed-Source Content (%)	Upstream-Source Content (%)	Lateral-Source Content (%)
1	1.8	3	94	3
2	2.8	13	85	2
2A	3.7	3	96	1
2B	2.4	17	81	2
3 (excluding upper turning basin)	15	3	95	2

Note: Average net sedimentation rate in upper turning basin is about 40 cm/yr.

4.3.2 Spatial Distributions of Surface-Layer Composition

A primary objective of this analysis was to evaluate the effects of external sediment loads on the composition of the surface-layer (0-10 cm) sediment. Large-scale comparisons of the three reaches provide a view of the relative effects of upstream and lateral sediment loads on surface-layer composition over the course of the 30-year period. Reach-average values of surface-layer composition in the three reaches at the end of the 30-year simulation are listed in Table 4-2. At the beginning of the 30-year simulation, the surface-layer composition is 100% bed-source sediment. Reach-average bed-source content decreases by 97%, 87%, and 97% in Reaches 1, 2, and 3, respectively, during the 30-year period. In Reaches 2A and 2B, bed-source content decreases by 97% and 83%, respectively. A large majority of the reduction in bed-source content is attributable to deposition of sediment from the upstream source. At the end of the 30-year period, the surface sediment in all of the reaches is dominated by the upstream-source load, with reach-average content ranging from 81% to 96%.

The spatial distribution of bed-source content in the surface layer at the end of the 30-year simulation period is shown in Figure 4-3. The relatively high net sedimentation rates in Reaches 1 and 3 cause significant decreases in bed-source content. In Reach 1, bed-source content is less than 25% everywhere except in a small area near RM 0.8-0.9 where the content is greater than 75%; net sedimentation rate is relatively low (i.e., less than 0.1 cm/yr) at this location, which is the cause of the high bed-source content. The high net sedimentation rates (i.e., greater than 3 cm/yr) in Reach 3 cause low values of bed-source content. Spatial variability in bed-source content exists in Reach 2 because of variability in net sedimentation rate in this reach. The highest spatial variability occurs between RM 2.6 and 3.9, which is primarily caused by spatial variations in erosion and deposition in this area during high-flow events. Relatively high bed-source content (i.e., greater than 75%) is predicted in portions of the east and west bench areas between RM 2.8 and 3.8. Net sedimentation rates of approximately 0.3 cm/yr or less occur in these areas of high bed-source content.

The spatial distribution of upstream-source content in surface-layer sediment at the end of the 30-year period is a mirror-image of the bed-source content; upstream-source content is high at locations where bed-source content is low and vice versa (Figure 4-4). The surface-layer composition in Reaches 1 and 3 is dominated by sediment from the upstream source, with a large majority of both reaches having upstream-source content values of 75% or greater because of the relatively high net sedimentation rates. Similar to bed-source content, spatial variability in upstream-source content occurs in Reach 2. The effects of sediment loads from lateral sources on upstream-source content are evident in the vicinity of the lateral-load discharge locations. For example, lower upstream-source content (i.e., 25% to 75%) is predicted in a small area along the east shore of the LDW near RM 0.4-0.5, which is the discharge location of the Duwamish/Diagonal storm drain and CSO.

Generally, the predicted effects of sediment loads from lateral sources are greatest in the vicinity of the representative discharge point of a storm drain or CSO (Figure 4-5). However, it is important to note that over 200 storm drains and CSOs were represented by 16 discharge locations in the model. Therefore, the true lateral-source content in the surficial bed layer is expected to be more widely distributed, and at lower content values, in certain locations than predicted by the model. The FS may identify areas where additional near-field investigations or modeling appear to be warranted during source control and/or remedial design phases to address location-specific uncertainties.

In Reaches 2 and 3, elevated lateral-source content (i.e., greater than 1%) in surface-layer sediment generally occurs in the slips near the storm drain/CSO discharge points. This effect is seen in Slips 4 and 6, located at approximately RM 2.9 and 4.2, as well as in the bench areas that extend downstream of near-shore discharge locations. The effects of lateral sources on surface-layer composition are more widely distributed in Reach 1, with elevated lateral-source content values (greater than 1%) occurring over a large portion of this reach. Tidal effects within this reach spread lateral-source sediment upstream and downstream of the discharge locations. Relatively high lateral-source content values (i.e., greater than 5%) are predicted in the grid cells where the lateral-load discharges are specified.

4.3.3 Temporal Changes in Surface-Layer Composition

The spatial distributions of surface-layer composition shown in Figures 4-3 through 4-5 represent conditions at the end of the 30-year simulation. Examination of temporal variations in surface-layer composition over the entire 30-year period provides insights into the effects of sediment transport processes on the rate of change of surface-layer composition (see Appendix F for details). The results of the analysis presented in Appendix F show that, generally, bed-source content decreases at an approximately exponential rate. For quantities that decrease exponentially with time, a measure of the rate of decline is the half-time, which is the time period over which the quantity decreases by 50%. The half-time metric is useful for expressing the relative rate of decrease in bed-source content caused by deposition of sediment from external sources; a comparatively short half-time represents a comparatively rapid rate of decrease. The spatial distribution of half-time for bed-source content in the surface layer (i.e., top 10 cm) of the bed is shown in Figure 4-6. In Reach 1, half-times are generally less than 10 years, except for a small area near RM 0.8-0.9 where the half-time is greater than 30 years. In Reach 2, the area between RM 2.6 and 3.9 has spatially variable half-times that range from less than 5 years to greater than 30 years. The high sedimentation rates in Reach 3 yield half-times of 10 years or less.

Additional analysis of the relationship between temporal changes in bed-source content and net sedimentation rate suggests an approximate correlation between these two quantities, see Appendix F for details. For areas with net sedimentation rates less than about 0.2 to 0.3 cm/yr, bed-source content in the surface layer decreases at a relatively low rate, with half-times of 30 years or greater. If the net sedimentation rate is greater than about 0.3 cm/yr, then the half-time of bed-source content is less than 30 years. A summary of the areal extent of bed-source content half-time values is given in Table 4-3. These results indicate that the half-times for bed-source content in surface-layer sediment are 10 years or less in about 92% of the LDW bed area, which has a total area of approximately 400 acres. Approximately 6% of the bed area has half-times greater than 30 years.

Table 4-3. Areal extent of half-times for bed-source content in surface-layer sediment.

Half-Time Range (years)	Area (acres)	Relative Portion of LDW Bed Area (%)
Less than 5	163	40
5 - 10	211	52
10 - 30	9	2
Greater than 30	22	6

4.3.4 Sediment Mass Balances

Sediment mass balances were constructed for the 30-year period to gain additional insights about the movement within the LDW of sediment from bed, upstream, and lateral sources. A mass balance for total sediment (i.e., sum of all three sources) is shown in Figure 4-7. The overall trapping efficiency (TE) for the LDW (RM 0.0 to 4.8) is 49%, where trapping efficiency is the portion of the incoming sediment load that is deposited within a particular region. Trapping efficiency varies between the three reaches because of differences in the hydrodynamic and sediment transport characteristics of those reaches. The TE of Reach 3 is 36%, which is higher than TE values of 12% and 9% for Reaches 1 and 2, respectively. The high TE value for Reach 3 is attributable to the presence of the upper turning basin, which is designed to be an efficient sediment trap and it captures a large portion of the sand that is transported from the river into Reach 3. The lowest TE value occurs in Reach 2, which is primarily a result of the hydrodynamic characteristics of this reach during high-flow events.

Reach 1 has a higher TE (12%) than Reach 2 because of the presence of the saltwater wedge in that reach and minimal erosion during high-flow events. Reach 1 has a substantially lower TE than Reach 3 because a relatively small amount of sand is transported into Reach 1, as compared to the amount of sand transported into and deposited within Reach 3.

The total sediment mass balance is separated into mass balances for the three sediment sources in Figures 4-8 and 4-9. These mass balances show that the transport of suspended sediment within the water column is dominated by the upstream-source, with that component composing over 99% of the total suspended sediment load. Among the sediment transported downstream of the LDW (i.e., past RM 0.0), sediments originating from the upstream source represent over 99% of the total load, with sediments originating from the bed and lateral sources composing about 0.2% and 0.5%, respectively, of the total sediment load exiting the LDW at RM 0.0. The contribution from lateral sources to the total suspended sediment load exiting the LDW at RM 0.0 is about two to three times greater than the contribution from the bed-source sediment.

The total mass of eroded sediment in Reach 3 is about a factor-of-two greater than the eroded mass in Reach 2, whereas about 95% less sediment is eroded in Reach 1 compared to Reach 2, on a mass basis, over the 30-year period. Similar to water-column transport, sediment bed dynamics (i.e., erosion, deposition) are dominated by the upstream-source component in most portions of the LDW. Erosion and deposition fluxes are composed of 84% or greater upstream-source sediment, except for erosion in Reach 3, where about one-third of the erosion mass is composed of bed-source sediment. Lateral-source sediment composed about 3% or less of the erosion and deposition masses.

The discussion presented above represents an overview of primary results from the 30-year simulation. Additional details and discussion are presented in Appendix F. The model predictions presented in this section, and Appendix F, were based on sediment loads from lateral sources that were aggregated and represented by 21 point sources that discharged into the LDW at 16 locations (see Section B.3). Subsequent to conducting the model simulations presented in this section, additional work was conducted to refine the spatial distribution of lateral-source sediment loads. This refinement will help to reduce the uncertainty in model simulations with respect to the prediction of lateral-source content in surface-layer sediment. The refined specification of lateral-source inputs to the STM will be included in a future 30-year simulation, and the results of that simulation will be included in the FS report.

4.4 SENSITIVITY ANALYSIS

The calibrated sediment transport model is a reliable tool for evaluating the effects of external sediment loads on surface-layer bed composition over multi-year periods. However, uncertainty exists in the results of the 30-year simulation because of uncertainty in model inputs. The effects of input uncertainty on model predictions were evaluated through a sensitivity analysis.

Because of the long computational time of a 30-year simulation, using the entire 30-year period to evaluate model sensitivity was not feasible. To solve the problem of impractical computational times, the first six years of the 30-year period were chosen for the sensitivity analysis. Numerical experiments demonstrated that the simulation for this 6-year period (i.e., 1960 through 1965) produced results that were comparable to the 30-year simulation period. Thus, the 6-year period chosen for the sensitivity analysis is an acceptable surrogate for the 30-year period.

The results of each 6-year sensitivity simulation were compared to results for the first six years of the 30-year simulation (i.e., base-case period). The 6-year period was used to evaluate the effects of varying the following model inputs: 1) magnitude of lateral-source loads; 2) composition of lateral-source loads; 3) magnitude of upstream-source load; and 4) composition of upstream-source load. Upper- and lower-bound estimates of load composition and magnitude were determined and those bounding values were used in the sensitivity simulations. Descriptions of the adjustments to these parameters for the sensitivity analysis are presented in Appendix F, as well as a detailed description of the results of the sensitivity analysis. A summary of the sensitivity analysis is presented here.

The effects of varying the composition and magnitude of the external sediment loads were quantified by comparing reach-average values of bed-source and lateral-source content in the surface layer of the sediment bed at the end of the 6-year period. Reach-average contents for Reaches 1, 2A, 2B, and 3 for the various sensitivity simulations are compared in Figures 4-10 through 4-12. The results of these comparisons show that the lateral-source content is within about 40% of the base-case value due to changes in magnitude or composition of the lateral-source load. The bed-source content varies non-linearly with respect to changes in the upstream-source load magnitude (e.g., doubling the upstream load causes the bed-source content to decrease by about 50%, while decreasing the load by 50% causes the bed-source content to increase by about 50%). Changes in the composition of the upstream-source load (see Table F-3) produced variations in bed-source and lateral-source content that are within 10% of the base-case value.

SECTION 5
SUMMARY AND SYNTHESIS OF RESULTS

The Phase 1 RI (Windward 2003) 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 an initial CSM. That CSM was considered to be preliminary because sufficient site-specific information and data were not available during the Phase 1 RI to confirm it. The initial CSM was refined based on analyses conducted during the STAR study (Windward and QEA 2007), and the CSM developed during the STAR study was presented in Section 1.3.

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 processes that affect sediment transport and bed stability in the system. Additional work on sediment stability was conducted during the STAR study (Windward and QEA 2007). The data and analyses from these earlier studies were combined with the modeling analyses discussed in this report to develop a quantitative tool that was used to evaluate sediment transport processes in the LDW.

Several issues concerning the potential effects of sediment transport on chemical transport and fate were addressed through application of the sediment transport model. Long-term, multi-year simulations were conducted to predict the spatial distribution of net sedimentation rates in the LDW. These results were used to develop insights concerning the rate of change of surface-layer sediment composition caused by external sediment sources. The effects of high-flow events on bed scour were evaluated with the model. Specific questions that were addressed using the sediment transport model were presented in Section 1.6.

The data and modeling analyses were combined and used to further refine the CSM that was developed during the STAR study. The refined CSM for sediment transport processes will support the FS for the LDW. 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 analyses that are aimed specifically at assessing the effectiveness of various remedial alternatives in the FS.

5.1 SUMMARY OF LDW DEPOSITIONAL ENVIRONMENT EVALUATION

The depositional environment of the LDW was characterized using the results of a geochronology study during the STAR study (Windward and QEA 2007). The geochronology study consisted of the collection and age-dating of sediment cores collected from the LDW in 2004. Results of the geochronology analysis are summarized as follows:

- Net sedimentation rates in the inter-tidal and sub-tidal 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., elevations above +0.4 ft. MLLW) than 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, and relationships between net sedimentation rates and sediment bed characteristics were not evident.
- 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.

An independent verification of net sedimentation rates estimated from the geochronology cores used several empirical lines-of-evidence from the LDW (Windward and QEA 2007). The available site data used in that analysis included: chemistry and stratigraphy data from 58 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 establishing a deposition date or period for a time marker and establishing the presence of the marker at a specific depth, the net sedimentation rate, representing the average rate of net deposition for the time period between the time marker and core collection, was estimated. Two primary conclusions from the analyses 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 sub-tidal bench areas (less than 2 cm/yr), and lowest in the inter-tidal bench areas (less than 0.5 cm/yr).
- The reliability of these results is increased because of 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. In addition, the net sedimentation rates estimated during these analyses were used during calibration of the sediment transport model.

5.2 SUMMARY OF SHIP-INDUCED BED SCOUR ANALYSIS

Gross bed scour potentially resulting from ship traffic along particular LDW transects was analyzed during the STAR study (Windward and QEA 2007). The focus of that analysis 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. The analysis was necessarily limited to estimating gross bed scour because it did not explicitly account for sediment transport and deposition processes. Results of the analysis indicated that:

- The bed scour results were considered to be upper-bound estimates, with actual bed erosion attributable 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 was estimated to cause average bed scour of less than 1 cm per ship passage in Reach 1 (RM 0 to 2.2), and less than 0.1 cm per ship passage in Reach 2 (RM 2.2 to 4.0). Within the bench areas, average bed scour of about 1-2 cm per ship passage occurs upstream of RM 3.0, and less than 1 cm per ship passage occurs in the region downstream of RM 3.0.
- 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 surface layer is equated to the depth of gross bed scour. 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 Reach 2, 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.
- 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.

In summary, an analysis of ship-induced bed scour was conducted independently of the sediment transport model. The results indicate that ship-induced bed scour behaves as a mixing process for surficial bed sediment and it does not affect the insights and conclusions developed from the sediment transport modeling.

5.3 SUMMARY OF SEDIMENT TRANSPORT MODEL CALIBRATION AND VALIDATION

The hydrodynamic model originally developed and calibrated during the STAR study was re-calibrated because modifications were made to the numerical grid. Modifications to the numerical grid used in the STAR study were necessary so that long-term, multi-year simulations could be accomplished during the STM study. The re-calibration results show that the hydrodynamic model realistically simulates all of the major characteristics of estuarine circulation in the LDW. The vertical structure of tidal current velocity is realistically simulated, with the model able to reproduce two-layer flow in the region occupied by the saltwater wedge. Strong vertical stratification of salinity is observed within the saltwater wedge and the model is able to simulate that stratification with acceptable accuracy. In addition, the model realistically simulates the dynamic nature of the saltwater wedge and the location of the toe of the wedge as it varies over the course of a tidal cycle, as well as variations associated with changes in freshwater inflow and phase of the tidal cycle (i.e., spring and neap tide conditions). Overall, re-calibration of the hydrodynamic model demonstrates that the model is sufficiently accurate and reliable for the objectives of this study.

The sediment transport model is built on a foundation of mechanistic formulations that are used to simulate erosion and deposition of cohesive (muddy) and non-cohesive (sandy) sediment. The erosion and deposition formulations used in the model are based on results from a large number of laboratory and field studies. Site-specific data were used to determine model inputs, with site-specific data used to determine two major inputs: sediment loading from the Green River and erosion properties of LDW sediments. The significant amount of site-specific data, in conjunction with the mechanistic nature of the model formulations, provided an opportunity to develop and calibrate a reliable sediment transport model that is well constrained.

5.4 SUMMARY OF MODEL PREDICTIVE CAPABILITY AND RELIABILITY

The results of the model calibration and validation, spatial-scale analysis, and uncertainty analysis presented in Section 2 indicate that the predictive capability and reliability of the sediment transport model are sufficient for achieving the overall objectives of this study:

- develop a quantitative tool to evaluate short-term and long-term sediment transport processes in the LDW;

- refine the CSM for the LDW; and
- provide information to support FS analyses and inform remedial decision-making.

Calibration and validation of the sediment transport model, in conjunction with the spatial-scale and uncertainty analyses, were used to evaluate the accuracy and reliability of the model. The 21-year simulation period used to calibrate and validate the model was a strong test of the model's capabilities because of the wide range of tidal and river flow conditions during that period. Results of the calibration and validation exercises, as well as the spatial-scale and uncertainty analyses, indicate that the sediment transport model is able to adequately predict NSRs and bed composition in the navigation channel and bench areas, which indicates that the model adequately simulates sediment transport processes in the LDW. Based on these results, the following conclusions concerning model reliability were developed:

- The STM may be used to refine, confirm, and validate the CSM.
- The analysis provides quantitative uncertainty estimates for STM predictions and CSM components.
- The STM provides a framework to support physical process evaluation and the effects of potential actions in the LDW.
- Over small spatial scales (i.e., areas corresponding to approximately one or two grid cells in size), the STM will typically demonstrate trends that may be used as one line-of-evidence, along with other information and data, to guide decision making.
- The STM is a reliable framework for supporting extrapolation to conditions where no erosion and/or NSR data are available.

The STM group collaborated and provided guidance during the calibration and validation process, with important contributions being made by various group members. The group reviewed the results of the calibration and validation simulations, as well as the spatial-scale and uncertainty analyses, during April 2008. After discussion among the members of the STM group, concurrence was reached on the five conclusions presented above.

Acceptable reliability of the STM makes it possible to use model results to support FS analyses. The model provides a reliable framework for use as a diagnostic and prognostic tool to extrapolate information to areas in the LDW where no or minimal data are available for FS evaluations. However, it is emphasized that the STM provides only one line-of-evidence for the FS analyses, which will typically rely on multiple lines-of-evidence to reach conclusions about the efficacy of a range of remedial alternatives.

5.5 SUMMARY OF SEDIMENT BED STABILITY ANALYSIS

The sediment transport model was used to evaluate the effects of high-flow events on bed stability in the LDW. High-flow events with return periods of 2, 10, and 100 years were simulated. Boundary conditions for the high-flow simulations were developed using the hydrograph of a high-flow event that occurred during November-December 1975. Spring tide conditions occurred during peak flow conditions of this high-flow event. Thus, the high-flow simulations produced conservative results that represent upper-bound estimates of bed scour depths during high-flow events.

Results of the high-flow simulations indicate that the LDW may be separated into three reaches, with each reach having different erosional and depositional characteristics during high-flow events:

- *Reach 1 (RM 0.0 to 2.2)*: This reach is primarily net depositional during high-flow events, with relatively small areas of net erosion. Net erosion depths are generally 2 cm or less, even during the 100-year high-flow event.
- *Reach 2 (RM 2.2 to 4.0)*: Net erosion occurs over a large portion of this reach during high-flow events, with relatively small areas of net deposition. Net erosion depths are typically less than 10 cm, with maximum net erosion depths of 14 and 21 cm predicted in the cohesive bed during high-flow events with return periods between 2 and 100 years, respectively.

- Reach 3 (RM 4.0 to 4.8): This reach is primarily net depositional during high-flow events, with a few areas of net erosion. Net erosion depths are typically less than 10 cm, with maximum erosion depths of 9 and 20 cm occurring in the non-cohesive bed during high-flow events with return periods between 2 and 100 years, respectively.

During a 100-year high-flow event, approximately 18% of the LDW bed area (i.e., RM 0.0 to 4.8) experiences net erosion, while the other 82% of the bed area is net depositional. Most of the erosion occurs in Reach 2 (RM 2.2 to 4.0). A large portion of the net erosion occurs in the surface layer (i.e., 0 to 10 cm), with 20% of the LDW bed area having net erosion depths greater than 10 cm. Maximum net erosion depths during a 100-year high-flow event are about 21 cm. Maximum bed scour depths were about 2 cm greater than net erosion depths. Thus, scour is limited to approximately the upper 20-cm layer of the sediment bed during the 100-year high-flow event, with this result being a conservative, upper-bound estimate. In most areas, the maximum scour depth is far less.

A sensitivity analysis was conducted to evaluate uncertainty in model predictions associated with uncertainty in model inputs and parameters. The model was most sensitive to the parameters controlling erosion rates, which were specified using Sedflume core data collected from the LDW. Results of the sensitivity analysis for a 100-year high-flow event indicate that uncertainty in predicted erosion area due to model input uncertainty is less than ± 50%, with respect to the base-case simulation, within the RM 0-4.3 region, including the three primary zones (i.e., navigation channel, west bench, east bench). Uncertainty in predicted sediment mass ranges from about -50% to +75% within the RM 0-4.3 region, as well as in the east bench and navigation channel. More uncertainty exists in the west bench zone for predicted sediment mass; the uncertainty range in the west bench is about -40% to +130%.

5.6 SUMMARY OF EXTERNAL SEDIMENT LOAD ANALYSIS

The main objective of the external sediment load analysis was to answer the four questions posed in Section 1.6. Answers to those questions are provided below.

What areas in the LDW are net depositional, net erosional, or in dynamic equilibrium? Over the 30-year period, three grid cells in Reach 2 are predicted to be net erosional, but these locations should be considered to be in a state of approximate dynamic equilibrium because the total net erosion over the 30-year period is predicted to be less than 1 cm. Other than these three locations, the sediment bed in the rest of the LDW is net depositional over the 30-year period, with average net sedimentation rates ranging from less than 0.1 cm/yr to greater than 3 cm/yr.

How does the composition of the surface-layer sediment change over time as external sediment loads (from upstream and lateral sources, such as storm drains) become incorporated into the sediment bed? The average bed-source content of the surface-layer (i.e., 0 to 10 cm deep) sediment decreases by 97%, 87%, and 97% in Reaches 1, 2, and 3, respectively, during of the 30-year period. In Reaches 2A and 2B, bed-source content decreases by 97% and 83%, respectively. A large majority of the reduction in bed-source content is attributable to deposition of sediment from the upstream sediment source. Generally, bed-source content decreases at an approximately exponential rate, which means that a representative measure of the rate of change bed-source content is the half-time (i.e., time for bed-source content to decrease by 50%). For areas with net sedimentation rates less than about 0.2 to 0.3 cm/yr, bed-source content in the surface layer decreases at a relatively low rate, with half-times of 30 years or greater. If the net sedimentation rate is greater than about 0.3 cm/yr, then the half-time of bed-source content is less than 30 years. Reach-average half-times for bed-source content in Reaches 1, 2, and 3 are 6, 10, and 6 years, respectively.

What is the effect of high-flow events on episodic scour in otherwise net depositional areas? Within Reach 1, negligible scour occurs during high-flow events in most of this reach, with minor effect on long-term deposition. A small area near RM 0.8-0.9 experiences bed scour during high-flow events, which tends to reduce long-term deposition and results in relatively slow reduction in bed-source content. A small, localized area near RM 0.1 also experiences bed scour during high-flow events. Bed scour is spatially variable in Reach 2 and episodic erosion during rare events tends to cause relatively low long-term net sedimentation rates at some locations. The relatively high net sedimentation rates in Reach 3 (i.e., greater than 3 cm/yr) minimize the effects of bed scour during high-flow events over multi-year periods.

In areas that are net depositional, what is the potential depth of scour during high-flow events? The depth of bed scour is dependent on river flow and tidal conditions during the high-flow event, as well as location in the LDW. For a 100-year high-flow event, approximately 18% of the LDW bed area experiences net erosion. Most of the erosion occurs in Reach 2. A large portion of the net erosion occurs in the surface layer (i.e., 0 to 10 cm), with about 6% of the LDW bed area having net erosion depths greater than 10 cm. Maximum net erosion depths during a 100-year high-flow event are about 21 cm.

In addition to answering these questions, the external sediment load analysis provided other insights about sediment transport processes in the LDW:

- The upstream-source dominates water-column transport and sediment bed dynamics (i.e., erosion, deposition) on a mass basis during the 30-year period.
- Among the sediments transported downstream of the LDW (i.e., past RM 0.0), sediments originating from the upstream source represent over 99% of the total load, with sediments originating from the bed and lateral sources composing about 0.2% and 0.5%, respectively, of the total load exiting the LDW at RM 0.0. The contribution from lateral sources to the total suspended sediment load exiting the LDW at RM 0.0 is about two to three times greater than the contribution from the bed-source sediment.
- Reaches 1, 2, and 3 have different sediment transport characteristics, primarily as a result of differences in the hydrodynamic characteristics of each reach during high-flow events and the sediment load from upstream sources.
- Reach 1 has relatively high net sedimentation rates, but these rates are generally lower than the rates in Reach 3 because less sand is transported into this portion of the LDW than into the upstream reach. Negligible bed scour occurs during high-flow events in most areas of this reach.
- Reach 2 has net sedimentation rates that are spatially variable but the reach-average rate is similar to the reach-average rate for Reach 1. This reach experiences the most erosion

during a high-flow event as a result of relatively high bed shear stresses caused by changes in hydrodynamics during an event (i.e., transition from estuarine circulation with a saltwater wedge during low-flow conditions to a tidal freshwater river during high-flow conditions).

- Reach 3 has the highest net sedimentation rates in the LDW because of the presence of the upper turning basin and deposition of a significant portion of the load of sand from the Green River.

Similar to the bed stability analysis, a sensitivity analysis was used to evaluate uncertainty in model predictions attributable to uncertainty in model inputs. The sensitivity of the model to changes in the magnitude and composition of external sediment loads was investigated. The results of the analysis showed that uncertainty in the lateral-source content is about ± 60% with respect to the base-case value. The bed-source content varies approximately linearly with respect to changes in the upstream load magnitude; doubling the upstream load causes the bed-source content to decrease by about 50%, while decreasing the load by 50% causes the bed-source content to approximately double. Changes in the composition of the upstream load produce variations that are within 30% of the base-case value.

5.7 INTEGRATION AND SYNTHESIS OF RESULTS

The modeling analyses conducted during this study, in conjunction with empirical analyses (e.g., estimation of net sedimentation rates in the bench areas) and ship-induced bed scour analyses from the STAR study, have produced an improved understanding of sediment transport processes in the LDW. A large amount of information on LDW hydrodynamics and sediment transport is presented in this report, and in Windward and QEA (2007). The summaries presented in the previous sub-sections provide overviews of the primary results from the major components of the sediment transport study. The objective of this sub-section is to integrate and synthesize the results and findings from the major components of the study so that a clear and concise picture of sediment transport in the LDW emerges.

The LDW was separated into three reaches as a convenient aid for understanding and describing hydrodynamic and sediment transport processes in the study area: Reach 1 (RM 0.0 – 2.2); Reach 2 (RM 2.2 – 4.0); and Reach 3 (RM 4.0 – 4.8). Separation of the study area into these three reaches was based on the hydrodynamic and sediment transport characteristics of the LDW during high-flow events.

The first step in understanding sediment transport in the LDW is to understand the hydrodynamics of this saltwater-wedge estuary. Hydrodynamic circulation in the LDW is controlled by the interaction of three primary components: 1) geometry and bathymetry of the system; 2) freshwater inflow from the Green River; and 3) tides in Elliott Bay, which transport saltwater into the LDW. These main components cause significant changes in the hydrodynamics of the LDW during conditions of low and high inflow from the Green River.

During low-flow conditions in the Green River, the saltwater wedge extends to or beyond the upstream portion of Reach 3 (i.e., RM 4.5 to 4.8), see Figure 5-1. The saltwater wedge is dominated by two-layer estuarine circulation, with saltier and denser water transported upstream in the lower-layer of the water column and fresher water transported downstream in the upper-layer. Near-bed velocities, and bed shear stresses, within the saltwater wedge are tidally driven and relatively low, which results in minimal bed scour within the saltwater wedge during low-flow conditions.

During a high-flow event in the Green River (which in the discussion presented in this sub-section is a discharge equivalent to a 2-year event or greater), the toe of the saltwater wedge is pushed downstream to the vicinity of the boundary between Reaches 1 and 2 (i.e., RM 2.0 to 2.5). Two-layer estuarine circulation exists within the saltwater wedge (Reach 1) during a high-flow event (Figure 5-2). The lower-layer of the water column in Reach 1, which contains saltier water that is being transported upstream, is thinner during a high-flow event than during low-flow conditions because of the larger volume of fresher water in the upper-layer. The decreased thickness of the lower-layer in Reach 1 increases near-bed velocities enough in the navigation channel near RM 0.8-0.9 for bed scour to occur during a high-flow event. High freshwater inflow causes the hydrodynamic characteristics of Reaches 2 and 3 to change from two-layer estuarine circulation (low-flow conditions) to a freshwater tidal river. This change in the hydrodynamic characteristics of these two reaches results in significant increases in near-bed current velocities and bed shear stresses in Reaches 2 and 3 during a high-flow event. Current velocities, and bed shear stresses, are higher in Reach 2 than in Reach 3 because the cross-sectional area of the channel is generally smaller in Reach 2 than in Reach 3.

Overall, Reaches 1, 2, and 3 have different sediment transport characteristics, primarily associated with differences in the hydrodynamic characteristics of each reach during high-flow events and the sediment load from upstream sources. Reach 1 has relatively high net sedimentation rates, but these rates are generally lower than the rates in Reach 3 because less sand is transported into this portion of the LDW than into the upstream reach. Reach 2 has net sedimentation rates that are spatially variable, with areas of relatively low net sedimentation. This reach experiences the most erosion during a high-flow event as a result of relatively high bed shear stresses caused by changes in hydrodynamics during an event (i.e., transition from estuarine circulation with a saltwater wedge during low-flow conditions to a tidal freshwater river during high-flow conditions). Reach 3 has the highest net sedimentation rates in the LDW, because of the presence of the upper turning basin, which acts as a sediment "sink" and captures a large portion of the load of sand from the Green River.

Most of the bed scour during a high-flow event occurs in Reach 2, with Reach 1 having minimal erosion except in a small area near RM 0.8-0.9. Limited net erosion occurs in Reach 3. During a high-flow event with a return period of 100 years, about 18% of the total bed area in the LDW (i.e., about 70 acres) is net erosional, with most of the bed scour occurring in Reach 2. The remaining 82% of the total bed area in the LDW experiences net deposition during a 100-year high-flow event (Figure 5-3). A large majority of the net erosion is limited to the surface layer (i.e., 0 to 10 cm) of the bed, with less than 6% of the total bed area (about 22 acres) having net erosion greater than about 10 cm during a 100-year high-flow event. The maximum depth of bed scour (i.e., net erosion) during a 100-year high-flow event is about 21 cm, with the effects of bed armoring limiting the depth of bed scour. About 80% of the total mass of eroded sediment originates from the surface layer, with the other 20% coming from the sub-surface layer (i.e., deeper than 10 cm). Approximately 78% of the sediment mass eroded from the bed is re-deposited within the LDW, with the remaining 22% transported out of the LDW. Sediment from the upstream source (i.e., sediment from the Green River) composes about 95% of the total sediment load transported past the downstream limit of the LDW (RM 0.0) during a 100-year high-flow event; sediment eroded from the surface and sub-surface layers during a 100-year event of the bed compose about 4% and 2%, respectively, of the total sediment load past RM 0.0. Areas that are predicted to experience net erosion during a 100-year high-flow event are typically net depositional over long-term, multi-year periods which include high-flow events that are similar in magnitude to a 100-year event..

Reaches 1, 2, and 3, and thus the entire LDW, are net depositional on annual timescales. The general effect of erosion during high-flow events is to reduce the net sedimentation rate in locations where bed scour occurs. Net sedimentation rates, on a reach-average basis, vary from about 2 cm/yr in Reaches 1 and 2 to over 15 cm/yr in Reach 3. Reach 2 was separated into two sub-reaches based on differences in net sedimentation rate, with the spatially-averaged rate in Reach 2A (RM 2.2-2.6) being about 50% higher than the average rate in Reach 2B (RM 2.6-4.0), see Figure 5-4. Within Reach 3, the upper turning basin, which is designed to be an effective sediment trap, has an average net sedimentation rate of over 40 cm/yr. Generally, spatially-averaged net sedimentation rates are similar in the navigation channel and bench areas, with differences between the zones being less than a factor-of-two in a particular reach. While the reach-average net sedimentation rate in Reach 1 is about 2 cm/yr, a small area near RM 0.8-0.9 has a relatively low rate (i.e., less than 0.1 cm/yr); this area experiences bed scour during high-flow events with return periods of 2 years or greater. The spatial variability of net sedimentation rates is relatively high in Reach 2B, ranging from less than 0.5 cm/yr to greater than 3 cm/yr; this variability is primarily a result of the effects of high-flow events.

Three sources of sediment are transported within the LDW: upstream source (Green River); lateral source (streams, stormwater runoff, storm drains, CSOs); and original bed source. The annual average sediment load from lateral sources is 0.6% of the annual average load from the Green River. Approximately 49% of the external sediment load, from upstream and lateral sources, is deposited (or trapped) in the LDW (Figure 5-4). Trapping efficiency (i.e., portion of incoming sediment load deposited within a reach) varies between the three reaches as a result of differences in the hydrodynamic and sediment transport characteristics of those reaches. The TE of Reach 3 is 36%, which is higher than TE values of 12% and 9% for Reaches 1 and 2, respectively. The relatively high TE value for Reach 3 is because of the presence of the upper turning basin, which is designed to be an efficient sediment trap; a large portion of the sand that is transported down the Green River is captured in the upper turning basin. The lowest TE value occurs in Reach 2, which is primarily a result of the hydrodynamic characteristics of this reach during high-flow events. A substantially lower TE for Reach 1 than for Reach 3 is attributable to the relatively low amount of sand that is transported into Reach 1, as compared to the amount of sand transported into Reach 3.

The transport of suspended sediment within the water column is dominated by the upstream source, with that component composing more than 99% of the suspended sediment load. Among the sediments transported downstream of the LDW (i.e., past RM 0.0), sediments originating from the upstream source represent over 99% of the total suspended load, with sediments originating from lateral and bed sources composing about 0.5% and less than 0.2% of the total suspended load exiting the LDW at RM 0.0, respectively. The contribution from lateral sources to the total suspended sediment load exiting the LDW at RM 0.0 is about two to three times greater than the contribution from the bed-source sediment.

The bed-source content of the surface (0-10 cm) layer decreases with time at an approximately exponential rate, primarily because of the deposition of upstream-source sediment. The rate of decrease is spatially variable within the LDW because of variations in net sedimentation rate. Half-time (i.e., time needed for a 50% reduction) is a convenient measure of the rate of decrease of bed-source content. Approximately 94% of the total bed area in the LDW has a half-time of 10 years or less. About 6% of the LDW bed area has a half-time of 30 years or more; net sedimentation rates in these areas are less than about 0.3 cm/yr. Predicted decreases in reach-average bed-source content over a 30-year period are shown in Figure 5-5. The reach-average decreases range from 83% in Reach 2B to 97% or more in Reaches 2A and 3. Corresponding reach-average half-times range from 6 to 12 years.

Generally, the effects of sediment loads from lateral sources are greatest in the vicinity of the discharge point of a storm drain, CSO, or stream. In Reaches 2 and 3, elevated lateral-source content (i.e., greater than 1%) in surface-layer sediment generally occurs in the slips near the storm drain/CSO discharge points. This effect is seen in Slips 4 and 6, located at approximately RM 2.9 and 4.2, as well as in the bench areas that extend downstream of near-shore discharge locations. The effects of lateral sources on surface-layer composition are more widely distributed in Reach 1, with elevated lateral-source content values (greater than 1%) occurring over a large portion of this reach. Tidal effects within this reach spread lateral-source sediment upstream and downstream of the discharge locations. Relatively high lateral-source content values (i.e.., greater than 5%) are predicted at locations of the lateral-load discharges. At the end of a 30-year period, reach-average values of lateral-source content in the surface layer of the bed are about 1% to 2% (Figure 5-6).

5.8 REVISED CONCEPTUAL SITE MODEL FOR SEDIMENT TRANSPORT

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 CSM developed during the STAR study.

The results and conclusions concerning the evaluation of sediment transport and bed stability in the LDW 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 have a higher level of uncertainty. The results of sensitivity analyses demonstrate that quantitative model results have an uncertainty level of a factor-of-two or less that is attributable to uncertainty in model inputs. This level of uncertainty is acceptable for the intended uses of the sediment transport model.

A goal of this study was to develop an improved understanding of sediment transport processes in the LDW. 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 were used to refine the Phase 1 CSM, which produced a better understanding of sediment transport and bed stability in the LDW. The revised CSM for sediment transport is:

- Reaches 1, 2, and 3, and thus the entire LDW, are net depositional 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 4.5) to downstream areas. For the bench areas, net sedimentation rates are higher in Reaches 1, 2A, and 3 than in Reach 2B. Net sedimentation rates tended to be lower in the inter-tidal areas than in the sub-tidal 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 2, was lower in Reach 3 than in Reach 2, and was minimal in Reach 1. Net erosion occurs over about 18% or less of the LDW bed area during high-flow events with return periods of 2 years or greater (i.e., erosional area increases with increasing return period); most of the bed scour is less than 10 cm deep and maximum net erosion depths are 21 cm or less.
- Ship-induced bed scour tends to behave as a mixing process for surficial sediment for typical ship traffic within the navigation channel. The effects of berthing operations may cause erosion at small, localized areas. 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 is presented in Section 4.3 (i.e., Figure 4-2). 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.

The revised CSM is extended to the three reaches of the LDW separately. 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: RM 0.0 to 2.2

This reach is net depositional on annual time scales, in both the navigation channel and the adjacent bench areas. Based on net sedimentation rates predicted by the model (i.e., Figure 4-2), the navigation channel is classified as intermediate and higher net depositional, with a small area near RM 0.8-0.9 being lower net depositional. The bench areas range from intermediate to higher net depositional, with two small areas classified as lower net depositional. With respect to episodic erosion, this reach is always within the saltwater wedge, even during a 100-year 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, resulting in relatively low bed scour (less than 2 cm) being limited to a small area near RM 0.8-0.9. The potential for re-exposing buried sediments as a result of 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 2.2 to 4.0

Reach 2 is net depositional on annual time scales. Net sedimentation is spatially variable in this reach, with classification in the navigation channel and bench area ranging from lower to higher net depositional. This reach experiences significantly more net erosion during high-flow events than Reaches 1 and 3, but erosion is generally limited to the upper 10 cm of the sediment bed and maximum net erosion depths are 21 cm or less. The primary cause of relatively high net erosion during high-flow events (i.e., return period of 2 years or greater) in Reach 2 is the hydrodynamic characteristics of this reach, which experiences relatively high bed shear stresses during high-flow events. 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: RM 4.0 to 4.8

This reach is net depositional on annual time scales. The relatively high net sedimentation rates in this reach indicate that the navigation channel and bench areas are classified as higher net depositional. Modeling results indicate that episodic erosion may occur during high-flow events in Reach 3, but the areal extent of net erosion is significantly less than the areal extent of net erosion in Reach 2. Bed scour during high-flow events (i.e., return period of 2 years or greater) is generally limited to the upper 15 cm of the sediment bed, with maximum scour depths of 20 cm. 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.

SECTION 6
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APPENDIX A
DETAILS OF SEDIMENT TRANSPORT MODEL THEORY AND FORMULATION

This appendix presents discussion of the theory and formulations used in the sediment transport model to calculate erosion and deposition fluxes at the sediment-water interface. For bed scour, erosion fluxes in cohesive and non-cohesive bed areas are treated differently. Two areas of the modeling domain are specified as "hard bottom" (see Section B.4). In a grid cell specified as hard bottom, the erosion and deposition fluxes are set to zero, so no change in bed elevation is calculated during a simulation.

A.1 CALCULATION OF BED SHEAR STRESS

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

$$\tau_{tot} = \tau_{sf} + \tau_{fd} \tag{A-1}$$

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 considered the dominant component of the bed shear stress for most applications. The hydrodynamic and sediment bed conditions in the LDW are not favorable for developing physical features (e.g., wavy beds) that induce form drag. Thus, it is a reasonable approximation, and a standard approach, to use the skin friction component and neglect form drag for calculating bed shear stress for a cohesive bed. This approach is consistent with accepted sediment transport theory (Parker 2004). Skin friction shear stress is calculated using the quadratic stress law:

$$\tau_{sf} = \rho_w C_f u^2 \tag{A-2}$$

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

$$C_f = \kappa^2 \ln^{-2}(11\, z_{ref} / k_s) \tag{A-3}$$

where z_{ref} is a reference height above the sediment bed, k_s is the effective bed roughness, and κ is von Karman's constant (0.4). The reference height (z_{ref}) is spatially and temporally variable because it is equal to half of the thickness of the bottom layer of the numerical grid. Because a stretched (sigma-layer) grid is used in the vertical direction, the thickness of the bottom layer of the vertical grid is equal to 10% of the local water depth, which varies due to changes in tidal elevation and river flow rate. Thus, the reference height properly incorporates temporal and spatial variations in water depth into the calculation of the bottom friction coefficient. The effective bed roughness is assumed to be proportional to the D_{90} of the surface sediment layer (Parker 2004, Wright and Parker 2004):

$$k_s = 2D_{90} \tag{A-4}$$

Grain size distribution data were used to specify D_{90} values for the surface layer of LDW sediments. The spatial variability of D_{90} in the LDW was evaluated (see Section B.4); accounting for potential spatial variation of D_{90} in the model produces qualitatively correct results (i.e., skin friction increases as bed roughness increases).

The validity of the above approach for calculating the bottom friction coefficient is evaluated as follows. Bottom friction coefficients were calculated for the LDW, using representative D_{90} values in the navigation channel and bench areas (see Section B.4), over a range water depths (see Table A-1). The range of bottom friction coefficient values in Table A-1 is consistent with expected values for cohesive beds (van Rijn 1993). This approach provides an objective method for estimating the effective bed roughness, which will decrease the uncertainty associated with subjective estimates of roughness.

Table A-1. Bottom friction coefficient values for a range of water depths.

Water Depth (m)	Bottom Coefficient: Navigation Channel (D_{90} = 360 μm)	Bottom Coefficient: East Bench (D_{90} = 940 μm)	Bottom Coefficient: West Bench (D_{90} = 790 μm)
1	0.0036	0.0050	0.0047
2	0.0030	0.0039	0.0037
3	0.0027	0.0035	0.0033
4	0.0025	0.0032	0.0031

For use in formulations presented below, a demonstrated accurate equation for bed-shear velocity (u*) is defined as (van Rijn 1993):

$$u_* = (\tau_{sf} / \rho_w)^{0.5} \tag{A-5}$$

Current velocity in turbulent flow, which exists in the LDW for all flow and tidal conditions, is the sum of two components: time-averaged mean velocity and turbulent fluctuations about the mean value. The bed-shear velocity (u*) corresponds to the turbulent-fluctuation component of the current velocity. Thus, the skin friction shear stress is driven by the turbulent fluctuations in the flow, which are randomly variable with time. Random variation in turbulence along the sediment bed is the primary reason that a probabilistic approach to calculating deposition and erosion fluxes is necessary; use of probability of deposition (see Equation A-6) and suspension (see Equation A-15) formulations have been incorporated into the model to account for these turbulence effects.

A.2 DEPOSITION PROCESSES

The deposition flux for size class k sediment (D_k) is expressed as (Ziegler et al. 2000):

$$D_k = P_{dep,k}\ W_{s,k}\ C_k \tag{A-6}$$

where $P_{dep,k}$ is probability of deposition of class k, $W_{s,k}$ is settling speed of class k, and C_k is near-bed suspended sediment concentration of class k. Deposition flux has units of mass per unit area per time (e.g., g/cm^2–s). The near-bed concentration (C_k) is calculated using the sediment transport model and is represented by the value in the vertical grid cell immediately above the bed.

Probability of deposition of cohesive sediment (i.e., classes 1A and 1B) is determined using the Krone formulation (van Rijn 1993):

$$P_{dep,k} = 1 - (\tau_{sf}/\tau_{cr,dep}) \quad \text{for} \quad \tau_{sf} < \tau_{cr,dep} \tag{A-7}$$

$$= 0 \quad \text{for} \quad \tau_{sf} > \tau_{cr,dep} \tag{A-8}$$

where τ_{sf} is bed shear stress (skin friction) and $\tau_{cr,dep}$ is the critical bed shear stress for deposition. The relationship between probability of deposition and bed shear stress for classes 1A and 1B is shown in Figure A-1.

For non-cohesive sediment (i.e., classes 2 and 3), the probability of deposition depends on bed shear stress and particle diameter, and is described by a Gaussian distribution (Gessler 1967, Ziegler et al. 2000):

$$P_{dep,k} = (2\pi)^{-0.5} \int \text{EXP}(-0.5x^2)\ dx \tag{A-9}$$

where the lower and upper limits of the integral are negative infinity and Y, respectively, and EXP corresponds to the exponential function with base e. The parameter Y is given by:

$$Y = 1.75\ (\tau_{c,k} / \tau_{sf} - 1) \tag{A-10}$$

where $\tau_{c,k}$ is critical shear stress for suspension of class k sediment, which is:

$$\tau_{c,k} = \rho_w\, u_{*,crs,k}^{\ 2} \tag{A-11}$$

where $u_{*,crs,k}$ is critical bed-shear velocity for initiation of suspension for class k:

$$u_{*,crs,k} = 4\ W_{s,k} / d_{*,k} \qquad \text{for } 1 < d_{*,k} \leq 10 \tag{A-12}$$

$$= 0.4\ W_{s,k} \qquad \text{for } d_{*,k} > 10$$

and:

$$d_{*,k} = d_k\ [(s-1)g/\nu^2]^{1/3} \tag{A-13}$$

where d_k is particle diameter for class k, s is specific density of particle (i.e., 2.65), g is acceleration caused by gravity, and ν is kinematic viscosity of water. The non-dimensional particle parameter ($d_{*,k}$) is commonly used in a wide range of sediment transport formulations (van Rijn 1993). The probability of deposition for classes 2 and 3 as a function of bed shear stress and particle diameter is presented in Figure A-2.

Numerous field and laboratory experiments have demonstrated that a physically realistic representation of the settling speed of a discrete particle is related to the particle diameter, representing size class k, as follows (Cheng 1997):

$$W_{s,k} = (\nu/d_k)\ [(25 + 1.5\ d_{*,k}^{\ 2})^{0.5}\ - 5]^{1.5} \tag{A-14}$$

The dependence of settling speed on particle diameter is shown in Figure A-3. As discussed in Section 2.4.1, the effective particle diameters for the four sediment classes (d_k), which determine the settling speeds of each class through use of Equation A-14, were specified as follows. Effective particle diameters for classes 1A and 1B (i.e., clay/fine silt and medium/coarse silt) were treated as adjustable calibration parameters (see Section 2.5). Specification of effective particle diameters for classes 2 and 3 (i.e., fine sand and medium/coarse sand) was based on an analysis of LDW grain size distribution data (see Appendix B).

A.3 EROSION PROCESSES: COHESIVE BED

Within sediment bed areas designated as cohesive, the following numerical algorithm is used to calculate the erosion flux of sediment from the bed to the water column, where it is transported as suspended sediment. The areas within the LDW designated as having a cohesive bed are shown in Figure B-16 (see Section B.4). The erosion flux for size class k sediment (E_k) from a cohesive bed is given by:

$$E_k = \rho_{dry}\, f_{AS,k}\, S_k\, P_{sus,k}\, E_{gross} \qquad \text{(A-15)}$$

where E_{gross} is the gross erosion rate, $P_{sus,k}$ probability of suspension for size class k, S_k is the particle-shielding factor for size class k, ρ_{dry} is dry density of bed sediment, and $f_{AS,k}$ is the fraction of size class k sediment in the active-surface layer. Erosion flux has units of mass per unit area per time (e.g., g/cm^2–s).

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). Factors such as TOC content, gas content and bioturbation are implicitly incorporated into the cohesive erosion algorithm through the use of site-specific erosion rate data (i.e., Sedflume core data). 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}). The near-bed layer discussed above is incorporated into a model of the sediment bed, which is described below.

Erosion rate data obtained from Sedflume testing were analyzed to develop an understanding of the erosion properties of LDW sediments (Windward and QEA 2007). The goal of that analysis was to develop a functional relationship between E_{gross} and other parameters that affect erosion rate. These relationships and parameters are incorporated into algorithms so that site-specific, spatially-variable erosion properties measured for the LDW can be represented in the model. Two parameters that affect E_{gross} are shear stress (τ) and bulk density (ρ) (Jepsen et al. 1997). An evaluation of Sedflume data indicated 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 skin friction shear stress (Jones and Lick 2001):

$$E_{gross} = A\,\tau_{sf}^{n} \quad \text{for } \tau_{sf} > \tau_{cr} \qquad \text{(A-16)}$$
$$= 0 \quad \text{for } \tau_{sf} \le \tau_{cr}$$

where E_{gross} is gross erosion rate (cm/s), τ_{sf} is skin friction 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 (generally less than 2 mm/hr). The erosion parameters, A and n, are site-specific and may be spatially variable, both horizontally and vertically. Discussion of spatial variations in the erosion parameters in Equation A-16 is presented in Section B.4.

The erosion rate of each sediment size class is affected by the probability of suspension for that size class ($P_{sus,k}$), which is given by (Jones and Lick 2001):

$$P_{sus,k} = 0 \quad \text{for } \tau_{sf} \le \tau_{c,k} \qquad \text{(A-17)}$$

$$= [\ln(\beta_1) - \ln(\beta_2)]/[1.39 - \ln(\beta_2)] \quad \text{for } \tau_{sf} \ge \tau \text{ and } \beta_1 \le 4$$

$$= 1 \quad \text{for } \beta_1 > 4$$

and the non-dimensional parameters are:

$$\beta_1 = u_*/W_{s,k} \qquad \text{(A-18)}$$

$$\beta_2 = u_{*,crs,k}/W_{s,k} \qquad \text{(A-19)}$$

The formulation presented in Equation A-17 was developed from the results of flume measurements of suspended and bedload transport of sand conducted by Guy et al. (1966). Jones and Lick (2001) analyzed the Guy et al. (1966) data, with Equation A-17 resulting from their analysis. Probability of suspension as a function of bed shear stress is shown in Figure A-4 for particle diameters of 130 and 540 μm (i.e., particle sizes for classes 2 and 3 in the LDW model). This figure shows that for a given shear stress value, the probability of suspension increases with decreasing particle size.

The particle-shielding factor, which is a positive number with a maximum value of one, is used to reduce the erosion flux of smaller particles within a graded bed (i.e., bed with wide range of particle sizes) that are sheltered by larger particles. The particle-shielding factor (S_k) for size class k is formulated as follows (Karim and Kennedy 1981, Rahuel et al. 1989):

$$S_k = (d_k/d_m)^{0.85} \quad \text{for } d_k \le d_m \qquad \text{(A-20)}$$

$$= 1 \quad \text{for } d_k > d_m$$

where d_m is the mean particle diameter in the active layer. The relationship between the particle-shielding factor and particle diameter, for three values of mean particle diameter, is shown in

Figure A-5. For a given particle diameter (d_k), the particle-shielding effect increases (i.e., S_k decreases) as the mean particle diameter increases. The particle-shielding factor was not included in the original version of the SEDZLJ algorithm (Jones and Lick 2001). The SEDZLJ algorithm was modified to include the particle-shielding factor because initial testing of the sediment transport model indicated that realistic deposition patterns could not be predicted in the LDW with the original version of the algorithm. Inclusion of the particle-shielding factor improved the predictive capability of the LDW model. In addition, the particle-shielding factor is consistent with erosion processes within a graded bed, where voids between larger particles provide areas where smaller particles may be shielded (i.e., “hide”) from the turbulence at the sediment-water interface that induces erosion. Thus, the particle-shielding factor is a mechanistic parameter that accounts for real processes that affect scour from a graded bed.

The sediment bed model used in the bed scour model is similar to the bed model described in Jones and Lick (2001). This bed model has been developed over the previous 20 years and used within the SEDZL and SEDZLJ algorithms (Ziegler and Lick 1988, Ziegler et al.,2000, Jones and Lick 2001). The SEDZL/SEDZLJ bed model has been successfully used in over 30 sediment transport modeling studies, including: Upper Hudson River, Lavaca Bay (Texas), Grasse River (New York), Upper Mississippi River (Minnesota), Watts Bar Reservoir/Tennessee River (Tennessee), and Patrick Bayou (Texas).

A multi-layer bed model is used in the SEDZLJ algorithm, with each bed layer having specific erosion rate parameters (i.e., τ_{cr}, A, and n). For this study, five bed layers are used, with the initial thickness of each layer being 5 cm. Use of 5-cm layers in the bed model is based on the vertical variation in erosion rate data obtained from the Sedflume cores; the shear stress series were repeated in approximately 5-cm increments in a core during the Sedflume tests. Discretizing the bed into five layers allows specifying vertical variation in erosion properties, with the erodibility of cohesive sediment generally decreasing with depth in the bed, primarily due to consolidation processes. Additional discussion about the 5-layer bed model is presented in Section B.4.

The effects of consolidation on erosion properties of deposited sediment are not explicitly incorporated into the bed model. If the initial layer 1 is present, then deposited sediment is added to layer 1 (i.e., surface layer) of the bed model and, thus, that sediment has the same erosion properties as the surface layer. If the initial layer 1 is not present (i.e., that layer has been eroded), then a new surface layer is created by the deposited sediment which has the same erosion properties as the initial layer 1. This approach produces conservative results during a high-flow event because the erosion properties of sediment deposited prior to the event will not have been reduced due to consolidation.

Erosion from cohesive and non-cohesive beds is affected by bed armoring, which is a process that tends to limit the amount of bed scour during a high-flow event. Bed armoring occurs in a bed that contains a range of particle sizes (e.g., clay, silt, sand). During a high-flow event when erosion is occurring, finer particles (i.e., clay and silt) tend to be eroded at a faster rate than coarser particles (i.e., sand). The differences in erosion rates of various particle sizes creates a thin layer at the surface of the bed, referred to as the active layer, that is depleted of finer particles and enriched with coarser particles. This depletion-enrichment process can lead to bed armoring, where the active layer is primarily composed of coarse particles that have limited mobility.

After bed armoring occurs during a high-flow event, various physical mixing processes in the surface layer of the bed (e.g., bioturbation, ship-induced resuspension) can affect the armor layer. The effects of physical mixing processes on bed armoring are not well understood at the present time; these effects are not explicitly incorporated into the bed model and bed armoring algorithm. However, the effects of physical mixing processes are implicitly included into the bed model through use of the Sedflume data, which incorporates these effects into the erosion rate data. Physical mixing in the surface layer is one reason why near-surface sediment is generally more erodible than deeper sediment.

The bed armoring process is simulated using an active layer at the surface of the bed, with the gross erosion rate being affected by the composition of the active layer (Jones and Lick 2001). The active layer is a theoretical construct that approximates the near-bed layer mentioned during the description of gross deposition and erosion rates previously in this section. The active layer is part of a numerical algorithm and it was created as a "holding area" such that the bed model realistically represents the complex processes at the sediment-water interface. Even though the active-layer approach used in the model is a simplification of various complex processes, it is conceptually realistic and has been shown to produce accurate results in previous modeling studies.

The surface-layer in the bed model (i.e., top 5-cm layer) is divided into two zones: 1) active layer; and 2) parent bed. The active layer is at the top of the surface layer and the parent bed is below it. The active layer interacts with the water column; erosion and deposition across the sediment-water interface occurs in the active layer. Use of an active layer to simulate the effects of bed armoring is frequently used in sediment transport models (Rahuel et al. 1989). In this study, four size classes of sediment were used. Classes 1A and 1B sediment represents cohesive sediment (i.e., clay and silt, less than 62 μm diameter). Class 2 sediment represents fine sand (i.e., 62 to 250 μm diameter). Class 3 sediment represents medium and coarse sand (i.e., 250 to 2,000 μm diameter). The bed model tracks changes in the composition of the active layer associated with erosion and deposition; temporal changes in active layer composition affect the erosion process.

The active layer is composed of two sub-layers: 1) active-surface layer; and 2) active-buffer layer. The active-surface layer interacts with the water column, while the active-buffer layer controls interactions between the active-surface layer and the parent bed (Figure A-6). The original version of SEDZLJ did not separate the active layer into two sub-layers (Jones and Lick 2001). This modification of the SEDZLJ algorithm was made because initial testing of the LDW model, without the active layer being separated into two sub-layers, indicated that unrealistic deposition and erosion patterns were predicted. It was determined that the original SEDZLJ algorithm tended to over-predict erosion due to repeated expansion and contraction of the active layer over the course of numerous tidal cycles; there was excessive interaction between the active and parent bed layers caused by "tidal pumping" of sediment from the parent bed to the active layer as the active layer expanded and contracted. The objective of separating the active layer into two sub-layers was to produce a more realistic representation of the interactions between the active and parent-bed layers in a tidal environment, such as the LDW, and eliminate tidal pumping in the model, which is an artifact of the numerical algorithm and does not occur in nature. The addition of the active-buffer layer will have minimal effect on model predictions during high-flow event simulations.

The thickness of the active-surface layer is assumed to depend on bed shear stress and grain size distribution. The formulation used to calculate active-surface layer thickness (T_{AS}) is (Jones and Lick 2001):

$$T_{AS} = 2\ d_m\ (\tau_{sf} / \tau_{cr}) \qquad \text{(A-21)}$$

where d_m is the mean particle diameter in the active layer. The active-surface layer thickness is temporally and spatially variable, and it changes as the composition of the bed and bed shear stress change with time. The active-surface layer thickness is determined using Equation A-21, with the bed model tracking the mass per unit area using:

$$M_{AS} = \rho_{dry}\ T_{AS} \qquad \text{(A-22)}$$

where M_{AS} is the total sediment mass per unit area in the active-surface layer and ρ_{dry} is the dry density of bed sediment. The thickness, or mass per unit area, of the active-surface layer changes with time as T_{AS} changes as a result of increases or decreases in mean particle diameter or bed shear stress. Let δ_{SB} represent changes in active-surface layer mass, for size class k, caused by temporal changes in M_{AS}. Expansion and contraction of the active-surface thickness (i.e., T_{AS}) causes interactions between the active-surface and active-buffer layers, which result in mass transfer between the two layers. For increasing M_{AS} (i.e., $M_{AS}^{N+1} > M_{AS}^{N}$, where the superscript N represent time-level N in the numerical model):

$$\delta_{SB,k} = f_{AB,k} (M_{AS}^{N+1} - M_{AS}^{N}) \qquad \text{(A-23)}$$

where $f_{AB,k}$ is the fraction of size class k sediment in the active-buffer layer. For decreasing or constant M_{AS} (i.e., $M_{AS}^{N+1} \leq M_{AS}^{N}$):

$$\delta_{SB,k} = f_{AS,k} (M_{AS}^{N+1} - M_{AS}^{N}) \qquad \text{(A-24)}$$

where $f_{AS,k}$ is the fraction of size class k sediment in the active-surface layer. The change in active-surface layer mass is calculated using:

$$M_{AS,k}^{N+1} = M_{AS,k}^{N} + \delta_{SB,k} + \Delta t\,(D_k - E_k - f_{AS,k}\, D_{tot} + f_{AB,k}\, E_{tot}) \qquad \text{(A-25)}$$

where $M_{AS,k}$ is active-surface layer mass per unit area for size class k sediment, E_k is the erosion flux for size class k sediment, D_k is the deposition flux for size class k sediment, and Δt is the numerical time-step. The total deposition and erosion fluxes are given by:

$$D_{tot} = \Sigma\, D_k \qquad \text{(A-26)}$$

$$E_{tot} = \Sigma\, E_k \qquad \text{(A-27)}$$

where the summations are over the four size classes. In Equation A-27, the values of E_k are calculated using Equation A-15 for each size class k. Thus, E_{tot} is affected by the composition of the active-surface layer. Note that the deposition and erosion flux terms in the parentheses on the right-hand side of Equation A-25 do not sum to zero for a specific size class k. This characteristic of the algorithm generates bed armoring effects due to unequal mass transfer of different sediment size classes between the active-surface, active-buffer and parent-bed layers. However, conservation of mass is assured when Equation A-25 is summed over all sediment size classes, which results in the sum of the deposition and erosion flux terms being equal to zero.

The terms on the right-hand-side of Equation A-25 correspond to the following changes in the mass of the active-surface layer: 1) $\delta_{SB,k}$ is an increase in mass of class k sediment if the total active-surface layer mass is increasing (i.e., mass added from active-buffer layer) and it is a decrease in mass of class k sediment if the total active-surface layer mass is decreasing (i.e., mass lost to active-buffer layer); 2) $\Delta t\ D_k$ is an increase in mass of class k sediment due to deposition from the water column to the bed; 3) $\Delta t\ E_k$ is a decrease in mass of class k sediment due to erosion from the bed to the water column; 4) $\Delta t\ f_{AS,k}\ D_{tot}$ is a decrease in mass of class k sediment caused by movement of sediment from the active-surface layer to the active-buffer layer due to deposition; and 5) $\Delta t\ f_{AB,k}\ E_{tot}$ is an increase in mass of class k sediment caused by movement of sediment from the active-buffer layer to the active-surface layer due to erosion (see Figure A-6).

The change in active-buffer layer mass for size class k ($M_{AB,k}$) is calculated using:

$$M_{AB,k}^{N+1} = M_{AB,k}^{N} - \delta_{SB,k} + \Delta t\ [(f_{AS,k} - f_{AB,k})D_{tot} - f_{AB,k}\ E_{tot}] \qquad \text{(A-28)}$$

It is assumed that there is no mass transfer between the buffer layer and the parent bed due to erosion processes. The terms on the right-hand-side of Equation A-28 correspond to the following changes in the mass of of the active-buffer layer: 1) $\delta_{SB,k}$ is a decrease in mass of class k sediment if the total active-surface layer mass is increasing (i.e., mass lost to active-surface layer) and it is an increase in mass of class k sediment if the total active-surface layer mass is decreasing (i.e., mass added from active-surface layer); 2) $\Delta t\ f_{AS,k}\ D_{tot}$ is an increase in mass of class k sediment caused by movement of sediment from the active-surface layer to the active-buffer layer due to deposition; 3) $\Delta t\ f_{AB,k}\ D_{tot}$ is a decrease in mass of class k sediment caused by movement of sediment from the active-buffer layer to the parent-bed layer due to deposition; and 4) $\Delta t\ f_{AB,k}\ E_{tot}$ is a decrease in mass of class k sediment caused by movement of sediment from the active-buffer layer to the active-surface layer due to erosion.

When the buffer layer is depleted of sediment (typically during an erosion event), the active-surface layer interacts directly with the parent bed (Figure A-7). Let $\delta_{SP,k}$ represent changes in active-surface layer mass, for size class k, caused by temporal changes in M_{AS} and expansion/contraction interactions between the active-surface and parent-bed layers. For increasing M_{AS}:

$$\delta_{SP,k} = f_{P,k}\,(M_{AS}^{N+1} - M_{AS}^{N}) \tag{A-29}$$

where $f_{P,k}$ is the fraction of size class k sediment in the parent-bed layer. For decreasing or constant M_{AS}:

$$\delta_{SP,k} = f_{AS,k}\,(M_{AS}^{N+1} - M_{AS}^{N}) \tag{A-30}$$

The change in active-surface layer mass for size class k is calculated using:

$$M_{AS,k}^{N+1} = M_{AS,k}^{N} + \delta_{SP,k} + \Delta t\,(D_k - E_k - f_{As,k}\,D_{tot} + f_{P,k}\,E_{tot}) \tag{A-31}$$

The terms on the right-hand-side of Equation A-31 correspond to the following changes in the mass of of the active-surface layer: 1) $\delta_{SP,k}$ is an increase in mass of class k sediment if the total active-surface layer mass is increasing (i.e., mass added from parent-bed layer) and it is a decrease in mass of class k sediment if the total active-surface layer mass is decreasing (i.e., mass lost to parent-bed layer); 2) $\Delta t\ D_k$ is an increase in mass of class k sediment due to deposition from the water column to the bed; 3) $\Delta t\ E_k$ is an decrease in mass of class k sediment due to erosion from the bed to the water column; 4) $\Delta t\ f_{AS,k}\ D_{tot}$ is a decrease in mass of class k sediment caused by movement of sediment from the active-surface layer to the parent-bed layer due to deposition; and 5) $\Delta t\ f_{P,k}\ E_{tot}$ is an increase in mass of class k sediment caused by movement of sediment from the parent-bed layer to the active-surface layer due to erosion.

The change in parent-bed layer mass for size class k ($M_{P,k}$) is determined from:

$$M_{P,k}^{N+1} = M_{P,k}^{N} - \delta_{SP,k} + \Delta t\ (f_{AS,k} D_{tot} - f_{P,k}\ E_{tot}) \qquad \text{(A-32)}$$

The terms on the right-hand-side of Equation A-32 correspond to the following changes in the mass of the parent-bed layer: 1) $\delta_{SP,k}$ is a decrease in mass of class k sediment if the total active-surface layer mass is increasing (i.e., mass lost to active-surface layer) and it is an increase in mass of class k sediment if the total active-surface layer mass is decreasing (i.e., mass added from active-surface layer); 2) $\Delta t\ f_{AS,k}\ D_{tot}$ is an increase in mass of class k sediment caused by movement of sediment from the active-surface layer to the parent-bed layer due to deposition; and 3) $\Delta t\ f_{P,k}\ E_{tot}$ is a decrease in mass of class k sediment caused by movement of sediment from the parent-bed layer to the active-surface layer due to erosion.

After the buffer layer is depleted, a new active-buffer layer is created when the active-surface layer decreases in thickness as a result of decreasing bed shear stress. For the condition when $M_{AB,k}^{N+1}$ equals zero and M_{AS} is decreasing (i.e., $M_{AS}^{N+1} \leq M_{AS}^{N}$), then the initial mass of the new active-buffer layer, for size class k, is:

$$M_{AB,k}^{N+1} = f_{P,k} (M_{AS}^{N} - M_{AS}^{N+1}) \quad \text{(A-33)}$$

This amount of mass is removed from the parent-bed layer, so that mass is conserved.

The fractions of each sediment size class are updated after the new sediment masses are calculated in each layer:

$$f_{AS,k} = M_{AS,k}^{N+1} / M_{AS}^{N+1} \quad \text{(A-34)}$$

$$f_{AB,k} = M_{AB,k}^{N+1} / M_{AB}^{N+1} \quad \text{(A-35)}$$

$$f_{P,k} = M_{P,k}^{N+1} / M_{P}^{N+1} \quad \text{(A-36)}$$

where M_{AS}^{N+1}, M_{AB}^{N+1},and M_{P}^{N+1} are total sediment mass per unit area in the active-surface, active-buffer, and parent-bed layers, respectively.

The numerical algorithm presented above for the interactions between the active-surface, active-buffer, and parent-bed layers may be difficult to understand from a conceptual viewpoint. The following sequence of figures is intended to clarify the mechanistic interactions between the three layers due to temporal variations in bed shear stress, which result in expansion and contraction of the active layer. It is assumed that initially (i.e., time = t_1) two layers exist: 1) active-surface layer (with thickness $T_{AS,1}$ corresponding to a shear stress value of $\tau_{sf,1}$); and 2) parent-bed layer (see Figure A-8). As the shear stress increases to $\tau_{sf,2}$ (which is greater than $\tau_{sf,1}$) at time = t_2, the active-surface layer thickness increases to $T_{AS,2}$ and sediment is transferred from the parent-bed layer to the active-surface layer (Figure A-9). The shear stress reaches a maximum value at time = t_2 and decreases to a value of $\tau_{sf,3}$ at time = t_3. As the shear stress decreases during this time interval (i.e., t_2 to t_3), an active-buffer layer is created as the active-surface layer contracts in size, which is the process that generates an active-buffer layer (Figure

A-10). This new active-buffer layer was created from a portion of the active-surface layer that existed at time = t_2; sediment was transferred from the active-surface layer to the active-buffer layer. As the shear stress continues to decrease during the time interval between t_3 and t_4, the active-surface and active-buffer layers decrease and increase in thickness, respectively (Figure A-11). The shear increases during the time interval between t_4 and t_5, which causes sediment to be transferred from the active-buffer layer (which is contracting) to the active-surface layer (which is expanding) (see Figure A-12). Note that during the time interval between t_2 and t_5, when the shear stress is less than the maximum value of $\tau_{sf,2}$, the sum of the thicknesses of the active-surface and active-buffer layers remains constant at a value of $T_{AS,2}$ (assuming that no deposition or erosion occurs). During the time interval between t_5 and t_6, the active-buffer layer is destroyed, and sediment is transferred from the parent-bed layer to the active-surface layer, as the shear stress exceeds the original maximum value of $\tau_{sf,2}$ and the active-surface layer expands to a thickness greater than $T_{AS,2}$ (Figure A-13). As the shear stress decreases from the new maximum value of $\tau_{sf,6}$, a new active-buffer layer is created from the active-surface layer as that layer contracts in size (Figure A-14).

The structure of the bed model described above is based on heuristic concepts that were developed from a general understanding of cohesive bed processes. The overall concepts applied to, and general behavior of, the model are consistent with known processes. However, uncertainty exists in some details of the model structure (e.g., transfer of sediment between the active-surface, active-buffer, and parent-bed layers as the active layer expands and contracts). Due to the complexity of the model structure, a unique methodology does not exist and a wide range of alternatives can be constructed from proposed general structure. However, the approach that is described above, and used in the LDW modeling study, is consistent with a general understanding of cohesive bed processes and it does produce reasonable results.

A.4 EROSION PROCESSES: NON-COHESIVE BED

Non-cohesive sediment bed transport is dominated by gravitational, lift, and drag forces acting on individual particles. Cohesive forces are negligible compared to these other forces and are not evident in non-cohesive bed behavior. Non-cohesive beds generally contain only a small amount of clay and silt particles. Numerous laboratory and field studies have been conducted on the erosion properties of non-cohesive sediments; see van Rijn (1993) for an overview. These investigations have lead to the development of various formulations for quantification of non-cohesive suspended and bedload transport. Several investigators have evaluated the accuracy of different quantitative approaches using laboratory and field data (Garcia and Parker 1991, Voogt et al. 1991, van den Berg and van Gelder 1993). The results of these investigations have shown that the formulations developed by van Rijn (1984a, b, c) provide one of the best methods for calculating suspended load transport of non-cohesive sediments. The van Rijn equation have been successfully used in sediment transport modeling studies of riverine (Ziegler et al. 2000) and estuarine (van Rijn et al. 1990) systems over a wide range of flow and sediment conditions.

The numerical algorithm discussed below is used to calculate the erosion flux of sediment from a non-cohesive bed to the water column, where it is transported as suspended sediment. The areas within the LDW specified as a non-cohesive bed are shown in Figure B-16 (see Section B.4). Following the van Rijn method, the equations presented below are used to calculate the erosion flux for sediment size class k, which is represented by an effective particle diameter (d_k). The critical bed-shear velocity for initiation of bedload transport ($u_{*,crb,k}$) is calculated using the Shields criteria (see Figure A-15):

$$u_{*,crb,k} = [(s-1)\ g\ d_k\ \theta_{cr,k}]^{0.5} \tag{A-37}$$

where θ_{cr} is the critical mobility parameter, which is approximated by (van Rijn 1993):

$$\begin{aligned} \theta_{cr,k} &= 0.24\ d_{*,k}^{-1} && \text{for } d_{*,k} \le 4 \\ &= 0.14\ d_{*,k}^{-0.64} && \text{for } 4 < d_{*,k} < 10 \\ &= 0.04\ d_{*,k}^{-0.10} && \text{for } 10 < d_{*,k} < 20 \\ &= 0.013\ d_{*,k}^{0.29} && \text{for } 20 < d_{*,k} < 150 \\ &= 0.055 && \text{for } d_{*,k} > 160 \end{aligned} \tag{A-38}$$

and $d_{*,k}$ is calculated using Equation A-13. Equation A-38 is a piece-wise fit to the Shields curve that was developed by van Rijn (1993). Critical shear stresses for initiation of bedload ($\tau_{crb,k}$) and suspended load ($\tau_{crs,k}$) transport are calculated as follows:

$$\tau_{crb,k} = \rho_w \, u_{*,crb,k}^2 \tag{A-39}$$

$$\tau_{crs,k} = \rho_w \, u_{*,crs,k}^2 \tag{A-40}$$

The relationships between particle diameter and the critical bed shear stresses for bedload and suspended load transport are shown in Figure A-16. For sediment classes 1A and 1B, which represent clay and silt, it is assumed that Equations A-12 and A-37 through A-40 can be extrapolated to particle sizes less than 62 μm (i.e., d* less than 1.47). This assumption is commonly used for simulation of non-cohesive sediment transport with a graded bed (i.e., mixture of sediment particle sizes), and it has a minimal effect on model predictions in non-cohesive bed areas.

If the bed shear stress exceeds the critical shear stress for suspended load transport, then the equilibrium sediment concentration ($C_{eq,k}$) at a reference height (z = a) above the bed is calculated using:

$$C_{eq,k} = 0.015 \, (d_k \, T_k^{1.5}) \, / \, (a \, d_{*,k}^{\ 0.3}) \tag{A-41}$$

where T_k is the transport stage parameter, given by:

$$T_k = (u_* / u_{*,crs,k})^2 - 1 \qquad \text{for} \qquad u_* > u_{*,crs,k} \tag{A-42}$$

The reference height (a) is calculated using:

$$a = \text{MAX}\,(0.01\,h,\ k_{nik}) \tag{A-43}$$

where h is water depth and k_{nik} is the Nikuradse roughness height:

$$k_{nik} = 33\ D_{90} \tag{A-44}$$

The erosion flux for size class k sediment for a non-armoring sediment bed is calculated using:

$$E_{na,k} = -\ W_{s,k}\ (C_{a,k} - C_{eq,k}) \qquad \text{for} \qquad C_{a,k} < C_{eq,k} \tag{A-45}$$

where $C_{a,k}$ is the suspended sediment concentration of size class k at z = a. For the three-dimensional model, $C_{a,k}$ is set equal to the suspended sediment concentration, as predicted by the water-column transport model, in the first grid cell above the bed. Similar to the cohesive bed discussed in Section A.3, bed armoring processes occur in the non-cohesive bed and those processes affect the erosion flux from that bed type. An active layer is assumed to exist at the surface of the non-cohesive bed, with the thickness of that layer calculated using Equation A-21. A bed model tracks changes in the composition of the non-cohesive active layer associated with erosion and deposition, as well as interactions between the active and parent bed layers. Thus, the erosion flux for size class k sediment from an armoring bed ($E_{non,k}$) is given by:

$$E_{non,k} = f_{non,a,k}\ S_k\ E_{na,k} \tag{A-46}$$

where $f_{non,a,k}$ is the fraction of class k sediment in the active layer of the non-cohesive bed and S_k is the particle-shielding factor (see Equation A-20). The particle-shielding factor (Karim and Kennedy 1981, Rahuel et al. 1989) was included in the erosion flux for an armoring bed because this factor accounts for the effects of differential erosion rates

A.5 BEDLOAD TRANSPORT

Bedload transport of class 3 sediment (i.e., medium and coarse sand) was simulated within the non-cohesive and cohesive bed areas in the study area (RM 0.0 – 4.8). Only class 3 sediment (i.e., medium/coarse sand with effective diameter of 540 μm) was included in the bedload transport simulation because the critical shear stresses for suspended and bedload transport for class 2 sediment (i.e., fine sand with effective diameter of 130 μm) are approximately equal. Thus, class 2 sediment is transported as suspended sediment once it is mobilized.

A quasi-bedload transport approach was used to effectively simulate the near-bed transport of class 3 sediment. This approach applied bedload formulations to estimate the erosion flux of class 3 sediment from the bed. The bedload erosion flux was treated in the same manner as the erosion flux for suspended load transport; erosion flux from bedload was a source of class 3 sediment to the water column. This approach was used because of the difficulty of formulating a two-dimensional transport equation, in the horizontal plane, for bedload transport that conserves mass within the EFDC modeling framework.

Bedload transport of class 3 sediment was predicted using a formulation developed by van Rijn (1984a):

$$q_{b,3} = 0.053\,[(s-1)g]^{0.5}\,(d_3^{1.5}/d_{*,3}^{0.3})\,T_3^{2.1} \quad \text{for } \tau_{sf} > \tau_{crb,3} \qquad \text{(A-47)}$$

$$= 0 \quad \text{for } \tau_{sf} \le \tau_{crb,3}$$

where $q_{b,3}$ is the bedload transport rate for class 3 sediment (m^2/s) and d_3 is the effective particle diameter for class 3 sediment (m). The bedload transport rate has units of m^2/s, which corresponds to a volumetric rate per unit width of channel (i.e., m^3/s per meter width). The bedload transport rate was calculated at the center of each grid cell. The transport rates at the interfaces, or boundaries, of a grid cell in the horizontal plane were calculated using:

$$q_{b,3}(i\text{-}1/2,j) = 0.5\ [q_{b,3}(i,j) + q_{b,3}(i\text{-}1,j)] \qquad \text{(A-48)}$$

$$q_{b,3}(i,j\text{-}1/2) = 0.5\ [q_{b,3}(i,j) + q_{b,3}(i,j\text{-}1)] \qquad \text{(A-49)}$$

where the i and j indices are grid cell array indices in the cross-channel and along-channel directions, respectively. The indices i-1/2 and j-1/2 correspond to the boundaries of the grid cell. Bedload fluxes are calculated at the grid cell interfaces. Transport direction was determined using an upwind approach:

$$Q_{b,3}(i\text{-}1/2,j) = \rho_{dry}\ SGN(u(i\text{-}1/2,j))\ \Delta y(i\text{-}1/2,j)\ q_{b,3}(i\text{-}1/2,j) \qquad \text{(A-50)}$$

$$Q_{b,3}(i,j\text{-}1/2) = \rho_{dry}\ SGN(v(i,j\text{-}1/2))\ \Delta x(i,j\text{-}1/2)\ q_{b,3}(i,j\text{-}1/2) \qquad \text{(A-51)}$$

where $Q_{b,3}$ is bedload mass transport rate (e.g., g/s) across the grid cell interface, u is horizontal velocity in the i-direction, v is horizontal velocity in the j-direction, SGN returns the sign of the velocity, $\Delta y(i\text{-}1/2,j)$ is the length of grid cell interface at (i-1/2,j), and $\Delta x(i\text{-}1/2,j)$ is the length of grid cell interface at (i,j-1/2). Differences between the fluxes at the four interfaces for a grid cell are summed to determine if net erosion as a result of bedload occurred in that grid cell, where the net summation is given by:

$$^{net}Q_{b,3}(i,j) = [Q_{b,3}(i+1/2,j) - Q_{b,3}(i\text{-}1/2,j) + Q_{b,3}(i,j+1/2) - Q_{b,3}(i,j\text{-}1/2)] \qquad \text{(A-52)}$$

If $^{net}Q_{b,3}(i,j)$ is positive, then net erosion as a result of bedload occurs in grid cell (i,j). If $^{net}Q_{b,3}(i,j)$ is negative, then net deposition occurs as a result of bedload.

The net flux of sediment into or out of grid cell (i,j) is calculated using Equation A-52. The net flux is used to properly adjust changes in bed elevation and composition due to bedload transport. For positive net flux, net erosion occurs and the erosion flux for grid cell (i,j) is calculated using:

$$E_{bed,3}(i,j) = (1 - P_{sus,3})\, f_{act,3}\; {}^{net}Q_{b,3}(i,j)/A_{horiz}(i,j) \qquad \text{for } {}^{net}Q_{b,3}(i,j) > 0 \tag{A-53}$$

where $E_{bed,3}$ is erosion flux for class 3 sediment associated with bedload, $f_{act,3}$ is fraction of class 3 sediment in the active layer (i.e., $f_{AS,k}$ for cohesive bed and $f_{non,a,3}$ for non-cohesive bed), and $A_{horiz}(i,j)$ is the horizontal area of grid cell (i,j). This approach is consistent with calculating the erosion flux for suspended load transport (see Equations A-15 and A-46). For negative net bedload flux, net deposition occurs and the deposition flux is calculated as:

$$D_{bed,3}(i,j) = -{}^{net}Q_{b,3}(i,j)/A_{horiz}(i,j) \qquad \text{for } {}^{net}Q_{b,3}(i,j) < 0 \tag{A-54}$$

The bedload erosion and deposition fluxes are used in a similar manner to the erosion and deposition fluxes for suspended load transport to calculate bed elevation changes.

Class 3 sediment (i.e., medium/coarse sand) was assumed to be transported as suspended and bed load. The quasi-bedload transport approach discussed above was used to calculate erosion ($E_{bed,3}$) and deposition ($D_{bed,3}$) fluxes of Class 3 sediment due to bedload (see Equations A-53 and A-54). These erosion and deposition fluxes were added to similar fluxes for Class 3 sediment due to suspended load transport (i.e., Equations A-6 and A-15). Thus, the total deposition and erosion fluxes for Class 3 sediment, due to a combination of suspended and bedload transport, are:

$$D_{tot,3} = D_3 + D_{bed,3} \tag{A-55}$$

$$E_{tot,3} = E_3 + E_{bed,3} \tag{A-56}$$

where D_3 and E_3 are suspended load fluxes and $E_{bed,3}$ and deposition $D_{bed,3}$ are bedload fluxes. The total deposition/erosion fluxes subtract/add Class 3 sediment from/to the bottom layer of the water column in the model, which affects the near-bed concentration of Class 3 sediment.

LIST OF FIGURES CITED IN APPENDIX A

APPENDIX B
DEVELOPMENT OF SEDIMENT TRANSPORT MODEL INPUTS

B.1 ESTIMATION OF EFFECTIVE DIAMETERS FOR CLASSES 2 AND 3

Multiple riverine and estuarine modeling studies have demonstrated that sediment transport can be adequately simulated using a limited number (i.e., two to four) of discrete particle size classes because simulation of the entire particle size spectrum is impractical (Lick et al. 1998, Jones and Lick 2000, Ziegler et al. 2000). For this study, four sediment size classes are used in the model to represent the distribution of particle sizes in the water column and sediment bed of the LDW. Therefore, particles were separated into these four classes: 1) clay and fine silt with particle diameters less than 10 μm; 2) medium and coarse silt (10 to 62 μm); 3) fine sand (62 to 250 μm); and 4) medium and coarse sand (250 to 2,000 μm). For convenience, the four sediment classes have been labeled as noted in Table B-1. Each sediment size class is represented as an effective particle diameter (d_k). Effective particle diameters for classes 1A and 1B were treated as adjustable calibration parameters (see Section 2.5).

Table B-1. Characteristics of sediment particle size classes.

Sediment Size Class	Particle Size Range (μm)
1A: clay, fine silt	< 10
1B: medium, coarse silt	10 – 62
2: fine sand	62 – 250
3: medium, coarse sand	250 – 2,000

Effective particle diameters for classes 2 and 3 were estimated using the following approach. This method provides an objective method for estimating the effective particle diameters for classes 2 and 3. Grain size distribution (GSD) data are available for the surface layer (i.e., top 1 ft.) of sediment cores collected from the LDW during various studies conducted between 1991 and 2006. The distribution of sand particles (i.e., 62 to 2,000 μm diameter particles) in the GSD data was separated into five ranges, with each range being represented by an effective diameter that corresponds to the geometric mean of that range (Table B-2). The GSD data provide information on the relative amounts of sand in each of the five size ranges.

The effective diameters of classes 2 and 3 (i.e., d_2, d_3) for a particular core sample were estimated from the GSD data using:

$$d_2 = (f_{r1}G_{r1} + f_{r2}G_{r2})/ (f_{r1} + f_{r2}) \tag{B-1}$$

$$d_3 = (f_{r3}G_{r3} + f_{r4}G_{r4} + f_{r5}G_{r5})/ (f_{r3} + f_{r4} + f_{r5}) \tag{B-2}$$

where f_{rk} is the fractional composition of size range k and G_{rk} is the geometric mean (effective diameter) of size range k.

Table B-2. Size ranges for sand in GSD data.

Size Range	Particle Size Range (μm)	Effective Diameter (μm)
1	62 – 125	88
2	125 – 250	177
3	250 – 500	354
4	500 – 1,000	707
5	1,000 – 2,000	1,414

Cumulative frequency distributions for effective diameters of classes 2 and 3, which were estimated using the approach described above, for sediment in the surface layer of the bed (i.e., top 1 ft.) are presented in Figure B-1 (see Table 2-2 for discussion of data source). The median values of effective diameters for classes 2 and 3 are 130 and 540 μm, respectively. These values are assumed to be representative and are used to specify the effective diameters for classes 2 and 3 in the sediment transport model. The settling speeds corresponding to the effective diameters of classes 2 and 3 are 770 and 5,500 m/day, respectively.

B.2 BOUNDARY CONDITIONS: UPSTREAM SEDIMENT LOADS

Sediment loads in the Green River need to be estimated for specification of the upstream inflow boundary in the sediment transport model. The USGS conducted sediment loading studies in the Green River during 1965-66 and 1996-97 (Harper-Owes 1981, Embrey and Frans 2003). The location of the USGS sediment sampling location near Tukwila is shown in Figure

1-2. Suspended sediment concentration (SSC) data were collected over a wide range of flow rates during those studies, including high-flow events with flow rates of approximately 11,000 cfs. An analysis of the 1965-66 data is presented in Harper-Owes (1981). That analysis produced this sediment load rating curve:

$$L_{sus} = 0.107\ Q^{2.09} \qquad \text{(B-1)}$$

where L_s is suspended sediment load (lb/day) and Q is daily-average flow rate (cfs). The results of an analysis of the 1996-97 data are given in Embrey and Frans (2003). In that study, the Linear Attribution Estimate (LAE) method was used to develop a regression equation (Embrey and Frans 2003), which was modified for use in this study as follows:

$$\ln(L_{sus}) = 13.4 + 1.8916\ \ln(Q^*) + 0.33201\ \ln(Q^*) \qquad \text{(B-2)}$$

and

$$\ln(Q^*) = \ln(Q) - \ln(Q_{ave}) \qquad \text{(B-3)}$$

where Q_{ave} is the average flow rate during the study period, which was 1,800 cfs. Note that the first term in Equation B-2 (i.e, 13.4) has a value of 12.6 in the original LAE equation presented in Embrey and Frans (2003). Estimates of the annual average sediment loads using the 12.6 parameter value in Equation B-2 produced values that were judged to be too low for producing acceptable model results during the initial phase of the model calibration process. The original parameter value (12.6) was adjusted to a value of 13.4 (i.e., Equation B-2) so that that suspended sediment loads predicted by Equations B-1 and B-2 were approximately equal when the daily-average flow rate was equal to 1,340 cfs (i.e., long-term average value). As discussed below, Equations B-1 and B-2 were combined to estimate sediment load in the Green River.

The sediment load rating curves from the two studies are compared in the top panel of Figure B-2. The bottom panel on this figure shows the relationship between SSC and flow rate, based on the load rating curves. The SSC rating curve (i.e., bottom panel) shows that the LAE method (i.e., Equation B-2) produces counter-intuitive results for flow rates below the long-term mean discharge in the river (1,340 cfs). For the low-flow region, the LAE method predicts that SSC increases as flow rate decreases. This trend is not typically observed in rivers and it appears to be a numerical artifact of the LAE method. Thus, the approach used in this study was to combine Equations B-1 and B-2 as follows. For flow rates less than the long-term average value (1,340 cfs), the load rating curve from the Harper-Owes (1981) study was used. For flow rates greater than the average value, the LAE method was applied. Use of the LAE method for river flow rates less than the average value would result in unrealistically high SSC values being specified at the upstream inflow boundary during low-flow conditions. Use of the Harper-Owes rating curve for the low-flow conditions produces realistic SSC values at the upstream inflow boundary. In addition, the combined approach (i.e., Harper-Owes method for low-flow conditions and LAE method for high-flow conditions) yields a lower estimate of annual sediment loading in the river than using the LAE method exclusively. Thus, the combined approach produces conservative results (i.e., lower annual sediment load) when compared to exclusive use of the LAE method.

The sediment load rating curves were developed using flow rates measured at the Tukwila gauging station. For calculation of suspended sediment load in the Green River, flow rates measured at the USGS gauging station at Auburn were used to specify model inputs. This approach was consistent with the specification of freshwater inflow to the hydrodynamic model from the Green River, which used the flow data collected at the Auburn gauging station. The Auburn gauging station is located about 12 miles upstream of the Tukwila gauging station, and the confluence of the Black and Green Rivers is between these two gauging stations. Thus, the flow rate at the Auburn gauging station is typically about 10% lower than the flow rate at the Tukwila gauging station. If the flow rates used in the sediment load rating curves to specify model inputs had been increased by about 10% to account for the flow differential between the Auburn and Tukwila locations, then the sediment loading from the Green River that was input to the model would have increased by about 20% to 25%, relative to the actual loads used as model input. Therefore, neglecting the increase in flow rate between the Auburn and Tukwila locations resulted in under-estimating the sediment load from the Green River by about 20% to 25%.

This approach was used to estimate suspended sediment load in the Green River for all sediment transport simulations presented in this report. Variation in the annual suspended sediment load in the river for the 30-year period (1960 through 1989) is shown in Figure B-3. The estimated average annual suspended sediment load during this period was 157,000 MT/yr, with a range of 36,000 (1978) to 477,000 (1975) MT/yr.

The composition of the suspended load in the river must also be specified. Composition data were collected during the two USGS studies, but only 11 samples were collected in those studies. The relationship between clay/silt content and flow rate for the two datasets is shown in Figure B-4. A strong correlation between clay/silt content and flow rate is not evident on this figure. The data shown in Figure B-4 suggest the possibility of a shift in the composition of the sediment load, with the 1996-97 composition being finer (i.e., more clay/silt) than the 1965-66 composition. No definitive conclusions can be reached about a shift in composition of the river load during the approximately 30-year period between the two USGS studies due to limited data. In addition, it is unknown whether there were differences in the measurement techniques used in the two studies.

An approximate method, which uses the available data, was developed to estimate the composition of the incoming suspended load. Generally, it is expected that clay/silt content will decrease and sand content will increase with increasing river flow. The estimation method produces results that are consistent with this trend. The fraction of the total suspended load that is composed of sediment size class k ($f_{s,k}$) is estimated using:

$$f_{s,k} = \omega_k P_{sus,k} / \sum (\omega_i P_{sus,i}) \qquad \text{(B-4)}$$

where ω_k is a weighting factor for size class k and $P_{sus,k}$ is the probability of size class k sediment being transported as suspended load (see Section A.2 and Equation A-16 for a detailed discussion of $P_{sus,k}$). In this analysis, class 1 is defined as the summation of classes 1A and 1B and, thus, represents the clay/silt content in the suspended sediment load. The summation in Equation B-4 is over the three size classes (i = 1, 3).

Calculation of $P_{sus,k}$ requires estimation of bed-shear velocity (i.e., u_*, see Equation A-5) as a function of river flow rate (Q). Combining Equations A-2 and A-5, the relationship between bed-shear velocity and current velocity (u) is:

$$u_* = C_f^{0.5} u \qquad \text{(B-5)}$$

where C_f is the bottom friction coefficient (see Equation A-3), which is dependent on water depth (h). The relationship between current velocity and river flow rate is:

$$Q = w\, h\, u \qquad \text{(B-6)}$$

where w is width of the river channel. Substituting Equation B-6 into Equation B-5 yields:

$$u_* = C_f^{0.5}\, Q / (w\, h) \qquad \text{(B-7)}$$

Standard hydraulic techniques were used to estimate water depth as a function of river flow rate (Chow 1959), where it was assumed that water depth was equal to the normal depth (Chow 1959):

$$h = 0.788\, [\, n\, Q/ (w\, S^{0.5}\,)]^{0.6} \qquad \text{(B-8)}$$

where n is Manning's coefficient and S is channel slope. Equation B-8 assumes English units for all variables. For calculating water depth (h) as a function of river flow rate (Q) in this equation, the following parameter estimates for the Green River were used: river width (w) is 150 ft., Manning's coefficient (n) is 0.025, and channel slope (S) is 0.0001. For calculating C_f in

Equation B-7, it was assumed that the D_{90} value for the river was 2,000 μm (i.e., upper-bound for coarse sand). Thus, for a given river flow rate (Q), water depth is calculated using Equation B-8, after which C_f is calculated using Equation A-3, then u_* is calculated using Equation B-7, and, finally, $P_{sus,k}$ is calculated using Equation A-16.

Equation B-4 was used to calculate f_k for the three size classes (i.e., k = 1, 2, 3) for flow rates ranging between 500 and 10,500 cfs. The weighting factors (ω_k) were adjusted using an iterative approach until the average value of the class 1 fraction (i.e., clay/silt content) calculated using Equation B-4 matched the average clay/silt content of the 1996-97 data, which is 88%. This process produced weighting factors (ω_k) for classes 1, 2, and 3 of 11, 3, and 1, respectively. The class 3 content of the suspended load was predicted to be zero for all flow rates using this approach, which is because of the high settling speed of this size class (i.e., 5,500 m/day for 540 μm diameter). This result is consistent with the hypothesis that class 3 sediment is primarily transported in the river as bedload, as discussed below. The relationships between class 1 and 2 fractions in the suspended load and flow rate are shown in Figure B-5.

This approach was used to specify the relative proportions of class 1 and 2 sediment in the suspended sediment load at the upstream boundary of the model as a function of river flow rate. After the class 1 fraction was calculated for a specific day during a simulation, based on the daily-average flow rate for that day, that portion of the suspended load was split into the fractions for classes 1A and 1B. Based on the calibration results, the class 1 portion of the incoming load consists of 80% class 1A and 20% class 1B. As discussed in Section 2.5, the model was calibrated using estimates of net sedimentation rates in the navigation channel and bench areas.

Because of limited bedload transport data in the Green River, the following method was developed to estimate bedload as a function of flow rate at the upstream boundary. The total sediment load (L_{tot}) in the river is given by:

$$L_{tot} = L_{bed} + L_{sus} \tag{B-9}$$

where L_{bed} is bedload and L_{sus} is suspended load. Assume that bedload is related to flow rate (Q) as follows:

$$L_{bed} = 0 \quad \text{for } Q \leq Q_m \tag{B-10}$$

$$= BQ^m \quad \text{for } Q > Q_m$$

where Q_m is the long-term mean flow rate in the river (1,340 cfs). The exponential relationship between sediment load and flow rate, as given by Equation B-10, is frequently observed in rivers (Leopold et al. 1964). Initial testing of the STM did not include the discontinuity in L_{bed} at the mean flow rate, as shown in Equation B-10, and L_{bed} was a continuous function of Q for all flow rates, which produced an average annual load of 54,000 MT/yr. This value is 8% higher than the average annual load calculated using Equation B-10. The discontinuity in L_{bed} at the mean flow rate was included in the bedload input equation to prevent numerical artifacts from occurring in the immediate vicinity of the upstream boundary. Numerical testing of the model indictated that introduction of bedload to the river during low-flow conditions resulted in anomalous deposition near the upstream boundary. Thus, use of the approximation in Equation B-10 of zero bedload input during low-flow conditions has a minor effect on the total annual amount of bedload input to the system, but it prevents the simulation of anomalous deposition in the river.

In Equation B-10, B and m are parameters that need to be determined. Let the fraction of the total sediment load that is bedload be defined as:

$$f_{bed} = L_{bed} / L_{tot} \tag{B-11}$$

Using Equations B-2 and B-10 in Equation B-9:

$$L_{tot} = BQ^m + L_{sus}(Q) \quad \text{for } Q > Q_m \tag{B-12}$$

where from Equation B-2, the suspended load transport is given by:

$$L_{sus}(Q) = EXP[13.4 + 1.8916 \ln(Q^*) + 0.33201 \ln(Q^*)] \qquad \text{(B-13)}$$

and Q* is calculated using Equation B-3. Substituting Equations B-10 and B-12 into Equation B-11:

$$f_{bed} = 0 \quad \text{for } Q \leq Q_m \qquad \text{(B-14)}$$

$$= BQ^m/[BQ^m + L_{sus}(Q)] \quad \text{for } Q > Q_m$$

Two measurements of f_{bed} were made during the 1965-66 study conducted by USGS (Harper-Owes 1981). These two values were collected during above-average and high-flow discharge conditions in the river (see Figure B-6). The two data points were used to determine the values of the two unknown parameters in Equation B-14 (i.e., two equations and two unknowns). This process yielded the values of 2.14 and 0.0228 for m and B, respectively in Equations B-10 and B-14, where bedload (L_{bed}) has units of lb/day. The relationships between flow rate and bedload (L_{bed}) and ratio of bedload to total load (f_{bed}) are shown in Figure B-6.

The estimation procedure discussed above was used to estimate bedload in the Green River for all sediment transport simulations presented in this report. Variation in the annual bedload at the upstream boundary of the model for the 30-year period (1960 through 1989) is shown in Figure B-7. The estimated average annual bedload during this period was 50,000 MT/yr, with a range of 10,000 (1978) to 132,000 (1975) MT/yr.

B.3 BOUNDARY CONDITIONS: LATERAL SEDIMENT LOADS

Sediment loads from lateral sources (i.e., storm drains, CSOs, streams) were included in the external sediment load analysis discussed in Section 4. Analyses were conducted by the City of Seattle (Schmoyer 2007) and King County (Nairn 2007) to estimate sediment loads from lateral sources in the LDW. The results of those analyses were used to specify lateral load inputs to the sediment transport model.

Storm drains, CSOs, and streams discharge into the LDW at over 200 locations (Figure B-8). Incorporating each individual discharge location into the model is not practical; even if each discharge location was incorporated into the model, it is doubtful that the reliability of model predictions would be significantly increased. Thus, the lateral sources were aggregated and represented by 21 point sources that discharged into the LDW at 16 locations (see Table B-3). The total annual sediment load from the lateral sources is 1,206 MT/yr, with loads from storm drains, CSOs, and streams composing 76%, 3%, and 21%, respectively, of the total load.

Sediment loads for storm drains were determined by multiplying estimated values of flow rate and total suspended solids (TSS) concentration. A watershed model was used to estimate the volume of stormwater discharge to the LDW. Flow estimates were made for a typical wet year (2002), dry year (1993), and average year (1986) based on precipitation data collected at Seattle Public Utilities rainfall gauges located at East Marginal Way South and 13th Avenue South. Lateral storm drain sediment loads used in the sediment transport model were determined for a medium precipitation year, with annual loads of about 900 and 1,500 MT/yr estimated for low and high precipitation years, respectively.

Table B-3. Lateral sources of sediment.

Lateral Load Name	Type of Source	Approximate Location	Annual Sediment Load (MT/yr)
Diagonal	Storm drain	RM 0.5, east bank	284
Norfolk	Storm drain	RM 4.9, east bank	121
Slip 4	Storm drain	RM 2.8, east bank	93
7th Avenue	Storm drain	RM 2.7, west bank	28
West Bank #5	Storm drain	RM 0.3, west bank	72
West Bank #6	Storm drain	RM 1.5, west bank	72
West Bank #7	Storm drain	RM 1.9, west bank	72

Lateral Load Name	Type of Source	Approximate Location	Annual Sediment Load (MT/yr)
West Bank #8	Storm Drain/Stream	RM 4.3, west bank	250
East Bank #9	Storm drain	RM 3.8, east bank	65
East Bank #10	Storm drain	RM 4.2, east bank	65
East Bank #11	Storm drain	RM 1.2, east bank	29
East Bank #12	Storm drain	RM 2.1, east bank	19
Duwamish PS West	CSO	RM 0.4, west bank	0.1
Duwamish PS East	CSO	RM 0.5, east bank	1.0
Hanford #1	CSO	RM 0.5, east bank	4.9
CSO 111	CSO	RM 0.5, east bank	3.4
Brandon Street	CSO	RM 1.1, east bank	15
Terminal 115	CSO	RM 1.5, west bank	1.5
Michigan Street	CSO	RM 1.9, east bank	9.0
Michigan West	CSO	RM 2.0, west bank	0.5
Norfolk Street	CSO	RM 4.9, east bank	0.1

The annual sediment loads for each storm were converted to monthly loads for input to the sediment transport model (i.e., the load for a particular month was specified at a constant rate for the entire month). Conversion from annual to monthly loads was accomplished by assuming that the monthly sediment load is proportional to variations in the average monthly precipitation in the region surrounding the LDW. Table B-4 lists the portion of the total annual precipitation that occurs during each month. For each storm drain, monthly sediment loads were estimated by multiplying the annual load by the proportions in Table B-4. The resulting temporal variations in monthly sediment loads for each storm drain are shown in Figures B-9, B-10, and B-11. Hamm Creek was assumed to behave as a storm drain in this analysis.

Table B-4. Monthly distribution of annual precipitation.

Month	Portion of Annual Total Precipitation Occurring During Each Month (%)
January	15.9
February	9.7
March	11.3
April	7.9
May	5.6
June	3.9
July	2.4
August	2.5
September	2.3
October	7.8
November	15.9
December	14.8

For CSOs, monthly sediment loads were estimated using a method that was similar to the one used for storm drains. The CSO-specific discharge volume was multiplied by an average TSS concentration. Average monthly discharge volumes for each CSO were determined from CSO flow data collected between June 1999 and May 2006. The relative portion of the total annual inflow during each month was determined and used to estimate the monthly sediment load for each CSO. Average TSS concentrations for King County CSOs were calculated from approximately 100 samples collected during 1995, 1996 and 1997 from five CSO outfalls (i.e., Brandon, Chelan, Connecticut, Hanford, King). Temporal variations in monthly sediment loads for each CSO are presented in Figures B-12, B-13, and B-14.

The composition of sediment loads from storm drains and CSOs also needs to be specified. Grain size distribution data collected from LDW stormwater grab samples were provided by the City of Seattle (Schmoyer 2007). These data were used to determine the relative portions of sediment size classes 1A, 1B, 2, and 3 in the stormwater samples. It is assumed that the stormwater samples are representative of the composition of sediment loads from storm drains. Cumulative frequency distributions of the proportional content of the four size classes are shown in Figure B-15. The median values of composition for the four size classes are given in Table B-5; these are used to specify the composition on storm drain loads. The composition of sediment loads from CSOs was based on the results of an analysis conducted by King County personnel (Nairn 2007).

Table B-5. Composition of sediment loads from storm drains and CSOs.

Sediment Size Class	Storm Drain Content (%)	CSO Content (%)
1A: clay and fine silt	55	48
1B: medium/coarse silt	18	36
2: fine sand	23	16
3: medium/coarse sand	4	0

B.4 SPECIFICATION OF BED PROPERTIES

Specification of bed properties within the LDW begins with separating the sediment bed into two distinct types of sediment: cohesive and non-cohesive. Cohesive sediment is described as a muddy bed that is composed of a mixture of clay, silt, sand, and organic matter. Non-cohesive sediment corresponds to a sandy bed that has a relatively low amount of clay, silt, and organic matter. Using available information and data on bed properties, the sediment bed in the upper turning basin, near RM 4.5, and upstream of that region was assumed to be non-cohesive, with the bed downstream of the upper turning basin assumed to be cohesive (Figure B-16). Average values of dry (bulk) density in the cohesive and non-cohesive bed areas are 0.91 and 1.57 g/cm^3, respectively (see Table 2-2 for discussion of data source).

Upstream and downstream of the LDW (i.e., upstream of RM 4.8 and downstream of RM 0.0), the sediment bed is assumed to be a hard bottom (see introductory paragraph of Appendix A for explanation of this bed type). This assumption is justified as follows. Erosion rate data are not available downstream of RM 0.0, and neither are bed-type data. Thus, specifying bed property parameters for that area is highly uncertain. Upstream of RM 4.8 (i.e., in the Green River, which is primarily composed of non-cohesive sediment), minimal bed property data are available for specifying model inputs. Previous modeling studies have demonstrated that realistic simulation of non-cohesive sediment transport in a river is highly dependent upon the spatial distribution of bed properties (Ziegler et al. 2000). Attempts to simulate non-cohesive bed transport in that area were unsuccessful, primarily due to data limitations and the inability to develop a reliable spatial distribution of non-cohesive bed properties in the Green River. Various estimation methods were used to develop spatial distributions, using limited grain size distribution data, of non-cohesive model inputs (e.g., D_{50} and initial bed composition). One method, which has been used successfully on other rivers (Ziegler et al. 2000), involved postulating a functional relationship between local bed shear stress and D_{50}. This approach provided an objective and mechanistic method for specifying D_{50} values for each grid cell in the non-cohesive bed. However, this method, along with other approaches that were tried, did not generate spatial distributions of bed properties that produced acceptable model results. The primary problem was that the non-cohesive bed model produced unrealistic predictions of erosion and deposition upstream of RM 4.8 (i.e., creation of "deep holes" and "mountains" in the river bed). The various attempts at simulating non-cohesive sediment transport in the Green River had negative effects on the predictive capability of the model in the LDW (i.e., RM 0-4.8), especially in the region upstream of RM 4.0. After numerous attempts at using an "active bed" in the Green River, a numerical experiment was conducted with the sediment bed in the river being specified as a hard bottom, and model performance in the LDW was significantly improved. See Section D.3 for additional discussion of the numerical testing and results. Thus, it was determined that model reliability was improved by treating the bed as a hard bottom (non-active bed) upstream of RM 4.8.

Grain size distribution data for surface-layer sediment were analyzed to determine effective bed roughness (i.e., D_{90}) values for use in calculating skin friction shear stress (see Section A.1). Grain size distribution data were analyzed to estimate median particle diameters (i.e., D_{50} values), which are used for determining the thickness of the active-surface layer (i.e., T_{AS}, see Equation A-21). Data sources for D_{50} and D_{90} values are presented in Table 2-2. Average D_{50} and D_{90} values for different areas in the LDW are listed in Table B-6. The average values are specified as model inputs and are assumed to be spatially constant and time invariant within a specific area.

Table B-6. Average D_{50} and D_{90} values in different LDW areas.

LDW Area	Average D_{50} (μm)	Average D_{90} (μm)
Cohesive bed: navigation channel	60	360
Cohesive bed: east bench	180	940
Cohesive bed: west bench	130	790
Non-cohesive bed	340	1,280

The spatial distribution of bed composition needs to be specified as an initial condition for the sediment transport model. The proportional content of the four sediment size classes (i.e., classes 1A, 1B, 2, and 3) in the bed must be specified at each grid cell at the beginning of a simulation. Initial conditions for bed composition were determined using the following procedure. Grain size distribution data were used to calculate average values of bed composition in four broad areas of the LDW: 1) navigation channel; 2) east bench; 3) west bench; and 4) non-cohesive bed (i.e., upper turning basin and area up to RM 4.8). The average values of bed content for classes 1A, 1B, 2, and 3 were applied to the three areas within the cohesive bed of the LDW (i.e., navigation channel, east and west benches) (see Figures B-17 through B-20). On those figures, the bin sizes used to present spatial variation in bed content are discrete numbers representing average values in the navigation channel and two bench areas. For example, Figure B-17 shows that the average class 1A content values in the west bench, navigation channel, and east bench are 31, 36, and 28%, respectively. This initial specification of bed content distribution is a crude approximation to the heterogeneous distribution that exists in the LDW. The spatial distribution of bed content that exists in the LDW is the result of hydrodynamic and sediment transport processes within the estuary. Thus, it was assumed that the sediment transport model provides a rational and mechanistic method for estimating the spatial distribution of bed content.

Within the non-cohesive bed area, a fifth class (i.e., class 4) representing gravel-sized particles was included in the bed composition. This sediment class was added during the attempts to simulate non-cohesive sediment transport in the Green River. Gravel is present in the Green River and inclusion of this coarse material in the model was necessary to simulate non-cohesive transport in the river. After the decision was made to treat the bed upstream of RM 4.8 as a hard bottom, the class 4 sediment was included in the non-cohesive bed downstream of RM 4.8 (i.e., turning basin region and river immediately upstream of that region). An effective diameter of 4,200 μm was specified for class 4 (i.e., fine gravel). The initial content of class 4 sediment in the non-cohesive bed was determined during the 21-year simulation that generated the evolved bed, with the class 4 content ranging from about 3% to 26% within this region. This content tended to decrease with time during the multi-year simulations (i.e., 21-year and 30-year simulation) because of deposition of incoming sediment from the Green River (primarily sand). Because class 4 is assumed to be non-mobile and none of this sediment was input at the upstream boundary of the model, the class 4 content decreases with time and, thus, its effect on non-cohesive transport also decreases.

Using the specification of bed content discussed above (i.e., average values in four broad areas) as initial conditions for the model, a 21-year simulation was conducted and the sediment bed was allowed to "evolve" during that period. Changes in bed composition occurred over that 21-year period as a result of erosion, deposition, and transport of sediment over a wide range of flow and tidal conditions. The predicted spatial distribution of bed content at the end of the 21-year simulation provides an improved estimate of conditions in the LDW. Comparisons of predicted and observed bed composition were conducted during model validation (see Section 2.6). Similar to Figure 2-11, the composition of the evolved bed in the RM 0-4.3 region (i.e., entire region, plus navigation channel, east bench and west bench) is compared to observed bed composition in this region in Figure B-21. Those comparisons indicate that the model adequately predicts bed composition in the LDW, which supports the use of this approach for estimating initial bed composition conditions. Additional numerical testing demonstrated that the "evolved" bed had reached a state of quasi-equilibrium at the end of the 21-year period; significant large-scale changes in bed composition did not occur during simulations that used the evolved bed as the initial condition.

The spatial distributions of classes 1A, 1B, 2, and 3 in surface-layer sediment at the end of the 21-year simulation are presented in Figures B-22 through B-25. Generally, the composition of the surface layer of the bed was finer at the end of the 21-year period; class 1A and 1B content tended to increase, while class 2 and 3 content tended to decrease as the bed evolved. The spatial distributions of bed content displayed in Figures B-22 through B-25 were used as initial conditions for the simulations discussed in Sections 2, 3, and 4.

As discussed in Section A.3, the sediment bed is separated into five layers, with each layer being 5-cm thick. The erosion rate parameters in Equation A-15 (i.e., A, n, τ_{cr}), which is used to calculate gross erosion rate (E_{gross}), vary with depth in the bed, with specific values of A, n, and τ_{cr} for each of the five bed layers. In addition to vertical variation, the erosion rate parameters may also be varied in the horizontal direction; erosion rate parameters need to be specified in each of the five bed layers for every grid cell in the cohesive bed area within the LDW.

The spatial distributions of erosion rate parameters for use in the sediment transport model were specified using the following procedure for each layer in the bed model. The erosion rate properties of cohesive sediment in the LDW were investigated during the STAR study (Windward and QEA 2007). Sedflume core data were analyzed and the cores were separated into groups with similar erosion rate properties (see Table B-7). The average, or representative, erosion parameters (i.e., A, n, τ_{cr}) for each core group and bed layer are listed in Table B-8. Parameter values in that table coincide with Equation A-16 as follows: gross erosion rate (E_{gross}) with units of cm/s and skin friction shear stress (τ_{sf}) with units of Pa.

Table B-7. Sedflume core groups.

Depth Layer (cm)	Core 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
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
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

Table B-8. Average erosion rate parameters for Sedflume core groups.

Depth Layer (cm)	Core Group Number	Average A ($\times 10^{-4}$)	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 first step in developing the spatial distribution of erosion parameters for a specific depth layer in the bed model was to establish a "zone of influence" for each Sedflume core. For a core located in the east or west bench areas, the zone of influence was assumed to extend from the core to the midpoint locations between the nearest upstream and downstream cores within the bench area. A similar procedure was used for cores located in the navigation channel. After establishing the zone of influence for each core, the erosion parameters for the core group corresponding to each core were assigned to all of the grid cells within that zone of influence. The resulting spatial distributions of erosion parameters, based on the core groups listed in Tables B-7 and B-8, are shown in Figures B-26 through B-30.

LIST OF FIGURES CITED IN APPENDIX B

APPENDIX C
RE-CALIBRATION AND VALIDATION OF HYDRODYNAMIC MODEL

C.1 RE-CALIBRATION AND VALIDATION OF HYDRODYNAMIC MODEL

The hydrodynamic model was calibrated and validated during the STAR study (Windward and QEA 2007). As discussed in Section 2.2, modification of the numerical grid made it necessary to re-calibrate the hydrodynamic model. The same datasets and approach used to calibrate the hydrodynamic during the STAR study were used during the re-calibration and validation process, which consisted of comparisons between predicted and observed hydrodynamic variables (i.e., tidal elevation, current velocity, and salinity) at various LDW locations during two periods: 1) August 1996 through June 1997; and 2) December 2003 through February 2004. For each time period, a 30-day spin-up simulation was conducted prior to the calibration/validation period to minimize the effects of initial conditions on model results. Temporal variations in river flow rate (i.e., changes in daily-average flow rate) were incorporated into the simulations, along with the neap-spring tidal cycle.

For the first calibration/validation period (August 1996 through June 1997), a 12-month simulation (including 30-day spin-up) was conducted; a 4-month simulation was carried out for the second period (December 2003 through February 2004, plus 30-day spin-up). Model performance was evaluated through comparisons with data during specific time intervals selected from the longer simulation periods. The comparisons presented below were selected so that model performance could be evaluated over a range of river flow and tidal conditions. Additional model-data comparisons were conducted but not included in the report due to space limitations. The comparisons presented below are representative of the overall performance of the hydrodynamic model.

Tidal elevation data collected at four locations within the study area from August 1996 through June 1997 were used for model calibration: 1) Seattle Ferry Pier; 2) Spokane Avenue Bridge; 3) 16th Avenue Bridge (approximately RM 3.35); and 4) Duwamish Yacht Club (approximately RM 4.15). These sampling locations are shown in Figure C-1. Results for two 15-day periods, which correspond to low- and moderate-flow conditions in the Green River, are presented in Figures C-2 and C-3. The low-flow period was from August 26 through September 9, 1996. The moderate-flow period was from October 25 through November 8, 1996. Comparisons between predicted and measured tidal elevation at the four locations during both periods show that the model is able to simulate temporal and spatial variations in tidal elevation within the study area. During a high-flow period in January-February 2004, tidal elevation data were obtained near RM 1.1 (see Figure C-16). Comparisons of predicted and measured tidal elevation at station BRD3 during the 15-day period from January 24 through February 7, 2004 are shown in Figure C-4. Similar to the results during the low- and moderate-flow conditions, the model is able to simulate temporal variations in tidal elevation during high-flow conditions at this location. Model calibration was achieved by adjusting the effective bottom roughness in the hydrodynamic model, with a value of 0.2 cm (2,000 μm) producing the results discussed above.

The excellent agreement between predicted and measured tidal elevations at multiple locations in the LDW for a wide range of river flow and tidal conditions demonstrates that the calibrated hydrodynamic model adequately represents the overall geometry and bathymetry of the LDW system. This achievement is the first step in evaluating the reliability of the hydrodynamic model. The next step is to evaluate the ability of the model to simulate current velocities and salinity transport in the LDW. These analyses were accomplished during the model validation process, which is discussed below. No model parameters were adjusted during validation.

Current velocity data were collected during 1996 at two stations in the LDW (Figure C-5): 1) Sea Boil Works (approximately RM 2.35); and 2) Boeing (approximately RM 3.5). Salinity data were obtained at two stations during 1996 (Figure C-6): 1) 16th Avenue Bridge (approximately RM 3.35); and 2) Duwamish Yacht Club (approximately RM 4.15). During the low-flow period in 1996 (August 26 through September 9), flow in the Green River was about 500 cfs and relatively steady (Figure C-7). Vertical profiles of predicted and measured current velocity at the Sea Boil Works station during a 10-hr period on August 28, 1996 are shown in Figures C-8a through C-8j. Vertical profiles of predicted and measured current velocity at the Boeing station during a 20-hr period on August 28, 1996 are shown in Figures C-9a through C-9j. Spring-tide conditions existed in the LDW on August 28. These model-data comparisons show that: 1) temporal variations in velocity over the course of a tidal cycle (i.e., tidal phase) are correctly reproduced by the model; 2) the vertical structure of current velocity, and temporal changes of that structure, are adequately simulated; and 3) the model is able to simulate the observed two-layer flow at these locations. Generally, the model is able to reproduce temporal changes in the vertical structure of current velocity, including two-layer flow, at both locations.

Vertical profiles of predicted salinity at the 16th Avenue Bridge during a 23-hour period on August 28 and 29, 1996 are compared to measured salinity values in Figures C-10a through C-10j. Vertical profiles of predicted salinity at the Duwamish Yacht Club during an 11-hour period on August 28 and 29, 1996 are compared to measured salinity values in Figures C-11a through C-11j. The model-data comparisons at these two locations, which are about 0.8 mile apart, demonstrate that the model: 1) simulates temporal variations in salinity over the course of a tidal cycle due to longitudinal movement of the salt wedge in the LDW; and 2) adequately reproduces significant vertical stratification during low-flow conditions. Even though the salinity data are relatively sparse, these validation results indicate that the model is capable of simulating spatial and temporal changes in vertical salinity gradients during a low-flow period when high salinity stratification occurs throughout most of the LDW (i.e., the saltwater wedge extends at least to the upper turning basin).

Flow in the Green River varied between about 1,000 and 2,500 cfs during the moderate-flow period between October 25 and November 8, 1996 (Figure C-12). Model-data comparisons are presented for the spring-tide conditions that existed in the LDW during October 25-27. Vertical profiles of predicted and measured current velocity at the Sea Boil Works station during a 20-hr period on October 27, 1996 are shown in Figures C-13a through C-13j. The model is able to simulate significant changes in the velocity profile during this period, which varies between upstream flow, downstream flow, and two-layer flow. Vertical profiles of predicted salinity at the 16th Avenue Bridge during a 13-hour period on October 25 and 26, 1996 are compared to measured salinity values in Figures C-14a through C-14j. Vertical stratification is greater at this location than during the low-flow period in August 1996 (see Figures C-10a through C-10j) as a result of the increased freshwater flow in the Green River. The model adequately captures the overall level of vertical stratification in the water column, but it is not always able to reproduce details of the salinity profile. Vertical profiles of predicted salinity at the Duwamish Yacht Club during an 8-hour period on October 25 and 26, 1996 are compared to measured salinity values in Figures C-15a through C-15j. This location is in the vicinity of the toe of the saltwater wedge for these flow conditions in the Green River. The model is able to satisfactorily reproduce significant changes in the level of salinity stratification as the toe of the saltwater wedge moves in the upstream-downstream direction in the LDW during this 8-hour period. These results demonstrate that the model is capable of simulating spatial and temporal changes in vertical salinity gradients during a moderate-flow period when the toe of the saltwater wedge is located in the vicinity of the upper turning basin. Some of the discrepancies between predicted and observed velocity and salinity profiles may be due to large spatial gradients that exist near the toe of the saltwater wedge, which was in the vicinity of the measurement locations during October 25-27. Even though the model was adequately predicting the overall structure of circulation in this region of the LDW on these three days, relatively small differences between predicted and actual locations of the saltwater wedge can produce relatively large differences in the model-data comparisons.

Current velocity data were collected at four locations near RM 1.1 during January and February 2004 (see Figure C-16). A high-flow event, with a maximum flow rate of about 7,500 cfs in the Green River, occurred during the 15-day period from January 24 through February 7, 2004 (Figure C-17). Comparisons of vertical profiles of predicted and measured velocities at station BRD3 during a 24-hour period on January 30, 2004 are shown in Figures C-18a through C-18j. Peak flows during this high-flow event occurred on January 30, which coincided with neap-tide conditions (see Figure C-17). Relatively strong two-layer flow was observed at this location, with upstream flow in approximately the lower two-thirds of water column at some times during this day. The model is able to simulate the strong two-layer flow but does not capture all of the details of the vertical profile. Vertical profiles of predicted and observed velocity during lower flow condition on the receding limb of the high-flow hydrograph (i.e., 2,000 to 3,000 cfs on February 4) are compared in Figures C-19a through C-19j. This day was selected because spring-tide conditions were occurring in the LDW, which is in contrast to the neap-tide conditions during the peak flow on January 30. Observed vertical gradients in current velocity are not as sharp as during the peak flow period; the model satisfactorily simulates changes in the vertical velocity profile for the lower flow conditions.

Results of the model re-calibration and validation indicate that the hydrodynamic model adequately simulates estuarine circulation in the LDW over a range of river flow and tidal conditions. The model simulates tidal elevations throughout the system, and is able to reproduce temporal and spatial variations in tidal phase and magnitude. As noted above, this result indicates that the geometry and bathymetry of the system are adequately incorporated into the model. The complex structure of estuarine circulation, due to the presence of a saltwater wedge, is reproduced by the hydrodynamic model. The model is able to reliably predict longitudinal changes in saltwater wedge location, both over the course of a tidal cycle and in response to changes in river flow rate. The vertical structure of current velocity, which exhibits high variability in space and time, is adequately simulated, with the model demonstrating the ability to reproduce the observed two-layer flow in the LDW. Model-data discrepancies do exist but these discrepancies do not invalidate the overall predictive capability of the model, which is adequate to achieve the objectives of the sediment transport modeling study (see Section 1.6).

C.2 ADDITIONAL EVALUATION OF MODEL PERFORMANCE

Additional evaluations of hydrodynamic model performance were conducted to investigate: 1) model-data comparisons of near-bed velocity and vertical gradients in salinity; 2) sensitivity of model results to effective bed roughness and vertical grid resolution; and 3) potential effects of deviations between measured and predicted near-bed velocities on STM predictions.

Near-bed current velocity is of importance for sediment transport simulations because hydrodynamic model output is used to calculate the skin friction shear stress in the STM. Thus, it is worthwhile taking a closer look at the results shown in Figures C-8, C-9, C-13, C-18 and C-19. While these results represent a range of river discharge conditions (from low-flow [about 500 cfs] to high-flow [about 7,500 cfs]), the current velocity data were collected at locations within the saltwater wedge of the LDW. As discussed in other section of this report, extensive analysis of hydrodynamic and sediment transport processes in the LDW has demonstrated that two-layer flow exists within the saltwater wedge and that this circulation pattern results in relatively low near-bed velocities and, subsequently, minimal bed scour during all river flow conditions within the saltwater wedge.

The results shown in Figure C-8 correspond to: Sea Boil Works station (RM 2.35) for 10-hour period on August 28, 1996 (low-flow period). For this location, the deepest data point in the water column is about 1.5 to 2 m above the sediment bed. This data point is located between model grid points 2 and 3 (model grid point 1 represents the near-bed velocity), so direct comparisons of predicted and observed near-bed velocities cannot be made. The model under-predicts the magnitude of the deepest point in the water column (about 1.5-2 m above the bed) by 5 cm/s or more during six of the ten snapshots shown in Figure C-8 (i.e., 1-hr interval), with the average and maximum deviations being 6 and 12 cm/s, respectively.

The results shown in Figure C-9 correspond to: Boeing station (RM 3.5) during 20-hour period on August 28, 1996. The model under-predicts the magnitude of the near-bed velocity by 5 cm/s or more during four of the ten snapshots shown in Figure C-9 (i.e., 2-hr interval), with the average and maximum deviations being 7 and 16 cm/s, respectively.

The results shown in Figure C-13 correspond to: Sea Boil Works station (RM 2.35) for 20-hour period on October 27, 1996 (moderate-flow period). For this location, the deepest data point in the water column is about 1.5 to 2 m above the sediment bed, so direct comparisons of predicted and observed near-bed velocities cannot be made. The model under-predicts the magnitude of the deepest point in the water column (about 1.5-2 m above the bed) by 5 cm/s or more during three of the ten snapshots shown in Figure C-13 (i.e., 2-hr interval), with the average and maximum deviations being 4 and 8 cm/s, respectively.

The results shown in Figure C-18 correspond to: BRD3 station (RM 1.1) during 24-hour period on January 30, 2004 (high-flow period). The model under-predicts the magnitude of the near-bed velocity during none of the ten snapshots shown in Figure C-18. The average and maximum deviations (over-prediction of near-bed velocity) are 7 and 14 cm/s, respectively.

The results shown in Figure C-19 correspond to: BRD3 station (RM 1.1) during 23-hour period on February 4, 2004 (high-flow period). The model under-predicts the magnitude of the near-bed velocity during one of the ten snapshots (8 cm/s deviation) shown in Figure C-19. For the other nine snapshots, the average and maximum deviations (over-prediction of near-bed velocity) are 3 and 12 cm/s, respectively.

The model-data comparisons of near-bed current velocity can be summarized as follows. The model over-predicted the deepest current velocity measurement (i.e., within 1.5-2 m above the bed) by 5 cm/s or more during 15 of the 50 snapshots in time (i.e., 30% of the snapshots). The average deviations between predicted and measured near-bed velocity ranged from 3 to 7 cm/s, with the maximum deviations ranging form 8 to 16 cm/s.

Comparisons of predicted and observed vertical salinity gradients were made using the results shown in Figure C-14 and C-15. The salinity data on these two figures were collected at sampling stations located at the 16th Avenue Bridge (RM 3.35) and Duwamish Yacht Club (RM 4.15) during October 25-26, 1996 (moderate-flow period). The vertical salinity gradient, which is defined as the difference between the near-surface and near-bottom salinities (predicted or measured), was calculated for each of the ten snapshots in time shown in Figures C-14 and C-15. For the 16th Avenue Bridge location, the measured and predicted salinity gradients ranged from 18-24 and 15-21 ppt, respectively. The model under-predicted the vertical salinity gradient by an average of 3.5 ppt, with under-predictions ranging from 1 to 8.5 ppt, during the ten snapshots shown in Figure C-14. For the Duwamish Yacht Club location, the measured and predicted salinity gradients ranged from about 1-17 and 9-25 ppt, respectively. The model under-predicted the vertical salinity gradient by an average of 11 ppt, with under-predictions ranging from 6 to 22.5 ppt, during the ten snapshots shown in Figure C-15.

The sensitivity of the hydrodynamic model to effective bed roughness was evaluated by decreasing and increasing the value of the calibration value (0.2 cm or 2,000 μm) by a factor-of-ten, so the lower- and upper-bound values were 200 and 20,000 μm, respectively. The lower-bound value (200 μm) is unrealistic because it is less than the values used for the effective bed roughness due to skin friction in the sediment transport model, which range from 780 μm in the navigation channel to 1,880 μm in the east bench. The effective bed roughness in the hydrodynamic model is greater than the effective bed roughness in the sediment transport model because it represents the combined effects of skin friction and form drag (see Section A.1). However, use of this lower-bound value, even though unrealistic, is valid for investigating model sensitivity.

Predicted current velocity profiles for the sensitivity simulations are compared in Figures C-20 through C-24, which correspond to Figures C-8, C-9, C-13, C-18 and C-19 that are discussed in Section C.1. These comparisons show that: 1) decreasing/increasing the effective bed roughness tends to increase/decrease near-bed velocity; 2) factor-of-ten decrease and increase in the effective bed roughness has a relatively minor effect on near-bed velocity and does not significantly improve model performance; and 3) the predicted current velocity profiles above the near-bed value are insensitive to the effective bed roughness. Predicted salinity profiles for the sensitivity simulations are compared in Figures C-25 through C-28, which correspond to Figures C-10, C-11, C-14 and C-15. These results show that effective bed roughness has minimal effect on vertical salinity profiles.

The results of the sensitivity simulations demonstrate that adjustment of effective bed roughness is not sufficient for improving the performance of the LDW model, which is a typical result for an estuarine hydrodynamic model. In a recently published journal article that examined a new method for quantifying uncertainty in an estuarine and coastal ocean circulation model (Blumberg and Georgas 2008), it was stated that three primary factors affect the accuracy of an estuarine hydrodynamic model: 1) lack of complete understanding of the governing physical processes (e.g., vertical turbulence); 2) discretization of continuous fields (i.e., grid resolution in the horizontal and vertical directions, limitations of numerical algorithm); and 3) degree of knowledge of drivers of the circulation (e.g., bathymetry/geometry, freshwater inflows). The article also states that: "Bottom topography has traditionally been considered as a major factor in determining the circulation in estuaries and the coastal ocean." The paper focuses on the sensitivity of an estuarine and coastal ocean modeling system to three primary drivers: 1) bathymetry (bottom topography); 2) freshwater inflow; and 3) wind forcing. Sensitivity of an estuarine and coastal ocean modeling system to effective bottom roughness was not considered in Blumberg and Georgas (2008) because this parameter typically has a secondary effect on estuarine model performance.

The results of the sensitivity analysis discussed above indicate that adjustment of the effective bed roughness does not significantly improve model performance. This conclusion is consistent with the discussion on factors that control the predictive capability of estuarine circulation models presented in Blumberg and Georgas (2008). Thus, deviations between predicted and observed vertical profiles of current velocity and salinity for the LDW hydrodynamic model are primarily affected by one or more of these controlling factors: 1) bathymetry/geometry inputs; 2) horizontal and vertical grid resolution; 3) limitations of numerical algorithm (e.g., numerical diffusion); 4) turbulence closure sub-model; and 5) specification of freshwater inflow. Conceptually, model performance might be improved through adjustment of one or more of these five controlling factors. Possible adjustment of these factors in the LDW model is discussed below.

The bathymetry/geometry inputs for the LDW model are based on the best data that are currently available. While the bathymetry data are uncertain due to inherent measurement error, it is not possible to systematically and objectively adjust the bathymetry data. In addition, it is unknown whether the discrepancies between predicted and observed vertical profiles of current velocity and salinity are primarily affected by small (local) or large spatial scale variations in bathymetry. Thus, adjusting bathymetry to reliably calibrate the model is not possible.

Increasing or modifying horizontal grid resolution is not practical because model simulations with the present horizontal resolution are near the limit of feasibility for conducting long-term, multi-year simulations in an acceptable period of time. Significantly increasing horizontal grid resolution would push simulation times beyond the limit of practicality. In addition, it is unclear *a priori* what level of increased horizontal grid resolution would be necessary to improve model performance.

The model tends to under-predict the sharpness of vertical gradients in current velocity and salinity. It is possible that increased grid resolution in the vertical direction may improve the ability of the model to reproduce these vertical gradients. To investigate the sensitivity of the hydrodynamic model to vertical grid resolution, the calibration simulation was repeated using 20 layers in the vertical (i.e., twice the resolution of the present model). Current velocity profiles for 10- and 20-layer simulations are compared during August 28 and October 27, 1996 on Figures C-29, C-30 and C-31. These results show that increasing the vertical grid resolution by a factor-of-two has minimal effect on the vertical current profile predicted by the model. Comparisons of predicted vertical salinity profiles for 10- and 20-layer grid resolution for August 28-29 and October 25-26, 1996 are presented on Figures C-32 through C-35. Increasing grid resolution from 10 to 20 layers has a minor effect on the predicted salinity profile, with the higher grid resolution producing a slightly higher level of vertical stratification.

Under-prediction of the sharpness of vertical gradients in current velocity and salinity may also be affected by numerical diffusion, which is generated by the numerical algorithms used in the model. This issue is an inherent limitation of the numerical algorithms used in EFDC, which are second-order accurate and designed to minimized numerical diffusion. Improvement in this area would thus require modification of EFDC to include a third-order accurate algorithm, which is beyond the scope of this study.

The turbulence closure sub-model is used to specify values of vertical eddy viscosity and diffusivity, which are spatially and temporally variable. The sub-model used in EFDC is the Mellor-Yamada 2.5 level algorithm, which is a well-tested and widely-used turbulence closure sub-model. Parameters in this sub-model are specified based on laboratory data and are rarely adjusted during development and calibration of an estuarine hydrodynamic model.

Freshwater inflow to the LDW is primarily from the Green River and this model input is specified using USGS gauging station data. Discharge measurements at this gauging station are rated as good, which means that the flow rate data have a measurement error of 10% or less. It is doubtful that uncertainty in Green River discharge, which is relatively low, has a significant effect on model performance, at least compared to other controlling factors.

The above analyses and discussion suggest that significant improvement in the performance of the LDW hydrodynamic model is beyond the scope of the present study. Significant improvement in model performance would probably require one or more of the following enhancements to model inputs and structure: 1) more accurate specification of bathymetry/geometry throughout the model domain, including the East/West Waterways and Elliott Bay; 2) increase horizontal grid resolution by at least a factor-of-two; 3) increase vertical grid resolution to more than 20 layers; 4) investigate incorporation of a third-order accurate transport algorithm to reduce the effects of numerical diffusion into EFDC; and 5) investigate incorporation of sophisticated vertical turbulence closure models (e.g., Reynolds stress or large eddy simulation models) into EFDC. These enhancements would require a significant amount of effort, time and commitment of resources to achieve.

Therefore, significant improvement of hydrodynamic model performance is problematic at the present time. Based on this conclusion, the question may arise as to whether or not the deviations between predicted and observed near-bed velocities shown in Figures C-20 through C-24 translate into significant uncertainty in STM results. Additional examination of the model-data comparisons of current velocity profiles provides insight about the potential effects of uncertainty in the prediction of near-bed velocity on sediment transport simulations.

Critical shear stress values for surface-layer sediments in the LDW are 0.16, 0.24 and 0.63 Pa for core groups 1, 2 and 3. These critical shear stress values correspond to near-bed velocities of 25, 31 and 50 cm/s, where a bottom friction coefficient of 0.0025 was assumed. As a conservative estimate, assume that a reasonable range of critical near-bed velocity for initiation of erosion of surface-layer sediment is 25 to 31 cm/s. This range of critical near-bed velocity has been added to Figures C-20 through C-24 so that the predicted and observed near-bed velocities can be compared to the critical near-bed velocity. These comparisons show that the observed near-bed velocity exceeded the critical value range only two times during the 50 snapshots shown in these figures; the critical value range was exceeded by a maximum of 5 cm/s (i.e., excess shear stress of about 0.06 Pa), see Figure C-21f. Thus, the observed near-bed velocities were below the critical value for initiation of erosion during 96% of the model-data comparisons. This result indicates that even if the model had been in perfect agreement with the measured near-bed velocities, the effect on STM simulations would have been minimal. This conclusion is consistent with the present understanding of sediment transport processes within the saltwater wedge of the LDW, where near-bed velocities, which are generated by density-driven circulation within the saltwater wedge, are relatively low and bed scour is minimal during all freshwater inflow conditions. Therefore, deviations between observed and predicted near-bed velocities within the saltwater wedge of the LDW, which is the location of current velocity data presently available for model calibration/validation, do not add significant uncertainty to STM predictions. This statement is supported by the adequate agreement between predicted and empirical NSR values, as well as the numerous diagnostic analyses that support the qualitative and quantitative performance of the STM.

LIST OF FIGURES CITED IN APPENDIX C

APPENDIX D
DETAILS OF SEDIMENT TRANSPORT MODEL CALIBRATION AND VALIDATION

D.1 SPECIFICATION OF BOUNDARY CONDITIONS

Daily-average flow rates measured at the USGS gauging station in the Green River from 1960 through 1980 were used to specify discharge at the upstream boundary of the model during the 21-year calibration period. The methods presented in Section B.2 were used to estimate the magnitude and composition of incoming sediment load at the upstream boundary. Time series of flow rate and sediment loading at the upstream boundary in the Green River for the 21-year period are shown in Figures D-1 through D-21. At the open boundary in Elliott Bay, tidal elevation was specified using data collected at NOAA's Seattle Ferry Pier tide gauge station.

D.2 SEDIMENTATION RATE DATA

During the development phase of the sediment transport model, estimates of net sedimentation rates in the navigation channel presented in Harper-Owes (1983) were chosen for use as a primary calibration target for the sediment transport model. The three data sources used to determine those estimates are described in Harper-Owes (1983) as follows: 1) USACE and Port of Seattle maintenance dredging data (1960-1980); 2) sediment input-output budgets; and 3) USACE channel condition maps corrected for dredge and fill projects (unpublished data, 1965-1970). Additionally, it was stated in Harper-Owes (1983) that: "Since errors associated with each method are felt to be random (as opposed to systematic), the average of the three estimates was used. Data from the COE [USACE] channel condition maps (unpublished data) were corrected for the 'three-method' average sedimentation rate and estuary width to determine longitudinal variations in sedimentation velocity throughout the Duwamish Waterway." The spatial distribution of net sedimentation rates presented in Harper-Owes (1983) is shown in Figure D-22.

Initial efforts to calibrate the sediment transport model using the Harper-Owes (1983) estimates of net sedimentation rates in the navigation channel as a calibration target were problematic. Predicted net sedimentation rates in the navigation channel in the region downstream of approximately RM 4.0 were significantly lower than the estimated values in Harper-Owes (1983). Numerous simulations were conducted in an attempt to decrease the differences between the predicted and estimated values of net sedimentation rate in the navigation channel. These simulations involved modifications to model structure (i.e., active layer in the sediment bed) as well as model inputs. Attempts to significantly improve agreement between predicted and estimated values of net sedimentation rate in the navigation channel were unsuccessful.

The inability to improve model-data agreement in the navigation channel led to an evaluation of the reliability of the Harper-Owes values. The consensus of the STM group was that the estimated values in Harper-Owes (1983) were based on data and information obtained during a time period when pre-dam conditions (i.e., prior to ca. 1960 when the Howard Hansen dam was constructed on the Green River) were still affecting sedimentation in the navigation channel. Thus, a fundamental incompatibility may exist between the sediment transport model inputs (i.e., geometry/bathymetry, sediment loading) and the Harper-Owes values; the Harper-Owes values may not be representative of the conditions being simulated by the sediment transport model.

To develop a calibration dataset that is consistent with post-dam conditions in the LDW, an analysis of USACE Conditions Survey data from the early 1980s through 2003 was conducted. Changes in average bed elevation across the navigation channel at various transect locations in the LDW were determined for specific time periods between 1981 and 2003. The bed elevations changes, over a specific time period, were converted to a net sedimentation rate that represents the average value for the navigation channel at a particular transect location. A complete description of this analysis is presented in RETEC (2007). This analysis produced the estimated values of net sedimentation rates in the navigation channel shown in Figure D-22. Generally, the rates based on the more recent USACE data are lower than the rates from the

Harper-Owes analysis. At two locations (i.e., RM 1.0 and 2.4), the updated analysis produced estimates of net erosion in the navigation channel. The updated net sedimentation rates are more representative of post-dam conditions in the LDW and were used to calibrate the sediment transport model.

Net sedimentation rates in the bench areas were estimated using two approaches during the STAR study (Windward and QEA 2007). The first approach used radioisotope data from geochronology cores collected from the bench areas to estimate net sedimentation rates. The second approach used several empirical lines-of-evidence (i.e., chemical, physical, and radioisotope) from the LDW. The available site data used in that analysis included: chemistry and stratigraphy data from 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. For most cores, 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. The estimated net sedimentation rates in the east and west bench areas that resulted from these analyses are shown in Figure D-23.

The NSR data used for model calibration and validation represent rates over different time periods:

- *Navigation channel:* bathymetry data collected during the period between 1981 and 2003.
- *Bench areas and navigation channel:* empirical estimates from core data represent average values between ca. 1963 and 2006.

The time periods represented by these NSR datasets correspond to post-dam conditions (i.e., after construction of the Howard Hansen dam) in the LDW. A review of Green River discharge data between 1961 and 2006 indicates that similar hydrologic conditions existed during the 30-year periods from 1960 through 1989 (i.e.., period used for model calibration/validation and long-term simulation) and from 1977 through 2006 (see Section 4.2). Thus, similar hydrologic and sediment load conditions existed in the Green River during the 30-year periods that occurred in the early or late portions of the approximately 45-year period (ca. 1961-2006) corresponding to post-dam conditions in the LDW. These 30-year periods overlap the time periods represented by the NSR estimates. Therefore, the NSR estimates provide the best dataset for model calibration and validation.

D.3 ADDITIONAL MODEL CALIBRATION RESULTS

Prior to final calibration of the model, extensive testing of the sediment transport model was conducted. This testing, which was conducted in collaboration with the STM group, resulted in modification of the structure of the SEDZLJ algorithm (see Appendix A). The modifications of the original SEDZLJ algorithm (Jones and Lick 2001) were made to improve the reliability of the model and its performance over long-term, multi-year periods in an estuarine system. In addition to changes to the basic algorithm, modifications were made to the initial structure of model inputs. The primary modifications to the algorithm and inputs were: 1) separation of the active layer into two sub-layers (i.e., active-surface and active-buffer layers), see discussion in Section A.3 for justification of this modification; 2) inclusion of the particle-shielding factor in the erosion rate calculation, see discussion in Sections 2.5 and A.3 for justification of this modification ; 3) separating class 1 sediment (i.e., clay/silt less than 62 μm) into two sub-classes (i.e., classes 1A and 1B) representing clay/fine silt (less than 10 μm) and medium/coarse silt (10 to 62 μm); 4) addition of bedload transport in cohesive and non-cohesive areas; 5) using the Krone approach instead of the Partheniades approach for probability of deposition for cohesive sediment; and 6) neglecting the effects of time-varying flocculation on cohesive sediment settling speed (see Table 2-1 for justification of this modification). Modification #3 (separating class 1 sediment into classes 1A and 1B) was needed so that variations in the effective settling speed of clay/silt, which ranges from less than 1 m/day to approximately 20-30 m/day, due to flocculation and other effects were incorporated into the model. Bedload transport was added to the sediment transport model after discussions among the STM group lead to the decision that this process was necessary for development of a credible model. Modification #5 (use of Krone approach) was made because the Krone and Partheniades approaches produce similar results, and the Krone approach is easier to understand and explain.

The sediment bed in the Green River upstream of the upper turning basin (i.e., upstream of RM 4.8) is primarily composed of non-cohesive sediment with areas that are rocky. The non-cohesive sediment bed in the region upstream of RM 4.8 contains a mixture of sand and gravel. During the initial phase of model calibration, the sediment bed in the Green River was treated as an "active" bed, which means that erosion and deposition of suspended-load sediment, as well as bedload transport, were simulated by the model. Realistic simulation of erosion and deposition of non-cohesive sediment in a river with a non-cohesive bed, such as the Green River, is highly dependent on the ability to specify the spatial distribution of bed properties within the river (Ziegler et al. 2000). Based on a relatively sparse dataset, initial conditions for the calibration simulation were developed using an approximate method to specify the spatial distribution of bed properties in the Green River (see Section B.2).

Initial calibration simulations using an "active" non-cohesive bed in the Green River, as discussed above, produced results that predicted that the region upstream of the upper turning basin was net erosional over the 21-year period. The model predicted unrealistically deep bed scour (i.e., greater than 500 cm) at some grid cells in the Green River. The mass of sediment predicted by the model to be eroded from the region upstream of RM 4.8 significantly increased the sediment load transported from the Green River to the LDW. For the 21-year calibration period, the total sediment load transport past RM 4.8 was about a factor-of-three greater than the sediment load specified at the upstream boundary. To solve this problem of unrealistically high bed erosion in the active non-cohesive bed, grid cells with excessive bed scour were converted from active to non-active. In a grid cell with a non-active bed, it is assumed that a rocky bed exists, which means no erosion or deposition of suspended sediment occurs but bedload transport is allowed. Bedload is transported as class 3 sediment (medium/coarse sand) in the bottom vertical grid cell of the water column.

After converting to grid cells with excessive bed scour in the Green River to a non-active bed, the model was calibrated by adjusting these parameters: 1) effective particle diameters of class 1A and 1B sediment; and 2) average composition of class 1A and 1B sediment in the incoming sediment load (see Section 2.5). Comparisons of predicted and empirically-derived estimates of net sedimentation rates in the navigation channel for the active non-cohesive bed simulation are presented in Figures D-24 and D-25. Similarly, predicted net sedimentation rates in the east and west bench areas are compared to empirically-derived estimates in Figure D-26. Overall, reasonable system-wide agreement between model results and empirically-derived estimates in the navigation channel and bench areas was achieved.

A sediment mass balance for the 21-year period showed that the model produced net erosion in the region upstream of RM 4.8, which caused the sediment load in the river to increase by about 10% between the upstream boundary and RM 4.8. Use of non-active grid cells at locations of excessive bed scour in the Green River significantly improved the ability of the model to produce realistic simulations. Further investigation of the effects of non-active grid cells in the Green River was conducted by converting all grid cells upstream of RM 4.8 to non-active status. Better agreement between predicted and estimated net sedimentation rates in the navigation channel and bench areas was achieved when all grid cells upstream of RM 4.8 were specified as a non-active bed. Comparisons of Figures D-24 through D-26 (active bed) to Figures 2-7 through 2-9 (non-active bed) show the improvement in model performance when the entire sediment bed upstream of RM 4.8 is assumed to be non-active. Additional support for use of a non-active bed in the Green River is provided through comparisons of predicted composition of sediment deposited in the LDW to the observed composition of surface-layer sediment (see Figure D-27). Use of active bed grid cells in the Green River produces net deposition in the LDW that is coarser than indicated by the Sedflume core composition data. Thus, the decision was made that use of non-active grid cells in the region upstream of RM 4.8 yields the most accurate and reliable calibration results.

D.4 ADDITIONAL MODEL VALIDATION RESULTS

Comparisons between predicted and observed bed composition in the LDW were used as one method to validate the sediment transport model (see Section 2.6). Grain size distribution data collected during the Sedflume study in December 2006 were used as the comparison dataset (Windward and QEA 2007). These data were obtained from 18 cores (0-30 cm depth) collected throughout the LDW. Additional grain size distribution data (i.e., historical data) were available from surface-layer samples collected during previous field studies between 1990 and 2005. Comparison of the Sedflume and historical datasets indicated that the Sedflume data are finer than the historical data (i.e., lower D_{50} value and higher clay/silt content). The exact cause for this difference between the datasets is unknown. However, differences between the laboratory techniques used to measure grain size distributions of the Sedflume (laser method) and historical (sieve method) core data may possibly contribute to differences in the results. The historical data typically have a higher content of coarse sand and gravel than the Sedflume data. In addition, comparisons of model predictions to the Sedflume core data are valid because the Sedflume core data are more representative of deposition integrated over time, whereas the historical data (primarily obtained from grab samples) represent a snapshot in time. Furthermore, neglecting this coarser sediment in the model produces conservative results during high-flow events (i.e., over-prediction of bed scour) because including the coarse sediment in the model would have resulted in an intensification of bed armoring effects.

As discussed in Section 2.6, additional validation of the model was accomplished using one-to-one comparisons of predicted and estimated NSR values, which provides a quantitative analysis of predictive capability at the grid-cell scale. Two measures of model accuracy were used in this analysis: absolute difference and relative difference. The absolute difference (Δabs) is defined as:

$$\Delta_{abs} = NSR_p - NSR_e \qquad \text{(D-1)}$$

where NSR_p is the net sedimentation rate predicted/calculated by the model and NSR_e is the value estimated from core data. The units of Δ_{abs} are cm/yr. The relative difference (Δ_{rel}) is defined as:

$$\Delta_{rel} = 100\ (NSR_p - NSR_e)/\ NSR_e \qquad \text{(D-2)}$$

and this quantity is expressed as percent. The one-to-one comparisons located a core within a specific grid cell and the predicted NSR is compared directly to the estimated NSR for that core. For a core with multiple NSR estimates (using different time horizon markers), the estimated NSR value used in the analysis was the average value of the multiple NSR values for that core.

This analysis was applied to the results of the 30-year simulation discussed in Section 4 and Appendix F. Spatial variations of absolute and relative differences in the navigation channel and bench areas are shown in Figures D-28 and D-29, respectively. These results show that model accuracy is similar in the two bench areas, with the region downstream of RM 2 generally exhibiting lower differences than the region upstream of RM 2. Cumulative frequency distributions of absolute and relative differences for the region between RM 0 and 4 are presented in Figures D-30 and D-31, respectively. The absolute differences are approximately normally distributed with a median value of about 0 cm/yr. The range of absolute differences is about -4 to +3 cm/yr, with one outlier at +6.5 cm/yr. The median value of relative differences is about 0%, with about 50-60% of the distribution with a factor-of-two of zero difference (i.e., -50% to 100% relative difference). Cumulative frequency distributions for RM 0-2 and RM 2-4 regions are shown in Figures D-32 through D-35. For the RM 0-2 region, the absolute differences are approximately normally distributed, with a median value of about -0.5 cm/yr. For the RM 2-4 region, the median value of absolute differences is about +0.5 cm/yr; the distribution in this region is not normally distributed.

D.5 SPATIAL-SCALE ANALYSIS

This analysis was conducted to determine the relationship between model predictive capability and spatial scale. The spatial-scale analysis was applied to the results of the 30-year simulation discussed in Section 4 and Appendix F. The one-to-one comparisons discussed in Section D.4 evaluated model accuracy at the grid-cell scale. For this analysis, absolute differences between predicted and estimated NSR values were calculated for zones located in the RM 0 to 4 region, with zonal areas ranging from about 5 acres to about 300 acres. Zones were defined for different groups of grid cells within the RM 0-4 region. The region upstream of RM 4 was not included in this analysis because of the very high NSR values in that region (both predicted and estimated) and analyzing the effects of spatial scale on model performance in that region would not be informative. In addition, the focus of FS analyses will be on the RM 0-4 region.

An example calculation is shown in Figure D-36. In this example, the zone is composed of six grid cells and there are three cores within the zone. The NSR values for the grid cells and cores are shown in the figure. The predicted NSR (NSR_p) for the zone is the average of the predicted values for the six grid cells, which is 1.0 cm/yr. The estimated NSR (NSR_e) for the zone is the average of the estimated values for the three cores, which is 1.7 cm/yr. Thus, the absolute difference for this zone is -0.7 cm/yr (i.e., = 1.0 – 1.7 cm/yr).

Two approaches were used to separate the RM 0-4 region into zones. Comparisons of the results from the two approaches were made to determine if the analysis results are sensitive to the types of zones that are selected. The first approach separated the RM 0-4 region into zones as follows: 1) three lateral regions (west bench, navigation channel, east bench); and 2) longitudinal regions using 0.25, 0.50 and 1.0 mile divisions. Thus, the RM 0-4 region was divided into 12, 24, and 48 zones, which are shown in Figures D-37, D-38 and D-39, respectively. The locations of the cores used in this analysis are also shown in those figures. Qualitative comparisons of predicted and estimated NSR values for the different zones can be made from an examination of the three figures. Generally, good qualitative agreement occurs between predicted and estimated NSR values.

Cumulative frequency distributions of absolute and relative differences for 12, 24, and 48 zones within the RM 0-4 region are shown in Figures D-40 and D-41, respectively. The distributions of the one-to-one differences are included on those figures. These results indicate that similar distributions exist for all three zonal analyses, as well as for the one-to-one analysis. Similar results are found for the RM 0-2 region (Figures D-42 and D-43). For the RM 2-4 region, the three zonal analyses have similar distributions, but the one-to-one analysis has a different distribution in this region (Figures D-44 and D-45). Overall, these results suggest that the model has similar reliability over the range of spatial areas investigated.

Spatial variation in the absolute and relative differences for the three zonal analyses in the bench areas and navigation channel are shown in Figures D-46 and D-47, respectively. In the bench areas, the model is generally unbiased downstream of RM 2 and it tends to over-predict NSR upstream of RM 2. In the navigation channel, the model tends to under-predict and over-predict NSR in the regions downstream and upstream of RM 2, respectively.

Another method for examining the effects of spatial scale on model accuracy is to directly compare predicted and estimated NSR values at the four different spatial scales (see Figure D-48). The results shown in this figure show that model predictions of NSR are not biased low or high at the four spatial scales investigated, with the results approximately evenly distributed about the line of perfect agreement (i.e., 45^{o} line). This figure also indicates that variability tends to decrease with increasing spatial area; the portion of points within a factor-of-two of the line of perfect agreement increases from 60% for the one-to-one analysis to about 70% for the zonal analysis. Similar results are found for the RM 0-2 and 2-4 regions (see Figures D-49 and D-50, respectively).

The relationship between average spatial area and average absolute difference for the three zonal analyses and one-to-one analysis is presented in Figure D-51. In addition to the average absolute difference, the 95% confidence interval about the average is shown in that figure. These results shows that the mean absolute difference for the one-to-one analysis is approximately zero, whereas the mean absolute differences for the 12-, 24- and 48-zone analyses range from about 0.25 to 0.50 cm/yr. The apparent over-prediction of the zonal analysis is primarily an artifact of the averaging process. In addition, the uncertainty in the one-to-one analysis is relatively large (i.e., 95% confidence interval about the mean value), and there is no statistical difference between the mean values of the one-to-one and three zonal analyses (at a 95% confidence level). Thus, these results show that the model accuracy is similar over the range of spatial areas investigated.

The second approach for the zonal analysis separated the RM 0-4 region into zones based on rows of grid cells across the LDW channel; generally, there are seven grid cells in the cross-channel direction. An idealized channel consisting of 11 rows in the longitudinal direction and 5 grid cells in the cross-channel direction is used to illustrate this approach. The smallest zones in this analysis are 1-row zones, which results in 11 zones for the idealized channel (Figure D-52). The next-largest zones are composed of 2-row zones (Figure D-53). For the 2-row zones, each zone is shifted by one row with respect to location, so that adjacent zones overlap by one row. This process results in ten 2-row zones. Similarly, there are nine 3-row zones, eight 4-row zones, and, finally, two 10-row zones (Figure D-54).

This process was applied to the RM 0-4 region and the results are presented in Figure D-55 (repeat of Figure 2-13). One benefit of this approach is that it produces significantly more results for spatial areas between 5 and 300 acres than the first approach. For reference, the results of the one-to-one comparison are also included in this figure (i.e., result plotted at 0.8 acre). The solid dots in Figure D-55 represent the average absolute difference, with the 95% confidence interval about the average shown as error bars Generally, the results for the second approach indicate that: 1) average absolute difference is less than ± 0.25 cm/year for spatial scales ranging from about 0.5 to 300 acres, which indicates that the predicted NSR values are not biased low or high over this range of spatial scales; 2) 95% confidence interval about the average absolute difference is about ± 0.5 cm/year for areas less than about 8 acres, about ± 0.38 cm/year for areas between about 8 and 20 acres, and less than ± 0.38 cm/year for areas between about 20 and 300 acres; and 3) variation (standard deviation) in absolute differences increases with decreasing spatial area, which is an expected characteristic.

D.6 UNCERTAINTY ANALYSIS

This analysis evaluated the effects of uncertainty in model inputs on model predictions. Based on sensitivity analysis results, see Sections 3.4 and 4.4, the effects of five inputs on model uncertainty were examined: 1) upstream sediment load: 2) settling speeds of class 1A/1B sediment; 3) erosion rate parameters; 4) effective bed roughness; and 5) class 2/3 particle diameter. Lower- and upper-bound limits of these five inputs were specified as follows:

- *Upstream sediment load:* ± a factor-of-two with respect to the base case (same as sensitivity analysis)
- *Class 1A/1B settling speed:* ± a factor-of-two with respect to the base case (same as sensitivity analysis)
- *Erosion rate parameters:* same as sensitivity analysis (see Section E.3)
- *Effective bed roughness:* ± 1 standard error about mean value, spatially variable
- *Class 2/3 particle diameter:* ± 1 standard error about median value

Values of the lower- and upper-bound limits, along with the base-case values are listed in Table D-1.

Table D-1. Model input values for uncertainty simulations.

Model Input	Base-Case Value	Lower-Bound Value	Upper-Bound Value
Upstream sediment load for 6-year simulation period (MT)	1,207,500	603,700	2,415,000
Class 1A/1B settling speed (m/day)	1.3/20	0.65/10	2.6/40
Effective bed roughness (range in μm)	360 ➔ 1,280	300 ➔ 930	420 ➔ 1,630
Class 2/3 particle diameter (μm)	130/540	110/450	150/630

To evaluate the effects of possible interactions between the five inputs, a factorial analysis was conducted, which resulted in 32 simulations to account for all of the possible combinations of the bounding limits of the five inputs. The parameter sets used in the 32 uncertainty simulations are provided in Table D-2, where "lower" refers to lower-bound value and "upper" refers to upper-bound value.

Table D-2. Bounding limits for uncertainty simulations.

Simulation Number	Erosion Rate Parameters Bound	Upstream Sediment Load Bound	Effective Bed Roughness Bound	Class 1A/1B Settling Speed Bound	Class 2/3 Particle Diameter Bound
1	Lower	Lower	Lower	Lower	Lower
2	Lower	Lower	Lower	Lower	Upper
3	Lower	Lower	Lower	Upper	Lower
4	Lower	Lower	Lower	Upper	Upper
5	Lower	Lower	Upper	Lower	Lower
6	Lower	Lower	Upper	Lower	Upper
7	Lower	Lower	Upper	Upper	Lower
8	Lower	Lower	Upper	Upper	Upper
9	Lower	Upper	Lower	Lower	Lower
10	Lower	Upper	Lower	Lower	Upper
11	Lower	Upper	Lower	Upper	Lower
12	Lower	Upper	Lower	Upper	Upper
13	Lower	Upper	Upper	Lower	Lower
14	Lower	Upper	Upper	Lower	Upper
15	Lower	Upper	Upper	Upper	Lower
16	Lower	Upper	Upper	Upper	Upper
17	Upper	Lower	Lower	Lower	Lower
18	Upper	Lower	Lower	Lower	Upper
19	Upper	Lower	Lower	Upper	Lower
20	Upper	Lower	Lower	Upper	Upper
21	Upper	Lower	Upper	Lower	Lower
22	Upper	Lower	Upper	Lower	Upper
23	Upper	Lower	Upper	Upper	Lower
24	Upper	Lower	Upper	Upper	Upper
25	Upper	Upper	Lower	Lower	Lower
26	Upper	Upper	Lower	Lower	Upper
27	Upper	Upper	Lower	Upper	Lower
28	Upper	Upper	Lower	Upper	Upper
29	Upper	Upper	Upper	Lower	Lower
30	Upper	Upper	Upper	Lower	Upper
31	Upper	Upper	Upper	Upper	Lower
32	Upper	Upper	Upper	Upper	Upper

The parameter sets discussed above were used to conduct 32 uncertainty simulations. Similar to the sensitivity analysis discussed in Section 4.4 and Section F.3, 6-year simulations were conducted and compared to the base-case simulation (i.e., using calibration parameters) for the 6-year period, which corresponded to the first 6 years of the 30-year period used for the external sediment load analysis. Use of the 6-year simulation period was necessary due to large numbers of simulations and relatively long simulation times (e.g., 3 days to complete one 6-year simulation).

The first step in analyzing the results of the 32 uncertainty simulations was to qualitatively compare all of the results to the base-case results in the navigation channel and bench areas (see Figures D-56 through D-79). Even though these figures may appear to be complex and difficult to interpret, the effects of the five model inputs on results may be evaluated through the following comparisons of figures. Groups of four uncertainty simulations were presented on each of these figures to improve the clarity of the presentation, with the four simulations presented on each figure represent the range of lower- and upper-bound limits for class 2/3 particle diameter and effective bed roughness. Generally, the figures show that these two model inputs have minor effect on the results. Evaluation of the effects of class 1A/1B settling speed may be made through direct comparisons of the following pairs of figures: 1) D-56 and D-57; 2) D-58 and D-59; 3) D-60 and D-61; and 4) D-62 and D-63. These comparisons indicate that class 1A/1B settling speed has a significant effect on model predictions of net sedimentation rate. Evaluation of the effects of upstream sediment load may be made through direct comparisons of the following pairs of figures: 1) D-56 and D-58; 2) D-57 and D-59; 3) D-60 and D-62; and 4) D-61 and D-63. Similar to class 1A/1B settling speed, the upstream sediment load has a major effect on model predictions. Evaluation of the effects of erosion rate parameters may be made through direct comparisons of the following pairs of figures: 1) D-56 and D-60; 2) D-57 and D-61; 3) D-58 and D-62; and 4) D-59 and D-63. These comparisons show that the erosion rate parameters have a minor effect on long-term sedimentation processes.

The second step in this analysis was to quantify the differences between the 32 simulations and compare those results to the base-case results. This comparison was accomplished by calculating the area-averaged bed elevation in nine zones in the LDW (Table D-3). Absolute and relative differences between the uncertainty and base-case simulations for the nine zones are compared in Figures D-80 through D-88. The uncertainty analysis focused on predicted NSR over multi-year periods (or, equivalently, bed elevation change during a multi-year period) and the effects of model input uncertainty on NSR. An appropriate approach to evaluate the effects of input uncertainty was to quantitatively compare NSR (or bed elevation change during the multi-year period) between the various uncertainty simulations for major regions of the LDW, which has been separated into three reaches (i.e., Reaches 1, 2 and 3) within the RM 0-4.8 region. Thus, this was the reason for using the RM 0-4.8 region in the uncertainty analysis.

Table D-3. Zones used for quantitative comparison of uncertainty simulations.

Zone Number	Reach	Cross-Channel Area
1	1 (RM 0 – 2.2)	Navigation channel
2	1 (RM 0 – 2.2)	East bench
3	1 (RM 0 – 2.2)	West bench
4	2 (RM 2.2 – 4.0)	Navigation channel
5	2 (RM 2.2 – 4.0)	East bench
6	2 (RM 2.2 – 4.0)	West bench
7	3 (RM 4.0 – 4.8)	Navigation channel
8	3 (RM 4.0 – 4.8)	East bench
9	3 (RM 4.0 – 4.8)	West bench

The top panel on each of these figures presents comparisons of the area-averaged bed elevation change, which was calculated using:

$$\delta z_K = (1/N)\, \Sigma\, \Delta z_{K,i,j} \qquad \text{(D-3)}$$

where $\Delta z_{K,i,j}$ is bed elevation change during simulation K at grid cell (i,j), N is the total number of grid cells and the summation ranges from 1 to N. The bottom panel on Figures D-80 through D-88 presents comparisons of the difference ratio of bed elevation change, which was calculated as follows. The ratio difference in bed elevation change at grid cell (i,j) between simulation K and the base-case simulation is:

$$R_{K,i,j} = (\Delta z_{K,i,j} - \Delta z_{BC,i,j}) / \Delta z_{BC,i,j} \qquad \text{(D-4)}$$

where $\Delta z_{BC,i,j}$ is bed elevation change during the base-case simulation at grid cell (i,j). The average difference ratio for simulation K is:

$$R_K = (1/N) \Sigma R_{K,i,j} \quad \text{(D-5)}$$

The values of R_K for the uncertainty simulations are compared in the bottom panel of Figures D-80 through D-88.

Examination of Figures D-80 through D-88, in conjunction with the results presented in Figures D-56 through D-79, produces the following conclusions: 1) upstream sediment load and class 1A/1B settling speed have relatively large effects on the results; 2) erosion rate parameters, effective bed roughness, and class 2/3 particle diameter have relatively small effects on the results; and 3) none of the 32 parameter sets produces results that clearly and definitively correspond to lower- and/or upper-bounds.

However, the quantitative results shown in Figures D-80 through D-88 allow the determination of two parameter sets that correspond to "ultimate" lower- and upper-bound results, corresponding to simulations 6 and 16, respectively. The selection of these two simulations is somewhat subjective because neither parameter set produces minimum or maximum area-averaged bed elevation changes in all nine zones, but these two simulations are consistently at or near the lower- and upper-bounds in all of the zones. A summary of the bounding parameter values for these two simulations is given in Table D-4, which shows that the two inputs with the most effect on model results (i.e., upstream sediment load and class 1A/1B settling speed) are both set at the limiting values for the ultimate bounding simulations. These two simulations have the same bounds for the other three inputs.

Table D-4. Parameter sets for ultimate lower- and upper-bound simulations.

Model Parameter	Ultimate Lower-Bound Parameter Set	Ultimate Upper-Bound Parameter Set
Upstream sediment load	Lower	Upper
Class 1A/1B settling speed	Lower	Upper
Erosion rate parameters	Lower	Lower
Effective bed roughness	Upper	Upper
Class 2/3 particle diameter	Upper	Upper

Comparisons of the ultimate bounding simulations to the base-case results in the navigation channel, east bench, and west bench are shown in Figures D-89, D-90, and D-91, respectively. Generally, the lower- and upper-bound results are less than and greater than the base-case results, as is expected. However, there are small areas in the LDW where the base-case results are outside of the envelope generated by the ultimate bounding simulations. This characteristic of the analysis demonstrates the importance of non-linear effects related to deposition and erosion processes in the LDW. Thus, sediment transport in the system does not react linearly or uniformly to perturbations in model inputs.

The non-linear effects of changes in model inputs are further illustrated in Figures D-92 through D-97. Spatial distributions of bed elevation changes for the ultimate lower-bound and base-case simulations are presented in Figures D-92 through D-94. These maps show that, generally, bed elevation change decreases for the lower-bound parameter set, as would be expected. However, areas of increased bed elevation change, relative to the base-case simulation, occur, particularly between RM 2.7 and 4.0 (i.e., Reach 2). Spatial distributions of bed elevation changes for the ultimate upper-bound and base-case simulations are presented in Figures D-95 through D-97. Increases in bed elevation change for the upper-bound simulation, relative to the base-case, occurred in most of the LDW, with small areas of predicted decreases near RM 3.1 and 3.7.

Sediment mass balances for the base-case, ultimate lower- and upper-bound simulations for the 6-year period are presented in Figures D-98, D-99, and D-100, respectively. These results show that the trapping efficiencies for the lower- and upper-bound simulations decreased and increased, respectively, with respect to the base-case trapping efficiency. The relative changes in trapping efficiency for the bounding simulations are consistent with changes in the class 1A/1B settling speed; decreasing/increasing settling speed causes a decrease/increase in trapping efficiency.

Comparisons of predicted net deposition mass in the three reaches between the ultimate bounding and base-case simulations aid in quantifying the differences between the bounding parameter sets. The relative decreases and increases in net deposition mass in Reaches 1, 2, and 3, with respect to the base-case results, are tabulated in Table D-5. Thus, differences in predicted net deposition mass between the ultimate lower- and upper-bound simulations in Reaches 1, 2, and 3 range between factors of 5 and 8.

Table D-5. Relative change in net deposition mass with respect to base-case results.

Reach	Relative Change in Net Deposition Mass: Ultimate Lower-Bound Parameter Set (%)	Relative Change in Net Deposition Mass: Ultimate Upper-Bound Parameter Set (%)
1	33	220
2	37	310
3	47	220

The relatively large differences in predicted net deposition mass between the ultimate lower- and upper-bound simulations, in conjunction with a relatively large bounding envelope around the base-case results (see Figures D-89 through D-91), raises the following question: do the ultimate bounding parameter sets produce realistic results? That is, are the ultimate bounding results consistent with the calibration data? It is possible that the ultimate bounding parameter sets yield results that may be judged as unacceptable with respect to model calibration.

To determine which bounding parameter sets produce realistic results (i.e., acceptable with respect to model calibration), the second method used in the spatial-scale analysis (see Section D.5) was applied to the uncertainty simulations. The results of the 32 spatial-scale analyses for the uncertainty simulations are shown in Figures D-101 through D-132. For comparison purposes, the base-case results for spatial-scale analysis (6-year simulation period) are included in these figures. The objective of this evaluation was to use a quantitative approach for comparing the accuracy of the uncertainty simulations with respect to each other, as well as to the base-case simulation. The results for the ultimate lower- and upper-bound analyses are shown in Figures D-106 and D-116, respectively. These figures demonstrate that the ultimate bounding parameter sets yield results that are significantly more inaccurate than other uncertainty simulations and, also, the base-case simulation. Thus, the ultimate bounding simulations should not be considered to be acceptable with respect to model calibration.

Examination of 32 spatial-scale analyses for the uncertainty simulations suggests that these results may be separated into five broad categories based on the following ranges of absolute difference in NSR: 1) greater than +2 cm/yr; 2) +1 to +2 cm/yr; 3) 0 to +1 cm/yr; 4) -1 to 0 cm/yr; and 5) -2 to -1 cm/yr. The simulations falling into these five categories are listed in Table D-6. Included in this table are the bounding limits for the two model inputs that have relatively large effects on the results (i.e., upstream sediment load and class 1A/1B settling speed). The ultimate bounding simulations (i.e., simulations 6 and 16) are in the greater than +2 cm/yr and -2 to -1 cm/yr categories; these two categories have both model inputs set at either the lower or upper bound values. Thus, parameter sets that produce acceptable results with respect to model calibration must have bounding limits of the upstream sediment load and class 1A/1B settling speed set at opposite ends of their respective limits (i.e., lower-upper or upper-lower). Table D-6 shows that simulations in the 0 to +1 cm/yr and +1 to +2 cm/yr categories correspond to upper- and lower-bound values of the upstream sediment load and class 1A/1B settling speed, respectively. Similarly, simulations in the -1 to 0 cm/yr category correspond to lower- and upper-bound values of the upstream sediment load and class 1A/1B settling speed, respectively. An examination of the absolute difference results for the simulations in the -1 to 0 cm/yr category indicates that simulation 20 is the closest simulation to the lower limit (i.e., -1 cm/yr) of this category. Thus, the parameter set for simulation 20 was selected as the realistic lower-bound set. For symmetry, the realistic upper-bound parameter set was selected from simulations with absolute difference results close to the +1 cm/yr value. Using this criterion, simulation 9 was selected as the realistic upper-bound set. The parameter sets for the realistic bounding simulations are presented in Table D-7.

Table D-6. Categories of absolute NSR difference for uncertainty simulations.

Range of Absolute NSR Difference (cm/yr)	Upstream Sediment Load Bound	Class 1A/1B Settling Speed Bound	Simulations
Greater than +2	Upper	Upper	11, 12, 15, 16, 27, 28,31,32
+1 to +2	Upper	Lower	9, 13, 25, 29
0 to +1	Upper	Lower	10, 14, 26, 30
-1 to 0	Lower	Upper	3, 4, 7, 8, 19, 20, 23, 24
-2 to -1	Lower	Lower	1, 2, 5, 6, 17, 18, 21, 22

Table D-7. Parameter sets for realistic lower- and upper-bound simulations.

Model Parameter	Realistic Lower-Bound Parameter Set	Realistic Upper-Bound Parameter Set
Upstream sediment load	Lower	Upper
Class 1A/1B settling speed	Upper	Lower
Erosion rate parameters	Upper	Lower
Effective bed roughness	Lower	Lower
Class 2/3 particle diameter	Upper	Upper

Spatial distributions of bed elevation changes for the realistic lower-bound and upper-bound simulations are presented in Figures D-133 through D-138. These maps show similar results and patterns as were found for the ultimate bounding bed elevation changes, as discussed above for Figures D-92 through D-97. The primary difference between the results for the ultimate and realistic analyses is that the realistic results are less spatially variable than the ultimate results.

Sediment mass balances for the base-case, realistic lower- and upper-bound simulations for the 6-year period are presented in Figures D-139, D-140, and D-141, respectively. These results show that the trapping efficiencies for the lower- and upper-bound simulations increased and decreased, respectively, with respect to the base-case trapping efficiency. As discussed for the ultimate bound mass balances, the relative changes in trapping efficiency are directly related to changes in class 1A/1B settling speed; decreasing/increasing settling speed causes a decrease/increase in trapping efficiency. The relative decreases and increases in net deposition mass in Reaches 1, 2 and 3, with respect to the base-case results, are tabulated in Table D-8. Thus, differences in predicted net deposition mass between the realistic lower- and upper-bound simulations in Reaches 1, 2, and 3 ranged between factors of 2 and 5, whereas the ultimate bounding results ranged between factors of 5 and 8.

Table D-8. Relative change in net deposition mass with respect to base-case results.

Reach	Relative Change in Net Deposition Mass: Realistic Lower-Bound Parameter Set (%)	Relative Change in Net Deposition Mass: Realistic Upper-Bound Parameter Set (%)
1	74	130
2	39	190
3	53	190

LIST OF FIGURES CITED IN APPENDIX D

APPENDIX E
DETAILS OF SEDIMENT BED STABILITY ANALYSIS

E.1 SPECIFICATION OF BOUNDARY CONDITIONS AND MODEL INPUTS

The high-flow event frequency analyses conducted during the STAR study used daily-average flow rates measured in the Green River (Windward and QEA 2007) instead of instantaneous measurements. However, flow rate fluctuates above and below the daily-average value during high-flow conditions. Of particular interest for the bed stability analysis is the relationship between the peak and daily-average flow rates during a high-flow event. Available discharge data collected at the Green River gauging station were used to evaluate the relationship between peak and daily-average flow rates during high-flow events. The relationship of peak flow rates during high-flow conditions (i.e., flow rate greater than 2-year discharge) to daily-average flow rates on the day that the peak flow occurred is shown in Figure E-1. The ratio of peak flow to daily-average flow (Q_{peak}:Q_{ave}) as a function of daily-average flow rate is presented in Figure E-2. The cumulative frequency distribution of the Q_{peak}:Q_{ave} ratio is shown in Figure E-3. These results indicate that peak flow rate is generally less than 10% greater than the daily-average flow rate.

As discussed in Section 3.2, hydrographs for high-flow events evaluated in this analysis were developed by linearly adjusting the measured daily-average flow rates during the 1975 event so that the peak daily-average flow rate during the high-flow event corresponded to the appropriate values for the 2-, 10-, and 100-year high-flow events. The 1975 high-flow event was chosen for the bed stability analysis because it is the largest high-flow event to occur between 1960 and 2006. In addition, the peak of the 1975 high-flow event coincided with spring tide conditions; this situation has been shown to maximize bed shear stresses in the LDW (Windward and QEA 2007). Due to USGS data retention policies, daily-average flow rate data are the only flow rate data available for the 1975 high-flow event. Thus, it was not possible to develop a high-flow event hydrograph that specified river discharge on an hourly basis. However, the above analysis indicates that use of daily-average flow rate results in an under-prediction of the peak flow rate of less than 10%, which is comparable to the uncertainty in the discharge measurements at this USGS gauging station. Thus, use of daily-average flow rates to specify the hydrograph for a high-flow event is a reasonable and acceptable approximation. The resulting hydrographs for the 2- and 10-year high-flow events are shown in Figures E-4 and E-5, respectively.

Sediment loads at the upstream boundary for the high-flow events were estimated using the methods described in Section B.2; both suspended and bed loads were specified at the upstream boundary. Total sediment loads for the 2-, 10-, and 100-year high-flow events are listed in Table E-1. The relative portion of the total load input as bedload is also presented in this table. The bedload content decreases with increasing flow rate, as shown in Figure B-6. The average annual total load at the upstream boundary for the 30-year period discussed in Section 4 was 207,000 MT/yr, with 76% and 24% of the total load being composed of suspended and bedload, respectively. The effects of high-flow events on sediment loading to the LDW from the Green River are evident when the loads in Table E-1 are compared to the average annual load. For example, the total load for a 100-year high-flow event is about 60% to 70% greater than the average annual total load. Classes 1A, 1B, and 2 composed 66, 17, and 17% of the suspended sediment load in all simulations.

Table E-1. Upstream sediment loading during high-flow events.

Return Period of High-Flow Event (years)	Peak Flow Rate (cfs)	Total Sediment Load (MT)	Bedload Portion of Total Load (%)
2	8,400	124,600	23
10	10,800	251,500	20
100	12,000	339,600	18

The initial conditions for sediment bed composition were the same as used for the 21-year calibration (Section 2) and 30-year external load analysis (Section 4) simulations. A description of the method for specifying the spatial distribution of initial bed composition is presented in Appendix B. All other model parameters were set at the same values as used in the calibration simulation.

E.2 RESULTS OF SEDIMENT BED STABILITY ANALYSIS

The accuracy of model predictions of NSR values over multi-year periods was evaluated using empirical estimates (see Section 2 and Appendix D). The accuracy of model predictions of bed scour during high-flow events was not explicitly determined due to a lack of data. However, the effects of bed scour were implicitly included in the NSR accuracy analysis because several high-flow events, including a 50-year high-flow event, occurred during the 30-year simulation period. Thus, the accuracy of model predictions during high-flow events cannot be quantified. However, the appropriate precision of the high-event simulations (i.e., number of significant figures used to express the results) was estimated to be two significant figures (e.g., 4.5 cm, 13 cm) because use of one significant figure would not be useful for comparing the results of different high-flow events and the use of three significant figures would not be appropriate based on the authors' modeling experience.

As discussed in Appendix A, erosion rate, and therefore bed scour, is dependent on skin friction shear stress. As the first step in evaluating LDW bed stability, spatial distributions of maximum skin friction shear stress during the 2-, 10- and 100-year high-flow events were examined (Figures E-6 through E-8). As expected, maximum shear stress values increase with increasing river flow rate, with the highest shear stresses occurring in Reaches 2 and 3.

A similar shear stress analysis was conducted during the STAR study (Windward and QEA 2007). Comparison of the results shown in Figures E-6 through E-8 to the STAR results shows that the present skin friction shear stress values are higher than the STAR values. For maximum shear stress values during a 100-year high-flow event, the present results range from less than 0.01 to about 3 Pa greater than the results from the STAR study, with the median increase being 0.07 Pa. The reason for this difference is the method used to calculate near-bed current velocity. In the STAR study, the method to extract and calculate near-bed current velocity involved spatial and temporal averaging that was different from the method used in the STM study.

Spatial distributions of maximum bed scour during 2- and 10-year high-flow events are shown in Figures E-9 and E-10, respectively. The locations of the maximum depth of bed scour in cohesive and non-cohesive bed areas are denoted on these figures. Maximum scour depths in the cohesive bed area occur in Reach 2, with maximum values of about 15 and 20 cm during the 2- and 10-year high-flow events, respectively. For comparison, the maximum bed scour during the 100-year high-flow event was about 22 cm (Figure 3-5).

Comparisons of the areal extents of net erosion and net erosion depth greater than 10 cm for the three high-flow events are provided in Table E-2, along with maximum scour depths in the cohesive bed area. Generally, maximum scour depths are about 1 cm or less deeper than the net erosion depth. Maximum scour depths, in cohesive and non-cohesive bed areas, are determined using a numerical algorithm that searches for and tracks the maximum scour depths in each bed type during the course of a high-flow event simulation. The cohesive bed area, which extends between RM 0.0 and the upper turning basin near RM 4.3, has maximum scour depths that increase with increasing flow rate, which is a result of increasing bed shear stresses. The non-cohesive bed area, which is confined to a relatively small portion of the LDW in the vicinity of the upper turning basin, has maximum bed scour depths of 10, 17, and 21 cm for the 2-, 10-, and 100-year high-flow events, respectively. The areal extent of net erosion greater than 10 cm ranging between 2 and 22 acres for 2- to 100-year high-flow events, with most of that area occurring in Reach 2.

Table E-2. Predicted bed scour during high-flow events.

Return Period of High-Flow Event (years)	Maximum Bed Shear Stress (Pa)	Maximum Net Erosion Depth in Cohesive Bed (cm)	Maximum Bed Scour in Cohesive Bed (cm)	Areal Extent of Net Erosion (acres)	Areal Extent of Net Erosion Greater than 10 cm (acres)
2	2.0	14	15	62 (16%)	2 (0.5%)
10	3.0	19	20	69 (17%)	15 (4%)
100	3.4	21	22	70 (18%)	22 (5.5%)

Note: (X%) is relative portion of total LDW surface area (406 acres).

The results presented in Table E-2 indicate that the effects of high-flow events with return periods of 10 and 100 years are not significantly different. This similarity is primarily caused by two factors. First, the erodibility of sediment deeper than 15 cm is much less than the erodibility of sediment in the top 15 cm of the bed, which limits scour depths during high-flow events with return periods greater than 10 years. Second, the peak flow rate during a 10-year high-flow event is only about 10% lower than during a 100-year high-flow event (see Table 3-1).

Overall sediment mass balances for the LDW (RM 0.0 to 4.8) for 2-, 10-, and 100-year high-flow events are shown in Figures E-11 and E-12. The LDW is net depositional on a global basis during these three high-flow events. Relatively small amounts (2% or less) of incoming class 1A sediment (i.e., less than 10 μm diameter) are deposited in the LDW during high-flow events, whereas large portions of the other three size classes are deposited. Trapping efficiency is the portion of the incoming sediment load that is deposited (i.e., trapped) in the LDW. Trapping efficiencies for the four size classes, as well as the overall value, for the different high-flow events are listed in Table E-3. Mass balances for Reaches 1, 2 and 3 for the 2-, 10-, and 100-year high-flow events are presented in Figures E-13 through E-15, respectively. These results indicate that Reach 2 is net erosional for 2-year and greater high-flow events, and that Reaches 1 and 3 are net depositional, even during a 100-year high-flow event.

Table E-3. Trapping efficiencies for bed stability simulations.

Return Period of High-Flow Event (years)	Class 1A (%)	Class 1B (%)	Class 2 (%)	Class 3 (%)	Overall (%)
2	2	57	100	100	43
10	0.2	46	98	100	39
100	< 0.1	42	98	100	38

Less net erosion occurs during events with return periods of 2 and 10 years than during the 100-year high-flow event as a result of the lower flow rates during the more frequent events. Comparisons of the relative area of net erosion and total mass of eroded sediment for the three high-flow events are presented in Figures E-16 and E-17, respectively. On those figures, the area of net erosion and mass of eroded of sediment for the 2- and 10-year high-flow events were normalized with respect to the values for the 100-year high-flow event (i.e., 70 acres and 69,900 metric tons). Relative differences between 2-, 10-, and 100-year high-flow events in the mass of eroded sediment are larger than relative differences in the area over which net erosion occurs. About 2.5 times more sediment mass is eroded during a 100-year high-flow event than during a 2-year high-flow event, while the difference between 2-year and 100-year high-flow events in the areal extent of net erosion is less than 20%.

Additional insights about sediment bed dynamics in areas where net erosion occurs during a high-flow event are gained by examining time series of the following model variables at specific locations (grid cells): near-bed velocity, bed shear stress, total suspended sediment concentration, bed elevation, erosion flux, and deposition flux. Grid cells at five locations in Reach 2 (i.e., near RM 2.85, 2.96, 3.10, 3.60, 3.80) were chosen for this evaluation (see Figure E-18 for specific locations). Time series of the six model variables during the 100-year high-flow event at the five grid cell locations are shown in Figures E-19 through E-23 respectively.

These figures illustrate several sediment transport processes during a high-flow event. First, most of the bed scour occurs during the period of the rising limb of the inflow hydrograph and peak flow in the Green River (i.e., days 4, 5, and 6). During this 3-day period, bed scour occurs episodically during ebb tide, which is when current velocities and bed shear stresses are relatively high. Corresponding increases, or spikes, in suspended sediment concentration occur during the short bursts of bed erosion. Second, bed armoring, particle-shielding, and probability of suspension processes, in combination with bed erosion properties that change with depth in the bed, limit the amount of erosion that occurs during the period of peak flow in the river. Maximum depth of bed scour is typically reached between days 4 and 6. Third, net deposition of sediment generally occurs during the falling limb of the hydrograph, which results in net erosion at the end of the event being less than the depth of maximum bed scour.

The effects of the bed model structure on predicted bed scour depth is evident in Figures E-19 through E-23. As discussed in Section B.4, 5-cm layers are used to specify the vertical distribution of erosion rate parameters in the bed, with each layer having a unique set of parameters assigned to it. This approach produces discontinuities in erosion rate parameters at bed depths of 5, 10, 15, and 20 cm. Thus, sharp gradients in erosion rate parameters can occur at these specific bed depths, which may result in a significant decrease in erosion rate/flux as bed elevation moves from one layer to the next deeper layer. The effects of this characteristic of the numerical algorithm are evident at several of the five locations discussed above. For example, at RM 2.96 (Figure E-20), an order-of-magnitude or more decrease in maximum erosion flux occurs between days 5 and 6, even though maximum bed shear stress only decreases by about 10%-20%. Examination of the bed elevation change during this period shows that the bed model transitions from the 15-20 cm layer to the 20-25 cm layer, with a concomitant change in erosion rate parameters and the subsequent large decrease in erosion flux.

Detailed views of bed shear stress, bed elevation change, and erosion/deposition fluxes during the first 10 days of the 100-year high-flow event at the five locations are shown in Figures E-24 through E-28. These figures provide a clearer illustration of the relationship between bed shear stress and erosion flux, with the effects of ebb (high shear stress) and flood (low shear stress) tide conditions on erosion flux evident. Bed armoring, particle-shielding, and probability of suspension processes produce a non-linear relationship between erosion flux and peak bed shear stress during ebb tide; this non-linear relationship is a major factor that controls the depth of bed scour. Temporal variations in erosion flux at the five locations are discontinuous because of bed shear stress values decreasing below a critical value, at which point the erosion flux is zero until the critical value is exceeded. Deposition fluxes are temporally variable and range over one or more orders-of-magnitude. Typically, deposition fluxes peak at about the same time during a tidal cycle that erosion fluxes peak, which corresponds to high bed shear stress values. This characteristic appears to be counter-intuitive but is explained as follows: 1) erosion flux increases as bed shear stress increases during a tidal cycle; 2) near-bed suspended sediment concentration increases as erosion flux increases (e.g., Figure E-19); and 3) deposition flux increases as near-bed suspended sediment concentration increases, even though bed shear stress is relatively high (i.e., 2-3 Pa), because the probability of deposition for sediment classes 2 and 3 ranges between about 0.05 and 0.3 in this shear stress range.

E.3 DEVELOPMENT OF MODEL INPUTS FOR SENSITIVITY ANALYSIS

The objective of the sensitivity analysis was to evaluate the effects of uncertainty in model inputs on high-flow event simulations. The following model inputs were varied during the sensitivity analysis: erosion rate parameters; upstream sediment load; effective particle diameter (D_{90}); settling speed of class 1A and 1B; particle-shielding factor; effect of tidal cycle conditions (i.e., neap tide during peak river discharge); and duration of flow rate in Green River. A summary of the adjustments for the first five parameters is provided below. In addition to these model inputs, a large number of other model inputs could have been incorporated into the sensitivity analysis, including: number of sediment size classes; initial conditions for bed composition; spatial distribution of bed properties; and active-surface layer thickness. Selection of the seven model inputs included in the sensitivity analysis was guided by experience with model performance, including extensive diagnostic evaluations, that was gained during the model development and calibration/validation process. This experience, along with discussion among the members of the STM group, was used to determine the group of model inputs that was judged to have the most potential effect on the high-flow event simulations.

Erosion Rate Parameters

Lower-bound erosion rate parameters tend to decrease predicted bed scour depths, while upper-bound erosion rate parameters tend to increase bed scour depths. For layer 1 (0-5 cm), the upper- and lower-bound erosion rate parameters were specified based on a visual inspection of the erosion rate relationships (i.e., E_{gross} versus τ_{sf}) for the 18 Sedflume cores. The upper- and lower-bound erosion rate curves corresponded to cores 14 and 15, respectively. For layers 2 through 5 (i.e., deeper than 5 cm), the upper- and lower-bound parameters were specified using upper- and lower-bound erosion rate curves for the core groups within each layer. Summaries of the parameters are provided in Tables E-4 and E-5.

Table E-4. Lower-bound erosion rate parameters.

Layer Depth (cm)	Core/Core Group Used to Specify Parameters	A	n	Critical shear stress (Pa)
0 – 5	Core 15	9.4×10^{-4}	1.8	0.29
5 – 10	Core group 4	2.2×10^{-5}	3.3	1.6
10 – 15	Core group 1	3.5×10^{-5}	3.2	1.4
15 – 20	Core group 1	4.2×10^{-5}	2.8	1.4
20 – 25	Core group 2	4.7×10^{-6}	2.5	1.3

Table E-5. Upper-bound erosion rate parameters.

Layer Depth (cm)	Core/Core Group Used to Specify Parameters	A	n	Critical shear stress (Pa)
0 – 5	Core 14	8.0×10^{-3}	2.4	0.16
5 – 10	Core group 3	2.4×10^{-3}	2.9	0.34
10 – 15	Core group 3	2.5×10^{-4}	4.0	0.79
15 – 20	Core group 3	8.6×10^{-4}	3.1	0.49
20 – 25	Core group 1	4.9×10^{-5}	3.3	1.3

Upstream Sediment Load

Decreasing (lower-bound) sediment load tends to increase predicted bed scour depths and increasing (upper-bound) sediment load tends to decrease bed scour depths. The upstream sediment load was increased and decreased by a factor-of-two when compared to the base-case simulation for the 100-year high-flow event. The composition of the load was not changed, only the magnitude. The loads for the sensitivity simulations are compared to the base-case loads in Table E-6.

Table E-6. Green River sediment loads.

Sensitivity Simulation	Suspended Load (metric tons)	Bedload (metric tons)	Total Load (metric tons)
Base case	277,700	61,900	339,600
Lower bound	138,900	30,900	169,800
Upper bound	555,400	123,700	679,100

Effective Bed Roughness (D_{90})

Decreasing (lower-bound) effective bed roughness causes a decrease in bed shear stress, which tends to decrease predicted bed scour depths. Increasing (upper-bound) effective bed roughness causes an increase in bed shear stress, which tends to increase bed scour depths. The effective bed roughness (D_{90}) was increased and decreased by a factor-of-two when compared to the values used in the base-case simulation for the 100-year high-flow event (Table E-7).

Table E-7. Effective bed roughness (μm).

Sensitivity Simulation	Navigation Channel	East Bench Area	West Bench Area
Base case	360	940	790
Lower bound	180	470	395
Upper bound	720	1,880	1,580

Settling Speed of Class 1A and 1B

Decreasing (lower-bound) class 1A/1B settling speeds will decrease deposition during a high-flow event, which will tend to increase predicted bed scour depths. Increasing (upper-bound) class 1A/1B settling speeds will increase deposition during a high-flow event, which will tend to decrease bed scour depths. The settling speeds of class 1A and 1B sediment were increased and decreased by a factor-of-two when compared to the values used in the base-case simulation for the 100-year high-flow event (see Table E-8). The settling speeds were adjusted by changing the effective particle diameters for the two size classes.

Table E-8. Effective particle diameters and settling speeds for class 1A and 1B.

Sensitivity Simulation	Class 1A: Effective Diameter (μm)	Class 1A: Settling Speed (m/day)	Class 1B: Effective Diameter (μm)	Class 1B: Settling Speed (m/day)
Base case	5	1.3	20	21
Lower bound	3.5	0.65	14	10
Upper bound	7	2.6	28	41

Particle-Shielding Factor

The particle-shielding factor (see Appendix A for description) is used to reduce the erosion rate of the finer sediment in the bed, primarily classes 1A and 1B. By setting the exponent on the particle-shielding factor to zero, the effect of the particle-shielding factor on erosion rate is removed and bed erosion is maximized.

E.4 RESULTS OF SENSITIVITY ANALYSIS

Comparisons of maximum values of predicted net erosion and maximum scour depths during the 100-year high-flow event for the sensitivity and base-case simulations in cohesive and non-cohesive bed areas are presented in Tables E-9 and E-10, respectively. The maximum scour depths listed in these tables are representative of a localized scour depth for a particular simulation and may not be indicative of the overall effect of a specific input on model results. Other measures that need to be considered when comparing sensitivity simulation results include areal extent of erosion and mass of eroded sediment (see Section 3.3); these measures provide improved understanding of the relative effects of different model inputs on high-flow event predictions.

Table E-9. Net/maximum bed scour depths for cohesive bed areas: 100-year event.

Model Input	Lower-Bound Maximum: Net/Maximum Scour Depth (cm)	Upper-Bound Maximum: Net/Maximum Scour Depth (cm)	Base-Case Maximum: Net/Maximum Scour Depth (cm)
Erosion rate	11/13	35/36	21/22
Upstream sediment load	23/24	19/23	21/22
Effective bed roughness	18/20	38/39	21/22
Class 1A/1B settling speed	21/22	21/24	21/22
Particle-shielding factor	NA	63/64	21/22
Neap tide	NA	16/16	21/22
Duration of peak flow rate	NA	24/24	21/22

Table E-10. Net/maximum bed scour depths for non-cohesive bed areas: 100-year event.

Model Input	Lower-Bound Maximum: Net/Maximum Scour Depth (cm)	Upper-Bound Maximum: Net/Maximum Scour Depth (cm)	Base-Case Maximum: Net/Maximum Scour Depth (cm)
Erosion rate	20/20	20/21	20/21
Upstream sediment load	21/25	11/12	20/21
Effective bed roughness	12/13	12/27	20/21
Class 1A/1B settling speed	19/26	21/22	20/21
Particle-shielding factor	NA	28/29	20/21
Neap tide	NA	14/17	20/21
Duration of peak flow rate	NA	30/40	20/21

Spatial distributions of maximum bed scour for lower- and upper-bound erosion rate parameters are presented in Figures E-29 and E-35, respectively. These distributions are similar to the net erosion map for the lower- and upper-bound parameters presented in Figures 3-6 and 3-7. Additional insights about model sensitivity to erosion rate parameters are provided through examination of temporal variations in bed shear stress, bed elevation, and bed flux at the five locations shown in Figure E-18. The lower-bound erosion rate parameter results are presented in Figures E-30 through E-34, with the upper-bound results provided in Figures E-36 through E-40. Included on these figures are comparisons to the base-case results (i.e., base-case results are presented as a dotted line).

Generally, the upper-bound erosion rate parameters produce maximum erosion fluxes that are about an order-of-magnitude greater than maximum erosion fluxes for the lower-bound parameters. The lower-bound parameters typically yield lower erosion fluxes than the base-case parameters, but the decreases are not uniform due to the non-linearity of the bed scour processes. At all five locations, bed elevation change at the end of the 10-day period was less for the lower-bound parameters than for the base-case parameters (see Figures E-30 through E-34). For the upper-bound parameters, erosion fluxes were generally higher than for the base-case parameters, but at specific times at certain locations, the base-case erosion flux was greater than the upper-bound erosion flux (e.g., at RM 2.96 on day 4-5, see Figure E-37). These results emphasize the importance of non-linear interactions between surface-layer bed composition (i.e., bed armoring) and vertical variations in erosion rate parameters on erosion flux and bed scour. The upper-bound parameters resulted in deeper bed scour than for the base-case parameters at four of the five locations. At the RM 2.96 location, the bed elevation change at the end of the 10-day period was the same for both the upper-bound and base-case simulations, even though the temporal pattern was different during this period (Figure E-37). With the final depth of scour at this location being about 20 cm for both simulations, it is evident that a significant change in erosion properties between the 15-20 and 20-25 cm layers in the bed model was the primary cause of this result.

Spatial distributions of net erosion and maximum bed scour depth for lower-bound upstream sediment loading are shown in Figures E-41 and E-42, respectively. Time-histories of bed fluxes for the lower-bound upstream sediment loading simulations at the five locations are presented in Figures E-43 through E-47. The results on these figures show that decreasing the upstream sediment load produced decreases in deposition flux, but with minimal differences in bed elevation change. Spatial distributions of net erosion and maximum bed scour depth for upper-bound upstream sediment loading are shown in Figures E-48 and E-49, respectively. Time-histories of bed fluxes for the upper-bound upstream sediment loading simulations at the five locations are presented in Figures E-50 through E-54. Similar to the lower-bound results, increasing the upstream sediment load produced increases in deposition flux, but with minimal differences in bed elevation change.

Spatial distributions of net erosion and maximum bed scour depth for lower-bound effective bed roughness are shown in Figures E-55 and E-56, respectively. Time-histories of bed fluxes for the lower-bound effective bed roughness simulations at the five locations are presented in Figures E-57 through E-61. Decreasing the effective bed roughness causes a decrease in bed shear stress, which reduces erosion flux and depth of bed scour (relative to the base-case results). Spatial distributions of net erosion and maximum bed scour depth for upper-bound effective bed roughness are shown in Figures E-62 and E-63, respectively. Time-histories of bed fluxes for the upper-bound effective bed roughness simulations at the five locations are presented in Figures E-64 through E-68. Increasing the effective bed roughness causes bed shear stress to increase, which increases erosion flux and depth of bed scour.

Spatial distributions of net erosion and maximum bed scour depth for lower-bound class 1A/1B settling speed are shown in Figures E-69 and E-70, respectively. Time-histories of bed fluxes for the lower-bound class 1A/1B settling speed simulations at the five locations are presented in Figures E-71 through E-75. Decreasing the class 1A/1B settling speed resulted in decreases in deposition flux, but with minimal differences in bed elevation change. Spatial distributions of net erosion and maximum bed scour depth for upper-bound class 1A/1B settling speed are shown in Figures E-76 and E-77, respectively. Time-histories of bed fluxes for the upper-bound class 1A/1B settling speed simulations at the five locations are presented in Figures E-78 through E-82. Similar to the lower-bound results, increasing the class 1A/1B settling speed produced increases in deposition flux, but with minimal differences in bed elevation change.

Spatial distributions of net erosion and maximum bed scour depth for the effect of the particle-shielding factor removed are shown in Figures E-83 and E-84, respectively. Time-histories of bed fluxes for the effect of the particle-shielding factor removed at the five locations are presented in Figures E-85 through E-89. Typically, removing the effects of the particle-shielding factor resulted in an increase in bed scour depth at these five locations, which was primarily due to increases in erosion flux relative to the base-case simulation. However, similar to the upper-bound erosion parameter simulation, non-linear interactions between the different bed erosion processes (e.g., bed armoring, vertical variation in erosion properties) resulted in periods when the base-case erosion flux was greater than the flux with particle-shielding effects removed (e.g., days 6 through 9 at RM 2.85, Figure E-85).

The 100-year high-flow event hydrograph and tidal elevations for the neap tide sensitivity simulation are shown in Figure E-90. These flow and tidal boundary conditions were created by adjusting the timing of the tidal forcing relative to the original 100-year high-flow event hydrograph. Spatial distributions of net erosion and maximum bed scour depth for the neap tide simulation are shown in Figures E-91 and E-92, respectively. Time-histories of bed fluxes for the neap tide simulation at the five locations are presented in Figures E-93 through E-97. Generally, bed shear stresses during the neap tide simulation are less than during the base-case simulation, which results in lower erosion fluxes and decreases in bed scour depth. However, there are significant differences between the temporal patterns of the erosion and deposition fluxes for the neap tide and base-case simulations.

The hydrograph for the extended (8-day) duration of peak flow rate and tidal elevations are shown in Figure E-98. The original 100-year high-flow event hydrograph was adjusted by holding the peak flow rate constant for 8 days. Spatial distributions of net erosion and maximum bed scour depth for the extended peak discharge simulation are shown in Figures E-99 and E-100, respectively. Time-histories of bed fluxes for the neap tide simulation at the five locations are presented in Figures E-101 through E-105. Extending the duration of the peak flow rate had minimal effect on the temporal patterns of bed shear stress, bed elevation change, and erosion/deposition fluxes at the five locations.

The effects of model parameter variation on bed elevation change were evaluated through comparisons of results for the base case and sensitivity simulations at each grid cell that had net erosion during the base-case simulation. The comparisons are presented in Figures E-106 through E-127, which show one-to-one comparisons of the base-case and sensitivity results. These results indicate that model sensitivity, with respect to one-to-one comparisons, is within a factor-of-two of the base-case results (i.e., sensitivity results are between 50% lower and 100% greater than base-case results) for these model inputs: lower- and upper-bound upstream sediment load; lower- and upper-bound class 1A/1B settling speed; and 8-day duration of peak flow rate.

Generally, one-to-one comparisons at most grid cells are within a factor-of-two of the base-case results for the other sensitivity simulations. However, outliers exist (i.e., greater than factor-of-two difference with respect to the base-case simulation) for some sensitivity simulations and the following discussion highlights the largest outliers. For lower-bound erosion parameters (Figure E-106), net bed elevation changes in three grid cells are about 75% to 90% lower than base-case results (i.e., about -18 to -20 cm for base-case results and about -2 to -5 cm for sensitivity results). For upper-bound erosion parameters (Figure E-108), net bed elevation changes in three grid cells are about 100% greater than base-case results (i.e., about -15 to -20 cm for base-case results and about -30 to -35 cm for sensitivity results). For lower-bound effective bed roughness (Figure E-114), net bed elevation changes in four grid cells are about 50% to 75% lower than base-case results (i.e., about -13 to -15 cm for base-case results and about -3 to -7 cm for sensitivity results). For upper-bound effective bed roughness (Figure E-116), net bed elevation changes in five grid cells are about 100% greater than base-case results (i.e., about -15 to -20 cm for base-case results and about -32 to -38 cm for sensitivity results). For particle-shielding factor removed (Figure E-122), net bed elevation changes in four grid cells are about 100% to 300% greater than base-case results (i.e., about -15 to -20 cm for base-case results and about -40 to -65 cm for sensitivity results). For neap tide conditions (Figure E-124), net bed elevation changes in seven grid cells are about 75% to 90% lower than base-case results (i.e., about -10 to -15 cm for base-case results and about -2 to -6 cm for sensitivity results). These results, which focus on small spatial scales, indicate that uncertainty due to model input uncertainty at the grid-cell spatial scale is greater than at larger spatial scales.

General trends in the sensitivity results, relative to the base-case results, are as follows: 1) less and more erosion for lower- and upper-bound erosion parameters, respectively; 2) more and less erosion for decreasing and increasing upstream sediment load, respectively; 3) less and more erosion for decreasing and increasing effective bed roughness, respectively; 4) more and less erosion for decreasing and increasing class 1A/1B settling speed, respectively; 5) more erosion when particle-shielding factor is set to zero: 6) less erosion during neap tide conditions; and 7) more erosion for extended duration of the peak flow rate. All of these general trends are consistent with what would be expected given the variation in selected model inputs.

E.5 ADDITIONAL RESULTS FOR 100-YEAR HIGH-FLOW EVENT

Mass balances for the 100-year high-flow event were constructed for the four sediment size classes (see Figures E-128 through E-131). These results show that for class 1A sediment (clay and fine silt, less than 10 μm) during the 100-year high-flow event: a relatively small amount of the upstream sediment load is deposited in the LDW; Reach 2 is net erosional; and Reaches 1 and 3 are net depositional, with more class 1A sediment being deposited in Reach 1 than in Reach 3. For class 1B sediment (medium/coarse silt, 10-62 μm): about 40-45% of the upstream load is deposited in the LDW, with most of that deposition occurring in Reach 1; Reach 2 is net erosional; and Reaches 1 and 3 are net depositional, with more class 1B sediment being deposited in Reach 1 than in Reach 3. For class 2 sediment (fine sand, 62-250 μm): nearly all of the upstream load (98%) is deposited in the LDW, with over half of the incoming load being deposited in Reach 3; and all three reaches are net depositional. For class 3 sediment (medium/coarse sand, 250-2,000 μm): all of the upstream load is deposited in the LDW, with 98% of the incoming load being deposited in Reach 3; and all three reaches are net depositional.

The relative effects of uncertainty in various model inputs on predicted net erosional area and mass during the 100-year high-flow event were compared in Figures 3-8 and 3-9. On those figures, the net erosional areas and masses for the navigation channel and bench areas were normalized to the total values for the RM 0-4.3 region. An alternative method of comparison is shown in Figures E-132 and E-133, where the normalization for each zone is with respect to the base-case value for that zone. While these figures present a different view of the sensitivity simulation results shown in Figures 3-8 and 3-9, the conclusions presented in Section 3.4 are not affected by this alternative method of comparison.

For clarification, the particle-shielding factor is not a single-valued input parameter that is spatially and temporally constant. The particle-shielding factor for sediment size class k (S_k) is defined by Equation A-20, which is repeated here:

$$S_k = (d_k/d_m)^{0.85} \quad \text{for } d_k \le d_m \qquad \text{(A-20)}$$

$$= 1 \quad \text{for } d_k > d_m$$

where d_k is the effective particle diameter of size class k and d_m is the mean particle diameter in the active layer. The maximum value of S_k is one and its minimum value is positive (i.e., greater than zero). The formulation expressed in Equation A-20 is presented in Karim and Kennedy (1981) and Rahuel et al. (1989), and it has been used in various sediment transport models to simulate bed armoring effects in a graded bed. This formulation was not adjusted during model calibration. The value of the particle-shielding factor is dynamic (i.e., temporally variable) and spatially variable because the value of the mean particle diameter in that active layer varies as the composition of this layer changes with time and location. The relationships between the particle-shielding factor and d_k and d_m are shown in Figure A-5. Thus, the particle-shielding factor should be viewed as representing a dynamic physical process in a graded bed (i.e., small particles being shielded by large particles) that affects bed erosion; it should not be viewed as a static input parameter that is adjusted to "tune" model predictions. The effects of the particle-shielding factor on the results of the 100-year high-flow event are most appropriately evaluated using mass eroded as a metric for comparison (see Figures 3-8, 3-9, E-132 and E-133). Over all areas in the

LDW, turning off the particle-shielding factor causes a 32% increase in eroded mass with respect to the base-case simulation, which is less than the effect of uncertainty in erosion rate parameters (77% increase) and peak-flow duration (42% increase). Within the east bench, turning off the particle-shielding factor (26% increase) has less effect than uncertainty in erosion rate parameters (72% increase), effective bed roughness (32% increase) and peak-flow duration (56% increase). Within the west bench, turning off the particle-shielding factor (50% increase) has less effect than uncertainty in erosion rate parameters (130% increase) and upstream load (100% increase), and approximately the same effect as uncertainty in effective bed roughness and peak-flow duration. Within the navigation channel, turning off the particle-shielding factor (24% increase) has less effect than uncertainty in erosion rate parameters (54% increase) and peak-flow duration (28% increase). Even though turning off the particle-shielding factor causes a significant increase in predicted bed scour depth during the 100-year high-flow event at a few isolated locations, the overall effect of the particle-shielding factor on model results is less than the effects of uncertainty in other model inputs.

The results in Table E-2 may be used to quantify the potential effects of uncertainty in peak river flow rate on bed scour depth. First, the relationship between maximum bed shear stress (skin friction) and peak flow rate is shown in Figure E-134. These results show a strong correlation between maximum bed shear stress in the cohesive bed area and peak river flow rate during high-flow events, which may be expressed as:

$$\tau_{sf,max} = 0.087\ (Q_{peak}/1{,}000)^{1.48} \qquad \text{(E-1)}$$

where $\tau_{sf,max}$ is maximum skin-friction shear stress (Pa) and Q_{peak} is peak river flow rate. As discussed in Section E.1, use of daily-average flow rate results in an under-prediction of the peak flow rate of less than 10%. Table E-2 lists the predicted maximum bed scour depth in the cohesive bed for the 2-, 10- and 100-year high-flow events. The relationship between maximum bed scour depth in the cohesive bed and peak river flow rate for these high-flow events is shown in Figure E-135. These results show a strong correlation between maximum bed scour depth and peak flow rate, with this relationship being quantified as follows:

$$D_{max} = 1.532 \, (Q_{peak} / 1{,}000)^{1.073} \qquad \text{(E-2)}$$

where D_{max} is maximum bed scour depth in the cohesive bed area (cm). This relationship between D_{max} and Q_{peak} can be used to evaluate the uncertainty in predicted bed scour depth due to uncertainty in river flow rate. For a 10% decrease/increase in peak flow rate during the 100-year high-flow event (i.e., 10,800 to 13,200 cfs), maximum bed scour depth will range from 19.7 to 24.4 cm (using Equation E-1), which corresponds to an uncertainty range of -10% to 11% with respect to the base-case value (22 cm). As discussed in Section E.5, the predicted maximum bed scour depth for the 100-year high-flow event during neap tide conditions was 16 cm; the base-case value of 22 cm was predicted during spring tide conditions. Thus, uncertainty in the timing of the peak flow rate during the spring-neap tidal cycle produces larger uncertainty in model results than uncertainty in the peak flow rate.

LIST OF FIGURES CITED IN APPENDIX E

APPENDIX F
DETAILS OF EXTERNAL SEDIMENT LOAD ANALYSIS

F.1 SPECIFICATION OF BOUNDARY CONDITIONS

The first 21 years of the 30-year period correspond to the calibration period and inputs at the upstream boundary for that period are presented in Section D.1. The same procedures used to specify flow rate and sediment loading at the upstream boundary during the 21-year period were applied to the last nine years of the 30-year period. Daily-average flow rates (i.e., average of measurements made once every 15 min over a 24-hour period) measured at the USGS gauging station at Auburn in the Green River from 1981 through 1989 were used to specify discharge at the upstream boundary during the last nine years of the 30-year period. The location of the USGS gauging station is shown in Figure 1-2. Time series of flow rate and sediment loading at the upstream boundary in the Green River for the last nine years of the 30-year simulation are shown in Figures F-1 through F-9. At the open boundary in Elliott Bay, tidal elevation was specified using data collected at NOAA's Seattle Ferry Pier tide gauge station.

As discussed in Section 4.2, the 30-year period used for prognostic simulations corresponded to the Green River hydrograph for the period from 1960 through 1989. A summary of high-flow events in the Green River during the 47-year period from 1960 through 2006 is presented in Table F-1. During this 47-year period, a total of thirty-five 2- to 10-year high-flow events and five 10- to 100-year high-flow events occurred. The maximum flow rate during this 47-year period was 11,600 cfs (during 1975), which is only 3% lower than the discharge for the 100-year high-flow event. For the 1960-89 period, twenty-three 2- to 10-year high-flow events occurred, which corresponds to 66% of the total number of high-flow events with this range of return periods. Three 10- to 100-year high-flow events occurred during the 1960-89 period, which is 60% of the total number of these high-flow events that occurred between 1960 and 2006. Note that high-flow events with 2-, 10-, and 100-year return periods have 50%, 10%, and 1% probabilities, respectively, of occurring in any particular year. Thus, there is a 38% probability of a 100-year high-flow event occurring during a 47-year period. The probability (P) of a 100-year high-flow event occurring during a period of n years is calculated using:

$$P(n) = 1 - (1 - p)^n \qquad \text{(F-1)}$$

where p is the probability of the event occurring in any particular year (i.e., 0.01 for 100-year high-flow event).

Table F-1. Summary of high-flow events in the Green River (1960-2006).

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
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

Calendar Year	Number of Events		Maximum Flow Rate (cfs)
	2-to-10-Yr High-Flow Event	10-to-100-Yr High-Flow Event	
1998	1	0	9,090
1999	2	0	8,940
2005	1	0	8,500
2006	0	1	11,200
Total	**35**	**5**	**11,600**

No entry was made in this table for years when river flow rate never exceeded discharge of a 2-year high-flow event.

Evidence was presented in Section 4.2 to support the conjecture that the 30-year period from 1960 through 1989 was representative of long-term flow conditions in the Green River. That evidence, when coupled with the discussion presented above, strongly supports the validity of using this 30-year hydrograph to specify incoming flow from the Green River for long-term simulations.

F.2 RESULTS OF EXTERNAL SEDIMENT LOAD SIMULATION

Temporal changes in the spatial distribution of bed-source content in the surface (0-10 cm) layer of the sediment bed at 5-year increments during the 30-year period are presented in Figures F-10 through F-15. Similarly, changes in spatial distributions of upstream-source and lateral-source content at 5-year increments are shown in Figures F-16 through F-27. These figures provide qualitative illustrations of temporal changes in bed-, upstream-, and lateral-source content in the surface layer over the 30-year period. Generally, bed-source content decreases with time, while upstream-source and lateral-source content increases with time. However, the temporal changes do not appear to occur at a linear rate. In particular, bed-source content may not decrease monotonically at all locations. Due to significant temporal variations in erosion and deposition fluxes over the 30-year period, bed-source content may increase during specific time periods (e.g., between years 5 and 10) at some locations.

The first step in analyzing the rate of temporal change in bed composition was to examine reach-average values of surface-layer content for Reaches 1, 2A, 2B, and 3 (see Figures F-28 through F-31). Average bed elevation in all reaches increases with time, but at different rates. Bed-source content decreases as upstream-source content increases with time due to net deposition. Lateral-source content tends to increase with time, but it is more temporally variable than content of the other two sediment sources.

These model results suggest that the bed-source content (C_{bed}) in each reach (upper right panel) decreases at an approximately exponential rate, which is expressed mathematically as (Thomann and Mueller 1997):

$$C_{bed}(t) = C_{bed,o} \ \mathrm{EXP}[- \lambda \ (t - t_o)] \qquad \text{(F-2)}$$

where $C_{bed,o}$ is bed-source content at time t_o, t is time, and λ is a coefficient with units of inverse time (e.g., $year^{-1}$). To evaluate the validity of the hypothesis that bed-source content decreases at an exponential rate, values of the coefficient λ, which represents a lumped parameter for the entire 30-year period based on beginning and ending values of bed-source content, for each reach were determined using:

$$\lambda = - \ln(C_{bed,30}/C_{bed,o}) \ / \ 30 \qquad \text{(F-3)}$$

where $C_{bed,30}$ is the predicted reach-average bed-source content at the end of the 30-year period and $C_{bed,o}$ is the initial bed-source content (i.e., 100%). The values of λ for each reach are listed in Table F-2. The theoretical exponential curve, based on Equation F-2 and values of λ in Table F-2, for temporal change in reach-average bed-source content is compared to the predicted rate of change on the upper right panels of Figures F-28 through F-31. These results indicate that exponential decrease of bed-source content is a reasonable assumption for some of the shown locations. For quantities that decrease exponentially with time, a useful measure of the rate of decrease is the half-time, which is the time needed for the quantity to decrease by a factor-of-two. Half-time ($T_{1/2}$) is calculated using:

$$T_{1/2} = -\ln(0.5) / \lambda \qquad \text{(F-4)}$$

Values of half-time for the 30-year period, on a reach-average basis, are given in Table F-2.

Table F-2. Reach-average values of bed-source content for 30-year period.

Reach	Bed-Source Content at End of 30-Year Period (%)	Coefficient λ (yr^{-1})	Half-Time (years)
1	3.6	0.111	6.0
2A	2.4	0.124	5.6
2B	17	0.059	12
3 (excluding upper turning basin)	3.0	0.117	5.9

Diagnostic analysis of temporal changes in bed elevation and surface-layer composition over the 30-year period were conducted at three locations: RM 1.42, 2.59, and 3.24 (see Figure F-32). Time-series of predicted bed elevation and surface-layer composition for the west bench location near RM 1.42 are shown in Figure F-33. The average net sedimentation rate at this location is 2.0 cm/yr. Temporal changes in bed elevation indicate that a depositional environment exists at this location with minimal erosion occurring during high-flow events. At this location, bed-source content decreases from 100% at the beginning of the 30-year period (i.e., $t = t_o = 0$) to about 0.5% at the end of the period (t = 30 years). This rate of decline yields a value of 0.176 yr^{-1} for the λ coefficient, with the resulting exponential curve compared to the predicted temporal change in bed-source content in upper right panel of Figure F-32. The comparison demonstrates that Equation F-2 is a valid approximation of the predicted changes in bed-source content at the given location.

The west bench location at RM 2.59 is net depositional over the 30-year period, with an average net sedimentation rate of 0.9 cm/yr (Figure F-34). However, bed scour occurs during high-flow events, with about 10 cm of erosion predicted during the 50-year high-flow event in 1975. Even with relatively high erosion during rare high-flow events, bed-source content in the surface layer decreases at an approximately exponential rate over the 30-year period. At this location, the λ coefficient has a value of 0.107 yr^{-1}, which corresponds to a half-time of 6.5

years. Comparing this result to the half-time for the RM 1.42 location indicates that half-time increases as net sedimentation rate decreases. The exponential decline model (i.e., Equation F-2) does not agree as well with model predictions of rate of decrease of bed-source content at this location as it did at the RM 1.42 location (Figure F-33). The effects of episodic erosion, which are not incorporated into the exponential model (which is a simplified approximation to sediment transport processes in the LDW), at the RM 2.59 are the primary cause for the discrepancy between the exponential model and the STM predictions.

A relatively low net sedimentation rate (i.e., average of 0.33 cm/yr for the 30-year period) is predicted for the west bench location at RM 3.24 (Figure F-35). Generally, this location is depositional with low erosion during high-flow events. However, a relatively small, but important, change in net sedimentation rate occurs between years 1-15 and 16-30 during the simulation. The net sedimentation rate is 0.27 cm/yr for the first 15 years of the 30-year simulation, with the net sedimentation rate increasing to 0.40 cm/yr during the second 15-year period. This change in net sedimentation rate has a significant effect on temporal changes in surface-layer composition. During the first 15-year period, there is no consistent temporal trend in bed-source content, with values ranging between 80% and 100%. With a 50% increase in net sedimentation rate during the second 15-year period (i.e., from 0.27 to 0.40 cm/yr), bed-source content declines at approximately an exponential rate, which has a half-time of about 8 years.

For a surface layer of thickness H (cm) that experiences net sedimentation at a rate of Γ (cm/yr), the concentration of a conservative substance in the surface layer will decrease at an exponential rate as given by Equation F-2 (Thomann and Mueller 1997). Other physical processes that may affect the concentration of a conservative substance in the surface layer (e.g., bioturbation, mixing due to ship-induced scour) have not been incorporated into this analysis. In this idealized situation, it is assumed that the sediment being deposited has zero concentration of the substance and that net burial occurs at the same rate as net sedimentation. For this situation, the coefficient λ in Equation F-2 is given by (Thomann and Mueller 1997):

$$\lambda = \Gamma / H \qquad \text{(F-5)}$$

where H is the surface layer of thickness (cm) and Γ is the net sedimentation rate (cm/yr). The idealized (or theoretical) decrease in substance concentration described above is similar to the exponential decrease in bed-source content in the LDW. The difference between the idealized situation and the LDW results is that the sediment transport model includes the effects of erosion when simulating changes in bed-source content in the surface layer.

A comparison of the idealized and predicted rates of decrease of bed-source content is shown in Figure F-36. The relationship between bed-source content at the end of the 30-year period and net sedimentation rate is illustrated on this figure. The idealized relationship, based on Equations F-2 and F-5, is shown as a red line. Model results for each grid cell in Reaches 1, 2, and 3 are presented as individual points on the figure. This comparison shows that the model results follow the same general trend as the idealized formulation. Variability in the model results (e.g., factor-of-ten variation in bed-source content for a net sedimentation rate of 1 cm/yr) is as a result of the complex interactions between erosion and deposition. Variability in bed-source content at a specific net sedimentation rate tends to increase as the net sedimentation rate increases.

Equation F-5 is combined with Equation F-4 to produce the half-time of bed-source content for the idealized situation:

$$T_{1/2} = -\ln(0.5)\ H / \Gamma \qquad \text{(F-6)}$$

The idealized half-time, as a function of net sedimentation rate, is shown as a red line in Figure F-37. Predicted values of half-time for the 30-year period at each grid cell location are also shown on this figure. The results shown on this figure indicate that the relationship between half-time values predicted by the model and net sedimentation rates agrees reasonably well with the idealized situation. Variability in the predicted half-time values is a result of the effects of erosion and deposition. Overall, the results shown in Figures F-36 and F-37 support the hypothesis that bed-source content in the surface layer tends to decrease at an exponential rate, with the rate of decrease being approximately dependent on net sedimentation rate. However, Reach 3 tends to deviate from the exponential model much more than do Reaches 1 and 2. The primary reason for temporal changes in bed-source content within Reach 3 not being consistent with the exponential model is because this reach experiences relatively high sedimentation and because deposition in this reach tends to be episodic. One of the primary simplifying assumptions in the exponential model is that deposition is continuous and occurs at a constant rate. As deposition and erosion processes at a specific location deviate from this simplifying assumption, the agreement between model predictions of bed-source content decline and the exponential model will degrade.

Predicted half-time values have a complex relationship to NSR, half-time tending to decrease with increasing NSR for half-times of 10 years or greater (i.e., NSR approximately less than 0.8 cm/yr), see Figure F-37. For half-times less than 10 years, and NSR greater than about 0.8 cm/yr, the idealized relationship between half-time and NSR, as given by Equation F-6, does not correspond to model predictions. This result indicates that for NSR values greater than about 0.8 cm/yr, the combined effects of erosion and deposition generally tend to produce a complex relationship between half-time and NSR. This complex behavior explains the counter-intuitive result of Reaches 1 and 3 having the same reach-average half-time, even though there is a significant difference between the reach-average NSR values.

F.3 SENSITIVITY ANALYSIS FOR EXTERNAL SEDIMENT LOAD SIMULATION

An analysis was conducted to investigate the sensitivity of the external sediment load simulation to the following model inputs: 1) magnitude of lateral-source loads; 2) composition of lateral-source loads; 3) magnitude of upstream-source load; and 4) composition of upstream-source load. The magnitude of the lateral-source load for the base-case simulation was about 1,200 MT/year (total for all lateral sources), which corresponds to the annual load for a year with average precipitation. Total lateral loads for years with low and high precipitation were estimated to be 900 and 1,500 MT/year, which represent the lower- and upper-bound values for this sensitivity analysis. The lower- and upper-bound values for the other three sensitivity inputs were specified as factor-of-two adjustments with respect to the base-case values. The bounding values for the eight sensitivity simulations are provided in Table F-3.

Table F-3. Bounding values of model inputs for sensitivity simulations.

Sensitivity Parameter	Base Case Value	Lower-Bound Value	Upper-Bound Value
Lateral-source load: magnitude (MT/year)	1,200	900	1,500
Lateral-source load: composition (class 2/3% in storm drains/CSOs)	27/16	14/8	54/32
Upstream sediment load: magnitude (MT/year)	221,000	110,500	442,000
Upstream sediment load: composition (class 2%)	12	6	24

As discussed in Section 4.4, a 6-year period was used to evaluate the sensitivity of model results to variations in the magnitude and composition of sediment loads from upstream and lateral sources, as well as the timing of CSO loads. Results of the sensitivity simulations are presented here as spatial distributions of the composition of sediment in the surface (0 – 10 cm) layer at the end of the 6-year simulations. These spatial distributions provide a method for qualitatively comparing the effects of variations in lateral and upstream sediment loads on surface layer composition.

The spatial distribution of lateral-source content in the surface layer for the base-case simulation is shown in Figure F-38 Adjusting the timing of CSO loads has minimal effect on lateral-source content (Figure F-39). Decreasing and increasing the magnitude of lateral loads has an approximately linear effect on lateral-source content in the surface layer (Figures F-40 and F-41); increasing or decreasing lateral loads by a factor-of-two causes corresponding increases or decreases in lateral-source content. Decreasing the amount of class 2 and 3 sediment (i.e., sand) in the lateral loads results in wider dispersion of lateral-source sediment within the LDW (Figure F-42). Increasing class 2 and 3 content in the lateral loads causes lateral-source sediment to be less widely dispersed in the system (Figure F-43). Decreasing and increasing the upstream sediment load causes the lateral-source content in the surface layer to increase and decrease, respectively, as shown in Figures F-44 and F-45. Changing the composition of the upstream load has minimal effect on lateral-source content (see Figures F-46 and F-47).

The spatial distribution of bed-source content for the base-case simulation is presented in Figure F-48. The bed-source content varies in a non-linear inverse manner with respect to changes in the upstream-source load magnitude; doubling the upstream load causes the bed-source content to decrease by about 50%, while decreasing the load by 50% causes the bed-source content to increase by about 50% (see Figures F-49 and F-50). Generally, changes in the composition of the upstream sediment load have a relatively minor effect on bed-source content (Figures F-51 and F-52).

The spatial distribution of upstream-source content for the base-case simulation is presented in Figure F-53. As expected, decreasing and increasing the magnitude of the upstream sediment load causes upstream-source content in the bed to decrease and increase, respectively (Figures F-54 and F-55). Generally, changes in the composition of the upstream sediment load have a relatively minor effect on upstream-source content (Figures F-56 and F-57).

F.4 ADDITIONAL ANALYSIS OF EXTERNAL LOAD SIMULATION RESULTS

Net sedimentation was predicted to occur within nearly the entire LDW over the 30-year period (see Section 4.2 and Figure 4-2). However, NSR values for this period are spatially variable, with a relatively large range of sedimentation rates being predicted in the LDW. Even though a specific location in the LDW may be net depositional over the 30-year period, net erosion, on an annual basis, may occur at that location during certain years. To examine long-term temporal variations in net deposition and erosion, locations in the LDW where net deposition, on an annual basis, occurred every year during the 30-year period were determined (Figure F-58). Also shown on that figure are locations where net erosion, on an annual basis, occurred and the number of years with net erosion. A large majority of the areas of Reaches 1 and 3 experienced net deposition during the entire 30-year period. Even though a location may be net depositional during every year of the 30-year period, the deposition (i.e., sedimentation) rate may vary in magnitude from one year to the next; net sedimentation does not necessarily occur at a constant rate at a particular location. Within Reach 2, net erosion occurs at a relatively large number of locations during one or more years over the course of the simulation period. These results are consistent with the CSM and other conclusions about sediment transport in the LDW that are discussed in Section 5.

Additional diagnostic evaluations of temporal and spatial variations in bed elevation and surface-layer composition were conducted at 16 locations, with 10 locations in Reach 1 and six locations in Reach 2 (Figure F-58). Temporal variations in bed elevation and surface-layer bed composition during the 30-year period at the 16 locations are presented in Figures F-59 through F-74. Also shown in these figures is the temporal change in bed elevation during 1975, which was the year during which the largest high-flow event (i.e., about 50-year high-flow event) occurred. The results shown in these figures indicate that: 1) class 2 and 3 (i.e., sand) content in the bed increases moving upstream from RM 0.0; 2) episodic effects of deposition and erosion on bed elevation and composition during high-flow events increase in magnitude moving upstream from RM 0.0; and 3) the 1975 high-flow event caused episodic deposition and erosion.

Temporal variations of annual NSR in Reaches 1, 2, and 3 are shown in Figures F-75, F-76, and F-77, respectively. On each of these figures, differences in long-term and annual NSR values between the west bench, navigation channel, and east bench are presented. The average NSR values for the 30-year period in the nine zones of the LDW are listed in Table F-4. Significant annual variability in net sedimentation rates occurs during the 30-year period within the nine zones. The navigation channel in Reach 2 experienced net erosion, on average, during 1965 and 1975, which were years with 10- to 100-year high-flow events.

Table F-4. Average NSR values for 30-year period.

Reach	Average NSR: West Bench (cm/yr)	Average NSR: Navigation Channel (cm/yr)	Average NSR: East Bench (cm/yr)
1	1.7	2.0	1.7
2	3.2	2.7	2.5
3	13	41	18

Analysis of annual variation in NSR, in conjunction with other analyses of model results, suggested that there may be a correlation between NSR and upstream sediment load. A correlation analysis between the annual NSR values for the nine zones and annual upstream sediment load during the 30-year period was conducted. The results of the correlation analysis are shown in Figure F-78, which demonstrates a high correlation between annual NSR and upstream sediment load. Thus, these results support the hypothesis that net sedimentation rates throughout the LDW are strongly influenced by sediment loading from the Green River.

Mass balances for the 30-year period were constructed for the four sediment size classes (see Figures F-79 through F-82). These results show that for class 1A sediment (clay and fine silt, less than 10 μm) during the 30-year period: about 10% of the upstream sediment load is deposited in the LDW; and 43%, 27%, and 30% of the total deposition of class 1A sediment occurs in Reaches 1, 2, and 3, respectively. For class 1B sediment (medium/coarse silt, 10-62 μm): about 75% of the upstream load is deposited in the LDW; and 38%, 25%, and 37% of the total deposition of class 1B sediment occurs in Reaches 1, 2, and 3, respectively. For class 2 sediment (fine sand, 62-250 μm): a large portion of the upstream load (95%) is deposited in the LDW; and 8%, 12%, and 80% of the total deposition of class 2 sediment occurs in Reaches 1, 2, and 3, respectively. For class 3 sediment (medium/coarse sand, 250-2,000 μm): nearly all of the upstream load is deposited in the LDW, with 98% of the incoming load being deposited in Reach 3.

To effectively illustrate spatial gradients in NSR values that are of primary importance for FS evaluations in Reaches 1 and 2 (i.e., less than 3 cm/yr), Figure 4-2 had an upper range of greater than 3 cm/yr. In Reach 3, relatively high NSR values are predicted by the model and Figure 4-2 does not adequately represent spatial gradients in that reach. Thus, the range of NSR values was extended to greater than 40 cm/yr, which provides improved definition of spatial variation of NSR in Reach 3 (see Figure F-83).

As shown in Figure F-83, the model predicts relatively high NSR values in Reach 3. Comparisons to NSR values estimated from core data in that reach indicate that the model tends to over-predict NSRs in Reach 3. Additional evaluation of predicted NSRs in Reach 3 was conducted to derive an improved understanding of model performance in that reach. Mass balances for the 30-year simulation indicate that most of the Class 3 sediment load (i.e., medium/coarse sand) transported down the river from the upstream boundary is deposited in Reach 3 (see Figure F-82). Class 3 load input at the upstream boundary was specified using an approximate technique for estimating bedload transport in the river (see Section B.2). The magnitude of this load is uncertain due to the estimation method and limited bedload data. The sensitivity of model predictions to the magnitude of bedload input at the upstream boundary was evaluated by conducting a 6-year simulation with the Class 3 load at the upstream boundary set to zero. The results of this sensitivity simulation are compared to the base-case simulation (i.e., same 6-year simulation period but with bedload input at the upstream boundary) in Figures F-84 through F-86. These results show that bedload transport in the river primarily affects sedimentation in Reach 3; bedload transport in the river has minimal effect on NSRs in Reaches 1 and 2.

Analysis of the spatial distribution of NSR values within different zones of Reach 3 provides additional insight about the effect of bedload transport on sedimentation in that reach. Overall, bedload transport in the river accounts for about 60% of the predicted net sedimentation in Reach 3, with about 80% of the predicted net sedimentation in the upper turning basin due to bedload from the river (see Table F-5). As expected, the effects of bedload on predicted net sedimentation decrease moving downstream of the upper turning basin, with about 10% to 20% of the predicted net sedimentation in the bench areas of the RM 4.0-4.3 zone being attributed to bedload from the river. These results indicate that over-prediction of net sedimentation in Reach 3 is primarily due to uncertainty in the magnitude of bedload input at the upstream boundary; the method used to specify the bedload input probably over-estimates the magnitude of that load.

Table F-5. Average NSR values for 6-year period within Reach 3.

Zone Within Reach 3	Zone Area (acres)	Average NSR in Zone: With Upstream Bedload (cm/yr)	Average NSR in Zone: Without Upstream Bedload (cm/yr)	Percentage of Average NSR Due to Upstream Bedload
RM 4.0 – 4.3, East Bench	16.5	7.7	6.1	21%
RM 4.0 – 4.3, West Bench	10.8	9.5	8.5	11%
RM 4.0 – 4.3, Navigation Channel	4.6	19	11	44%
RM 4.3 – 4.6, East Bench	6.3	44	19	57%
RM 4.3 – 4.6, West Bench	6.6	11	7.8	26%
RM 4.3 – 4.8, Turning Basin	19.4	41	7.5	82%
Total	**64.2**	**23**	**8.7**	**62%**

As shown in Figure 4-2 and discussed in Section 4.3.1, net sedimentation occurs in nearly all of the LDW, except for 3 grid cells of net erosion, during the 30-year simulation period. Net sedimentation is not a continuous process in the LDW, with deposition and erosion at a specific location varying with time, as was shown in Figures F-59 through F-74. To better understand temporal variations in bed elevation and net sedimentation in LDW, the results of the 30-year simulation were examined to determine which locations in the LDW experienced bed scour greater than 10 cm below the initial bed elevation (i.e., at the start of the simulation) at some point during the 30-year period. The results of that analysis are presented in Figure D-87, which shows that bed scour greater than 10 cm below the initial bed elevation occurred at 14 grid cells in the cohesive bed area (maximum scour depth of 20 cm) and 2 grid cells in the non-cohesive bed area (maximum scour depth of 25 cm). These 16 grid cells represented a total area of 9.1 acres. Within the cohesive bed area, net sedimentation occurred at all of the 14 grid cells with bed scour greater than 10 cm at some point during 30-year period (Figure F-88). Total net bed elevation change over this 30-year period ranged from about 10 to 145 cm at these 14 locations. This figure also shows that maximum scour depth at 10 of the 14 locations was about 15 cm. The clustering of maximum scour depths at this depth in the sediment bed is due to a significant change in the erosion rate properties between the 10-15 and 15-20 cm layers in the bed model, with 15-20 cm layer being less erodible than the 10-15 cm layer.

Even though net sedimentation occurs at the 14 grid cells, temporal variations in bed elevation and bed-source content of surface-layer (0-10 cm) sediment occurs during the 30-year period at these grid cells. The locations and identifiers (i.e., (i,j) location) of the 14 grid cells are presented in Figure F-89. Time histories of bed elevation change and bed-source content of surface-layer sediment at the 14 locations are shown in Figures F-90 through F-103. Average NSR values (i.e., averaged over the 30-year period) at these locations range from 0.4 to 4.8 cm/yr. Decreases in bed-source content in surface-layer sediment over the 30-year period range from about 89% to 99%. These rates of decrease in bed-source content correspond to average half-time values, for the 30-year period, that range from about 5 to 9 years.

Temporal variations in bed elevation change and bed-source content of surface-layer sediment show that the effects of specific high-flow events during the 30-year period can be significant. In addition, a specific high-flow event may have very different effects on bed-source content at the 14 grid cells. An excellent example of the spatial variability in the effect of a single event is the 1975 high-flow event, where the effects at the 14 grid cells ranged from minimal to large. At some locations, bed scour during a specific high-flow event can cause the bed-source content to increase from less than 10% to about 90% in a very short period of time (see Figure F-92). However, at locations where a discontinuous increase in bed-source content occurs during a high-flow event, bed-source content tends to decrease with time, at approximately an exponential rate, after a high-flow event.

As discussed in Section B.2, the regression equation developed by Embrey and Frans (2003) using data collected during a USGS sediment loading study conducted in 1996-97 was modified as shown in Equation B-2. This modification produced an increase in the average annual sediment load from the Green River of approximately a factor-of-two, relative to the original regression equation presented in Embrey and Fran (2003). The effects of decreasing the upstream (Green River) sediment load by a factor-of-two on model results were investigated through the sensitivity analysis discussed in Sections 4.4 and F.3. Generally, predicted NSR values are approximately linearly correlated to upstream sediment load. A factor-of-two decrease in upstream sediment load produces a 50% decrease in predicted NSR values for about 70% of the grid cells in the study area. Thus, a factor-of-two decrease in upstream sediment loads produces predicted NSR values that are low compared to estimated NSR values based on sediment core data. This observation is consistent with the results of the uncertainty analysis, which were presented in Sections 2.8 and D.6. As a result of the uncertainty analysis, a realistic lower-bound parameter set was determined to consist of lower-bound upstream sediment load (i.e., factor-of-two decrease relative to base-case value) and upper-bound class 1A/1B settling speeds (i.e., factor-of-two increase relative to base-case values). The predictive capability of the realistic lower-bound parameter set is demonstrated in Figures 2-14, 2-15, 2-16 and D-120. These figures demonstrate that the realistic lower-bound parameter set tends to under-predict NSR in the LDW, and that the base-case parameter set (i.e., upstream sediment load estimated using the modified regression equation) produces more reliable predictions. While it may have been possible to re-calibrate the STM using the original regression equation from Embrey and Frans (2003), the same calibration targets (i.e., empirical estimates of NSR) would have been used and the calibration parameters would have been adjusted to optimize the agreement between predicted and empirical NSR values. Therefore, the re-calibrated model, based on a factor-of-two decrease in upstream sediment load, would produce results that are very similar to the present configuration of the STM, which uses the modified regression equation.

LIST OF FIGURES CITED IN APPENDIX F