4 Remedial Action Objectives and Preliminary Remediation Goals

This section of the feasibility study (FS) identifies narrative remedial action objectives (RAOs) and numerical preliminary remediation goals (PRGs) for cleanup of the Lower Duwamish Waterway (LDW). RAOs for the LDW describe what a proposed cleanup remedy is expected to accomplish to protect human health and the environment (EPA 1999b) PRGs are the contaminant endpoint concentrations or risk levels associated with each RAO that are believed to be sufficient to protect human health and the environment based on available site information (EPA 1997b).

The step of identifying narrative RAOs provides a transition between the findings of the human health and ecological risk assessments and development of remedial alternatives in the FS. The RAOs pertain to the specific exposure pathways and receptors evaluated in the risk assessments and for which unacceptable risks were identified.

RAOs are developed herein for cleanup of contaminated sediment in the LDW Superfund site. Surface water within the site is also a medium of concern. However, no active remedial measures are anticipated for the water column. Improvements in surface water quality are expected following sediment cleanup and implementation of upland source control measures. Further, water quality monitoring will be part of long-term monitoring for the site.

PRGs are intended to protect human health and the environment and to comply with applicable or relevant and appropriate requirements (ARARs) for specific contaminants (EPA 1991b). For the LDW, PRGs are numerical concentrations or ranges of concentrations in sediment that protect a particular receptor from exposure to a hazardous substance by a specific pathway. The PRGs are expressed as sediment concentrations for the identified risk drivers because the alternatives in this FS address cleanup of contaminated sediments. PRGs are not developed in this FS for surface water because actions to directly address water quality are not included among the FS alternatives. Instead, surface water quality will be discussed as water quality ARARs, which are equivalent to PRGs. The RAOs, ARARs, and PRGs presented here may be modified and will be finalized by the U.S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology (Ecology) in the Record of Decision (ROD).

4.1 Development of Remedial Action Objectives

The RAOs are narrative statements of the medium-specific or area-specific goals for protecting human health and the environment. RAOs describe in general terms what the sediment cleanup will accomplish for the LDW. RAOs help focus the development and evaluation of remedial alternatives and form the basis for establishing PRGs.

EPA's *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA* (EPA 1988) specifies that RAOs are to be developed based on the results of the human health risk assessment (HHRA) and ecological risk assessment (ERA). Other EPA guidance (EPA 1991a, 1999a) states that RAOs should specify:

- The exposure pathways, the receptors, and the contaminants of concern (COCs)
- An acceptable concentration or range of concentrations for each exposure pathway.

Section 2 summarized the remedial investigation (RI), including the chemical and physical conceptual site model. Section 3 summarized the results of the risk assessments, which identified receptors, exposure pathways, risk drivers, and, where calculable, risk-based threshold concentrations (RBTCs). The RAOs presented here were crafted based on the RI and findings from the baseline ERA and HHRA (Windward 2010, 2007a, 2007b).

4.1.1 Remedial Action Objectives for the Lower Duwamish Waterway

The results of the baseline HHRA and ERA indicate that remedial action is warranted to reduce unacceptable human health and ecological risks posed by COCs in LDW sediments. Unacceptable risks were estimated for certain human health exposure scenarios (through seafood consumption and direct contact exposure pathways) and for certain ecological risks (for benthic organisms and for other ecological receptors).

For human health, EPA defines a generally acceptable risk range for excess cancer risks as between one in ten thousand (1×10^{-4}) and one in one million (1×10^{-6}) (i.e., the "target risk range") and for non-cancer risks a hazard index (HI)[1] of 1 or less is considered acceptable (EPA 1991a). Excess cancer risks greater than 10^{-4} or HIs greater than 1 generally warrant a response action (EPA 1997b).

To establish cleanup levels and remedial action levels (RALs), the Washington State Model Toxics Control Act (MTCA) specifies that individual excess cancer risks for identified COCs should be 1×10^{-6} or less, and total excess cancer risks (all carcinogens combined) should not exceed one in one hundred thousand (1×10^{-5}). Cleanup levels should be adjusted downward to take into account exposure to multiple hazardous substances if the total excess cancer risk exceeds 1×10^{-5}. MTCA also specifies that risks resulting from exposure to multiple hazardous substances may be apportioned among hazardous substances in any combination as long as: 1) the total excess cancer risk (all carcinogens combined) does not exceed 1×10^{-5}; and 2) the health threats resulting from exposure to two or more non-carcinogenic hazardous substances with similar types of toxic response does not exceed an HI of 1 (WAC 173-340-708).

1 HIs are calculated as the sum of hazard quotients with similar non-cancer toxic endpoints.

Based on guidance provided by EPA under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and other requirements provided in MTCA/Sediment Management Standards (SMS), four RAOs have been identified for the cleanup of LDW sediments. These RAOs are identified below, and a discussion of each RAO follows.

RAO 1: Reduce human health risks associated with the consumption of resident LDW fish and shellfish by reducing sediment and surface water concentrations of COCs to protective levels.

Lifetime excess cancer risks from human consumption of resident LDW seafood are estimated to be greater than 1×10^{-6} for some individual carcinogens, and greater than 1×10^{-4} for carcinogens cumulatively under reasonable maximum exposure (RME) seafood consumption scenarios. In addition, the estimated non-cancer risks exceed an HI of one (see Tables 3-4a and 3-4b of Section 3). These estimated risks warrant response actions to reduce exposure.

Total polychlorinated biphenyls (PCBs), arsenic, and carcinogenic polycyclic aromatic hydrocarbons (cPAHs) are the primary risk drivers that contribute to the estimated risks based on consumption of resident seafood. As discussed in Section 3, although risks associated with consumption of dioxins/furans in resident seafood were not quantitatively assessed in the baseline HHRA, those risks were assumed to be unacceptable; thus, dioxins/furans are also considered risk drivers with respect to the consumption of resident seafood.

Achieving RAO 1 requires that site-wide average[2] concentrations of COCs in sediment be reduced, which in turn is expected to reduce tissue COC concentrations in fish and shellfish exposed to these sediments. Exposure of fish and shellfish to COCs in sediment occurs within the biologically active zone. As reported in the RI (Windward 2010), this zone is estimated to be the upper 10 cm of sediment. Deeper, undisturbed sediments contribute negligibly to the risks addressed by this RAO if contaminants in these deeper sediments do not migrate into the biologically active zone. However, deeper sediments that contain contaminants at concentrations above action levels and that are potentially subject to disturbance (e.g., erosion, propeller scour, earthquakes) or otherwise may migrate into the biologically active zone through advection or other mechanisms may warrant response actions to satisfy this RAO.

With regard to seafood consumption, bioaccumulative COCs enter the food web from both sediment and water. For example, the food web model used to predict tissue PCB concentrations (refer to Appendix D of the RI; Windward 2010) assumes that the

[2] The FS uses average concentrations to evaluate the effectiveness of alternatives in attaining RAOs. In practice, compliance with clean-up levels will be based on the 95% upper confidence limit on the mean (UCL95).

exposure of fish and shellfish to PCBs occurs through their exposure to both sediments and surface water.

Substantial reductions in the concentrations of such COCs in sediment achieved through remediation should also reduce the concentrations of those COCs in surface water, thereby contributing to reducing their concentrations in fish and shellfish tissue and ultimately reducing human health risks, as stated in RAO 1. The relationships between sediment, surface water, and tissue concentrations are complex, and will be assessed through long-term monitoring of the remedial actions.

RAO 2: Reduce human health risks associated with exposure to COCs through direct contact with sediments and incidental sediment ingestion by reducing sediment concentrations of COCs to protective levels.

Lifetime excess cancer risks from human direct contact and incidental sediment ingestion RME scenarios (netfishing, tribal clamming, and beach play) are estimated to be within EPA's 10^{-4} to 10^{-6} target risk range (Tables 3-6a and 3-6b of Section 3) for the individual risk drivers. Some individual excess cancer risks exceed 1×10^{-6}, and total risks from all risk drivers exceed 1×10^{-5}, both of which are MTCA thresholds. Therefore, the risks associated with these exposure pathways warrant response actions to reduce exposure. No HIs were greater than 1 for any of the direct contact or incidental ingestion sediment RME scenarios, with the exception of one individual beach (Beach 4). Total PCBs, arsenic, cPAHs, and dioxins/furans are the primary risk drivers that contribute to the estimated excess cancer risks, and total PCBs are also a risk driver for noncancer risks based on direct contact.

Achieving RAO 2 requires that average concentrations of COCs be reduced at locations and depths within the sediment where people have the potential to be exposed. For netfishing activities, exposure is over the entire LDW and to surface sediments (0 to 10 cm). Direct contact risks in the beach play and clamming areas are assumed to result from exposure to the upper 45 cm depth interval, which accounts for potential exposures to children and clammers, who may dig holes deeper than 10 cm. Deeper sediments in other areas do not contribute appreciably to these risks unless they could be exposed by future disturbances (e.g., erosion, propeller scour, earthquakes). Achieving and maintaining this RAO may include response actions to address deeper sediments containing concentrations of the risk drivers above action levels if such disturbances of the overlying sediments over time may potentially expose these sediments.

RAO 3: Reduce risks to benthic invertebrates by reducing sediment concentrations of COCs to comply with the Washington State SMS.

The SMS provide both chemical and biological effects-based criteria. The numerical SMS chemical criteria are available for 47 contaminants or groups of contaminants (i.e., sediment quality standards [SQS] and cleanup screening levels [CSL]). These numerical chemical criteria are based on apparent effects thresholds (AETs) developed for four different benthic endpoints by the Puget Sound Estuary Program (PSEP) (Barrick et al. 1988). An AET is the highest "no effect" sediment concentration of a specific contaminant above which a significant adverse biological effect always occurred among the several hundred samples used in its derivation. In general, the lowest of the four AETs for each contaminant was identified as the SQS; the second lowest AET was identified as the CSL. According to the SMS (WAC 173-204), locations with all contaminant concentrations less than or equal to the SQS are defined as having no acute or chronic adverse effects on biological resources, locations with any contaminant concentrations between the SQS and the CSL are defined as having minor adverse effects, and locations with any contaminant concentration greater than the CSL are defined as having more pronounced adverse effects (refer to Section 5 of the RI, Windward 2010).

The baseline ERA (Windward 2007a) reported that 41 contaminants were detected in surface sediment at one or more locations within the LDW at concentrations exceeding their respective SQS (see Table 3-1, Section 3 of this FS). Thus, the ERA determined that these 41 contaminants are COCs because they pose a risk to the benthic invertebrate community. These 41 COCs are designated as risk drivers for this pathway.

Benthic organisms reside primarily in the biologically active zone (uppermost 10 cm) of intertidal and subtidal sediments of the LDW (Section 2 of the RI, Windward 2010). Deeper sediments in areas subject to disturbance (e.g., erosion, propeller scour, earthquakes) that contain COCs at concentrations above the SQS may warrant response actions to satisfy RAO 3.

RAO 4: Reduce risks to crabs, fish, birds, and mammals from exposure to COCs by reducing concentrations of COCs in sediment and surface water to protective levels.

The ERA (Windward 2007a) determined that exposure to seven contaminants, identified as COCs, exceeded toxicity benchmarks for fish, birds, or mammals. In consultation with EPA and Ecology, total PCBs were designated as the risk driver associated with seafood consumption based on estimated risks to river otters. Thus, achievement of RAO 4 is based on addressing PCB risk to river otters (see Section 3.1.3 for discussion of other ecological COCs).

River otters are indirectly exposed to PCBs in sediment primarily through the consumption of prey. Therefore, achieving this RAO requires that site-wide average concentrations of PCBs in sediment be reduced, with the expectation that sediment cleanup will reduce PCB concentrations in fish and shellfish, and that concentrations of the remaining six COCs identified for this exposure pathway will also be reduced to acceptable levels for other receptors (Windward 2010).

The potential for exposure of prey to COCs occurs primarily within the biologically active zone (upper 10 cm of sediment). Deeper sediments, if left undisturbed, contribute negligibly to the risks addressed by this RAO. Deeper sediments in areas subject to disturbance (e.g., erosion, propeller scour, earthquakes) that contain COCs at concentrations above action levels may warrant response actions to satisfy RAO 4.

Remediation will reduce COC concentrations in the LDW sediments; this in turn should also reduce those same COC concentrations in surface water, thereby contributing to a reduction of their concentrations in the tissue of fish and shellfish (including prey species). The relationships between sediment, surface water, and tissue concentrations are complex, and will be assessed through long-term monitoring following completion of the remedial actions.

4.1.2 Role of Source Control

Controlling sources of contamination to the LDW to the maximum extent practicable is an explicit MTCA expectation when natural attenuation is part of the remedial action (WAC 173-340-370). Active sediment remediation of COCs that have accumulated in sediments over time will address a major portion of the risks addressed in each RAO; however, without continued source control to keep reducing COC inputs to the LDW, sediments will likely recontaminate and water quality may continue to be impaired. Source control must include continued involvement by the Source Control Work Group (SCWG) to protect the long-term investments in the LDW cleanup.

Contaminated media from within the LDW drainage basin can affect sediments through several pathways, which can be organized into seven general types based on the origin of contamination, pathways to sediments, and the types of source control available:

- Direct discharge into the LDW (e.g., CSOs, storm drains)
- Surface water runoff or sheet flow
- Spills and/or leaks to the ground, surface water, or directly into the LDW
- Groundwater migration/discharge
- Bank erosion/leaching
- Atmospheric deposition
- Transport of resuspended contaminated sediments.

Understanding how each of these potential sources and pathways may impact a given sediment area is a complex undertaking and beyond the scope of this FS. Whether additional localized source control actions, beyond what has already been done, are needed before in-water work can begin will be considered in remedial design. This will require a recontamination/source control assessment study that varies in scope and magnitude depending on the specific project area.

Currently, source identification and implementation of effective control efforts in the LDW watershed are supported by a cooperative interagency program with the goal of identifying sources of potential contamination and recontamination in coordination with sediment cleanups and promoting their control. Ecology, as the lead entity for implementing source controls in the LDW, formed the LDW SCWG in 2002, which conducts several source control activities within the LDW area. The SCWG is composed primarily of public agencies responsible for source control, including EPA, Seattle Public Utilities, King County, and the Port of Seattle. The LDW source control strategy (Ecology 2004) also identifies various regulatory programs at EPA and Ecology that are called upon as needed for source control as well as several *ad hoc* members of the SCWG, including the City of Tukwila, Puget Sound Clean Air Agency, and Washington State Departments of Transportation (WSDOT) and Health (WDOH). All LDW SCWG members are public agencies with various source control responsibilities; the group's collective purpose is to share information, identify issues and data gaps, develop action plans for source control tasks, coordinate implementation of various source control measures, and share progress reports on these activities. Individually, these agencies are able to use their regulatory authority to promote source control in the LDW via source tracing sampling, stormwater and combined sewer overflow (CSO) programs, permits, hazardous waste management and pollution prevention programs, inspection and maintenance programs, water quality compliance and spill response programs, and environmental and pathway assessments.

Ecology's *Lower Duwamish Waterway Source Control Strategy* (Ecology 2004) is consistent with sediment source control protocols described in EPA guidance (2002b) and the SMS (Ecology 1995). The strategy describes the process and timing for implementing source control and the roles of various regulatory agencies responsible for conducting source control (e.g., SCWG) and enforcement. The strategy also provides for tracking and documenting source control progress in the LDW.

The focus of the LDW source control strategy is to identify and manage sources of COCs to waterway sediments in coordination with sediment cleanups and to prevent post-cleanup recontamination to levels exceeding cleanup goals established in the ROD to the extent practicable (Ecology 2004). Specific goals for the source control program are:

- Minimize the potential for contaminants in sediments to exceed the SMS criteria (as stated in WAC 173-204) and the LDW sediment cleanup levels (to be established in the ROD).
- Achieve adequate source control that will allow sediment cleanups to begin.
- Increase opportunities for natural recovery of sediments.

- Support long-term suitability and success of current and future habitat restoration opportunities.

Source control started in 2002 and is an ongoing, iterative process that continually produces new information. During remedial design, the work accomplished by Ecology and other public entities will serve as a foundation for any additional source control investigations and actions necessary before implementing various components of the sediment cleanup.

4.2 Applicable or Relevant and Appropriate Requirements (ARARs)

CERCLA Section 121(d) requires remedial actions to achieve (or formally waive) ARARs, which are defined as any legally applicable or relevant and appropriate standard, requirement, criterion, or limitation under any federal environmental law, or promulgated under any state environmental or facility siting law that is more stringent than the federal law. Similarly, MTCA requires that all cleanup actions comply with all legally applicable or relevant and appropriate requirements in applicable state and federal laws, as set forth in WAC 173-340-710. Given these substantive similarities in language between CERCLA and MTCA on the role of legal requirements, the FS uses the term ARARs to identify requirements that will satisfy or comply with both statutes. This subsection identifies ARARs for cleanup of the LDW. Section 9 of this document evaluates whether the remedial alternatives developed for cleanup of the LDW comply with these ARARs.

The National Contingency Plan (40 CFR 300.5) defines applicable requirements as the more stringent among those cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental or state environmental or facility siting laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstances found at a CERCLA site. A requirement may not be applicable, but nevertheless may be relevant and appropriate. Relevant and appropriate requirements address problems or situations sufficiently similar to those encountered at CERCLA and MTCA sites that their use is well-suited to the particular site. Relevant and appropriate requirements have the same effect as applicable requirements. They are not treated differently in any way.

Washington State has promulgated environmental laws and regulations to implement or co-implement several major federal laws through federally approved programs, for example, the Clean Water Act, Clean Air Act, and RCRA. The ARAR is the more stringent of either a federal requirement or a state requirement. Because this FS is being conducted under a joint CERCLA and MTCA order, applicable or relevant and appropriate provisions of MTCA and the SMS are considered to be ARARs for CERCLA, as well as governing requirements under MTCA. MTCA is a particularly important CERCLA ARAR. As will be seen, its background standards for final sediment cleanups are more stringent, and its allowable excess cancer risk standards are considerably more stringent. CERCLA permits risk-based cleanup standards within a range of 10^{-4} to 10^{-6} excess cancer risks. EPA policy and guidance recommends trying to achieve the more stringent 10^{-6} standard but accepts lesser standards within the range based on many factors. MTCA requires risk-based cleanup standards to be set at one in one million (1×10^{-6}) excess cancer risk levels for all individual carcinogens (such as PCBs) at a site, and a total excess cancer risk of one in one-hundred thousand (1×10^{-5}) for all carcinogens cumulatively at a site. Procedural requirements under state laws (e.g., MTCA disproportionate cost analysis methodology) are not CERCLA ARARs, but are required to comply with MTCA.

Table 4-1 lists and summarizes ARARs for the LDW site. Some ARARs prescribe minimum numerical requirements or standards for cleanup of specific media such as sediment, surface water, fish tissue, and groundwater. Other ARARs place requirements or limitations on actions that may be undertaken as part of a remedy. Table 4-2 lists other requirements or laws that are not considered ARARs by EPA and Ecology, generally because their primary purpose is not environmental protection (or state facility siting), but rather, for example, historical preservation of archaeological artifacts, endangered species, or workplace protection. Consideration of or compliance with requirements under these laws is anticipated for implementing most of the alternatives in this FS. While all federal, state, and local laws have to be complied with (except the need to acquire federal, state, or local permits for onsite cleanup work), it is helpful in considering remedial alternatives to list other laws or requirements alongside ARARs that will be implemented.

Some ARARs contain numerical values or methods for developing such values. These ARARs establish minimally acceptable amounts or concentrations of hazardous substances that may remain in or be discharged to the environment, or minimum standards of effectiveness and performance expectations for the remedial alternatives. RBTCs based on risks to human health or the environment may dictate setting more stringent standards for remedial action performance, but they cannot be used to relax the minimum legally prescribed standards in ARARs. The rest of this subsection focuses on ARARs containing specific minimum numerical standards.

There are no federal ARARs providing numerical standards for hazardous substances, pollutants, or contaminants in sediment. However, Washington State has promulgated numerical standards in the SMS for the protection of benthic invertebrates, and these regulations are cross-referenced in MTCA. Under CERCLA, the SMS criteria are considered ARARs and are promulgated standards for the LDW under MTCA. However, although the SMS contain narrative standards to protect human health and other biological resources, no SMS or other state numerical sediment criteria have been established to protect human health, including human consumers of seafood, or for other biological resources such as birds, fish, or mammals. Cleanup levels or standards for protection of these receptors are derived from RBTCs developed during the risk assessments performed during the LDW RI (Windward 2010).

Surface water (i.e., the water column) is also a medium of concern in the LDW. Therefore, federal water quality criteria (WQC) developed to protect ecological receptors and human consumers of fish and shellfish are relevant and appropriate requirements or minimum levels or standards for remedial action pursuant to CERCLA Section 121 (d)(2)(A)(ii) and RCW 70.105D.030(2)(e). Under CERCLA and MTCA, state water quality standards (WQS) approved by EPA are generally applicable requirements under the Clean Water Act (CWA). National recommended federal WQC established pursuant to Section 304(a)(1) of the CWA are compiled and presented on the EPA website at http://www.epa.gov/waterscience/criteria/wqctable/. Although these criteria are advisory for CWA purposes (to assist states in developing their standards), the last sentence of CERCLA Section 121(d)(2)(A)(ii) makes them minimum cleanup levels or standards, where relevant and appropriate under the circumstances, for CERCLA site remedial actions.

Consequently, the more stringent of the federal WQC and the state WQS are the cleanup levels or standards for the site. Washington State WQS for the protection of aquatic life are found at WAC 173-201A-240. The numerical criteria for aquatic life meet the federal requirements of Section 303(c)(2)(B) of the CWA and are at least as stringent as the federal WQC. Table 4-3 presents state and federal marine and freshwater values that have been developed for aquatic life and human health WQC. Specific considerations for compliance with federal and state aquatic life WQC and human health WQC are discussed in Section 4.2.2 of the RI (Windward 2010).

4.3 Process for Development of Preliminary Remediation Goals

PRGs are the COC endpoint concentrations initially identified for each RAO that are believed to be sufficient to protect human health and the environment based on available site information (EPA 1997b). The PRGs are used in the FS to guide the geographic definition of areas of potential concern (AOPCs) and the evaluation of proposed sediment remedial alternatives. PRGs are not final CERCLA/MTCA cleanup levels and standards. EPA and Ecology will select CERCLA/MTCA cleanup levels and standards in the ROD.

PRGs are developed in this subsection for each risk-driver COC, and are expressed as sediment concentrations that are intended to achieve the corresponding RAO. PRGs are based on considering the following factors:

- ARARs, including MTCA risk requirements, and SMS criteria
- RBTCs based on the human health and ecological risk assessments

- Background concentrations if protective RBTCs are below background concentrations
- Analytical practical quantitation limits (PQLs) if protective RBTCs are below concentrations that can be quantified by chemical analysis.

This section presents the numerical criteria in these categories to enable a comprehensive analysis and identification of PRGs. The pertinent information is then compiled and numerical PRGs are identified for each risk driver and each RAO.

4.3.1 Role of ARARs

Certain PRGs in this FS are set based on MTCA's more stringent (than CERCLA) excess cancer risk standards and its requirement that final cleanups achieve natural background levels when RBTCs are below background. The SMS (WAC 173-204) also contain numerical sediment contaminant concentration criteria pertinent for protecting the marine benthic invertebrate community (and hence the SMS criteria apply to PRGs for RAO 3).[3]

The SMS chemical and biological criteria are applied on a point basis to the biologically active zone of the sediments (i.e., upper 10 cm). Under the SMS, sediment cleanup standards may be established on a site-specific basis within an allowable range of contamination. The SQS, also called the sediment cleanup objective, and the CSL, also called the minimum cleanup level (MCUL), define this range. WAC 173-204-570(4) specifies that the site-specific cleanup standards shall be as close as practicable to the cleanup objective (the SQS) but in no case shall exceed the minimum cleanup level (the CSL). For this reason, in developing PRGs and analyzing alternatives, the SQS is used in this FS.[4] This WAC subsection also states that the cleanup standards shall be defined in consideration of the net environmental effects, cost, and engineering feasibility of different cleanup alternatives. The following WAC subsection (WAC 173-204-570(5)) emphasizes that all cleanup standards must ensure protection of human health (for which there are no SMS numerical criteria) and the environment (which encompasses receptors beyond the benthic invertebrate community). The SMS also require that contaminant concentrations (and toxicity) meet the cleanup standards within a reasonable time frame, as defined by a number of factors in WAC 173-204-580(3)(a).

As described in Section 4.2, surface water quality criteria are ARARs for the site because the water column is part of the site. The water column is affected by the sediment contaminant concentrations, as well as other factors, including ongoing releases, inflowing water from the Green/Duwamish River system, direct discharges to the LDW, and aerial deposition. However, the water column cannot practicably be directly

3 The SMS are ARARs under CERCLA and promulgated numerical standards under MTCA.

4 Co-located sediment toxicity test results that "pass," (i.e., indicate no toxicity) override exceedances of the SMS numerical criteria only for determining compliance with RAO 3.

remediated. Thus, while surface water is included as a medium of concern to be addressed by RAOs 1 and 4, surface water quality ARARs have not been identified as numerical PRGs at the site. However, because the WQC are CERCLA ARARs, the quality of LDW surface water will have to meet the more stringent of the federal and state aquatic life and human health WQC (Table 4-3) or be waived at or before completion of CERCLA remedial action.

Significant water quality improvements are anticipated as a result of sediment remediation and source control. Water quality monitoring will be part of the selected remedy to help measure the efficacy of sediment remediation and source control, and to assess compliance with ARARs. The remedial alternatives developed and evaluated in this FS may not comply with all surface water quality standards, or with natural background sediment standards required under MTCA in lieu of protective human seafood consumption RBTCs, in which case surface water quality and MTCA ARAR waivers could be issued by EPA at or before the completion of the remedial action. Potential ARAR waivers are listed in Section 121(d)(4) of CERCLA. The most common waiver is for technical impracticability, the standards for which are explained in detail in comprehensive EPA guidance designed to ensure a rigorous evaluation, and that only genuine demonstrated technical impracticability will qualify.

4.3.2 Role of RBTCs

The RI developed site-specific sediment RBTCs (summarized in Section 3.3 of this document) for each of the risk-driver COCs. RBTCs for human health were calculated based on risks associated with the direct sediment contact RME scenarios and seafood consumption RME scenarios. RBTCs for wildlife receptors were calculated based on prey consumption by river otters. For the benthic invertebrate community, RBTCs were set at the SQS and CSL.

Total PCBs, cPAHs, arsenic, and dioxins/furans are the risk drivers for the human seafood consumption pathway. Sediment RBTCs for total PCBs were calculated for the 1×10^{-4} excess cancer risk level and are applied as site-wide average concentrations.[5] As discussed in Section 3.3, sediment RBTCs based on the seafood consumption pathway were not calculated for arsenic and cPAHs, because correlations between sediment contaminant concentrations and receptor tissue concentrations could not be established. Sediment RBTCs were also not calculated for dioxins/furans. Fish and shellfish tissue data were not collected for this risk driver during the RI because it was determined that sediment concentrations would exceed RBTCs, which would be more stringent than

[5] For the excess cancer risk levels of 1 in 1,000,000 (1×10^{-6}) and 1 in 100,000 (1×10^{-5}) and for the non-cancer HQ of 1, even at a total PCB concentration of 0 µg/kg dw in sediment, the food web model predicted total PCB concentrations in tissue that would result in a risk estimate greater than the risk levels for the RME seafood consumption scenarios because of the contribution of total PCBs from water alone, even at concentrations similar to those in upstream water (i.e., 0.3 ng/L). Therefore, sediment RBTCs for these risk levels were represented as "< 1" (see Table 3-9).

natural background, resulting in natural background concentrations in sediment being the PRG for dioxins/furans.

Total PCBs, cPAHs, arsenic, and dioxins/furans are also the human health risk drivers for the direct sediment contact pathway. Sediment RBTCs for these hazardous substances were presented in Table 3-10 for each of the three direct sediment contact RME scenarios (i.e., netfishing, tribal clamming, and beach play). These sediment RBTCs are average concentrations applied to the spatial area over which exposure would reasonably be expected.

A total PCB sediment RBTC was calculated to protect wildlife. It protects river otters as the most sensitive representative wildlife species from the ERA, based on their consumption of prey species (Windward 2007a). The RBTC is applied as a site-wide average concentration.

4.3.3 Role of Background Concentrations

Both CERCLA and MTCA consider background hazardous substance concentrations when formulating PRGs and cleanup levels. Both recognize that setting numerical cleanup goals at levels below background is impractical (because of the potential for recontamination to the background concentration). MTCA (WAC 173-340-200) defines natural background as the concentrations of hazardous substances that are consistently present in an environment that have not been influenced by localized human activities. Thus, under MTCA, a natural background concentration can be defined for man-made compounds even though they may not occur naturally (e.g., PCBs deposited by atmospheric deposition into an alpine lake). According to CERCLA guidance, natural background refers to substances that are naturally present in the environment in forms that have not been influenced by human activity (e.g., naturally occurring metals).

MTCA cleanup levels cannot be set at concentrations below natural background (WAC 173-340-705(6)). Similarly, CERCLA guidance states that natural background concentrations establish a limit below which a lower cleanup level cannot be achieved (EPA 2005b).

Both cleanup programs also recognize that natural and man-made hazardous substance concentrations can occur at a site in excess of natural background concentrations, not as a result of local site-related releases but caused by human activities in areas remote from the site and natural processes that transport the contaminants to the site (e.g., atmospheric uptake, transport, and deposition). CERCLA defines “anthropogenic background” as natural and human-made substances present in the environment as a result of human activities, but not related to a specific release from the CERCLA site undergoing investigation and cleanup (EPA 2002c). MTCA defines the term “area background” as media-specific concentrations that are consistently present in the environment in the vicinity of a site that are attributable to human activities unrelated to specific releases from the site. CERCLA generally does not require cleanup to concentrations below anthropogenic background concentrations. In states that have a more stringent state standard, CERCLA cleanups must try to meet state ARARs, or EPA must waive the ARAR at or before completion of the remedial action. MTCA defines natural background as the cleanup standard required for final remedies when natural background concentrations are higher than the calculated risk-based cleanup levels (i.e., RBTCs). Thus, a CERCLA remedy in Washington State that cannot achieve natural background concentrations is not final unless this MTCA requirement is achieved or waived, or residual risks are otherwise sufficiently controlled. Under MTCA, because a waiver is not available, a remedy that cannot achieve natural background concentrations remains "interim" by default (see WAC 173-340-430) unless it is technically impossible to implement a more permanent cleanup action for all or a portion of the site (see WAC 173-340-360(2)(e)(iii)), and residual risks can be sufficiently controlled with institutional controls.

As a result, PRGs have been set at natural background concentrations for hazardous substances that have risk-based concentrations below natural background concentrations. EPA and Ecology recognize that natural background concentrations are unlikely to be achieved at the site and that long-term sediment contaminant concentrations following active sediment remediation will be governed primarily by concentrations in incoming sediment from the Green/Duwamish River system and new or continuing releases from other sources subject to further source control actions (see Section 5). Long-term monitoring will be used to determine what the technically practicable lower limits are for site concentrations, as well as where source control should continue to be focused. When these lower limits are reached, as demonstrated by monitoring data, a CERCLA technical impracticability (TI) waiver of the MTCA ARAR, in conjunction with institutional controls, could be used to provide administrative closure of the LDW cleanup. The TI waiver would address the gap between the technically practicable limit and natural background concentrations. Under MTCA, sufficient institutional controls that address remaining human health risks may similarly allow a final cleanup determination, where it is technically impossible to implement a more permanent cleanup action for all or a portion of the site (see WAC 173-340-360(2)(e)(iii)).

4.3.4 Natural Background in Sediment

This section presents estimates of natural background concentrations for total PCBs, arsenic, cPAHs, and dioxins/furans in sediment.[6] To characterize natural background, marine sediment data were compiled from areas within Puget Sound that have not been influenced by localized human activities. These data represent non-urban, non-localized concentrations that exist as a result of natural processes and/or the large-scale distribution of these hazardous substances from anthropogenic sources.

6 EPA and Ecology will set natural background concentrations and remediation goals in the ROD.

The Dredged Material Management Program (DMMP) (comprised of the U.S. Army Corps of Engineers [USACE], EPA, Ecology, and the Washington State Department of Natural Resources [DNR]) collected sediment data throughout Puget Sound in the summer of 2008 and documented the results in a study called *Final Report: Puget Sound Sediment PCB and Dioxin 2008 Survey, OSV BOLD SURVEY REPORT* (EPA OSV *Bold* Survey; EPA 2008b). EPA and Ecology have determined that the 95% upper confidence limit on the mean (UCL95) of the data from the EPA OSV *Bold* Survey will be used in this FS for natural background concentrations. Data were collected from 70 sampling locations throughout Puget Sound, as well as from the area around the San Juan Islands and the Strait of Juan de Fuca. Locations for each target sampling station are displayed in Figure 4-1. A subset of these sample locations (N = 20) were located within four reference areas (Carr Inlet, Samish Bay, Holmes Harbor, and Dabob Bay) established by Ecology. In each of these reference areas, five target sediment sampling locations were located based on a stratified random sampling design. The remaining 50 sample locations were spread throughout Puget Sound and the straits of Georgia and Juan de Fuca and were intended to represent areas outside the influence of urban bays and known point sources. At five stations, a duplicate sample (or field split) was collected for quality assurance purposes. Samples were analyzed for the full suite of DMMP contaminants, including semi-volatile organic compounds, PAHs, PCB Aroclors and PCB congeners, organochlorine pesticides, and trace metals, as well as for sediment conventionals (e.g., total organic carbon [TOC], grain size, percent solids). Summary statistics (see Table 4-4) were then calculated for the EPA OSV *Bold* Survey data for each of the four human health risk drivers using the statistical software ProUCL version 4.00.04. Statistical analyses of these sediment data did not adjust for the spatial bias resulting from repeated sampling of four reference areas, or other spatial aspects of how the sample locations were distributed.

4.3.4.1 Natural Background for Arsenic in Sediment

Arsenic was detected in all of the samples from the EPA OSV *Bold* Survey (Table 4-4). Concentrations ranged from 1.1 to 21 milligrams per kilogram dry weight (mg/kg dw), with a mean concentration of 6.5 mg/kg dw, and an UCL95 of 7.3 mg/kg dw. Using the UCL95 statistic, the background concentration for arsenic is rounded to 7 mg/kg dw.

4.3.4.2 Natural Background for Total PCBs in Sediment

Total PCBs as Aroclors were below reporting limits in the majority of sediment samples from the EPA OSV *Bold* Survey (Table 4-4). The PCB congener method, with its lower reporting limits, produced a detection frequency of 100%, based on quantifying at least one PCB congener in each sample. Total PCBs in each sample were calculated by summing the concentrations of all detected PCB congeners, consistent with the protocol in the SMS for reporting total PCBs by summing the concentrations of all detected PCB Aroclors. Using the congener results, total PCB concentrations ranged from 0.01 to 10.6 micrograms per kilogram (µg/kg) dw, with a mean of 1.2 µg/kg dw and an UCL95 of 1.5 µg/kg dw. Using the UCL95 statistic, the background concentration for total PCBs is rounded to 2 µg/kg dw.

4.3.4.3 Natural Background for cPAHs in Sediment

The detection frequency for cPAHs in the EPA OSV *Bold* Survey was 87%, based on quantifying at least one cPAH compound in each sample (Table 4-4). Total cPAHs in each sample were calculated by summing the concentrations of all detected cPAH compounds multiplied by their respective benzo(a)pyrene potency equivalency factors (PEFs), along with half the reporting limits of any undetected cPAH compounds multiplied by their respective PEFs. Concentrations ranged from 1.3 to 57.7 µg toxic equivalent (TEQ)/kg dw, with a mean concentration of 7.1 µg TEQ/kg dw and an UCL95 of 8.9 µg TEQ/kg dw.[7] Using the UCL95 statistic, the background concentration for cPAHs is rounded to 9 µg TEQ/kg dw.

4.3.4.4 Natural Background for Dioxins/Furans in Sediment

The detection frequency for dioxins/furans in the EPA OSV *Bold* Survey was 100%, based on quantifying at least one congener in each sample (Table 4-4). The total TEQ of dioxins/furans (relative to that of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin) in each sample was calculated by summing the concentrations of certain detected polychlorinated dibenzo-*p*-dioxin or furan congeners multiplied by their respective toxic equivalency factors (TEFs), along with half the reporting limits of undetected polychlorinated dibenzo-*p*-dioxin or furan congeners multiplied by their respective TEFs. Concentrations ranged from 0.2 to 11.6 ng TEQ/kg dw, with a mean of 1.4 ng TEQ/kg dw (Table 4-4) and an UCL95 of 1.6 ng TEQ/kg dw.[8] Using the UCL95 statistic, the background concentration for dioxins/furans is rounded to 2 ng TEQ/kg dw.

4.3.5 Role of Practical Quantitation Limits

Both CERCLA and MTCA allow consideration of PQLs when formulating PRGs to address circumstances in which a concentration determined to be protective cannot be reliably detected using state-of-the-art analytical instruments and methods. For example, if an RBTC is below the concentration at which a contaminant can be reliably quantified, then the PRG for that contaminant may default to the analytical PQL.

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[7] The uncertainty associated with handling the undetected cPAH data is negligible. To determine how nondetects affected the overall statistics, a sensitivity analysis was run. For this analysis, the concentrations of the undetected cPAH compounds were set to zero. The concentrations of the individual detected cPAH compounds were multiplied by their respective PEFs and the products were summed. The results indicate a mean of 6.9 µg TEQ/kg dw and an UCL95 of 8.0 µg TEQ/kg dw.

[8] The uncertainty associated with handling the undetected dioxin/furan data is negligible. To determine how nondetects affected the overall statistics, a sensitivity analysis was run. For this analysis, the concentrations of the undetected dioxin/furan congeners were set to zero. The concentrations of the individual detected dioxin/furan congeners were multiplied by their respective TEFs and the products were summed. The results indicate a mean of 1.2 ng TEQ/kg dw and an UCL95 of 1.5 ng TEQ/kg dw.

MTCA defines the PQL as:

> *…the lowest concentration that can be reliably measured within specified limits of precision, accuracy, representativeness, completeness, and comparability during routine laboratory operating conditions, using department approved methods* (WAC 173-340-200).

In simpler terms, the PQL is the minimum concentration for an analyte that can be reported with a high degree of certainty.

Tables 4-5 and 4-6 list the risk-driver specific PQLs developed for the RI sediment sampling programs and documented in the associated quality assurance project plans. These PQLs represent the lowest values that can be reliably quantified when the sample matrix (in this case, sediment) is free of interfering compounds that can reduce sensitivity and raise reporting limits. Also, these tables present the range of actual sample PQLs reported by the laboratories for the data in the RI database. These results reflect the range of what the laboratories were able to achieve given the composition of and matrix complexity associated with LDW sediment samples.

Analytical quantitation limits are generally not expected to exceed RBTCs, SQS, or natural background concentrations for samples of low matrix complexity. However, empirical evidence from the RI suggests that, on a case-by-case basis, matrix interferences have the potential to preclude quantification to concentrations below the PRGs (and ultimately the cleanup levels and standards) established for cleanup of LDW sediments.

4.4 Preliminary Remediation Goals

PRGs for sediment are derived from a comparison of ARARs, RBTCs, background concentrations, and PQLs. For each RAO and risk driver, the PRG is the higher value between the natural background concentration and the lowest RBTC.[9] PQLs were also considered and were not found to influence selection of the PRGs (i.e., all PRGs are above PQLs). The RAOs and PRGs are used in Section 6 of the FS to identify AOPCs and were considered in selecting the RALs. Section 9 compares estimated concentrations of risk drivers to PRGs as one measure of the effectiveness of the remedial alternatives.

Tables 4-7 and 4-8 summarize the analysis and selection of sediment PRGs for the risk-driver COCs. Table 4-7 focuses on the four human health risk drivers and the wildlife risk driver, and is subdivided to address the various spatial applications of the PRGs for each RAO. Table 4-8 contains the PRG analysis for the remaining SMS risk drivers (i.e.,

[9] SQS and CSL values for the 41 SMS risk-driver COCs are the RBTCs for protection of benthic organisms. Sediment RBTCs were calculated (see Section 3) for protection of ecological receptors (river otters) and humans.

the risk-driver COCs for RAO 3). PRGs were not developed for the other COCs identified in the RI. The potential for risk reduction for the other COCs following remedial action is evaluated in Section 9.

The PRGs identified in Tables 4-7 and 4-8 are derived from RBTCs, natural background, or SQS values. The PRGs are applied on either a point basis or an average basis over a given exposure area depending on the COC, exposure pathway, and receptor of concern. PRGs for RAOs 1, 2, and 4 are applied on a site-wide average basis that requires a sediment spatially-weighted average concentration (SWAC) over the applicable exposure area to be below the PRG. These SWACs have been calculated to evaluate and compare remedial alternatives; ultimate compliance for remedial actions will be based on the UCL95.

For RAO 1, the numerical PRG for total PCBs is natural background because the sediment RBTCs[10] are below natural background for the RME seafood consumption scenarios. RBTCs were not derived for dioxins/furans (see Section 3.2.4), but were presumed also to be below natural background levels for the RME seafood consumption scenarios. Therefore, natural background is the PRG for dioxins/furans for RAO 1. Arsenic and cPAH PRGs were not identified for the human health seafood consumption pathway (RAO 1). Excess cancer risks for these two risk drivers were largely attributable to the consumption of clams. Based on data collected during the RI, there is no credible relationship between cPAH or arsenic concentrations in sediment and concentrations in clam tissue (Section 8 of the RI, Windward 2010). However, the development and evaluation of remedial alternatives in the latter sections of the FS discuss the need for future investigations of the sediment/clam tissue relationships for arsenic and cPAHs. Further, meeting the PRGs defined in Tables 4-7 and 4-8 should lead to reductions in sediment concentrations of arsenic and cPAHs (see discussion of RALs in Section 6). PRGs based on natural background are unlikely to be achieved by any of the remedial alternatives developed in this FS. This is partly because of COC concentrations in inflowing sediment from the Green/Duwamish River system, as predicted in the bed composition model used in this FS (see Section 5). In addition, the urban setting of the LDW will make it difficult to achieve natural background for PCBs and dioxins/furans. However, in accordance with MTCA, natural background concentrations were used in this FS for setting background-based PRGs.

For RAO 2, PRGs are based on the sediment RBTCs (1×10^{-6} or natural background, whichever is higher) developed for three exposure scenarios: netfishing, tribal clamming, and beach play. PRGs are applied on a spatially-weighted average basis over

[10] Sediment RBTCs were calculated only for the 1×10^{-4} risk threshold. The contribution of PCBs in water alone (even at concentrations similar to those in upstream water) was high enough to result in seafood consumption risks for Adult and Child Tribal RME and Asian and Pacific Islander RME scenarios exceeding the 1×10^{-6} and 1×10^{-5} excess cancer risk thresholds even in the absence of any contribution from sediment (Table 3-9).

a given exposure area (e.g., site-wide for netfishing). Except for arsenic, the PRGs for the RAO 2 risk drivers are based on their RBTCs. The arsenic PRG for RAO 2 is based on natural background, which may be difficult to achieve by any of the remedial alternatives developed in this FS, for the same reasons explained above for total PCBs and dioxins/furans for RAO 1.

For RAO 3, the SMS numerical criteria apply on a point basis (Table 4-6). As noted in Section 4.3.1, WAC 173-204-570(4) specifies that the site-specific cleanup standards shall be as close as practicable to the cleanup objective (the SQS) but in no case shall exceed the minimum cleanup level (the CSL). For this reason, the PRGs for RAO 3 in this FS are set to the SQS. However, where co-located toxicity test data are available, sediment toxicity results override the numerical criteria for RAO 3. (However, toxicity test results do not override PRGs for RAOs 1, 2, and 4 because toxicity test results are only relevant for an assessment of effects on benthic fauna, not on other ecological or human receptors.)

For RAO 4, the PRG for seafood consumption by ecological receptors is set to the sediment RBTC for river otter (hazard quotient less than 1).

Table 4-1 ARARs for the Lower Duwamish Waterway

Topic	Standard or Requirement	Regulatory Citation		Comment
		Federal	State	
Sediment Quality	Sediment quality standards; cleanup screening levels		Sediment Management Standards (WAC 173-204)	The SMS are MTCA rules and an ARAR under CERCLA. Numerical standards for the protection of benthic marine invertebrates.
Fish Tissue Quality	Concentrations of contaminants in fish tissues	Food and Drug Administration Maximum Concentrations of Contaminants in Fish Tissue (49 CFR 10372-10442)		The Washington State Department of Health assesses the need for fish consumption advisories.
Surface Water Quality	Surface Water Quality Standards	Ambient Water Quality Criteria established under Section 304(a) of the Clean Water Act (33 USC 1251 et seq) http://www.epa.gov/ost/criteria/wqctable/	Surface Water Quality Standards (RCW 90-48; WAC 173-201A)	State surface water quality standards apply where the State has adopted, and EPA has approved, Water Quality Standards that are more stringent than Federal recommended Water Quality Criteria established under Section 304(a) of the Clean Water Act. Both chronic and acute standards, and marine and freshwater are used as appropriate.
Land Disposal of Waste	Disposal of materials containing PCBs	Toxic Substances Control Act (15 USC 2605; 40 CFR Part 761)		
	Hazardous waste	Resource Conservation and Recovery Act Land Disposal Restrictions (42 USC 7401-7642; 40 CFR 268)	Dangerous Waste Regulations Land Disposal Restrictions (RCW 70.105; WAC 173-303, 140-141)	
Waste Treatment Storage and Disposal	Disposal limitations	Resource Conservation and Recovery Act (42 USC 7401-7642;40 CFR 264 and 265)	Dangerous Waste Regulations (RCW 70.105; WAC 173-303)	
Noise	Maximum noise levels		Noise Control Act of 1974 (RCW 80.107; WAC 173-60)	
Groundwater	Groundwater quality	Safe Drinking Water Act MCLs and non-zero MCLGs (40 CFR 141)	RCW 43.20A.165 and WAC 173-290-310	For on-site potable water, if any.

Table 4-1 ARARs for the Lower Duwamish Waterway (continued)

Topic	Standard or Requirement	Regulatory Citation		Comment
		Federal	State	
Dredge/Fill and Other In-water Construction Work	Discharge of dredged/fill material into navigable waters or wetlands	Clean Water Act (33 USC 401 et seq.; 33 USC 141; 33 USC 1251-1316; 40 CFR 230, 231, 404; 33 CFR 320-330) Rivers and Harbors Act (33 USC 401 et seq.)	Hydraulic Code Rules (RCW 75.20; WAC 220-110)	For in-water dredging, filling, or other construction.
	Open-water disposal of dredged sediments	Marine Protection, Research and Sanctuaries Act (33 USC 1401-1445; 40 CFR 227)	DMMP (RCW 79.90; WAC 332-30-166)	
Solid Waste Disposal	Requirements for solid waste handling management and disposal	Solid Waste Disposal Act (42 USC 215103259-6901-6991; 40 CFR 257-258)	Solid Waste Handling Standards (RCW 70.95; WAC 173-350)	
Discharge to Surface Water	Point source standards for new discharges to surface water	National Pollutant Discharge Elimination System (40 CFR 122, 125)	Discharge Permit Program (RCW 90.48; WAC 173-216, 222)	
Shoreline	Construction and development		Shoreline Management Act (RCW 90.58; WAC 173-16); King County and City of Seattle Shoreline Master Plans (KCC Title 25; SMC 23.60); City of Tukwila Shoreline Master Program (TMC 18.44)	For construction within 200 feet of the shoreline.
Floodplain Protection	Avoid adverse impacts, minimize potential harm	Executive Order 11988, Protection of Floodplains (40 CFR 6, Appendix A); FEMA National Flood Insurance Program Regulations (44 CFR 60.3Ld)(3)).		For in-water construction activities, including any dredge or fill operations. Includes local ordinances: KCC Title 9 and SMC 25.09.
Critical (or Sensitive) Area ARAR	Evaluate and mitigate impacts		Growth Management Act (RCW 36.70a); King County Critical Area Ordinance (KCC Title 21A.24); City of Seattle (SMC 25.09); City of Tukwila Sensitive Area Ordinance (TMC 18.45)	

Table 4-1 ARARs for the Lower Duwamish Waterway (continued)

Topic	Standard or Requirement	Regulatory Citation		Comment
		Federal	State	
Habitat for Fish, Plants, or Birds ARAR	Evaluate and mitigate habitat impacts	Clean Water Act (Section 404 (b)(1)); U.S. Fish and Wildlife Mitigation Policy (44 CFR 7644); U.S. Fish and Wildlife Coordination Act (16 USC 661 et seq.); Migratory Bird Treaty Act (16 USC 703-712)		
Pretreatment Standards	National Pretreatment Standards		40 CFR Part 403; Metro District Wastewater Discharge Ordinance (KCC) to be considered (as is local requirement)	
Environmental Impact Review	State Environmental Policy Act		State Environmental Policy Act RCW 43.21C; WAC 197-11-790)	Applicable to MTCA cleanups. Because the LDW is under a joint EPA/Ecology Order, Ecology has determined that CERCLA requirements are the functional equivalent of NEPA and SEPA

Notes:

ARAR = applicable or relevant and appropriate requirement; CERCLA = Comprehensive, Environmental Response, Compensation, and Liability Act; CFR = Code of Federal Regulations; DMMP = Dredged Material Management Program; EPA = U.S. Environmental Protection Agency; FEMA = Federal Emergency Management Act; KCC = King County Code; MCL = maximum contaminant level; MCLG = maximum contaminant level goal; MTCA = Model Toxics Control Act; NEPA = National Environmental Policy Act; PCB = polychlorinated biphenyl; RCW = Revised Code of Washington; SEPA = State Environmental Policy Act; SMC = Seattle Municipal Code; SMS = Sediment Management Standards; TMC = Tukwila Municipal Code; USC = United States Code; WAC = Washington Administrative Code

Table 4-2 Other Legal Requirements for the Lower Duwamish Waterway

Topic	Standard or Requirement	Regulatory Citation		Comment
		Federal	State	
Native American Graves and Sacred Sites	Evaluate and mitigate impacts to cultural resources	Native American Graves Protection and Repatriation Act (25 USC. 3001 et seq.; 43 CFR Pt. 10) and American Indian Religious Freedom Act (42 USC 1996 et seq.)		
Critical Habitat for Endangered Species	Conserve endangered or threatened species, consult with species listing agencies	Endangered Species Act of 1973 (16 USC 1531 et seq.; 50 CFR 200, 402); Magnuson-Stevens Fishery Conservation and Management Act (16 USC 1801-1884)	Endangered, threatened, and sensitive wildlife species classification (WAC 232-12-297)	Consult and obtain Biological Opinions.
Historic Sites or Structures	Requirement to avoid, minimize, or mitigate impacts to historic sites or structures	National Historic Preservation Act (16 USC 470f; 36 CFR Parts 60, 63, and 800)		Considered if implementation of the selected remedy involves removal of historic sites or structures.
Occupational Health and Safety	Requirements to provide for worker health and safety	Occupational Safety and Health Act (29 USC; 29 CFR)	Washington Industrial Safety and Health Act (RCW 49.17; WAC 296)	

Notes:

CFR = Code of Federal Regulations; RCW = Revised Code of Washington; USC = United States Code; WAC = Washington Administrative Code

Table 4-3 State and Federal Aquatic Life and Human Health Water Quality Criteria

Contaminant	State WQC (µg/L)[a]				Federal AWQC (µg/L)[b]				
	Freshwater[c]		Marine[c]		Freshwater[c]		Marine[c]		Human Health[d]
	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Organisms Only
Metals and Trace Elements									
Antimony	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	640
Arsenic	360	190	**69**	**36**	**340**	**150**	69	36	0.14[g,h]
Cadmium	3.7	1.0	42	9.3	**2.0**	**0.25**	**40**	**8.8**	n/a
Chromium (hexavalent)	**15**	**10**	**1,100**	**50**	16	11	1,100	50	n/a
Chromium (trivalent)	**550**	180	n/a	n/a	570	**74**	n/a	n/a	n/a
Copper	**17**	**11**	**4.8**	**3.1**	nc[j]	nc[j]	4.8	3.1	n/a
Lead	**65**	**2.5**	**210**	**8.1**	65	2.5	210	8.1	n/a
Mercury	2.1	**0.012**	**1.8**	**0.025**	**1.4**	0.77	1.8	0.94	0.15[i]
Nickel	1,400	160	**74**	**8.2**	**470**	**52**	74	8.2	4,600
Selenium	**20**	**5**	**290**	**71**	n/a	5	290	71	4,200
Silver	3.4	n/a	**1.9**	n/a	**3.2**	n/a	1.9	n/a	n/a
Thallium	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.47
Zinc	**110**	**100**	**90**	**81**	120	120	90	81	26,000
PAHs									
2-Chloronaphthalene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,600
Acenaphthene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	990
Anthracene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	40,000
Benzo(a)anthracene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.018[g]
Benzo(a)pyrene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.018[g]
Benzo(b)fluoranthene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.018[g]

Table 4-3 State and Federal Aquatic Life and Human Health Water Quality Criteria (continued)

Contaminant	State WQC (µg/L)[a]				Federal AWQC (µg/L)[b]				
	Freshwater[c]		Marine[c]		Freshwater[c]		Marine[c]		Human Health[d]
	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Organisms Only
***PAHs** (continued)*									
Benzo(k)fluoranthene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.018[g]
Chrysene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.018[g]
Dibenzo(a,h)anthracene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.018[g]
Fluoranthene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	140
Fluorene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5,300
Indeno(1,2,3-cd)pyrene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.018[g]
Pyrene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4,000
Phthalates									
BEHP	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.2[g]
Butyl benzyl phthalate	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,900
Diethyl phthalate	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	44,000
Dimethyl phthalate	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,100,000
Di-n-butyl phthalate	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4,500
SVOCs									
1,2,4-Trichlorobenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	70
1,2-Dichlorobenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,300
1,2-Diphenylhydrazine	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.2[g]
1,3-Dichlorobenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	960
1,4-Dichlorobenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	190
2,4,6-Trichlorophenol	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.4[g]
2,4-Dichlorophenol	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	290

Table 4-3 State and Federal Aquatic Life and Human Health Water Quality Criteria (continued)

Contaminant	State WQC (µg/L)[a]				Federal AWQC (µg/L)[b]				
	Freshwater[c]		Marine[c]		Freshwater[c]		Marine[c]		Human Health[d]
	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Organisms Only
SVOCs (continued)									
2,4-Dimethylphenol	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	850
2,4-Dinitrophenol	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5,300
2,4-Dinitrotoluene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.4[g]
2-Chlorophenol	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	150
3,3'-Dichlorobenzidine	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.028[g]
4,6-Dinitro-o-cresol (2-methyl-4,6-dinitrophenol)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	280
Benzidine	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0002
Bis(2-chloroethyl)ether	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.53[g]
Bis(2-chloroisopropyl)ether	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	65,000
Hexachlorobenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.00029[g]
Hexachlorobutadiene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	18[g]
Hexachlorocyclopentadiene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,100
Hexachloroethane	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.3[g]
Isophorone	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	960[g] (**600**[i])
Nitrobenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	690
n-Nitrosodimethylamine	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3[g]
n-Nitroso-di-n-propylamine	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.51[g]
n-Nitrosodiphenylamine	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6[g]
Pentachlorophenol	20[k]	**13**[k]	**13**	**7.9**	**19**[k]	15[k]	13	7.9	3[g]
Phenol	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	860,000

Table 4-3 State and Federal Aquatic Life and Human Health Water Quality Criteria (continued)

Contaminant	State WQC (µg/L)[a]				Federal AWQC (µg/L)[b]				
	Freshwater[c]		Marine[c]		Freshwater[c]		Marine[c]		Human Health[d]
	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Organisms Only
PCBs									
PCBs	**2**	**0.014**	**10**	**0.03**	n/a	0.014	n/a	0.03	0.000064[g]
Pesticides									
4,4'-DDD	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.00031[g]
4,4'-DDE	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.00022[g]
4,4'-DDT	**1.1**	**0.001**	**0.13**	**0.001**	1.1	0.001	0.13	0.001	0.00022[g]
Aldrin	n/a	n/a	n/a	n/a	**3.0**	n/a	**1.3**	n/a	0.000050[g]
Dieldrin	n/a	n/a	n/a	n/a	**0.24**	**0.056**	**0.71**	**0.0019**	0.000054[g]
Aldrin/dieldrin (sum)[l]	**2.5**	**0.0019**	**0.71**	**0.0019**	n/a	n/a	n/a	n/a	n/a
alpha-BHC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0049[g]
beta-BHC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.017[g]
gamma-BHC (Lindane)	2.0	**0.08**	**0.16**	n/a	**0.95**	n/a	0.16	n/a	1.8
alpha-Endosulfan	**0.22**[m]	**0.056**[m]	**0.034**[m]	**0.0087**[m]	0.22	0.056	0.034	0.0087	89 (**2**[i])
beta-Endosulfan	**0.22**[m]	**0.056**[m]	**0.034**[m]	**0.0087**[m]	0.22	0.056	0.034	0.0087	89 (**2**[i])
Endosulfan sulfate	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	89 (**2**[i])
Endrin	0.18	**0.0023**	**0.037**	**0.0023**	**0.086**	0.036	0.037	0.0023	0.06
Endrin aldehyde	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.3
Heptachlor	**0.52**	**0.0038**	**0.053**	**0.0036**	0.52	0.0038	0.053	0.0036	0.000079[g]
Heptachlor epoxide	n/a	n/a	n/a	n/a	**0.52**	**0.0038**	**0.053**	**0.0036**	0.000039[g]
Toxaphene	**0.73**	**0.0002**	**0.21**	**0.0002**	0.73	0.0002	0.21	0.0002	0.00028[g]
Chlordane	**2.4**	**0.0043**	**0.09**	**0.004**	2.4	0.0043	0.09	0.004	0.00081[g]

Table 4-3 State and Federal Aquatic Life and Human Health Water Quality Criteria (continued)

Contaminant	State WQC (µg/L)[a]				Federal AWQC (µg/L)[b]				
	Freshwater[c]		Marine[c]		Freshwater[c]		Marine[c]		Human Health[d]
	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Organisms Only
VOCs									
1,1,2,2-Tetrachloroethane	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4[g]
1,1,2-Trichloroethane	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	16[g]
1,1-Dichloroethene (1,1-dichloroethylene)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7,100
1,2-Dichloroethane	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	37
1,2-Dichloropropane	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	15[g]
Acrolein	n/a	n/a	n/a	n/a	**3**	**3**	n/a	n/a	9
Acrylonitrile	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.25[g]
Benzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	51[g]
Bromodichloromethane (dichlorobromomethane)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	17[g]
Bromoform	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	140[g]
Bromomethane (methyl bromide)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,500
Carbon tetrachloride	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.6[g]
Chlorobenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,600
Chloroform	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	470
Dibromochloromethane (chlorobromomethane)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	13[g]
Dichloromethane (methylene chloride)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	590[g]
Ethylbenzene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2,100
Tetrachloroethene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.3[g]
Toluene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	15,000
trans-1,2-Dichloroethene	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10,000
Trichloroethene (trichloroethylene)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	30g

Table 4-3 State and Federal Aquatic Life and Human Health Water Quality Criteria (continued)

Contaminant	State WQC (µg/L)[a]				Federal AWQC (µg/L)[b]				
	Freshwater[c]		Marine[c]		Freshwater[c]		Marine[c]		Human Health[d]
	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Acute[e]	Chronic[f]	Organisms Only
***VOCs** (continued)*									
Vinyl chloride	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.4[g]
Dioxins and Furans									
2,3,7,8 TCDD	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.1E-09[g]

Notes:

1. Underlined values are hardness-dependent, and were calculated using a hardness value of 100 mg/L, which is the default assumption when site-specific hardness data are not available. Existing site-specific data or site-specific data that may be collected can be used to adjust values rather than using a default hardness value of 100 mg/L. Bolded criteria are the lower of the state and federal criteria (state criteria are bolded if the state and federal criteria are the same). The lower of the human health criteria (when multiple criteria are available) is also bolded.

a. Standards are from WAC 173-201A-240. Available from: http://apps.leg.wa.gov/wac/default.aspx?cite=173-201A-240 (accessed on June 4, 2010).

b. Standards are from the national recommended EPA AWQC (except where noted). National recommended EPA AWQC available from: http://www.epa.gov/waterscience/criteria/wqctable/ (accessed on June 4, 2010).

c. Aquatic life WQC are based on dissolved concentrations for metals (except mercury) and total concentrations for mercury and organic compounds.

d. Human health WQC are based on dissolved concentrations for all contaminants.

e. Acute WQC are 1-hr average concentrations not to be exceeded more than once every 3 years, with the exception of silver and pesticide concentrations, which are instantaneous concentrations not to be exceeded at any time, or the PCB concentration, which is a 24-hr average not to be exceeded at any time.

f. Chronic WQC are 4-day average concentrations not to be exceeded more than once every 3 years, with the exception of pesticide and PCB concentrations, which are 24-hr average concentrations not to be exceeded at any time.

g. Human health WQC are based on 1 x 10^{-6} excess cancer risk for carcinogenic contaminants.

h. Criterion represents the inorganic fraction of arsenic.

i. Standards are from 40 CFR 131.36 (NTR), as referenced in WAC 173-201A-240. Available from: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=879a68e0f8b500cb27fc2f8df4ec7f56&rgn=div5&view=text&node=40:21.0.1.1.18&idno=40 (accessed on June 4, 2010).

j. Criteria based on the biotic ligand model. The acute and chronic biotic ligand model-based criteria for copper would be 2.3 and 1.5 µg/L, respectively, assuming DOC = 0.5 mg/L, pH = 7.5, hardness = 85 mg/L, and temperature of 20°C.

k. The freshwater aquatic life WQC for pentachlorophenol is pH-dependent; a pH of 7.8 was assumed, which is the default assumption.

l. Aldrin is metabolically converted to dieldrin. Therefore, the sum of aldrin and dieldrin concentrations is compared with the dieldrin criteria.

m. Standards are for endosulfan.

AWQC = ambient water quality criteria; BEHP = Bis(2-ethylhexyl) phthalate; BHC = benzene hexachloride; DDD – dichlorodiphenyldichloroethane; DDE = dichlorodiphenyldichloroethylene; DDT = dichlorodiphenyltrichloroethane; DOC = dissolved organic carbon; MCL= maximum contaminant level; µg/L = microgram per liter; n/a = not available; nc = not calculated; NTR = National Toxics Rule; PAH = polycyclic aromatic hydrocarbon; PCB = polychlorinated biphenyl; SVOC = semivolatile organic compound; TCDD = tetrachlorodibenzo-*p*-dioxin; VOC = volatile organic compound; WAC = Washington Administrative Code; WQC = water quality criteria

Table 4-4 Summary of Arsenic, Total PCB, cPAH, and Dioxin/Furan Datasets for Natural Background

Human Health Risk-Driver COC	Detection Frequency	Concentration							UCL Type
		Minimum	Maximum	Mean	Median	90th Percentile[a]	UCL95	UCL95 (rounded value)[b]	
Arsenic (mg/kg dw)	70/70	1.1	21	6.5	5.9	11.0	7.3	7	Approximate Gamma UCL95
Total PCBs as Aroclors (μg/kg dw)	6/70	2.1	31	11	4.4	8.0	6.5	7	KM (Percentile Bootstrap) UCL95
Total PCBs as Congeners (μg/kg dw)	70/70	0.01	10.6	1.2	0.6	2.7	1.5	2	Approximate Gamma UCL95
cPAHs (μg TEQ/kg dw)	61/70	1.3	57.7	7.1	4.5	14.7	8.9	9	KM (BCA) UCL95
Dioxins/Furans (ng TEQ/kg dw)	70/70	0.2	11.6	1.4	1.0	2.2	1.6	2	H-UCL95

Notes:

1. Dataset collected throughout Puget Sound by EPA in 2008 and referred to as the EPA OSV *Bold* Survey.
2. Summary statistics and UCL were calculated using ProUCL 4.00.04 statistical software.
3. Total PCBs were calculated by summing the concentrations of detected PCB Aroclors or detected PCB congeners. In cases where no PCB Aroclors were detected, the highest reporting limit for an individual PCB Aroclor was used as the value of total PCBs. Total cPAHs were calculated by summing the concentrations of all detected cPAH compounds multiplied by their respective potency equivalency factors (PEFs), along with half the reporting limits of any undetected cPAH compounds multiplied by their respective PEFs.
4. The total toxic equivalent (TEQ) of dioxins/furans (relative to that of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin) was calculated by summing the concentrations of detected polychlorinated dibenzo-*p*-dioxin or furan congeners multiplied by their respective toxic equivalency factors (TEFs), along with half the reporting limits of undetected polychlorinated dibenzo-*p*-dioxin or furan congeners multiplied by their respective TEFs.

a. Using MTCAStat software, instead of EPA's ProUCL, risk drivers may be slightly higher.

b. Rounded values of UCL95s are used as natural background in this FS.

BCA = bias-corrected accelerated; COC = contaminant of concern; cPAH = carcinogenic polycyclic aromatic hydrocarbon; dw = dry weight; FS = feasibility study; H-UCL = UCL based on Land's H-statistic; kg = kilogram; KM = Kaplan Meier method for calculating a UCL; µg = micrograms; mg = milligram; ng = nanogram; PCB = polychlorinated biphenyl; PEF = potency equivalency factor; TEF = toxic equivalency factor; TEQ = toxic equivalent; UCL95 =95% upper confidence limit on the mean

Table 4-5 Practical Quantitation Limits, Natural Background, and Risk-Based Threshold Concentrations for the Human Health and Ecological Risk-Driver COCs

Human Health& Ecological Risk-Driver COC	Practical Quantitation Limits			Natural Background[b]	Risk-Based Threshold Concentrations				
	EPA Method	RI QAPP RLs[a]	Range of RLs from undetected values		Spatial Scale of Exposure[c]	RAO 1: Human Seafood Consumption	RAO 2: Human Direct Contact	RAO 3: Benthic Organisms	RAO 4: Ecological (River Otter)
Total PCBs (µg/kg dw)	8082	4[d]	0.56 – 50[e]	2	Site-wide	nc (7 - 185)[f]	1,300	n/a	(128 - 159)[g]
					Tribal Clamming	n/a	500	n/a	n/a
					Beach Play	n/a	1,700	n/a	n/a
					Point	n/a	n/a	12/65[h]	n/a
Arsenic (mg/kg dw)	6010B	5	3.1 – 31	7	Site-wide	n/c[i]	3.7	n/a	n/a
					Tribal Clamming	n/a	1.3	n/a	n/a
					Beach Play	n/a	2.8	n/a	n/a
					Point	n/a	n/a	57/93[h]	n/a
cPAH (µg TEQ/kg dw)	8270D	6.3 – 20 µg/kg [j]	9.0 – 130 µg/kg [j]	9	Site-wide	n/c[i]	380	n/a	n/a
					Tribal Clamming	n/a	150	n/a	n/a
					Beach Play	n/a	90	n/a	n/a
					Point	n/a	n/a	n/a[k]	n/a
Dioxins/Furans (ng TEQ/kg dw)	1613B	1 – 10 ng/kg [l]	0.12 – 7.7 ng/kg [l]	2	Site-wide	nc (bg)	37	n/a	n/a
					Tribal Clamming	n/a	13	n/a	n/a
					Beach Play	n/a	28	n/a	n/a
					Point	n/a	n/a	n/a	n/a

Notes:

a. Reporting limits from Table A-1, Round 3 Surface Sediment QAPP Addendum (Windward 2006) in dry weight units on untransformed data.

b. UCL95 values are calculated from the EPA OSV *Bold* Survey dataset using ProUCL.

Table 4-5 Practical Quantitation Limits, Natural Background, and Risk-Based Threshold Concentrations for the Human Health and Ecological Risk-Driver COCs (continued)

c. The spatial scale of site-wide exposure is RAO-specific: (seafood consumption for RAO 1 and RAO 4; netfishing for RAO 2).

d. PCB RLs (as Aroclors) reported in Table A-1, Round 3 Surface Sediment QAPP Addendum (Windward 2006). RLs for individual PCB congeners are much lower (0.5 to 1 ng/kg).

e. Range of RLs for undetected values were queried from the RI database and represent RLs for undetected total PCBs. For samples in which none of the individual Aroclors are detected, the total PCB concentration value is represented as the highest RL of an individual Aroclor, and assigned a U-qualifier, indicating no detected concentrations. Individual undetected Aroclors were not reported because they are not included in the calculation of total PCBs when other Aroclors are detected in the sample.

f. RBTC <1 µg/kg dw at risk levels of 10^{-5} and 10^{-6}, and RBTC range of 7 to 185 µg/kg dw for the three RME seafood consumption scenarios at the 10^{-4} risk level.

g. Values represent best-fit estimates for two different dietary scenarios as reported in the RI (Windward 2010).

h. Total PCB concentration units are mg/kg oc and the two values are SQS/CSL. Arsenic concentration units are mg/kg dw and the two values are SQS/CSL.

i. Arsenic and cPAH PRGs are undefined for the human health seafood consumption pathway (RAO 1). Seafood consumption excess cancer risks for these two risk drivers were largely attributable to the consumption of clams. There is no credible relationship, based on site data, relating cPAH or arsenic concentrations in sediment to concentrations in clam tissue (Section 8 of the RI, Windward 2010). Section 8 of the FS discusses the need for future investigations of the sediment/tissue relationships for arsenic and cPAHs.

j. cPAH TEQ RLs are based on those for the individual PAH compounds used in the TEQ calculation. All individual PAH compounds used in the cPAH calculation have an RL of 20 except for dibenzo[a,h]anthracene, which has an RL of 6.3. RLs reported for undetected values are based on calculated cPAHs and can be found in Table A-1, of Round 3 Surface Sediment QAPP Addendum (Windward 2006).

k. Low- and high-molecular weight PAHs are addressed by the SMS. Criteria are set for both groupings and for individual PAH compounds.

l. Dioxin/furan TEQ RLs are based on those for the individual congeners used in the TEQ calculation. RLs for undetected values are in Table A-1, Round 3 Surface Sediment QAPP Addendum (Windward 2006).

bg = natural background; COC = contaminant of concern; cPAH = carcinogenic polycyclic aromatic hydrocarbon; CSL = cleanup screening level; dw = dry weight; EPA = U.S. Environmental Protection Agency; LDW = Lower Duwamish Waterway; µg/kg = micrograms per kilogram; mg/kg = milligrams per kilogram; n/a = not applicable; nc = no value calculated; nc (bg) = not calculated, RBTC value expected to be below background; ng/kg = nanograms per kilogram; oc = organic carbon; PCB = polychlorinated biphenyl; QAPP = quality assurance project plan; RAO = remedial action objective; RBTC = risk-based threshold concentration; RI = remedial investigation; RL = reporting limit; RME = reasonable maximum exposure; SQS = sediment quality standard; TEQ = toxic equivalent; UCL95 = 95% upper confidence limit on the mean

Table 4-6 Practical Quantitation Limits and Risk-Based Threshold Concentrations for Benthic Risk-Driver COCs

Benthic Risk-Driver COC	Practical Quantitation Limits			Risk-Based Threshold Concentrations RAO 3: Sediment Management Standards[c]		
	EPA Method	RI QAPP RLs[a]	Range of RLs from Undetected Values[b]	Spatial Scale of Exposure	Sediment Quality Standard (SQS)	Cleanup Screening Level (CSL)
SMS Metals		(mg/kg dw)			(mg/kg dw)	
Arsenic	6010B	5	3.1 – 31	Point	57	93
Cadmium	6010B	0.2	0.4 – 2.5		5.1	6.7
Chromium	6010B	0.5	0.25 – 1		260	270
Copper	6010B	0.2	0.5 – 1		390	390
Lead	6010B	2	1.25 – 8		450	530
Mercury	7471A	0.05	0.02 – 0.1		0.41	0.59
Silver	6010B	0.3	0.046 – 5		6.1	6.1
Zinc	6010B	2	0.5 – 2		410	960
Dry Weight Basis SMS Organic Compounds		(µg/kg dw)			(µg/kg dw)	
4-methylphenol	8270D	6.7	8.6 – 2,000	Point	670	670
2,4-dimethylphenol	8270D	6.7	6.0 – 2,000		29	29
Benzoic acid	8270-SIM	20	13 – 3,000		650	650
Benzyl alcohol	8270-SIM	2	9.2 – 690		57	73
Pentachlorophenol	8270-SIM	10	7.6 – 4,900		360	690
Phenol	8270D	20	7.3 – 790		420	1,200
oc-normalized SMS Organic Compounds[d]		(µg/kg dw)			(mg/kg oc)	
Total PCBs	8082	4	0.56 – 50	Point	12	65
Acenaphthene	8270D	20	1.8 – 2,000		16	57
Anthracene	8270D	20	13 – 2,000		220	1,200
Benzo(a)pyrene	8270D	20	6.4 – 350		99	210
Benz(a)anthracene	8270D	20	6.4 – 200		110	270
Total benzofluoranthenes	8270D	20	n/a		230	450
Benzo(g,h,i)perylene	8270D	20	13 – 2,000		31	78
Chrysene	8270D	20	18 – 170		110	460
Dibenz(a,h)anthracene	8270D	6.3	1.0 – 2,000		12	33
Indeno(1,2,3-cd)pyrene	8270D	20	6.4 – 1,600		34	88
Fluoranthene	8270D	20	19 – 340		160	1,200
Fluorene	8270D	20	1.8 – 2,000		23	79
Naphthalene	8270D	20	1.0 – 2,000		99	170
Phenanthrene	8270D	20	18 – 200		100	480
Pyrene	8270D	20	18 – 170		1,000	1,400
HPAH	8270D	n/a	n/a		960	5,300
LPAH	8270D	n/a	n/a		370	780
Bis(2-ethylhexyl)phthalate	8270D	20	15 – 1,500		47	78
Butyl benzyl phthalate	8270-SIM	2	1.8 – 2,000		4.9	64
Dimethyl phthalate	8270D	20	1.8 – 2,000		53	53
1,2-dichlorobenzene	8270-SIM	2	0.4 – 2,000		2.3	2.3
1,4-dichlorobenzene	8270-SIM	2	0.2 – 2,000		3.1	9
1,2,4-trichlorobenzene	8270-SIM	2	0.4 – 2,000		0.81	1.8
2-methylnaphthalene	8270D	20	1.0 – 2,000		38	64
Dibenzofuran	8270D	20	1.7 – 2,000		15	58
Hexachlorobenzene	8081A	1.0	0.11 – 2,000		0.38	2.3
n-Nitrosodiphenylamine	8270-SIM	10	1.8 – 2,000		11	11

Notes:
1. All QAPP-based RLs are below the SQS except for n-nitrosodiphenylamine.
2. Background concentrations were not calculated for the COCs listed in this table because benthic RBTCs are not below natural background.

a. Reporting limits from Table A-1, Round 3 Surface Sediment QAPP Addendum (Windward 2006) in dry weight units. Low level reporting limits for contaminants analyzed by EPA method 8279-SIM from Analytical Resources, Incorporated (www.arilabs.com).
b. Range of RLs reported in Remedial Investigation dataset in instances where constituent(s) were not detected. All RLs shown in dry weight units.
c. Under the SMS, sediment cleanup standards are established on a site-specific basis within an allowable range of contamination. The SQS and CSL define this range. However, the final cleanup level will be set in consideration of the net environmental effects, cost, and engineering feasibility of different cleanup alternatives (WAC 173-204-570(4)).
d. The tabulated SMS values are oc-normalized and are screened against the RLs using the underlying apparent effects threshold concentrations, which are dry weight-based.

COC = contaminant of concern; CSL = cleanup screening level; dw = dry weight; EPA = U.S. Environmental Protection Agency; HPAH = high-molecular-weight polycyclic aromatic hydrocarbon; LDW = Lower Duwamish Waterway; LPAH = low-molecular-weight polycyclic aromatic hydrocarbon; µg/kg = micrograms per kilogram; mg/kg = milligrams per kilogram; n/a = not applicable; oc = organic carbon; PQL = practical quantitation limit; QAPP = quality assurance project plan; RAO = remedial action objective; RL = reporting limit; SIM = selected ion monitoring; SMS = Sediment Management Standards; SQS = sediment quality standard

Table 4-7 Preliminary Remediation Goals for Total PCBs, Arsenic, cPAHs, and Dioxins/Furans for Human Health and Ecological Risk-Driver COCs

Risk-Driver COC	Preliminary Remediation Goals					
	RAO 1: Human Seafood Consumption	RAO 2: Human Direct Contact	RAO 4: Ecological (River Otter)	Basis	Statistical Metric for Application	Spatial Scale of PRG Application
Total PCBs (µg/kg dw)	2	1,300	128-159	bg (RAO 1) RBTC (RAO 2) RBTC (RAO 4)	SWAC	Site-wide
	n/a	500	n/a	RBTC	SWAC	Clamming Areas
	n/a	1,700	n/a	RBTC	SWAC	Individual Beaches
Arsenic (mg/kg dw)	n/a	7[a]	n/a	bg	SWAC	Site-wide
	n/a	7	n/a	bg	SWAC	Clamming Areas
	n/a	7	n/a	bg	SWAC	Individual Beaches
cPAH (µg TEQ/kg dw)	n/a	380[a]	n/a	RBTC	SWAC	Site-wide
	n/a	150	n/a	RBTC	SWAC	Clamming Areas
	n/a	90	n/a	RBTC	SWAC	Individual Beaches
Dioxins/Furans (ng TEQ/kg dw)	2[b]	37	n/a	bg (RAO 1) RBTC (RAO 2)	SWAC	Site-wide
	n/a	13	n/a	RBTC	SWAC	Clamming Areas
	n/a	28	n/a	RBTC	SWAC	Individual Beaches

Notes:

1. The PRGs for RAO 3 are shown separately in Table 4-8. The PRGs were developed for the 41 COCs that have been identified as benthic risk drivers for RAO 3.

a. Arsenic and cPAH PRGs are undefined for the human health seafood consumption pathway (RAO 1). Seafood consumption excess cancer risks for these two risk drivers were largely attributable to the consumption of clams. There is no credible relationship, based on site data, relating cPAH or arsenic concentrations in sediment to concentrations in clam tissue (Section 8 of the RI, Windward 2010). Section 8 of the FS discusses the need for future investigations of the sediment/tissue relationships for arsenic and cPAHs.

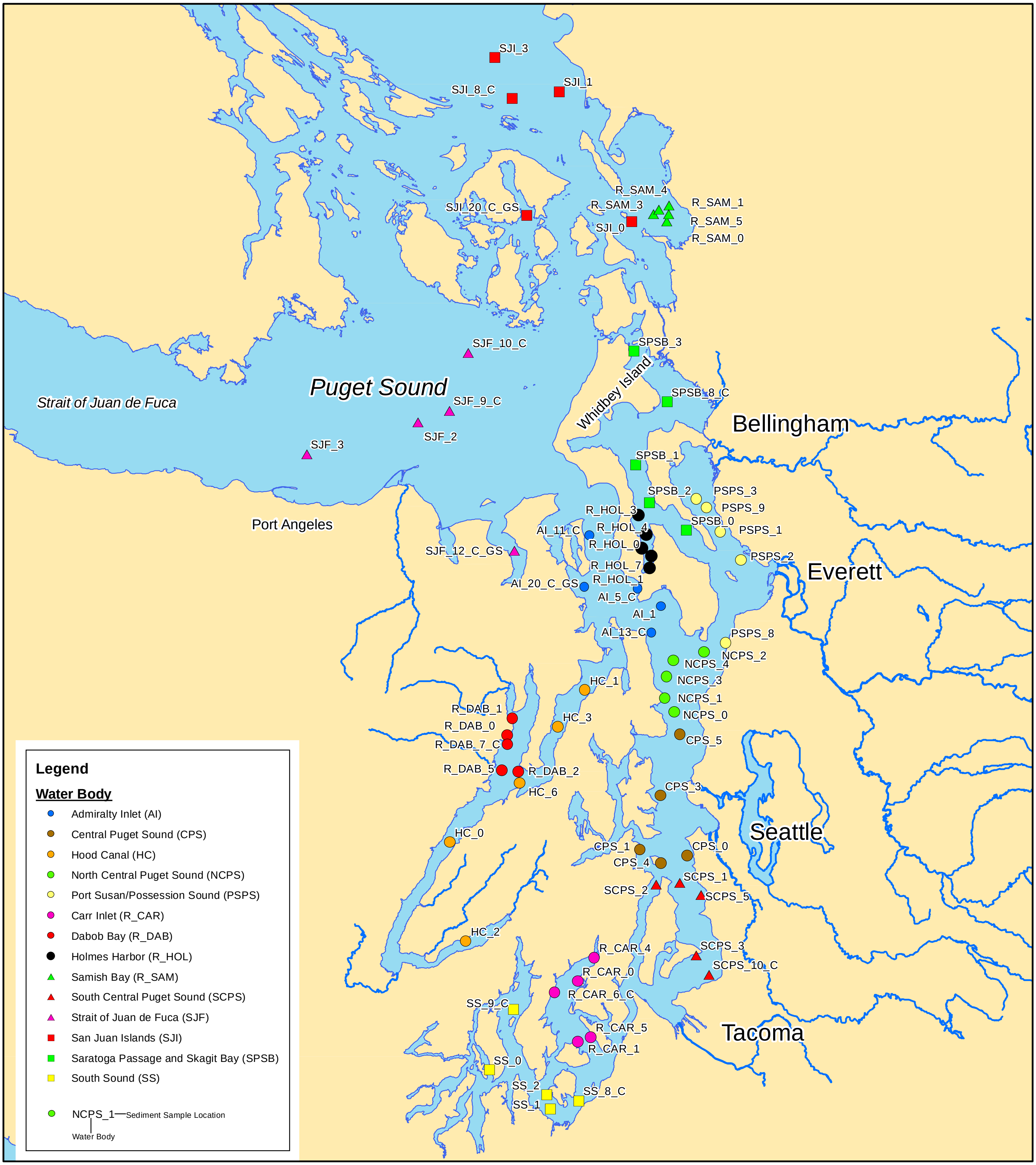
b. Although risks associated with consumption of dioxins/furans in resident seafood were not quantitatively assessed in the baseline HHRA, those risks were assumed to be unacceptable, and the associated sediment concentration was assumed to be below natural background concentrations.

bg = natural background; COC = contaminant of concern; cPAH = carcinogenic polycyclic aromatic hydrocarbon; µg/kg = micrograms per kilogram; mg/kg = milligrams per kilogram; n/a = not applicable; ng/kg = nanograms per kilogram; oc = organic carbon; PCB = polychlorinated biphenyl; PRG = preliminary remediation goal; RAO = remedial action objective; RBTC = risk-based threshold concentration; SMS = Sediment Management Standards; SWAC = spatially-weighted average concentration; TEQ = toxic equivalent

Table 4-8 Preliminary Remediation Goals for Benthic Risk-Driver COCs

Benthic Risk-Driver COC	Preliminary Remediation Goals for RAO 3			
	Value	Basis	Statistical Metric	Spatial Scale of PRG Application
SMS metals	**(mg/kg dw)**			
Arsenic	57	SQS	Point Concentration or Toxicity Test Override	Point
Cadmium	5.1	SQS		
Chromium	260	SQS		
Copper	390	SQS		
Lead	450	SQS		
Mercury	0.41	SQS		
Silver	6.1	SQS		
Zinc	410	SQS		
Dry Weight Basis SMS Organic Compounds	**(µg/kg dw)**			
4-methylphenol	670	SQS	Point Concentration or Toxicity Test Override	Point
2,4-dimethylphenol	29	SQS		
Benzoic acid	650	SQS		
Benzyl alcohol	57	SQS		
Pentachlorophenol	360	SQS		
Phenol	420	SQS		
oc-normalized SMS Organic Compounds[d]	**(mg/kg oc)**			
Total PCBs	12	SQS	Point Concentration or Toxicity Test Override	Point
Acenaphthene	16	SQS		
Anthracene	220	SQS		
Benzo(a)pyrene	99	SQS		
Benz(a)anthracene	110	SQS		
Total benzofluoranthenes	230	SQS		
Benzo(g,h,i)perylene	31	SQS		
Chrysene	110	SQS		
Dibenz(a,h)anthracene	12	SQS		
Indeno(1,2,3-cd)pyrene	34	SQS		
Fluoranthene	160	SQS		
Fluorene	23	SQS		
Naphthalene	99	SQS		
Phenanthrene	100	SQS		
Pyrene	1,000	SQS		
HPAH	960	SQS		
LPAH	370	SQS		
Bis(2-ethylhexyl)phthalate	47	SQS		
Butyl benzyl phthalate	4.9	SQS		
Dimethyl phthalate	53	SQS		
1,2-dichlorobenzene	2.3	SQS		
1,4-dichlorobenzene	3.1	SQS		
1,2,4-trichlorobenzene	0.81	SQS		
2-methylnaphthalene	38	SQS		
Dibenzofuran	15	SQS		
Hexachlorobenzene	0.38	SQS		
n-Nitrosodiphenylamine	11	SQS		

COC = contaminant of concern; µg/kg = micrograms per kilogram; mg/kg = milligrams per kilogram; n/a = not applicable; oc = organic carbon; PRG = preliminary remediation goal; SMS = Sediment Management Standards; SQS = sediment quality standard



Notes:
1. Surface sediment samples collected in 2008 by EPA aboard the Ocean Survey Vessel (OSV) *Bold*.

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0 5 10 20 Miles

AECOM

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

Lower Duwamish Waterway Final Feasibility Study 60150279-14.36			**2008 Puget Sound *OSV Bold* Survey Locations**
DATE: 10/31/12	DWRN:mvi/SEA	Revision: 0	**FIGURE 4-1**

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5 Evaluation of Sediment Movement and Recovery Potential

This section presents a summary of the sediment transport and related contaminant transport modeling, as well as empirical data, and develops an understanding of potential natural recovery based on the models and data. The overall modeling approaches are presented in this section. The sediment transport model (STM) is presented in the STM Report (QEA 2008). The sediment-related contaminant transport modeling is presented in Appendix C, Part 1. The data evaluations supporting the natural recovery analysis are presented in Appendix F.

One of the U.S. Environmental Protection Agency (EPA) guiding principles for managing sediments is to develop a conceptual site model (CSM) that considers sediment stability and evaluates the assumptions and uncertainties associated with site data and models (EPA 2005b). Model results are used to inform the CSM. A well-developed and calibrated model can assist in adaptively managing a site and adjusting or refining site predictions to the actual response of a system after various remedial actions and source control measures have either been completed or are under way. Sediment experts and site managers all recognize the unique challenges and difficulties in understanding the natural forces and man-made events that affect sediment movement, stability, and recovery potential, and that some uncertainty will always be present. Consistent with EPA's guiding principles, in this feasibility study (FS), the STM, the bed composition model (BCM), and the potential for sediments to be exposed at the surface are used to predict responses after applying the different remedial actions.

The hydrodynamic and sediment transport CSM for the Lower Duwamish Waterway (LDW), as described in Section 2, is largely influenced by the reduction and control of inflows through diversion of the rivers that historically flowed into the Green River and ongoing water management practices at the Howard Hanson Dam. Peak inflows have been greatly reduced, and the LDW has been widened and deepened to permit navigation. The increased cross-section acts as a natural sediment trap for incoming coarse-grained sediment. The STM simulates natural transport and bed evolution processes in this highly modified riverine/estuarine system. In addition, some effects of ships transiting the navigation channel and berthing areas under routine operating procedures are implicitly included in the STM/BCM by calibration to measured sedimentation rates. The goals of the LDW-wide modeling efforts for this FS are:

- Illustrate how contaminant concentrations vary spatially in the LDW via sediment movement, scour, and deposition processes and empirical trends.
- Predict contaminant fate and recovery potential for risk drivers over periods of time (e.g., 10 years) via the primary mechanisms of burial and source control.

- Demonstrate that model predictions and empirical measurements are comparable. Both the modeling results and empirical data have some measure of uncertainty; therefore, multiple lines of evidence are evaluated collectively to examine and reduce these uncertainties and to refine the CSM (EPA 2005b).
- Consider how navigation activities may disrupt natural recovery processes and affect BCM recovery predictions.

The four modeling process steps to address these goals are described below.

First, the STM results are used to look at general trends in an analysis of net sedimentation rates and to review agreement with the CSM with respect to the depositional environment in the absence of deep scour events. This is accomplished by comparing the estimated net sedimentation trends to empirical data. Empirical data include subsurface cores used to determine historical trends in net sedimentation rates and surface sediment locations that have been resampled over time. The STM is used to evaluate sediment movement as it relates to potential remedial areas and alternatives. This step includes an evaluation of net sedimentation rates, sediment transport into early action areas (EAAs), and other specific model runs to better understand sediment dynamics in the system (Section 5.1).

Second, the BCM, which takes output directly from the physical STM and applies contaminant concentrations to modeled sediment particles, was developed to predict future contaminant concentrations in surface sediments, and therefore recovery potential. The BCM is based on STM output, and BCM predictions assume that contaminant concentrations will be influenced only by sedimentation and resuspension due to natural processes. The BCM and associated empirical evidence are used in the FS to provide a predictive tool for evaluating whether contaminant concentrations in the surface layer/biologically active zone will decrease through natural recovery processes. The STM, BCM, and empirical evidence are used to evaluate whether the sediment bed is stable (i.e., not subject to significant scour, erosion, and transport) and whether the sedimentation rate is sufficient for burial of contaminated sediments to occur in the absence of navigation-caused disturbances. If these conditions are met in a given location, then monitored natural recovery (MNR) or enhanced natural recovery (ENR) may be appropriate response actions for evaluation in one or more remedial alternatives. Conversely, if natural processes are not effectively reducing concentrations of contaminants of concern (COCs) in surface sediments, then capping or dredging may be more appropriate choices (Section 5.2).

STM/BCM predictions of net sedimentation over much of the LDW are consistent with the CSM when ongoing navigation activities are assumed to constitute a minor influence on surface sediment contaminant concentrations (e.g., propeller wash does not expose, resuspend, and mix deeper subsurface contamination with surface sediment).

Third, smaller scale areas are analyzed to evaluate local recovery potential and assess whether empirical data and predictive models agree. MNR is a potential remedy that relies on ongoing, naturally-occurring processes (such as sediment deposition, mixing, and burial) to reduce COC concentrations in surface sediment. Several lines of evidence (e.g., isotope cores, sediment transport analysis, contaminant trends analysis, evaluation of erosion potential) are combined to assess whether contaminated subsurface sediments are stable, if they are effectively isolated, and whether surface sediment contaminant concentrations are predicted to decrease over time. The STM and BCM do not incorporate disturbances to bed sediments from propeller wash; therefore, bathymetric imaging data were used to identify these areas. These lines of evidence are used in the FS both when configuring remedial alternatives and when evaluating the long-term effectiveness of remedial alternatives (Sections 5.3 and 5.4). Local recovery potential under routine navigation procedures is discussed in Section 5.3.2.7.

Fourth, this FS considers the potential influence of contaminated subsurface sediments that may be exposed at the surface. Some effects of ships transiting the navigation channel and berthing areas under routine operating procedures are included in the STM/BCM by calibration to measured sedimentation rates. However, additional navigation and construction-related activities, as well as natural events, may result in sediment bed disturbance causing increased surface sediment contaminant concentrations that are not addressed by the STM/BCM. The STM and BCM were designed to consider only external and surface sediment sources of contamination to the LDW system. They were not set up to model deeper disturbance events, so this FS conducted a separate sensitivity analysis of deep sediment disturbance to consider the potential effects of such disturbance events on STM/BCM-predicted spatially-weighted average concentrations (SWACs; see Section 5.2.3).

This section of the FS focuses on details related to the six modeling goals:

- Providing an overview of the physical CSM and the STM relative to recovery.
- Discussing briefly the multiple lines of empirical evidence (i.e., sediment core trends, surface sediment sample trends at resampled stations, and physical features) that validate the STM and identify trends not accounted for by the predictive model.
- Developing a predictive recovery model (i.e., the BCM) and inputs to the BCM.
- Developing methods to either account for or assess the potential for scour to affect sedimentation and recovery in two ways: shallow mixing from routine

vessel operating procedures through resuspension and mixing; and episodic deep disturbances that result in subsurface contaminated sediments being exposed at the surface layer (thereby affecting the SWAC).

- Performing additional STM scenario runs to help answer FS-specific questions related to sediment movement and MNR and ENR recovery potential.
- Defining uncertainties of the STM model, including a brief overview of how it affects uncertainties in the fate and transport processes for risk drivers.

Potential application of MNR and ENR and general response actions are described in Section 7, Identification and Screening of Remedial Technologies. Additional STM runs are described in Appendix C. Empirical trends for individual areas of potential concern (AOPCs) are presented in Section 6.

5.1 Sediment Transport Modeling

Modeling of particle movement in and out of the LDW and sediment transport within the LDW was undertaken during the remedial investigation (RI) to better understand the CSM and support various FS elements.[1] The site-wide STM, which simulates the natural sediment resuspension and sedimentation processes active to varying degrees within the LDW (with the caveats noted above), has shown that the LDW is net depositional on a site-wide scale and is divided into Reaches 1, 2, and 3 based on hydrodynamic characteristics and geomorphology (see Section 2 for more details regarding the CSM). Model development and calibration are detailed in the *Final Sediment Transport Analysis Report* (STAR; Windward and QEA 2008) and the *Final Sediment Transport Modeling Report* (QEA 2008). This section reviews the resulting general trends in a site-wide analysis (Section 5.1.1) and evaluates the STM's ability, when combined with the BCM, to predict contaminant trends. This is accomplished by comparing the predicted trends to empirical data (Section 5.4).

5.1.1 Composition and Sources of Sediment Loads

The STM estimated the movement of sediment from three sources over time into and through the LDW:

- Sediment from the upstream Green/Duwamish River system

[1] The STM tracks particle movement, but it does not model contaminant transport processes or mechanical transport processes such as the effect of vessel traffic or waves on net sedimentation rates. The effect of vessel traffic was analyzed separately for moving and maneuvering tugs. The analysis of moving tugs is presented in the *Final Sediment Transport Analysis Report* (STAR; Windward and QEA 2008) and the effect of maneuvering tugs is summarized in Section 5.3.1 and in Appendix C, Part 7 of this FS.

- Sediment from lateral sources (i.e., storm drains, streams, and combined sewer overflows [CSOs]) that discharge to the LDW
- Surface sediment existing in the LDW bed at the onset of the model period.

The STM modeled both the transport of total suspended solids (TSS) and bed load. The transport of TSS is the movement of suspended particles in the water column. Bed load transport is the movement of sand and gravel in a thin layer (about 1 millimeter [mm] to 1 centimeter [cm] in thickness) located along the surface of the sediment bed. The Green/Duwamish River is the predominant source of sediment to the LDW. Figures 5-1a and 5-1b show that surface sediment (0 to 10 cm) in over 90% of the LDW model area will be comprised of over 50% upstream solids at the end of the 10-year model simulation and over 75% upstream solids at the end of the 30-year simulation. The STM quantified sediment loading from this upstream source using a flow-rating curve for the Green/Duwamish River based on discharge data gathered from 1960 to 1980 and from 1996 to 1998. The grain size characteristics of the in-flow material from both periods were also evaluated to determine the contribution from suspended material in contrast to bed load. Of the total upstream solids load, approximately 24% is bed load and 76% is suspended load in both the 10-year and 30-year simulation periods. Nearly all of the bed load and suspended load in the sand-size range settles in the LDW. Of the clay and silt suspended load, approximately 10% of the clay-size particles and 76% of the silt-size particles are predicted to settle in the LDW. All of the bed load entering the LDW from upstream is deposited within the Upper Turning Basin and the upstream portions of the navigation channel, which are periodically dredged by the U.S. Army Corps of Engineers (USACE). Approximately 50% of the total solids load entering the LDW from upstream is deposited in the LDW, with approximately 80% of this deposition occurring in the vicinity of the Upper Turning Basin in Reach 3 (QEA 2008, see Appendix B of the STM Report).

Sediment loads from lateral sources were derived from analyses conducted by the City of Seattle and King County (Nairn 2007; Seattle Public Utilities 2008). Storm drains, CSOs, and streams discharge into the LDW at over 200 locations. These were initially aggregated in the STM report into 21 discrete discharges at 16 locations to simplify modeling. In the STM, the total annual sediment load from the lateral sources was estimated to be 1,257 metric tons per year (MT/year); of this, 76% was attributed to storm drains, 3% to CSOs, and 21% to streams.

The distribution and magnitude of sediment loads from lateral sources were updated after the STM report (QEA 2008) was completed. These updated sediment loads are presented in Appendix C, Part 4, Scenario 2. The updated loads provide a more accurate distribution of the loads, reflecting better distribution of inputs and more actual outfall locations. Figure 5-2 illustrates the spatial distribution of the percentages of sediment from lateral sources at the end of the 10-year model simulation, using the updated lateral loads distribution. Updated lateral loads were used in all subsequent modeling in this FS. The areas with the greatest predicted lateral sediment contribution (i.e., the sediment bed after 10 years includes more than 10% lateral contribution) are limited to the following areas in the LDW: at the heads of Slips 4 and 6, Hamm Creek at river mile (RM) 4.3W, RM 1.8W, near Glacier at RM 1.5W, RM 1.2E, RM 0.3W, and in the Duwamish/Diagonal EAA at RM 0.5.

A third component of sediment load is the movement of surface sediment from one model grid cell to another. Bed sediment can be resuspended during a high-flow event, after which it either resettles nearby or is transported downstream. The STM tracks the movement of these particles throughout the LDW, from grid cell to grid cell. The ability of the STM to track the movement of particles within the LDW was used to evaluate the transport of sediment between Reaches 1, 2, and 3, as summarized in Figure 5-3 and in Appendix C, Part 4, Scenario 4.

The highest percentage of original bed sediments remaining in the surface layer after 10 years occurs in the grid cells east of Kellogg Island at RM 0.9 and at the Terminal 117 EAA (RM 3.0 to RM 3.5). The areas that have the highest percentage of original bed sediment remaining at the end of the 30-year simulation are consistently the highest throughout the simulation and are not the result of a short-term scour event. A higher percentage of original bed sediment indicates that much of the surface layer is not being replaced by upstream or lateral sediment (i.e., the bed surface sediments are not receiving much deposition and could be interpreted as having a more constant composition over time).

5.1.2 Solids Balance In and Out of the LDW

Figure 5-3 shows the mass of sediment moving through and within the three reaches of the LDW over 10-year and 30-year modeling periods. Year-to-year variation in sediment load occurs because of variability in river flow, with total sediment load increasing during years with relatively high flows. Over the 10-year period, more than 99% of the incoming sediment load (1,850,850 MT) originates from the Green/Duwamish River (upstream); less than 1% (12,580 MT, or an annual average of 85,000 MT/yr) enters the LDW from lateral sources. Over a 30-year period, a cumulative total of 6.2 million MT enters the LDW (for an annual average of approximately 207,000 MT/yr). The magnitude of the sediment mass movement increases, but the percent contribution from upstream and lateral sources is essentially the same as for the 10-year period. About 50% of the incoming solids (approximately 100,000 MT annually) deposit within the LDW and are not exported farther downstream into the East and West Waterways and Elliott Bay. Approximately 51% of the sediment that settles in the LDW is removed by periodic maintenance dredging, mostly in the Upper Turning Basin.[2] Thus, approximately 25% of the incoming sediment load remains in the LDW basin after dredging.

Bed load (heavier, larger particles that skip and travel along the sediment bed[3]) comprises 24% of the total incoming sediment load, on average, at the upstream boundary of the area modeled by the STM, with the remaining 76% entering the LDW as sediment suspended in the water column (QEA 2008). According to the STM, most of the bed load deposits above RM 4.0; the suspended sediment primarily deposits farther downstream or is transported through the system. The proportion of bed load to total load is inversely dependent on flow rate, decreasing from 30% to about 17% to 18% as the flow rate increases (24% on average). The estimated average annual bed load transported during the 30-year model period was 50,000 MT/year, with a range of 10,000 MT/year (1978) to 132,000 MT/year (1975) for low-flow and high-flow years, respectively (QEA 2008). This solids mass balance supports the CSM conclusion that the LDW is net depositional over long time periods and that lateral sources are important, but their effect is localized to the receiving sediments in the vicinity of these sources. The CSM and dredge records both indicate that the majority of the Upper Turning Basin dredged material is from upstream (Green/Duwamish River).

5.1.3 Scour Potential from High-flow Events and Vessel Traffic

Figure 5-4 shows potential scour areas derived from two processes: high-flow events and scour from vessel traffic. Areas of erosion from both high flows and vessel scour were considered during delineation of AOPCs (see Section 6).

Few areas in the LDW that show significant high-flow erosion potential (10 cm scour depth or more) also have subsurface contamination. These areas are identified in Appendix C (Part 4, Scenario 5) and are evaluated in Section 6 for the delineation of the AOPCs. Alternatively, most areas with significant subsurface contamination (greater than sediment quality standards [SQS]) do not show erosion potential beyond a few centimeters in depth during high-flow events. An analysis of how erosion and deposition impact surface COC concentrations over time is discussed in Section 5.2.

The STM models sedimentation and resuspension in the absence of deep sediment disturbance and exposure of contaminated subsurface sediment. No available transport model has the capacity to include anthropogenically induced resuspension and transport with confidence. Development and validation of the STM is most reliable in regions where naturally occurring sedimentation dominates transport and in areas with relatively little anthropogenic activity. The effects of such anthropogenic activity on the

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2 Dredging averages 38,000 MT/yr within the navigation channel and 13,000 MT/yr in the berthing areas. The average total dredged is 51,000 MT/yr.

3 The mean percent of fines in surface sediment of Reach 3 is 34%. The mean percent of fines in surface sediment of Reaches 1 and 2 is 69%. Bed load is mostly sand and gravel-sized particles. See Appendix C, Part 3, Tables 5a and 5b for more information.

STM/BCM are separately evaluated in Section 5.3.1.2 by modifying long-term BCM SWAC estimates to include episodic disturbance of surface and subsurface sediments.

The 100-year high-flow event produces a maximum erosion depth of less than 1 foot (less than 30 cm) in limited areas (see Figure 2-9). Most of these areas do not show COC concentrations at this depth that are greater than the SQS and that are not already expressed as SQS exceedances at the surface. Subsurface COC concentrations in areas with scour greater than 10 cm are analyzed in Appendix C (Part 4, Scenario 5) and discussed in Section 5.3.2.5.

Although this FS focuses on single high-flow events, the 30-year hydrograph record used for the STM analysis included numerous high-flow events of more than 10,000 cfs. In some years, two high-flow events occurred in the same year. Therefore, the STM inherently accounts for multiple scour events in the same year (Appendices D and F in QEA 2008).

5.2 Bed Composition Model (BCM)

Output from the STM was coupled with contaminant concentrations in sediments from various sources to enable prediction of future surface sediment contaminant concentrations under various remedial action scenarios. This analysis is termed the BCM. This section of the FS describes the BCM, its applications, and its limitations.

Output from the STM is directly applied to the BCM. A basic and conservative assumption is that all contaminants are strongly bound to sediment particles. The BCM is conservative with respect to sediment concentrations because it only accounts for contaminant movement associated with particles (i.e., transport, resuspension, burial) and assumes no loss of contaminant mass via other physical, chemical, or biological degradation processes (e.g., desorption, diffusion, volatilization, biotransformation, dechlorination, etc.). Other degradation processes explored at other sites are documented at the end of this section to provide some context for understanding these processes. The BCM does not account for contaminant transfer from sediments to the water column. However, polychlorinated biphenyl (PCB) flux from sediments to the water column and to biota was estimated in the food web model (RI Appendix D; Windward 2010).

The BCM is used later in the FS as one line of evidence to evaluate recovery potential of LDW sediments (Section 6), to identify and screen remedial technologies (Section 7), and to develop and evaluate remedial alternatives (Sections 8 and 9). The sensitivity of the BCM is also investigated by looking at how changes in input parameters affect the output (Section 9). Sediment disturbance resulting from episodic emergency and high-power ship maneuvering and maintenance/construction is not included in the BCM. The potential influence of these disturbances on the sediment bed is discussed in Section 5.3.1.

5.2.1 The BCM Calculation

The BCM is a spreadsheet-based tool that predicts COC concentrations at individual model grid-cell locations[4] in the surface sediment layer (0 to 10 cm) by using a simple mass balance formula (RETEC 2007c, Appendix C):

$$C_{(time)} = C_{bed}{*}f_{bed\ (time)} + C_{lateral}{*}f_{lateral\ (time)} + C_{upstream}{*}f_{upstream\ (time)} \qquad \textbf{Equation 5-1}$$

Where:

- f_{bed}, $f_{lateral}$, and $f_{upstream}$ are, respectively, the fractions of surface sediment sourced from existing bed sediment, from lateral source sediment, and from upstream Green/Duwamish River sediment in each grid cell at a specific point in time. These surface sediment fractions change over time and are direct outputs of the surface sediment layer of the STM. The sum of these fractions in each grid cell is 1.
- C_{bed}, $C_{lateral}$, $C_{upstream}$ are the concentrations of a COC associated with each sediment source. These concentrations are derived from existing bed contaminant concentrations, lateral source samples (i.e., stormwater and CSO discharges), and upstream (Green/Duwamish River) lines of evidence.

An example of how the BCM computation uses the STM output is shown in Figure 5-5. Additional mechanics of the BCM are provided in Appendix C.

As noted in Equation 5-1, the sediment composition fractions (f) vary with time because the STM output varies with time[5] and ongoing sediment transport changes the bed composition of each fraction. The concentration terms for the lateral source and upstream sediments ($C_{lateral}$ and $C_{upstream}$) are assumed to be constant over time for modeling purposes, representing current best estimates of the long-term average inputs over time.[6] The derivation of these values is discussed in greater detail in Section 5.2.3. The BCM assigns the same COC concentration (input value) to the lateral source and upstream sediments regardless of the variability observed over time or spatially (such as among different outfalls for the lateral sources). The bed concentration (C_{bed}) is the

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4 STM grid cells are taken directly from the STM setup, as described in the STM report (QEA 2008), and overlain with inverse distance weighting 10-ft by 10-ft chemistry grid cells in the BCM. Consequently, the BCM calculates results for 100-ft^2 areas.

5 STM output in 5-year increments is used in the BCM runs. The STM runs continuously for the entire 30-year simulation period at time steps on the order of minutes. The FS presents results in 5- or 10-year increments following the start of remedy construction. For remedial scenarios that take longer than 30 years to implement, the simulation starts over at the beginning of the 30-year hydrograph used for the STM.

6 However, high and low "sensitivity" concentrations were also used as input values to bracket the range of uncertainty in the input values and demonstrate the effects from anticipated reductions in contaminant concentrations over time.

best estimate of the COC concentration in the surface sediment bed at a given location at the start of the model period, defined by the FS surface sediment dataset. The BCM is implemented in a geographic information system (GIS) framework and MS Excel platform (described in Appendix B of RETEC 2007b).

The BCM (Equation 5-1) can be used to estimate COC concentrations in surface sediment at each grid cell location in the LDW as a function of time under various remedial alternatives. Where active remediation is assumed within an alternative, the grid cells contained within the actively remediated footprint receive a post-remedy bed sediment replacement value for C_{bed}. The new value is an estimate of the COC concentration that exists in the surface sediment at the completion of the remediation (see Section 5.2.3.4).

5.2.2 BCM Assumptions

The predictive accuracy of the BCM hinges on two important findings from the STM:

- Over time, the surface sediment that erodes, moves, and redeposits within the LDW originates primarily from the Green/Duwamish River, as shown in Figure 5-3. STM results indicate that movement of bedded sediment from within the LDW is a very minor component of overall sediment transport in the LDW. The effect of bedded sediment was further analyzed by a simulation that tracked the movement of bedded sediment. This analysis is presented in Appendix C, Part 4, Scenario 4 and Part 5, Scenario 6.

- The magnitude of high-flow bed scour is sufficiently minor such that subsurface sediments with COC concentrations that exceed the SQS are generally not exposed, eroded, or redistributed within the LDW. Even after a high-flow event, the bed height increases from deposition (see Appendix E, Figures E-19 through E-23 in QEA 2008). From the sediment mass balance analysis, the new sediment that accumulates is largely from the Green/Duwamish River. Given the limited movement of bed sediment during high-flow events, bed COC contaminant concentrations at the reach- or site-wide scale would not be predicted to change significantly during a high-flow event (Appendix C, Part 5).

Although the assumption of assigning the contaminant concentrations to resuspended bed sediment is not inherently mass conservative, it will not significantly impact model predictions, because: 1) in the LDW, the mass of bed sediment resuspended is much less than the mass of sediment from upstream; and 2) COC concentrations in resuspended sediments become similar to those in upstream solids over time and as the cleanup proceeds. Consequently, redistribution of existing sediments with COC concentrations that exceed the SQS is not a significant process, and future bed sediment chemistry can be reasonably estimated as a mass balance between present bed sediment and incoming sediment loads from the Green/Duwamish River and lateral sources.

These key findings are supported in three ways: 1) by the CSM (Section 2.3), 2) by a comparison of empirical trends to model estimates of net sedimentation and recovery rates (Section 5.4), and 3) by additional STM special scenario runs (Section 5.3.2) used to help refine the CSM for the FS.

In addition, the BCM assumes that:

- All COCs are permanently bound to sediment particles; degradation or phase transfer processes such as solubilization are assumed not to reduce COC concentrations over time. This assumption is generally consistent with the known properties of the COCs, and is inherently conservative because some degree of degradation or phase transfer likely occurs. The assumption could result in higher predicted concentrations in surface sediment with time.

- COC concentrations from drainage basins were derived from all storm drain and other solids sample data, but samples were collected from only a portion of the LDW drainage basin conveyances. These data are assumed to be representative of all lateral COC inputs. COC contributions from eroding bank material and groundwater were not included in the lateral source estimates.

- COC concentrations from drainage basins that have not been sampled are assumed to be similar to or lower than those in drainage basins sampled for source control evaluation. This is consistent with the sampling strategy of the Source Control Work Group (SCWG), which has focused first on areas with the most significant sediment contamination and associated outfalls identified as being the most likely sources of contaminated sediments to the LDW. The COC concentrations derived from the empirical data are then applied to all lateral sources in the model.

- The biologically active zone for most of the LDW is approximately 10 cm, and therefore the top 10-cm model layer represents exposure concentrations for benthic organisms. This depth is consistent with results from the sediment profile imaging (SPI) analyses conducted in the LDW for the Washington State Department of Ecology (Ecology 2007b) and King County (King County 2007a), as described in the RI (Windward 2010).[7] The 95% upper confidence limits (UCL95) on the mean of maximum sediment feeding void depths for benthic organisms (a conservative measure of the biologically active zone) used in the Ecology dataset was 11 cm with a mean

[7] The assumption of 10 cm can be reasonably applied as the biologically active zone in the LDW based on several factors: representativeness of entire benthic community, relationship with void depths, and central tendency of void depths (Windward 2010).

of 10 cm. The King County dataset was even shallower (9 cm with a mean of 8 cm). The 10-cm depth is used as the STM and BCM assumption for the active mixed layer.

5.2.3 Input Values to the BCM for Risk Drivers

Concentrations of risk drivers associated with the three sources or types of solids (i.e., upstream, lateral, and bed sediments) were estimated as inputs to the BCM. Samples from media representative of these three sources were analyzed for several COCs over a period of years, and the resulting concentrations were selected for use in the BCM based on summary statistics from compiled datasets. Some best professional judgment was incorporated into these datasets with assumptions about current and potential future conditions, including future source control efforts, the amount of solids entering the LDW, and potential biases of particular datasets. In selecting the BCM lateral input parameters, the median, the mean, and the 90th percentile of the datasets were used as the low, mid-range, and high values, respectively. High values were removed from the dataset, as described in Section 5.2.3.2, because it was assumed that they would be addressed by ongoing source control actions. For the BCM upstream input parameters, mean values of the most representative of several upstream datasets were selected for the low and mid-range input values, and the UCL95 was used for the high input value. High, medium, and low post-remedy bed sediment replacement values were derived assuming varying degrees of mixing of clean sediments in the remediated footprint with contaminated sediments remaining in the rest of the LDW, as described in Section 5.2.3.4. Selected values and ranges for the BCM input values for total PCBs, arsenic, carcinogenic polycyclic aromatic hydrocarbons (cPAHs), and dioxins/furans are provided in Tables 5-1a through 5-1c. The ranges of concentrations reported from various data sources are provided in Tables 5-2a through 5-2d.

5.2.3.1 Contaminant Concentrations Associated with Upstream Solids

Contaminant concentrations associated with Green/Duwamish River solids were compiled from various data sources, which are described in Appendix C, Part 3. These data provide multiple lines of evidence that characterize the contaminant concentrations associated with sediments entering the LDW from the Green/Duwamish River system. Data from the various studies were used to develop a range of input values for each risk driver (Table 5-1a).

The data sources evaluated included:

- Upstream whole-water samples collected by King County
- Upstream centrifuged suspended solids samples collected by Ecology
- Upstream surface sediment samples (containing fines greater than 30%) collected by Ecology between RM 5.0 and 7.0

- Upstream surface sediment samples from RM 5.0 to 7.0 included in the RI dataset
- Core data collected by the USACE to characterize sediment prior to dredging in the navigation channel from RM 4.3 to 4.75, which is assumed to represent the Green/Duwamish River combined bed load and suspended material that settles in the upper reach of the LDW.

The upstream King County whole-water concentrations were normalized to the value of the concurrently collected TSS, so that the concentration units were comparable with the sediment concentration units (i.e., both on a dry weight basis).[8]

A subset of the Ecology upstream surface sediment data was developed by excluding samples that contained less than 30% fines. This approach accommodates the systematic differences in grain size distributions between upstream (e.g., mid-channel) data and average conditions in the LDW. Both the full dataset and the subset with fines greater than 30% were used as lines of evidence to develop the range of BCM upstream input parameters.

Upstream surface sediment samples from RM 5.0 to 7.0, included in the RI dataset, were evaluated, but were not used in selecting BCM input values. The rationale for this approach is explained in Appendix C, Part 3. Instead, the more recent upstream surface sediment data collected by Ecology were used. The upstream surface sediment data had lower total PCB and cPAH concentrations than other upstream lines of evidence. This may reflect the coarser (i.e., sandier) material encountered during sampling that is characteristic of bed load[9] being transported down the Green/Duwamish River—very little of which is transported beyond the Upper Turning Basin. The surface sediments upstream of the LDW are generally coarser than those in the LDW because there is little net sedimentation upstream of the Upper Turning Basin as a result of higher stream velocities above RM 4.75.

The subsurface sediment cores collected by the USACE to characterize sediment prior to dredging in the navigation channel from RM 4.3 to 4.75 represent the Green/Duwamish River bed load and suspended material that settles in the upper reach of the LDW.[10] The Upper Turning Basin is a natural sink for incoming sediment loads from upstream, and

[8] Normalizing to TSS likely produces a high estimate of the COC concentration on sediment particles because some of the COC mass is likely dissolved or on colloidal particles that do not settle in the LDW.

[9] Bed load is heavier, sandier material that travels along the bed surface; it is not suspended in the water column and thus, typically travels shorter distances than do suspended solids.

[10] The RI summarized USACE cores in the Upper Turning Basin from RM 4.0 to 4.75. The FS screened this dataset to exclude the potential influence of sources (e.g., Hamm Creek) in the downstream portion between RM 4.0 and 4.3. The FS dataset also includes more recent data collected by USACE above RM 4.3.

because the navigation channel is dredged every 2 to 4 years from RM 4.0 to 4.75, this area is a good indicator of suspended solids settling in the upper reach of the LDW.

The upstream solids values selected for use in the BCM were based on these four datasets as values representing the best estimate concentrations of the risk-driver COCs entering and settling in the LDW. Each dataset contains information that represents, to a degree, the COC concentrations in sediment particles that enter and deposit within the LDW. As discussed below, these datasets are considered reasonable lines of evidence for developing incoming concentrations to the LDW from upstream, although each type of data collection tends to bias the results toward lower or higher values (e.g., low percent fines versus high percent fines; single collection events instead of seasonal collection events; potential influence of sources). In general, the value representing a mid-range of the various lines of evidence was considered for the input value, and then values representing upper and lower bounds were selected for the high and low sensitivity input values, respectively. One goal of including a range in the input values is to account for uncertainty in all the datasets representing upstream inputs and show how these data ranges affect the predictions of natural recovery for the remedial alternatives.

For total PCBs and cPAHs, the means of the LDW RM 4.3-4.75 USACE core data were selected as the upstream input values (35 microgram per kilogram dry weight [μg/kg dw] and 70 μg toxic equivalent [TEQ]/kg dw, respectively). To address sensitivity around the mid-range value for both total PCBs and cPAHs, the low upstream input values were the means of the Ecology upstream surface sediment samples containing fines greater than 30%. The high upstream input values were the UCL95s of the TSS-normalized King County whole-water datasets.

For arsenic, the selected upstream input value was the mean (9 milligrams per kilogram dry weight [mg/kg dw]) of the Ecology upstream samples containing fines greater than 30%. The mean of the LDW RM 4.3 to 4.75 USACE core data (7 mg/kg dw) was selected as the low sensitivity value. The high sensitivity value (10 mg/kg dw) was the UCL95 of the Ecology upstream sediment samples containing fines greater than 30%. King County surface water TSS-normalized data and Ecology centrifuged solids data were not used in the selection of BCM upstream values for arsenic because the UCL95 for both of these datasets would have resulted in much higher modeled surface sediment concentrations than in the LDW baseline dataset. It is likely that these two datasets, especially the surface water dataset, contain finer particulates with higher arsenic concentrations than those that deposit in the LDW. These finer particles tend not to settle in the LDW (approximately 50% of the Green/Duwamish River solids [bed load and suspended solids combined] do not settle in the LDW).

For dioxins/furans, the Ecology upstream sediment samples (containing fines greater than 30%) and the Ecology upstream centrifuged solids were the only datasets used for selecting the BCM input values; there were neither core data from RM 4.3 to 4.75 nor whole-water dioxin/furan data among the other datasets. Because of the smaller datasets and the desire to evaluate a range of input values, a slightly different approach was used to select dioxin/furan BCM input values. The midpoint between the means of the two datasets is the mid-range value (4 ng TEQ/kg dw); the low sensitivity value is the mean of the Ecology upstream sediment samples containing fines greater than 30% (2 ng TEQ/kg dw); and the high sensitivity value is the midpoint between the mean and UCL95 of the Ecology upstream centrifuged solids dataset (8 ng TEQ/kg dw).

Dry weight concentrations for COCs based on upstream surface sediment samples may be biased low and may underrepresent the concentrations associated with the fraction of solids entering the LDW that have finer grain size and higher organic carbon concentrations. Silt- and clay-sized suspended solids represent 67% of the sediment entering the LDW. As a result of the settling of most sand-sized particles in Reach 3, silt- and clay-sized particles make up only about 35% of the sediment that settles in Reach 3, but more than 90% of the sediment that settles in Reaches 1 and 2. Case study literature and LDW data exist that support the relationship between COC concentrations, organic carbon content, and particle size. The relationship between particle size and organic carbon content and the various methods to account for these relationships and their potential effect on model results is explored in Section 5.3.3.

5.2.3.2 Contaminant Concentrations Associated with Lateral Source Sediments

Contaminant concentrations associated with storm drains and CSOs were evaluated to estimate concentrations associated with lateral source sediments.[11] The storm drain solids and CSO data were collected as part of ongoing source control programs for the LDW. All available storm drain data were compiled by Seattle Public Utilities (SPU) for source samples collected in areas draining to the LDW through June 2009 by SPU, the Boeing Company, and King County. These data included storm drain solids collected from on-site and right-of-way catch basins, in-line grab samples, and in-line sediment traps. The storm drain solids data were used to generate a range of lateral input concentrations for total PCBs, arsenic, and cPAHs for use in the BCM. Storm drain solids and sediment data collected near large stormwater outfalls draining urban areas in the greater Seattle area were used to establish BCM lateral input values for dioxins/furans. The King County CSO whole-water data were also considered and found to support the ranges of BCM lateral input values estimated from the storm drain solids dataset. Consequently, the same COC concentration values were used for both storm drains and CSOs and were also assumed for the stream inputs.

The lateral input values selected for use in the BCM are estimates, based on the assumption that contaminant concentrations in storm drain solids will decrease as a

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11 Lateral source sediments include inputs from storm drains, CSOs, and streams discharging to the LDW.

result of source control efforts in the LDW drainage basin. The following assumptions were made for the BCM input values:

- The mid-range, or best-estimate, input value is a pragmatic assessment of what might be achieved in the future with anticipated levels of source control. This value is based on mean/median concentrations observed in the lateral dataset after excluding the highest concentrations in the dataset to represent control of high and medium priority sources.
- The high sensitivity value is a conservative representation of near future conditions assuming only modest success in management of high priority sources already identified by the SCWG.
- The low sensitivity value is an estimate of the best that might be achievable in 30 to 40 years with increased coverage and continued aggressive source control.

The assumed level of source control was based on best professional judgment of the SCWG and what is currently known about the distributions and current source(s) of each COC within the LDW drainage basin. The BCM input values reflect potential levels of source control that could occur over time. To simulate potential lateral inputs after implementing varying degrees of source control, the source tracing datasets were screened to remove all values above various concentrations already targeted for source control. Summary statistics were then generated for each level of assumed source control (high, medium, low). Table 5-1b presents the best-estimate BCM input values for lateral sources. The summary statistics for the four human health risk drivers (total PCBs, arsenic, cPAHs, and dioxins/furans) are provided in Tables 5-2a through 5-2d.

A general summary of the lateral input values selected for the BCM is presented below. The lateral sources memo (King County and SPU 2010) found in Appendix C, Part 3 describes the selection of the lateral input values in more detail. It should be noted that the high lateral input value is not intended to represent what sources could potentially exist throughout the drainage basins tributary to the LDW. This high value is used only to determine sensitivity of the model and the implications of inadequate source control at individual discharge locations; it is not an estimate of actual source loads or a target value for source control work. Similarly, the low sensitivity value should not be construed as a prediction of source control efficiency or as a determination of source control effectiveness or completeness. The actual effectiveness of source control can only be assessed after the fact because "complete" source control is the aggregate of many different actions applied to any given media, pathway, or source of COCs.

Total PCBs

Prior to generating summary statistics for total PCBs and to avoid skewing the summary statistics, the data were flow-weighted, including data from these targeted and known source areas: Rainier Commons, North Boeing Field/Georgetown Steam Plant, Terminal 117, and Boeing Plant 2/Jorgensen Forge. Flow-weighting takes into account the relative contribution of a specific contaminant by adjusting its concentration based on the land area and estimated annual runoff volume relative to the total contributing area in the LDW drainage basin. To reflect potential levels of source control that could occur over time, a range of screening concentrations was used to select the BCM lateral values for total PCBs. The mid-range BCM input value (300 µg/kg dw) is represented by the mean of data after excluding concentrations greater than 5,000 µg/kg dw.

Screening values of 2,000 and 10,000 µg/kg dw total PCBs were used to define the low and high BCM sensitivity values, respectively. If all samples with a total PCB concentration above a screening value of 2,000 µg/kg dw are removed from the dataset, the median of the remaining data is 100 µg/kg dw. This value was selected as the low BCM sensitivity value (100 µg/kg). When all samples with total PCB concentrations above a screening value of 10,000 µg/kg dw are removed from the dataset, the 90th percentile value of the remaining data is 1,000 µg/kg dw, which was selected as the high BCM sensitivity value.

cPAHs

Unlike total PCBs, cPAHs are expected to be difficult to control due to urbanization and major transportation routes in the LDW basin, and a multitude of current sources. Consequently, a more cautious approach was taken with the source tracing dataset by excluding cPAH concentrations above a single source control level of 25,000 µg TEQ/kg dw. Data for cPAHs were not flow-weighted because cPAH concentrations in the storm drain solids samples do not show a distinct geographic distribution, and higher concentrations of cPAHs are found throughout the LDW drainage basins, typically in drainage structures (catch basins and oil/water separators) at facilities engaged in transportation-related activities (e.g., bus and airport operations), maintenance facilities, service stations, foundries, and fast food facilities. The mean (1,400 µg TEQ/kg dw) of the data, excluding all samples with cPAH concentrations greater than 25,000 µg TEQ/kg dw, was selected as the BCM input value. The median (500 µg TEQ/kg dw) was selected as the low sensitivity value. The 90th percentile (3,400 µg TEQ/kg dw) was selected as the high BCM sensitivity value.

Arsenic

For arsenic, two different screening values (the SQS and cleanup screening level [CSL]) were used to reflect different potential levels of source control. The mid-range BCM input value of 13 mg/kg dw was selected based on the mean of the dataset, excluding all samples with arsenic concentrations above a screening value of 93 mg/kg dw (the CSL). The 90th percentile of the same dataset is 30 mg/kg dw, and this value was selected to represent the high BCM sensitivity value. If all samples with arsenic concentrations above a screening value of 57 mg/kg dw (the SQS) are removed from the dataset, the median of the remaining data is 9 mg/kg dw. This value was selected as the low BCM sensitivity value.

Dioxins/Furans

Available storm drain solids data for dioxins/furans were also used along with surface sediment sample data collected for the LDW RI in the vicinity of storm drains throughout the Greater Seattle metropolitan area to establish BCM lateral input values. By combining these two datasets (because the storm drain solids dataset was small compared to the other risk-driver datasets) and excluding one outlier, BCM lateral values were selected for dioxins/furans. The mean of 20 ng TEQ/kg dw was selected as the BCM input value; the median of 10 ng TEQ/kg dw as the low BCM sensitivity value; and the UCL95 of 40 ng TEQ/kg dw as the high BCM sensitivity value. In addition, the UCL95 rather than the 90th percentile was used to establish the high BCM sensitivity value, because it resulted in a more reasonable upper end estimate for the sensitivity analysis.

King County CSO Whole-Water Samples

In addition to the storm drain solids dataset, whole-water samples collected from CSOs by King County for analyses of PCBs, arsenic, and cPAHs were also considered when developing BCM lateral values. For both total PCBs and cPAHs, whole-water concentrations were divided by their sample-specific TSS concentrations to calculate TSS-normalized concentrations. This gives a conservative estimate that is likely biased high because it is assumed that all of the PCBs and cPAHs are on the particulate fraction and none are in the dissolved or colloidal phases. For arsenic, paired total and dissolved concentrations were used to estimate the portions of the total arsenic concentrations associated with the particulate fraction. These were then divided by the sample-specific TSS concentrations to calculate a TSS-normalized concentration for arsenic. Whole-water samples collected from CSOs in the LDW had not been analyzed for dioxins/furans at the time this document was prepared. Summary statistics for CSO data are provided in the lateral source memo (King County and SPU 2010) found in Appendix C, Part 3.

5.2.3.3 Contaminant Concentrations of Existing Bed Sediments

Existing bed sediment contaminant concentrations were developed by spatially interpolating surface sediment data from the FS baseline dataset for total PCBs, arsenic, and cPAHs. An inverse distance weighting (IDW) algorithm was used to interpolate the data. The IDW methodology is documented in Appendix A.

Existing bed sediment concentrations for dioxins/furans were developed by applying Thiessen polygons to the dioxin/furan surface sediment data from the FS baseline dataset. For Washington State Sediment Management Standards (SMS) contaminants, SQS and CSL exceedances at surface sediment stations were also spatially applied using

Thiessen polygons. In this case, dry weight or organic carbon (oc)-normalized concentrations were compared to SQS/CSL or apparent effects threshold criteria, as appropriate for each contaminant. Thiessen polygons were designated as a pass, SQS exceedance, or CSL exceedance. Sediment toxicity results trumped SMS chemistry results. For example, a Thiessen polygon with a contaminant CSL exceedance, but a toxicity pass, was coded as a pass.

Collectively, these risk drivers comprise the FS baseline dataset used to map "existing conditions" in the LDW. The FS baseline dataset spans about 18 years (1991 to 2009) of data collection efforts. It is likely that current concentrations of some COCs at stations sampled many years ago may now be lower than what is reflected in the FS baseline dataset (see Appendix F).

5.2.3.4 Post-Remedy Bed Sediment Replacement Values

In areas that would be actively remediated under different cleanup alternatives, the existing bed sediment concentration (C_{bed}) is replaced with a value representing near-term (0 to 2 years) conditions following the cleanup. The post-remedy surface sediment conditions are influenced by multiple factors. This subsection describes the assumptions used to model the post-cleanup concentrations.

Experience at other sediment remediation sites has shown that contaminant concentrations in the sediment bed shortly after the completion of dredging or capping cannot be assumed to be zero and are often above background (NRC 2007, EPA 2005b, Anchor 2003). This occurs because: 1) some degree of residual surface contamination always exists from the resettling of contaminated sediments suspended during remedial activities; 2) material used for capping of subsurface sediment exposed after dredging contains low concentrations of these COCs; and 3) existing adjacent sediments can become resuspended and then deposited in remediated areas.

Post-remedy bed sediment replacement values within a remediated area reflect an assumed combination of clean backfill material (e.g., from capping or ENR, and using or not using post-dredge residuals management) and the average concentration of surrounding unremediated sediments. To derive a replacement value based on this assumption, estimates of both values are required. The UCL95 values for the 2008 EPA Puget Sound Ocean Survey Vessel (OSV) *Bold* survey (EPA OSV *Bold* survey) data were used to estimate the contaminant concentrations in clean backfill. These data correspond to natural background estimates for Puget Sound.[12]

However, once clean material is placed, other sediments start settling on the backfill. These sediments are some combination of upstream and lateral inputs, resuspended bed sediments, and dredge residuals. For the purposes of this FS, the average concentration of bed sediments that will not be actively remediated was assumed to be

[12] Data were also collected from the Strait of Juan de Fuca and Strait of Georgia.

representative of this mixture of inputs onto the clean backfill. The average concentration of unremediated sediments was derived using the SWACs outside of remediated areas. The average concentrations remaining outside of AOPC 1 and outside AOPC 2 for Alternative 6 (see Section 6 for AOPCs and Section 8 for alternative footprints) were used in this analysis. The post-remedy bed sediment replacement value was applied to the actively remediated footprint. Clean material was assumed not to be deposited outside of the active footprint.[13]

To calculate a range of post-remedy bed sediment replacement values, the following ratios of clean material to the post-remedy SWAC were assumed: 50:50 for the mid-range BCM input value, 75:25 for the low sensitivity value, and 25:75 for the high sensitivity value.

Post-remedy bed sediment replacement values for total PCBs, arsenic, cPAHs, and dioxins/furans are presented in Table 5-1c. The degree of residual contamination is dependent on several factors, including the type of remedial activity, specific design elements, construction methods, best management practices, engineering controls, and contingency measures (discussed further in Section 7.1). Therefore, post-remedy bed sediment replacement values for use as input parameters to the BCM were developed as a range using the proportioning values described above and best professional judgment. The same post-remedy bed sediment replacement value is applied to areas that are to be dredged, capped, undergo ENR, or have a thin-layer placement of sand inside the dredge footprint for residuals management.

5.2.4 Inputs and Application of the BCM for Other SMS Contaminants

The BCM can also be used to estimate future SQS and CSL exceedances for SMS contaminants. In the BCM, a particular SMS contaminant is selected for each point, and the BCM assigns that point into one of three categories in the future: below the SQS, SQS exceedance (but below the CSL), or CSL exceedance. The BCM equation (Equation 5-1) can be used to estimate future concentrations for any contaminant having available upstream and lateral input values. For the FS, these calculations were conducted on a subset of the SMS contaminants, termed "representative" contaminants. This subset was chosen from the full list of SMS contaminants because: 1) not every SMS contaminant has lateral and upstream data available; 2) several SMS contaminants had very low detection frequencies; and 3) indicator SMS contaminants within a specific class (e.g., PAHs) may well represent the behavior of that class. The representative SMS contaminants were identified by querying the database and counting the number of samples that exceeded the SQS for each contaminant. Those with the most frequently

[13] The post-remedy bed sediment replacement value was not applied outside of the active remedial footprint because a thin layer of sand will be applied to manage dredge residuals where needed. It was assumed that such application would, on average, return any sediments affected by residuals outside of the dredge footprint to preconstruction concentrations.

detected exceedances were selected to represent a group/class (Table 5-3). They include bis(2-ethylhexyl)phthalate (BEHP) (phthalate group); chrysene, fluoranthene, and phenantherene (PAH group); and mercury and zinc (metal group). Arsenic and total PCBs were also included to assess the spatial distribution of these risk drivers in a manner consistent with the other SMS contaminants. Detected SQS/CSL exceedances for total PCBs were assessed using sample-by-sample oc-normalizations to ensure that detected exceedances were not missed in the interpolated IDW maps based on dry weight (see Table 5-2a).

After the initial representative SMS contaminant list was established, locations were identified that exceeded the SQS for other SMS contaminants, and additional SMS contaminants were added to the list so that at least one representative SMS contaminant was identified for each location. As a result, butylbenzyl-phthalate, phenol, acenaphthalene, and indeno(1,2,3-cd)pyrene were added. Table 5-3 lists these SMS contaminants and the upstream and lateral values established for each.

For each location that had a detected SQS exceedance in the FS baseline dataset, the maximum exceedance ratio above the SQS and the SMS contaminant responsible for that exceedance were determined. Typically, the SMS contaminant responsible for the highest exceedance was one of the representative SMS contaminants, and was usually total PCBs.[14] If the SMS contaminant with the maximum exceedance ratio was not in the representative SMS contaminant list, a representative SMS contaminant of the same chemical class that also exceeded the SQS at that location was used in the BCM. The future BEHP concentrations were also predicted by the BCM for each location because this SMS contaminant is a concern due to lateral sources.

5.2.4.1 Input Values for Representative SMS Contaminants

Lateral input values were determined by querying the City of Seattle's lateral source database (SPU 2010). Upstream input values were derived from the USACE Dredged Analysis Information System (DAIS) core database using data through 2009 (USACE 2009b, 2009c). For the City of Seattle data, all storm drain solids data were queried for each COC. The log-normal mean of the dataset was then calculated and used as the lateral inflow value for that contaminant (Table 5-3) after outliers were removed. The USACE core data from the Upper Turning Basin, RM 4.3 to 4.75, were used to represent the incoming sediment from upriver because that is the only upstream dataset analyzed for all SMS contaminants over a sufficient period of time. The data were screened to include only those collected after 1990 (prior data were excluded). The median of the dataset for each contaminant was then calculated and used as the upstream value for that contaminant. Table 5-3 lists the lateral and upstream inflow values used for each representative contaminant. No post-remedy bed sediment replacement values were used for these points. If a point was located in an actively remediated area, it was

[14] Several locations were sampled only for PCBs.

considered to be remediated below the SQS and removed from further bed composition modeling at that location.

5.2.4.2 BCM Equation Using Lateral and Upstream Input Parameters

For those locations where the detected concentration of any SMS contaminant exceeded the SQS at the start of the modeling period (and was not a toxicity pass), the BCM equation was run using Equation 5-1. The upstream and lateral input values discussed in Section 5.2.4.1 were employed for the contaminant selected to represent that location. Equation 5-1 was also used to estimate exceedances at the end of 10 years for BEHP, a contaminant that chronically exceeds the SQS and is generally associated with non-point source lateral discharges.

Because the lateral and upstream input parameters are on a dry weight basis, the BCM Equation 5-1 was run for the representative SMS contaminants using dry weight concentrations. For each SMS contaminant modeled at a location and having oc-normalized SMS criteria, the dry weight concentrations predicted for each time period modeled were compared to the baseline dry weight concentration. This process yielded a percent reduction that was then applied to the baseline oc-normalized concentration. If the resulting value exceeded the SQS, then the station was considered to be an SQS exceedance at the end of the modeling period.

5.2.5 BCM Output and Model Sensitivity

The output of the BCM is predicted contaminant concentrations for each grid cell[15] at specified time intervals (i.e., 5, 10, 15, 20, 25, 30, 35, 40, and 45 years). Summary statistics, such as site-wide and area-specific SWACs can be calculated for the distributions of surface sediment concentrations and used in assessing remedy effectiveness. Area-specific statistics can be calculated to assess beach play and potential clamming area-focused remedies.

Sensitivity runs of the BCM are used to evaluate the effect of varying contaminant concentrations associated with upstream and lateral source sediments and post-remedy bed sediment replacement values (in remediated areas) on bed sediment concentrations over time. The sensitivity of the BCM was investigated by looking at how changes in input parameters affect the output (Appendix C, Part 5).

When evaluating model uncertainty, it is important to understand that the contaminant concentration in a specific area is not as straightforward as selecting a specific cell and assuming that the concentration in that cell is accurately represented by the BCM value. For developing the initial contaminant concentration, the BCM uses a 10 ft × 10 ft cell size to capture the spatial scale of surface sediment contaminant concentrations used in IDW interpolations (see Appendix A). The BCM grid is used for computing SWACs in

[15] The BCM analysis uses grid cell sizes of 10-ft by 10-ft, the same as those used for the IDW interpolation of surface sediment concentrations.

this FS. However, it should not be construed that the 10 × 10-foot grid is appropriate for design purposes and the grid should not be used beyond this FS. Remedial design should be based on data and analysis specific to a design area.

Existing surface sediment contaminant data are more sparsely located in some areas and the initial contaminant concentration for a grid cell of interest may be represented using a data point that was collected anywhere from a few feet up to more than one hundred feet from the location of the grid cell. Nevertheless, when averaged over larger areas, model results are still relevant. However, the BCM model resolution on finer scales is limited not only by resolution of initial condition data but also by STM grid cell resolution[16] and other factors (such as representation of lateral load distribution). For example, specific "hot spots" may cover only a small part of an STM grid cell that extends from the bank to fairly deep water. The model-predicted current velocity and sedimentation rate are assumed to be spatially constant over this STM grid cell. The actual current velocity, and therefore sedimentation rate, may vary substantially over this STM grid cell, especially for cells that are near-channel or near-shore. The current velocity and sedimentation rate may be representative of the average for the area covered by the STM grid cell, but may not accurately represent these parameters within some subdomain of the STM grid cell. It will always be important to investigate and understand model input and processes (such as the scale of predicted sedimentation rates from the STM) when evaluating the appropriate size of areas where BCM-predicted contaminant concentrations are valid.

5.3 Additional Analyses Related to Natural Recovery Potential

The STM and the BCM presented above address most of the processes that affect natural recovery. However, this FS assesses several processes not explicitly addressed in the RI (Windward 2010) and the Final STM report (QEA 2008). These include:

- The effect of tugs on sediments in berthing areas (disturbance activity)
- Additional model scenario runs using the calibrated STM to answer several specific FS questions
- Influence of grain size and organic carbon on sediment contaminant concentrations.

The following sections discuss these other processes that may affect natural recovery.

5.3.1 Incorporating Effects of Disturbance Activity

The STM and BCM predict changes to the sediment bed for long time periods from natural processes and estimated contaminant loadings. However, STM and BCM

[16] STM grid cells range in size from range from 0.1 to 4 acres, with the median area of a grid cell being 0.5 acre (e.g., a 100 ft-by-200 ft area is roughly 0.5 acres).

predictions do not incorporate long-term changes to the sediment bed that could be caused by deep disturbance of sediments (i.e., up to 2 ft), such as:

- Emergency and high-power (i.e., outside of routine operating procedures) tug or ship maneuvering, ship grounding, small boat activities in shallow water, and construction and maintenance-related activities in the LDW may cause deep scour (Section 5.3.1.3), which mixes subsurface sediments with surface sediments, resulting in higher contaminant concentrations at the surface.

- Seismic events (earthquakes) could result in liquefaction-induced ground movements that could damage in-water and upland infrastructures and could result in deep disturbance of subsurface contamination, resulting in higher contaminant concentrations at the surface.[17]

Such disturbances would likely be isolated and infrequent, but the cumulative effects could be of concern over the long term. Several approaches were utilized to increase our understanding of how BCM-predicted SWAC values are influenced by both natural and anthropogenic processes. This section discusses two topics:

- Influence on bed erosion of vessels maneuvering in the navigation channel and in areas deep enough to accommodate vessel drafts based on propeller shear stress modeling

- Areas where episodic, high-energy disturbance activity can expose more highly contaminated underlying sediments.

5.3.1.1 Propeller-Scour Model of Maneuvering Vessels

Propeller scour from tugs transiting the navigation channel under routine operating procedures in the LDW was evaluated in the STAR (Windward and QEA 2008). The analysis showed that the maximum scour from tugs transiting the navigation channel is less than 1 cm within the navigation channel and approximately 1 to 2 cm on the benches adjacent to the navigation channel. The higher potential scour on the benches is due to tugs traveling on the edge of the navigation channel adjacent to shallower depths on the benches.

Assuming that sediments resuspended by propellers redeposit near the resuspension site, then anthropogenic scour in the navigation channel and benches acts only as a mixing process in the surface layer, augmenting the mixing induced by bioturbation (which is typically greatest within the top 10 cm of sediment). The STM assumes a 0- to 10-cm mixed layer of sediment at the surface; hence, the effects of propeller scour

[17] Although earthquakes can also result in admixture of subsurface and surface sediments, this potential disturbance is not explicitly discussed in this section, because the range of effects is not readily modeled with the information currently available. However, see Section 8.1.3 for more information.

associated with vessels moving in the navigation channel are consistent with the STM assumptions for tugs operating in the navigation channel.

However, the propeller scour analysis presented in the STAR is not applicable to tugs or vessels maneuvering in areas shallower than the navigation channel or when emergency and high-power operations are needed. Tugs may occasionally need to use more power while maneuvering barges in and out of berths, and tugs may be stationary for longer periods of time (while still operating their propellers).

A modeling approach developed by the USACE was applied to the LDW for maneuvering vessels. This model was developed with an analysis of currents and shear stresses induced by towboats and barges on the Mississippi River (Maynord 2000). The methods and model were used for computing bottom currents and shear stresses caused by moving barges and propeller scour in the LDW. A detailed discussion of the Maynord model is presented in Appendix C, Part 7. Briefly, the model maps the velocity and the associated shear stress induced by the propellers that reaches the river bottom. The shear stress time series and the sediment characteristics at the river bottom determine the amount of scour that will occur over a period of time. The velocity is related to the amount of power applied by the tug. However, tugs may operate at higher power for short periods of time. The applied power under different operating conditions and durations was determined from interviews with tug operators. The analysis followed a similar approach as in the STAR (Windward and QEA 2008), using the same two tugs for model input parameters. The larger tug, *Sea Valiant*, operates downstream of the First Avenue South bridge (RM 2.1), while the smaller tug (*J.T. Quigg*) is able to operate in shallower water upstream of the bridge.

No precise methods are available to relate propeller-induced shear stress to sediment erosion. However, rough estimates of the scour magnitude can be developed. Based on the analysis,[18] localized deep (more than 10 cm) vessel scour may occur for tugs operating in shallow water and at higher power, as described by tug operators working under emergency conditions (see Appendix C, Part 7). Vessel scour depth is strongly affected by the distance between the propeller and the sediment bed, with substantially less scour in deeper water. Other factors influencing propeller scour are propeller angle, thrust, blade configuration, and duration of the high-power event under stationary conditions. For most berthing areas and operational conditions (in deeper water operations under normal power conditions), the depth of scour is estimated to be 10 cm or less, which would not necessarily disturb and expose subsurface contaminant concentrations (see Appendix C, Part 7). However, as described in Section 5.3.1.2, infrequent events can scour more than 10 cm. Results of this scour analysis, combined with empirical evidence of scour, have been incorporated into the FS in two ways: the

[18] This analysis was limited to the vertical depth of the Sedflume core data collected during the RI (about 30 cm).

development of recovery categories (Section 6) and in the technology assignments for individual remedial alternatives (Section 8). The following section discusses other components of scour.

5.3.1.2 Episodic Deep Disturbances Leading to Exposure of Subsurface Contamination

Potential influences on SWAC from routine vessel operations are described above. However, less frequent and episodic events in an active navigation area such as the LDW may induce disturbance of subsurface sediments, exposing subsurface contamination. In this FS, this process is called deep disturbance. Deep disturbances may involve ships operating with excessive propeller power, ship groundings, emergency maneuverings, or seismic events. Maintenance operations such as dock construction/maintenance and vessel maintenance may also cause deep disturbance.

The STM/BCM models were not set up to model deeper disturbance events, so this FS conducted a separate sensitivity analysis of deep sediment disturbance to consider the potential effects of such disturbance events on STM/BCM-predicted SWACs. This disturbance analysis introduces an additional, local source of contamination: the subsurface sediment bed. Natural processes (apart from earthquakes) and routine ship operations in the LDW will not typically mix the surface 0- to 10-cm layer with deeper subsurface sediments except in areas that were identified on the basis of known ship activity and from precision bathymetry, which suggested deeper erosion (Section 5.3.2.7). However, some lines of empirical evidence (geochronology cores and sediment concentration profiles) suggest that in some areas subsurface sediments may have been disturbed as a result of anthropogenic activity. There is evidence, based on contaminant profiles in some cores and geochronological data, that deep disturbance events may have hindered recovery at localized areas. The frequency and magnitude of these events is unknown. Influence of such events on BCM SWAC projections was analyzed in Appendix M, Part 5, and results are compared in Section 10. Changes in the long-term SWAC, based on potential exposure of contamination remaining in the subsurface sediment after dredging or capping, are estimated for each alternative as a function of the long-term SWAC, the size of the area disturbed, and the average contaminant concentration remaining in the subsurface after remediation. Because the total area of deep disturbance is unknown, results are presented as change in SWAC as a function of acreage that has experienced deep disturbance. Because the frequency of such events is also unknown, this FS assumes that disturbed areas would have to be exposed continuously to produce a measurable difference in the long-term model-predicted SWAC of 25%. This 25% threshold is considered the minimum change needed to detect a difference between two SWAC values (see Section 9.1.2.1). Results for the deep disturbance analysis (provided in Section 10) range from 11 to 43 acres (2% to 10% of the total LDW acreage).

5.3.2 Additional Special Scenario STM Runs

Six additional scenarios were run using the STM to further understand the movement of sediment particles within the LDW and the potential effects on the natural recovery analysis. The additional runs assessed:

1) Potential for recontamination of EAAs
2) Effect of more detailed distribution of discharges from lateral sources on the bed composition
3) Movement via tidal currents of resuspended sediment from reaches downstream of the Upper Turning Basin upstream into the Upper Turning Basin
4) Movement and deposition of sediment between Reaches 1, 2, and 3
5) Fate of sediment scoured from depths greater than 10 cm
6) Tracking of existing bed sediment movement
7) Natural recovery hindered in selected berthing areas.

A description of each of these scenarios and a summary of the results are presented in Table 5-4. A detailed accounting of scenarios 1 through 6 is presented in Appendix C, Parts 4 and 5. The findings of this work are generally consistent with the CSM (see Section 2) and support key assumptions and analyses inherent in the BCM and the assignment of remedial technologies (Section 8). The primary findings of the special scenario STM runs are discussed below.

5.3.2.1 Scenario 1: Potential Recontamination of EAAs

The purpose of this scenario was to assess the potential for remediated EAAs to be recontaminated over time by areas located outside of the EAA footprints that would be allowed to recover naturally. This may affect decisions concerning the timing and sequencing of remedial activities at specific EAAs.

The results of this analysis indicate it is unlikely that remediated areas will be recontaminated by unremediated areas unless the areas are adjacent to each other. Material resuspended from unremediated areas during high-flow events is estimated to account for less than 5% of the material that settles in remediated EAA footprints over a 10-yr period[19] (see Figure 5-6). The BCM analysis on this scenario indicates that recontamination of EAAs above the SQS (the SQS was used as a point of comparison for this analysis because other potential remedial action levels [RALs] vary by alternative)

[19] Only a few grid cells have been identified as having non-EAA source material in the range of 5 to 20% and most of these are in Reach 2. The average across the LDW is generally less than 5%.

is more likely to occur near outfalls as a result of lateral source inputs than to scour and settling of bed sediment from outside EAAs.

5.3.2.2 Scenario 2: Distributed Discharges from Lateral Sources

This scenario examined certain simplifying assumptions that were used in the STM for lateral discharge locations (for storm drains and streams), and refined those assumptions to better account for actual lateral discharge distribution. In the original STM (QEA 2008), all Duwamish watershed discharges were aggregated into 16 discharge points along the LDW. The discharge points consolidated total area runoff from storm drains to the major outfalls and did not include the more widely distributed smaller outfalls located along the shoreline. CSOs that discharge to the LDW were also included, but these were modeled at their actual locations.

In this distributed discharges modeling scenario, finer drainage basin delineations were used to more accurately reflect actual drainage subbasins and outfalls (pipe locations) of storm drains, resulting in 13 major storm drains, 9 CSOs, and 11 waterfront areas that discharge to the LDW through numerous small outfalls. The revised load estimates and drainage basins for storm drains, creeks, and City CSOs (SPU 2008) were presented and are summarized in Appendix C. Because the distributed load simulation more accurately represents the distribution of lateral loads along the shoreline, it was carried forward as the FS base case loading condition. The lateral loads used in the FS base case are shown in Figure 5-7.

5.3.2.3 Scenario 3: Movement of LDW Bed Sediment into the Upper Turning Basin

This scenario examined the degree to which bed sediments from elsewhere in the LDW may become resuspended, transported upstream, and deposit in the Upper Turning Basin (above RM 4.0). The Upper Turning Basin sediment composition and chemistry is only minimally affected (less than 0.01%) by sediment moving upstream with tidal currents (Figure 5-8). Figure 5-8 shows the geographic distribution of sediment settling in Reach 3 but originating from downstream of RM 4.0 (from Reaches 1 and 2). Only the area between RM 4.0 and 4.1, Slip 6, and a few other isolated grid cells in Reach 3 are estimated to have more than 0.01% sediment contribution from bed sediment downstream of RM 4.0, and even these areas are less than 0.05%. This estimate is in agreement with the 10-year sediment mass balance, which indicates that about 240 MT moves from Reaches 1 and 2 and is expected to deposit in Reach 3 (see Scenario 4). This is extremely small compared to the estimated total sedimentation in Reach 3 of 2.3 million MT over 30 years; 99.99% of this sedimentation is from upstream sediments. Based on this analysis and the contribution of sediments from lateral sources (see Section 5.3.2.2), the sediment in the Upper Turning Basin and the navigation channel above RM 4.1 should not be adversely affected by sediments transported from other portions of the LDW. The BCM analysis for this scenario shows that the predicted COC concentrations in the Upper Turning Basin are for the most part very low and negligibly affected by the amount of sediment deposited from downstream. This analysis also supports the use of Upper Turning Basin sediments in the navigation channel (RM 4.3 to RM 4.75) as representing the COC concentrations in sediments originating from the Green/Duwamish River.

5.3.2.4 Scenario 4: Movement of Bed Sediments between Reaches

This scenario examined the degree to which bed sediments in one reach of the river may be resuspended and transported to another reach. These results may be important in assessing recontamination potential between reaches and in assessing if locations would be important for sequencing the remedial alternatives. Sediment exchange (either upstream or downstream) is strongest between Reach 1 and Reach 2, while Reach 3 primarily contributes sediment to downstream reaches with very little sediment transported from downstream reaches back to Reach 3 (Figure 5-9). In addition, much of the bed sediment that is resuspended in a reach resettles in that same reach.

Reach 3 receives a large amount of sediment from the Green/Duwamish River as a combination of suspended load and bed load, the latter consisting mostly of sand. This reach is regularly dredged by the USACE, particularly in the Upper Turning Basin. Maintenance dredging, applied by the USACE on the cycles that we have seen in the past, should not change current natural recovery processes because it primarily removes sand that is not readily transported downstream and therefore is not a significant component of net sedimentation and natural recovery in Reaches 1 and 2.

5.3.2.5 Scenario 5: Sediment Scoured from Greater than 10 cm Depth

This analysis was used to evaluate whether scour and transport of deeper sediments may influence the waterway-wide SWAC during an extreme high-flow event. Scour during a 100-year high-flow event was analyzed in the STM report as a 30-day simulation (QEA 2008). Scour in excess of a 10-cm depth (up to about 22 cm) occurs in portions of the LDW from RM 2.9 to RM 3.9 and in isolated areas between RM 4.2 and RM 4.7. Most of these areas are in the navigation channel.

Sediment scoured from below 10 cm during a 100-year high-flow event was modeled over a 10-year period. In Figure 5-10a, the STM estimates that approximately 200,000 MT of sediment settles in the LDW during a 100-year high-flow event and of that amount, approximately 70,000 MT is eroded from the bed. However, as shown in Figure 5-10b, only about 6,600 MT of the sediment that settles is eroded from below 10 cm, which is only about 3% of the deposition during the 100-year high-flow event. Consequently, sediment eroded from below 10 cm during high-flow events, and mostly from Reach 2, makes a negligible contribution to sediment transport and deposition in the LDW during those high-flow events. In Reach 2, about 45% of eroded material is estimated to redeposit in the same reach (3,800 MT deposited out of 8,700 MT eroded) while deposition of upstream sediment and eroded shallow sediments from other areas of the LDW is estimated to be approximately ten times this amount. Consequently, erosion and redeposition of sediment scoured below 10 cm makes a negligible contribution to the potential for redistribution of subsurface sediment between reaches during high-flow events. In addition, very few sediment cores in these potential scour areas had SQS exceedances and those with exceedances were located in or adjacent to EAAs (see Appendix C, Part 4).

The areas estimated to have greater than 10 cm of scour total about 22 acres (Figure 5-11: and see Appendix C, Part 4, Scenario 5). Subsurface bed sediments (below the 10-cm depth) are generally more contaminated than surface sediments (0- to 10-cm depth). However, core data indicate that only a few areas have contaminant concentrations above the SQS or CSL in areas prone to natural erosion. The total area with surface exceedances above the SQS in areas with more than 10 cm of scour during high-flow events is 5.4 acres; of that, 1.5 acres are in the EAAs. In summary, empirical and modeling data indicate that the majority of subsurface sediment eroded will not have significantly higher contaminant concentrations.

5.3.2.6 Scenario 6: Movement of Existing Bed Sediment

This scenario was conducted to track the movement of sediment within the LDW. In the BCM, the initial COC concentration in the bed sediment at a given point is assumed to be unchanged through time. This means that the changes in COC concentrations at any given location are attributable only to the net sedimentation of upstream and lateral source sediments and mixing with bed sediments at that location. In actuality, bed sediments from other areas of the LDW are resuspended and settle throughout the waterway. The movement of resuspended bed sediment (distal sediment) and its effect on COC concentrations was evaluated by separately tracking the deposition of resuspended bed sediment and original bed sediment over time. This allows the COC concentration to change as a result of deposition of bed sediment as well as deposition of upstream and lateral source sediments. The STM analysis results are presented in Appendix C, Part 5 (LDW STM Bed-tracking Scenario Simulation).

The STM output was used in a BCM analysis with four contaminant inputs, one each for upstream, lateral, bed, and distal sediments. To account for the effect redeposition of sediment would have in a reach (the distal fraction), the total PCB concentration on resuspended sediment was based on a weighted average of the mass of sediment resuspended from each of the three reaches multiplied by the reach-wide SWAC for the reach where the sediment originated. For example, the PCB concentration associated with distal sediment from Reach 3 uses the SWAC from Reach 3 as the input value. This is an approximation that does not strictly conserve contaminant mass. However, it provides a check on the standard BCM analysis and shows the importance of resuspension and redeposition of bed sediment relative to other processes in the LDW on future SWACs. This analysis was conducted with the assumption that remediation of the EAAs had been completed.

This analysis indicates that accounting for bed sediment movement produces no substantial change to the total PCB SWAC at the end of 10 years, both on a site-wide and reach-wide basis (Table 5-5). The calculated total PCB SWAC, when this effect is considered, is unchanged in Reaches 1 and 3, and 6% lower in Reach 2. Site-wide, the decrease in predicted SWAC is approximately 1%. The changes are small because throughout the LDW, resuspended bed sediment that resettles in the LDW is a small component of the sediment mass balance. The resuspended bed sediment that settles in the LDW is only 5%, 12%, and 9% of the total mass of sediment depositing in Reaches 1, 2, and 3, respectively (see Appendix C, Part 5). In Reach 2, which has the highest fraction of bed sediment that resettles, most of the sediment that resettles originates in Reach 3, where total PCB concentrations are generally lower than in the other reaches. Overall, this simulation shows that redistribution of existing bed sediment by high-flow events has a minor effect on recovery predictions. The largest change is in Reach 2; however, the approach used in the BCM base case analysis likely underestimates natural recovery in Reach 2 compared to a model that actually tracks the movement of individual sediment particles.

5.3.2.7 Scenario 7: Natural Recovery Hindered in Selected Scour and Berthing Areas

In localized areas where high levels of routine ship activity occur and depths are sufficiently shallow to permit disturbance of the sediment bottom, natural recovery may still be occurring, but over longer periods.[20] Propeller scour from ordinary ship maneuvering activities temporarily resuspends surficial bed sediment, after which a portion of that material resettles in the same footprint, with the coarser material more likely to resettle and fines more likely to be transported away, depending on tides and currents. A constant source of incoming material from upstream also amends the bed sediment so that any exposed contaminant concentrations are reduced over time. Regular maintenance dredging in the navigation channel and active berthing areas indicates that net sedimentation is occurring and that sediment removal is required to maintain acceptable water depths for navigation. Empirical trends, where data are available, show that burial and sediment recovery are occurring in most of these areas (see Appendix F). Berthing areas were considered on a case-by-case basis during development of technology assumptions.

Some empirical data indicate that recovery may be hindered by normal navigation activities. These activities only rarely induce deep disturbance but, by continual resuspension of the unconsolidated surface sediment layer could reduce accumulation of layers of cleaner upstream sediments. To examine effects of such navigation activities on BCM predictions, a scenario was developed that assumes that natural recovery does not occur in areas considered prone to regular anthropogenic resuspension and transport of sediments (i.e., the berthing areas). At many of these locations, the STM

[20] This is for normal or routine operating conditions. See Section 5.3.1.2 for evaluation of extreme, episodic conditions.

indicates sedimentation during the recovery period. In this sensitivity analysis, the initial bed contaminant concentrations in potential scour areas and berthing areas are held constant for all BCM analyses throughout the 10-year period modeled in the BCM (i.e., no sedimentation and recovery). This assumption is the best available approach to bound uncertainty pertaining to effects of vessel scour on surface concentrations predicted by the BCM.

Areas held constant in this analysis were selected to include areas of potential scour from routine navigational activities: 1) berthing areas with net sedimentation rates less than 0.5 cm/yr (see Figure 2-11), and 2) vessel scour areas identified using sun-illuminated maps (Figure 5-4). This method has several limiting assumptions. Specifically, sun-illuminated maps are a snapshot in time of bed locations that have been disturbed by ship activity. The areas identified using this method may change in the future. Therefore, the selected areas for propeller scour are not intended as a robust indicator of all areas that may be influenced by propeller scour.

A BCM sensitivity was conducted over the 10 years following construction in order to compare the site-wide and reach-wide total PCB SWACs for the base case to a case with constant bed sediment total PCB concentration in potential scour areas.

Alternative 3: 10-Year Model Condition[a]	Total PCB SWAC (µg/kg dw)			
	Site-Wide	Reach 1	Reach 2	Reach 3
Base Case (includes modeled recovery in vessel scour areas)	62	68	61	39
Holding Cells Constant in vessel scour areas and berthing areas with net sedimentation rates <0.5 cm/yr	69	75	72	42

a. Exploratory test case condition at 10 years following remedy completion of Alternative 3 using mid-range BCM values, FS baseline data, and model assumptions used in the Draft Final FS.

This bounding exercise indicates that estimates of total PCB SWAC are not very sensitive to scour effects from normal operation of transiting vessel traffic. Vessel traffic can have some influence on SWACs (by hindering natural sedimentation and recovery), but this effect is less than a 25%[21] difference (considered the minimum detectable difference between SWAC estimates). For this scenario, the SWAC is about 10% higher for site-wide and reach-wide total PCB SWACs, except in Reach 2, which is 18% higher. However, scour and the resuspension of freshly deposited material may result in greater increases in localized areas and will need to be factored into remedial design in potential areas where natural recovery is hindered by vessel scour (see Section 6).

5.3.3 Influence of Grain Size and Organic Carbon on Sediment Chemistry

Hydrophobic compounds, such as PCBs, more readily adsorb to the organic substances attached to sediment particles than they do to the inorganic surface of sediment

[21] A threshold of 25% is considered the minimum change needed to detect a difference between two SWAC values (see Section 9.1.2.1).

particles. As a result, the amount of organic carbon influences the potential adsorption of PCBs (and other hydrophobic COCs) to the particles. In addition, higher contaminant concentrations are generally associated with finer-grained sediment (clay/silt). This may be particularly important in the LDW as the grain-size distribution becomes finer from upstream to downstream (Figure 5-12), and the risk drivers are positively correlated with total organic carbon (TOC) and percent fines in the LDW (see Appendix C, Part 3b, Table 8).

Contaminant concentrations in the BCM were assigned equally to all grain sizes. In this evaluation, the sensitivity of the BCM is tested to determine the influence that size fractionation of COCs has on SWAC results. Total PCBs were assigned to the four STM particle size classes (Classes 1A [less than 10 microns], 1B [10 to 62 microns], 2 [62 to 250 microns], and 3 [250 to 2,000 microns]) in varying concentrations based on particle size (for additional details of this analysis, see Appendix C, Part 9). Three different partitioning approaches were used for assigning total PCB concentrations to the different particle size fractions (Table 5-6a). The results of the three analyses are shown in Table 5-6b.

Overall, this sensitivity analysis demonstrated that different approaches to assigning total PCB concentrations by size fraction did not substantially change the results for the BCM analysis unless the assumptions produced an increase in mass loading of total PCBs. For example, Approaches 2 and 3 demonstrated that the SWAC would decrease (14%) or remain approximately the same for cases where mass loading of the COC was not changed. This is because higher PCB concentrations are being assigned to Class 1A particles compared to the other size classes, but 90 percent of the Class 1A material passes through the LDW without settling. Approach 1 resulted in an increase in the site-wide SWAC by approximately 42% because the approach also increased the PCB loading from upstream and lateral sources by approximately 100%.

Preferential partitioning of contaminants to finer size fractions is well documented in the literature and can affect the distribution and bioavailability of contaminants. To account for this preferential partitioning, dry weight values are often normalized to the amount of organic carbon present in a sample (i.e., oc-normalization; Michelsen 1992). Many of the SMS contaminants have oc-normalized criteria.

5.4 Empirical Trends and STM/BCM Reliability

The reliability of the STM to estimate net sedimentation rates, and of the BCM to predict changes in contaminant concentrations, is supported by empirical trends (i.e., net sedimentation rates from time markers in cores and changes in contaminant concentrations over time). Consistency between empirically-derived net sedimentation rates and the STM and between the BCM and empirical trends in COC concentrations in surface sediments lends credibility to the STM/BCM prediction of natural recovery in the future. Contaminant trends in surface sediments were evaluated both by changes in risk-driver concentrations by depth in cores and by changes in their concentrations over time at resampled surface sediment locations. Appendix F presents these empirical data and the methods by which these data were evaluated. This section summarizes the findings presented in Appendix F.

Net sedimentation rates calculated from time markers (Pb210, Cs137, and contaminant peak dating) in cores that supported net sedimentation are in general agreement with rates estimated by the STM. Seven out of the 62 cores (11%) in the LDW provided no data on recovery rates, had low concentrations such that trends could not be determined, or indicated disruption to recovery. Chemical trends in most cores and at most resampled surface sediment stations show reductions in risk-driver concentrations over time. Both of these findings demonstrate that recovery is occurring in much of the LDW (as discussed and presented below for total PCBs, cPAHs, and other SMS contaminants). In areas either where these lines of evidence are not similar to one another or to the STM outputs, or where recovery is not predicted by the BCM, more attention is given to ascertain the reasons for these differences (see Appendix F). In some small-scale areas, these lines of evidence suggest that recovery is not occurring, and these areas are incorporated into assignment of recovery categories (see Section 6).

5.4.1 Net Sedimentation Rates

Net sedimentation rates were estimated from 74 cores for which time markers could be identified (Table F-3; Figure 5-13). These markers provide evidence of new material being deposited in the LDW, showing that burial, the dominant recovery mechanism, is occurring. The time markers were used to calibrate the net sedimentation rates estimated by the STM. STM calibration is discussed in Appendix F of the STAR report (Windward and QEA 2008). This analysis is also discussed in Appendix F of this FS. In the RI (Windward 2010), the depth of the peak total PCB concentration in each core was used to support the sedimentation rates estimated from the STM, and this analysis is discussed below in Section 5.4.1.1. Some cores indicated either no recovery or reduced recovery. The causes for these discrepancies are unclear. In some cases, the cores may not have been deep enough to show the time markers, concentrations were too low to detect trends, surface concentrations were too high from ongoing sources, or the area may have been previously dredged or otherwise disturbed. Deep disturbance may remove freshly deposited cleaner sediments or mix surface and subsurface sediments, resulting in exposure of higher contaminant concentrations at the surface.

System-wide statistical analysis suggests that the STM tends to underpredict sedimentation when compared to empirical data, and thus underpredict natural recovery potential. However, many of these sedimentation-rate underpredictions occur in Reach 3, which has very high sedimentation rates; thus, it does not influence model recovery predictions because both model and empirical data indicate rapid recovery. In Reaches 1 and 2, with less overall sedimentation compared to Reach 3, net sedimentation is sometimes underpredicted and sometimes overpredicted by the model. Several cores in these reaches did not have time markers preserved in the core profile from which to estimate sedimentation and recovery. Reaches 1 and 2 generally have lower empirically-derived net sedimentation rates compared to model predictions, as well as several cores that did not exhibit discernible recovery, and therefore the STM may somewhat over-predict recovery in these reaches. The base-case best-estimate STM predictions should be confirmed in localized areas during remedial design where MNR is being considered.

5.4.1.1 Vertical PCB Concentration Trends Compared to Net Sedimentation Rates

The PCB "peak" analysis presented in the RI (Windward 2010) combined information on depth patterns in PCB sediment chemistry (from sediment cores) with net sedimentation and erosion estimates from the STM to determine whether vertical patterns of total PCB concentrations are consistent with the STM's estimated net sedimentation rates and the CSM (Figure 5-14). Much of the sediment contamination in the LDW, and particularly PCB contamination, is believed to have originated from historical sources in the LDW.[22] In undisturbed depositional areas with no ongoing or recent sources, PCB concentrations should be higher in deeper core intervals than in shallower intervals. In areas with little or no deposition, localized disturbances, or ongoing or recent secondary sources (e.g., erosion of contaminated upland soil), this pattern may be altered, with higher PCB concentrations in the shallowest core intervals or relatively even distribution among core intervals.

Assuming that an area is depositional and has not been disturbed, the depth of the maximum total PCB concentration within a core should be a function of both the time since peak PCB use and release and the estimated rate of net sedimentation (from the STM). As a result, the expected depth of peak (or maximum) total PCB concentration was estimated for each core using Equation 5-2.

$$D = (T_c - T_m) \times S \qquad \textbf{Equation 5-2}$$

Where:

- D = expected depth of peak total PCB concentration (cm)
- T_c = year of core collection
- T_m = assumed year of maximum concentration in surface sediment, corresponding to the assumed peak in PCB use and releases to the LDW

[22] Peak PCB use was recorded in Puget Sound sediment cores between 1960 and 1970 (Van Metre and Mahler 2005; Battelle 1997); the commercial production of PCBs was banned in 1978, and they were subsequently phased out. Although PCBs historically used in paints, caulking, and other products continue to be released into the LDW, it is believed these ongoing sources represent a smaller contribution to the LDW than historical releases.

- S = net sedimentation rate (cm/yr) estimated from the STM for the grid cell containing the core (or the closest grid cell for cores outside the STM domain).

General uncertainties associated with estimating the depth of the peak total PCB concentration include uncertainties in the net sedimentation rate estimated by the STM and uncertainty in the estimate of the year of the peak release of PCBs. In addition, uncertainty is associated with identifying the exact depth of the peak total PCB concentration within a core because of compositing within each core section. Uncertainty is particularly high at locations where the core intervals analyzed were 3 feet (ft) or greater and is lowest at locations where the core was sectioned into 0.5-ft intervals. Location-specific uncertainties include the possibility of sediment disturbance near berthing areas or local structures, and the potential for localized PCB releases to continue after the peak use/release date. To address the uncertainty in the year of maximum historical PCB releases to the LDW, a range of estimated depths of the peak total PCB concentration was calculated for each core (i.e., estimated depths within each core were calculated by assuming maximum PCB releases in 1960, 1965, and 1974).[23] These depth estimates were then compared to the depth of the peak total PCB concentration in each core. If the observed depth of the peak total PCB concentration was at or deeper than the estimated depth, the core was considered to be consistent with the CSM, and with the STM's estimated net sedimentation rates.

Of the 366 cores available in the RI dataset, 157 cores were used in the analysis and 209 cores were not used because the type of information needed for the analysis was not available for those cores. Cores were excluded if at least one of the following conditions were met:

- Only one core interval was analyzed for total PCBs
- No core interval was analyzed within the depth range of the expected peak
- PCBs were not detected in any core interval
- The sediment was disrupted by dredging prior to sampling.

Of the 157 cores included in the analysis, 110 cores (70%) had peak total PCB concentrations at depths equal to or greater than the estimated depths, consistent with the STM's estimated net sedimentation rates. Forty-seven cores (30%) had maximum total PCB concentrations that were shallower than the estimated depth range based on net sedimentation rates from the STM, or the concentrations were too diffuse to detect a significant peak at depth. For recovery estimates, the LDW model and field data are divided into three reaches. Reach 3 (the upper LDW) includes high rates of

[23] The analysis used both nationwide trends for PCB peak release (1960 and 1965; Van Metre and Mahler 2004; Battelle 1997), and the year of a PCB spill in Slip 1 (1974; Blazevich et al. 1977).

sedimentation and most maintenance dredging occurs in this reach. None of the cores in Reach 3 had maximum PCB concentrations at depths that were less than model predictions. Reach 2 includes both areas of high sedimentation and areas where no sedimentation was evident (net scour). Of the cores in this reach, 35% had maximum PCB concentrations at depths that were less than model predictions and 2% showed no discernible trend. Reach 1, which is near the mouth of the LDW, has lower sedimentation rates compared to Reach 3. Of the cores in this reach, 25% had maximum PCB concentrations at depths that were less than model predictions and 5% showed no recovery.

5.4.2 Chemical Trends at Resampled Surface Sediment Locations

Generally, chemical trends in resampled surface sediment locations show that recovery is occurring over much of the LDW, which supports the BCM findings of decreasing contaminant concentrations over time. Resampled surface sediment locations are surface sediment samples collected at different times from the same station (within 10 ft of one another). The contaminant concentrations in the LDW surface sediments have heterogeneous, but restricting the distance between older and newer locations to 10 ft reduces the uncertainty introduced by comparing samples from different locations. Appendix F describes the details, statistical results, and limitations associated with this type of comparison (analytical accuracy, etc.).

In the FS dataset, the data from 70 resampled stations (67 locations with 3 outliers excluded, and excluding those collected at the Norfolk Area and Duwamish/Diagonal EAAs) were grouped into two populations: older/original data and newer (FS baseline) data (see Table 5-7). The statistical difference between total PCB concentrations in these two groups was evaluated to provide evidence of general LDW-wide trends using simple data distributions. The comparisons of total PCB concentrations between the older and newer data show a 62% decrease in the mean value. As shown in Table 5-7, the 25th and 90th percentiles of these datasets also decreased by 31% and 64%, respectively, revealing that, in general, the empirical data support the STM findings that the LDW is recovering (at least for PCBs). Table 5-7 also summarizes these trends for arsenic, cPAHs, and BEHP. These data demonstrate that, on average, total PCBs, cPAHs, and BEHP concentrations are decreasing over time (more than or equal to a 50% reduction in concentration) while arsenic is in equilibrium (see Appendix F) and relatively close to urban background levels (see Appendix J).[24] For total PCBs and cPAHs, the mean for the older dataset is more than 20 times higher than their mid-range BCM upstream input values (Table 5-1a). For arsenic, the mean of the older dataset is only 4 times higher than the mid-range BCM upstream input value. This means that new sediment from upstream will have a greater effect on reducing concentrations of total PCBs and cPAHs over time than on reducing concentrations of

[24] The arsenic data have a narrower range of concentrations in the LDW than the other risk drivers, and are more similar to background conditions.

arsenic. Station-by-station results are presented in Appendix F for total PCBs, arsenic, cPAHs, BEHP, and SMS contaminants with detected exceedances in either the newer or older data.

5.5 Uncertainties Related to Predictive Modeling

The goal of an uncertainty analysis is to both qualitatively and quantitatively define the degree of confidence in site characterization data, both conceptual and predictive site models, and predictions of the results of remedial actions to the degree possible.[25] Bounding the certainty of estimates, especially in modeling, is a developing science. In accordance with an EPA guidance document (EPA 2005b), the potential areas of uncertainty to be identified and addressed in an FS include the CSM, data uncertainty, temporal uncertainty, spatial variability, and quantitative uncertainty. Several elements of uncertainty related to the predictive models (STM and BCM) are described below.

5.5.1 Net Sedimentation Uncertainty

Extensive sensitivity analyses were conducted on the STM and are described in detail in the STM report (QEA 2008). Sensitivity analyses were conducted on both high-flow event simulations and long-term, net sedimentation simulations. The net sedimentation sensitivity analysis showed that the model was most sensitive to the upstream sediment load and the settling speed of the fine-grain sediment classes, which make up the majority of the incoming sediment load. In this FS, because two, site-wide, independent datasets were not available for net sedimentation, uncertainty and sensitivity analyses both utilize the same input parameters. An appropriate measure for uncertainty in model predictions and application in this FS is the spatial scale analysis (QEA 2008; see Figure 2-13 from the STM Report). This analysis examined the accuracy of the model with respect to estimating net sedimentation rates from the large scale (LDW-wide) to the small scale (location-specific areas). This analysis found that the capability of the model was not affected by spatial scale (minimal bias), and that, on average, the model is able to estimate net sedimentation rates to within ±0.5 cm/yr on a typical net sedimentation rate of 1 cm/yr.

The incoming sediment load and depth of scour are affected by high-flow events. The STM used Green/Duwamish River flows from 1960 to 1989 as input flows. The maximum flow rate and upstream sediment loading for these years are shown on Figures 5-15a and 5-15b. The figures indicate that the upstream sediment load was

[25] Sensitivity analysis differs from uncertainty analysis in terms of goals and inputs. A sensitivity analysis looks at how the model responds to a range of input values, which may be extreme or not realistic, but are designed to stress the model and produce changes from the calibrated model results. Uncertainty analysis addresses the model’s resolution, that is, its ability to replicate natural processes in light of unaccounted processes. Uncertainty analyses should be based on realistic and statistically defensible methods for developing a reasonable set of input parameters and conditions, which are then used to demonstrate a range in model results in order to inform decision-makers of potential model errors.

below average for the first 10 years of the simulation. Consequently, the STM and BCM may be conservatively predicting net sedimentation through the first 10-year modeling period.

The flow period represented in the STM (1960 to 1989) and shown on Figures 5-15a and 5-15b is representative of current conditions. Annual precipitation since 1989 and up to the present has not changed significantly. Global warming is also not expected to change average annual precipitation significantly (Mote and Salathe 2009). By the late 1990s, when the U.S. Geological Survey (USGS) sediment loading study was conducted, the Green/Duwamish River basin was already under control by the Howard Hanson Dam and heavily developed with agricultural, urban, and suburban land uses. For these reasons, Green/Duwamish River flows and sediment loads are not expected to change substantially in the future as long as the river flow continues to be dam controlled in a manner generally consistent with historical water management practices.

5.5.2 STM Uncertainty – Lower and Upper Bound Simulations

The effects of uncertainty in STM inputs on model estimates were analyzed and quantified in the STM report (QEA 2008; see Section 2.8 and Appendix D.6 of the STM). The results of the input parameter sensitivity analysis were used to generate reasonable lower- and upper-bound limits on the base-case results, which are based on the calibration parameter set. The upper- and lower-bound cases were a result of changing the upstream sediment loading and settling speed of Class 1A and 1B solids. The base-case upstream loading rates were developed from two USGS studies to provide a good estimate of the magnitude of Green/Duwamish River input to the LDW, and the Class 1A and Class 1B settling rates were selected during the STM calibration process because they were reasonable and because they best match the empirically-derived LDW net sedimentation rates. Therefore, the values for these two model input parameters in the STM base case were reliably defined by site-specific data and model calibration.

The base-case simulations provide the best estimates of net sedimentation rate, but the reasonable lower- and upper-bound simulations provide an acceptable range of net sedimentation rates resulting from uncertainty in model inputs, with the “true” value of net sedimentation rate being within this range. As noted in Section 5.4.1, field sedimentation data are sparse and variable by reach and location, and the STM predictions will need to be confirmed for areas where MNR is proposed during remedial design. The highest empirically-derived net sedimentation rates occur in Reach 3 and were higher than model predictions; therefore, the STM may under-predict recovery there. Reaches 1 and 2 generally have lower empirically-derived net sedimentation rates compared to model predictions, as well as several cores that did not exhibit discernible recovery, and therefore the STM may somewhat over-predict recovery in these reaches.

To demonstrate the effect of model parameters on long-term changes in bed composition, the upper- and lower-bound results have been analyzed and used to estimate uncertainty in the predicted half-time of bed-source content[26] in surface-layer (0 to 10 cm) sediment for the long-term, multi-year (e.g., 21-year calibration period) simulations. Half-time values of bed-source content in surface-layer sediment were estimated using relationships between net sedimentation rates and half-time values developed from model results presented in the STM report (QEA 2008). The approximate relationship between half-time of bed-source content and net sedimentation rate can be used to estimate the spatial distributions of half-time and recovery potential if the starting concentrations are known.

Generally, the half-time of bed-source content in surface-layer sediment tends to decrease as the net sedimentation rate increases, see Section F.2 and Figure F-37 of the STM report (QEA 2008). In general, most areas have a half-time of less than 10 years based on net sedimentation rates of 1.0 cm/yr or more. This analysis indicated a general trend of decreasing half-life of bed-source content with an increasing net sedimentation rate. Spatial distributions of the net sedimentation rate for the lower- and upper-bound simulations are shown in figures in Appendix C, Part 6. The best-fit model prediction from the bounding exercise is about 5 to 10 years (±5 years if the net sedimentation rate is more than 1 cm/yr and longer with lower net sedimentation rates). Because the bounding exercise does not represent the calibrated dataset, this characterization of uncertainty is more appropriate for those regions farther from the locations where the model was calibrated. Areas near calibrated locations have significantly lower levels of uncertainty. This level of uncertainty is acceptable for the FS. The uncertainty in the reasonable lower- and upper-bound STM runs and its effect on PCB concentrations are discussed in Section 5.5.4.

5.5.3 Uncertainty around the BCM Contaminant Input Values

For the BCM, uncertainty exists in the assumptions about contaminant concentrations in lateral and upstream sources (from both non-point and point sources). This uncertainty will exist well into the future based on the variable nature of these sources, but is managed by expressing BCM inputs as a range of concentrations (low, high, and best-estimate values). These input values are based on actual data collected over the past 20 years. BCM uncertainty is managed by bracketing the best-estimate BCM value with lower- and upper-bound BCM input values representing the mean, UCL95, or percentiles of the existing data. For the lateral inputs, the low and high estimates are meant to capture a range of uncertainty associated with potential future source control measures.

[26] The half-time is defined as the time needed for 50% of material in the initial surface layer (0 to 10 cm) of the sediment bed to be replaced with depositing sediments.

These input values were estimated from summary statistics for various datasets (surface water, surface sediment, in-line sediments, catch basin solids, etc.). Each dataset has some degree of sample uncertainty associated with it, relating to aspects such as the matrix from which the sample was collected, the location from which the sample was collected, the differences in TOC and grain size among the datasets, the time (season, river flow, portion of storm event [e.g., first flush]) of sample collection, ongoing source control efforts, and other aspects that can affect contaminant concentrations in a sample. The high end of the range (high lateral, high Green/ Duwamish River, and high post-remedy bed sediment replacement values) is intended to capture variability in the source concentrations, worst-case recontamination potential, and regular, seasonal high flows from urbanized areas. The low end of the range (low lateral values, low Green/ Duwamish River, and low post-remedy bed sediment replacement values) represents a non-conservative set of assumptions that is considered likely to underestimate future contaminant concentrations. The probability that site conditions will produce a high-high-high contaminant concentration (lateral, Green/Duwamish, bed) is likely very small.[27] A similar low probability of occurrence exists for the low-low-low end of the range.

Another source of uncertainty related to lateral inputs is the fact that lateral contributions to the LDW can come from many different sources, including storm drains, CSOs, surface water runoff, and atmospheric deposition anywhere along the LDW and in its drainage basin. These sources were aggregated into 11 waterfront areas and 16 discharge points to the LDW for the purposes of sediment transport modeling. Of these, only the CSOs have measured discharge flows; runoff flows are estimated for other discharges. Some localized discharge points may not be adequately characterized by the 11 general waterfront areas. In addition, CSO control plans will result in reduced flows in the future for many CSOs.

Similar uncertainty exists for the post-remedy bed sediment replacement values used as input in the BCM. These values represent the bed sediment contaminant concentrations in the near-term (0 to 2 years) following completion of active remediation, including influence from multiple recontamination mechanisms. Evidence from other sediment sites shows that post-construction COC concentrations become higher than detection limits and natural background after this initial time frame. Limitations in the

[27] The likelihood of occurrence for the high-high-high contaminant concentration (lateral, Green/Duwamish, bed) is the product of the likelihood of each occurring independently. The likelihood of the upper bound representing the contaminant concentration for either upper, lateral, or bed source material is small. Therefore, the likelihood of all three upper bounds occurring is much smaller. It should be noted that a contaminant concentration value for any of these three variables that is higher than the medium, but less than the upper bound is not small. One can expect that the probability of occurrence of any combination is highest for medium-medium-medium and decreases moving toward either upper-upper-upper or lower-lower-lower combinations. The shape of this distribution is unknown.

dredging/capping equipment leave behind dredging residuals that resettle within the remedial footprint. Residual COC concentrations are typically proportional to the average COC concentration of the dredged material, and typically higher than the COC concentration in surrounding sediments (see Section 9 for a discussion on dredging residuals for each alternative). Post-construction surface sediments in the LDW may come into equilibrium with the sediments surrounding the remediated area. The equilibrium concentration of COCs in the sediment bed may be higher than the COC concentration in upstream sediments because of increased urbanization as one moves downstream toward downtown Seattle (more cars, vessel traffic, non-point sources, air emissions, accidental spills, and storm drain runoff). To address this uncertainty, the best-estimate for the post-remedy bed sediment replacement value is bracketed by low and high BCM input values that are a combination of clean backfill material (based on natural background concentrations) and the surrounding unremediated sediments, assuming various proportioning percentages, as described in Section 5.2.3.4. In addition, the effect of the post-remedy bed sediment replacement values on predicted total PCB concentrations for selected alternatives is presented in Appendix M.

By using many lines of evidence and a range of input values derived from these data, some quantitative analysis of the uncertainty is provided, and confidence in the model representing long-term conditions over time is increased. However, it is also uncertain how these input concentrations may change over time. In summary, these BCM input values are considered adequate for the purposes of assembling remedial alternatives (Section 8) and evaluating the short- and long-term effectiveness of the alternatives (Section 9) in the FS.

5.5.4 Combined STM and BCM Uncertainty

Both the STM and BCM have uncertainty associated with model input values, process descriptions, and discretization. Uncertainty in STM predictions that results from uncertainty in the input parameters was extensively examined in the STM report (QEA 2008). The uncertainty analysis in the STM report was used to develop reasonable and maximum upper and lower bounding simulations. The reasonable upper- and lower-bound simulations provide a realistic range of net sedimentation rates for the LDW and were used to examine the effect of STM uncertainty on BCM results. The maximum simulations were considered unrealistic and not carried forward in the BCM uncertainty analysis. The results from these bounding simulations are discussed in Section 5.5.2 and in Appendix C, Part 6. Uncertainty in the BCM chemistry input values is discussed in Section 5.5.3.

The STM base-case composition results were taken at the end of the 10-year model run for reasonable upper and lower bounding simulations as input to the BCM to compute the total PCB SWAC for each simulation following remediation of the EAAs. This analysis is presented in Appendix C, Part 6. The STM bounding simulations are presented in Section 2.8 of the STM report (QEA 2008). Reasonable upper and lower bounds are defined as net sedimentation rates that varied by ± 1 cm/yr from the STM base case. This provides a greater than 95 percent confidence interval around the data.[28] The reasonable lower to upper STM simulations produced a range in total PCB SWACs from 65 to 101 µg/kg dw or about -16% and +31% from the base case prediction, respectively (see Appendix C, Part 6, Table 5). However, the STM base case (with lower to upper BCM input values) produced a range in total PCB SWACs from 49 to 122 µg/kg or about -36% and +58% from the base case prediction, respectively. The analysis showed the total PCB SWAC is more sensitive to the range of BCM chemistry input values than it is to the range of net sedimentation rates from the reasonable upper and lower bounding STM simulations. Although the SWAC range based on BCM bounding is greater than the range based on STM bounding, both are still sufficiently large that they must be accounted for in future assessments. The range of total PCB SWAC values attributable to STM and BCM uncertainty is illustrated in Appendix C, Part 6, Figure 11.

5.5.5 BCM Input Values for Other SMS Contaminants

A total of 41 COCs with SMS criteria were identified for the protection of benthic invertebrates. It was not practical to run the BCM 41 times to evaluate recovery potential for every SMS contaminant. Therefore, a smaller subset of representative contaminants was selected because:

- Many co-occur with other SMS contaminants (e.g., PAHs)
- Groups of contaminants have similar modes of toxicity (e.g., phthalates)
- Lateral source data have not been collected, or at least compiled, for every contaminant
- Many of these COCs do not have widespread SQS exceedances in the LDW.

Application of the BCM using representative SMS contaminants is based on the fact that the representative contaminants account for the majority of the SQS exceedances and the assumption that all SMS contaminants within a group will behave/recover in a similar manner. Uncertainty exists with this simplifying assumption. In reality, each SMS contaminant may have a different starting concentration, recovery and/or recontamination potential, sediment-water partitioning dynamics, bioavailability based on organic carbon content, and lateral and upstream sources. Estimated exceedances of the SQS and CSL at the end of the 10-year modeling period may be biased high or low relative to the representative SMS contaminant predictions. This uncertainty will be managed during remedial design and by refinement of the CSM for remedial areas.

[28] The confidence interval for the reasonable upper and lower bounds was not specifically defined in the STM analysis. However, the 95 percent confidence interval was defined as a net sedimentation rate of ± 0.5 cm/yr.

5.5.6 Age and Spatial Extent of Contaminant Data

Over the past 18 years, numerous investigations have been conducted to determine the nature and extent of sediment contamination associated with past and present contaminant releases at various locations within the LDW. These investigations have included in-water investigations involving surface and subsurface sediment sampling, toxicity testing, shoreline habitat inventories, seep surveys, and porewater sampling. These data have been aggregated into the FS baseline dataset. There is uncertainty associated with these data related to detection limits that exceed the screening criteria, especially in older data; contaminant compositing with depth; and interpolation between sampling points. An additional large source of uncertainty is the age of the data. Many of the surface sediment data comprising the FS baseline dataset are over 10 years old and do not represent current conditions. Active remedial technologies are being assigned to particular areas based on surface sediment exceedances that may have improved (or worsened) over the past few years. Because the CSM and empirical data have shown that the LDW is recovering (in many areas), there is likely a high bias introduced into the assembly of alternatives. Remedial alternatives are being assembled on fairly conservative assumptions that no recovery has occurred between when the data were collected and now. This source of uncertainty is being managed in two ways: 1) the modeling is conservative and does not account for 10 years or more of potential recovery from when the sample was collected; and 2) areas with older data, but which are predicted to recover, will be subject to verification monitoring (see Sections 6 and 8) to confirm current contaminant concentrations and degree of recovery. Other sources of data uncertainty such as vertical and horizontal extent of contamination, elevated detection limits, and SMS compliance may also be refined during remedial design.

5.5.7 Chemical Degradation and Transport Processes

Many of the LDW risk drivers (total PCBs, cPAHs, BEHP, arsenic, dioxins/furans, and other SMS contaminants) have similar fate and transport properties in that they are strongly bound to sediment particles and do not readily degrade. Compounds that readily degrade or desorb from sediments are not persistent in sediments because the concentration declines naturally over time. Persistent contaminants cause long-term sediment contamination. The following discussion focuses on PCBs because a large body of research exists for this COC at many sites across the country. However, for most of the COCs, degradation and desorption processes decrease the concentrations in sediment over time. By not accounting for these processes, the analysis is conservative with respect to sediment contamination and natural recovery because it will overestimate both long-term sediment concentrations and the time required for natural recovery to occur.

PCBs, in particular, are stable compounds that do not degrade easily. Under certain conditions, they may be broken down by chemical, thermal, and biological processes (Erickson 1986). In the environment, photolysis (breakdown by light) is the only significant chemical degradation process, but it is not likely a significant means of PCB losses from sediments because of low PCB solubility and limited penetration of sunlight into the solid media (the sediment bed) (Hutzinger et al. 1974). Microbial processes are the main route of environmental degradation of PCBs in sediments. Reductions in the sediment concentrations of PCBs can happen via desorption from sediments into the overlying water column and volatilization. The breakdown of PCBs is generally discussed below, and implied for many other risk drivers; it is assumed to be occurring in the LDW, although these processes have not been modeled in the FS. Changes in PCB concentrations in the sediment bed can be translated into predicted concentrations of PCBs in fish and shellfish tissue via the PCB food web model (FWM) developed for the LDW (Appendix D of the RI, Windward 2010; see Section 9.3.5.2 of this FS for a discussion of uncertainties associated with FWM estimates). Section 3 evaluated whether varying water concentrations account for the effects of desorption and how other inputs into the water column would affect tissue concentrations (see Figure 3-2).

The King County model was used to predict contaminant concentrations in the water column; it employed containment flux from the sediment bed to estimate desorption of PCBs into the water column.

The effects of varying PCB concentrations in the water column and the site-wide sediment SWACs on predicted residual risks from seafood consumption are discussed in Section 9; results are presented in Appendix M.

5.5.7.1 Microbial Degradation

The viability of biodegradation as a natural method of sediment recovery for sediment-bound PCBs has been documented in several studies (RETEC 2002; Appendix F).

PCBs can undergo microbial degradation in natural environments under both aerobic (i.e., in the presence of oxygen) and anaerobic (i.e., in the absence of oxygen) conditions. PCBs are a class of 209 individual contaminants (PCB congeners), in which 1 to 10 chlorine atoms are attached to a biphenyl molecule. Most Aroclors (commercially produced groups of PCBs) contain 60 to 90 different PCB congeners, with varying numbers and positions of the chlorine atoms on the biphenyl rings.

Microbes degrade PCBs by breaking the carbon-to-carbon bond of PCBs, or by substituting the chlorine atoms with hydrogen atoms in the PCB molecule under aerobic and anaerobic conditions, respectively (McLaughlin 1994). The latter method results in the transformation of PCB congeners into other less chlorinated PCB congeners in a process called dechlorination (Abramowicz 1990). Aerobic degradation, on the other hand, results in a net PCB loss from a given PCB inventory. In river sediments, aerobic conditions are typically found in the top few centimeters of the sediment bed, while anaerobic conditions are found at greater depths below the sediment surface.

Aerobic Degradation

Even though laboratory studies have documented the existence of naturally occurring aerobic bacteria capable of degrading a large spectrum of PCB congeners, there is little direct evidence indicating that the aerobic degradation process is effective at reducing the PCB mass under field conditions. In laboratory studies of the Hudson River, PCB losses were highest in the less chlorinated congeners (43 to 47% reduction) and lowest in the more chlorinated congeners (17 to 5% reduction) (Harkness et al. 1993 and 1994). The in-field studies yielded similar results (less than 50% reduction). A study of PCB patterns in Green Bay sediments suggests that aerobic degradation is not a significant transformation mechanism for those sediments (McLaughlin 1994).

Anaerobic Dechlorination

Reduction through dechlorination (under anaerobic conditions) is generally viewed as a viable means of biodegradation for numerous compounds, including PCBs at higher concentrations. This process can alter the toxicity of these compounds and make them more readily degradable. The extent to which PCBs can degrade depends on several factors (Bedard and Quensen 1995), including the nature of the active microbial population, the type of chlorine substitution, the chlorine configuration, the initial PCB concentration, and the substrate conditions (temperature, redox conditions, ionic strength, amount of carbon, and presence of other oily contaminants, etc.). For example, no anaerobic dechlorination of PCBs was observed in the downstream deposits of the Fox River where the maximum PCB concentration was approximately 30 mg/kg dw (limited effectiveness at lower concentrations). Dechlorination activity was limited to sediment PCB concentrations of 30 mg/kg dw or greater (McLaughlin 1994). The overall PCB loss due to microbial degradation in several Fox River sediment deposits was estimated to be less than 10% with respect to the original inventory of PCBs deposited in the river.

A similar threshold for degradation of 50 mg/kg dw was observed in Sheboygan River sediments (David 1990). For Grasse River sediments (Minkley et al. 1999a, 1999b), some dechlorination activity was suggested at total PCB concentrations below 7 to 10 mg/kg dw, but the statistical evidence of dechlorination was less strong than at higher concentrations. Attempts in a laboratory study to further dechlorinate Fox River sediments met with limited success and similar results, up to 10% dechlorination on a total chlorine basis (Hollifield et al. 1995).

In the Fox River, physical loss through desorption from sediments (into the water column) exceeded any biodegradation in the sediment. It was estimated that 33% of the original PCB mass originally deposited in the Lower Fox River was lost due to desorption.

5.5.7.2 Volatilization and Desorption

Volatilization and desorption remove contaminants from sediment particles without changing the chemical make-up of the contaminant. In desorption, the contaminant is removed from the sediment and becomes dissolved in water. Volatilization is the process of a contaminant going into the gaseous state and being released to the atmosphere.

Both of these processes are relatively weak for the COCs in the LDW. For instance, all of the inorganic compounds (with the exception of mercury) and low molecular weight PCBs generally do not undergo volatilization. For PCBs, volatilization into the air can be important in shallow arable soils, but less so for subsurface soils (Meijer et al. 2003). Limited volatilization of some organics could occur from exposed intertidal sediments at low tides, but this transport mechanism would be further limited by the high water content of the sediments. COCs may diffuse from sediment into porewater and then into the water column and/or atmosphere, but these transport pathways occur at very slow rates. Because subtidal sediments are covered with water and are not in contact with the atmosphere, a very limited amount of volatilization occurs from dissolved PCBs in the water column, rather than directly from sediments. Consequently, volatilization is not considered a major process in the dynamics of PCBs or other COCs in LDW sediment.

Desorption is related to how strongly a contaminant binds to sediment or to organic carbon in sediment. All of the COCs in the LDW strongly bind to sediment. If the COCs did not bind strongly to sediments, they would have desorbed, become dissolved in surface water, and have been discharged downstream, effectively removing them from LDW sediments. Empirical evidence demonstrates the persistence of these contaminants with depth in the LDW. Many of the organic compounds, such as PCBs, PAHs, and dioxins/ furans, are referred to as hydrophobic compounds. That is, the compounds preferentially partition to solids rather than become dissolved in water.

By not including volatilization and desorption in the natural recovery analysis, estimated future contaminant concentrations in sediment are conservative because these processes should slightly accelerate the predicted natural recovery in surface sediments.

5.5.8 High-Flow Scour Potential

As discussed in Sections 5.3.1 and 5.3.2.5, the maximum scour depth during a 100-year high-flow event is estimated by the STM to be about 22 cm for the base case, and the upper bound of estimated scour is 36 cm, based on upper-bound erosion sensitivity simulations. Areas with subsurface sediment contamination located in potential scour areas, whether from high-flow events or propeller scour, are explored in Section 6 and are included in the AOPC footprints. Scour areas defined in Section 2.3.1.1 and illustrated in Figures 2-9 and 2-10 were used to assign recovery categories in Section 6.

Section 5.3.2.5 illustrates that potential exposure and transport of subsurface sediments during high-flow events is small compared to the incoming sediment loads. To explore the net effect of propeller scour events, Appendix F illustrates that empirical chemical trends from many of the resampled surface sediment stations and sediment cores have decreasing contaminant trends (or trends in equilibrium) in scour areas. The FS assumes that scour potential (less than 10 cm) in areas with subsurface exceedances of SMS criteria is of concern even if empirical evidence indicates that some recovery and scour areas with adequate net sedimentation rates and water depth may eventually recover. Uncertainty related to scour potential with subsurface exceedances is inherently accounted for in Section 6. Areas with subsurface exceedances in potential scour areas are included in the AOPC footprints for the FS, and these areas are given equal consideration as surface exceedances in the assembly of alternatives and assignment of remedial technologies to those areas (Section 8). Active remediation is assigned to scour areas (within the depth of scour potential, typically RAL exceedances in the upper 2 ft) in the absence of empirical trends showing recovery.

A sensitivity analysis was conducted to evaluate uncertainty in STM predictions that may have resulted from uncertainty in model input parameters, including those that control erosion rates. Uncertainty in the extent of areas estimated to have erosion was less than ±50% within the area from RM 0.0 to 4.3, relative to the base-case simulation. Uncertainty in predicted sediment mass eroded ranged from about -50 to +75% within the area from RM 0.0 to 4.3 as well as in the east bench and navigation channel, and ranged from -40 to +130% in the west bench. The analysis showed that the predicted depth of scour, area of scour, and mass of sediment scoured are not very sensitive to erosion rate parameters used in the model.

5.5.9 Anthropogenic and Natural Deep Disturbance Uncertainty

Section 5.3.1.3 introduces the potential for both anthropogenic and natural disturbance of subsurface sediments in the LDW that may result in contaminant exposure. These subsurface sediments are an additional potential source of contaminant mass to LDW surface sediments, similar to upstream and lateral loadings. The RI did not extensively characterize subsurface contaminant concentrations. In addition, deep disturbance is inferred in some geochronologic and chemical records. However, these data are sparse relative to the size of the study area and the frequency, cause, and magnitude of deep disturbances cannot be estimated with confidence. The data can, however, provide general, first-order estimates of bounds on reasonable minimum and maximum acreages of continuous disturbance (0 to 45 acres). These acreage bounds are used to bound the possible effects on the predicted total PCB SWAC. This analysis is provided in Appendix M, Part 5, and results are discussed in Sections 9 and 10.

The approach used for this analysis is based on some assumptions that will overestimate the predicted SWAC with time. Specifically: 1) the same area is assumed to be repeatedly disturbed (e.g., perhaps a tug regularly has trouble maneuvering a barge into a particular spot); 2) there is no mixing of ongoing sedimentation with deeper sediment during a deep disturbance event; and 3) the subsurface concentrations never change. These conditions were not factored into the analysis and would mitigate some of the increases in SWAC predicted in the analysis. In addition to change in the SWAC, ongoing deep disturbances could result in longer recovery times being required to achieve the cleanup objectives.

5.5.10 Bathymetric Changes and Dredging of Upper Turning Basin Sediments

A hydrodynamic model was used to generate flow velocities, which were then used in the STM. The hydrodynamic model was not revised for changes in bathymetry due to scour or net sedimentation. However, the STM does track the changes in bed elevation over time as sediment is scoured or deposited. Analysis of specific model cells in the navigation channel and on the benches shows that the change in bed elevation in the first 10 years of the simulation is on the order of 10 cm (4 inches). This change in bathymetry would not be expected to affect the hydrodynamic model because the water depth is much greater than the change in bed elevation.

In Reach 3, the Upper Turning Basin has much more net sedimentation than Reaches 1 and 2. However, the Upper Turning Basin is regularly dredged. By ignoring the changes in bathymetry due to deposition in the Upper Turning Basin, the model essentially assumes that the Upper Turning Basin is continually dredged. If the hydrodynamic model and STM were modified for bathymetric changes between dredging events, the Upper Turning Basin would become shallower and more sediment would move downstream, resulting in higher net sedimentation rates downstream of the Upper Turning Basin. However, the hydrodynamic model does not consider the hypothetical possibility of a cessation of dredging at the Upper Turning Basin, and therefore retains the present mass inputs and grain-size distribution into the future.

5.6 Modeling Summary and Conclusions

In summary, predictive modeling is a useful tool for the FS to evaluate the value or effectiveness of remedial alternatives and the recovery potential of the system. Some alternatives will include MNR and others will not (see Section 8). The STM and BCM support decision-making regardless of which remedial alternative is selected. However, it is understood that both tools have a large degree of uncertainty (see discussion following bullets). For the purposes of the FS, a bounded margin of uncertainty is acceptable, but this FS assumes that this uncertainty can be further managed during remedial design and future monitoring. The modeling presented in this section concluded that:

- The LDW is net depositional over time and its physical characteristics and natural processes are reasonably well understood through fine-scale hydrodynamic and sediment transport modeling. The STM output has been supported by several lines of evidence, including chemistry profiles in sediment. Areas where the STM output doesn't match empirical data are generally found in locations with features and activities that the STM didn't incorporate (e.g., bridges and pilings, high-powered ship maneuvering, and other berthing activities).Three key outputs from the STM are used in the FS: net sedimentation rates, areas subject to scour from high-flow events, and bed composition. The third output provides the framework for predictive contaminant modeling in the BCM.

- Sediment is continually depositing within the LDW. Almost all new sediment (99%) that enters the LDW originates in the Green/Duwamish River system. The STM estimates that, on average, over 185,000 MT of sediment per year enters the LDW, with approximately 100,000 MT depositing in the LDW. Approximately 90% of the total bed area in the LDW receives 10 cm of new sediment within 10 years or less. This sediment is mixed with the existing bed sediment through various processes, including bioturbation and propeller wash. On average, the annual volume dredged over the past 15 years is approximately 51% of the deposited sediment load. An annual average of approximately 38,000 MT has been dredged within the authorized navigation channel and 13,000 MT within the berthing areas, for a total annual dredge volume of about 51,000 MT.
- Overall, the maximum net erosion depth during a 100-year high-flow event is approximately 22 cm, with most areas experiencing less than 10 cm of scour, while 82% of the LDW experiences net deposition rather than net erosion over the 30-year model period.
- The effects of propeller-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. Propeller-induced bed scour from transiting ships and typical berthing activities is viewed as an impulsive erosion-deposition process that tends to behave like an ongoing mixing process for surficial bed sediment. Transiting ships in the navigation channel are not a major source of sediment transport or erosion in the LDW, except where slightly greater erosion depths (net erosion) are possible in shallower areas adjacent to the navigation channel. However, the analysis of scour prepared for this FS does not consider some possible irregular events. These events, outside of normal operating procedures, may include emergency and high-power maneuvering of tug boats under unexpected conditions, high-powered navigation activities, ships running aground, seismic events, and disturbance resulting from riverine structure maintenance construction/repair. Such events are likely infrequent relative to ships transiting the LDW, but could result in deep disturbances that affect long-term SWACs and hinder natural recovery. These events can disturb

subsurface sediments and mix subsurface contamination with the surface layer. A series of post-STM/BCM analyses were performed to address the potential importance of both routine navigation activity and episodic, high-powered navigation and maintenance construction/repair events on long-term SWACs (Appendix M, Part 5). These analyses indicate that long-term recovery and SWACs could be influenced by navigation and riverine activities in the LDW, with the magnitude of the impact dependent upon the frequency and extent of the disturbance event.

- The BCM estimates changes in risk driver contaminant concentrations over time. Output from the BCM includes contaminant concentrations (point concentrations and area-based SWACs) at 5-year increments for 45 years.
- Empirical data show that, on average, LDW surface sediment contaminant concentrations are decreasing over time, consistent with BCM predictions of surface sediment concentrations approaching equilibrium over time. Appendix F shows specific locations where the empirical data demonstrate recovery. However, recovery can be locally hindered by vertical mixing of surface and subsurface sediments disturbed by anthropogenic and natural activities.
- Contaminant input values used in the BCM (lateral source, Green/ Duwamish River upstream, and post-remedy bed sediment replacement) were derived from actual input data (catch basin solids, sediment trap samples, upstream surface sediment and surface water data, USACE sediment cores) from the Upper Turning Basin. A range of values (high-medium-low) are used to address uncertainty and potential temporal variability in the range of contaminant inputs associated with each source type.
- Both the BCM predictions and empirical contaminant trends show that natural recovery is occurring in some areas of the LDW (see Appendix F). According to the BCM, MNR is a viable technology for many (but not all) areas of the LDW with moderate levels of contamination (below the CSL), net sedimentation rates of more than 1 cm/yr, and minimal scour potential (see Section 6).
- The BCM uses the FS baseline dataset (where the data are already more than 10 years old in some areas) and assumes no recovery or age-consideration for the older data in existing bed sediments; therefore, the initial bed contaminant concentrations at the start of construction may be lower than estimated in the BCM.

- The STM and BCM are not contaminant fate and transport models, and the numerous assumptions made throughout model development were designed to provide reasonable estimates with respect to predicted sediment concentrations based on available data for model development. Many assumptions used to develop model input and process descriptions are conservative. For example, the models assume no chemical transformation or degradation over time. Mass is not conserved in the BCM; however, additional analyses presented in Appendix C were used to investigate the significance of this on predictions of natural recovery. Changes in tissue and surface water COC concentrations are predicted as sediment concentrations change (i.e., through burial, scour, and resuspension processes). Changes in seafood consumption risks are evaluated for each remedial alternative in Section 9 via the PCB FWM developed as part of the RI (Windward 2010).
- The BCM may underestimate potential COC concentrations in localized areas near active discharges due to variation in loading estimates among the outfalls. These localized areas should be evaluated for adequate source control during remedial design.

Uncertainty in both the STM and BCM is recognized in sedimentation rates, erosion depths, scour areas, and contaminant inputs over time. Varying levels of confidence can be attached to these model predictions depending on: 1) the COC (i.e., arsenic has a higher level of certainty compared to PAHs, which may have increasing concentration trends from urbanization) and 2) the location in the LDW (areas with estimated net sedimentation greater than a few centimeters have a higher expectation that natural recovery will occur because the estimated net sedimentation is much greater than model error). By using many lines of evidence and a range of input values derived from these data, the uncertainty can be bounded. Overall, the uncertainty in BCM contaminant concentration input parameters has a slightly greater effect on predictions of natural recovery than does the uncertainty in sedimentation rates. Therefore, the ranges of STM and BCM input parameters are useful tools to bracket uncertainties in the evaluation of FS alternatives. Regardless, monitoring will be needed to confirm that recovery is occurring wherever MNR is proposed.

Finally, the BCM analysis is considered adequate for estimating future COC concentrations in LDW sediments (combined with the analysis of deep disturbances and exposure of subsurface contamination in Appendix M, Part 5), assigning a range of suitable remedial technologies (Section 8), and evaluating short-term and long-term effectiveness of remedial alternatives (Section 9). Model uncertainties and limitations do not negate the use of the model as a predictive tool in this FS, but must be accounted for when considering the predicted outcomes of the remedial alternatives, as discussed in Sections 9 and 10. Sections 9 and 10 also include additional detailed analysis of the effects of deep disturbance induced by anthropogenic and natural activities on long-term SWACs. Spatial areas where model predictions agree or do not agree with empirical trends and physical site conditions are accounted for in the FS in the designation of recovery categories (Section 6).

Table 5-1a Bed Composition Model Upstream Input Parameters for Human Health Risk Drivers

Rationale

Range of concentrations considered representative of current and potential future conditions for solids entering and settling in the LDW from upstream. Four different datasets used to establish range of parameter values for upstream sources because of potential biases inherent to each.

Contaminant	BCM Parameters			Basis for BCM Upstream Input and Sensitivity Values[a]
	Input	Low	High	
Total PCBs (µg /kg dw)	35	5	80	**Input:** Mean of LDW RM 4.3 to 4.75 DMMP (2001 – 2009) core data (36 rounded to 35 µg /kg dw). **Low:** The mean of Ecology upstream sediment samples containing fines >30%. **High:** UCL95 of TSS-normalized King County (whole-water) (82 rounded to 80 µg /kg dw).
Arsenic (mg/kg dw)	9	7	10	**Input:** Mean of Ecology upstream sediment samples containing fines >30%. **Low:** Mean of LDW RM 4.3 to 4.75 DMMP (2001 – 2009) core data. **High:** UCL95 of Ecology upstream sediment samples with fines >30%.
cPAHs (µg TEQ/kg dw)	70	40	270	**Input:** Mean of LDW RM 4.3 to 4.75 DMMP (2001 – 2009) core data (73 rounded to 70 µg TEQ/kg dw). **Low:** Mean of Ecology upstream sediment samples containing fines >30% (37 rounded to 40 µg TEQ/kg dw). **High:** UCL95 of TSS-normalized King County (whole-water) (269 rounded to 270 µg TEQ/kg dw).
Dioxins and Furans (ng TEQ/kg dw)	4	2	8	**Input:** Midpoint between mean of Ecology upstream centrifuged solids and mean of Ecology upstream sediment samples containing fines >30% **Low:** Mean of Ecology upstream sediment samples containing fines >30%. **High:** Midpoint between mean and UCL95 of Ecology centrifuged solids data.

Notes:

a. Upstream BCM parameter values were revised using updated datasets and statistics reflective of current conditions (i.e., material entering the LDW from the Green/Duwamish River). The four primary datasets used for BCM parameterization are as follows (see Tables 5-2a through 5-2d for statistical summaries of supporting datasets):

- Ecology's 2008 upstream bed sediment chemistry data: This dataset was screened to exclude samples with ≤30% fines in consideration of the systematic differences in grain size distributions between upstream (e.g., mid-channel) data and average conditions in the LDW.
- TSS-normalized King County data: King County surface water data were normalized to solid fractions by dividing by the TSS in the individual sample.
- Ecology 2008 centrifuged suspended solids data: The Ecology samples are representative of sediments suspended mid-channel in the Green/Duwamish River that enter the LDW.
- Upper-reach USACE DMMP core data (RM 4.3 to 4.75): This dataset is representative of Green/Duwamish River suspended material that settles in the upper section of the LDW.

BCM = bed composition model; cPAHs = carcinogenic polycyclic aromatic hydrocarbons; DMMP = Dredged Material Management Program; dw – dry weight; fines = sum of silt and clay grain size fractions; kg = kilograms; LDW = Lower Duwamish Waterway; µg = micrograms; mg – milligrams; ng = nanograms; PCBs = polychlorinated biphenyls; RM = river mile; TEQ = toxic equivalent; TSS = total suspended solids; UCL95 = 95% upper confidence limit on the mean; USACE = U.S. Army Corps of Engineers

Table 5-1b Bed Composition Model Lateral Input Parameters for Human Health Risk Drivers

Rationale

1. High – Conservative representation of current conditions assuming modest level of source control (e.g., management of high priority sources).
2. Input (Mid-range) – Pragmatic assessment of what might be achieved in the next decade with anticipated levels of source control.
3. Low – Best that might be achievable in 30 to 40 years with increased coverage and continued aggressive source control.

Contaminant	BCM Parameters			Basis for BCM Lateral Input and Sensitivity Values
	Input	Low	High	
Total PCBs[a] (µg /kg dw)	300	100	1,000	Used a range of screening concentrations to reflect potential levels of source control that could occur over time. **Input:** Mean of flow-weighted dataset excluding values >5,000 µg/kg dw (315 rounded to 300 µg /kg dw). **High:** 90th percentile of flow-weighted source tracing dataset excluding values >10,000 µg/kg dw (1,009 rounded to 1,000 µg /kg dw). **Low:** Median of flow-weighted source tracing dataset excluding values >2,000 µg/kg dw (102 rounded to 100 µg/kg dw).[a]
Arsenic[a] (mg/kg dw)	13	9	30	Screened the source-tracing dataset to exclude concentrations above assumed SMS-based source control levels (93 and 57 mg/kg dw) **Input:** Mean excluding values >93 mg/kg (the CSL). **High:** 90th percentile excluding values >93 mg/kg (the CSL). **Low:** Median of all samples, excluding values >57 mg/kg (the SQS).[a]
cPAHs[a] (µg TEQ/kg dw)	1,400	500	3,400	Screened the source-tracing dataset to exclude concentrations above an assumed source control level. cPAHs are expected to be difficult to control due to the petroleum-based economy, intensity of urbanization in the LDW, and myriad ongoing sources. **Input:** Mean of source-tracing dataset excluding values >25,000 µg TEQ/kg dw (1,370 rounded to 1,400 µg TEQ/kg dw). **High:** 90th percentile of source-tracing dataset excluding values >25,000 µg TEQ/kg dw (3,366 rounded to 3,400 µg TEQ/kg dw). **Low:** Median of source tracing dataset excluding values >25,000 µg TEQ/kg dw (490 rounded to 500 µg TEQ/kg dw). [a]
Dioxins and Furans[b] (ng TEQ/kg dw)	20	10	40	Based on combined Greater Seattle metropolitan sediment and SPU catch basin solids datasets.[b] **Input:** Mean (22 rounded to 20 ng TEQ/kg dw) **High:** UCL95 (41 rounded to 40 ng TEQ/kg dw). **Low:** Median (15 rounded to 10 ng TEQ/kg dw).

Notes:

a. Used Lower Duwamish Waterway source tracing dataset (compiled by SPU) through June 2009 as the primary basis for establishing lateral BCM parameter values for arsenic, total PCBs, and cPAHs. The dataset was screened to remove concentrations using various source control practicability assumptions (best professional judgment by the Source Control Work Group). Total PCB data were flow-weighted before generating statistics because PCBs exhibit a distinct geographic distribution with hot spots identified at Terminal 117, North Boeing Field/Georgetown Steam Plant, Rainier Commons, and Boeing Plant 2/Jorgensen Forge. These four areas have been extensively sampled and make up a significant portion of the overall source tracing dataset. Therefore, the PCB source-tracing data were flow-weighted to avoid skewing the summary statistics used in the BCM. Arsenic and cPAH data were not flow-weighted prior to the statistical analysis because these contaminants lack a pronounced geographic dependency that would warrant flow-weighting. See Tables 5-2a through 5-2d for statistical summaries of supporting datasets.

b. Parameter estimation for dioxins and furans was based on the Greater Seattle metropolitan area receiving sediment dataset collected as part of the RI (Windward 2010) and sediment and SPU catch basin solids datasets (City of Seattle 2010; data collected through 2009). The summary statistics used to estimate parameter values correspond to the combined datasets, as supported by statistical analysis, and include the removal of outliers. See Tables 5-2a through 5-2d for statistical summaries of supporting datasets.

BCM = bed composition model; cPAHs = carcinogenic polycyclic aromatic hydrocarbons; CSL = cleanup screening level; dw = dry weight; kg = kilograms; LDW = Lower Duwamish Waterway; µg = micrograms; mg – milligrams; ng = nanograms; PCBs = polychlorinated biphenyls; RI = remedial investigation; SPU = Seattle Public Utilities; TEQ = toxic equivalent; SQS = sediment quality standard; UCL95 = 95% upper confidence limit on the mean

Table 5-1c Bed Composition Model Post-Remedy Bed Sediment Replacement Values for Human Health Risk Drivers

Rationale

Range of concentrations considered representative of current and potential near-term (0-3 years) post-remedy surface sediment conditions influenced by multiple recontamination mechanisms. Values expected to vary spatially.[a]

Contaminant	SWAC Outside of AOPC 1[b]	Clean Fill Material[c]	Input and Sensitivity Values					
			Proportioned Values Using SWAC Outside of AOPC 1[d]			Proportioned Values Using SWAC Outside of AOPC 2[d,e]		
			Input	Low Input	High Input	Input	Low Input	High Input
Total PCBs (µg /kg dw)	120	2	60	30	90	20	10	40
Arsenic (mg/kg dw)	12	7	10	9	11	9	8	10
cPAHs (µg TEQ/kg dw)	270	9	140	70	200	100	50	140
Dioxins and Furans (ng TEQ/kg dw)	7	2	4	2[f]	6	n/a	n/a	n/a

Notes:

a. Actively remediated areas within the AOPC 1 footprint receive the higher input values. Actively remediated areas within AOPC 2 footprint would receive lower input values. See Section 6 for a definition of AOPCs.

b. The SWAC outside of AOPC 1 is assumed representative of concentrations adjacent to remediated areas for arsenic, total PCBs, and cPAH. The representative dioxins and furans concentration outside of AOPC 1 is based on the arithmetic mean of the point values located outside of AOPC 1. See Section 6 for definition of AOPC 1.

c. The contaminant composition of clean fill material is based on the UCL95 of 2008 EPA OSV *Bold* Survey data. Use of qualified maintenance dredged materials (e.g. from the Upper Turning Basin) for capping would, in practice, lead to higher range of post-remedy bed-sediment replacement values than calculated in this table.

d. Range of representative post-remedy bed sediment replacement values assumes combinations of clean backfill material (e.g., whether capping, ENR, or post-dredge residuals management) and surrounding representative bed sediment concentrations. Assumed proportioning percentages are as follows:

BCM Parameter	Post-Remedy Bed Sediment Replacement Value Proportioning Assumptions	
	% of Clean Import Material	% of SWAC Outside of AOPC 1
Input	50	50
Low	75	25
High	25	75

Shading indicates input value used in the BCM

e. As discussed in Section 6, a larger footprint referred to as AOPC 2 was developed. The remedial alternative that evaluates this footprint will use lower input values after all high to moderate PCB concentration areas have been remediated.

f. In this case, the "low" value of 2 is used to maintain a reasonable range of concentrations. The adjustment is considered reasonable because of the small dataset available for calculating the concentration outside of AOPC 1.

AOPC = area of potential concern; BCM = bed composition model; cPAHs = carcinogenic polycyclic aromatic hydrocarbons; OSV = ocean survey vessel; ENR = enhanced natural recovery; kg = kilograms; µg = micrograms; mg – milligrams; n/a = not available; ng = nanograms; PCBs = polychlorinated biphenyls; SWAC = spatially-weighted average concentration; TEQ = toxic equivalent; UCL95 = 95% upper confidence limit on the mean.

Table 5-2a BCM Parameter Line of Evidence Information for Total PCBs (µg/kg dw)

Study/Source			*No. of Samples*	Mean	Median	90th Percentile	UCL95	Comments
Green/Duwamish River Inflow								
Green River Water Quality	King County Whole Water		*22*	50	21	107	82	Normalized to TSS; data from 2005 to 2008, provided by King County.
	Ecology Centrifuged Solids		*7*	14	8	54	36	Data from 2008, downloaded from EIM database, stats calculated by AECOM.
	King County and Ecology Data Combined		*29*	42	11	120	127	Calculation of all upstream surface water data by AECOM; unpublished.
Upstream Surface Sediment	LDW RI Data		*37*	23	19	40	21	Data from 1994 to 2005 between RM 5 and 7 included in the RI baseline dataset.
	Ecology	Fines >30%	*30*	5	2	13	8	Data from 2008, downloaded from EIM database, stats calculated by AECOM, screened to exclude samples ≤ 30% fines; outlier excluded: 770 µg/kg dw; unpublished.
		All	*73*	3	3	6	3	Data from 2008, downloaded from EIM database; stats calculated by AECOM and outlier excluded: 770 µg/kg dw.
	LDW RI and Ecology Data Combined		*110*	8	3	23	13	Calculation of all upstream surface sediment data by AECOM and outlier excluded: 770 µg/kg dw; unpublished.
USACE Upper Turning Basin Cores		RM. 4.5 – 4.75 (1991-2009)	*10*	23	22	38	23	Calculation of DAIS core data by AECOM; unpublished.
		RM. 4.3 – 4.75 (1991-2009)	*20*	36	33	56	42	Calculation of DAIS core data by AECOM; unpublished.
Lateral Inflow								
City of Seattle Storm Drain Data	Minus samples >2,000 µg/kg dw		*625*	223	102	534	—	Flow-weighted average of storm drain solids data screened to exclude samples >2,000 µg/kg dw; data collected through June 2009. SPU data provided by B. Schmoyer, 2010.
	Minus samples >5,000 µg/kg dw		*692*	315	125	718	—	Flow-weighted average of storm drain solids data screened to exclude samples >5,000 µg/kg dw; data collected through June 2009. SPU data provided by B. Schmoyer, 2010.
	Minus samples >10,000 µg/kg dw		*755*	508	146	1,009	—	Flow-weighted average of storm drain solids data screened to exclude samples >10,000 µg/kg dw; data collected through June 2009. SPU data provided by B. Schmoyer, 2010.
King County CSO Water Quality Data			*28*	638	580	920	—	TSS-normalized values of CSO water data provided by D. Williston, King County, 2010. Estimates biased high because method assumes all PCBs in whole-water sample in particulate phase.
Post-Remedy Bed Sediment Replacement Value								
Post-Maintenance Dredge Surface Data		0 – 2 years after dredging	*18*	120	120	—	150	Calculation of post-maintenance dredge surface data by AECOM; unpublished.
Duwamish/Diagonal Post-Capping Data		Thick Cap	—	Mean = 45 (yr 0.5), 84 (yr 3)				Calculation of D/D post-capping data by AECOM; data available in King County monitoring reports (King County 2006; 2009).
		ENR	—	Mean = 6 (yr 0), 23 (yr 1), 62 (yr 2)				
Puget Sound Survey (*OSV BOLD*)			*70*	1	1	3	2	Calculation of Puget Sound Survey stats by AECOM.
Outside AOPC 1 Footprint			*n/a*	IDW interpolated SWAC = 120				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.
Outside AOPC 2 Footprint			*n/a*	IDW interpolated SWAC = 47				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.

Notes: See Table 5-2d for notes.

Table 5-2b BCM Parameter Line of Evidence Information for Arsenic (mg/kg dw)

Study/Source			*No. of Samples*	Mean	Median	90th Percentile	UCL95	Comments
Green/Duwamish River Inflow								
Green River Water Quality	King County Whole Water		*100*	37	29	73	47	Normalized to TSS; data from 2001 to 2006. All detected arsenic concentrations associated with TSS were calculated as the difference between whole-water (i.e., unfiltered) and filtered sample data.
Green River Water Quality	Ecology Centrifuged Solids		*7*	17	14	24	22	Data from 2008, downloaded from EIM database, stats calculated by AECOM.
Upstream Surface Sediment	LDW RI Data		*24*	7	5	11	8	Data from 1994 to 2005 between RM 5 and 7 included in the RI baseline dataset.
Upstream Surface Sediment	Ecology	Fines >30%	*31*	9	9	11	10	Data from 2008, downloaded from EIM database, stats calculated by AECOM and screened to exclude samples ≤ 30% fines; unpublished.
Upstream Surface Sediment	Ecology	All	*74*	7	6	10	7	Data from 2008, downloaded from EIM database, stats calculated by AECOM.
Upstream Surface Sediment	LDW RI and Ecology Data Combined		*98*	7	6	10	7	Calculation of all upstream surface sediment data by AECOM; unpublished.
USACE Upper Turning Basin Cores	RM. 4.5 – 4.75 (1991-2009)		*8*	5	5	7	7	Calculation of DAIS core data by AECOM; unpublished. 1990 data excluded.
USACE Upper Turning Basin Cores	RM. 4.3 – 4.75 (1991-2009)		*18*	7	6	12	8	Calculation of DAIS core data by AECOM; unpublished. 1990 data excluded.
Lateral Inflow								
City of Seattle Storm Drain Data		Minus samples >57 mg/kg dw	*553*	12	9	29	—	Storm drain solids data screened to exclude samples >57 mg/kg dw; data collected through June 2009. SPU data provided by B. Schmoyer, 2010.
City of Seattle Storm Drain Data		Minus samples >93 mg/kg dw	*563*	13	10	30	—	Storm drain solids data screened to exclude samples >93 mg/kg dw; data collected through June 2009. SPU data provided by B. Schmoyer, 2010.
King County CSO Water Quality Data			*21*	9	11	13	—	TSS-normalized values of CSO water data provided by D. Williston, King County, 2010.
Post-Remedy Bed Sediment Replacement Value								
Post-Maintenance Dredge Surface Data		0 – 2 years after dredging	*8*	11	12	—	14	Calculation of post-maintenance dredge surface data by AECOM; unpublished.
Duwamish/Diagonal Post-Capping Data		Thick Cap	—	Mean = 3 (yr 0.5), 10 (yr 3)				Calculation of D/D post-capping data by AECOM; data available in King County monitoring reports (King County 2006; 2009).
Duwamish/Diagonal Post-Capping Data		ENR	—	Mean = 2 (yr 0), 4 (yr 1), 8 (yr 2)				
EPA OSV *Bold* Survey			*70*	7	6	11	7	Calculation of Puget Sound Survey stats by AECOM.
Outside AOPC 1 Footprint			*n/a*	IDW interpolated SWAC = 12				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.
Outside AOPC 2 Footprint			*n/a*	IDW interpolated SWAC = 10				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.

Notes: See Table 5-2d for notes.

Table 5-2c BCM Parameter Line of Evidence Information for cPAHs (µg TEQ/kg dw)

Study/Source			*No. of Samples*	Mean	Median	90th Percentile	UCL95	Comments
Green/Duwamish River Inflow								
Green River Water Quality	King County Whole Water		*18*	151	74	354	269	Normalized to TSS; data from 2008, provided by King County.
	Ecology Centrifuged Solids		*7*	138	53	400	432	Data from 2008, downloaded from EIM database, stats calculated by AECOM.
	King County & Ecology Data Combined		*25*	135	58	330	266	Calculation of all upstream surface water data by AECOM; unpublished.
Upstream Surface Sediment	LDW RI Data		*16*	55	18	135	100	Data from 1994 to 2005 between RM 5 and 7 included in the RI baseline dataset.
	Ecology	Fines >30%	*31*	37	16	77	72	Data from 2008, downloaded from EIM database, stats calculated by AECOM and screened to exclude samples ≤30% fines. Note: Outlier of 230 µg TEQ/kg dw was not excluded from any statistical calculations.
		Fines >50%	*18*	50	44	91	75	Data from 2008, downloaded from EIM database, stats calculated by AECOM and screened to exclude samples ≤ 50% fines. Note: Outlier of 230 µg TEQ/kg dw was not excluded from any statistical calculations.
		All	*74*	18	9	57	43	Data from 2008, downloaded from EIM database, stats calculated by AECOM. Note: Outlier of 230 µg TEQ/kg dw was included in statistical calculations.
	LDW RI and Ecology Data Combined		*90*	25	10	73	55	Calculation of all upstream surface sediment data by AECOM; unpublished.
USACE Upper Turning Basin Cores	RM. 4.5 – 4.75 (1991-2009)		*9*	37	41	63	52	Calculation of DAIS core data by AECOM; outlier excluded: 1051.5 µg TEQ/kg dw; unpublished.
	RM. 4.3 – 4.75 (1991-2009)		*19*	73	57	180	134	Calculation of DAIS core data by AECOM; outlier excluded: 1051.5 µg TEQ/kg dw; unpublished.
Lateral Inflow								
City of Seattle Storm Drain Data (minus samples >25,000 µg TEQ/kg dw)			*533*	1,370	490	3,366	—	Storm drain solids data screened to exclude samples >25,000 µg TEQ/kg dw; data collected through June 2009. SPU data provided by B. Schmoyer (2010).
King County CSO Water Quality Data			*26*	1,051	714	2,728	—	TSS-normalized values of CSO water data provided by D. Williston, King County, 2010. Estimates biased high because method assumes all cPAHs in whole-water samples in particulate phase.
Post-Remedy Bed Sediment Replacement Value								
Post-Maintenance Dredge Surface Data	0 – 2 years after dredging		*8*	180	170	—	250	Calculation of post-maintenance dredge surface data by AECOM; unpublished.
Duwamish/Diagonal Post-Capping Data	Thick Cap		—	Mean = 63 (yr 0.5), 159 (yr 3)				Calculation of D/D post-capping data by AECOM; data available in King County monitoring reports(King County 2006; 2009).
	ENR		—	Mean = 11 (yr 0), 43 (yr 1), 89 (yr 2)				
Puget Sound Survey (OSV BOLD)			*70*	7	4	15	9	Calculation of Puget Sound Survey stats by AECOM.
Outside AOPC 1 Footprint			*n/a*	IDW interpolated SWAC = 270				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.
Outside AOPC 2 Footprint			*n/a*	IDW interpolated SWAC = 190				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.

Notes: See Table 5-2d for notes.

Table 5-2d BCM Parameter Line of Evidence Information for Dioxins/Furans (ng TEQ/kg dw)

Study/Source			*No. of Samples*	Mean	Median	90th Percentile	UCL95	Comments
Green/Duwamish River Inflow								
Green River Water Quality	Ecology Centrifuged Solids		*6*	6	3	13	10	Data from 2008, downloaded from EIM database, stats calculated by AECOM.
Upstream Surface Sediment	LDW RI Data		*4*	Range of Values (Median): 1.1 - 2.6 (1.7)				Data from 1994 to 2005 between RM 5 and 7 included in the RI baseline dataset.
	Ecology	Fines >30%	*31*	2	2	3	2	Data from 2008, downloaded from EIM database, stats calculated by AECOM and screened to exclude samples ≤ 30% fines; unpublished.
		Fines >50%	*18*	2	2	3	3	Data from 2008, downloaded from EIM database, stats calculated by AECOM and screened to exclude samples ≤ 50% fines; unpublished.
		All	*74*	1	0.3	3	2	Data from 2008, downloaded from EIM database, stats calculated by AECOM.
USACE Upper Turning Basin Cores RM 4.3 – 4. 75 (1991-2009)			*2*	2 and 2.8 ng TEQ/kg dw				Calculation of DAIS core data by AECOM; unpublished.
Lateral Inflow								
Greater Seattle Sediment and SPU Catch Basin Solids			*23*	22	15	48	41	Calculation of stats based on combined Greater Seattle sediment and SPU catch basin solids datasets by AECOM; outlier excluded: 187 ng TEQ/kg dw; unpublished.
Post-Remedy Bed Sediment Replacement Value								
Puget Sound Survey (OSV BOLD)			*70*	1	1	2	2	Calculation of Puget Sound Survey stats by AECOM.
Post- Maintenance Dredge Area Surface Data			*3*	Mean = 8.3 ng TEQ/kg dw				Calculation of post-maintenance dredge surface data by AECOM; unpublished.
Outside AOPC 1 Footprint			*18*	Mean = 7 ng TEQ/kg dw				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.
Outside AOPC 2 Footprint			*11*	Mean = 5 ng TEQ/kg dw				Calculation of IDW interpolated SWAC by AECOM; unpublished. See Section 6 for AOPCs.

[green] Value(s) used for central tendency BCM input value. (mid point between mean Ecology Centrifuged solids and mean upstream fines >30% used for Green/Duwamish River)
[orange] Value(s) used as basis for low-sensitivity BCM value.
[red] Value(s) used as basis for high-sensitivity BCM value.(mid-point between mean and UCL95 Ecology Centrifuged Solids used for Green/Duwamish River)

Notes:
1. Statistics for these datasets were calculated using ProUCL 4.0, except that statistics for the City of Seattle Storm Drain Solids, King County CSO Water Quality, and Post-Remedy Bed Sediment Replacement Values datasets were calculated with Excel.
2. TEQs were calculated using one-half RL for undetected individual dioxin/furan congeners or PAH compounds.

'—' = not calculated; n/a = not available

AOPC = area of potential concern; BCM = bed composition model; cPAHs = carcinogenic polycyclic aromatic hydrocarbons; CSO = combined sewer overflow; DAIS = Dredged Analysis Information System; D/D = Duwamish/Diagonal; dw = dry weight; EIM = Ecology Information Management Database; ENR = enhanced natural recovery; fines = sum of silt and clay grain size fractions; IDW = inverse distance weighting; kg = kilogram; LDW = Lower Duwamish Waterway; µg = microgram; mg = milligram; ng = nanograms; OSV = ocean survey vessel; PCBs = polychlorinated biphenyls; RI = remedial investigation; RL = reporting limit; RM = river mile; SPU = Seattle Public Utilities; SWAC = spatially-weighted average concentration; TEQ = toxic equivalent; TSS = total suspended solids; USACE = U.S. Army Corps of Engineers; UCL95 = 95 percent upper confidence limit on the mean

Table 5-3 BCM Input Values for Representative SMS Contaminants[a]

Contaminant	Upstream Inflow (n = 22 to 23)		Lateral Inflow (n = 531 to 579)	
	BCM Input Value (µg/kg dw)[b]	Basis	BCM Input Value (µg/kg dw)[b]	Basis
BEHP	120	Median of USACE Dredged Material Characterization Core Data (RM 4.3 to 4.75; USACE 2009a, 2009b)	15,475	Log-normal mean of City of Seattle source-tracing data through July 2009 with outliers removed[c] (SPU 2010)
Chrysene	49		1,807	
Fluoranthene	190		3,989	
Phenanthrene	53		2,010	
Mercury (mg/kg dw)	0.1		0.14	
Zinc (mg/kg dw)	64		626	
Acenaphthalene	8		209	
Butylbenzyl-phthalate	11		972	
Indeno(1,2,3-cd)pyrene	31		675	
Phenol	10		237	

Notes:

a. FS dataset used to generate summary statistics.

b. Units are in µg/kg dw, unless otherwise noted. Input values are not flow-weighted.

c. Values that were at least two times the next highest value were removed from the analysis as outliers.

BCM = bed composition model; BEHP = bis(2-ethylhexyl)phthalate; dw = dry weight; kg = kilogram; µg = micrograms; mg = milligrams; n= number of; RM = river mile; SMS = Sediment Management Standards; SPU = Seattle Public Utilities; USACE = U.S. Army Corps of Engineers

Table 5-4 Results of Additional STM Special Scenario Runs

Purpose	Description	Results
1: Potential Recontamination of EAAs	An additional bed sediment class is added to differentiate sediment within EAAs from sediment outside of EAAs. This addition results in 16 sediment variables (four size classes for each of four sediment types): EAA bed sediments, non-EAA bed sediments, lateral source sediments, and upstream Green/Duwamish River source sediments). Model is run for 10-year period to predict how unremediated areas may contribute to recontamination of remediated area, assuming EAAs have been remediated.	• Contribution from non-EAA areas to remediated EAAs is less than 5% of the surface sediments at most EAAs after 10 years.
2: Distributed Discharges from Lateral Sources	The STM input is modified to have the discharges from lateral sources distributed to more closely describe actual drainage distribution among shoreline outfalls. The updates primarily affect private nearshore drainage basins. The model is run for both 10-year and 30-year periods to compare what was reported in the STM report (QEA 2008)(the lateral load distributed via 21 outfalls) with the redistributed lateral loads used in the FS.	• Lateral source sediments are more widely distributed, often at lower percent composition, along the nearshore STM grid cells. • Lateral source sediments are more widely distributed throughout the LDW, but most of the changes only result in some areas increasing from <1.0% lateral load content to 1.0 - 2.0%. • The greatest changes were observed around Hamm Creek and between RM 2 and 3. • Updated load distribution used in all subsequent analyses; it was used in all STM base-case model runs.
3: Movement of LDW Bed Sediment into the Upper Turning Basin	10-year model run that tracks bed sediment from four sources: Upper Turning Basin, navigation channel from RM 4.0 to 4.3, bench areas upstream of RM 4.0, and all sediment downstream of RM 4.0. The model run predicts whether downstream LDW sediments resuspend and settle upstream in the Upper Turning Basin area.	• Contribution of downstream sediment to the Upper Turning Basin area is negligible (<0.01%). • Only 240 MT of sediment is transported upstream to Reach 3 from downstream areas over 10 years compared to over 800,000 MT that settles in Reach 3 from upstream. • Supports use of USACE sediment cores collected from RM 4.3 to 4.75 in navigation channel as one line of evidence of upstream solids (i.e., negligible input from downstream sediments).
4: Movement of Bed Sediments between Reaches	Evaluation of the mass balance of sediment originating from each reach that moves between reaches and out of the LDW. This scenario is conducted for the 30-year model period.	• Much of the sediment resuspended in a reach that resettles in the LDW settles within the same reach. • There is more of an exchange of sediments between Reach 1 and 2, than from Reach 1 and 2 to Reach 3. • Reach 3 sediments are widely distributed throughout the LDW, while very little sediment from Reach 1 or 2 resettles in Reach 3.

Table 5-4 Results of Additional STM Special Scenario Runs (continued)

Purpose	Description	Results
5: Sediment Scoured from Greater than 10-cm Depth	Areas that are estimated to scour greater than 10-cm depth are assigned a new variable to represent a new sediment class. The 100-year high-flow simulation is used to predict where these >10 cm scoured sediments resettle.	• Sediment eroded from below 10 cm makes up a very small fraction of the total sediment mass moving over a 100-year high-flow event. • Sediment eroded from below 10 cm is greatest in Reach 2 and lowest in Reach 1. • Most of the scour >10 cm occurs in localized navigation channel above about RM 2.9.
6: Movement of Existing Bed Sediment (bed-tracking)	An additional bed sediment class is added to differentiate bed sediment that was resuspended and redeposited into another model cell from original bed sediment over a 10-year period. This scenario tracks the movement of bed sediments with the LDW and its effect on bed composition and SWACs.	• Resuspended bed sediment makes up less than 30% of the total original + resuspended bed fraction, and typically less than 5 to 10%. • The BCM construct is considered appropriate for use in the FS.
7: Holding Cells Constant in Selected Scour and Berthing Areas (no natural recovery)	The analysis was a 10-year model run that assumed no natural recovery in areas with high-flow scour, evidence of propeller scour, and berthing areas with less than 0.5 cm/yr of sedimentation. These areas were essentially "held constant" at their FS baseline total PCB concentrations. The analysis was conducted over 10 years following construction of Alternative 3C and then compared to the site-wide and reach-wide best-estimate total PCB SWAC model predictions.	• Total PCB SWACs increased about 10% compared to best-estimate model predictions and up to 18% in Reach 2.

Note:

BCM = Bed Composition Model; cm = centimeter; EAA = early action area; FS = feasibility study; LDW = Lower Duwamish Waterway; MT = metric ton; PCBs = polychlorinated biphenyls; RM = river mile; STM = sediment transport model; SWAC = spatially-weighted average concentration; USACE = U.S. Army Corps of Engineers; yr = year

Table 5-5 Comparison of Year 10 Total PCB SWACs between the Bed Tracking Scenario and STM Base Case

Scenario	Total PCB SWACs (µg/kg dw)			
	Site-wide	Reach 1	Reach 2	Reach 3
Post-Alternative 1				
Year 0	180	190	220	56
Year 10 STM Base Case	73	84	70	40
Year 10 modified STM Bed Tracking with resuspended bed variable	72	84	66	40
Distal Sediment Concentration Input Values to the Analysis				
Distal Bed (µg/kg dw) – reach-wide post-Alternative 1 SWAC	n/a	176	117	57

Notes:

1. For a detailed discussion of the analyses supporting this table, see Part 5 of Appendix C.

dw = dry weight; kg = kilogram; µg =micrograms; n/a = not applicable; PCB = polychlorinated biphenyl; STM = sediment transport model; SWAC = spatially-weighted average concentration

Table 5-6a Total PCB Input Concentrations for the Particle Size Fractionation Analysis

Solids Source and Class	Percentage of Solids by Mass	Total PCB Concentration (µg/kg dw)			
		FS mid-range BCM Input Value	Approach 1	Approach 2	Approach 3
Green/Duwamish (Upstream) Solids					
Class 1A	70	35	80	42	38
Class 1B	18	35	80	21	38
Class 2	12	35	5	13	11
Class 3	0	35	5	3	2
Aggregate concentration on upstream solids		35	71	35	35
Lateral Source Solids					
Class 1A	55	300	1,000	422	374
Class 1B	18	300	1,000	211	374
Class 2	23	300	100	127	112
Class 3	4	300	100	25	22
Aggregate concentration on lateral solids		300	757	300	300

Notes:

1. For Green/Duwamish solids Classes 1A, 1B, and 2 are suspended load and Class 3 is bed load. However, there is very little bed load that reaches the LDW beyond river mile 4.5.
2. The Draft Final FS mid-range BCM input values are shown for reference when comparing input values for the three approaches.
3. Approach 1 essentially increases PCB mass from upstream and lateral sources by approximately 100 percent over the mid-range BCM input values, while Approaches 2 and 3 maintain the same PCB mass as in the mid-range BCM case.

Table 5-6b Effect of Particle Size Fractionation on Total PCB SWACs

LDW Reach	Total PCB SWAC (µg/kg dw) Resulting from Use of:			
	FS Mid-range BCM Input Value	Approach 1	Approach 2	Approach 3
1	84	120	78	85
2	67	100	60	66
3	40	51	23	28
Site-Wide	73	104	65	71

Notes:

BCM = bed composition model; dw = dry weight; FS = feasibility study; kg = kilogram; LDW = Lower Duwamish Waterway; µg = micrograms; PCB = polychlorinated biphenyl; SWAC = spatially-weighted average concentration

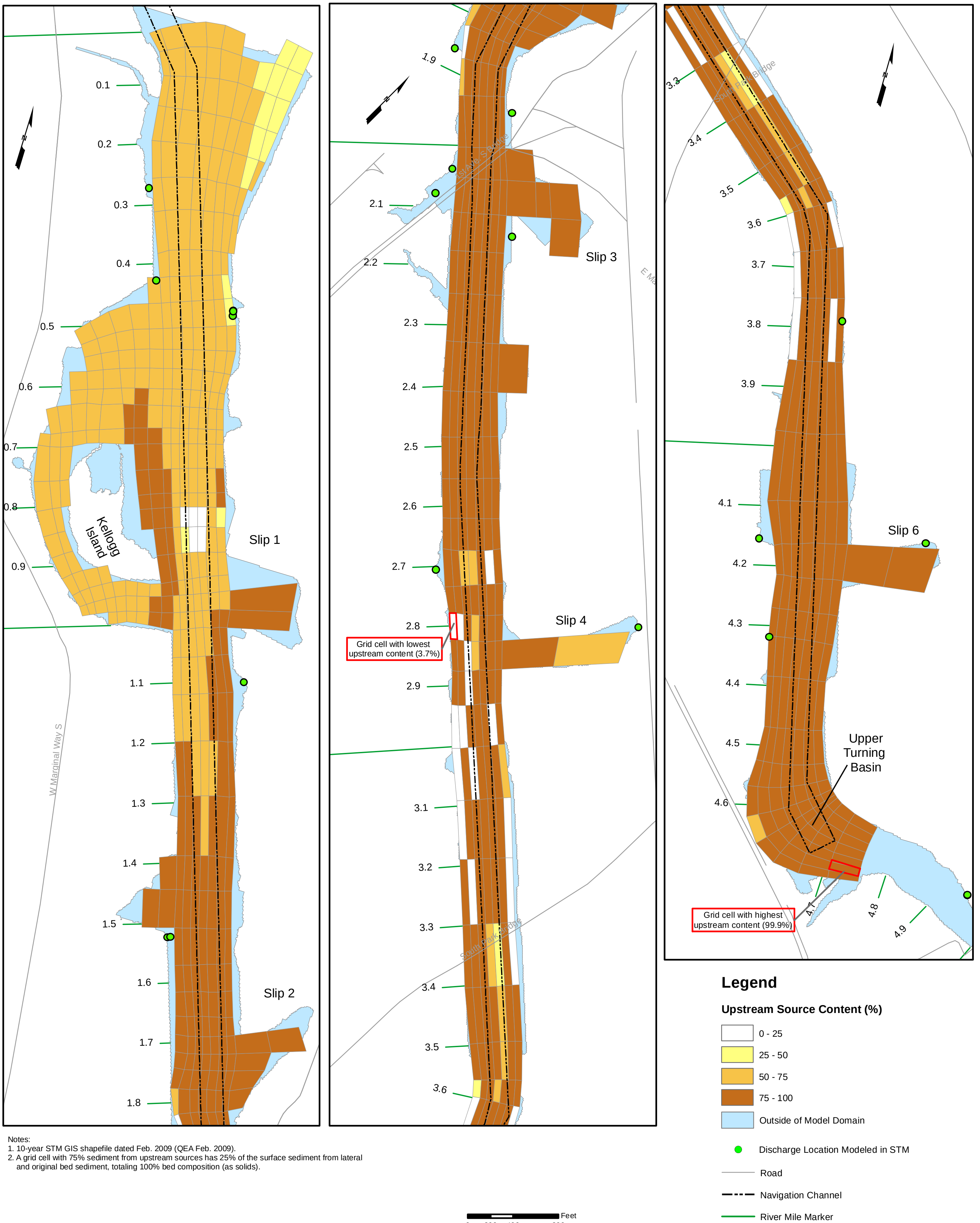
Table 5-7 Changes in Contaminant Concentrations at Resampled Surface Sediment Stations

Contaminant and Metric	Original/Older Data (1991–2006)	Newer (FS Baseline) Data (1998–2008)	Percent Decrease between Older and Newer Concentrations (%)
Total PCBs (µg/kg dw); N = 67			
25th Percentile	107	74	31
Mean	939	354	62
90th Percentile	2,141	776	64
Arsenic (mg/kg dw); N = 56			
25th Percentile	10	11	Minimal change; in equilibrium
Mean	40	35	
90th Percentile	41	40	
cPAHs (µg TEQ/kg dw); N = 53			
25th Percentile	200	145	28
Mean	1,534	437	72
90th Percentile	2,070	803	61
BEHP (µg/kg dw); N = 53			
25th Percentile	230	92	60
Mean	827	310	63
90th Percentile	1,570	606	61

Notes:

1. Newer data are co-located with older data (i.e., within 10 ft). Older data are not included in the FS baseline dataset.
2. Statistics calculated using ProUCL v.4.00.04.
3. Undetected data were set to the reporting limit.
4. Three PCB locations omitted to generate the n=67 dataset: LDW-SS110/SD-323-S; LDW-SS111/DR186; and SD-320-S/SD-DUW92. These are located within the Boeing Plant 2/Jorgensen Forge EAA.
5. Results on a station-by-station basis are provided in Appendix F.

BEHP = bis(2-ethylhexyl)phthalate; cPAHs = carcinogenic polycyclic aromatic hydrocarbons; dw = dry weight; EAA = early action area;
FS = feasibility study; kg = kilogram; LDW = Lower Duwamish Waterway; µg = micrograms; mg = milligrams; N = number of;
PCB = polychlorinated biphenyl; TEQ = toxic equivalent



Notes:
1. 10-year STM GIS shapefile dated Feb. 2009 (QEA Feb. 2009).
2. A grid cell with 75% sediment from upstream sources has 25% of the surface sediment from lateral and original bed sediment, totaling 100% bed composition (as solids).

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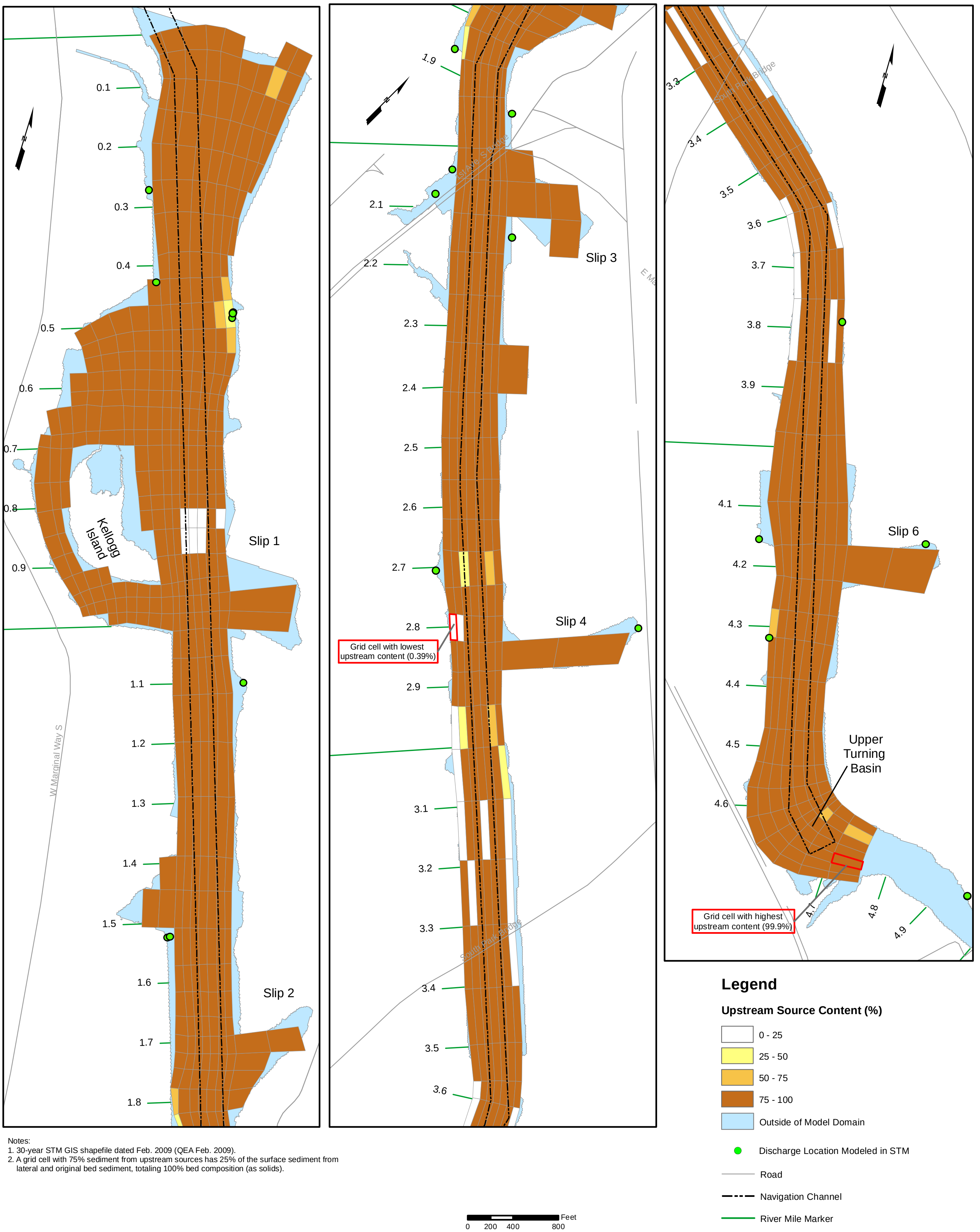
Lower Duwamish Waterway Final Feasibility Study 60150279-14.49			**Percentage of Bed Sediment from Upstream Sources after 10 Years**
DATE: 10/31/12	DWRN:MVI/sea	Revision: 0	**FIGURE 5-1a**



Notes:
1. 30-year STM GIS shapefile dated Feb. 2009 (QEA Feb. 2009).
2. A grid cell with 75% sediment from upstream sources has 25% of the surface sediment from lateral and original bed sediment, totaling 100% bed composition (as solids).

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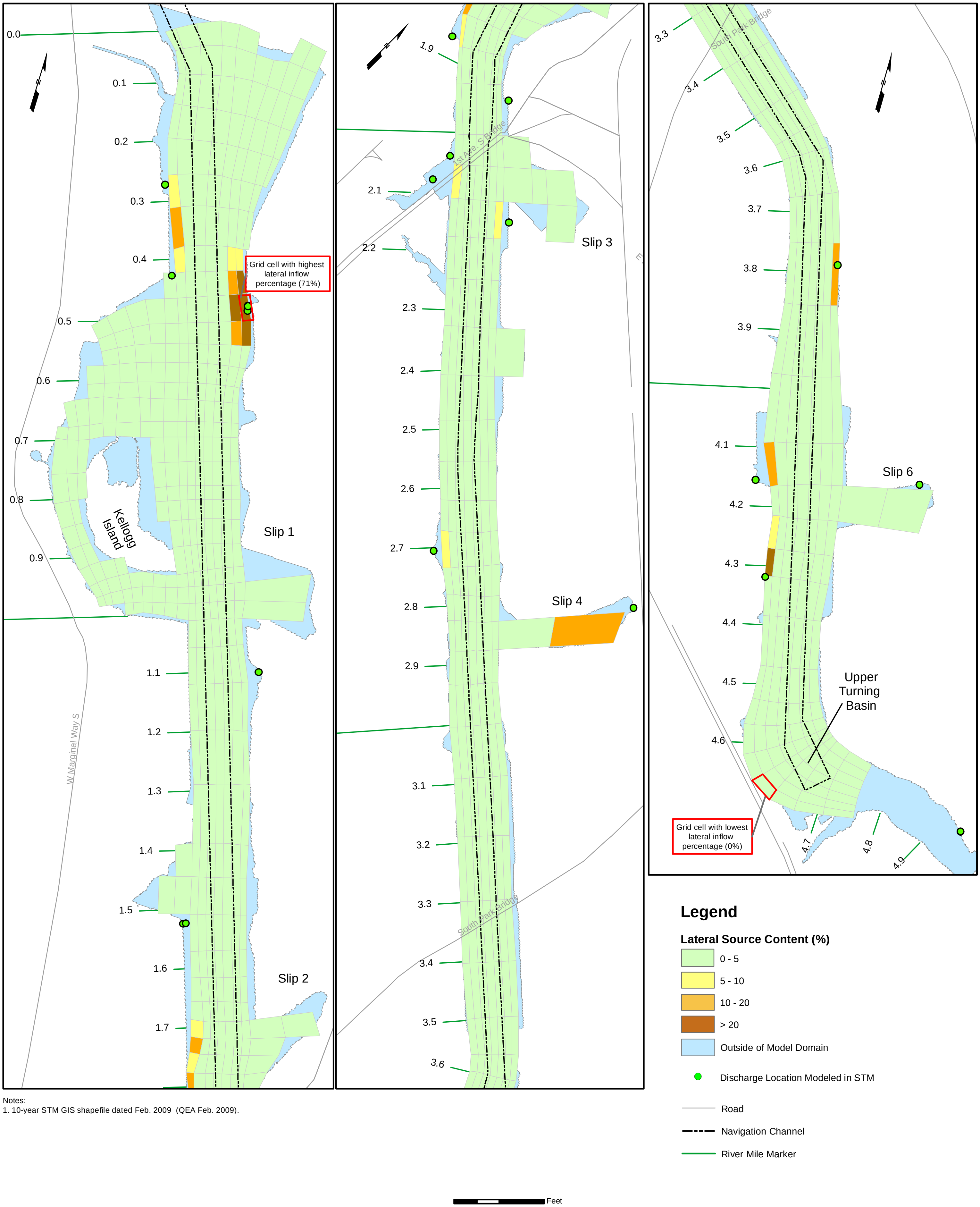
Lower Duwamish Waterway Final Feasibility Study 60150279-14.8			Percentage of Bed Sediment from Upstream Sources after 30 Years
DATE: 10/31/12	DWRN:MVI/sea	Revision: 1	FIGURE 5-1b



Notes:
1. 10-year STM GIS shapefile dated Feb. 2009 (QEA Feb. 2009).

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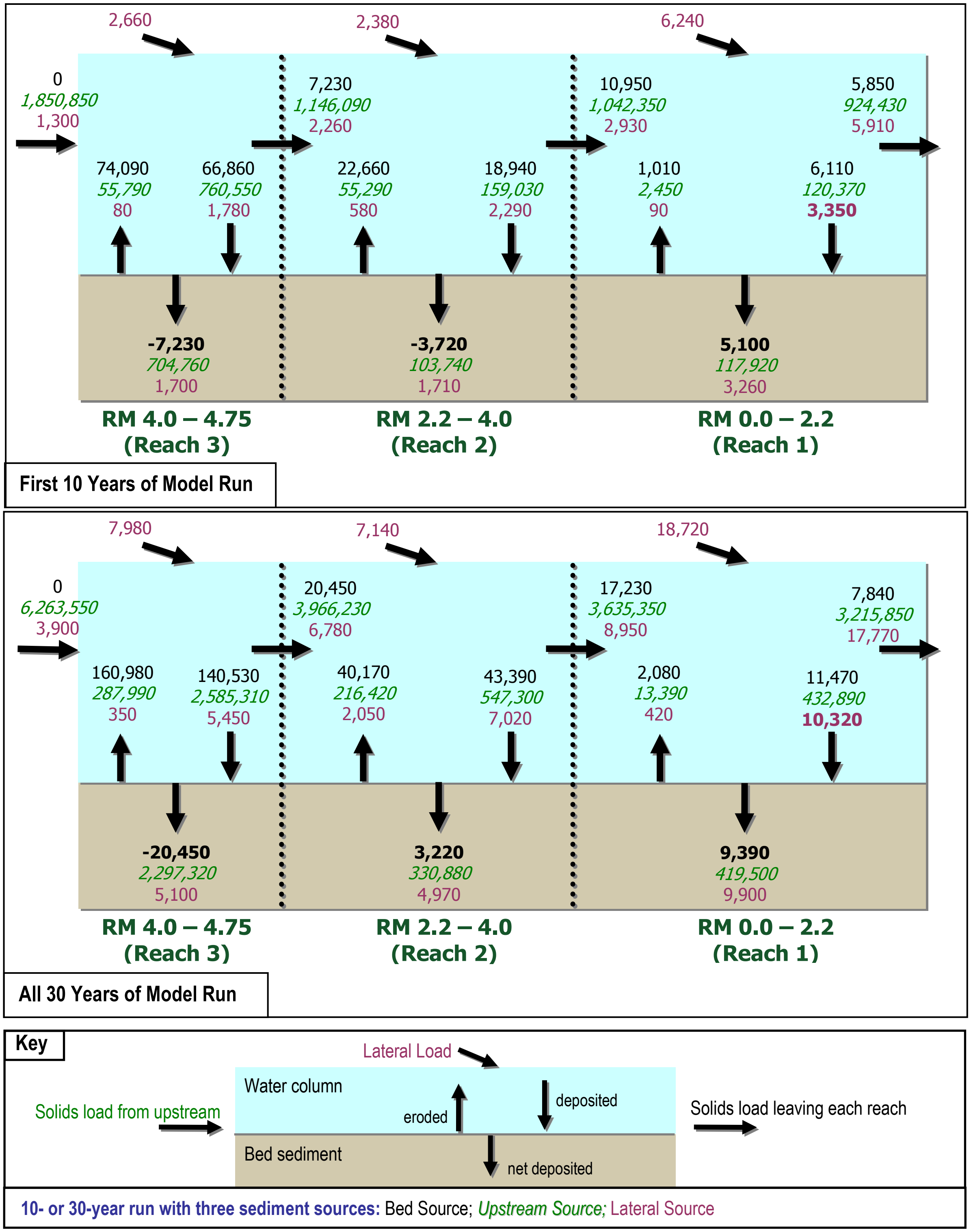
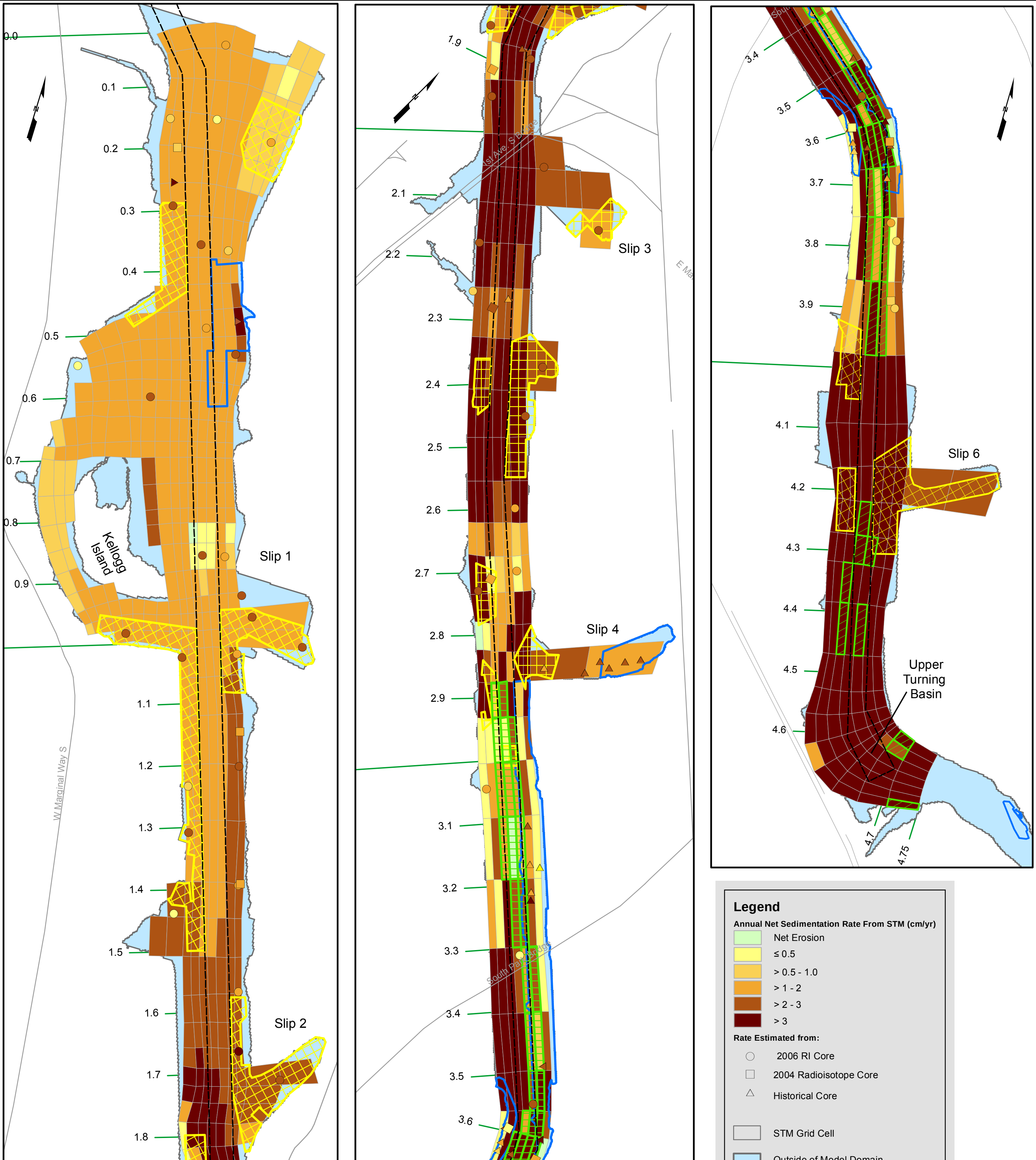
Lower Duwamish Waterway Final Feasibility Study 60150279-14.49	**Percentage of Bed Sediment from Lateral Sources after 10 Years**
DATE: 10/31/12 DWRN:MVI/sea Revision: 0	**FIGURE 5-2**

Figure 5-3 Sediment Loading to, within, and through the LDW over Two STM Time Periods



Notes:
1. Sediment loads are in metric tons over a 10- or 30-year model run, and include both suspended sediment and bed load material.
2. Upper end of modeled reach extends to RM 4.75.
3. Most of the incoming bed load (sand) settles in Reach 3. Of the incoming fines fractions, 10% of clay and 76% of the silt settle in the LDW.
LDW = Lower Duwamish Waterway; RM= river mile; STM = sediment transport model.



Notes:
1. Net sedimentation rates estimated from radioisotope core data provided by QEA LLC; and 2006 core chemistry data and historical core data provided by Windward Environmental LLC.
2. Numerous time markers used to estimate net sedimentation rates are from radioisotope, physical, and chemical geochronology profiles.
3. Ranges shown are calculated from recovered depths.
4. STM GIS shapefile from 30-year run (QEA Feb. 2009).
5. High-flow scour of 10 cm or more over 30-year simulation (QEA 2008).

0 400 800 Feet

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Final Feasibility Study
60150279-14.8

Potential Scour Areas and Estimated Net Sedimentation Rates

DATE: 10/31/12 | DWN. BY: MVI/sea

FIGURE 5-4

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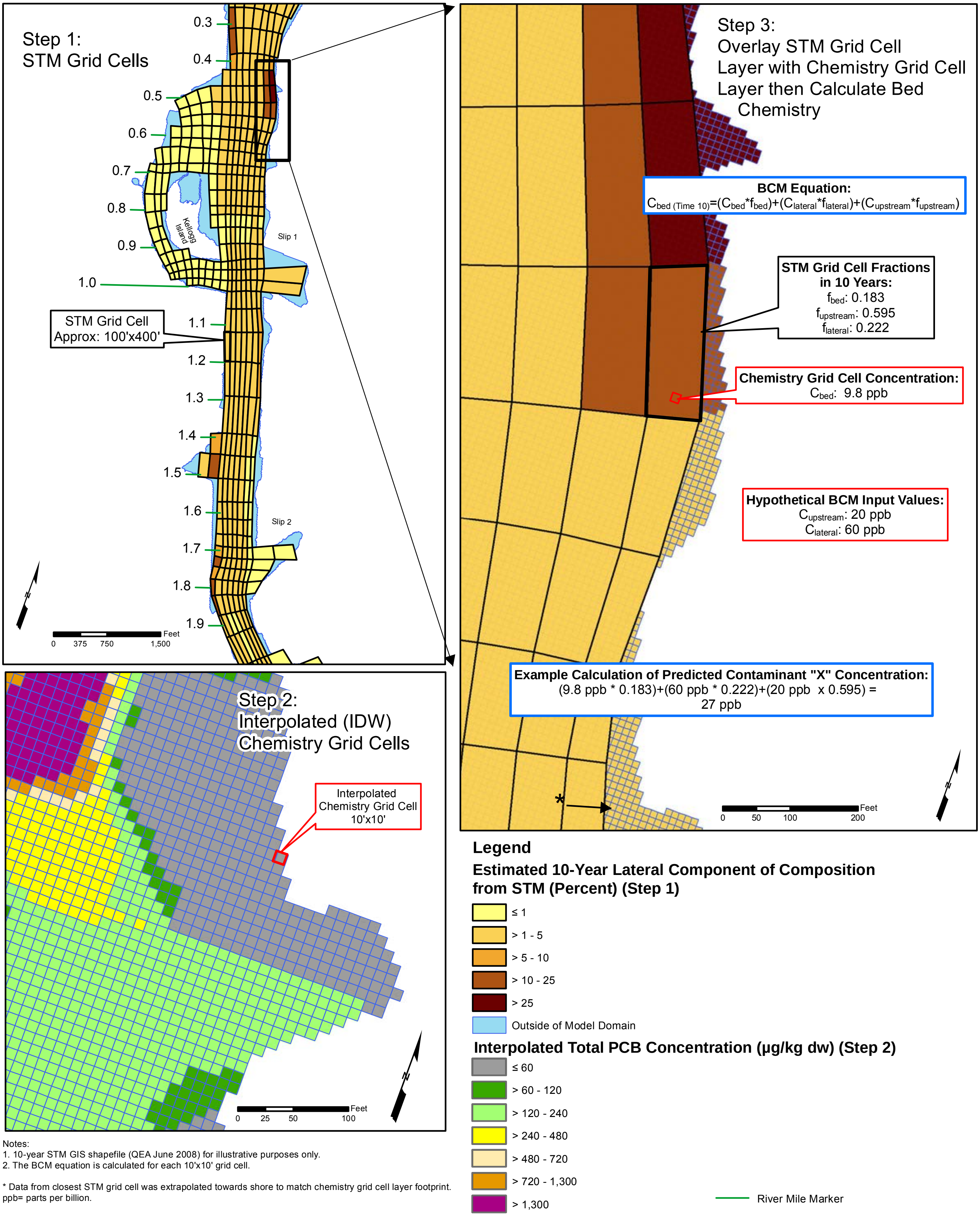

Notes:
1. 10-year STM GIS shapefile (QEA June 2008) for illustrative purposes only.
2. The BCM equation is calculated for each 10'x10' grid cell.

* Data from closest STM grid cell was extrapolated towards shore to match chemistry grid cell layer footprint.
ppb= parts per billion.

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60150279-14.49

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BCM Calculation in Model Grid Cells

FIGURE 5-5

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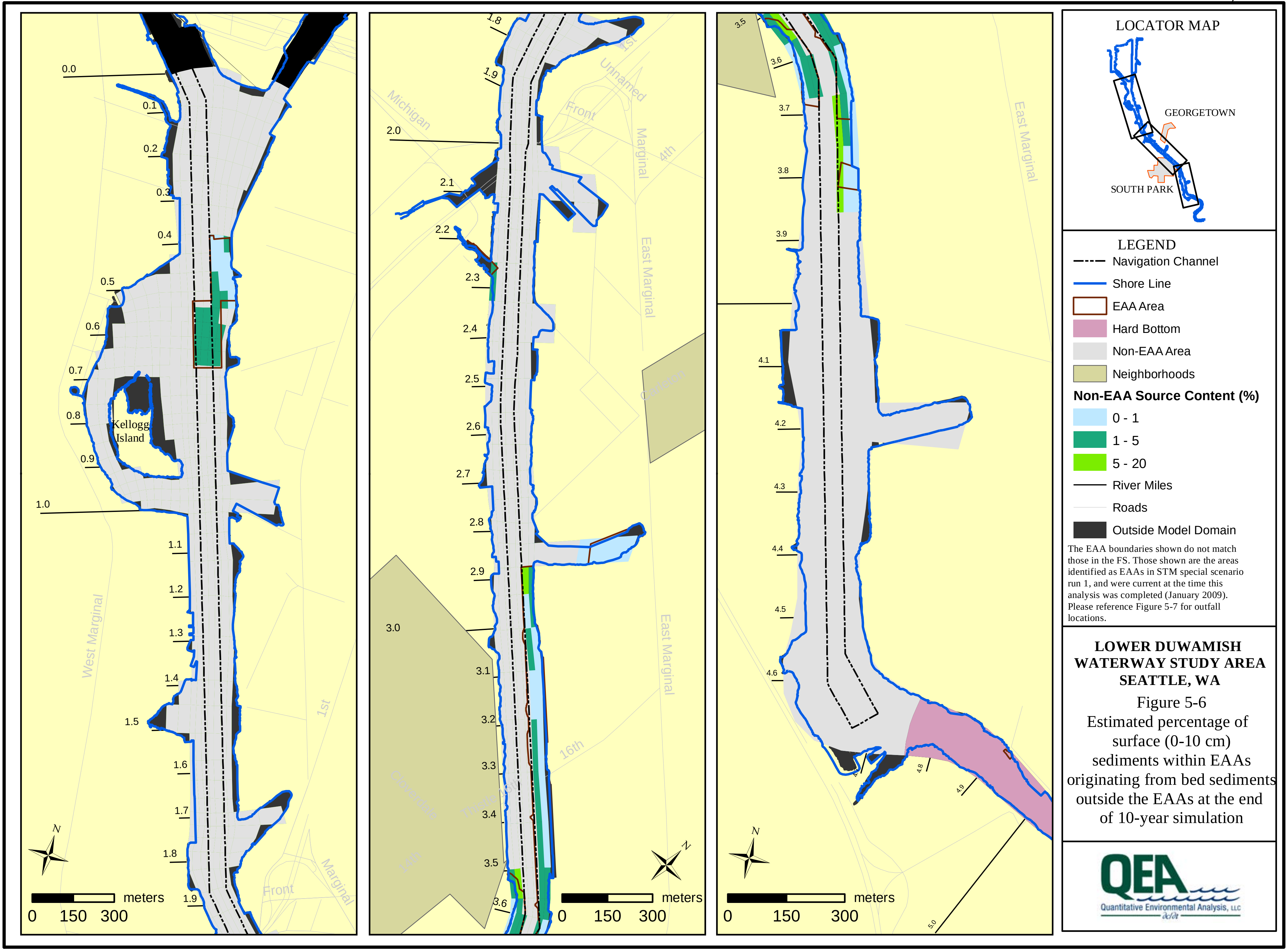

Figure 5-6
Estimated percentage of surface (0-10 cm) sediments within EAAs originating from bed sediments outside the EAAs at the end of 10-year simulation

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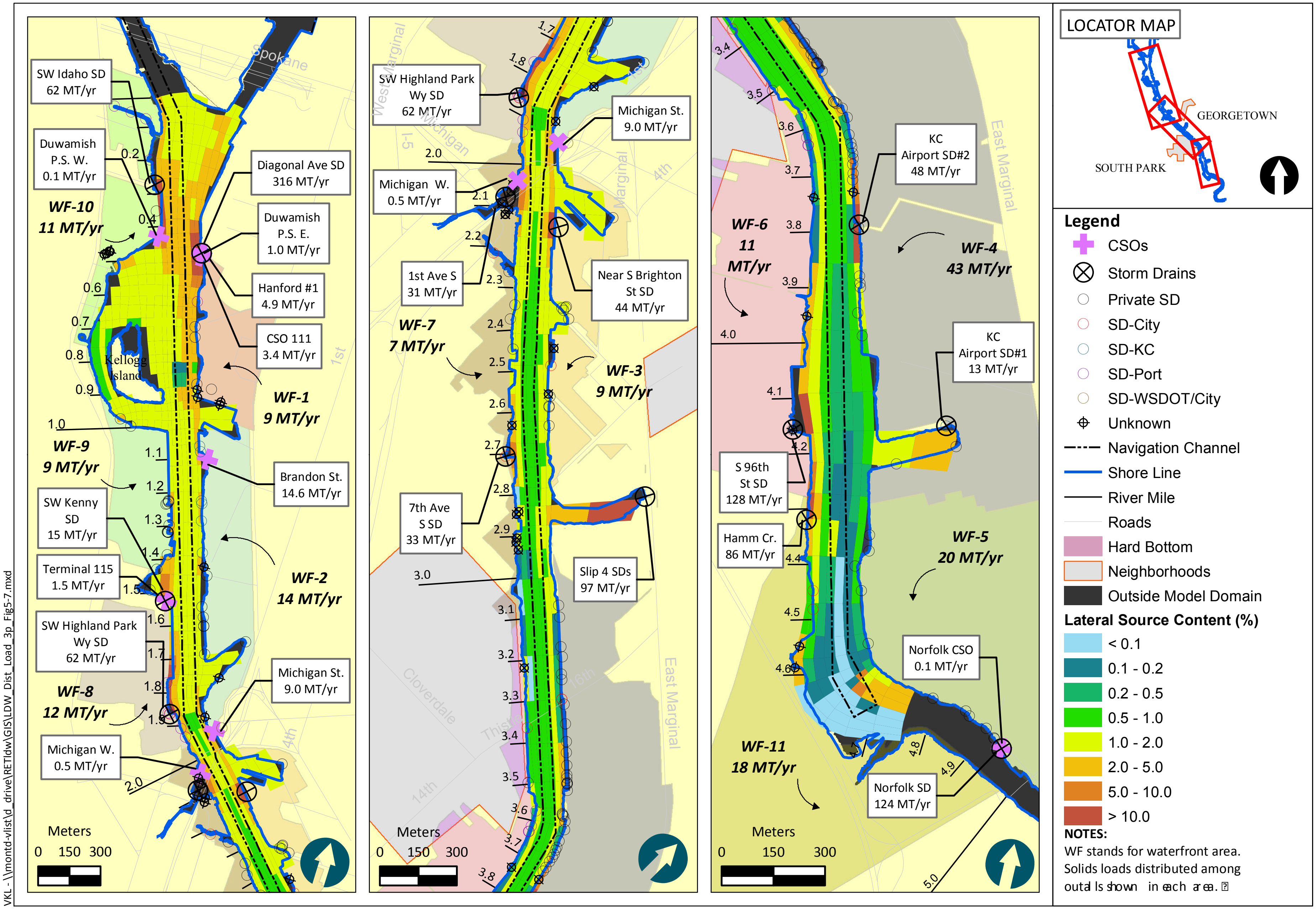

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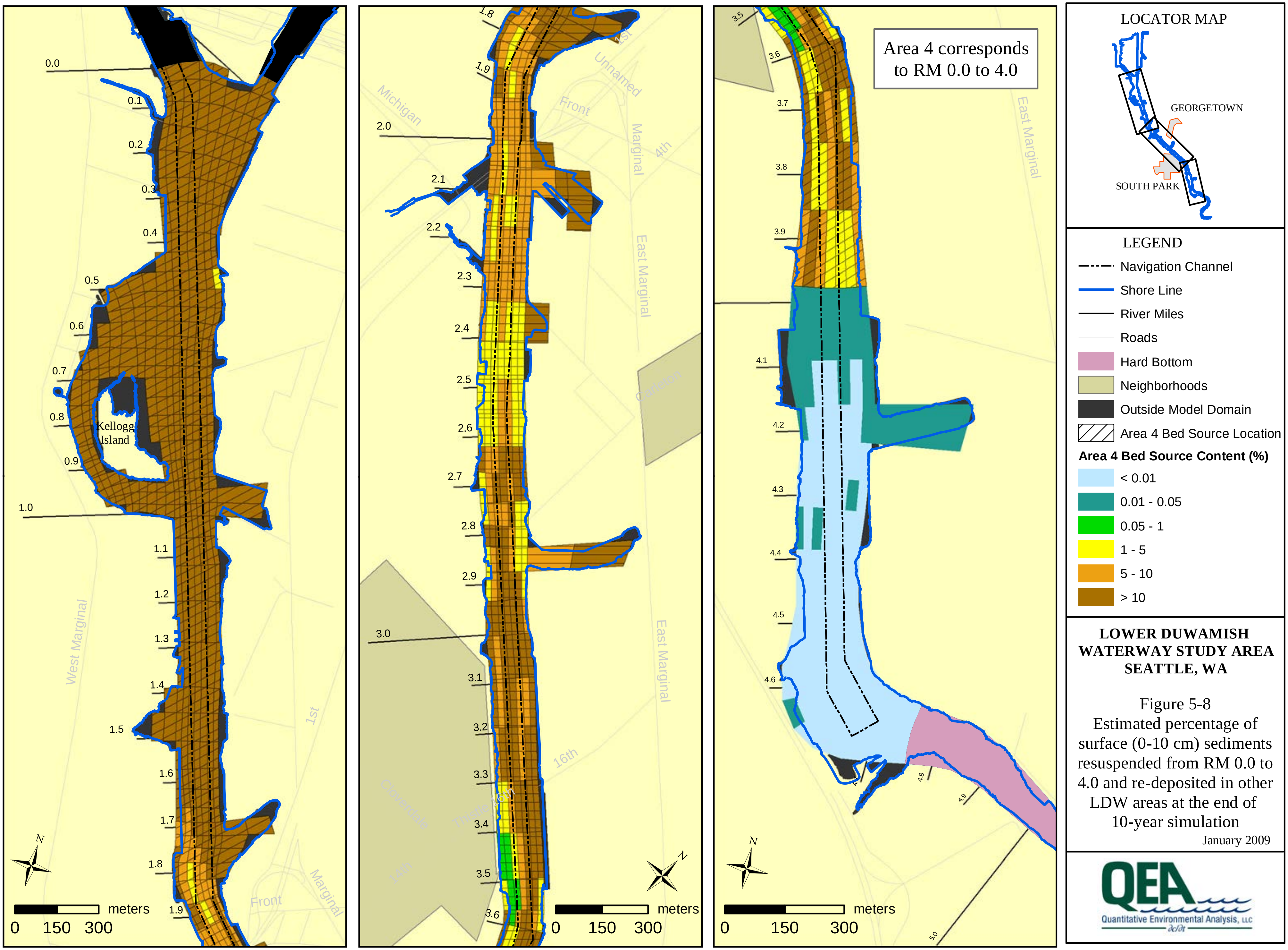
Figure 5-7
Distributed lateral annual loads and lateral source content in surface (0-10 cm) sediments at end of 10-year simulation

Quantitative Environmental Analysis, LLC



LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

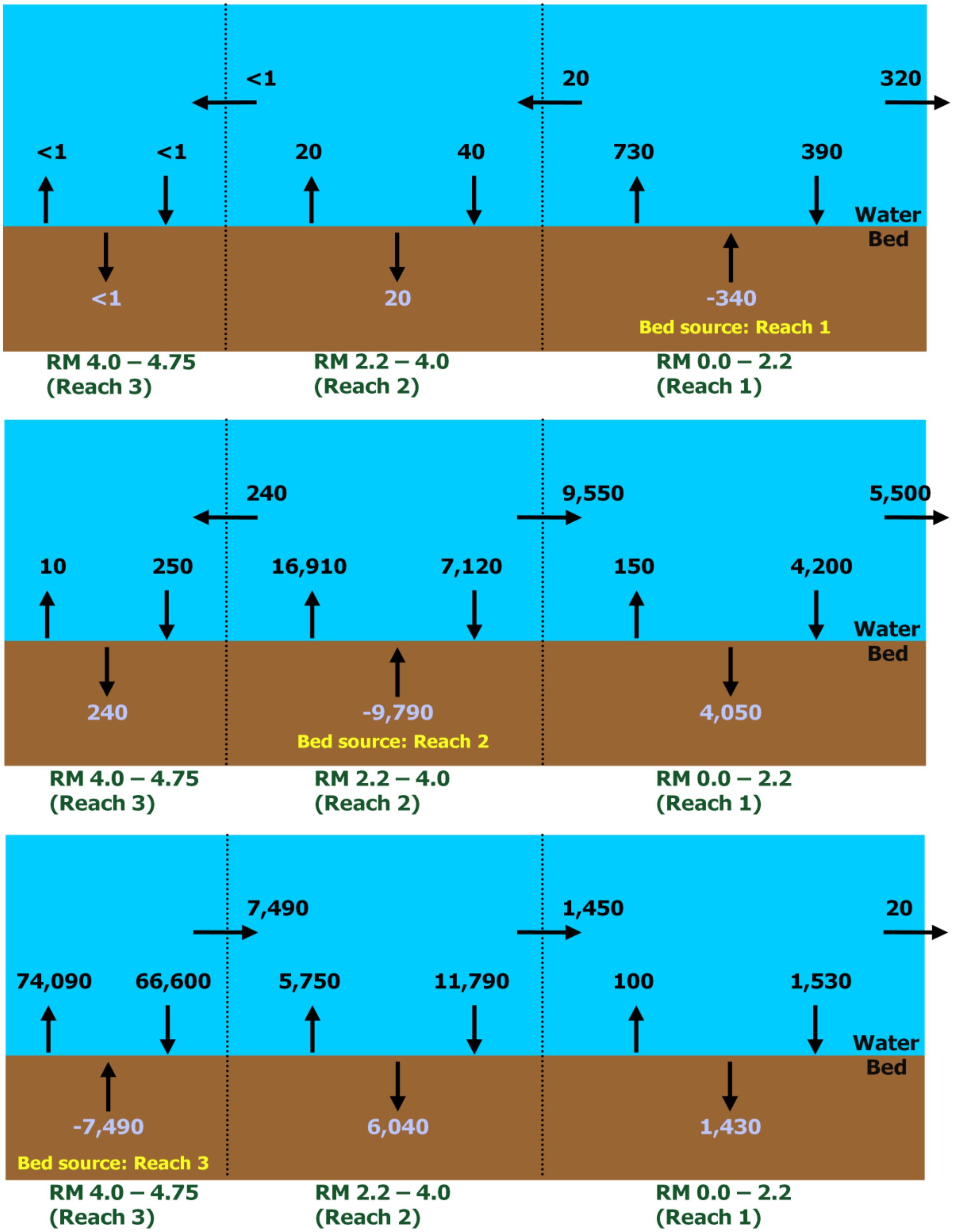
Figure 5-8
Estimated percentage of surface (0-10 cm) sediments resuspended from RM 0.0 to 4.0 and re-deposited in other LDW areas at the end of 10-year simulation

January 2009

QEA Quantitative Environmental Analysis, LLC

FC/JC- \\Jill\D_drive\Jobs\RETltw\Documents\Scenario_Memo\RETldw_tech_memo_fig_3-4_FS_fig_5-11.mxd

Figure 5-9 Mass Balances for Bed Sediment Originating from Reaches 1, 2, and 3 for 10-year STM Simulation



Note:
Sediment mass units are in metric tons, rounded to the nearest 10 metric tons.

Figure 5-10a Total Sediment Mass Balance for 100-year High-flow Event Simulation

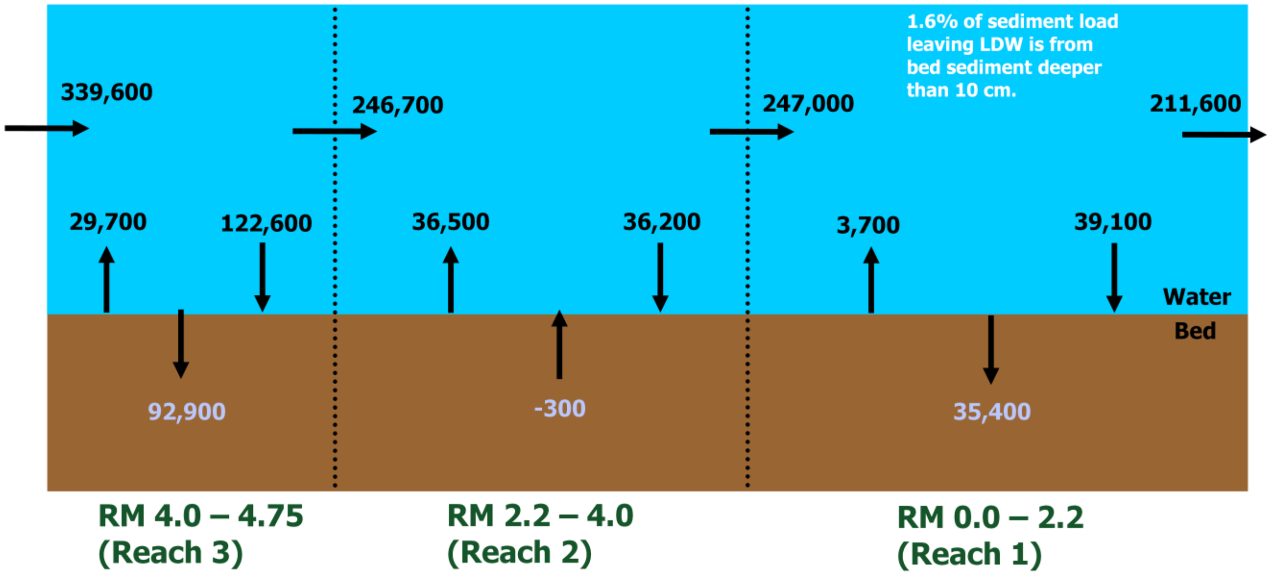
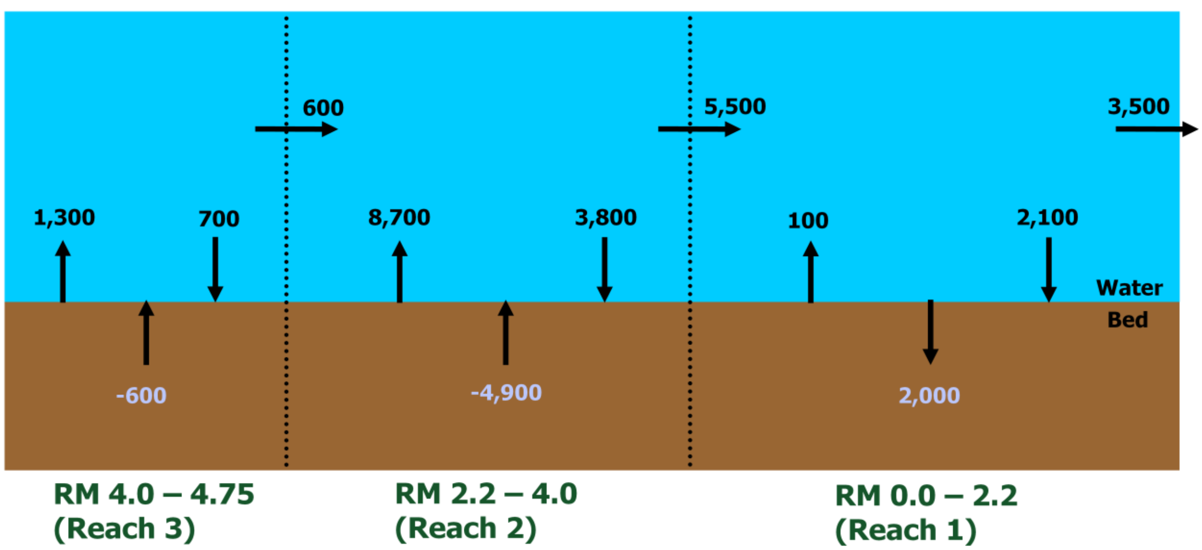
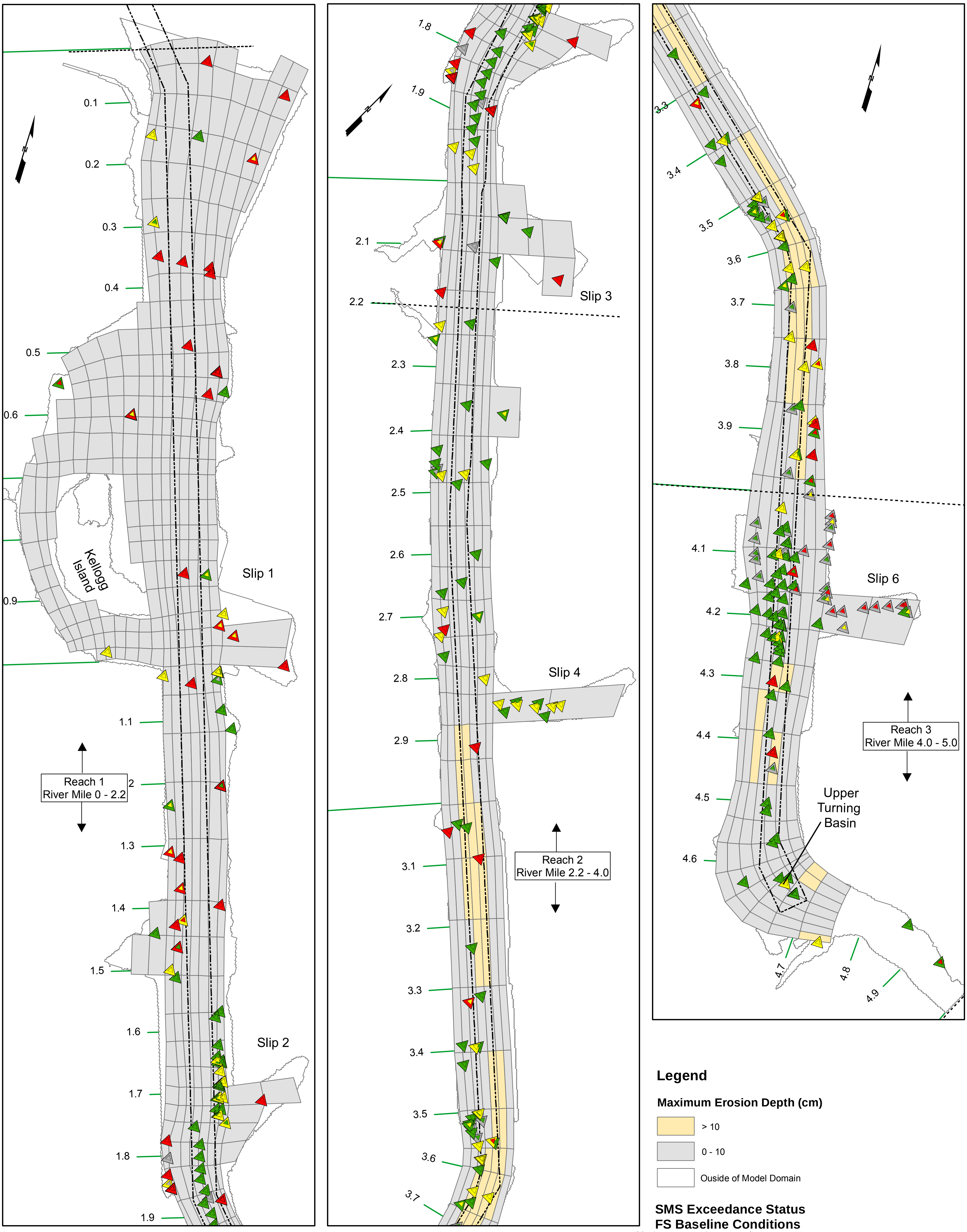


Figure 5-10b Mass Balance for Bed Sediment Originating from Deeper-than-10-cm Layer during 100-year High-flow Event Simulation





Notes:
1. Scenario 5 STM run showing maximum erosion for a 100-year high-flow event in each model grid cell (QEA 2009).
2. Sediment cores form the FS baseline dataset show the Sediment Management Standard (SMS) exceedance status in the upper 2 and 4-ft intervals of each core, at baseline conditions.
3. Sample intervals are approximate.

Legend

Maximum Erosion Depth (cm)
- > 10
- 0 - 10
- Ouside of Model Domain

SMS Exceedance Status
FS Baseline Conditions

Maximum exceedance 0-2 ft in core — Maximum exceedance 2-4 ft in core

- > CSL
- >SQS and ≤ CSL
- ≤ SQS or Non-detect
- Interval Not Analyzed
- Extent of Conceptual Site Model Reach
- Navigation Channel
- River Mile Marker

Feet
0 200 400 800

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Lower Duwamish Waterway Final Feasibility Study 60150279-14.49	Subsurface Sediment SMS Exceedance Locations with > 10 cm Erosion Depth During 100-year High-flow Event
DATE: 10/31/12 DWRN:MVI/sea Revision: 1	FIGURE 5-11

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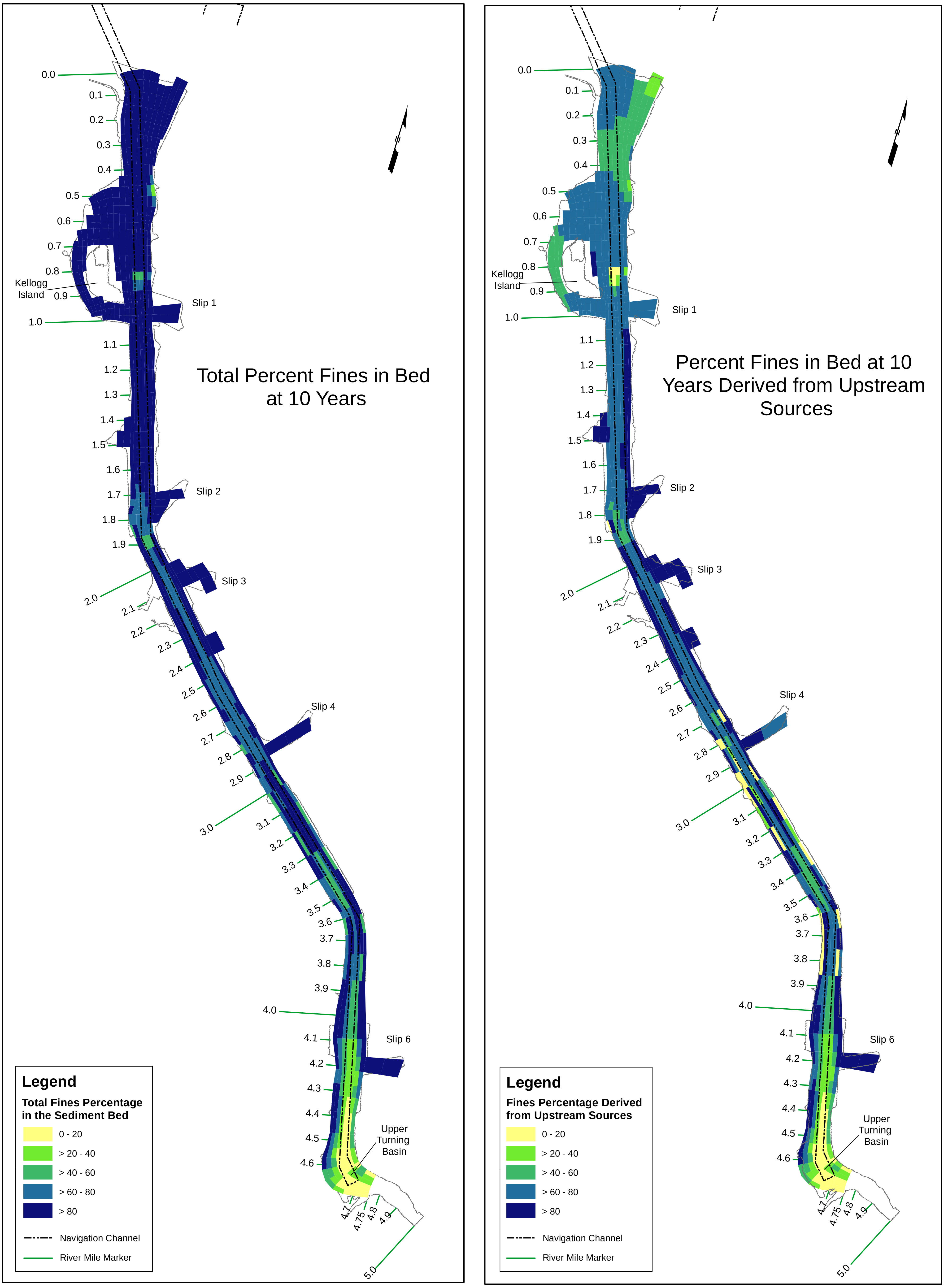

Notes:
1. 10-year STM GIS shapefile (QEA Feb. 2009).
2. Total fines represents the sum of fine-grained sediment from bed, lateral, and upstream sources in each grid cell at 10 years.
3. Upstream fines represents the percentage of fine-grained sediment from upstream sources in each grid cell at 10 years.
4. Fine-grained sediment is the sum of grain size classes 1A and 1B modeled in the STM. The fines are mostly class 1B, only about 10% of the class 1A material settles in the LDW.

Feet: 0 | 750 | 1,500 | 3,000

AECOM

Lower Duwamish Waterway Group
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Lower Duwamish Waterway Final Feasibility Study 60150279-14.49			Estimated Distribution of Grain Size After 10 Years - Total Percent Fines and Fines Sourced from Upstream
DATE: 10/31/12	DWRN: MVI/sea	Revision: 1	FIGURE 5-12

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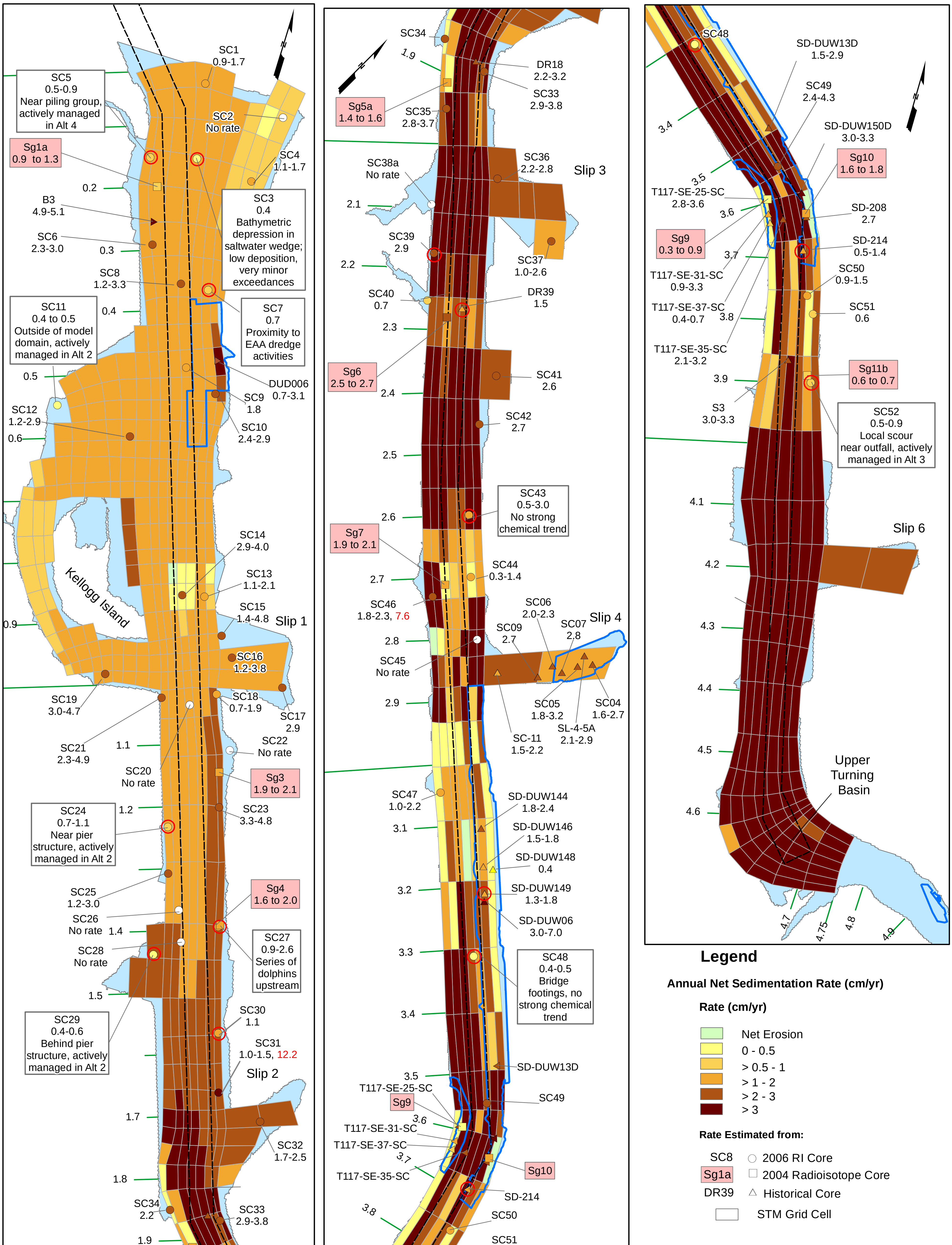

Legend

Annual Net Sedimentation Rate (cm/yr)

Rate (cm/yr)

- Net Erosion
- 0 - 0.5
- > 0.5 - 1
- > 1 - 2
- > 2 - 3
- > 3

Rate Estimated from:

- SC8 — 2006 RI Core
- Sg1a — 2004 Radioisotope Core
- DR39 — Historical Core
- STM Grid Cell

- Net Sedimentation Rate Estimated from Core is Less than Rate from STM
- Outside Model Domain
- Early Action Area
- Navigation Channel
- River Mile Marker

0 400 800 Feet

Core Number — SC48 0.4-0.5 Bridge Footings — Net Sedimentation Rate (cm/yr) — Possible Reason for Difference

Notes:
1. Net sedimentation rates estimated from radioisotope core data, 2006 core chemistry data and historical core data in FS project database.
2. Numerous time markers used to estimate net sedimentation rates are from radioisotope, physical, and chemical geochronology profiles.
3. Ranges shown are calculated from recovered depths.
4. Red font represents rate from dredging event marker outside range of other rates.
5. STM GIS shapefile from 30-year run (QEA Feb. 2009).
6. Seven RI cores for which rates could not be calculated are displayed as white circles. Historical cores for which rates could not be calculated are not shown.
7. Cores SC11, SC40 and SC42 are outside of the model domain and therefore are not circled. Core SC46 has interference from a dredge event and was not circled. Historical core SC11 (in Slip 4) range matched model predictions. Core SC51 straddled two grid cells and therefore was not circled.

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Comparison of Net Sedimentation Rates Estimated from the STM and from Sediment Cores

DATE: 10/31/12 | DWN. BY: MVI/sea | **FIGURE 5-13**

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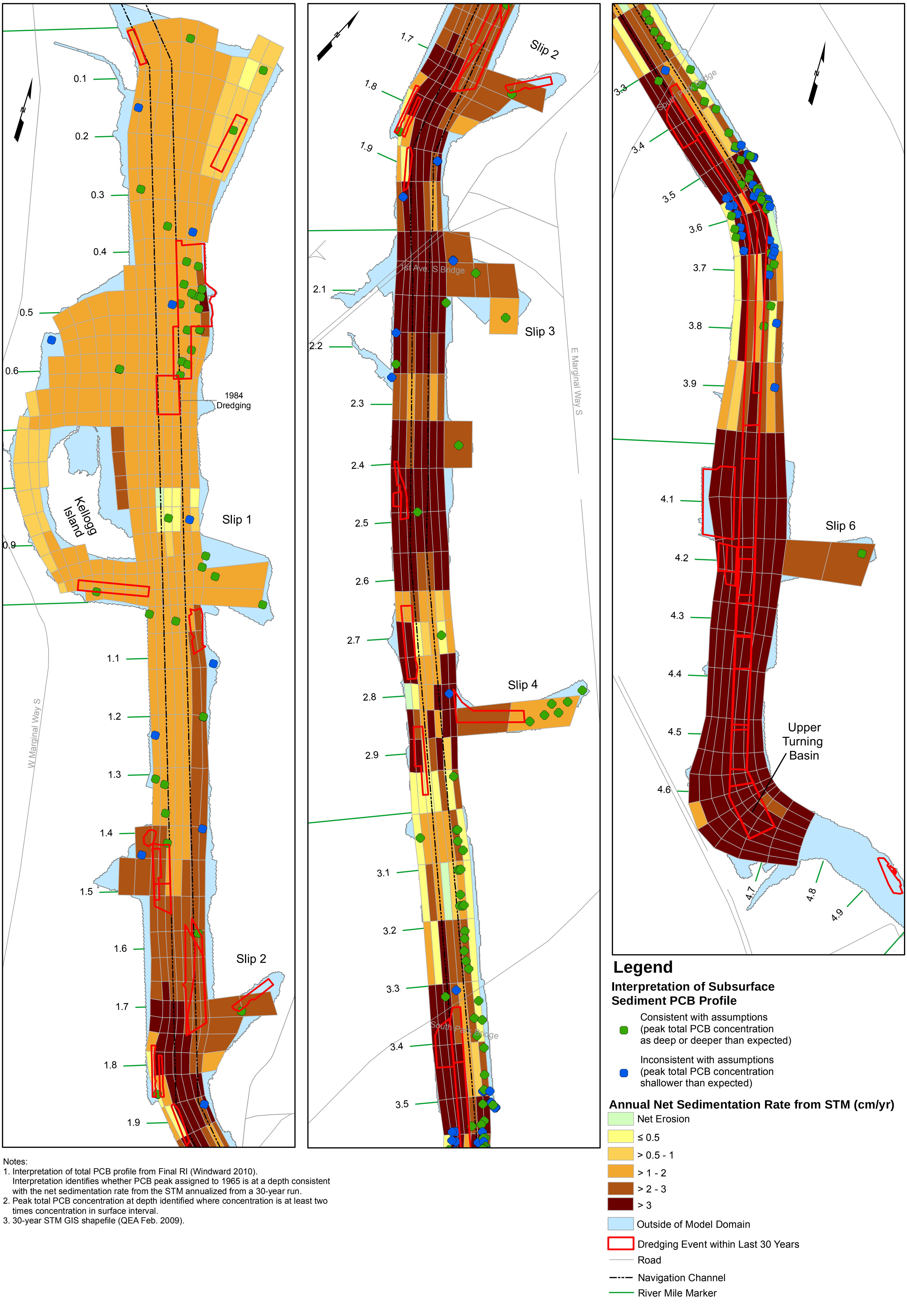

Notes:
1. Interpretation of total PCB profile from Final RI (Windward 2010). Interpretation identifies whether PCB peak assigned to 1965 is at a depth consistent with the net sedimentation rate from the STM annualized from a 30-year run.
2. Peak total PCB concentration at depth identified where concentration is at least two times concentration in surface interval.
3. 30-year STM GIS shapefile (QEA Feb. 2009).

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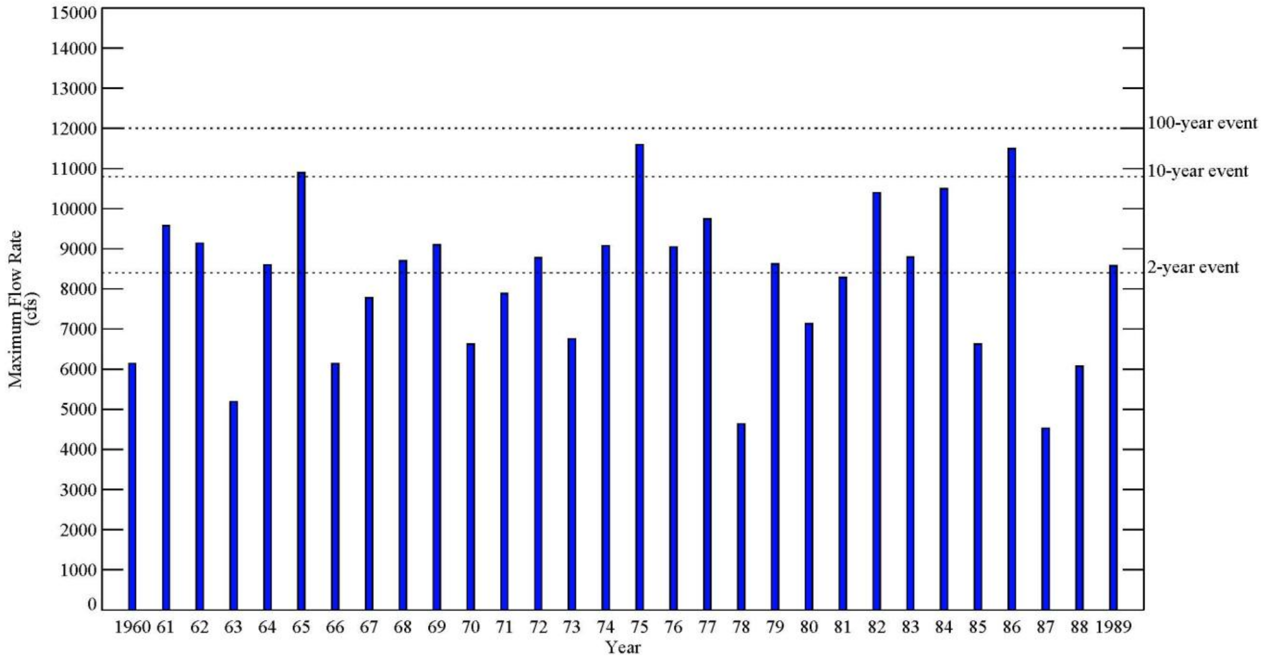
Annual Net Sedimentation Rates and Empirical PCB Trends in Subsurface Core Data

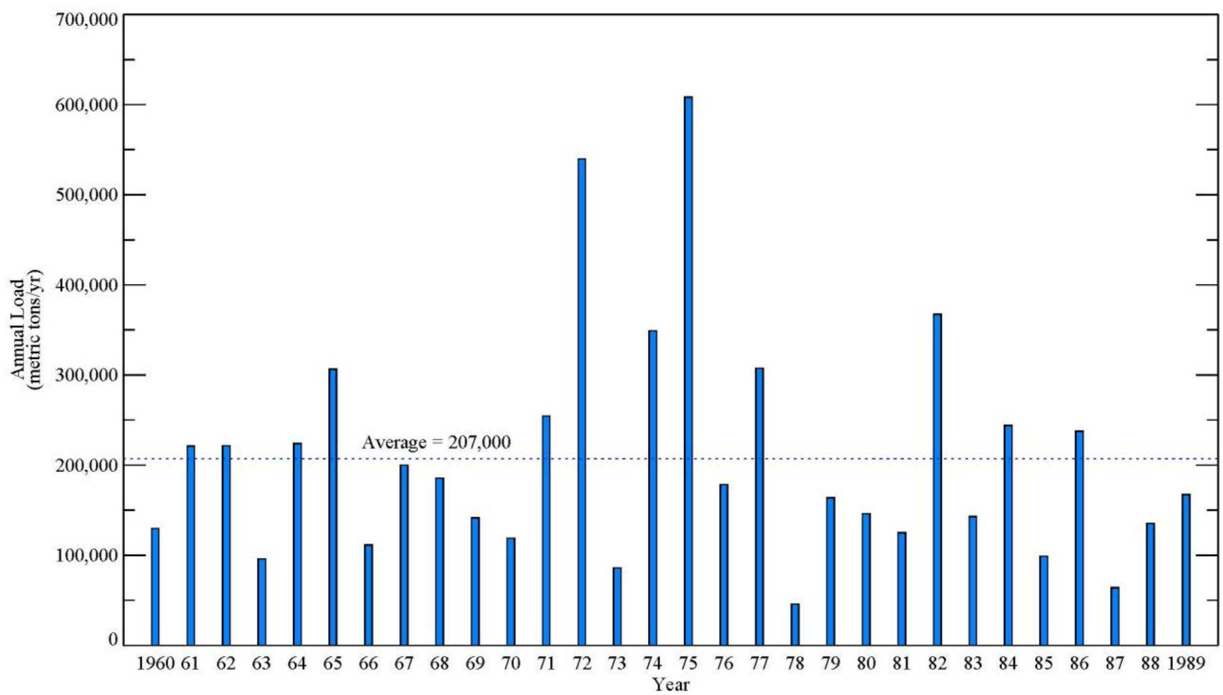
FIGURE 5-14

Figure 5-15a Maximum Flow Rate during Each Year from 1960 to 1989



Flow data: Fresh Water Discharge at USGS 12113000 (Green River).

Figure 5-15b Estimated Annual Total Sediment Load (suspended and bed load) in the Green River from 1960 through 1989



Note: 207,000 metric tons (MT) is annual average sediment load over 30-yr period. The annual average sediment load over the first 10 years (1960 – 1969) is 185,000 MT.