Lower Duwamish Waterway Group

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

Appendix C
Sediment Modeling Memoranda

Final Feasibility Study

Lower Duwamish Waterway
Seattle, Washington

FOR SUBMITTAL TO:

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

The Washington State Department of Ecology
Northwest Regional Office
Bellevue, WA

October 31, 2012

Prepared by: AECOM

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Part 1: Bed Composition Model for the Lower Duwamish Waterway Feasibility Study: Mechanics of Model Application

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AECOM

Memorandum

Date: August 28, 2007[1]

To: Lower Duwamish Waterway Group

From: AECOM

Subject: Bed Composition Model for the Lower Duwamish Waterway Feasibility Study: Mechanics of Model Application

Introduction

This memorandum describes the Bed Composition Model (BCM) proposed for use in the *Lower Duwamish Waterway* (LDW) *Feasibility Study* (FS) to estimate long-term changes in the chemistry of the surface sediment bed. Briefly, the BCM imports results from the Sediment Transport Model (STM; QEA 2007) onto interpolated chemical distribution maps prepared in the ArcGIS® Geographic Information System (GIS) for the LDW. A computational algorithm is then applied to estimate changes in chemical concentrations with time (10 and 30 years) resulting from the physical processes of sediment burial, resuspension, and mixing. The BCM accommodates sediment loading to the study area from upstream and lateral inflows. It also has the capability of differentiating sediment particle size fractions and associated fraction-specific chemistry.

This memorandum was prepared to facilitate discussions with the U.S. Environmental Protection Agency (EPA) and the Washington Department of Ecology (Ecology) about the basis for and mechanics of the BCM. Consistent with the *Feasibility Study Work Plan* (FSWP; RETEC 2007a), the FS will document the BCM and its output in the context of natural recovery. BCM results will be used to inform the selection of remedial action levels and the assembly and analysis of remedial alternatives. Final application of the BCM for evaluating remedial alternatives and natural recovery in the FS (e.g., selection of input values) will be determined in consultation with EPA and Ecology.

The BCM will initially be used to predict temporal changes in the concentrations of total PCBs and arsenic, as there are sufficiently complete datasets available on the chemistry of these risk drivers in both the surface sediment bed and external inputs. The methodology cannot be applied to chemicals with limited surface sediment datasets that preclude interpolation (e.g., dioxins/furans) or where there is insufficient information on external inputs. Therefore, this memorandum also describes a location-specific methodology for evaluating long-term concentration changes with time for other risk drivers and chemicals of concern (COCs) not suited to the BCM methodology.

1 Revised June 18, 2010 to be consistent with revisions to the FS requested by the agencies.

General Description of the BCM Framework

The BCM is constructed within a GIS framework, and consists of the following steps:

1. Develop chemical concentration (i.e., total PCBs, arsenic) maps using Inverse Distance Weighting (IDW) interpolation on a 10-ft by 10-ft grid.
2. Map the output of the STM surface sediment bed composition (i.e., percent contributions of three different types of solids: suspended solids from the upstream inflow, suspended solids from lateral inflows, and bed sediments) onto the interpolated chemical concentration grids for a specific time period (e.g., 10 years).
3. Create an attribute table from the GIS grids that contains the information derived in steps 1 and 2. Export the table into Excel® 2007.
4. Develop chemical input values that represent the solids-associated concentration(s) of risk drivers (i.e., total PCBs, arsenic) for three types of solids:
   - Upstream (i.e., Green River)
   - Lateral (i.e., storm water, combined sewer overflows [CSOs], and streams)
   - Where active remedial actions occur (e.g., dredging or capping), a post-remedy bed sediment replacement value.
5. For a specific potential remedial alternative, define the areas where active remedial measures (e.g., dredging, capping) could occur and identify the underlying grid-cells that will be assigned a post-remedy bed sediment replacement value. Within the Excel® 2007 worksheet, define and enter the post-remediation (time = 0) bed concentrations for the targeted chemical in each applicable 10-ft x 10-ft grid-cell.
6. Within the Excel worksheet, apply the BCM time-dependent bed composition algorithm to each GIS 10-ft x 10-ft grid cell using input parameters derived in the previous two steps. (Note: this step generates a new sediment bed chemical concentration for each grid cell.)
7. From the resulting BCM output, calculate the spatially-weighted average concentration (SWAC), the 95% upper confidence limit (UCL) on the SWAC, and, if required, plot the output as a chemical distribution map.

Each of these steps is described in more detail below.

Interpolated Chemical Concentration Maps

Interpolated chemical concentration maps provide the initial condition against which future changes can be predicted with the BCM. To date, two interpolation methods have been used to create bed maps for the LDW Remedial Investigation and Feasibility Study (RI/FS): Thiessen polygons and Inverse Distance Weighting (IDW). IDW interpolation of total PCBs was used in the technical memorandum *Draft Preliminary Screening of Alternatives* (PSA; RETEC 2006) and is being used in the RI (Windward, in prep), and are planned for application in the FS. Thiessen polygons for total PCBs were used in the human health risk assessment (Windward 2007) as a means of spatially representing the observed data and to calculate SWACs and 95% UCLs on the mean for net-fishing and clamming exposure areas. Interpolated arsenic concentration maps have not been prepared for any RI/FS documents to date. The IDW methods and assumptions used previously for total PCB interpolation were documented in the technical memorandum *GIS Interpolation of Total PCBs in LDW Surface Sediment* (Windward 2006) and in Appendix B of the PSA (RETEC 2006). The methods described in that memo for total PCBs were re-evaluated for both total PCBs and arsenic to: 1) identify a set of IDW parameters that allowed for interpolation of total PCB concentrations for the whole LDW as a single unit, 2) develop IDW parameters to interpolate arsenic concentrations, and 3) provide a simple method for calculating an LDW-wide UCL on a SWAC derived from an IDW-interpolated chemical concentration map. The dataset used to evaluate the parameters included the Round 3 data, which were not yet available at the time of the 2006 technical memorandum (Windward 2006).

The IDW methodology and parameters developed for total PCBs and arsenic specifically for use in the FS, and methods for calculating a 95% UCL on a SWAC, will be the subject of a separate memorandum to EPA and Ecology.

Mapping Output of the STM to the GIS Chemical Distribution Maps

The next step in the BCM is to map the surface sediment bed composition predicted by the STM onto the interpolated chemical distribution maps. The STM report presents results of the long-term (30 years) sediment transport simulation in the LDW (QEA 2007). The STM predicts changes in the composition of the surface sediment bed over time and in response to inputs from external sediment inflows. External sediment inputs are defined for upstream (i.e., Green River) and lateral (i.e., storm drains, CSOs, and streams) inflows. Bed sediments are treated as a third type of solid. The STM output yields the composition of the sediment bed in each grid-cell as the fraction or percentage of each type of solid contributing to the sediment in that location (Figures 1 through 3). Model results are saved at 5-year intervals in GIS attribute tables. The methods and output examples are presented in Section 4 of the STM report (QEA 2007).

The STM grid (727 cells over 398 acres) and the chemical distribution grid (>186,000 cells over 430 acres) differ both in the total area covered and in the size of individual cells. The rule adopted to account for cell-size disparity was to uniformly assign STM bed composition percentages to all chemical distribution grid-cells falling fully within a given STM cell. For example, Figure 4(A) shows the STM-predicted lateral load compositions for the section of the LDW between river mile (RM) 0.3 to 2.0. In this example, chemical distribution grid-cells that lie fully within the STM cell having a lateral composition percentage of 27.2% are assigned the same lateral composition value of 27.2% (Figure 4B). In cases where an STM grid boundary crosses a chemical distribution grid-cell, the composition assigned to the grid-cell is that for the dominant STM cell (i.e., the one that occupies greater than 50% of the chemistry grid-cell area).

Some chemical distribution grid-cells located along the edges of the LDW study area are not overlain by an STM cell (Figure 4). Chemical distribution grid-cells not collocated with a STM cell were assumed to have a composition corresponding to the nearest adjacent (i.e., along lateral transect) STM cell. As shown in Figure 4, chemical distribution grid-cells lying outside an STM cell (Figure 4B) were assigned a value based upon the value of the nearest neighboring cell (Figure 4C). In this manner, all chemical distribution grid-cells were assigned a composition corresponding to the percent contribution from the upstream and lateral inflows, and from the initial sediment bed.

Composition and Chemical Concentration Attribute Table

Following the mapping exercise, the surface sediment bed composition and chemical concentrations for each grid-cell are exported from the GIS attribute table to an Excel® 2007 workbook. Excel® 2007 has the capacity to process and store the information for all 180,000 grid-cells that are generated for each model run of the BCM. In addition, the BCM calculations are performed within Excel® 2007. This allows for transparency and quality control because Excel, unlike GIS, retains the formulas used. Table 1 is an example that shows the GIS coordinates (X,Y), the 10- and 30-year surface sediment bed composition percentages (bedded sediments, upstream, and lateral), a check on each grid-cell to ensure the percentages total 100 percent, and, in this example, the initial dry weight concentration of total PCBs, total organic carbon content (%), and the organic carbon normalized concentration of total PCBs for each grid-cell.

Chemical Composition Input Parameters

Estimates of the concentrations of chemicals associated with each of the three types of solids (i.e., upstream, lateral, and LDW surface sediments[2]) are required as inputs to the BCM. An initial set of chemical concentrations was provided in the technical memorandum *Initial Bed Sediment Composition Model Range-Finding Parameters for Total PCBs and Arsenic* (RETEC 2007b) for use in the BCM range-finding exercise. That memorandum specifically developed an initial range of total PCB and arsenic concentrations for upstream and lateral inflows, and for post-remedy bed sediment replacement values. The range development work attributed uniform chemical concentrations to the multitude of lateral inflows, as there is insufficient information available for establishing unique input concentrations for individual inflows.

Input parameters for additional risk-drivers (e.g., cPAH) may also be developed in consultation with EPA and Ecology as needed, after completion of this initial modeling effort for total PCBs and arsenic.

BCM Time-Bed Composition Algorithm

Changes in the chemical concentrations of surface sediment over time are calculated as a function of the initial surface sediment concentrations (time=0)[3] and the STM-predicted changes in bed composition (i.e., changes in percent composition of the three types of solids). For each 10-ft by 10-ft grid-cell in the interpolated chemical concentration maps, the following simple algorithm is used to predict changes in bed sediment concentrations at specified time intervals:

$$C_{(time)} = C_{lateral} * fraction_{lateral} + C_{river} * fraction_{river} + Cbed * fraction_{bed} \quad (1)$$

Where:

$C_{lateral}$ represents the concentration of a chemical (i.e., total PCBs or arsenic) on “lateral” inflow solids

C_{river} represents the concentration of a chemical on “upstream” (i.e., Green River) solids

C_{bed} represents the chemical concentration in the surface sediment bed at time = 0.

The bed fraction ($fraction_{bed}$) represents the fraction of sediment in each grid-cell derived from the initial (time=0) LDW sediment bed. Depending on the scenario being modeled, the bed sediment chemical concentration assigned to this parameter at any given location may be:

- The initial sediment condition in the absence of any remediation (i.e., “no action” or monitored natural recovery alternative)
- The sediment condition present in an area immediately after active remediation (which might include capping, dredging, or a combination of dredging and capping).

In areas experiencing net sediment deposition, the bed sediment fraction will decrease over time as it is diluted by the settling of sediments from the lateral ($fraction_{lateral}$) and upstream ($fraction_{river}$) inflows. In its current form, the BCM does not specifically account for the potential movement (i.e., erosion and

2 Bedded sediment values can be either the interpolated initial chemical concentrations in surface sediments or post-remedy bed sediment replacement values applied within a remediated area.

3 “time = 0” corresponds to the time when active remedial measures of a specific remedial alternative are completed. For a “no action” alternative, “time = 0” sediment concentrations correspond to the initial interpolated surface sediment chemical concentration maps.

redeposition) of bed sediment throughout the study area. The effect of erosion and redeposition of bed sediment relative to other transport processes was previously computed as part of the STM (QEA 2007). Redeposition of suspended bed sediments was estimated to constitute 2.5% of total deposition in Reach 1, 5.4% in Reach 2, and 2.5% in Reach 3 over 30 years. These percentages show that erosion and redeposition represent a minor contribution relative to the combined lateral and upstream inputs.

In all areas that are not actively remediated, the chemical concentrations within the sediment bed (C_{bed}) at time = 0 are assumed to be equivalent to those interpolated from the initial surface sediment dataset. To account for uncertainties, a range of concentrations will be evaluated for the post-remedy bed sediment replacement value in areas that are actively remediated, $C_{lateral}$, and C_{river} (RETEC 2007b).

Evaluation of Potential Remedial Alternatives

Remedial alternatives for the LDW will be developed and evaluated in the FS as described in the FSWP (RETEC 2007a). The effectiveness of each alternative over the short-term (5 to 10 years) and long-term (10 to 30 years) will be evaluated, in part, using the BCM. In the case of a "no action" alternative, only ranges of chemical input parameters for upstream and lateral inflows will be used to assess changes in surface sediment bed concentrations at 10 and 30 years. C_{bed}, in this case, is the initial interpolated chemical concentration in the surface sediment at any given location.

Alternatives that include an active remediation component (e.g., dredging, capping) combined with natural recovery will also be evaluated using a range of upstream and lateral inflow chemical concentrations. In addition, a range of post-remedy bed sediment replacement values will be applied within the boundaries of the active remediation areas.

The direct outputs from the BCM are the LDW-wide SWAC, 95% UCL on the SWAC, and concentration values for each grid-cell at specified time intervals. Interpolated chemical base maps can be constructed from the output, which, in turn, enables scrutiny of localized effects (e.g., individual recreational areas or areas around outfalls) with respect to changes in point concentration, SWAC, and 95% UCLs over time. The BCM can be run over a range of shorter time intervals (e.g., 5-year intervals) to allow an evaluation of changes in bed sediment concentrations over time. Finally, the effects of varying chemical concentrations associated with the two types of solids (i.e., upstream and lateral loads) on bed sediment concentrations can be plotted and used to evaluate the impacts of source control activities.

Use of the STM Output to Evaluate Other COCs

The FS will evaluate long-term concentration changes (i.e., restoration time frame) for other chemicals of concern that exceed preliminary remediation goals on a location-specific basis. Such evaluations will be performed where, for example, a sediment quality standard (SQS) is exceeded at a specific sample station or a group of stations exceed the SQS within a sediment management area. Equation (1) can be used on a point basis. However, for many COCs, the terms $C_{lateral}$ and C_{river} are supported by limited or no data and are therefore difficult to quantify. In some cases, this limitation can be addressed by assuming that the chemical contribution from external inflows is small compared to the initial sediment bed concentrations. This assumption is supported by the influx of suspended solids being dominated by the upstream (Green River) component, which contains low (near background) concentrations of many COCs. In these cases, the sum of the external input terms in equation (1) (i.e., $C_{lateral}$*$fraction_{lateral}$ + C_{river}*$fraction_{river}$) is very low relative to C_{bed}*$fraction_{bed}$ and may be neglected thereby reducing Equation (1) to:

$$C_{(time)} = C_{bed} * fraction_{bed} \quad (2)$$

Thus, in many cases, it can be expected that the STM output of bed fractions as a function of time will provide a good approximation of the chemical concentration changes expected for the other COCs at particular locations.

The concept of bed half-life, as described in the STM (QEA 2007) and derived from Equation (2), may be a convenient and mathematically equivalent method of expressing changes in chemical concentration. Existing data from sediment core analyses may provide an opportunity to empirically check the validity of the half-life concept if the rate of change in chemical concentrations with depth can be transposed to a rate of change with time.

Handling Uncertainty

Translating the STM output to the interpolated chemical distribution maps requires accepting certain limits on the predictive application of the BCM. Figures 1 through 3 show the predicted bed composition for a 30-year STM simulation (Figures 4-3 through 4-5 from the STM report, QEA 2007). The “active” modeled portion of the bed of the LDW extends from RM 0.0 to RM 4.8, whereas the study area for the interpolated chemical distribution maps in the FS is from RM 0.0 to 5.0. The riverbed upstream of RM 4.8 is assumed to have a “hard bottom” in which no erosion or deposition of suspended sediment occurs but bed load transport is allowed. Thus, the BCM is limited to RM 0.0 to 4.8. Long-term changes in sediment concentrations in the region from RM 4.8 to 5.0 will need to be addressed in the FS by a different approach than the BCM described herein.

Uncertainties in the concentration ranges for the post-remedy bed sediment replacement value, $C_{lateral}$ and C_{river}, will be evaluated (RETEC 2007b). Experience at other sediment remediation sites shows that chemical concentrations in the sediment bed (C_{bed}) shortly after the completion of active remediation cannot conservatively be assumed to be zero (NRC 2007; EPA 2005; Anchor 2003). This occurs because there is always some degree of residual surface contamination from the resettling of contaminated sediments suspended during remedial activities. The degree of residual contamination is dependent on the type of remedial activity, specific design elements, construction methods, best management practices, engineering controls, contingency measures, etc., the effects of which cannot be accurately predicted through modeling. (The STM does not estimate the degree of residual contamination in actively remediated areas.) Therefore, it will be necessary to assume a post-remedy bed sediment replacement value as an input parameter to the BCM using various lines of evidence and best professional judgment.

Summary

LDWG plans to use the BCM methodology presented herein to aid in the development and evaluation of sediment remedial alternatives in the FS. Concentrations of PCBs and arsenic in solids from lateral and upstream inflows are reasonably well described, and initial model runs are being performed for these chemicals. Information on the concentrations of chemicals other than PCBs and arsenic in suspended solids from upstream and lateral inflows is limited, so application of this model to these other chemicals may be limited or require generalized assumptions. LDWG is currently proceeding with computational runs using the BCM. Preliminary results of these runs will be evaluated and presented to EPA and Ecology at the August 30, 2007 meeting.

Attachments

Table 1 Example Attribute Table Produced in GIS and Exported to Excel® 2007

Figure 1 STM-Predicted Baseline Sediment Solids Composition in Surface Sediments (0-10 cm) at the End of 30-Year Period

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Table 1 Example Attribute Table Produced in GIS and Exported to Excel® 2007

Grid Cell	GRID LOCATION[1]		STM OUTPUT: 10-YEAR COMPOSITION (%)				STM OUTPUT: 30-YEAR COMPOSITION (%)				CHEMICAL INTERPOLATION: INITIAL SURFACE SEDIMENT CONCENTRATIONS[2]		
	X	Y	Bed	Upstream	Lateral	Total Check	Bed	Upstream	Lateral	Total Check	Total PCBs (µg/kg dw)	TOC (%)	Total PCBs (mg/kg OC)
1	1266078.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	161.00	1.58	10.19
2	1266088.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	160.99	1.58	10.19
3	1266098.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	160.92	1.58	10.18
4	1266108.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	160.51	1.58	10.15
5	1266118.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	158.30	1.59	9.95
6	1266128.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	149.72	1.62	9.22
7	1266138.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	133.64	1.69	7.92
8	1266148.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	122.81	1.73	7.09
9	1266158.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	119.29	1.75	6.83
10	1266168.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	118.38	1.75	6.77
11	1266178.34	211399.00	35.73	63.08	1.19	100.00	2.45	95.84	1.71	100.00	118.14	1.75	6.75
12	1266188.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	118.08	1.75	6.75
13	1266198.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	118.07	1.75	6.75
14	1266208.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	118.08	1.75	6.75
15	1266218.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	118.13	1.75	6.75
16	1266228.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	118.26	1.75	6.76
17	1266238.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	118.62	1.75	6.77
18	1266248.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	119.64	1.75	6.82
19	1266258.34	211399.00	34.04	64.80	1.16	100.00	2.04	96.32	1.64	100.00	122.57	1.76	6.97
20	1266898.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.01	1.31	10.46
21	1266908.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.00	1.31	10.46
22	1266918.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.00	1.31	10.46
23	1266928.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.00	1.31	10.46
24	1266938.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.00	1.31	10.46
25	1266948.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.00	1.31	10.46
26	1266958.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.00	1.31	10.46
27	1266968.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.00	1.31	10.46
28	1266978.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.01	1.31	10.46
29	1266988.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.03	1.31	10.46
30	1266998.34	211399.00	65.88	33.21	0.91	100.00	20.34	77.86	1.81	100.00	137.08	1.31	10.46
31	1267008.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	137.23	1.31	10.45
32	1267018.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	137.58	1.32	10.45
33	1267028.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	138.39	1.33	10.44
34	1267038.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	140.05	1.34	10.45
35	1267048.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	143.09	1.36	10.48
36	1267058.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	148.06	1.40	10.59
37	1267068.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	155.36	1.44	10.83
38	1267078.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	165.12	1.48	11.18
39	1267088.34	211399.00	63.31	35.73	0.97	100.00	17.79	80.41	1.80	100.00	177.20	1.52	11.67

Notes:

[1] NAD83 Washington State Plane North Coordinates in feet (FIPS 4601)

[2] This map was overlaid with an interpolated total organic carbon (TOC) map to determine carbon-normalized (OC) values for each grid cell.

Figure 1 STM-predicted baseline sediment solids composition in surface sediments (0-10 cm) at the end of 30-year period

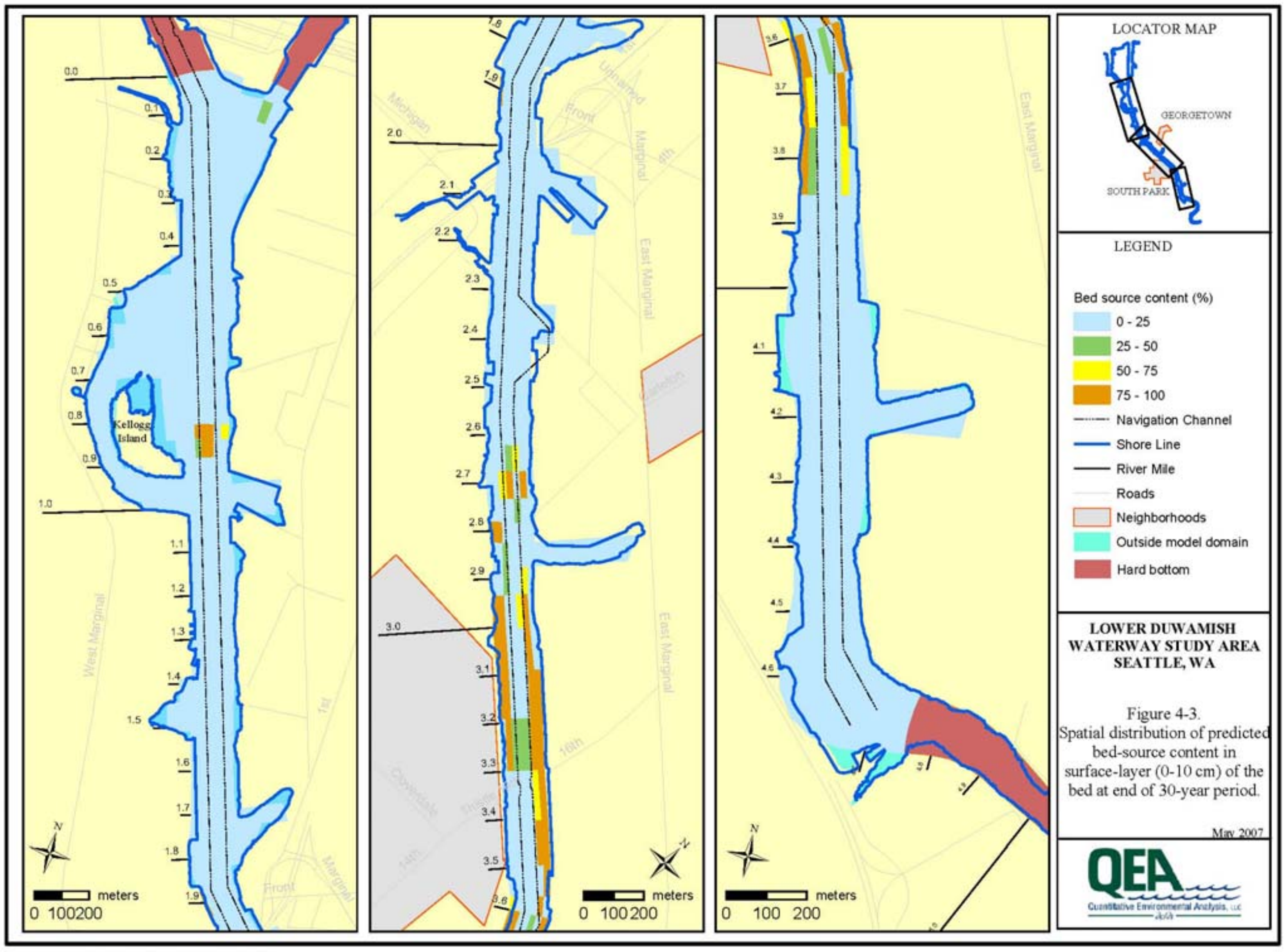


Figure 2 STM-predicted upstream sediment solids composition in surface sediments (0-10 cm) at end of 30-year period

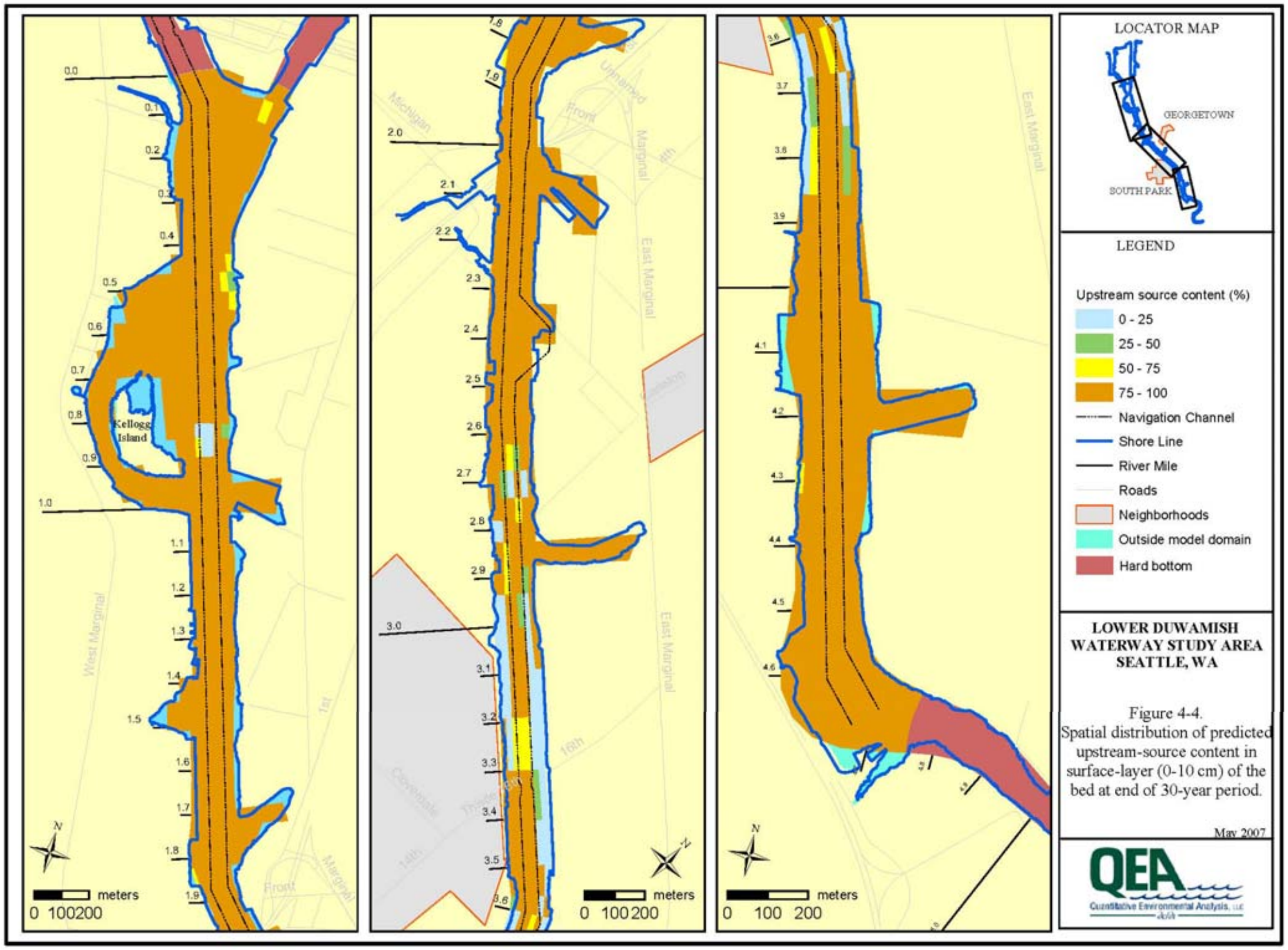
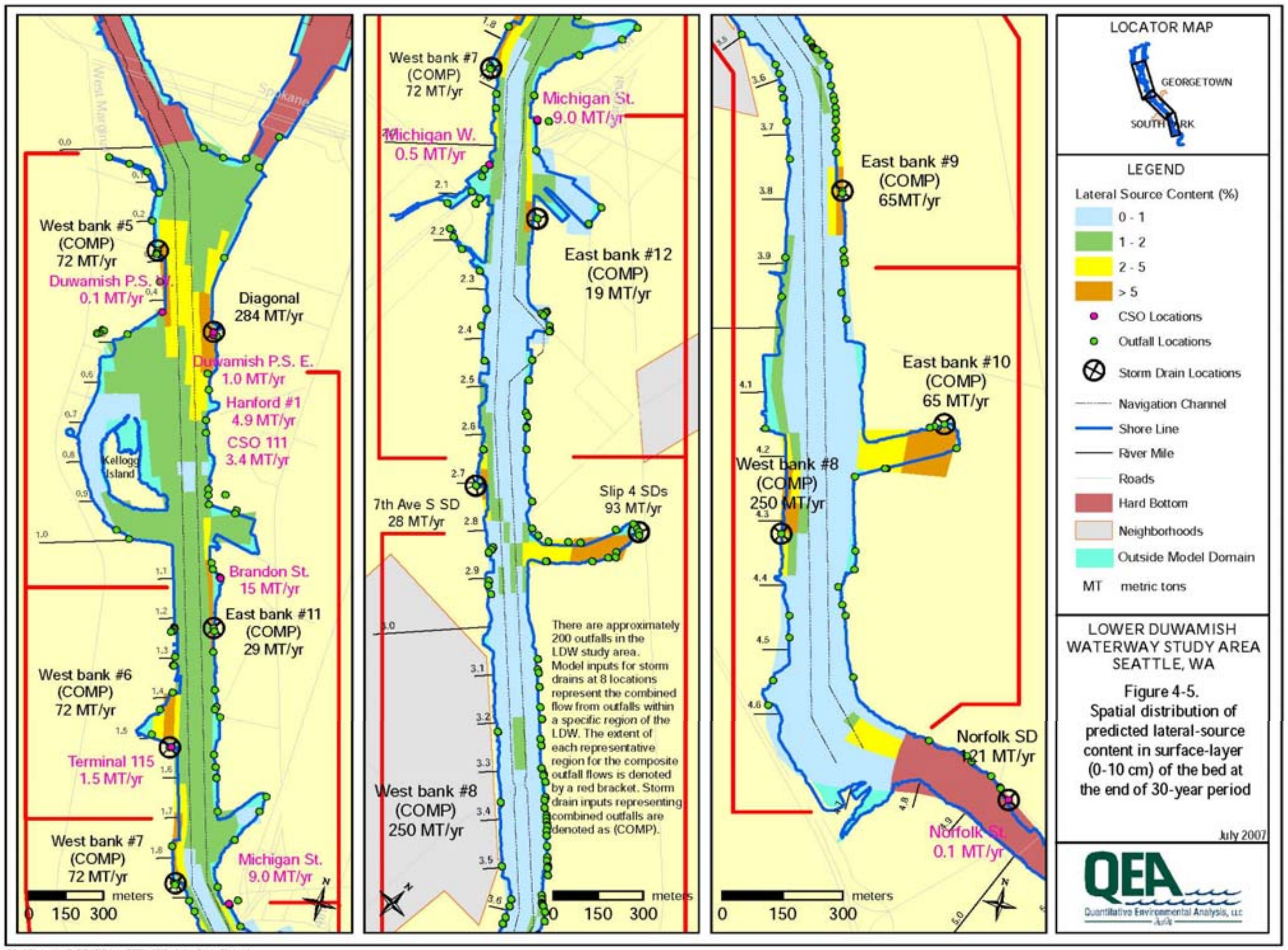
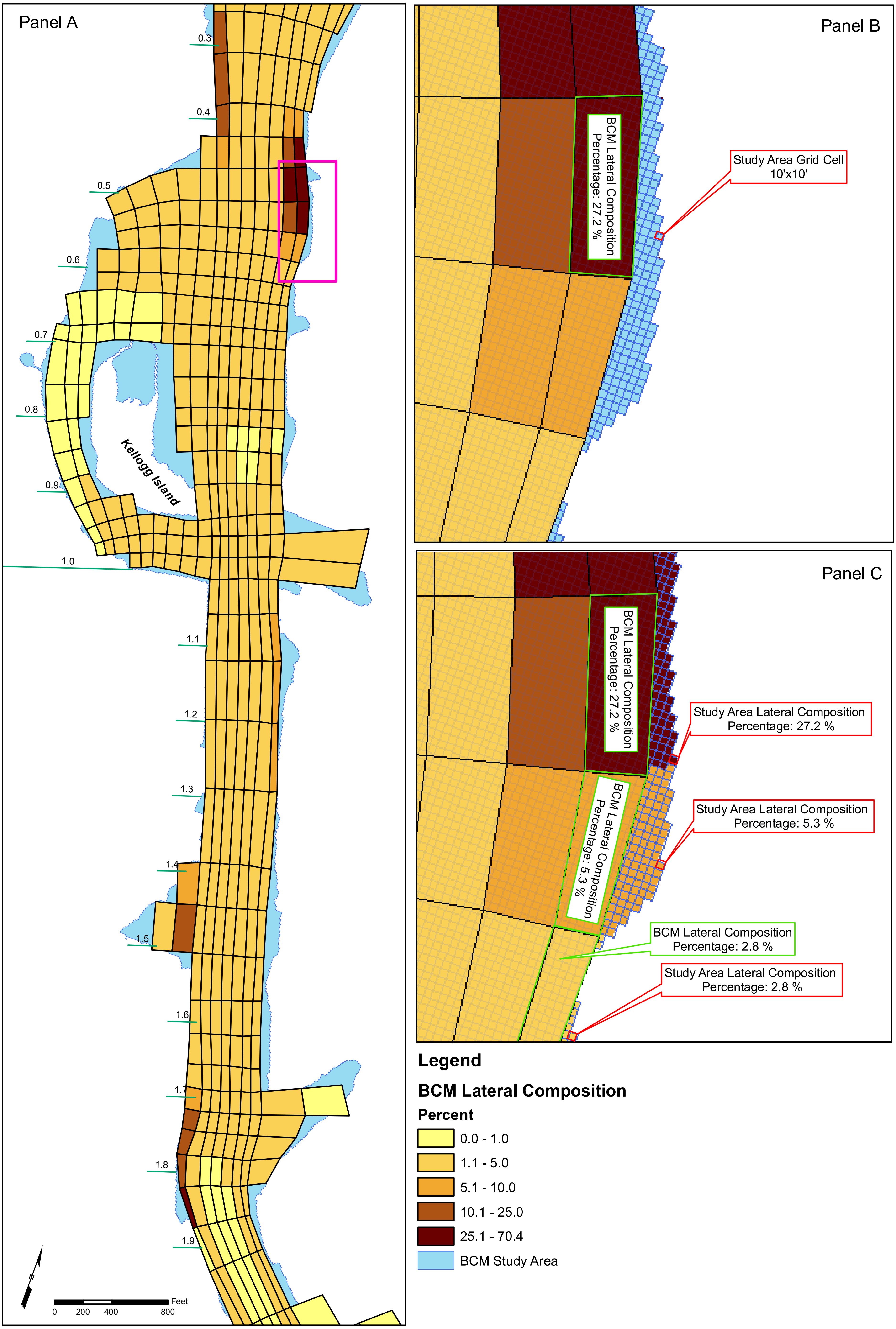


Figure 3 STM-predicted lateral solids composition in surface sediments (0-10 cm) at the end of 30-year period





F:\PROJECTS\GIS\Lower Duwamish FS\Projects\SDM Input Parameters\SDM input parameter memo\BCM Memo6.mxd (Creted in ArcGIS 9.2)

ENSR | AECOM

Merged with ENSR in 2007 RETEC

STM Modeling ENSR, Lower Duwamish Waterway, WA (05482015-615)			**Transposing STM Composition Results onto the Chemical Distribution Grid**
DATE: 8/17/07	DWRN:MVI/Sea	Revision: 6	**FIGURE 4**

Part 2: Mathematical Basis for the LDW Bed Composition Model

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AECOM

Draft Memorandum

Date: April 17, 2009

To: Lower Duwamish Waterway Group

From: Mike Riley, SSPA; Nicole Ott, AECOM

Subject: Mathematical Basis for the LDW Bed Composition Model

Introduction

This memorandum describes the mathematical basis for the bed composition model (BCM) proposed for use in the Lower Duwamish Waterway (LDW) feasibility study (FS) to estimate long-term changes in the chemistry of the surface sediment bed. Briefly, the BCM estimates the change in chemical concentrations in bed sediments over time due to sediment inflows from upstream sources (Green/Duwamish River) and lateral sources (storm drains, combined sewer overflows [CSOs], and streams) and chemical concentrations in the sediment bed at some specified initial point in time.

BCM Time-bed Composition Algorithm

Changes in the chemical concentrations in surface sediment over time are calculated as a function of the initial surface sediment concentrations (referred to as time=0)[1] and the changes in bed composition (i.e., changes in percent composition from the three sources of solids) predicted by the sediment transport model (STM) over some time period. The three sources of solids are lateral, upstream, and original sediment bed.

The basic equation for the BCM is:

$$dC/dt = d(C_{bed}*f_{bed} + \Sigma C_i*f_i)/dt \qquad \text{Equation (1)}$$

Where:

C	is the chemical concentration at some time **t**
C_{bed}	is the chemical concentration in the original bed sediment at time **t**
f_{bed}	is the fraction of the original bed sediment at time **t**
C_i	is the chemical concentration associated with inflows (lateral and upstream) at time **t**
f_i	is the fraction of inflow sediment at time **t**

[1] ”time = 0” corresponds to the time when active remedial measures of a specific remedial alternative are completed. For a “no action” alternative, “time = 0” sediment concentrations correspond to the initial interpolated surface sediment chemical concentration maps. Composition (or fraction) of bed at time=0 is 100% original bed, 0% lateral, and 0% upstream sources.

Using the assumptions that: 1) the concentration in the original bed and concentrations in the inflows do not change significantly over time (dt), and 2) that all lateral inflow discharge points have the same chemical concentration in a particular time period, the concentration at a given time is dependent on the change in composition over that time period. Then, Equation (1) becomes:

$$C_{(time)} = C_{lateral} * f_{lateral(time)} + C_{upstream} * f_{upstream(time)} + C_{bed} * f_{bed} \quad \text{Equation (2)}$$

Where:

$C_{lateral}$	represents the concentration of a chemical (i.e., total PCBs or arsenic) on lateral inflow solids
$f_{lateral}$	is the fraction of sediment from lateral inflows
$C_{upstream}$	represents the concentration of a chemical on upstream (i.e., Green/Duwamish River) solids
$F_{upstream}$	is the fraction of sediment from the Green/Duwamish River
C_{bed}	represents the chemical concentration in the surface sediment bed at time=0

The bed fraction (f_{bed}) represents the fraction of sediment at any point in the LDW. Depending on the scenario being modeled, the bed sediment chemical concentration assigned to this parameter at any given location may be:

- The initial sediment condition in the absence of any remediation (i.e., “no action” or monitored natural recovery alternative)
- The sediment condition present in an area immediately after active remediation (which might include capping, dredging, or a combination of dredging and capping).

In areas experiencing net sediment deposition, the bed sediment fraction will decrease over time as it is diluted by the settling of sediments from the lateral ($f_{lateral}$) and upstream (f_{river}) inflows. In its current form, the BCM does not specifically account for the potential movement (i.e., erosion and redeposition) of bed sediment throughout the study area. The effect of erosion and redeposition of bed sediment relative to other transport processes was previously estimated as part of the STM (QEA 2007). Redeposition of suspended bed sediments was estimated to constitute 2.5% of total deposition in Reach 1, 5.4% in Reach 2, and 2.5% in Reach 3 over 30 years. These percentages show that erosion and redeposition represent a minor contribution relative to the combined lateral and upstream inputs.

The BCM approach is a conservative method for estimating changes in chemical concentration in bed sediment over time for any chemical that is expected to decline in concentration associated with inflows over time. For instance, with the combined benefit of limited PCB commercial use, reduction in the primary sources of PCBs, and continued source control efforts from adjacent upland areas, the inflows that drain the Duwamish watershed can be expected to decline over time. Total PCB concentrations can be expected to decline in lateral and upstream inflows even though the assumption used in the BCM is that the concentrations will stay relatively constant.

Part 3: Lines of Evidence for the Development of BCM Input Parameters

Memorandum

To: Merv Coover, Anne Fitzpatrick, AECOM

From: Debra Williston, King County Department of Natural Resources and Parks; Beth Schmoyer, Seattle Public Utilities

Date: March 17, 2010

Re: BCM Lateral Input and Sensitivity Values for the LDW FS

The bed composition model (BCM) requires lateral input values for chemical concentrations associated with particles discharged to the LDW from storm drains, combined sewer overflows (CSOs), and streams. This text describes how the BCM lateral input values were selected for total PCBs, arsenic, cPAHs, and dioxins/furans.

The source tracing dataset for the LDW was used to establish BCM lateral values for PCBs, arsenic, and cPAHs for the FS. The dataset consists of storm drain solids data collected by various parties, including Seattle Public Utilities (SPU), The Boeing Company, and King County. SPU compiled and categorized the data by sample type and geographic area. The dataset includes samples of storm drain solids collected from on-site and right-of-way catch basins, as well as in-line grab samples and in-line sediment trap samples. Over 500 samples have been collected within drainage basins tributary to the LDW and analyzed for metals and semivolatile organic compounds. Over 900 samples have been analyzed for PCBs. Samples were collected from throughout drainage basins tributary to the LDW. However, because source control activities initially focused on the early action areas, these areas typically have the highest number of source tracing samples (see Figure 1). Table 1 provides a summary of the numbers and types of samples for these three chemicals.

Table 1: Numbers of storm drain solids samples collected within drainage basins tributary to the LDW

	Arsenic	Total PCBs	cPAHs
Onsite catch basins	137	345	114
Right-of-way catch basins	123	133	121
Inline grab samples	175	303	166
Sediment trap samples	141	172	142
Total	576	953	543

The lateral input values selected for use in the BCM should account for improvements in storm drain solids chemical concentrations resulting from source control efforts in the LDW drainage basin. In order to simulate potential lateral inputs after implementation of various degrees of source control, the source tracing datasets were screened to remove all values above various concentrations. Summary statistics were then generated for each level of assumed source control. These included sample count, detection frequency, minimum, maximum, median, mean, and 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentiles (see Attachment A). The intent was to have a mid or base case BCM input value and a range about that value from high to low to investigate the sensitivity of the BCM to that input value. The following three BCM input values were therefore selected:

- BCM High Sensitivity Value – Conservative representation of current conditions assuming modest level of source control (e.g., management of high priority sources).
- BCM Input (Mid or Base Case) Value – Pragmatic assessment of what might be achieved in the next decade with anticipated levels of source control.
- BCM Low Sensitivity Value – Best that might be attainable 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 source control work group and what is currently known about the distribution within the LDW drainage basin and the ongoing source(s) of each chemical of concern. These reflect potential levels of source control that could occur over time. The screening values used in these analyses are not intended to be target values for source control.

While the screening values differed for PCBs, arsenic, and cPAHs, the same summary statistics were used to select the input (base case), low, and high BCM lateral values. For the input or base case value, the mean value was used. For the low and high value, the median and 90^{th} percentile values were selected, respectively.

The evaluations of the source tracing dataset for total PCBs, arsenic, and cPAHs are described in the following sections. A somewhat different approach, also described below, was used for dioxins/furans because of the considerably smaller datasets available for dioxins/furans.

Total PCBs

PCBs were detected in 84 percent of the storm drain solids samples. Concentrations exceeded the lowest apparent effects threshold (LAET) value of 130 ug/kg dw in 67 percent of the samples and exceeded the second lowest apparent effects threshold (2LAET) value of 1,000 ug/kg dw in 41 percent of the samples. PCBs have been found in various building materials (e.g., paint, caulk, and other sealants) and there is also a continued global source from atmospheric deposition. Although PCBs are no longer manufactured, it is expected that the historical reservoir of PCB-containing materials will continue to act as a source to the LDW for many years. Therefore, complete elimination of PCBs will not be possible. However, inputs to the LDW from lateral sources are expected to be reduced with continued source control activities.

Unlike other chemicals, PCBs exhibited a distinct geographic distribution, with hotspots identified at Terminal 117 (T117), Rainier Commons, North Boeing Field/Georgetown Steam Plant, and Boeing Plant 2/Jorgensen Forge (Figure 2). The latter two have been sampled extensively and make up a significant portion of the overall source tracing data set. The Rainier Commons area does not have as large a dataset but it shows a distinctive hot spot when compared to other areas in the LDW. Therefore, prior to generating summary statistics for total PCBs, the data from Rainier Commons, North Boeing

Field/Georgetown Steam Plant, and Boeing Plant 2/Jorgensen Forge were flow-weighted to avoid skewing the summary statistics used to establish inputs for the BCM model. Flow-weighting takes into account the relative contribution of a chemical by adjusting the concentration based on the land area and estimated annual runoff volume relative to the total contributing area in the LDW (Table 2). Data from the T117 hot spot were not included with the storm drain solids data for this analysis because these T117 data are a mix of soil and street dirt samples. Recent storm drain data indicate that the interim action completed in 2004 has largely controlled the PCBs at this site. Therefore, the soil and street dirt samples were not included in the lateral source tracing dataset.

Table 2: Total PCBs Flow-Weighting Information

Subasin	Area (acre)	Average Annual Runoff (Mgal/yr)	Percent of Total Runoff[a]	Description
LDW SD basin	8,936	4,065	100%	Total area draining to LDW
North Boeing Field/Georgetown Steamplant	110	69.7	1.8%	Area of North Boeing Field downstream of the runway that drains to Slip 4
Boeing Plant 2/Jorgensen Forge	132	87	2.2%	All of Boeing Plant 2 from Slip 4 to Jorgensen property
Rainier Commons	1.2	0.8	0.02%	Portion of Rainier Commons property that drains to LDW via the Diagonal Ave S CSO/SD storm drain system
Remaining	8,693	3,908	96.1%	Remaining LDW storm drainage basin

a. Factor used to flow-weight PCB\s concentrations for each geographic area.

For purposes of the FS, three screening values were considered to generate a reasonable range of BCM lateral values for PCBs. If all samples with total PCB concentrations above a screening value of 5,000 ug/kg dw are removed from the dataset, the mean of the remaining data is 300 ug/kg dw[1]; this value was selected to represent the BCM input or base case value. The screening value of 5,000 ug/kg dw was chosen to account for the presence of PCBs in building materials on older structures that may exist within drainage basins tributary to the LDW. These types of sources will be difficult to identify and control in the near term. Other lines of evidence support the use of 300 µg/kg dw as a reasonable input value. The mean total PCB concentration in all of the right-of-way catch basin samples was 689 ug/kg dw and dropped to 291 ug/kg dw when the three samples from catch basins located immediately downstream of the Rainier Commons site (23,000, 17,000, and 17,500 ug/kg dw) were removed. Right-of-way catch basin sample are less likely to be affected by high concentrations associated with activities on a particular property, and more likely to be representative of area-wide inputs such as vehicular traffic and atmospheric deposition. Sediment trap samples are also considered to reflect average conditions, because they represent contributions from all the runoff upstream of the sampling station. The mean total PCB concentration in all of the

[1] PCB values are rounded to one significant figure for the BCM model.

sediment trap samples outside of North Boeing Field was 371 ug/kg dw, or 284 ug/kg when the one sample greater than 10,000 ug/kg dw was removed.

Screening values of 2,000 and 10,000 ug/kg dw were selected for purposes of defining the low and high BCM sensitivity values, respectively. If all samples with total PCB concentrations above a screening value of 2,000 ug/kg dw are removed from the dataset, the median of the remaining data is 100 ug/kg dw, and this was selected as the low BCM sensitivity value. If all samples with total PCB concentrations above a screening value of 10,000 ug/kg dw are removed from the dataset, the 90th percentile value of the remaining data is 1,000 µg/kg dw, and this was selected as the high BCM sensitivity value. The high value is not intended to represent what sources could be throughout the drainage basins tributary to the LDW. This high value is used only to determine sensitivity of the model; it is not an estimate of actual source loads or a target value for source control work. Table 3 summarizes the BCM lateral input and sensitivity values for PCBs.

Arsenic

Arsenic was detected in 52 percent of the storm drain solids samples, but concentrations were relatively low, with only 5 percent of the samples exceeding the sediment quality standard (SQS, 57 mg/kg dw) and only 3 percent exceeding the cleanup screening level (CSL, 93 mg/kg dw). Samples containing elevated concentrations were not clustered in any geographic area. For this reason, the source tracing data were not flow-weighted for the evaluation of BCM inputs (Figure 3). Arsenic is a naturally occurring metalloid found in the Green/Duwamish river basin at concentrations ranging from non-detect to 20 mg/kg dw (http://www.ecy.wa.gov/programs/tcp/sites/tacoma_smelter/extended_footprint_study_kc/e_f_s.html). Arsenic will always be present in lateral inputs to the LDW.

Two different screening values (the SQS and CSL) were used to reflect different potential levels of source control. If all samples with arsenic concentrations above a screening value of 93 mg/kg dw (the CSL) are removed from the dataset, the mean of the remaining data is 13 mg/kg dw (this value was selected to represent the BCM input or base case value) and the 90th percentile is 30 mg/kg dw (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 to represent the low BCM sensitivity value). The high value is not intended to represent what sources could be throughout the drainage basins tributary to the LDW. This high value is used only to determine sensitivity of the model; it is not an estimate of actual source loads or a target value for source control work. Table 3 summarizes the BCM lateral input and sensitivity values for arsenic.

cPAHs

cPAHs were detected in 93 percent of the storm drain solids samples. Unlike PCBs, cPAHs have many ongoing sources, primarily associated with combustion sources such as vehicle emissions, home heating oil use, and wood burning. As a result, cPAHs will continue to be deposited on roadways and other land surfaces in the basin, and transported to the LDW in urban runoff. Therefore, this chemical will be difficult to control. Consequently, a more cautious approach was taken with the source tracing dataset.

Data for cPAHs were not flow-weighted because cPAH concentrations in the storm drain solids samples do not show a distinct geographic distribution (Figure 4). Higher concentrations of cPAHs are found throughout the basin. A single screening value (25,000 ug TEQ/kg dw) was used based on best professional judgment regarding the difficulty of effectively controlling this chemical group. cPAHs are present at concentrations >25,000 ug TEQ/kg dw at various locations throughout drainage basins tributary to the LDW, typically in onsite drainage structures (catch basins and oil/water separators) at sites engaged in transportation-related activities (e.g., bus and airport operations), maintenance facilities, service stations, foundries, and fast food facilities. This screening value is considered an appropriate representation of source control effectiveness in controlling significant sources. If all samples with cPAH concentrations above the screening value of 25,000 ug TEQ/kg dw are removed from the dataset, the mean of the remaining data is 1,400 ug TEQ/kg dw[2] (selected to represent the BCM input or base case value); the median is 500 ug TEQ/kg dw (selected to represent the low BCM sensitivity value); and the 90th percentile is 3,400 ug TEQ/kg dw (selected to represent the high BCM sensitivity value) (Table 3).

Dioxins/Furans

Available storm drain solids data for dioxins and furans were also used along with data for surface sediment samples collected for the LDW RI in the vicinity of storm drains throughout the Greater Seattle area to establish BCM lateral values for dioxins and furans. These two datasets were combined because the storm drain solids dataset was small compared to the other risk driver datasets. There are 11 dioxin and furan storm drain solids samples collected from on-site catch basins and in-line grab samples, as well as one street dirt sample. There are 12 surface sediment samples from the vicinity of storm drains throughout the Greater Seattle area that were analyzed for dioxins/furans that are included for this analysis; two of these 12 samples that had high concentrations of dioxins/furans were not included following an outlier analysis. Combining the two datasets results in the following: mean of 20 ng TEQ/kg dw (selected as the BCM input or base case value); median of 10 ng TEQ/kg dw (selected as the low BCM sensitivity value); and a 95% upper confidence limit on the mean (UCL) of 40 ng TEQ/kg dw (selected as the high BCM sensitivity value) (Table 3). The combined dioxin/furan dataset was not screened the same way other storm drain solids data were because of the limited data available. In addition, the UCL 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. The goal was to estimate, using best professional judgment, a reasonable range of BCM lateral input as sensitivity values.

King County CSO data

In addition to the storm drain solids dataset, King County data for PCBs, arsenic, and cPAHs in whole-water samples collected from CSOs were also considered when developing BCM lateral values. For both total PCBs and cPAHs, whole-water concentrations were divided by their sample-specific total suspended solids (TSS) concentrations (in mg/L) to calculate TSS-normalized concentrations. This gives a

[2] The cPAH input (or base case) and high BCM sensitivity values were rounded to two significant figures and the low BCM sensitivity value was rounded to one significant figure.

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, which were then divided by the sample-specific TSS concentrations to calculate a TSS-normalized concentration for arsenic. The summary statistics for these analytes are provided in Table 4. The median, mean, and 90th percentile values for these three chemicals generally fall within the ranges selected for the BCM lateral input values.

Table 4. Summary of TSS-normalized PCBs, cPAHs, and arsenic data for samples collected from King County Duwamish combined sewer basins.

	TSS-normalized Concentration		
	Total PCBs (µg/kg)	**Total cPAHs (µg TEQ/kg)**	**Arsenic (mg/kg)**
Count	28	26	21
Minimum	89	28.9	1.1
Maximum	1,627	4,136	15.8
Median	580	714	10.6
Mean	638	1,051	9.3
25th percentile	441	134	6.2
75th percentile	724	1,627	11.7
90th percentile	920	2,728	13.2

Table notes:

TSS = total suspended solids

Total PCBs based on sum of detected congeners

TSS-normalized calculation for PCBs and cPAHs based on sample-specific whole-water concentration divided by TSS concentration; this assumes all PCBs and cPAHs on particulate/solid fraction

TSS-normalized calculation for arsenic based on sample-specific total arsenic minus dissolved arsenic divided by TSS concentration

Table 3 - Revised BCM Lateral Input and Sensitivity Values for LDW Feasibility Study

Rationale

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

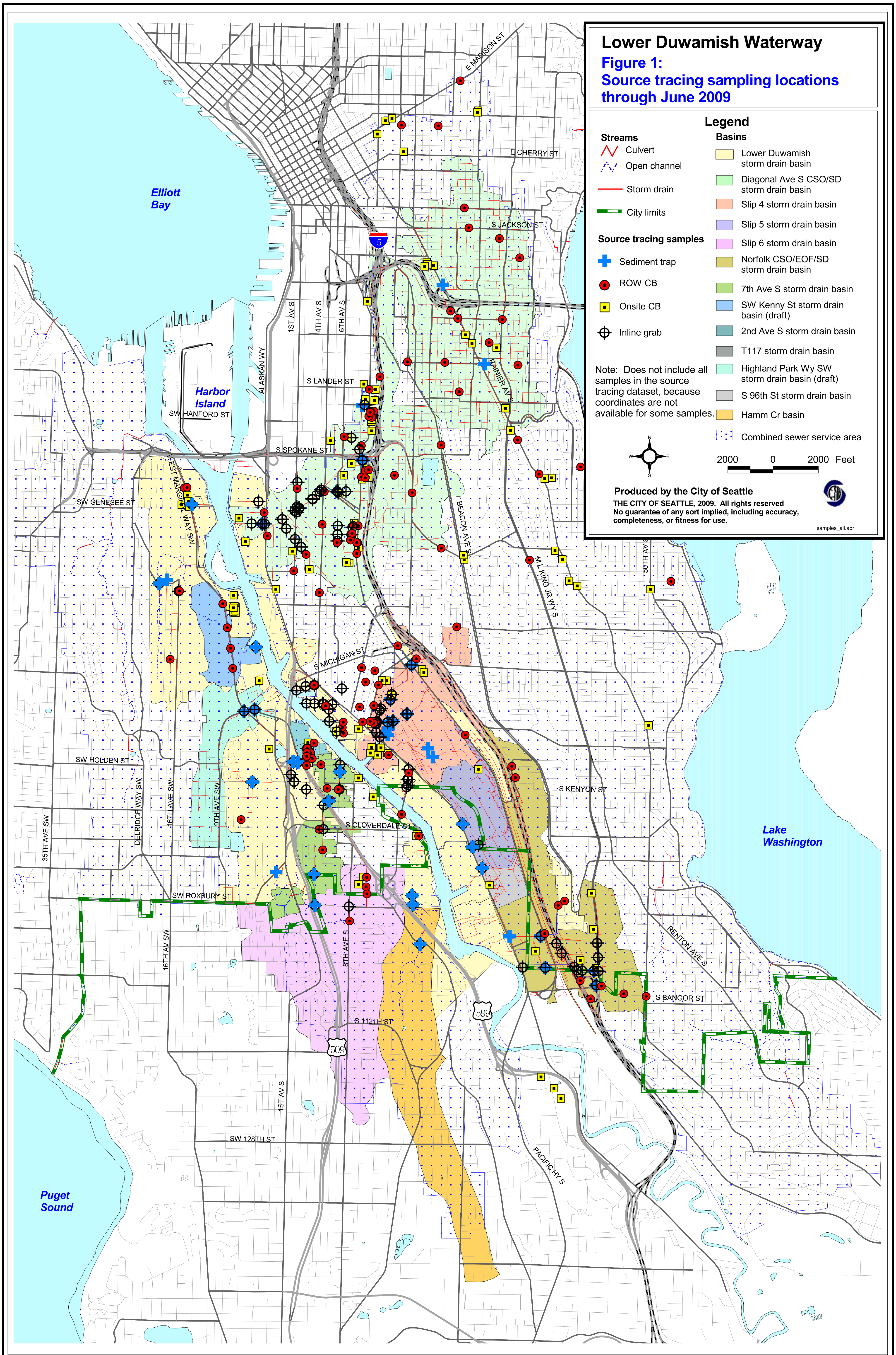
Chemical	Values Used in the Draft FS			Proposed Values for the Revised FS			Basis for Proposed BCM Input and Sensitivity Values
	Input	Low	High	Input	Low	High	
Arsenic[a] (mg/kg dw)	13	7	23	13	9	30	Screened the source tracing dataset to exclude concentrations above assumed SMS-based source control levels (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].
Total PCBs[a] (µg /kg dw)	660	60	1,200	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. **High:** 90th percentile of flow-weighted source tracing dataset excluding values >10,000 µg/kg dw. **Low:** Median of flow-weighted source tracing dataset excluding values >2,000 µg/kg dw.[a]
cPAH[a] (µg TEQ/kg dw)	2,800	200	5,000	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 ug TEQ/kg dw. **High:** 90th percentile of source tracing dataset excluding values >25,000 ug TEQ/kg dw. **Low:** Median of source tracing dataset excluding values >25,000 ug TEQ/kg dw.[a].
Dioxins and Furans[b] (nq TEQ/kg dw)	20	10	100	20	10	40	Based on combined Greater Seattle sediment and SPU catch basin solids datasets. [b] **Input:** Mean. **Low:** Median (rounded to10). **High:** UCL95.

Notes:

[a] Used Lower Duwamish Waterway source tracing dataset (compiled by SPU) through June, 2009 (SPU_StormDrainSolids_LDW_data_thru_6-30-09_.xls) as the primary basis for establishing lateral BCM parameter values for arsenic, total PCBs, and cPAH. The dataset was screened to remove concentrations using various source control practicability assumptions (best professional judgment). Total PCB data were flow-weighted before generating statistics because PCBs exhibit a distinct geographic distribution with hotspots identified in Terminal 117, NBF/GTSP, Rainer Commons, and Boeing Plant 2. These three areas have been extensively sampled and make up a significant portion of the overall source tracing dataset. Therefore, these source tracing data were flow-weighted to avoid skewing the summary statistics used in the BCM model. Arsenic and cPAH data were not flow-weighted prior to the statistical analysis because these chemicals lack a pronounced geographic dependency that would warrant flow-weighting.

[b] Parameter estimation for dioxins and furans was based on the Greater Seattle sediment and SPU catch basin solids datasets. The summary statistics used to estimate parameter values (see table entries) correspond to the combined datasets, as supported by statistical analysis. See source file (DioxinFuranBCMparameterMPC012-09-09.xls) for data and statistical analysis, including removal of outliers.

BCM = bed composition model; cPAH = carcinogenic polycyclic aromatic hydrocarbon; CSL = cleanup screening level; FS = feasibility study; GTSP = Georgetown Steam Plant; NBF = North Boeing Field; PCB = polychlorinated biphenyl; SPU = Seattle Public Utilities; TEQ = toxic equivalent; SQS = sediment quality standard; UCL95 = 95% upper confidence limit on the mean


Lower Duwamish Waterway
Figure 1:
Source tracing sampling locations through June 2009
Legend
Streams
Culvert
Open channel
Storm drain
City limits
Source tracing samples
Sediment trap
ROW CB
Onsite CB
Inline grab
Note: Does not include all samples in the source tracing dataset, because coordinates are not available for some samples.
Basins
Lower Duwamish storm drain basin
Diagonal Ave S CSO/SD storm drain basin
Slip 4 storm drain basin
Slip 5 storm drain basin
Slip 6 storm drain basin
Norfolk CSO/EOF/SD storm drain basin
7th Ave S storm drain basin
SW Kenny St storm drain basin (draft)
2nd Ave S storm drain basin
T117 storm drain basin
Highland Park Wy SW storm drain basin (draft)
S 96th St storm drain basin
Hamm Cr basin
Combined sewer service area
2000 0 2000 Feet
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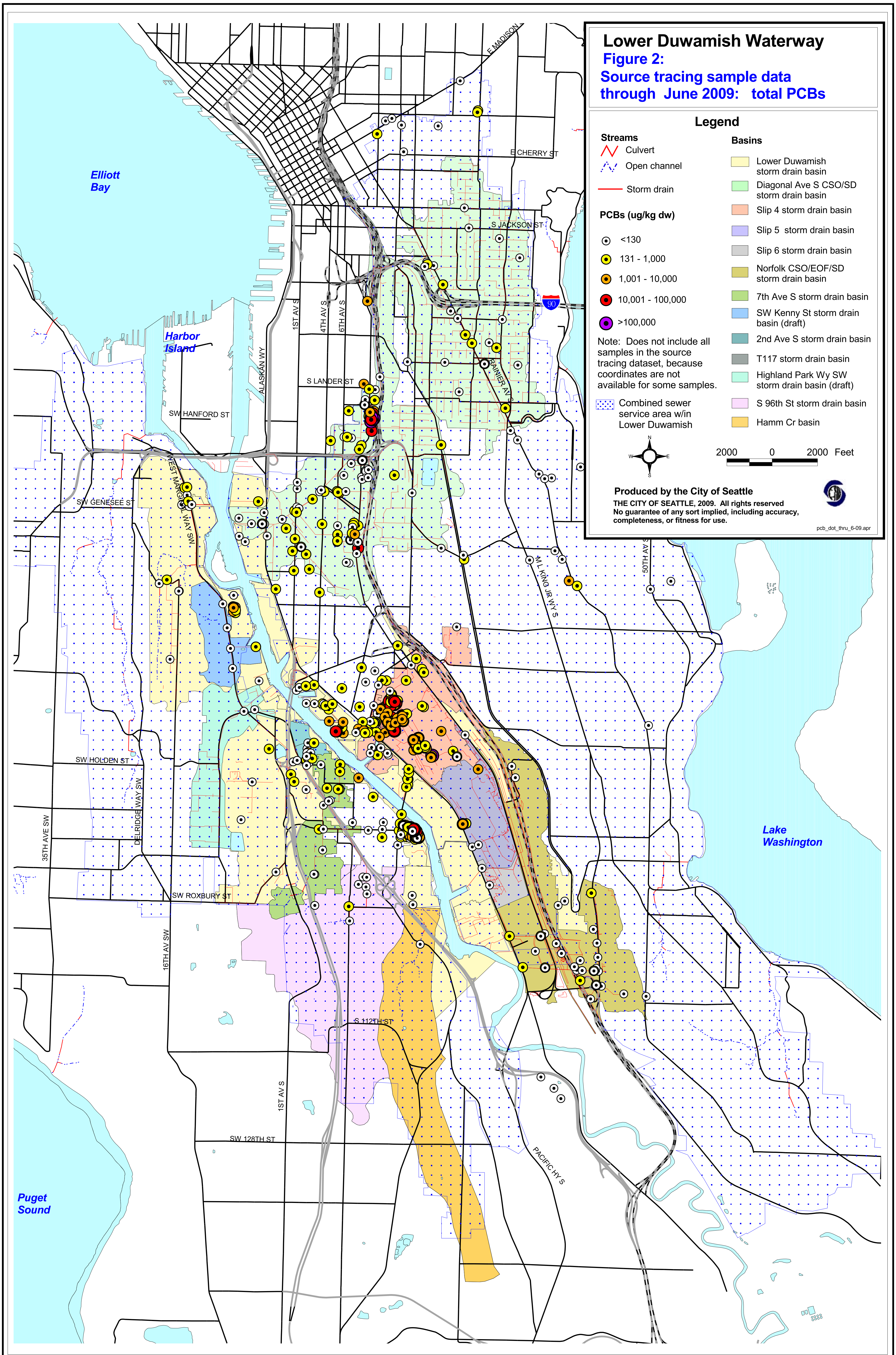
samples_all.apr
Elliott Bay
Harbor Island
Puget Sound
Lake Washington
E MADISON ST
E CHERRY ST
S JACKSON ST
1ST AV S
4TH AV S
6TH AV S
ALASKAN WY
S LANDER ST
SW HANFORD ST
S SPOKANE ST
SW GENESEE ST
WEST MARGINAL WAY SW
RAINIER AV S
BEACON AVE S
M L KING JR WY S
50TH AV S
S MICHIGAN ST
SW HOLDEN ST
S KENYON ST
DELRIDGE WAY SW
16TH AVE SW
9TH AVE SW
35TH AVE SW
S CLOVERDALE ST
SW ROXBURY ST
16TH AV SW
8TH AVE S
RENTON AVE S
S BANGOR ST
S 112TH ST
599
509
1ST AV S
SW 128TH ST
PACIFIC HY S


Lower Duwamish Waterway
Figure 2:
Source tracing sample data through June 2009: total PCBs
Legend
Streams
Culvert
Open channel
Storm drain
PCBs (ug/kg dw)
<130
131 - 1,000
1,001 - 10,000
10,001 - 100,000
>100,000
Note: Does not include all samples in the source tracing dataset, because coordinates are not available for some samples.
Combined sewer service area w/in Lower Duwamish
Basins
Lower Duwamish storm drain basin
Diagonal Ave S CSO/SD storm drain basin
Slip 4 storm drain basin
Slip 5 storm drain basin
Slip 6 storm drain basin
Norfolk CSO/EOF/SD storm drain basin
7th Ave S storm drain basin
SW Kenny St storm drain basin (draft)
2nd Ave S storm drain basin
T117 storm drain basin
Highland Park Wy SW storm drain basin (draft)
S 96th St storm drain basin
Hamm Cr basin
2000 0 2000 Feet
Produced by the City of Seattle
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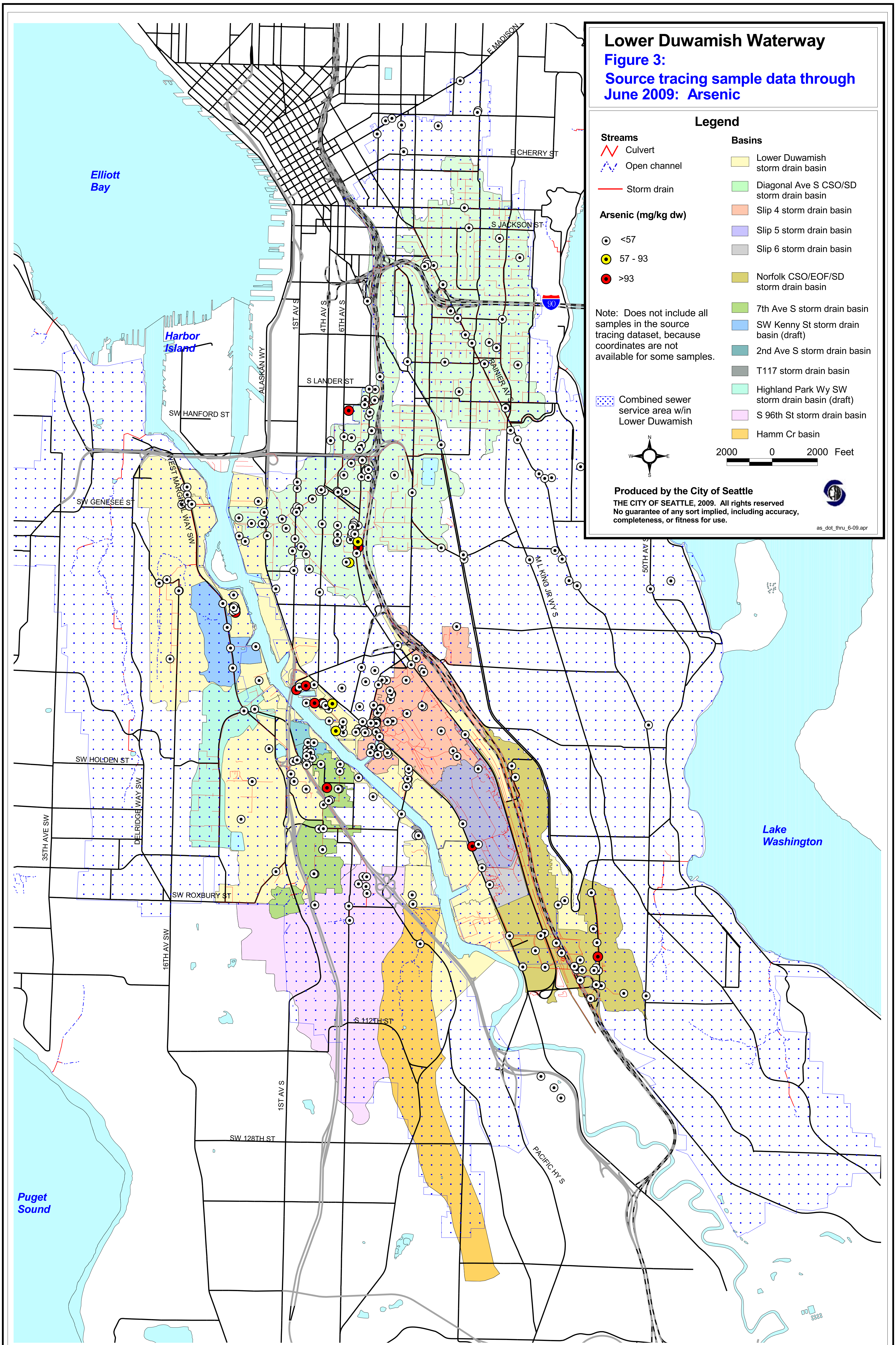
pcb_dot_thru_6-09.apr
Elliott Bay
Harbor Island
Lake Washington
Puget Sound
E MADISON
E CHERRY ST
S JACKSON ST
1ST AV S
4TH AV S
6TH AV S
ALASKAN WY
S LANDER ST
SW HANFORD ST
RAINIER AV S
WEST MARGINAL WAY SW
SW GENESEE ST
M L KING JR WY S
50TH AV S
SW HOLDEN ST
DELRIDGE WAY SW
35TH AVE SW
SW ROXBURY ST
16TH AV SW
S 112TH ST
1ST AV S
SW 128TH ST
PACIFIC HY S


Lower Duwamish Waterway
Figure 3:
Source tracing sample data through June 2009: Arsenic
Legend
Streams
Culvert
Open channel
Storm drain
Arsenic (mg/kg dw)
<57
57 - 93
>93
Note: Does not include all samples in the source tracing dataset, because coordinates are not available for some samples.
Combined sewer service area w/in Lower Duwamish
Basins
Lower Duwamish storm drain basin
Diagonal Ave S CSO/SD storm drain basin
Slip 4 storm drain basin
Slip 5 storm drain basin
Slip 6 storm drain basin
Norfolk CSO/EOF/SD storm drain basin
7th Ave S storm drain basin
SW Kenny St storm drain basin (draft)
2nd Ave S storm drain basin
T117 storm drain basin
Highland Park Wy SW storm drain basin (draft)
S 96th St storm drain basin
Hamm Cr basin
2000 0 2000 Feet
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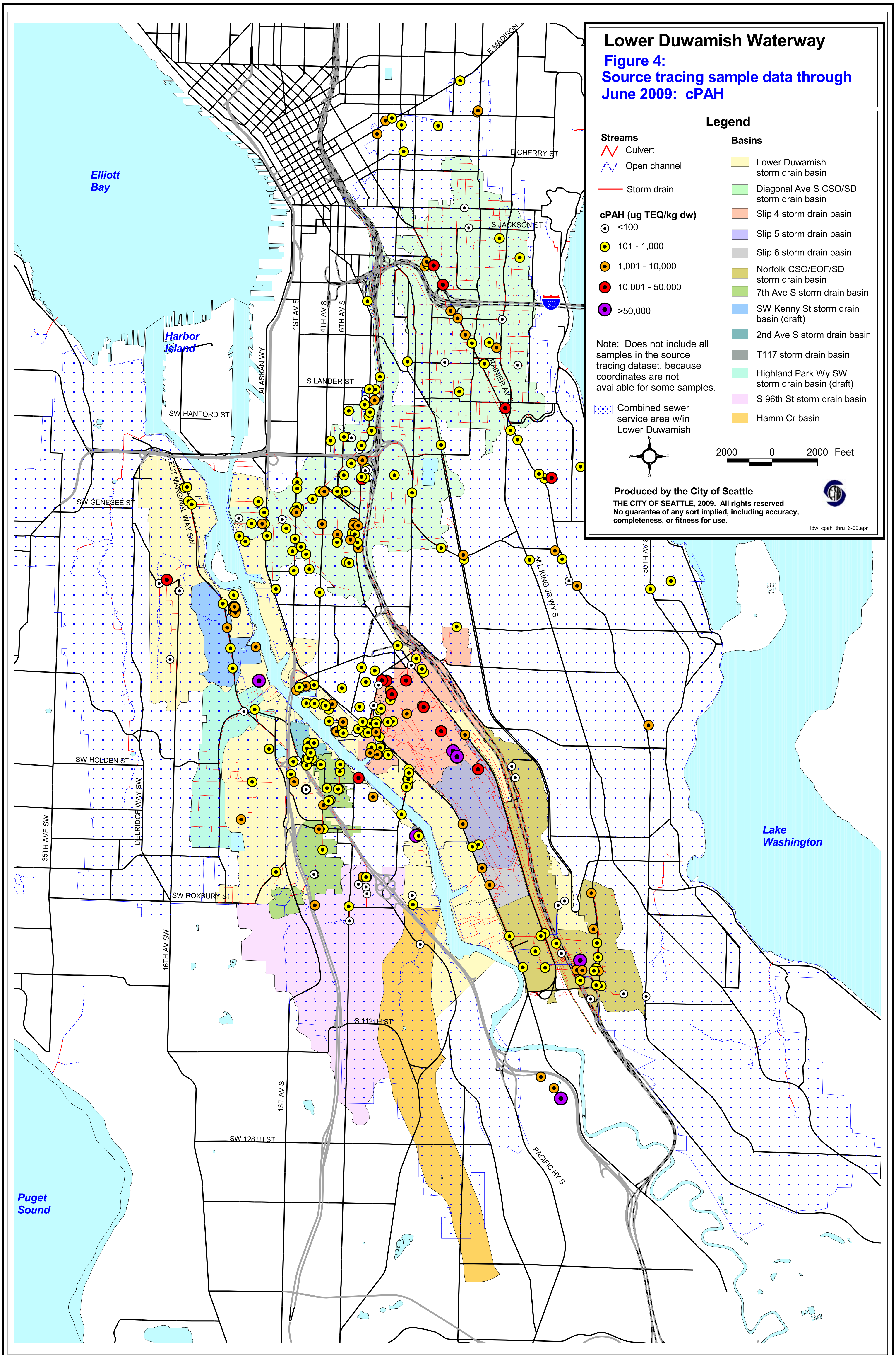
as_dot_thru_6-09.apr
Elliott Bay
Harbor Island
Lake Washington
Puget Sound
E MADISON
E CHERRY ST
S JACKSON ST
1ST AV S
4TH AV S
6TH AV S
ALASKAN WY
S LANDER ST
SW HANFORD ST
SW GENESEE ST
WEST MARGINAL WAY SW
RAINIER AV S
M L KING JR WY S
50TH AV S
SW HOLDEN ST
DELRIDGE WAY SW
35TH AVE SW
SW ROXBURY ST
16TH AV SW
S 112TH ST
1ST AV S
SW 128TH ST
PACIFIC HY S
90


Lower Duwamish Waterway
Figure 4:
Source tracing sample data through June 2009: cPAH
Legend
Streams
Culvert
Open channel
Storm drain
cPAH (ug TEQ/kg dw)
<100
101 - 1,000
1,001 - 10,000
10,001 - 50,000
>50,000
Note: Does not include all samples in the source tracing dataset, because coordinates are not available for some samples.
Combined sewer service area w/in Lower Duwamish
Basins
Lower Duwamish storm drain basin
Diagonal Ave S CSO/SD storm drain basin
Slip 4 storm drain basin
Slip 5 storm drain basin
Slip 6 storm drain basin
Norfolk CSO/EOF/SD storm drain basin
7th Ave S storm drain basin
SW Kenny St storm drain basin (draft)
2nd Ave S storm drain basin
T117 storm drain basin
Highland Park Wy SW storm drain basin (draft)
S 96th St storm drain basin
Hamm Cr basin
2000 0 2000 Feet
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ldw_cpah_thru_6-09.apr
Elliott Bay
Harbor Island
Lake Washington
Puget Sound
E MADISON
E CHERRY ST
S JACKSON ST
1ST AV S
4TH AV S
6TH AV S
ALASKAN WY
S LANDER ST
SW HANFORD ST
RAINIER AV
SW GENESEE ST
WEST MARGINAL WAY SW
M L KING JR WY S
50TH AV S
SW HOLDEN ST
DELRIDGE WAY SW
35TH AVE SW
SW ROXBURY ST
16TH AV SW
S 112TH ST
1ST AV S
SW 128TH ST
PACIFIC HY S
90

Attachment A: Summary of LDW Storm Drain Solids Data, Including the Effects of Applying Various Screening Values

	n	Detect freq	SQS/LAET Exceed[c]	CSL/2LAET Exceed[c]	25th percentile	75th percentile	10th percentile	90th percentile	Min	Max	Median	Mean
Arsenic (mg/kg dw)												
All samples combined	576	52%	5%	3%	5	20	4	30	2	1,420	10	22
Minus samples > 93	563	51%	2%	1%	5	20	4	**30**	2	87	10	**13**
Minus samples > 57	553	50%	1%	1%	5	17	4	29	2	51	**9**	12
cPAHs (µg TEQ/kg dw)[c]												
All samples combined	543	93%	NA	NA	195	1,392	82	3,960	17	492,000	520	3,230
Minus Basin Oil	542	93%	NA	NA	195	1,385	82	3,926	17	83,540	517	2,328
Minus samples >50,000	537	93%	NA	NA	194	1,273	82	3,455	17	45,990	501	1,648
Minus samples >25,000	533	93%	NA	NA	194	1,267	81	**3,366**	17	22,390	**490**	**1,370**
Minus samples >10,000	521	93%	NA	NA	191	1,206	78	2,838	17	9,965	471	1,048
Total PCBs (µg/kg dw)												
All data												
All samples combined	953	84%	67%	41%	73	6,600	10	40,120	5	10,000,000	440	42,512
LDW minus RainCom/NBF/Plant2-Jorg	522	72%	44%	10%	25	302	10	936	5	92,000	101	1,200
Rainier Commons	15	100%	100%	87%	5,500	99,000	1,160	879,600	201	2,200,000	17,500	268,673
NBF[a]	350	99%	95%	80%	1,450	26,725	390	94,400	10	1,310,000	7,000	38,786
Plant 2-Jorgensen[b]	66	95%	92%	67%	523	76,500	201	620,000	19	10,000,000	7,250	337,600
Flow-weighted average	953	84%	NA	NA	63	2,489	21	16,554	5	334,650	387	9,409
Minus samples >20,000												
All samples combined	816	81%	62%	31%	50	1,705	10	7,900	5	19,800	253	2,149
LDW minus RainCom/NBF/Plant2-Jorg	514	71%	43%	8%	25	289	10	766	5	18,300	100	486
Rainier Commons	10	100%	100%	80%	2,375	17,400	380	18,000	201	19,800	12,700	10,310
NBF[a]	249	98%	94%	72%	860	8,020	250	13,720	10	19,700	2,880	5,077
Plant 2-Jorgensen[b]	43	93%	88%	49%	293	6,000	131	9,040	19	14,200	970	3,177
Flow-weighted average	816	81%	NA	NA	46	558	17	1,186	5	18,263	171	631
Minus samples >10,000												
All samples combined	755	80%	59%	25%	47	1,021	10	4,050	5	9,300	206	1,166
LDW minus RainCom/NBF/Plant2-Jorg	512	71%	43%	8%	25	288	10	729	5	8,300	99	418
Rainier Commons	5	100%	100%	60%	400	2,600	281	6,080	201	8,400	2,300	2,780
NBF[a]	198	97%	92%	65%	580	4,297	184	7,200	10	9,300	1,735	2,785
Plant 2-Jorgensen[b]	40	95%	88%	45%	283	3,998	129	8,020	19	9,300	895	2,523
Flow-weighted average	755	80%	NA	NA	40	443	16	**1,009**	5	8,353	146	508
Minus samples >5,000												
All samples combined	692	78%	55%	18%	38	580	10	1,898	5	4,900	161	613
LDW minus RainCom/NBF/Plant2-Jorg	500	71%	42%	6%	22	264	10	602	5	3,950	94	272

Attachment A: Summary of LDW Storm Drain Solids Data, Including the Effects of Applying Various Screening Values

	n	Detect freq	SQS/LAET Exceed[c]	CSL/2LAET Exceed[c]	25th percentile	75th percentile	10th percentile	90th percentile	Min	Max	Median	Mean
Rainier Commons	4	100%	100%	50%	350	2,375	261	2,510	201	2,600	1,350	1,375
NBF[a]	156	97%	90%	56%	473	2,578	131	3,700	10	4,900	1,300	1,589
Plant 2-Jorgensen[b]	32	94%	84%	31%	236	1,428	117	3,280	19	4,800	505	1,098
Flow-weighted average	692	78%	NA	NA	35	332	15	718	5	3,992	125	**315**
Minus samples >2,000												
All samples combined	625	76%	50%	10%	30	405	10	992	5	1,980	133	321
LDW minus RainCom/NBF/Plant2-Jorg	489	70%	40%	3%	22	250	10	496	5	1,980	86	205
Rainier Commons	2	100%	100%	0%	251	350	221	380	201	400	301	301
NBF[a]	108	96%	85%	36%	273	1,313	97	1,647	10	1,900	680	796
Plant 2-Jorgensen[b]	26	92%	81%	15%	192	828	98	1,240	19	1,620	330	531
Flow-weighted average	625	76%	NA	NA	30	282	14	534	5	1,973	**102**	223
Minus samples >1,000												
All samples combined	562	73%	44%	0%	26	280	10	520	5	980	99	187
LDW minus RainCom/NBF/Plant2-Jorg	471	69%	38%	0%	20	220	10	442	5	940	79	156
Rainier Commons	2	100%	100%	0%	251	350	221	380	201	400	301	301
NBF[a]	67	97%	76%	0%	139	580	42	796	10	980	390	396
Plant 2-Jorgensen[b]	22	91%	77%	0%	148	508	84	841	19	970	293	372
Flow-weighted average	562	73%	NA	NA	25	233	12	458	5	943	89	166

BCM inputs:

Low = median concentration with concentrations above a certain screening level removed

Med = mean concentration with concentrations above a certain screening level removed

High = 90th percentile concentration with concentrations above a certain screening level removed

Includes all source samples (sediment) collected through June 2009. Includes samples collected by SPU, King County, and Boeing.

a. Catch Basin samples from North Boeing Field area (all areas downstream of the runway, Cargill 2007).

b. Plant 2-Jorgensen source control area delineated by Ecology. Catch basin and in-line samples collected from Plant 2 storm drains and from the storm drain between Plant 2 and Jorgensen Forge (Floyd Snider 2005, Cargill 2005, Flint 2005).

c. LAET and 2LAET used for total PCBs; SQS/CSL used for arsenic.

Notes:

NA = not applicable

Total PCBs = sum of the detected Aroclors

cPAH = sum of toxic equivalents calculated using toxic equivalency factors for the individual cPAHs, the concentrations of detected cPAHs, and half the detection limits for undetected cPAHs

For summary statistics, half the detection limit used for non-detects.

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AECOM

Memorandum

Date: August 5, 2010[5]

To: Lower Duwamish Waterway Group

From: AECOM

Subject: Datasets Used in the Development of Upstream BCM Model Input Parameters

The majority of solids deposited within the Lower Duwamish Waterway (LDW) originates as bed load and suspended solids transported into the LDW from the Green/Duwamish River. Therefore, the risk-driver concentrations associated with sediments and suspended solids in the Green/Duwamish River upstream of the LDW substantially influence the resulting LDW sediment concentrations and are an important determinant for the bed composition model (BCM).This memorandum presents the datasets used to estimate the risk-driver concentrations in sediment particles from upstream sources that enter and deposit within the LDW. The datasets include concentrations of total polychlorinated biphenyls (PCBs), arsenic, carcinogenic polycyclic aromatic hydrocarbons (cPAHs), and dioxins/furans associated with the upstream sources of sediments over a period of years. From these datasets, concentrations representing the potential range of upstream concentrations of each constituent were determined. These representative values are important in the evaluation of the LDW because each dataset is influenced by various sediment transport phenomena, spatially varying physical properties, and localized geographical, meteorological, and chemical loading factors; therefore, no one dataset adequately represents the actual risk-driver concentrations on sediment depositing in the LDW. Having a range of upstream values was essential in defining the upstream input parameters for the BCM described in Section 5.

Upstream Datasets

Four sources of data are presented and discussed below to characterize upstream concentrations for use as upstream input parameters to the BCM:

- Estimated risk-driver concentrations associated with suspended solids in the Green/Duwamish River inflow, based on upstream water quality monitoring data collected by King County from 2001 through 2008 (data received from King County by Windward)
- Data from centrifuged solids samples collected in the Duwamish River upstream of the LDW by the Washington State Department of Ecology (Ecology) in 2008 and 2009 (Ecology 2009)
- Upstream surface sediment data collected from 1994 through 2006 between river mile (RM) 5.0 and 7.0 by multiple parties (data from LDW Remedial Investigation), and surface sediment samples collected in 2008 between RM 4.9 and RM 6.5 by Ecology (data received from Ecology by Windward)
- U.S. Army Corps of Engineers (USACE) dredged material characterization core data collected from the upper reach of the LDW between RM 4.3 and RM 4.75 from 1990 through 2009 (USACE 2009a, 2009b).

[5] Revisions shown are for consistency with the FS; no new analysis was performed.

All of these data have been incorporated into the feasibility study (FS) project database maintained by Windward Environmental on behalf of the Lower Duwamish Waterway Group.

King County's Green/Duwamish River Whole-Water Data

King County whole-water samples were collected from two sampling locations in the Green/Duwamish River (Figure 1). These sampling locations are located approximately 1.3 miles (Duwamish River at Marginal Way; RM 6.3) and 5.9 miles (Green River at Fort Dent; RM 10.9) upstream of the LDW. These samples were collected as part of the county's routine monthly stream sampling and as part of targeted wet weather event sampling.

Table 1 summarizes the available total PCB, arsenic, and cPAH surface water data from King County, and Table 2 provides a summary of the overall data quality. Chemistry data for the whole-water samples were referenced or normalized to the total suspended solids (TSS) concentrations of the samples as an estimate of the equivalent concentration in settleable material (Table 1). In the case of arsenic, the calculation was made using the concentration of arsenic associated only with particulate matter (total minus dissolved fraction). In the case of the hydrophobic organics (total PCBs and cPAHs), the calculation used the whole-water sample concentration (filtered samples were not collected for analysis of organic compounds). This conservatively assumes that all of the organic compound mass in any given sample is adsorbed to the suspended solids.[6]

The Green/Duwamish River whole-water data collected by King County are considered to be of good quality and of sufficient quantity to enable statistical calculations. Table 2 notes aspects of this dataset that could lead to bias and the expected direction of that bias. The most noteworthy aspects of the whole-water sample data that could lead to bias are:

- The sample collection technique may not capture the full particle size distribution (especially sands, which are transported primarily in the bed load), and thus samples may contain a higher percentage of fines than the material that settles in the LDW.
- The samples are temporal "snapshots" of water quality conditions that can vary significantly in response to river flow, rainfall, and other factors.[7] In the aggregate, the water quality data can be analyzed to identify central-tendency estimates of upstream inflows.
- Changes in geochemical conditions between the aerobic freshwater riverine environment and the reduced anoxic conditions of the saline bed sediment environment can profoundly influence arsenic chemistry and partitioning (Peterson and Carpenter 1986). The particulate load of arsenic in the water column represents an upper limit on the potential arsenic loading to sediments. In the water column, arsenic is most likely present in its oxidized form (arsenate), which is strongly adsorbed by particulate iron and manganese oxides and to a lesser degree, clays. As these arsenic-bearing particles settle to the sediment-water interface and are buried over time, reducing conditions are established (below the top few centimeters of the sediment) as a result of the depletion of dissolved oxygen by the decay of organic matter. Under these anoxic conditions, further decay of organic matter is coupled to the reductive dissolution of the iron and manganese oxides and to the reduction of arsenate to arsenite through microbial metabolic processes. The reduced sorption capacity of the sediment and transformation of arsenic to a less strongly adsorbing form (arsenite) results in repartitioning of a significant part of the accumulated arsenic to the porewater, which may be released to the overlying water column.

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6 This is a conservative assumption because the fraction of the contaminant mass that is either dissolved or may be associated with colloidal particles is assumed to be included within the TSS fraction.

7 Because variability of a dataset can range naturally by differing site conditions over time during sampling, it is difficult to conduct an "outlier analysis." An apparent "outlier" may truly represent observed variability of the site during some river flow or wet weather conditions.

- Differential settling (by particle size and density) of Green/Duwamish River TSS, induced by variable hydrodynamic conditions within the LDW, may lead to systematic spatial variations in bed-sediment chemistry.

However, even with these biases, the Green/Duwamish River whole-water data collected by King County are considered to be of good quality and of sufficient quantity to enable statistical calculations for use in determining the range of upstream input parameters for the BCM.

Ecology's Green River Centrifuged Solids Data

Centrifuged solids data were collected by Ecology in late 2008 and early 2009 (Ecology 2009), at the 119th Street footbridge location near Tukwila (RM 6.7) (see Figure 1). Samples of suspended material were collected on seven occasions at this location during varying flow and rainfall conditions (see Figure 2). Sampling was conducted by pumping river water into continuous-flow centrifuges and through stainless steel sieves to collect enough mass of suspended sediment from the water column to analyze risk-driver concentrations that are associated with different size ranges of suspended sediments (particles collected in a 250 µm mesh sieve [medium-coarse sands], particles collected in a 63 µm mesh sieve [fine-medium sands], and other fine particles). Several discrete samples were collected from the water column every 3 hours (to coincide with tidal phases) over 1 to 2 full tidal cycles (24-48 hours) and then composited. Water quality parameters such as TSS, total organic carbon (TOC), and dissolved organic carbon (DOC) were analyzed, as well as PCB Aroclors, arsenic, PAHs, and dioxins/furans. These data are summarized in Table 1, and a summary of the overall data quality is provided in Table 2. Table 3 provides the risk-driver concentrations for each sample since these data were not presented in the remedial investigation (RI; Windward 2010).

The Ecology samples are generally representative of sediments suspended mid-channel in the Green River that would have entered the LDW. This is based on elements of the study design, choice of field methods, field measurements, and validated analytical results. Samples were collected:

- During a reasonable range of flow (391-4,800 cfs) and TSS conditions (5-76 mg/L), capturing some seasonal variability
- From a location in the Green River not influenced by downstream/local contaminant sources
- During full tidal cycles (24 or 48 hours) for each sampling event, tempering short-term temporal variability in suspended sediment concentrations
- From one or more depths in the water column at RM 6.7 (the pump intake depth was monitored and periodically adjusted to a target of 0.6 times the mid-channel maximum depth; depth adjustments were based on stage height, tidal phase, and the maximum water depth)
- Over time to integrate environmental variability (composite and continuous sampling).

It is noted that only seven sampling events, with only one being during a wet weather event, occurred during this study, which is considered to be insufficient to represent actual seasonal variability. In addition, some sampling events did not include any sampling during spring seasonal flows or during the rising stage of high-flow events. Thus, in these events, a portion of the load entering the LDW may have been missed. Further, samples were not truly depth-integrated, because water was pumped from a single target depth, which may underestimate the concentration on suspended sediments and not be representative of the average distribution of suspended sediment.

However, even with these biases, the Green River centrifuged solids data collected by Ecology are considered to be of good quality (although limited quantity) for use in determining the range of upstream input parameters for the BCM.

Upstream Surface Sediment Data

Sediment data have been collected by multiple parties from locations upstream of the LDW (RM 5.0 to RM 7.0) (see Figure 3); these data were collected between 1994 and 2006 and were compiled in the RI (Windward 2010). Further, Ecology collected surface sediment data upstream of the LDW (RM 4.9 to RM 6.5) in 2008 and are presented in Table 4 since these data were not presented in the RI (Windward 2010). These datasets were compiled to evaluate the quality of sediment potentially being transported into the LDW from the Green/Duwamish River. Bed sediments just upstream of the LDW can be resuspended under high-flow conditions, and then transported to, and redeposited in the LDW, thereby contributing to the chemical composition of LDW sediment. Table 5 summarizes the upstream surface sediment data included in the analysis, and Table 6 summarizes the overall quality of the data collected upstream of the LDW.

As a result of the diverse sediment transport processes in the LDW, sediments sampled in various locations tend to have differing physical properties. Table 7a summarizes the TOC content and percent fines (sum of silt and clay fractions) of the upstream sediment data (i.e., surface sediment data from RM 5.0 to RM 7.0) and surface sediment data from RM 0.0 up to RM 4.0 in the LDW.

The TOC and percent fines values for available surface sediment samples upstream of RM 5.0 were much lower than those values for surface sediments below RM 4.0. These results are consistent with the observation that suspended solids, which primarily consist of fine particles with relatively higher TOC content (compared to sand), are transported from upstream regions (above RM 5.0) throughout the LDW. The subsurface sediment data from RM 4.0 to RM 4.3 were similar in grain size and TOC to the data from surface sediment in RM 0.0 to RM 4.0 (Table 7a). In contrast, the RM 4.3 to RM 4.75 data close to the Upper Turning Basin more closely resemble the surface sediment data from upstream of RM 5.0 (sand sized particles). These results are consistent with the observation that coarser bed load fractions from upstream regions are preferentially deposited within and near the Upper Turning Basin compared to more downstream locations. Fine-grained particles will stay suspended longer and travel farther downstream than will sand-sized particles.

Table 7a shows that samples from the upstream sediment dataset, in the aggregate, contain significantly lower TOC and fines than those found in sediment within the LDW. The median TOC of the upstream dataset is less than one-half the median TOC of the entire LDW (RM 0.0 to RM 5.0) dataset (Table 7b). The importance of this difference stems from the often observed correlation between contaminant concentrations, TOC, and fines in soil and sediment (Hedges and Keil 1995), which holds true for LDW sediment. Total PCBs, arsenic, and cPAHs in LDW sediment (RM 0.0 to RM 5.0) are all positively correlated with TOC, and arsenic and cPAHs are positively correlated with percent fines (Table 8). This suggests that differential settling of particles between upstream and downstream locations of the waterway and resulting variations in the percentage of fines and TOC influence the concentrations of contaminants in deposited sediment. This observation, coupled with the previous observation that TOC and fines are lower in the upstream surface sediment dataset compared to surface sediment in the Upper Turning Basin (see Figure 4), suggests that the upstream surface sediment data may be biased low with respect to the concentrations on the upstream particles that settle in the LDW. Thus, the upstream surface sediment dataset may have a low bias and should be used in consideration with other datasets for determining upstream BCM input parameters. To account for the grain size bias, only samples with >30% fines will be considered in the statistical analysis and in setting the range of upstream input values for the BCM.

The 2008 Ecology study was conducted to provide a better characterization of the contaminants in upstream surface sediments. This study assessed the potential point sources located in these upstream areas and provides an unbiased representation of risk-driver concentrations. The dataset is a newer source compared to the 1994-2006 upstream surface sediment data collected during the RI; moreover, it has a larger number of samples (N=74) with very low reporting limits. Therefore, it is the preferred surface sediment dataset for developing upstream BCM input parameters. Table 5 summarizes the Ecology upstream surface sediment data included in the analysis, and Table 6 summarizes the overall data quality. However, as discussed above, upstream sediment datasets may also have low bias and should be used in consideration with other datasets for determining upstream input parameters for the BCM.

Core Data from the Upper Turning Basin and Navigation Channel

The entire upper reach of the LDW (RM 4.0 to RM 4.75) functions as a trap for approximately one-third of the sediment entering the waterway from the Green/Duwamish River, and the navigation channel portion of this river segment is frequently dredged to maintain adequate channel depths. RM 4.75 coincides with the upstream end of the Upper Turning Basin, which is part of the navigation channel. RM 4.0 is the approximate downstream boundary of the area the USACE dredges frequently to maintain the navigation channel.

Chemical and physical data for subsurface sediment samples collected between RM 4.0 and RM 4.75 from 1990 through 2003 were obtained from a query of the Dredged Analysis Information System [DAIS]), and the USACE provided more recent subsurface sediment data from 2008 and 2009. For the purposes of dredged sediment characterization, the USACE has been compositing sediment cores for characterization vertically (generally 0- to 4-foot [ft] intervals, but occasionally over deeper intervals, up to 10 ft), and in some cases, horizontally (compositing two or more cores collected within a dredged material management unit; DMMU).

Figures 5a and 5b show the sampling locations and associated dredging footprints for 10 dredging events conducted between 1990 and 2010. The data presented are spatially limited to the portion of the LDW between RM 4.3 and RM 4.75. Table 9 summarizes the data[8] and Table 10 describes the overall data quality, including potential bias. The most noteworthy aspect of the frequently dredged area that could lead to bias is the contribution from lateral sources.

It is noted that only data from RM 4.3 and RM 4.75 (including subsurface sediment samples collected in this area in 2008 and 2009) are used in the FS, because: 1) contaminant concentrations in this section are lower than those collected farther downstream; 2) contaminant concentrations are not likely to be influenced by lateral sources (e.g., Hamm Creek, which discharges at approximately RM 4.3; a major storm drain at the head of Slip 6, at approximately RM 4.2); 3) contaminant concentrations represent relatively recent material deposited from upstream sources, and 4) the USACE conducts routine dredging in this part of the LDW.

The navigation channel in the upper reach of the LDW collects most of the bed load and a portion of the suspended solids that enter the LDW from the Green/Duwamish River. The net sedimentation rates in this area are as high as 4 ft per year near RM 4.75. These high sedimentation rates necessitate frequent dredging of the Upper Turning Basin by the USACE (USACE 2009a). The section between RM 4.3 and RM 4.75 is dredged approximately every 2 years. Almost all of the dredged material from this area over the past 15 years was deemed suitable for open-water disposal by the Dredged Material Management Program (DMMP) agencies, with the exception of dredged sediments adjacent to and immediately south of Slip 6 that failed testing in 1995 and 1996 (USACE 2009b). Additionally, some of this dredged material has been beneficially used for capping at a number of sediment remediation projects in the area. Data from this portion of the navigation channel provides another line of evidence for characterizing the potential contribution of upstream sediment to the LDW because they represent relatively recent material deposited from upstream sources.

The vertical compositing of these cores decreases the influence of potential outliers and “averages” the incoming sediment contaminant concentrations toward a central tendency. Since cores represent a longer period of deposition, this data may also represent a longer term average of input to the LDW

8 Data results for PCB Aroclors analyzed by TestAmerica for Rounds 1 and 2 met quality assurance level 1 (QA1) data evaluation requirements but were rejected by a more rigorous independent data validation by USACE. Core data presented and used in these analyses were analyzed from archived sediment by ARI Laboratory and independently validated by EcoChem Inc. in 2009 (USACE 2009b).

than surface data. Figure 6 illustrates an example of the typical depth of the DAIS sediment cores relative to the typical dredging depths in the navigation channel associated with maintenance dredging that occurred in 2004 and 2007. This figure shows that the DAIS samples are fairly large vertical composites of material that has settled since the previous dredging event.

Even with potential bias, the data collected by USACE over a period of years is representative of material settling in the LDW. The data are considered to be of good quality and of sufficient quantity to enable statistical calculations for use in determining the range of upstream input parameters for the BCM.

Summary Statistics for the Upstream Datasets

The datasets identified above were used to establish a range of upstream BCM input parameters for total PCBs, arsenic, cPAHs, and dioxins/furans. The datasets were evaluated using methods prescribed in Ecology's *Statistical Guidance for Site Managers* (1992) and U.S. Environmental Protection Agency's (EPA) *ProUCL v.4.00.04 Technical and User's Guide* (2009). Each dataset was conditioned in accordance with procedures recommended in the guidance (e.g., goodness-of-fit, identification of outliers, handling of non-detect values) before analysis using the ProUCL software. The goodness-of-fit tested for the type of distribution (normal, lognormal, gamma, or non-parametric) of the population at 95% confidence level, based on its skewness, sample size and number of non-detects. In addition to this formal test, the informal histogram and quantile-quantile (Q-Q) plot were also conducted to visually test data distributions. Potential extreme values were also identified as statistical outliers (with the exception of the water quality data) that do not fit with the distribution of the remainder of the data. With regard to non-detect values for total PCBs, the sum of the detected concentrations of the individual PCB Aroclors or PCB congeners was used. 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. Other individual PCB Aroclors or PCB congeners may have been present at concentrations below the laboratory reporting limit, but those PCB Aroclors or PCB congeners are not included in the sums. Both cPAHs and dioxins/furans used one-half the reporting limit in the toxic equivalents (TEQs) calculations, where individual PAH compounds or dioxin/furan congeners were not detected. For arsenic in water, only total and dissolved detected value pairs were used; and in sediment, one-half the reporting limit was used for non-detect values.

A summary of these statistical analyses is provided in Tables 11 through 14 for total PCBs, arsenic, cPAHs, and dioxins/furans, respectively.

Total PCBs

Table 11 presents the total PCB summary statistics for the upstream datasets. As discussed previously, the data sources evaluated are the King County whole-water data, the Ecology centrifuged solids data, the RI and the Ecology upstream surface sediment data, and the USACE Upper Turning Basin core data (RM 4.3 and RM 4.75). In all datasets, the concentration of total PCBs represents the sum of the detected concentrations of the individual PCB Aroclors or of the detected PCB congeners.

The statistical analysis of the USACE Upper Turning Basin core data (RM 4.3 to RM 4.75) and King County whole-water data generated similar results. The mean total PCB concentrations in these two datasets were 36 and 50 µg/kg dw, and the 95% upper confidence limit on the mean (UCL) values were 42 and 82 µg/kg dw, respectively. By comparison, the upstream surface sediment samples (RM 5.0 to RM 7.0) and the Ecology centrifuged solids contained much lower mean concentrations of total PCBs
(3 to 23 µg/kg dw). 95% UCL values for these datasets ranged from 3 to 36 µg/kg dw. This disparity may be attributable to the relatively low fines content in the upstream surface sediment samples, the majority of which were less than 50%. The low fines content is consistent with the observation that this section of the river is mostly non-depositional with a sandy or "hard bottom" surface.

Figure 7 shows the concentration of total PCBs in Upper Turning Basin core samples (RM 4.3 – 4.75) as a function of time. These data suggest that following the 1990 dredging, total PCB concentrations in navigation channel sediment in the upper portion of the river remained comparatively constant and in the approximate range of 2 to 94 µg/kg dw, with a mean of 36 µg/kg dw.

Figure 8 summarizes statistics for the multiple datasets presented above. The overall weight of evidence suggests a range of 5 µg/kg dw (mean of Ecology upstream surface sediment data with fines >30%) to 107 µg/kg dw (90th percentile of King County whole-water data).

Arsenic

Table 12 presents the arsenic summary statistics, which yield mean concentrations on the order of 8 mg/kg dw and 95% UCL values on the order of 10 mg/kg dw. The range is fairly small, with a 90th percentile value of 11 mg/kg dw. The exception is the King County whole-water data, in which the mean and the 95% UCL for arsenic are 37 and 47 mg/kg dw, respectively.

The King County whole-water sample concentrations for arsenic are much higher than concentrations in either the upstream surface sediment or USACE Upper Turning Basin cores. Possible explanations for this disparity are differential particle settling and arsenic geochemistry:

- The full distribution of suspended solids in the water column includes fines that do not fully settle in the upstream areas or in the LDW. If arsenic concentrations are higher on smaller particles, the TSS-normalized water data for arsenic may be biased high relative to the comparatively coarser grain size distribution of sediments that actually deposit in the LDW.
- Equilibrium arsenic concentrations in sediment are sensitive to reduction/oxidation (redox), pH, and sediment mineralogy. Therefore, TSS-associated arsenic may not be conserved between the two environments (i.e., water column and settled sediment), an otherwise reasonable assumption when applied to persistent hydrophobic organic compounds.

Therefore, these King County data were not used as a line of evidence for developing the upstream BCM input parameter for arsenic.

Figure 9 shows the concentration of arsenic in the USACE Upper Turning Basin core samples as a function of time relative to the USACE dredging events. The data from RM 4.3 to RM 4.75 are consistent and range between approximately 3 and 13 mg/kg dw, with a mean of 7 mg/kg dw; a steady trend is observed with time (last 20 years).

Figure 10 summarizes statistics for the multiple datasets presented above. If the King County whole-water dataset is discounted as unrepresentative of settled sediment conditions for reasons discussed above, then the overall weight of evidence suggests a range of 7 mg/kg dw (mean of RI surface sediment data) to 24 mg/kg dw (90th percentile of Ecology centrifuged solids data).

cPAHs

Table 13 presents the cPAH summary statistics. For cPAHs, TEQs were calculated using one-half the reporting limit in cases where individual cPAH compounds were not detected. The King County whole-water data and the Ecology centrifuged solids data have similar mean concentrations (138 and 151 µg TEQ/kg dw). Much lower cPAH concentrations are observed in upstream surface sediment and USACE core datasets. Again, the low percentage of fines and TOC in the upstream surface sediment samples suggests that those samples may under-represent concentrations for chemicals typically associated with finer particle size solids.

Figure 11 shows the concentration of cPAHs in USACE core samples as a function of time relative to the USACE dredging events. The data are variable and do not suggest a temporal trend.

Figure 12 summarizes statistics for the multiple datasets presented above. Considering both the King County whole-water data and the Ecology centrifuged solids data, the overall weight of evidence suggests a range of 37 µg TEQ/kg dw (mean of Ecology upstream surface sediment data with fines >30%) to 432 µg TEQ/kg dw (95% UCL of Ecology centrifuged solids data[9]).

Dioxins / Furans

The analysis for dioxins/furans differs from the analysis for total PCBs, arsenic, and cPAHs, primarily because of the limited data available. For example, the USACE cores between RM 4.3 and RM 4.75 contain only two samples analyzed for dioxins/furans and King County did not analyze water samples for dioxins/furans. Therefore, the statistical analysis makes use of the Ecology centrifuged solids and surface sediment datasets, and the RI surface sediment data collected upstream of the LDW. For dioxins/furans, toxic equivalents (TEQs) were calculated using one-half the reporting limit in cases where individual dioxin/furan congeners were not detected.

Table 14 identifies the dioxin/furan datasets and provides statistics used in developing the upstream BCM input parameters. The population of each dataset is low (less than 6), except for the 2008 Ecology surface sediment dataset (N=74). The mean concentrations of the three datasets ranged between 1 and 6 ng TEQ/kg dw, and the 95% UCL values ranged between 2 and 10 ng TEQ/kg dw.

Figure 13 summarizes statistics for the multiple datasets presented above. Considering all of the data, the overall weight of evidence suggests a range of 2 ng TEQ/kg dw (mean of Ecology upstream surface sediment data with fines >30%) to 13 µg TEQ/kg dw (90^{th} percentile of Ecology centrifuged solids data).[10]

Conceptual Site Model and Support for Use of Upstream Datasets

The use of data collected from the upper reach of the LDW is supported by the conceptual site model (CSM). Approximately 99% of the total sediment load to the LDW from external sources comes from the Green/ Duwamish River upstream of the LDW, and over 24% of the total sediment load (as both bed load and suspended solids) entering the LDW settles in the Upper Turning Basin (RM 4.5 to RM 4.75) (QEA 2008).

The remainder of the total sediment load entering the STM study area (76%) is suspended material. This material generally consists of finer fractions (i.e., clay, silt, and fine sand) with lower settling velocities compared to bed load sand, and therefore, is generally transported greater distances in the LDW. Approximately 50% of this material is the very fine fraction that does not settle in the LDW (QEA 2008), The finer fractions may have higher contaminant concentrations than the coarser bed load sand (i.e., medium and coarse sand) because of the affinity of chemicals (such as hydrophobic PCBs, cPAHs, and dioxins/ furans) to sorb to these finer sediments, which have high surface area-to-volume ratios and TOC (Hedges and Keil 1995). Potential differences in contaminant concentrations between larger-size-fraction bed load and smaller-size-fraction suspended materials may also be mirrored by differences in contaminant concentrations among the various size fractions of the suspended materials themselves. Much of the finest particulate matter from upstream may be carried through the LDW without depositing, and contaminant concentrations in the depositing sediments may increase as particle size decreases.

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9 The 95% UCL of the Ecology centrifuged solids data overestimates cPAH current concentrations in the LDW, and therefore, it does not represent average upstream conditions. Only upstream surface sediment with >30% fines is considered.

10 The 95% UCL and 90^{th} percentile of the Ecology centrifuged solids data overestimate dioxin/furan current concentrations in the LDW, and therefore, they do not represent average upstream conditions. Only upstream surface sediment with >30% fines is considered.

The use of the datasets described previously is consistent with the CSM for the LDW and the STM findings that most of the sediment in the LDW is derived from upstream sources.

Attachments

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Table 1 Summary of King County Whole-Water Samples and Ecology Centrifuged Solids Samples

Sample Type	Number of Samples (number of detections)	Sample Period	Total Water Concentration	Dissolved Concentration (µg/L)	Particulate Value (µg/L)	TSS (mg/L)	Total Value Normalized to TSS or Centrifuged Particulate Value	Data Source
Total PCBs								
King County Whole-Water Samples[a]	22 (22)	2005 – 2008	24 – 2,400 (pg/L)	n/a	n/a	1.3 – 77.8	2.8 – 162 (µg/kg dw)	Data provided by King County 2008, 2009
Ecology Centrifuged Solids Samples[b]	7 (4)	2008, 2009	n/a	n/a	n/a	6.1 – 55.6	1.2U – 64 (µg/kg dw)	Data from Ecology EIM query 2009 (Ecology 2009)
Arsenic								
King County Whole-Water Samples[a]	100 (100)[c]	2001 – 2008	0.83 – 4.16 (µg/L)	0.44 – 0.84	0.01 – 3.91	1 – 312	0.5 – 133 (mg/kg dw)	Data from King County LIMS query 2007
Ecology Centrifuged Solids Samples[b]	7 (7)	2008, 2009	n/a	n/a	n/a	6.1 – 55.6	9.2 – 24 (mg/kg dw)	Data from Ecology EIM query 2009 (Ecology 2009)
cPAHs								
King County Whole-Water Samples[a]	18 (13)	2008	0.5U – 4.0 (ng TEQ/L)	n/a	n/a	1.4 – 22	22U – 408 (µg TEQ/kg dw)	Data provided by King County 2008, 2009
Ecology Centrifuged Solids Samples[b]	7 (7)	2008, 2009	n/a	n/a	n/a	6.1 – 55.6	14.9 – 621 (µg TEQ/kg dw)	Data from Ecology EIM query 2009 (Ecology 2009)
Dioxins/Furans[d]								
Ecology Centrifuged Solids Samples[b]	6 (6)	2008, 2009	n/a	n/a	n/a	6.1 – 55.6	0.83 – 16 (ng TEQ/kg dw)	Data from Ecology EIM query 2009 (Ecology 2009)

Note:

a. Surface water samples were collected at Ft. Dent (RM 10.9) on the Green River and at Marginal Way (RM 6.3) on the Duwamish River (see Figure 1).

b. Suspended solids samples were collected at the Tukwila footbridge (RM 6.7) on the Green River (see Figure 1).

c. Number of detected samples based on total arsenic data used to calculate TSS-normalized particulate arsenic. Total arsenic method reporting limit is 0.5 µg/L.

d. Surface water samples collected by King County were not analyzed for dioxins/furans.

dw = dry weight; EIM = Environmental Information Management; kg = kilograms; L = liter; LIMS = Laboratory Information Management System; µg = micrograms; mg = milligrams; n/a = not available; ng = nanogram; pg = picogram; TEQ = toxic equivalent; TSS = total suspended solids; U = undetected at the reporting limit shown

Table 2 Data Quality Summary for King County Whole-Water Samples and Ecology Centrifuged Solids Samples

Risk Driver (Sample Period)	Number of Samples	Data Selection	Overall Strengths of Line of Evidence	Data Quality Considerations for Developing BCM Parameters of Upstream Sediment Settling in the LDW					
				Level of Data Validation	Precision	Representativeness	Accuracy/Potential Bias Effects	Completeness	Comparability
King County Whole-Water Data									
Total PCBs (2005, 2008)	22	All available low-level whole-water data used (there are no dissolved data). Sample count is averaged to the station; count would be 28 if field replicates are considered.	Data are recent and of high quality. Data characterize contaminant concentrations on suspended solids that flow into the LDW. Sampling covers a range of flow conditions.	2008 PCB data validated by LDC. 2005 PCB data validated by King County.	Acceptable	Samples collected may exclude sands in bed load and thus contain a higher percentage of fines than material that settles in the LDW.	High bias	Acceptable. Sample numbers allow statistical interpretation.	Water samples have inherent representativeness limitations for comparison to sediment data. Water samples generally have greater temporal variability in concentrations than sediment samples. A large dataset reduces this effect.
						Ft. Dent station may exclude some anthropogenic inputs farther downstream.	Low bias		
						TSS normalization of whole-water sample assumes dissolved and colloidal fractions of contaminant are present on the settling solids	High or Low bias		
Arsenic (2001 - 2008)	100	Only samples with corresponding total arsenic, dissolved arsenic, and TSS used. Samples where total arsenic concentration was less than dissolved arsenic were not used.	Data are numerous, recent and of high quality. Data characterize contaminant concentrations on suspended solids that flow into the LDW. Sampling covers a range of flow conditions.	Data validated by Herrera for King County.		Samples collected may exclude sands in bed load and thus contain a higher percentage of fines than material that settles in the LDW.	High bias		
						Ft. Dent station may exclude some anthropogenic inputs farther downstream.	Low bias		
						TSS normalization of arsenic assumes all particulate arsenic associated with solids and expected to settle in LDW, TSS normalization does not account for geochemical properties of arsenic in LDW.	High bias		
cPAHs (2008)	18	All available low-level whole-water data used (there are no dissolved data). Sample count includes field replicates.	Data are recent and of high quality. Data characterize contaminant concentrations on suspended solids that flow into the LDW. Sampling covers a range of flow conditions.	Data validated by King County.		Samples collected may exclude sands in bed load and thus contain a higher percentage of fines than material that settles in the LDW.	High bias		
						Ft. Dent station may exclude some anthropogenic inputs farther downstream.	Low bias		
						TSS normalization of whole-water samples assumes dissolved and colloidal fractions of contaminant are present on the settling solids.	High or Low bias		
Ecology Centrifuged Solids Data									
Total PCBs (2008, 2009)	7	All available centrifuged solids data used. Sample count is low.	Data are recent and of high quality. Data characterize contaminant concentrations on suspended solids that flow into the LDW. Sampling covers a range of flow conditions.	Data validated by EPA.	Acceptable	Samples are representative of sediments suspended mid-channel in the Green River that would have entered the LDW.	High bias	Sample counts are low for statistical analysis and interpretation.	The analytical method used to measure TSS may underestimate true concentrations of suspended solids. This happened for samples containing appreciable sand-sized particles. Centrifuged samples may be representative but limited for comparison to sediment data.
Arsenic (2008, 2009)	7					Short-term temporal variability was captured by centrifuging suspended sediment throughout full tidal cycles.			
cPAHs (2008, 2009)	7								
Dioxins / Furans (2008, 2009)	6					Some variability was captured by the seven sampling events covering a range of flow conditions (spring seasonal flows were not included and only one wet weather event was included).			

Notes:

No surface water data available from King County for dioxins/furans.

BCM = Bed Composition Model; cPAH = carcinogenic polycyclic aromatic hydrocarbons; dw = dry weight; Ecology = Washington State Department of Ecology; EPA = U.S. Environmental Protection Agency; kg = kilograms; L = liter; LDC = Laboratory Data Consultants; LDW = Lower Duwamish Waterway; LIMS = laboratory information management system; µg = micrograms; mg = milligrams; n/a = not available; ng = nanogram; PCBs = polychlorinated biphenyls; pg = picogram; TEQ = toxic equivalent; TSS = total suspended solids; U = undetected at the reporting limit shown

Table 3 Human Health Risk Driver Concentrations from Ecology Centrifuged Solids

Sample Date	Total PCBs (µg/kg dw)	Arsenic (mg/kg dw)	cPAHs (µg TEQ/kg dw)	Dioxin/furan (ng TEQ/kg dw)
7/15/2008	7.5	13.5	58.44	NA
8/25/2008	63.5	22.4	620.55	16.2
9/29/2008	10.8	24.3	40.85	8.35
10/15/2008	15.8	23.6	158.45	4.97
11/17/2008	2.5 U	9.2	14.87	1.51
12/15/2008	2.7 U	14	53.31	1.38
1/20/2009	1.2 U	9.39	17.55	0.83

Notes:

1. Significant figures for the data are shown as reported in *Contaminant Loading to the Lower Duwamish Waterway from Suspended Sediment in the Green River* (Ecology 2009).

cPAH = carcinogenic polycyclic aromatic hydrocarbons; dw = dry weight; Ecology = Washington State Department of Ecology; kg = kilograms; µg = micrograms; mg = milligrams; ng = nanograms; NA = not analyzed; PCBs = polychlorinated biphenyls; TEQ = toxic equivalent; U = undetected at the reporting limit shown.

Table 4 Human Health Risk Driver Concentrations from Ecology Upstream Surface Sediment Event

Sample Date	Location ID	Sample ID	Total PCBs (µg/kg dw)	Arsenic (mg/kg dw)	cPAHs (µg TEQ/kg dw)	Dioxins/furans (ng TEQ/kg dw)
4/28/2008	DR-01	DR-01-VV-11	3.6	6.1	16	0.287
4/28/2008	DR-02	DR-02VV12	7.2 U	5.3	0.84 U	0.107 U
4/28/2008	DR-03	DR-03VV15	3.4	5.1	2	0.109 U
4/28/2008	DR-04	DR-04VV15	2.9	4.9	0.88	0.108 U
4/28/2008	DR-05	DR-05VV15	2.6	8.6	2.1	0.132 U
4/28/2008	DR-06	DR-06VV16	3	4.7	0.76 U	0.091 U
4/28/2008	DR-07	DR-07VV15	2.3	5.6	9.7	0.095 U
4/28/2008	DR-08	DR-08VV16	2.6	4.5	0.82	0.084
4/28/2008	DR-09	DR-09VV15	2.7	4.8	0.84 U	0.135
4/28/2008	DR-10	DR-10VV16	2.5	5.7	0.8	0.1569
4/28/2008	DR-11	DR-11VV13	7.7 U	4.7	2.1	0.114
4/28/2008	DR-12	DR-12VV14	2.7	3.7	2.1	0.262
4/29/2008	DR-14	DR-14VV16	6.7 U	4.5	5.6	0.137
4/29/2008	DR-15	DR-15VV15	7 U	4.5	0.76 U	0.102
4/29/2008	DR-16	DR-16VV15	3.5	5.4	2.1	0.088 U
4/29/2008	DR-17	DR-17VV16	3.1	4.4	1.7	0.144
4/29/2008	DR-18	DR-18VV14	6.7 U	5.2	0.77 U	0.087 U
4/30/2008	DR-19	DR-19VV15	6.8 U	5.4	0.76 U	0.232
4/30/2008	DR-20	DR-20VV15	5.9 U	5.4	0.75	0.237 U

Table 4 Human Health Risk Driver Concentrations from Ecology Upstream Surface Sediment Event (continued)

Sample Date	Location ID	Sample ID	Total PCBs (µg/kg dw)	Arsenic (mg/kg dw)	cPAHs (µg TEQ/kg dw)	Dioxins/furans (ng TEQ/kg dw)
4/30/2008	DR-21	DR-21VV15	7.2 U	4.5	29	0.126
4/30/2008	DR-22	DR-22VV14	7.1 U	4.9	3.3	0.518
4/30/2008	DR-23	DR-23VV14	7.1 U	5.6	0.82 U	0.384
4/30/2008	DR-24	DR-24VV15	6.7 U	4.8	0.76 U	0.137
4/30/2008	DR-25	DR-25VV15	6.4 U	5.8	0.76 U	0.129 U
4/29/2008	DR-26	DR-26VV15	5.9 U	4	0.74	0.188 U
4/29/2008	DR-27	DR-27VV17	6.3 U	4.6	0.71 U	0.073 U
4/29/2008	DR-28	DR-28VV15	3	4.2	0.7 U	0.094 U
4/29/2008	DR-36	DR-36VV15	6.1 U	4.2	0.78	0.112
5/8/2008	DRB-100W	DRB-100W	8.4	7.3	55	1.58
5/8/2008	DRB-101	DRB-101W	2	5.3	18	0.870
5/8/2008	DRB-103	DRB-103E	1.2	7.6	17	1.240
5/8/2008	DRB-104	DRB-104W	0.99	7.8	8.4	1.070
5/9/2008	DRB-105	DRB-105	1	7.7	6.2	0.850
5/9/2008	DRB-106	DRB-106W	1.5	9.1	9.1	0.950
5/9/2008	DRB-107	DRB-107W	0.73	4.5	6.2	0.341
5/9/2008	DRB-108	DRB-108W	10 U	8.3	48	1.45
5/9/2008	DRB-108	DRB-50W	20 U	7.9	54	1.46
5/9/2008	DRB-109	DRB-109W	10 U	8.4	40	1.84
5/9/2008	DRB-110	DRB-110E	1.6	6.8	10.6	0.790

Table 4 Human Health Risk Driver Concentrations from Ecology Upstream Surface Sediment Event (continued)

Sample Date	Location ID	Sample ID	Total PCBs (µg/kg dw)	Arsenic (mg/kg dw)	cPAHs (µg TEQ/kg dw)	Dioxins/furans (ng TEQ/kg dw)
5/9/2008	DRB-111	DRB-111E	22 U	9.4	54	1.44
5/9/2008	DRB-112	DRB-112W	1.9	10	13.8	1.24
5/9/2008	DRB-113	DRB-113W	2.7 U	9.5	70	1.78
5/9/2008	DRB-114	DRB-114W	11 U	9.7	90	2.25
5/9/2008	DRB-115	DRB-115W	2.1	6.8	16	1.09
5/9/2008	DRB-116	DRB-116W	1.7	6.9	10.9	1.00
5/9/2008	DRB-117	DRB-117W	0.86	5.5	10	1.32
5/1/2008	NFK501	NFK-501VV16	7	15	230	2.21
4/30/2008	NFK502	NFK502VV12	7.2 U	6	40	0.339
5/1/2008	OF-28	OF-28HS10	2.4	9.2	9.9	3.00
5/1/2008	OF-33	OF-33VV10	7.1 U	4.3	0.83 U	0.111 U
5/1/2008	OF-36	OF-36VV13	7 U	4.6	12	0.119
5/1/2008	OF-41	OF-41VV16	7.2 U	4.9	0.82 U	0.072 U
5/1/2008	OR-01	OR-01VV16	2.2	9.4	23	2.50
5/2/2008	OR-02	OR-02VV9	1.9	8.3	9.9	1.55
5/5/2008	OR-04	OR-04VV09	6.3 U	6.5	0.97	0.146 U
5/5/2008	OR-05	OR-05VV10	6.3 U	5.9	0.88	0.161 U
5/5/2008	OR-06	OR-06VV13	6.5 U	9.1	1	0.155 U
5/5/2008	OR-07	OR-07VV13	5.8 U	5	0.71	0.530

Table 4 Human Health Risk Driver Concentrations from Ecology Upstream Surface Sediment Event (continued)

Sample Date	Location ID	Sample ID	Total PCBs (µg/kg dw)	Arsenic (mg/kg dw)	cPAHs (µg TEQ/kg dw)	Dioxins/furans (ng TEQ/kg dw)
5/5/2008	OR-08	OR-08VV14	6.1 U	4.7	0.74	0.082 U
5/5/2008	OR-09	OR-09VV14	6.3 U	4.2	0.71 U	0.104 U
5/5/2008	OR-10	OR-10VV14	12	9.2	43	1.59
5/5/2008	OR-11	OR-11VV12	17 U	6.3	29	0.611
5/5/2008	OR-12	OR-12VV05	6.9 U	4.9	0.87	0.180
5/5/2008	OS-03	OS-03VV08	7.2 U	5.1	9.9	0.155
5/2/2008	OS-05	OS-05VV16	3.2	13	16	3.34
5/2/2008	OS-06	OS-06HS10	770	11	92	8.40
5/5/2008	OS-10	OS-10HS10	20 U	7.7	77	1.42
5/6/2008	OS-14	OS-14HS10	2.6	8.6	18	1.27
5/6/2008	OS-15	OS-15HS10	4.6	9	13	2.10
5/6/2008	OS-18	OS-18HS10	2	10	55	1.35
5/6/2008	OS-21	OS-21HS10	1.5	9.4	16.1	1.93
5/6/2008	OS-22	OS-22HS10	2.8	8.9	16	1.57
5/6/2008	OS-23	OS-23HS10	1.1	9.2	11.4	1.59
5/6/2008	OS-24a	OS-24AHS10	1.4	16	9.8	3.00

Notes:
1. Significant figures for the data are shown as reported by the Washington State Department of Ecology to Windward.

cPAH = carcinogenic polycyclic aromatic hydrocarbons; dw = dry weight; Ecology = Washington State Department of Ecology; ID = identification number; kg = kilograms; µg = micrograms; mg = milligrams; ng = nanograms; PCBs = polychlorinated biphenyls; TEQ = toxic equivalent; U = undetected at the reporting limit shown

Table 5 Surface Sediment Sampling Events Conducted Upstream of the Lower Duwamish Waterway (RI Data)

Sampling Event (Event Code)	Sampling Year	River Mile	Number of Samples (Number of Detections)				Range of Concentrations			
			Total PCBs	Arsenic	cPAHs	Dioxins/ Furans	Total PCBs (µg/kg dw)	Arsenic (mg/kg dw)	cPAHs (µg TEQ/kg dw)	Dioxin/Furans (ng TEQ/kg dw)
LDW Upstream Surface Sediment Samples During RI										
LDW RI: surface sediment sampling for chemical analyses and toxicity testing (LDW RI – Surface Sediment Round 2)	2005	5.1 – 5.8	6 (0)	6 (6)	6 (4)	0	19 U – 20 U	3.3 – 7.3	9 U – 56	—
LDW RI: surface sediment sampling for chemical analyses and toxicity testing (LDW RI – Surface Sediment Background)	2005	5.3 (PCBs) 6.1 – 7.0 (arsenic) 5.3 and 10.2 [a] (dioxins/furans)	1 (0)	8 (8)	0	2 (2)	20 U	4.6 – 10.9	—	1.7 – 2.9
EPA Site Inspection: Lower Duwamish River (EPA SI)	1998	5.3 – 5.5	5 (0)	5 (5)	5 (0)	2 (2)	40 U	4.0 – 5.1	18 U	1.1 – 1.2
Duwamish Waterway Phase 1 site characterization (Boeing Site Char; upstream reference samples)	1997	6.1	3 (0)	3 (3)	3 (2)	0	38 U – 40 U	4.5 – 7.2	17 U – 260	—
Duwamish Waterway sediment characterization study (NOAA Site Char)	1997	5.2 – 6.0	20 (18)	0	0	0	0.6 U – 140	—	—	—
Norfolk CSO sediment cleanup study – Phase 1 (Norfolk cleanup 1)	1994	5.4 – 5.5	2 (0)	2(2)	2 (1)	0	15 U – 26 U	11 – 22	18 U – 64	—
Total No. of Samples Used in Statistics			**37 (18)**	**24 (24)**	**16 (7)**	**4 (4)**	**0.6 U – 140**	**3.3 – 22**	**9 U – 260**	**1.1 – 2.9**
Other Upstream Surface Sediment Samples										
Ecology Study	2008	4.9 – 6.5	73[b] (38)	74 (74)	74 (60)	74 (54)	2.7 U – 22	3.7 - 16	0.7U - 230	0.07U - 8.4

Notes:

a. This sample was collected in Springbrook Creek, which enters the Green/Duwamish River at approximately RM 10.2.

b. Outlier of 770 µg/kg dw for total PCBs was excluded from the dataset statistics, because it appeared to be related to an outfall.

cPAH = carcinogenic polycyclic aromatic hydrocarbons; CSO = combined sewer overflow; Ecology = Washington State Department of Ecology; EPA = U.S. Environmental Protection Agency; LDW = Lower Duwamish Waterway; µg = micrograms; mg = milligrams; NOAA = National Oceanic and Atmospheric Administration; ng = nanograms; PCBs = polychlorinated biphenyls; RI = remedial investigation; SI = site investigation; TEQ = toxic equivalent; U = undetected at the reporting limit shown

Table 6 Data Quality Summary for Upstream Surface Sediment Data (RM 5 to RM 7) Collected During the RI

Study Event[a]	Risk Driver	Number of Samples	Data Selection	Overall Strength of Line of Evidence	Data Quality Considerations for Developing BCM Parameters of Upstream Sediment Settling in the LDW					
					Level of Data Validation	Precision	Representativeness	Accuracy / Potential Bias Effects	Completeness	Comparability
Multiple (1994-2006)	Total PCBs	37 / 20	37 samples considered.[a] Data evaluated in two ways: all data and only detected data. In the latter, only 20 samples from NOAA 1997 event (non-standard method[b]) were evaluated because all other events did not yield detectable concentrations.	Data characterize contaminant concentrations of surface sediments immediately upstream of the LDW.	Data quality reviewed for inclusion in RI database. Only acceptable data included in database.	Acceptable	Upstream samples are more coarse-grained and contain lower TOC than LDW sediments. Some datasets are over 10 years old and have small numbers of samples	PCBs: High bias with N=37 (many values based on reporting limits). Low bias with N=20 (NOAA values may be underestimated). [a]	Acceptable: Numbers allow for statistical interpretation.	Upstream surface sediment generally not directly comparable to LDW surface sediment because of different grain size distributions and TOC contents. The finer fractions settling in the LDW are under-represented in upstream surface sediment samples.
	Arsenic	24	All available data used.					As: Low bias	Acceptable: Numbers allow for statistical interpretation	
	cPAHs	16	All available data used.					cPAHs: Low bias	Less than 20 samples. Most based on undetected data.	
	Dioxins/Furans	4	All available data used.					D/F: Low bias	Only 4 samples	
Ecology (2008)	Total PCBs	74/73	73 samples considered (one outlier was excluded because it appeared to be related to an outfall).	Data characterize contaminant concentrations of surface sediments immediately upstream of the LDW.	Data quality reviewed and acceptable.	Acceptable	Data more representative because they are more recent, with larger datasets and lower reporting limits.	Low bias, most data were detected.	Acceptable: Numbers allow for statistical interpretation.	Upstream surface sediment generally not directly comparable to LDW surface sediment because of different grain size distributions and TOC contents. The finer fractions settling in the LDW are under-represented in upstream surface sediment samples.
	Arsenic	74	All available data used.							
	cPAHs	74	All available data used.							
	Dioxins/Furans	74	All available data used.							

Notes:

a. Ecology data from 2008 were the only data used in the BCM input parameter selection, because they are from a newer, larger dataset, with low reporting limits.

b. A non-standard PCB method was used for the NOAA event. Total PCBs were quantified as the difference between total polychlorinated terphenyls (PCTs) (using GC/ECD) and PCBs+PCTs (using HPLC/PDA). Data results from 100 to 600 µg/kg dw are not biased. Data below 100 µg/kg dw are JL qualified because they may have a large potential negative bias (i.e., total PCB concentrations may be underestimated).

BCM = bed composition model; cPAH = carcinogenic polycyclic aromatic hydrocarbons; CSO = combined sewer overflow; EPA = U.S. Environmental Protection Agency; LDW = Lower Duwamish Waterway; NOAA = National Oceanic and Atmospheric Administration; PCBs = polychlorinated biphenyls; RI = remedial investigation; SI = site investigation; TEQ = toxic equivalent; TOC = total organic carbon; U = undetected at the reporting limit shown

Table 7a Summary of Total Organic Carbon (TOC) and Percent Fines Data for Upstream Surface Sediment Datasets Compared to LDW Surface and Subsurface Sediment from RM 0.0 to RM 4.0

Statistical Parameter	LDW Surface Sediment (RM 0.0 to RM 4.0)	LDW Subsurface Sediment (RM 4.0 to RM 4.3)	LDW Subsurface Sediment (RM 4.3 to RM 4.75)	Upstream Surface Sediment (RM 5.0 to RM 7.0)
Total Organic Carbon (%)				
Minimum	0.1	0.6	0.03	0.07
10th percentile	0.9	1.4	0.4	0.08
Mean	2.0	1.9	1.3	0.8
90th percentile	2.9	2.6	2.7	1.9
Maximum	12	2.8	3.1	2.3
Percent Fines				
Minimum	1.6	23	2.6	0.01
10th percentile	14	49	6.0	0.01
Mean	53	58	17	24
90th percentile	86	69	34	57
Maximum	100	78	37	65

Table 7b Percent Fines and TOC Property Differences of LDW and Upstream (RM 5.0 to RM 7.0) Surface Sediment

Parameter	LDW Surface Sediment (RM 0.0 to RM 5.0)		Upstream Surface Sediment (RM 5.0 to RM 7.0)		Result of Mann-Whitney 2-tailed test	
	Number of Samples	Median	Number of Samples	Median	p value	Are the Datasets Statistically Different?
TOC (% dw)	1,146	1.8	37	0.7	0.000	Yes
Fines (% dw)	1,085	57.4	44	37.8	0.000	Yes

Notes:
ProUCL v.4.0 determined all data distributions to be non-parametric, and was used to identify outliers.
Mann-Whitney, the non-parametric equivalent of the t-test, was used on the untransformed data.

dw = dry weight; fines = sum of silt and clay grain-size fractions; LDW = Lower Duwamish Waterway; RM = river mile; TOC = total organic carbon

Table 8 Correlation of Lower Duwamish Waterway (RM 0 – 5) Surface Sediment Chemistry to TOC and Fines

Parameter	Metric	TOC (%)	Fines (%)
Total PCBs	Correlation Coefficient	**0.397***	0.218*
	Significance (2-tailed)	**0.000**	0.000
	N	**833**	823
Arsenic	Correlation Coefficient	**0.526***	**0.505***
	Significance (2-tailed)	**0.000**	**0.000**
	N	**546**	**549**
cPAHs	Correlation Coefficient	**0.433**	**0.382***
	Significance (2-tailed)	**0.000**	**0.000**
	N	**557**	**558**
TOC	Correlation Coefficient		**0.602***
	Significance (2-tailed)	**n/a**	**0.000**
	N		**828**

Notes:
1. Correlation tests were performed with SPSS 13.0 statistical software; asterisk (*) indicates correlation significant at the 0.01 level (2-tailed).
2. ProUCL 4.0 was used to identify outliers.
3. Sample size is less than Table 5b because only data with complimentary chemistry, grain size, and TOC data were used in this analysis.

Bold values indicate statistically significant relationship.

Shading indicates significant relationship between risk-driver parameter and conventional parameter.

cPAHs = carcinogenic polycyclic aromatic hydrocarbons; fines = sum of silt and clay grain-size fractions; N = number of samples; n/a = not applicable; PCBs = polychlorinated biphenyls; RM = river mile; TOC = total organic carbon

Table 9 Summary of USACE DMMP Core Data (RM 4.3 to RM 4.75)

USACE Sampling Event	Sampling Year	Number of Samples[a] (Number of Detections): Total PCBs	Arsenic	cPAHs	Dioxins/ Furans	Range of Concentrations: Total PCBs (µg/kg dw)	Arsenic (mg/kg dw)	cPAHs (µg TEQ/kg dw)	Dioxin/Furan (ng TEQ/kg dw)	Dredging Event[b]: Year	Footprint (RM)
DR09-Round 2	2009	2 (1) [c]	2 (2)	2 (2)	—	2U - 27	4 - 6	8 - 26	—	2010	4.18 – 4.49, 4.55 – 4.65
DR08-Round 1	2008	2 (2) [c]	2 (2)	2 (2)	2 (2)	25 - 53	10 - 14	41 - 108	2 - 3		
DUWO41AF189	2003	5 (5)	5 (5)	5 (5)	—	11 – 42	4 – 7	29 – 64	—	2004 2007	4.35 – 4.65 4.25 – 4.65
DUWA81BF128	1998	3 (1)	3 (3)	3 (3) 2 (2)	—	38U - 82	5 - 11	57 – 1,052 57 - 89[d]	—	1999 2002	3.45 – 4.65 4.25 – 4.65
DUWA71BF107	1996	1 (1)	1 (1)	1 (1)		94	7	185		1997	4.25 – 4.65
DUWA61BF132	1995	1 (1)	1 (1)	1 (1)	—	28	13	226	—	1996	4.0 – 4.5
DUWA21BF038	1991	4 (2)	4 (4)	4 (4)	—	32U – 34	3 – 9	14 – 181	—	1992 1994	3.35 – 4.65 4.35 – 4.65
DUWA01BF014	1990	2 (0)	0	2 (2)	—	20U	—	19 – 67	—	Data were post-dredging results for 1990 event.	
All Events		**20 (13)**	**18 (18)**	**20 (20) 19 (19)[d]**	**2 (2)**	**2U – 94**	**3 – 14**	**8 – 226[d]**	**2 – 3**	—	

Notes:

1. Stations downstream of RM 4.3 not used in any statistical analysis.
2. Core data queried from DAIS.

a. Subsurface sediment samples are either discrete vertically-composited samples or horizontally-composited samples from multiple cores.

b. Dredging event for which samples characterized the dredged material.

c. Data results for PCB Aroclors analyzed by TestAmerica for Rounds 1 and 2 met quality assurance level 1 (QA1) data evaluation requirements but were rejected by a more rigorous independent data validation by USACE. Core data presented and used in these analyses were analyzed from archived sediment by ARI Laboratory and independently validated by EcoChem Inc. in 2009 (USACE, 2009b).

d. Range of concentrations for cPAHs without an outlier of 1,052 µg TEQ/kg dw.

— = no data collected; cPAHs = carcinogenic polycyclic aromatic hydrocarbons; DAIS = Dredged Analysis Information System; DMMP = Dredged Material Management Program; dw= dry weight; µ = microgram; PCBs = polychlorinated biphenyls; RM = river mile; TEQ = toxic equivalent; U = undetected at the reporting limit shown; USACE = U.S. Army Corps of Engineers

Table 10 Data Quality Summary for USACE DMMP Core Data in the Frequently Dredged Area (RM 4.3 to 4.75)

Study Event	Risk Driver	Number of Samples	Data Selection	Overall Strength of Line of Evidence	Data Quality Considerations for Developing BCM Parameters of Upstream Sediment Settling in the LDW					
					Level of Data Validation	Precision	Representativeness	Accuracy / Potential Biasing Effects	Completeness	Comparability
Multiple (1990 – 2009)	Total PCBs	20	20 samples considered. Only data from 1990 - 2009 used.	Data characterize material that actually settles in the LDW.	Data are validated at QA-1 level for DMMP program.	Acceptable.	DAIS cores are generally similar to material that settles in the remainder of the LDW. Coarser material present above RM 4.5, consistent with bed load materials. Modeling indicates negligible contribution of lateral source material or downstream material to bed sediment composition in this reach.	Minor potential biases associated with sediment composition (low percent fines and TOC above RM 4.5). Low to medium bias associated with potential contributions from lateral sources. Modeling calculations demonstrate that lateral sources have minimal influence on sediment chemistry in this reach.	Acceptable. Sample numbers allow statistical interpretation.	The sample matrix is comparable to LDW sediment samples. Sample search is extended downstream to RM 4.3 to include samples with higher percent fines (than Upper Turning Basin) to match physical conditions in LDW.
	Arsenic	18	18 samples considered. Only data from 1991 - 2009 used. No arsenic data for 1990 event.							
	cPAHs	19	19 samples considered. Only data from 1990 - 2009 used one outlier was excluded).							
	Dioxins/Furans	2	2 samples considered. Data available only for 2009 event.							

Notes:
BCM = bed composition model; cPAHs = carcinogenic polyaromatic hydrocarbons; DAIS = Dredged Analysis Information System; DMMP = Dredged Material Management Program; LDW = Lower Duwamish Waterway; PCBs = polychlorinated biphenyls; RM = river mile; TOC = total organic carbon; USACE = U.S. Army Corps of Engineers.

Table 11 Summary Statistics of Total PCBs for the Development of Upstream BCM Input Parameters

Data Sources	Number of Observations	Data Distribution	Total PCB Concentration (µg/kg dw)			
			Mean	Median	90th Percentile	95% UCL[a]
Green/Duwamish River Water Quality						
King County Whole-Water Data (2001-2008)	*22*	Lognormal	50	21	107	82
Ecology Centrifuged Solids Data (2008, 2009)	*7*	Lognormal	14	8	54	36
King County Whole Water and Ecology Centrifuged Solids Combined	*29*	Lognormal	42	11	120	127
Upstream Surface Sediment (RM 5.0 to 7.0)						
LDW RI Upstream Sediment Data (1994-2006)[b]	*37*	Non-parametric	23	19	40	21[e]
Ecology Upstream Surface Sediment Data (2008)[c]						
Fines > 30 %	*30*	Non-parametric	5	2	13	8
All	*73*	Non-parametric	3	3	6	3
LDW RI and Ecology Surface Sediment Combined [c]	*110*	Non-parametric	8	3	23	13
Upper Turning Basin and Navigation Channel						
USACE DMMP Core Data (1990-2009)[d] RM 4.3 - RM 4.75	*20*	Lognormal	36	33	56	42

Notes:

a. Reported value is the 95% UCL recommended by ProUCL 4.00.04.
b. Surface sediment samples between RM 5 and 7 that are included in the RI baseline dataset.
c. Outlier excluded for total PCBs: 770 µg/kg dw.
d. Dredged Analysis Information System (DAIS) data obtained from USACE.
e. The 95%UCL is lower than the mean because this is a non-parametric distribution, left-censored dataset with 51% non-detects. Therefore, the 95%UCL is based on a bias-corrected accelerated (BCA) bootstrap method. UCL95 is the one recommended by ProUCL software.

BCM = bed composition model; DMMP = Dredged Material Management Program; LDW = Lower Duwamish Waterway; µg/kg dw = micrograms per liter dry weight; mg/L = milligram per liter; PCB = polychlorinated biphenyl; RI = remedial investigation; RM = river mile; TSS = total suspended sediments; UCL = upper confidence limit on the mean; USACE = U.S. Army Corps of Engineers

Table 12 Summary Statistics of Arsenic for the Development of Upstream BCM Input Parameters

Data Sources	Number of Observations	Data Distribution	Arsenic Concentration (mg/kg dw)			
			Mean	Median	90th Percentile	95% UCL[a]
Green/Duwamish River Water Quality						
King County Whole-Water Data (2001-2008)	*100*	Non-parametric	37	29	73	47
Ecology Centrifuged Solids Data (2008, 2009)	*7*	Lognormal	17	14	24	22
Upstream Surface Sediment (RM 5.0 to 7.0)						
LDW RI Upstream Sediment Data (1994-2006)[b]	*24*	Lognormal	7	5	11	8
Ecology Upstream Surface Sediment Data (2008)						
Fines > 30 %	*31*	Non-parametric	9	9	11	10
All	*74*	Non-parametric	7	6	10	7
LDW RI and Ecology Surface Sediment Combined	*98*	Non-parametric	7	6	10	7
Upper Turning Basin and Navigation Channel						
USACE DMMP Core Data (1990-2009)[c] RM 4.3 - RM 4.75	*18*	Lognormal	7	6	12	8

Notes:

a. Reported value is the 95% UCL recommended by ProUCL 4.00.04.
b. Surface sediment samples between RM 5 and 7 that are included in the RI baseline dataset.
c. Dredged Analysis Information System (DAIS) data obtained from USACE.

BCM = bed composition model; DMMP = Dredged Material Management Program; LDW = Lower Duwamish Waterway; mg/kg dw = milligrams per kilogram dry weight; RI = remedial investigation; RM = river mile; UCL = upper confidence limit on the mean; USACE = U.S. Army Corps of Engineers.

Table 13 Summary Statistics of cPAHs for the Development of Upstream BCM Input Parameters

Data Sources	Number of Observations	Data Distribution	cPAH Concentration (µg TEQ/kg dw)			
			Mean	Median	90th Percentile	95% UCL[a]
Green/Duwamish River Water Quality						
King County Whole Water Data (2001-2008)	*18*	Lognormal	151	74	354	269
Ecology Centrifuged Solids Data (2008, 2009)	*7*	Lognormal	138	53	400	432
King County Whole Water and Ecology Centrifuged Solids Combined	*25*	Lognormal	135	58	330	266
Upstream Surface Sediment (RM 5.0 to 7.0)						
LDW RI Upstream Sediment Data (1994-2006)[b]	*16*	Non-parametric	55	18	135	100
Ecology Upstream Surface Sediment Data (2008)						
Fines > 30 %	*31*	Non-parametric	37	16	77	72
All	*74*	Non-parametric	18	9	57	43
LDW RI and Ecology Sediment Combined	*90*	Non-parametric	25	10	73	55
Upper Turning Basin and Navigation Channel						
USACE DMMP Core Data (1990-2009)[c] RM 4.3 - RM 4.75	*19*	Lognormal	73	57	180	134

Notes:

a. Reported value is the 95% UCL recommended by ProUCL 4.00.04.
b. Surface sediment samples between RM 5 and 7 that are included in the RI baseline dataset.
c. Dredged Analysis Information System (DAIS) data obtained from USACE. Outlier excluded for cPAHs: 1,052 µg TEQ/kg dw.

BCM = bed composition model; cPAH = carcinogenic polycyclic aromatic hydrocarbon; DMMP = Dredged Material Management Program; LDW = Lower Duwamish Waterway; µg TEQ/kg dw = micrograms toxic equivalent per kilogram dry weight; RI = remedial investigation; RM = river mile; TEQ = toxic equivalent; UCL = upper confidence limit on the mean; USACE = U.S. Army Corps of Engineers.

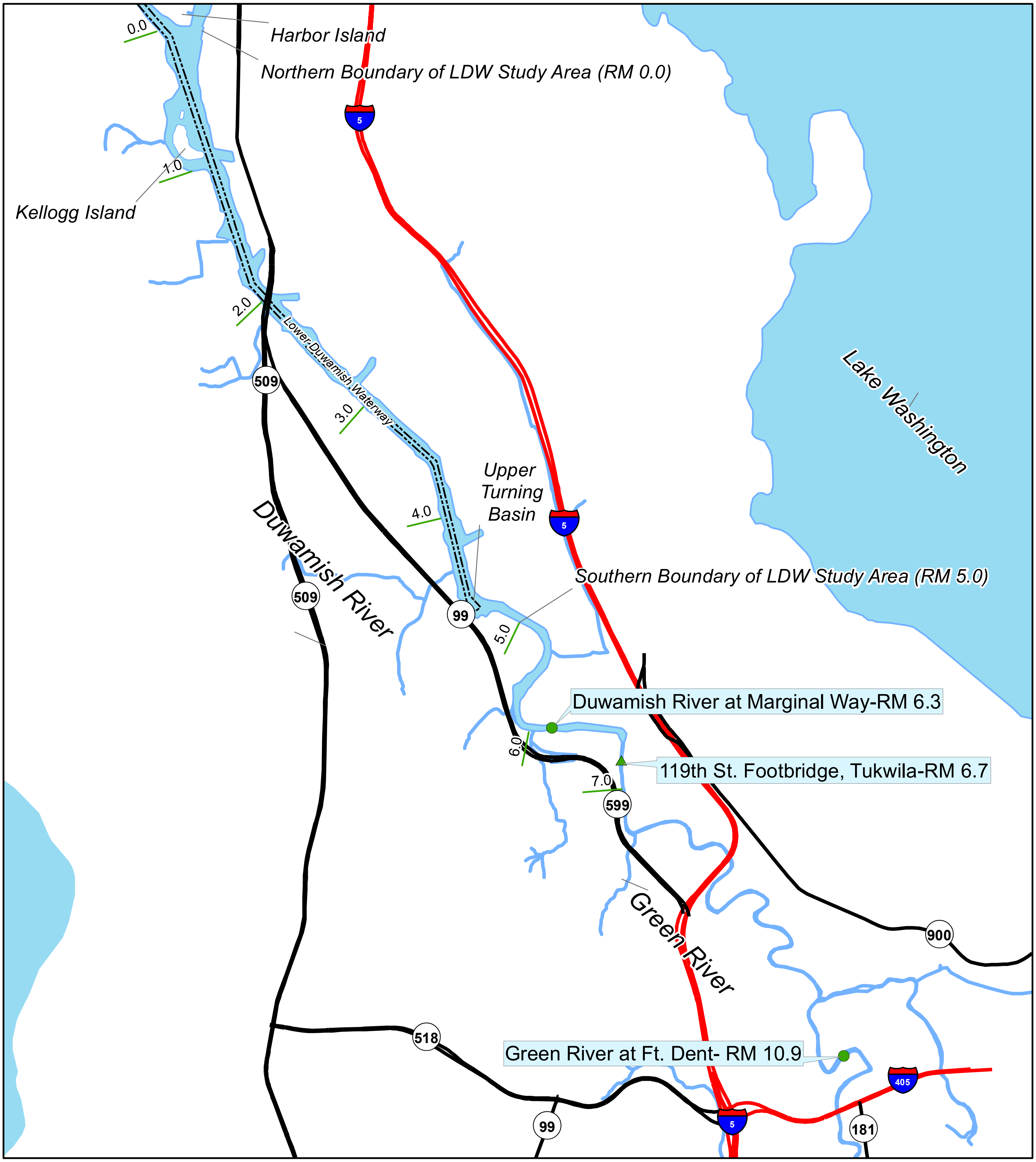
Table 14 Summary Statistics of Dioxins and Furans for the Development of Upstream BCM Input Parameters

Data Sources	Number of Observations	Data Distribution	Dioxin/Furan Concentration (ng TEQ/kg dw)			
			Mean	Median	90th Percentile	95% UCL[a]
Duwamish River Water Quality						
Ecology Centrifuged Solids Data (2008, 2009)	6	Lognormal	6	3	13	10
Upstream Surface Sediment (RM 5.0 to 7.0)						
LDW RI Upstream Sediment Data (1994-2006)[b]	4	—	Range of Values (Median): 1.1 - 2.6 (1.7)			
Ecology Upstream Surface Sediment Data (2008)						
Fines > 30 %	31	Non-parametric	2	2	3	2
All	74	Non-parametric	1	0.3	3	2
Upper Turning Basin and Navigation Channel						
USACE DMMP Core Data (1990-2009)[c] RM 4.3 - RM 4.75	2	—	2 and 2.8 ng TEQ/kg dw			

Notes:

a. Reported value is the 95% UCL recommended by ProUCL 4.00.04.
b. Surface sediment samples between RM 5 and 7 that are included in the RI baseline dataset.
c. Dredged Analysis Information System (DAIS) data obtained from USACE.

LDW = Lower Duwamish Waterway; ng TEQ/kg dw = nanograms toxic equivalent per kilogram dry weight; RI = remedial investigation; RM = river mile; TEQ = toxic equivalent; UCL = upper confidence limit on the mean; USACE = U.S. Army Corps of Engineers.



Notes:
1. Stations sampled by King County are located in the Duwamish River at the Marginal Way station (identified by locator 0309) and in the Green River at the Ft. Dent station (identified by locators A310, 3106, and TGS/1).
2. The station sampled by Ecology is at the 119th Street Footbridge near Tukwila (RM 6.7).

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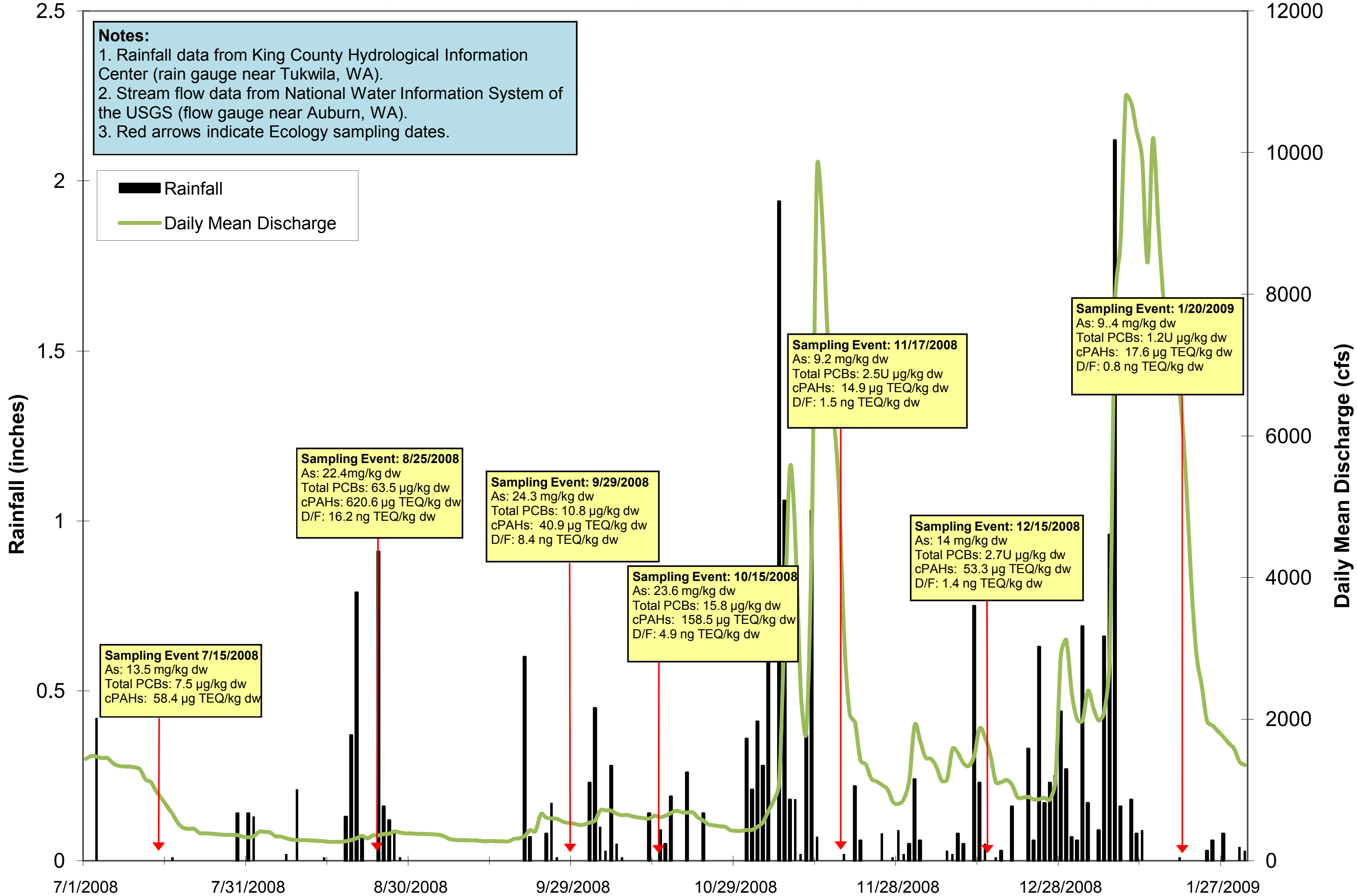
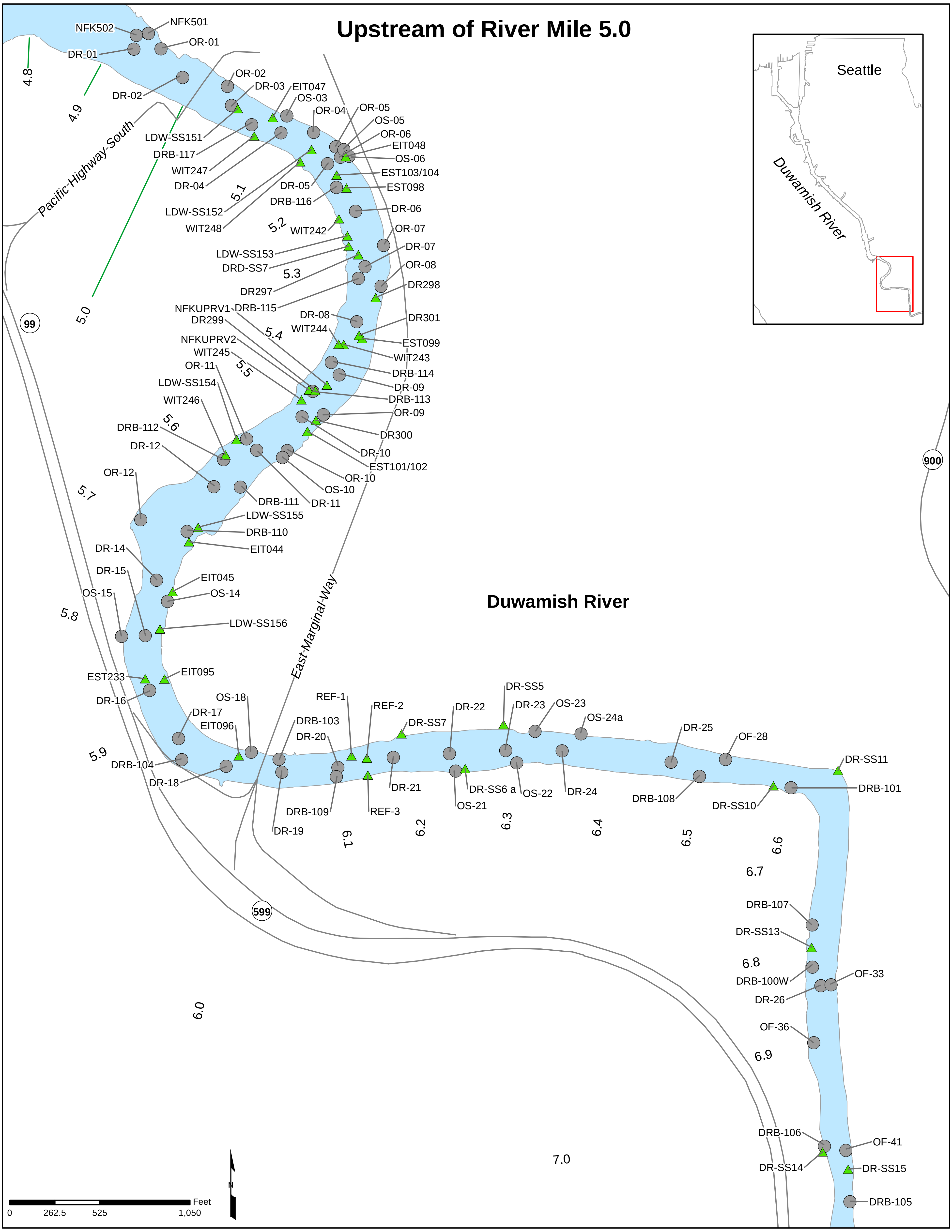
Lower Duwamish Waterway Final Feasibility Study 60150279-14.46	Upstream Surface Water Sampling Locations
DATE: 10/31/12 · DWRN:MVI/sea · Revision: 0	FIGURE 1

Figure 2
Green River Discharge and Rainfall During Ecology Centrifuged Solids Sampling Project



Notes:

As = arsenic; cfs = cubic feet per second; cPAH = carcinogenic polycyclic aromatic hydrocarbon; D/F = dioxins and furans; dw = dry weight; PCB = polychlorinated biphenyl; TEQ = toxic equivalent



Notes:

1. Surface sediment samples from RM 5.0 to 7.0 are from RI baseline dataset (1994 - 2006).
2. Surface sediment samples from RM 4.9 to 6.5 are from 2008 Ecology study. DR = center channel samples, OS = samples near the discharge points of outfalls, OR = samples within the Duwamish River approximately 15 meters downstream of outfall discharge points, DRB = bank samples that appear to be depositional environments, OF = bank samples at discharge points of selected newly identified outfalls upstream of RM 6.5, NFK = samples near the Norfolk combined sewer overflow.
3. Surface sediment samples collected at depths between 0 and 10 cm.

Legend

Upstream Surface Sediment Sample Location

- ▲ LDW Remedial Investigation Dataset
- ● Ecology 2008 Study
- River Mile Marker
- State Highway

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Lower Duwamish Waterway
Final Feasibility Study
60150279-14.46

Surface Sediment Sampling Stations Used to Characterize Sediments from Upstream

DATE: 10/31/12	DWRN: MVI/sea	Revision: 0	**FIGURE 3**

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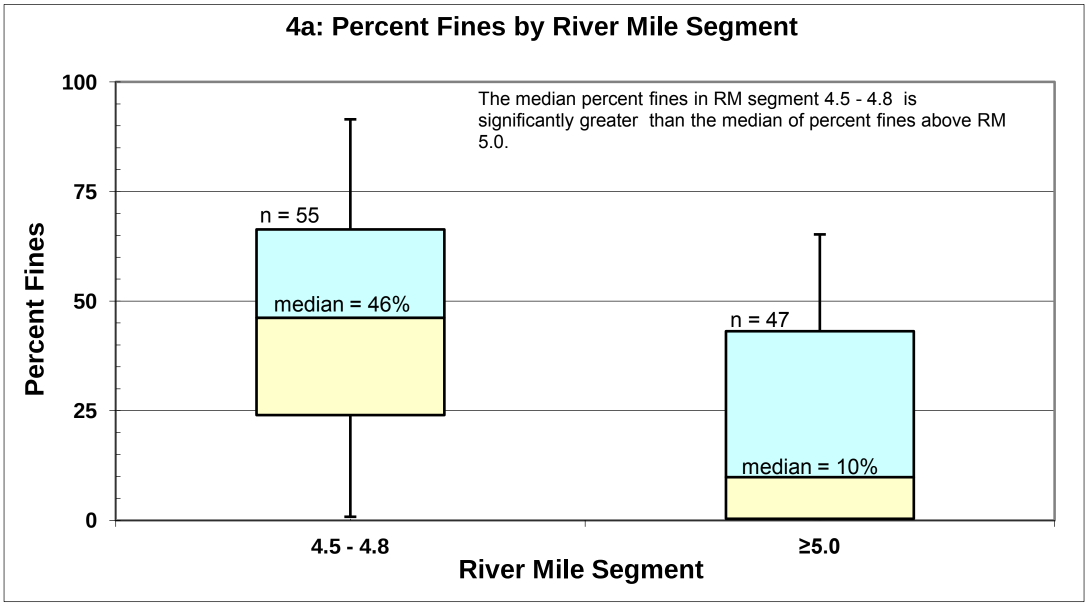
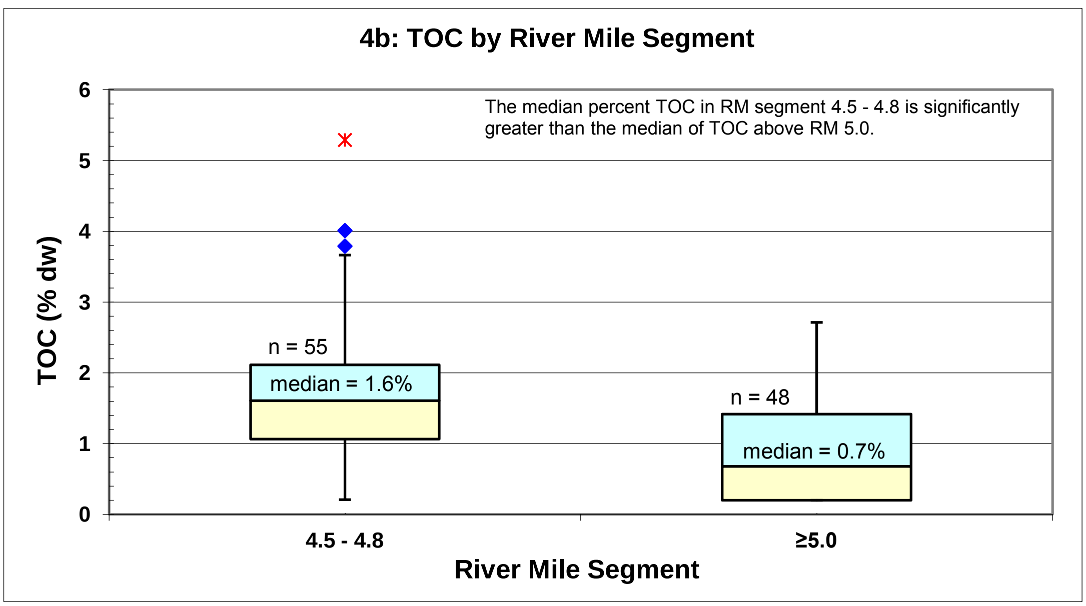
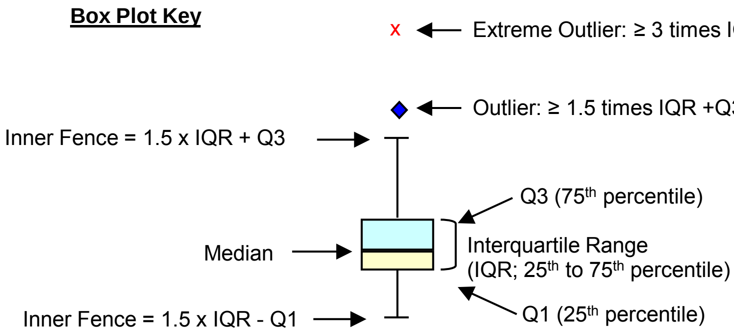
Figure 4
Comparisons of Surface Sediment Percent Fines and TOC in the Upper Turning Basin (RM 4.5 - 4.8) and Upstream of the LDW (RM ≥ 5.0)

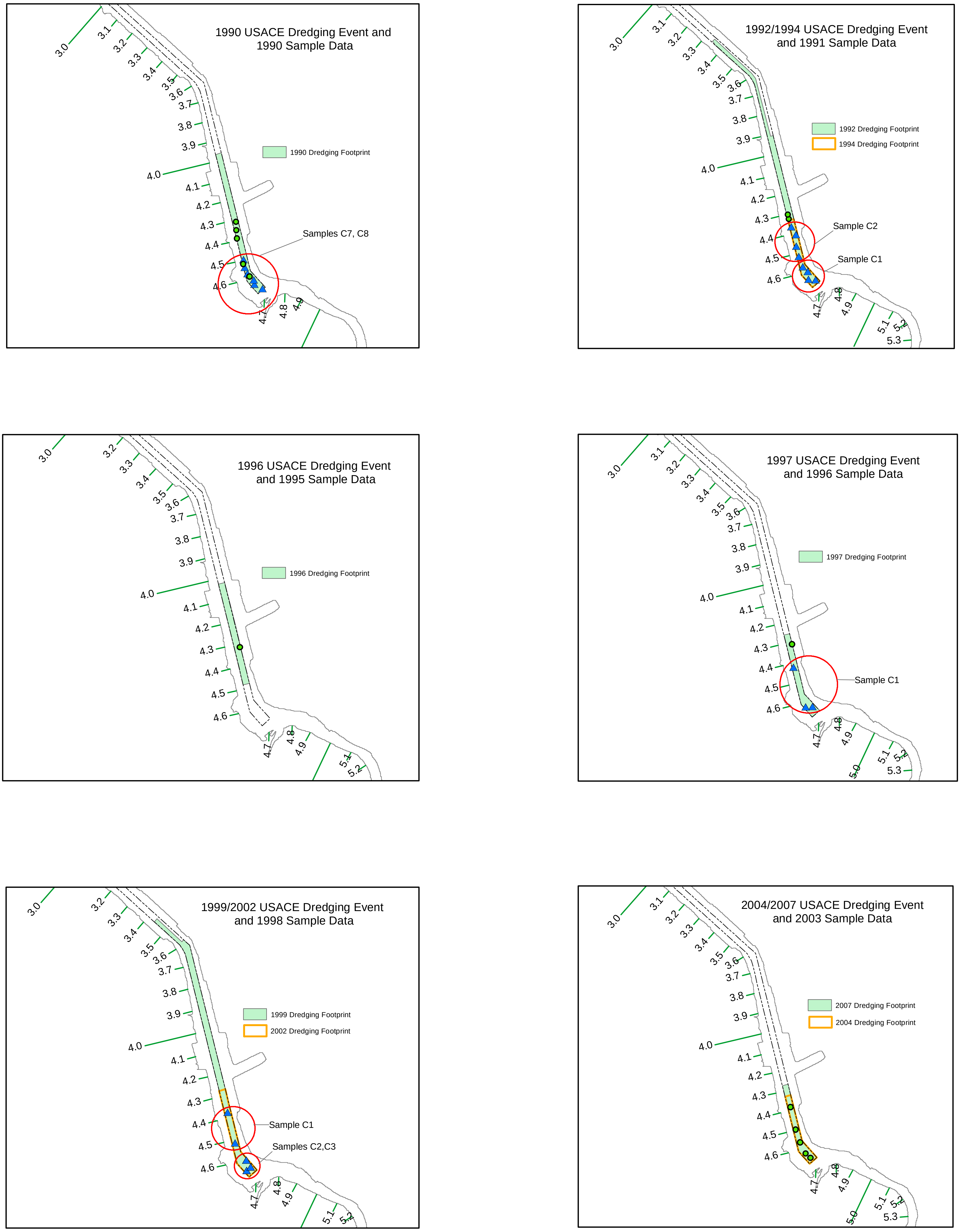




Box Plot Key



Notes
IQR = interquartile range
Figures generated in Excel



Notes:
1. Sample data provided by David Fox, USACE, in March 2007.
2. Dredging footprints from USACE Dredge Summary and Analysis Reports.
3. Single sample locations represent stations where sediment data were collected and analyzed without horizontal compositing. Composite sample locations represent stations where sediment was collected and then composited with sediment from other stations before analysis.
4. Stations downstream of RM 4.3 not shown.
5. Most 1990-2003 sediment samples collected from 0 to 4 ft below mudline.
6. USACE= US Army Corps of Engineers

Legend

- Single Sample Core Location
- Composite Sample Core Location
- Navigation Channel
- River Mile Marker

0 800 1,600 3,200 Feet

N

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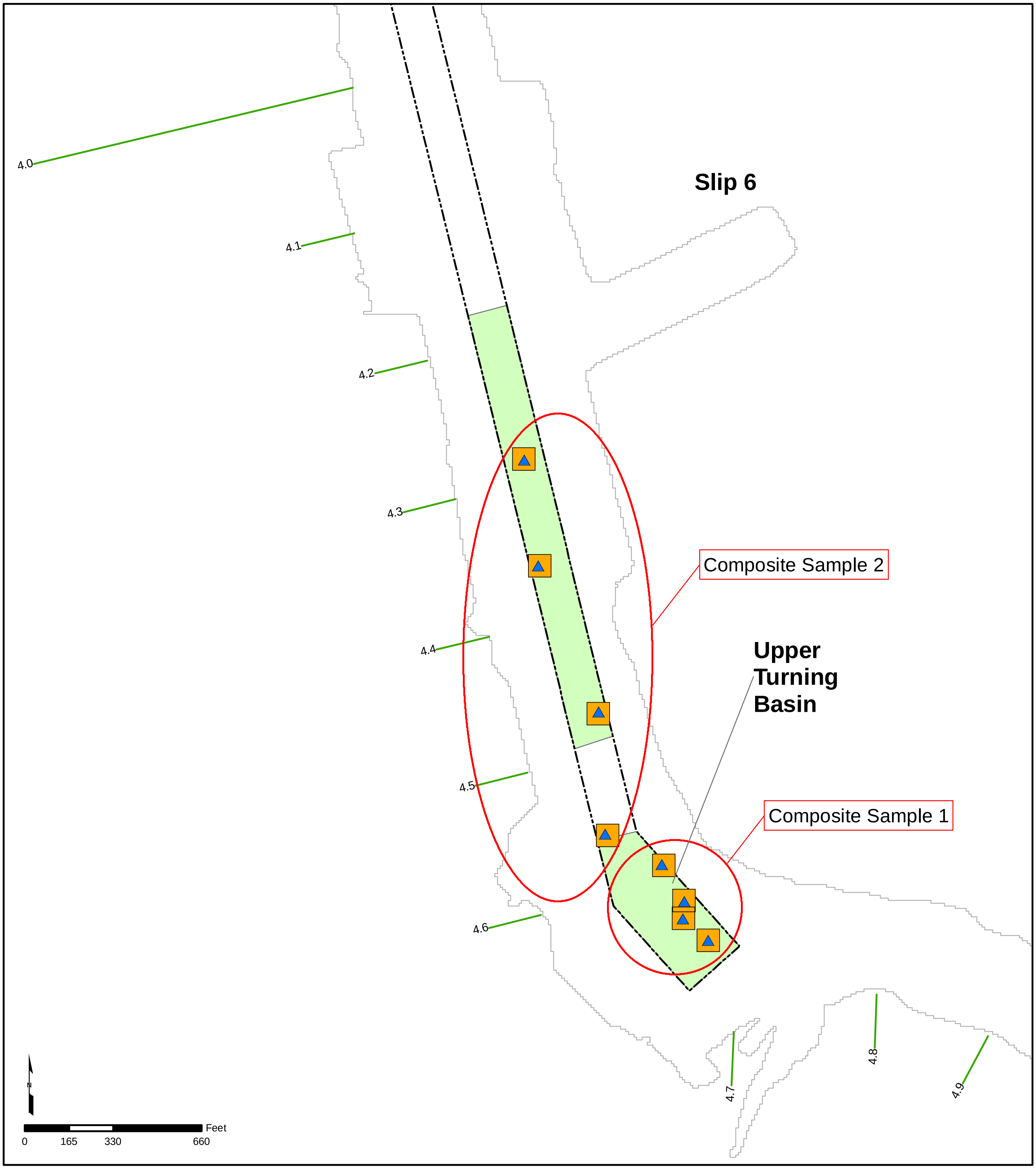
Lower Duwamish Waterway Final Feasibility Study 60150279-14.46			**1990-2003 Pre-Dredging Event Sampling Locations from Upper Reach**
DATE: 10/31/12	DWRN:MVI/sea	Revision: 0	**FIGURE 5a**



Notes:
1. Sample data provided by SAIC and USACE in September 2009. Final data reports published in October and November 2009.
2. Stations downstream of RM 4.3 not shown.

Legend

- River Mile Marker
- Navigation Channel
- 2008 Surface Sample Location
- 2009 Core Sample Location
- 2010 Dredging Footprint

L:\Lower Duwamish FS\FS_Final_GIS\Oct2012\FS_GIS_MXDs_Oct12\Appendix C\FigureC-3_5b_DAIS_USACEdredge.mxd

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

Lower Duwamish Waterway Final Feasibility Study 60150279-14.46	**2008 & 2009 Pre-Dredging Event Sampling Locations from Upper Reach**
DATE: 10/31/12 · DRWN:MVI/sea · Revision: 0	**FIGURE 5b**

Figure 6
Conceptual Diagram of USACE Core Sample Depths to Mudline

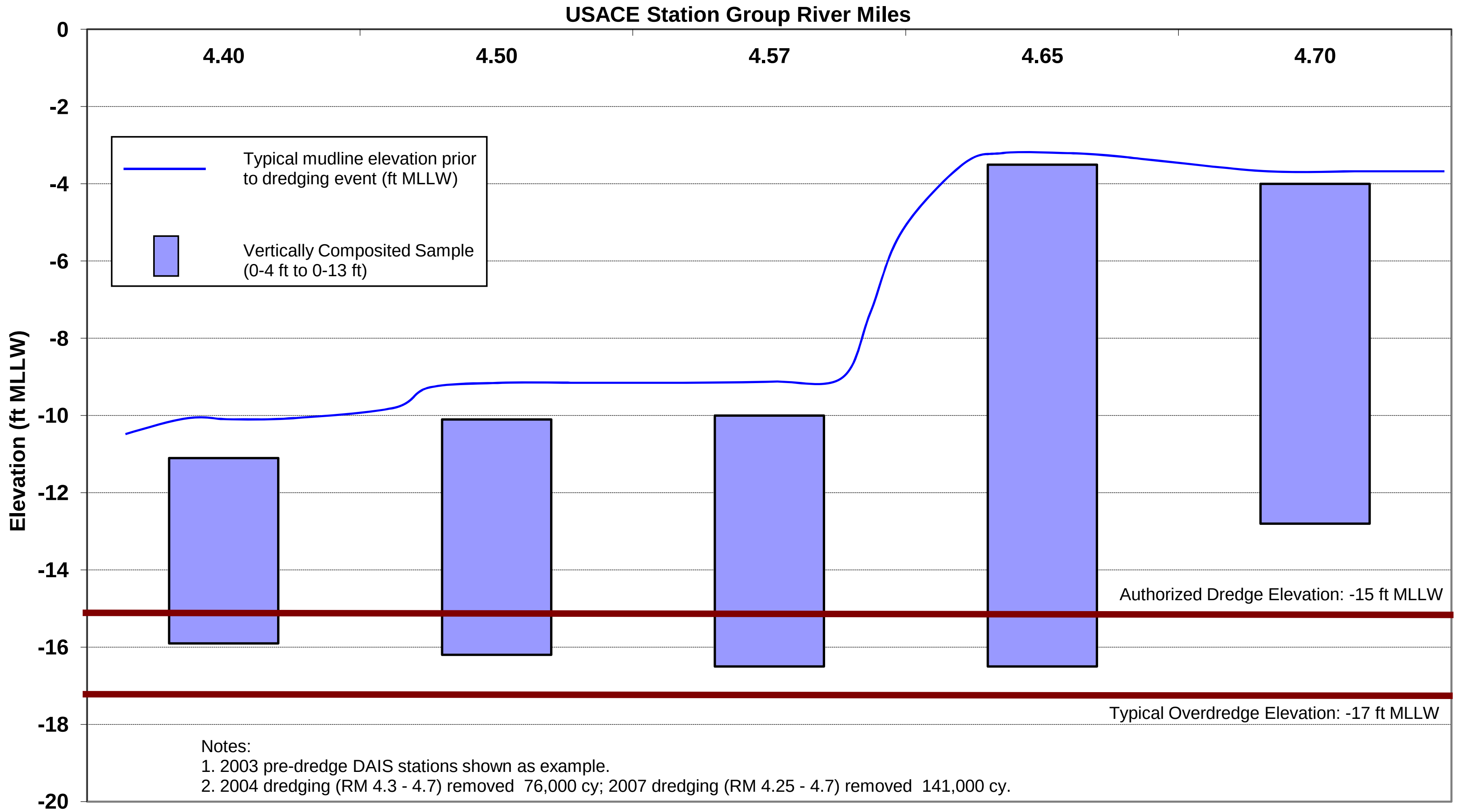


Figure 7
Temporal Representation of USACE Core Data - Total PCBs by Location and Year

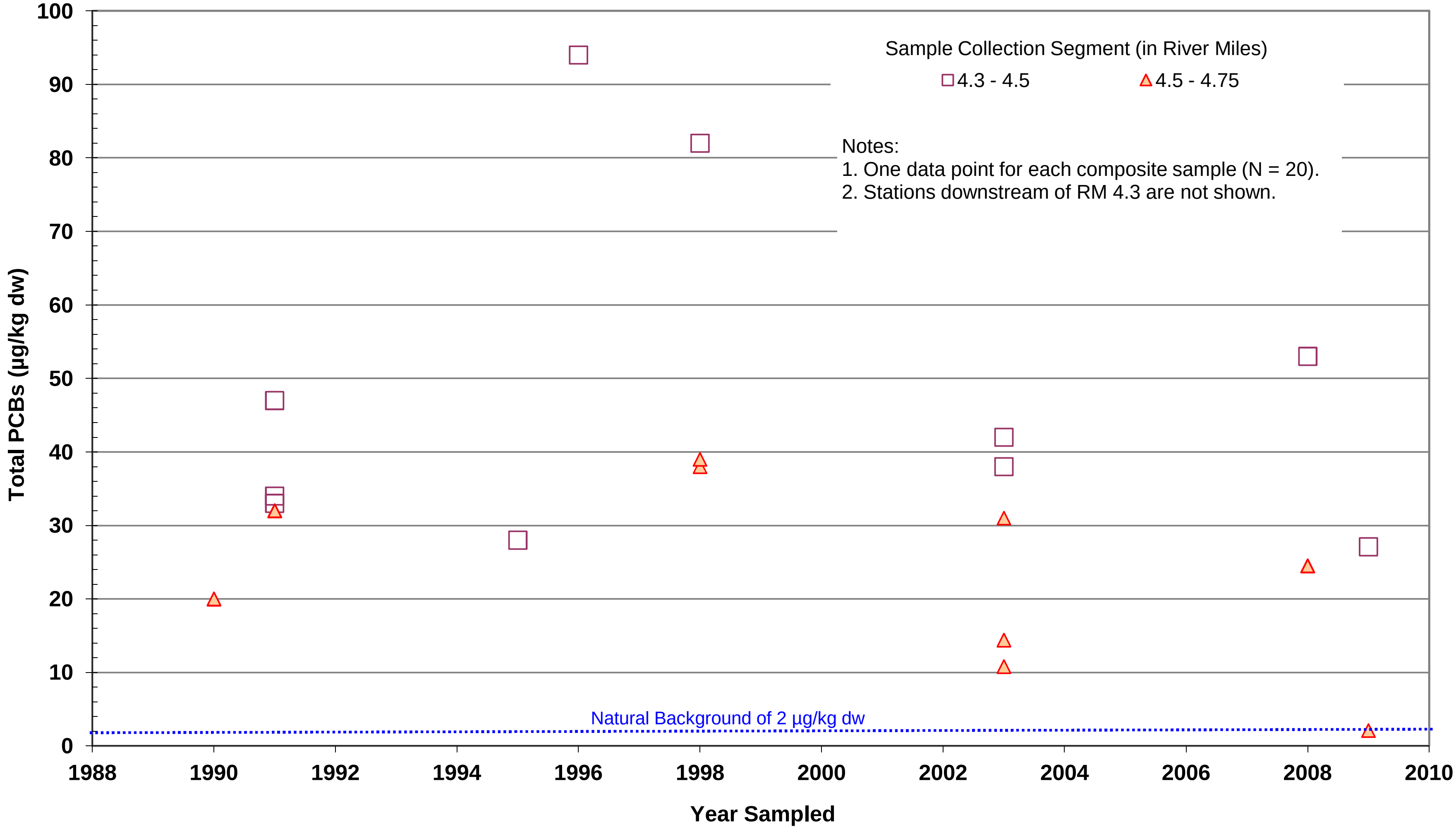


Figure 8
Summary of Lines of Evidence for Upstream BCM Input Parameter Development - Total PCBs

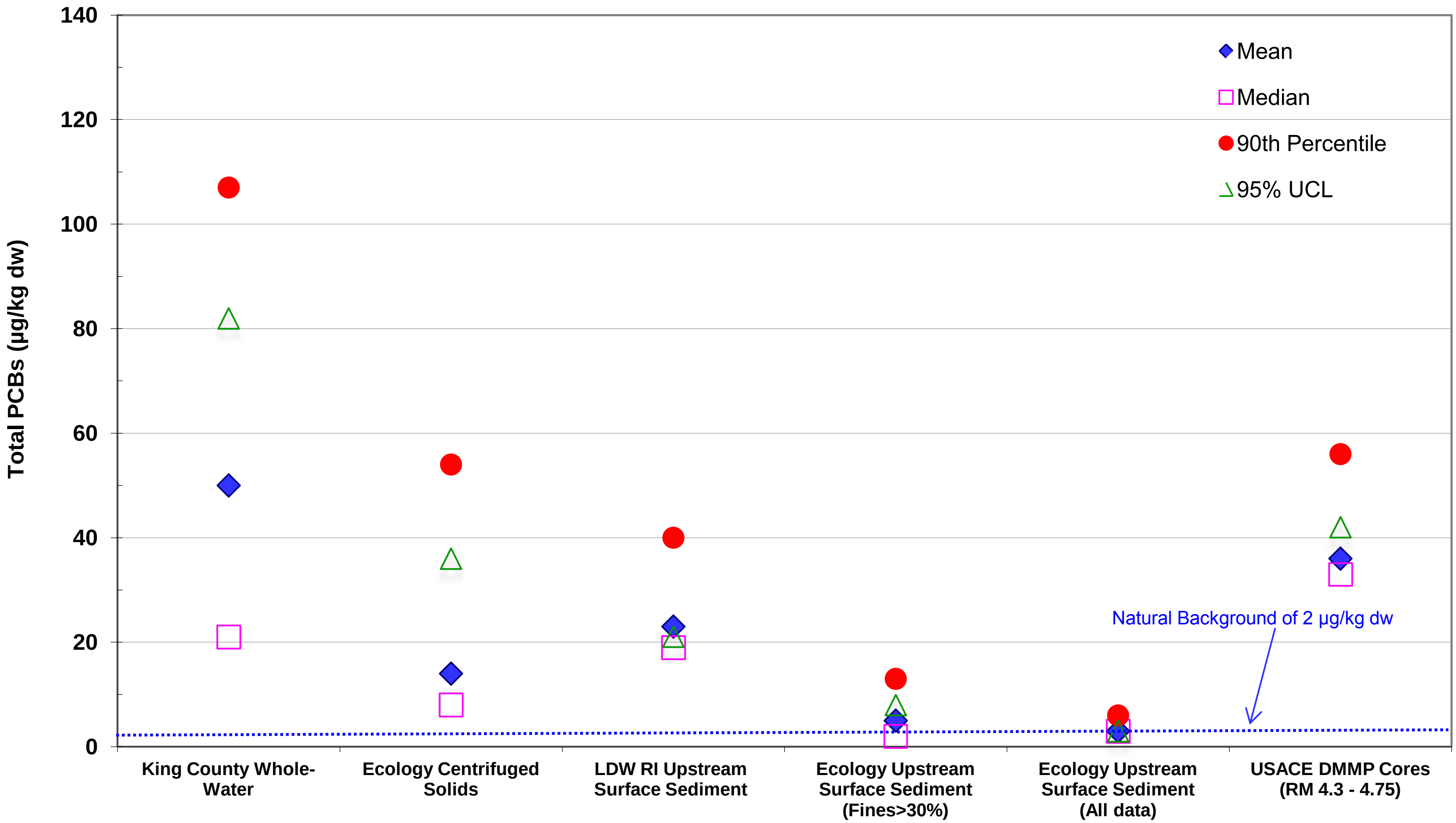


Figure 9
Temporal Representation of USACE Core Data - Arsenic by Location and Year

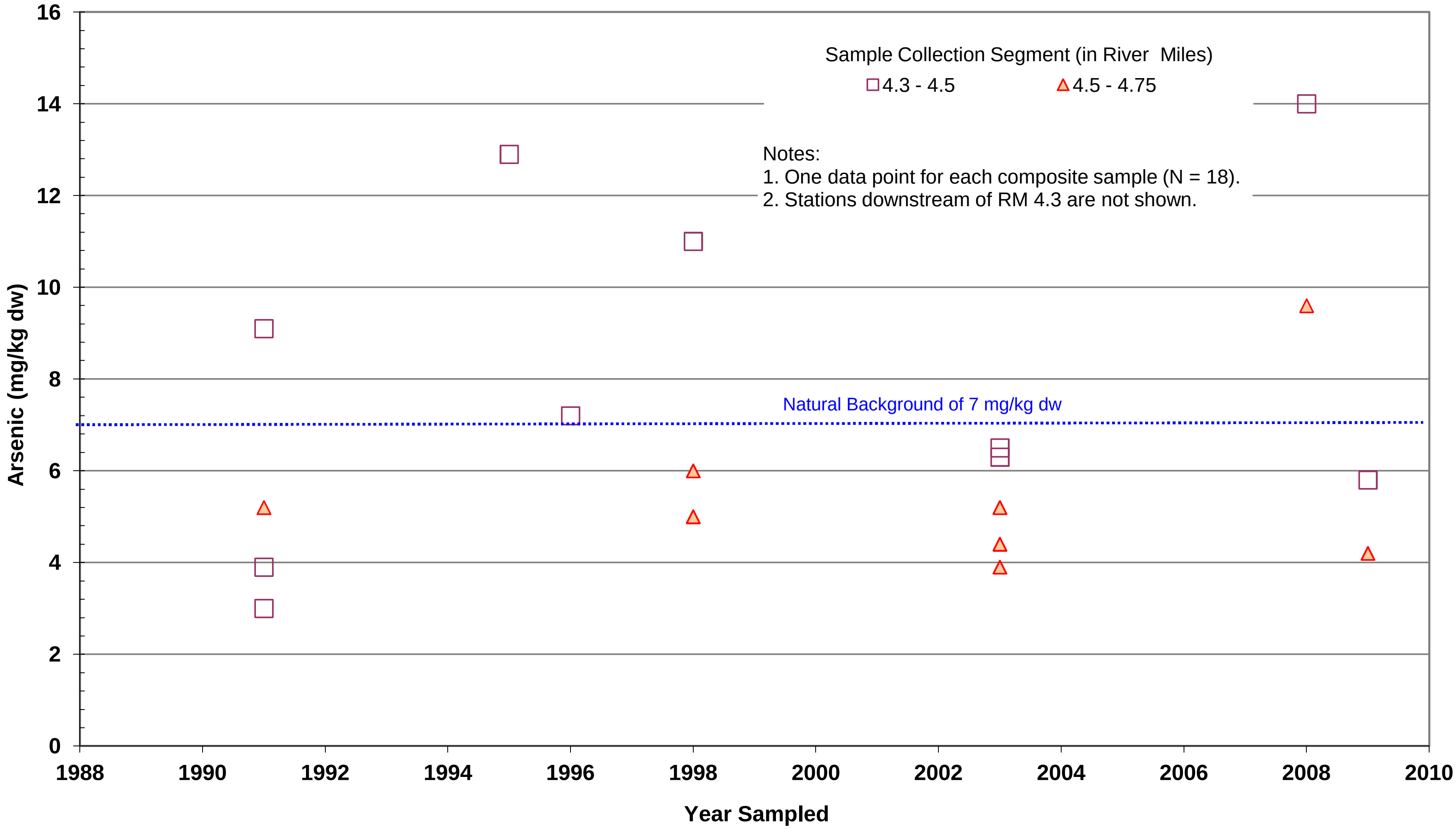


Figure 10
Summary of Lines of Evidence for Upstream BCM Input Parameter Development - Arsenic

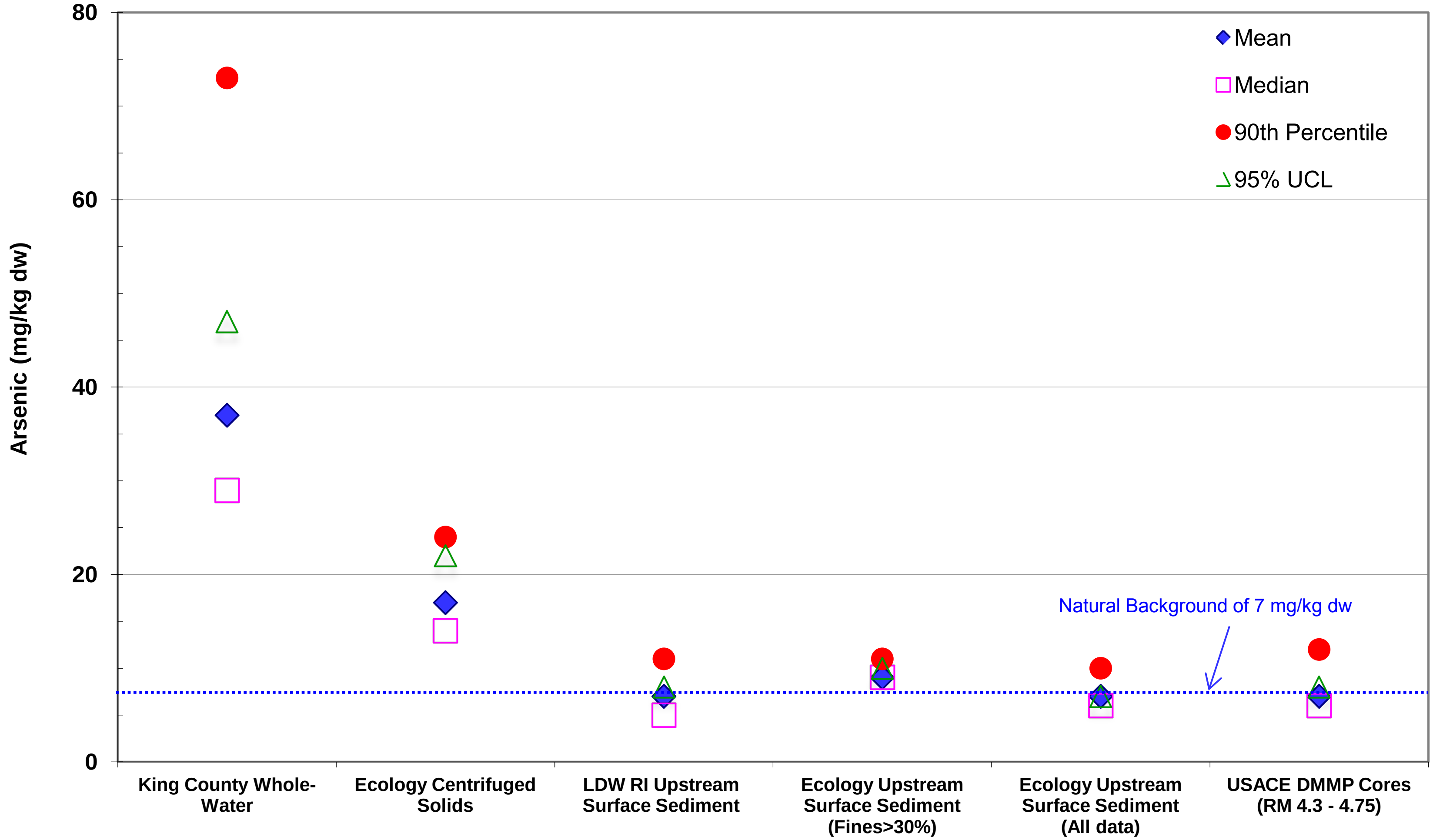


Figure 11
Temporal Representation of USACE Core Data - cPAHs by Location and Year

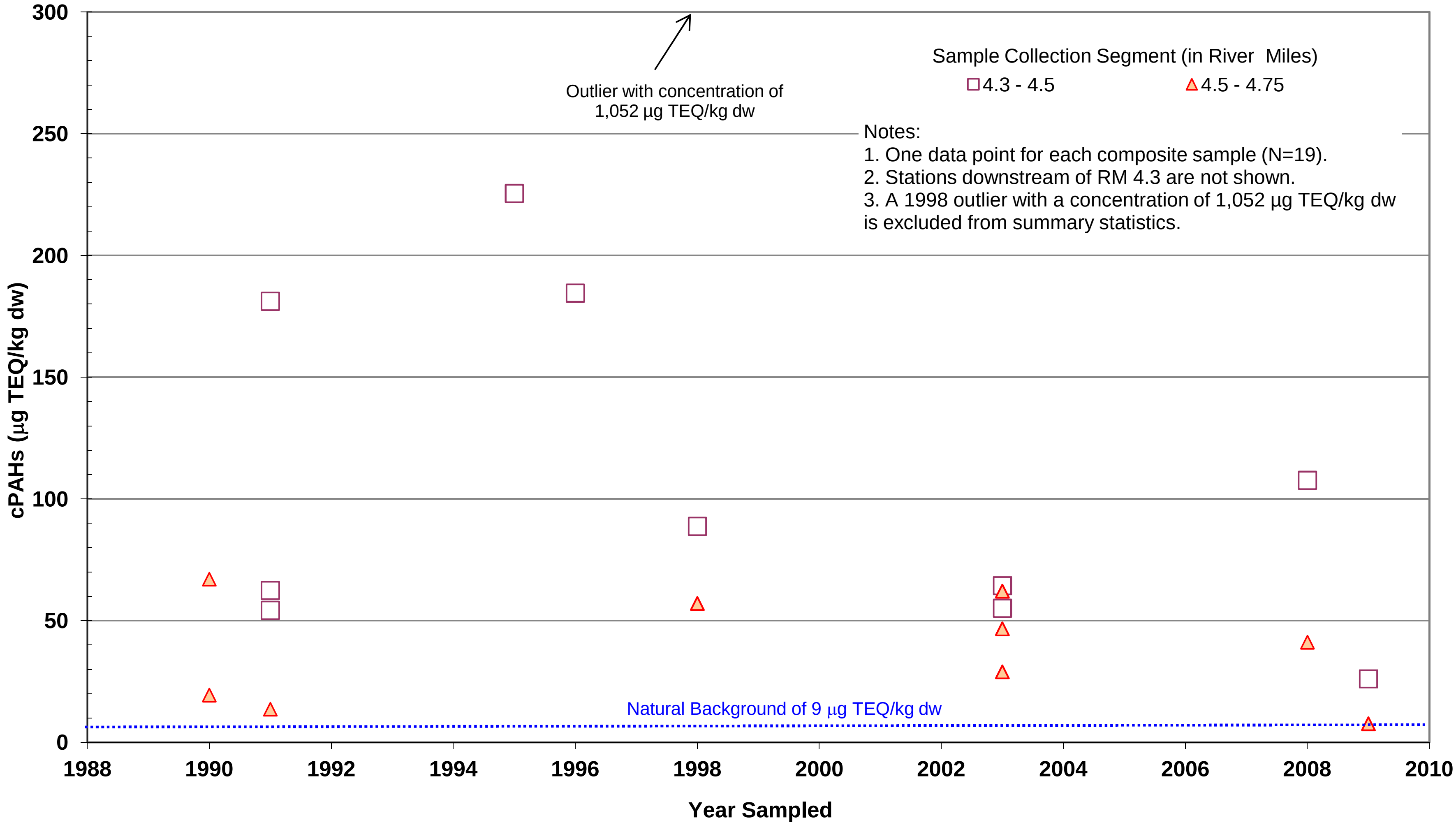


Figure 12
Summary of Lines of Evidence for Upstream BCM Input Parameter Development - cPAHs

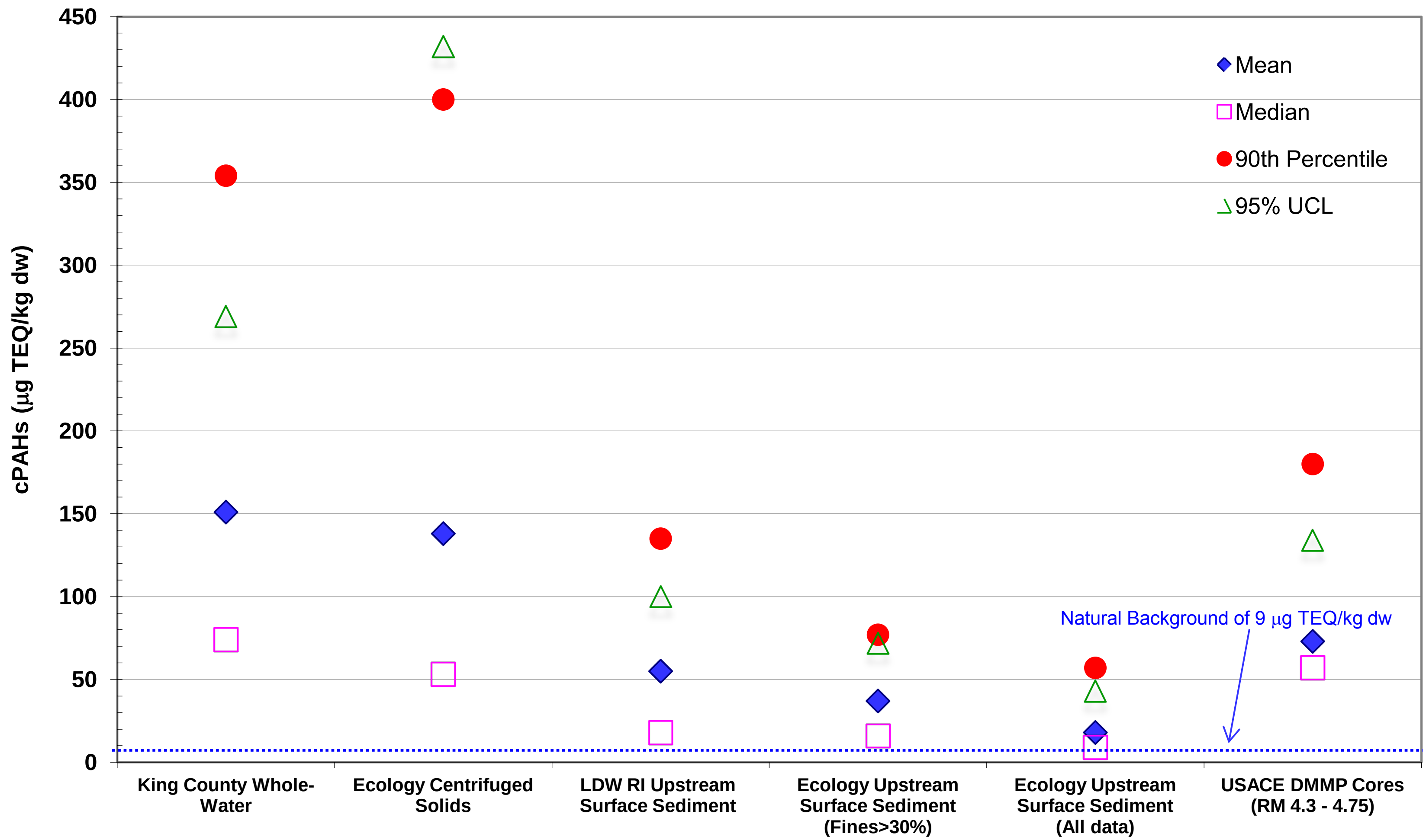
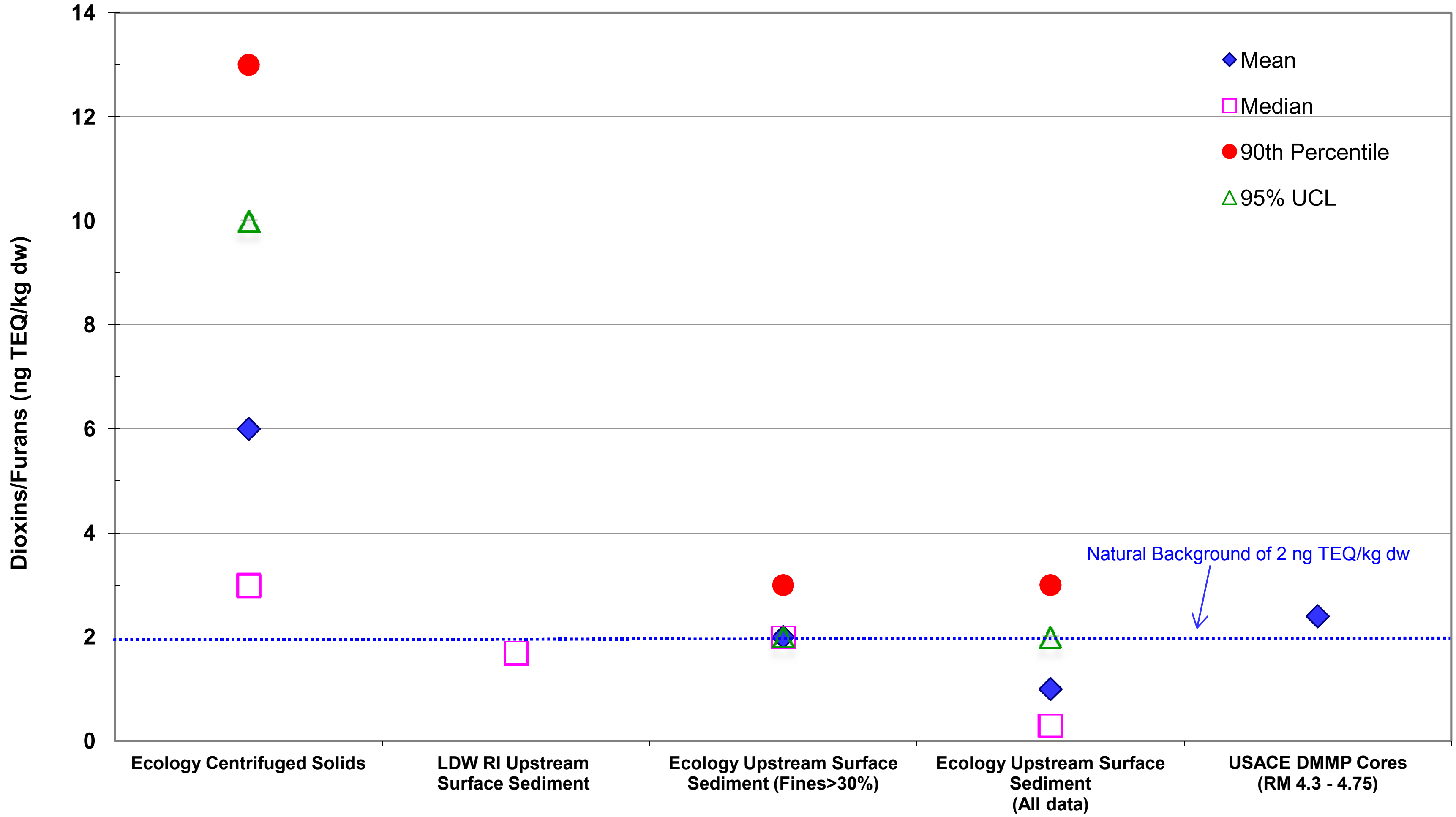


Figure 13
Summary of Lines of Evidence for BCM Upstream Input Parameter Development - Dioxins/Furans



Part 4: LDW Sediment Transport Model: Results of Five Scenario Simulations

Scenario 1: **Potential Recontamination of Early Action Areas**

Scenario 2: **Distributed Discharges from Lateral Sources**

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

Scenario 4: **Movement of Bed Sediments between Reaches**

Scenario 5: **Sediment Scoured from Greater than 10-cm Depth**

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MEMORANDUM

To:	Lower Duwamish Waterway Group	**Date:**	April 20, 2009[1]
From:	C. Kirk Ziegler, Anchor QEA	**Project:**	RETldw:230
Cc:	Files		
Re:	LDW Sediment Transport Model: Results of Five Scenario Simulations		

INTRODUCTION

A Sediment Transport Model (STM) for the Lower Duwamish Waterway (LDW) has been developed, calibrated, and validated (QEA 2008). Extensive evaluation of the STM indicated that the model adequately simulates sediment transport processes in the LDW for the purposes and applications specified in the final STM Report (QEA 2008) approved by the U.S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology (Ecology) on October 31, 2008. Based on these results, the following conclusions concerning model reliability were developed:

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

[1] Revised October 15, 2010 to be consistent with revisions to the FS requested by the agencies.

The STM has been used as a diagnostic tool to quantitatively evaluate five scenarios in the LDW. This technical memorandum describes the five scenarios and presents the results of the scenario simulations. The five scenario simulations are summarized in Table 1.

Table 1
Summary of Five Scenario Simulations

Scenario	Primary Objective	General Description of Simulation
1. Potential Recontamination of Early Action Areas (EAAs)	Evaluate changes in bed sediment within EAAs after removal actions are simulated in EAAs.	10-year simulation that tracked sediment from four sources: 1) EAA bed sediment; 2) bed sediment from areas outside the EAAs; 3) lateral source; and 4) upstream (Green River) source.
2. Distributed Discharges from Lateral Sources	Evaluate the effects of spatially distributed lateral-source discharge locations.	10-year simulation that is modified to have the lateral load distributed among the near-shore cells adjacent to shoreline outfalls. The model is run for a 10-year period to compare the STM base case (the lateral load distributed via 21 outfalls) with the redistributed lateral loads via x point sources.
3. Movement of LDW Bed Sediment into the Upper Turning Basin	Determine the amount of bed sediment originating from downstream of RM 4.0 that is eroded and redeposited in the region upstream of RM 4.0.	10-year simulation that tracked bed sediment from four sources: 1) Upper Turning Basin, RM 4.3 to 4.75; 2) navigation channel, RM 4.0 to 4.3; 3) bench areas upstream of RM 4.0; and 4) all sediment downstream of RM 4.0. The model run predicts whether downstream LDW sediments resuspend and settle upstream in the turning basin.
4. Movement of Bed Sediment Between Reaches	Determine the fate of bed sediment from Reaches 1, 2, and 3.	30-year simulation resulting in a mass balance of sediment movement between reaches and out of the LDW for each reach.
5. Sediment Scoured From Greater Than 10-cm Depth	Determine fate of bed sediment from 0-to-10-cm and deeper-than-10-cm layers, following scour by a 100-year high-flow event.	Areas that are predicted 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.

EAA=Early Action Area; RM=river mile

The 10-year period used for Scenarios 1 through 4 corresponds to the first 10 years of the 30-year simulation presented in the final STM (QEA 2008). Comparison of the STM results for this 10-year period to the results for the entire 30-year period indicated that the 10-year period is representative of multi-year periods; the 10-year period results are similar to the 30-year period results. The initial conditions for the spatial distribution of bed composition were the same as those used for the diagnostic simulations presented in the final STM.

SCENARIO 1: POTENTIAL RECONTAMINATION AT EARLY ACTION AREAS

The objective of the Scenario 1 simulation was to evaluate temporal changes in the composition of surface (0 – 10 cm) sediment within early action areas (EAAs). The locations of the EAAs are shown in Figure 1-1. The Norfolk EAA is outside the area represented in the STM. To accomplish this objective, a 10-year simulation was conducted and the fate of sediment originating from the following four sources was tracked: 1) EAA bed sediment; 2) non-EAA bed sediment; 3) lateral sources; and 4) upstream (Green River) source. The bed properties within the EAA bed source areas were not modified for this scenario simulation (i.e., the EAA bed properties were assumed to represent current conditions). No adjustment of bed properties in the EAA bed source areas was made to represent post-remediation conditions.

The predicted spatial distributions of the relative amounts of sediment from the four sources in the surface sediment at the end of the 10-year period are presented in Figures 1-2 through 1-5. Some sediment from outside the EAAs has been resuspended and redeposited within the EAAs, with the non-EAA sediment contributing 5% or less to the surface sediment within the EAAs (Figure 1-3). Generally, the composition of surface sediment in the EAAs at the end of the 10-year period is dominated by sediment from the upstream source (Figure 1-5).

Quantitative comparisons of the relative amounts of sediment from the four sources in surface sediment at the end of the 10-year period in each of the six EAAs are shown in Figure 1-6. Upstream-source sediment comprises about 55% to 75% of the surface-layer composition in the EAAs. The relative amount of the original sediment in the EAAs, which was 100% at the beginning of the simulation, decreased to about 15% to 35% after 10 years. Sediment resuspended from outside the EAAs and redeposited within the EAAs comprises

3% or less of the surface sediment within the EAAs at the end of the 10-year period. The contribution of lateral-source sediments to the EAA surface sediments is variable, with this content ranging between about 1% and 15% for the EAAs.

The Scenario 1 simulation tracks the movement of bed sediment inside and outside of the EAAs for 10 years, following cleanup of the EAAs. Cleanup was simulated by setting feasibility study (FS) baseline total PCB concentrations in the EAAs to the recommended post-remedy bed sediment replacement value (RV) of 60 µg/kg dw. The bed composition model (BCM) equation used to calculate the 10-year period was modified by including two bed sediment sources. For sediments in EAAs, the bed concentration was equal to the RV. The bed concentration of sediment sourced from outside of the EAAs was set to the site-wide spatially-weighted average concentration (SWAC) for the grid cells not located in the EAAs, which are equal to 271 µg/kg dw in Reach 1 and 435 µg/kg dw in Reach 2. There are no EAAs in the STM domain in Reach 3, therefore, the Reach 3 site-wide SWAC was not changed. The upstream and lateral chemical input parameters were set to the recommended mid range values used in the base case, which are 35 and 300 µg/kg dw, respectively.

This simulation demonstrates that very little bed sediment is suspended from outside of the EAAs and redeposited within the EAAs with averages of 1.9% and 4.0% in Reaches 1 and 2, respectively. The EAA SWACs at the end of 10 years in Reaches 1 and 2 are 86 and 66 µg/kg dw, respectively. The predicted total PCB concentrations at the end of 10 years in the EAAs are displayed in Figure 1-7. The EAA SWAC in Reach 1 exceeds that in Reach 2 because the STM grid cells in the Reach 1 EAA (Duwamish/Diagonal) have, on average, a higher percentage of sediment originating from the lateral sources than those in Reach 2 (15% vs. 2.8%).

SCENARIO 2: DISTRIBUTED DISCHARGES FROM LATERAL SOURCES

Storm drains, combined sewer overflows (CSOs), and streams discharge into the LDW at over 200 locations; in the STM report (base-case runs), these lateral sources were aggregated and represented by 21 point sources (9 CSOs and 12 storm drains) that discharged into the LDW at 16 locations (i.e., 16 individual grid cells). Sediment loads specified as “storm drains” in the base-case simulation included aggregated flow due to runoff from waterfront areas and streams. Aggregating the lateral sources introduces uncertainty into the model predictions of surface (0 - 10 cm) sediment composition (i.e., relative amounts of sediment originating from the original bed, lateral, and upstream sources). Therefore, the objective of Scenario 2 was to evaluate the effects of the spatial distribution of lateral-source discharge locations on surface sediment composition. The base-case version of the Scenario 2 simulation is used throughout the FS. Therefore, BCM methods and findings using this simulation are not discussed in this appendix, but can be found throughout the FS, primarily in Sections 5 and 9.

A 10-year simulation was conducted with the spatial distribution of lateral sources being increased, relative to the simulation presented in Section 4 of the final STM. For the Scenario 2 simulation, lateral loads were separated into three broad categories: 1) CSOs; 2) storm drains (including streams); and 3) waterfront areas. Total sediment loads from these three sources for the base-case and Scenario 2 simulations are compared in Table 2, which shows that: 1) total CSO load did not increase; 2) total storm drain load decreased by 9.5%, due to transfer of a portion of the aggregated load in the base-case simulation to waterfront areas and reassessment of storm drain loads at some locations; and 3) distributed runoff from waterfront areas was incorporated into the model. As a result of more recent refinements in the overall loading estimates, the total sediment load from lateral sources increased by 4.3% (i.e., 52 MT/yr) for the Scenario 2 simulation, relative to the base-case simulation. The CSO sediment loads at nine locations, which were unchanged between the base-case and Scenario 2 simulations, are presented in Table 3.

Table 2
Total Sediment Loads for Base-Case and Scenario 2 Simulations

Type of Lateral Load	Base-Case Sediment Load (MT/yr)	Scenario 2 Sediment Load (MT/yr)	Relative Change in Sediment Load (%)
CSOs	35.1	35.1	0.0
Storm Drains	1,170	1,059	-9.1
Waterfront Areas	0	163	+100
Total	**1,205.1**	**1,257.1**	**+4.3**

CSO = combined sewer overflow

Table 3
Base-Case and Scenario 2 Sediment Loads at 9 CSO Locations

Location Name	River Mile Location	Sediment Load (MT/yr)
Duwamish P.S. W.	0.44 W	0.1
Hanford #1 (Hanford @ Rainier)	0.49 E	4.9
CSO 111	0.49 E	3.4
Duwamish P.S. E.	0.49 E	1.0
Brandon St.	1.11 E	14.6
Terminal 115	1.53 W	1.5
Michigan St.	1.96 E	9.0
Michigan W.	2.06 W	0.5
Norfolk St.	4.93 E	0.1
Total		**35.1**

E = east bank; W = west bank; MT = metric tons
CSOs located at 8th Ave. and E. Marginal PS have zero sediment loads, so were not included in this analysis.

The revised storm drain loads for Scenario 2 are compared to the base-case loads in Table 4. Note that discharges from Hamm and Puget Creeks are included with the storm drain discharges. The base-case load at the east bank #11 location (RM 1.24 E) was removed from the Scenario 2 simulation. This sediment load was incorporated into the waterfront area loads discussed below. Storm drain loads were added at two locations for Scenario 2: 1st Ave S (RM 2.10 W) and S 96th St (RM 4.17 W). Thus, storm drain loads were specified at 13 locations for Scenario 2, whereas 12 storm drain locations were used in the base-case simulation. For the 11 storm drain locations with unchanged locations, the load was decreased at six locations and increased at five locations for Scenario 2. Overall, the total storm drain load decreased by 9.5% (111 MT/yr) for the Scenario 2 simulation.

Table 4
Base-Case and Scenario 2 Sediment Loads at 14 Storm Drain Locations

Scenario 2 Name (Base-Case Name)	River Mile Location	Base-Case Sediment Load (MT/yr)	Scenario 2 Sediment Load (MT/yr)	Relative Change in Sediment Load (%)	Description of Change
SW Idaho SD (West bank #5)	0.28 W	72	62	-14	Original Location; Load Decreased
Diagonal Ave SD (Diagonal)	0.49 E	284	316	+11	Original Location; Load Increased
N/A (East bank #11)	1.24 E	29	0	-100	Storm Drain Source Removed
SW Kenny SD (West bank #6)	1.53 W	72	15	-79	Original Location; Load Decreased
SW Highland Park Wy SD (West bank #7)	1.87 W	72	62	-14	Original Location; Load Decreased
1st Ave S (N/A)	2.10 W	0	31	+100	Storm Drain Source Added
Near S Brighton St SD (East Bank #12)	2.17 E	19	44	+132	Original Location; Load Increased
7 Ave S SD (7 Ave S SD)	2.73 W	28	33	+18	Original Location; Load Increased
Slip 4 SDs (Slip 4 SDs)	2.83 E	93	97	+4	Original Location; Load Increased
KC Airport SD #2 (East bank #9)	3.80 E	65	48	-26	Original Location; Load Decreased
KC Airport SD #1 (East bank #10)	4.16 E	65	13	-80	Original Location; Load Decreased
S 96th St SD (N/A)	4.17 W	0	128	+100	Storm Drain Source Added
Hamm Creek (West bank #8)	4.33 W	250	86	-66	Original Location; Load Decreased
Norfolk SD (Norfolk SD)	4.93 E	121	124	+2	Original Location; Load Increased
Total		**1,170**	**1,059**	**-9.5**	**Total SD Load Decreased**

KC = King County; SD = storm drain; E = east bank; W = west bank; N/A = not applicable; MT = metric tons

Runoff sediment loads from waterfront areas adjacent to the LDW were estimated and distributed along the east and west banks of the LDW for the Scenario 2 simulation. The waterfront loads, which had been aggregated into the storm drain loads for the base-case simulation, were separated into 11 waterfront areas, with the total sediment load from the waterfront areas being 163 MT/yr, see Table 5. The 11 waterfront areas represent discharges from about 161 individual outfalls along the LDW. Within a specific waterfront area, the sediment load for that area, as input to the STM, was distributed over a distinct section of the LDW shoreline; see below for more discussion about specification of model inputs.

Table 5
Sediment Loads for 11 Waterfront Areas for Scenario 2

Waterfront Area	River Mile Location	Sediment Load (MT/yr)
WF-1	0.44 – 1.0 E	9
WF-2	0.98 – 1.96 E	14
WF-3	2.0 – 2.8 E	9
WF-4	2.94 – 4.4 E	43
WF-5	4.28 – 5.2 E	20
WF-6	3.1 – 4.28 W	11
WF-7	1.96 – 3.12 W	7
WF-8	1.53 – 1.96 W	12
WF-9	0.84 – 1.53 W	9
WF-10	-0.15 – 0.86 W	11
WF-11	4.28 – 5.98 W	18
Total		**163**

WF = waterfront area; E = east bank; W = west bank; MT = metric tons

Sediment loads from CSOs, storm drains, and waterfront areas were input at 87 individual locations (i.e., grid cells) in the STM for Scenario 2. Table 6 presents a summary of model inputs for lateral loads for Scenario 2. Multiple CSO and storm drain loads are input to a single grid cell at three locations: 1) RM 0.49 east bank (Diagonal Ave SD; Duwamish P.S. E; Hanford #1; CSO 111; total load of 325.3 MT/yr); 2) RM 1.53 west bank (SW Kenny SD; Terminal 115; total load of 16.5 MT/yr); and 3) RM 4.93 east bank (Norfolk SD; Norfolk CSO; total load of 128.1 MT/yr).

Table 6
Specification of Lateral-Load Model Inputs for Scenario 2

Lateral Load	Number of Grid Cells Used for Model Input	River Mile Location	Average Sediment Load Per Grid Cell (MT/yr)	Sediment Load (MT/yr)
WF-1	6	0.44 – 1.0 E	1.5	9.0
WF-2	8	0.98 – 1.96 E	1.5	11.6
WF-3	6	2.0 – 2.8 E	1.5	9.0
WF-4	13	2.94 – 4.4 E	3.1	40.2
WF-5	6	4.28 – 5.2 E	2.7	16.0
WF-6	7	3.1 – 4.28 W	1.3	9.0
WF-7	8	1.96 – 3.12 W	0.6	5.1
WF-8	2	1.53 – 1.96 W	3.0	6.0
WF-9	6	0.84 – 1.53 W	1.5	9.0
WF-10	4	-0.15 – 0.86 W	2.8	11.0
WF-11	4	4.28 – 5.98 W	4.5	18.0
SW Idaho SD	1	0.28 W	62.0	62.0
Duwamish P.S. W.	1	0.44 W	0.1	0.1
- Diagonal Ave SD - Duwamish P.S. E - Hanford #1 - CSO 111	1	0.49 E	325.3	325.3
Brandon St.	1	1.11 E	16.2	16.2
- SW Kenny SD - Terminal 115	1	1.53 W	16.5	16.5
SW Highland Park Wy SD	1	1.87 W	68.0	68.0
Michigan St.	1	1.96 E	9.8	9.8
Michigan W.	1	2.06 W	0.9	0.9
1st Ave S.	1	2.1 W	32.1	32.1
Near S Brighton St SD	1	2.17 E	44.0	44.0
7th Ave S SD	1	2.73 W	33.4	33.4
Slip 4 SDs	1	2.83 E	97.0	97.0
KC Airport SD #2	1	3.8 E	48.9	48.9
S 96th St SD	1	4.17 W	130.0	130.0
KC Airport SD #1	1	4.16 E	14.9	14.9
Hamm Cr.	1	4.33 W	86.0	86.0
- Norfolk SD - Norfolk CSO	1	4.93 E	128.1	128.1
Total	**87**	**---**	**---**	**1257.1**

KC = King County; SD = storm drain; CSO = combined sewer overflow; WF = waterfront area; E = east bank; W = west bank; MT = metric tons

The percentages of surface sediment originating from lateral sources at the end of the 10-year simulations for the base-case and Scenario 2 input distributions are shown in Figures 2-1 through 2-3. Generally, the spatial distributions of lateral-source content are similar, with no large-scale differences between the two simulations. Noticeable changes between the base-case and Scenario 2 input distributions typically occur over relatively small areas that are in the vicinity of storm drains where changes occurred between the two simulations (i.e., change in input location and/or magnitude of sediment load).

A one-to-one comparison of predicted lateral-source percentages for each grid-cell in the LDW at the end of the 10-year simulation is presented in Figure 2-4. This figure indicates that no apparent bias exists between the base-case and Scenario 2 results. The cumulative frequency distribution of the absolute difference (i.e., difference between Scenario 2 and base-case predictions) between lateral-source percentages at the end of the 10-year simulation is shown in Figure 2-5. These results show that the absolute difference in lateral-source content is less than +1% at about 94% of the grid-cells in the LDW.

SCENARIO 3: MOVEMENT OF LDW BED SEDIMENT INTO THE UPPER TURNING BASIN

The Scenario 3 simulation was conducted to analyze the fate of bed-source sediment originating from areas located upstream and downstream of RM 4.0. A specific focus of this simulation was determining the amount of bed-source sediment from the region downstream of RM 4.0 that is resuspended and redeposited in the region upstream of RM 4.0. This type of upstream transport is possible due to the estuarine circulation caused by the saltwater wedge in the LDW. For Scenario 3, a 10-year simulation was conducted, and the fate of bed sediment originating from the following four areas in the LDW was tracked: 1) Upper Turning Basin (Area 1); 2) navigation channel, RM 4.0 to 4.3 (Area 2); 3) bench areas upstream of RM 4.0 (Area 3); and 4) area downstream of RM 4.0 (Area 4).

The predicted spatial distributions of the relative amounts of bed sediment originating from the four areas in surface (0 - 10 cm) sediment at the end of the 10-year simulation are presented in Figures 3-1 through 3-4. Some sediment from Area 1 (Upper Turning Basin), which is primarily composed of sand, was resuspended and redeposited downstream of RM 4.0, but relatively small amounts of sediment from Area 1 were redeposited downstream of approximately RM 1.7 (Figure 3-1). Sediment from Area 2 (navigation channel, RM 4.0 to

4.3) represented 1% or less of surface sediments throughout the LDW at the end of the 10-year period, with sediment resuspended in this area being redeposited primarily between RM 1.6 and RM 4.0 (Figure 3-2). Similarly, sediment from Area 3 (bench areas upstream of RM 4.0) typically represented 1% or less of surface sediments throughout most of the LDW at the end of the 10-year period (Figure 3-3). The results shown on Figure 3-4 indicate that a relatively small amount of sediment from Area 4 (downstream of RM 4.0) was resuspended and redeposited upstream of RM 4.0, with Area 4 sediment representing 0.05% or less of the surface sediments upstream of RM 4.0 at the end of the 10-year period.

The total sediment mass balance for the 10-year period is shown in Figure 3-5. Additional quantification of the transport and fate of bed sediment originating from downstream of RM 4.0 is provided in Figure 3-6. The mass balance on Figure 3-6 shows that 240 MT of bed sediment originating from Area 4 was transported upstream and redeposited in the region upstream of RM 4.0 (i.e., Areas 1, 2, and 3). This amount of sediment deposition (240 MT) is compared to the total net deposition of 699,500 MT in the region upstream of RM 4.0 (see Figure 3-5). These results demonstrate that only about 0.03% of the net deposition in the region upstream of RM 4.0 (i.e., Areas 1, 2, and 3) consists of bed sediment originating from the region downstream of RM 4.0 (i.e., Area 4).

For the Scenario 3 simulation, total PCB concentrations for the 10-year period were predicted using the BCM equation. For the area being modeled, the bed sediment concentration was set equal to the FS baseline interpolated value. For bed sediment from other areas, the bed concentration was set equal to the SWAC of the grid cells located within the area from which the bed sediment originated. Using the FS baseline dataset, these SWACs, and the predicted SWACs for the 10-year period are listed in Table 7. The upstream and lateral chemical input parameters were set to the recommended mid range values used in the base case, which are 35 and 300 µg/kg dw, respectively. The predicted total PCB concentrations for the 10-year period are displayed in Figure 3-7.

Table 7
Predicted SWACs for Year 10 in Different Areas of the LDW

	Upper Turning Basin	Navigation Channel RM 4.0 to 4.3	Bench Areas Upstream of RM 4.0	Downstream of RM 4.0
Year 0 SWAC	77	48	54	470
Year 10 SWAC	40	44	42	N/A

Based on this analysis and the contribution from lateral loads, the sediment in the Upper Turning Basin and the navigation channel above RM 4.0 should not be adversely affected by surrounding sediment within the study area.

SCENARIO 4: MOVEMENT OF BED SEDIMENTS BETWEEN REACHES

The Scenario 4 simulation is similar to Scenario 3, with the difference being that Scenario 4 tracked the fate of bed sediment originating from three reaches in the LDW: 1) Reach 1 (RM 0.0 to 2.2); 2) Reach 2 (RM 2.2 to 4.0); and 3) Reach 3 (RM 4.0 to 4.75). These three reaches, as shown in Figure 4-1, were defined in the final STM (QEA 2008) based on differences in the hydrodynamic and sediment transport characteristics of each reach. The predicted spatial distributions of the relative amounts of bed sediment originating from the three reaches in surface (0 – 10 cm) sediment at the end of the 10-year simulation are presented in Figures 4-2 through 4-4. BCM simulations were not performed on the results of the Scenario 4 simulation.

The mass balances for bed sediment originating from each of the three reaches are of particular interest for Scenario 4; see Figures 4-5 through 4-7. The mass balance for bed sediment from Reach 1 shows that 20 MT was transported upstream and redeposited in Reach 2, with this mass of sediment corresponding to 6% of the net erosion from Reach 1 (Figure 4-5). A negligible amount of the sediment originating from Reach 1 was redeposited in Reach 3 (i.e., less than 3 MT, which corresponds to less than 0.001% of total net deposition in Reach 3). About 2% (240 MT) of the bed sediment resuspended within Reach 2 was transported upstream and redeposited in Reach 3 (Figure 4-6). Of the remaining 98% of sediment originating from Reach 2, 41% was redeposited in Reach 1 and 57% was transported downstream past RM 0.0. Nearly all of the bed sediment (greater than 99%) resuspended within Reach 3 was redeposited in the LDW (Figure 4-7).

SCENARIO 5: SEDIMENT SCOURED FROM GREATER THAN 10-CM DEPTH

An analysis of the effects of high-flow events on bed stability in the LDW was presented in the final STM (QEA 2008). Additional analysis of the 100-year high-flow event was conducted to determine the fate of bed sediment originating from two bed layers: 1) the 0- to 10-cm layer; and 2) the layer deeper than 10 cm. Areas in the LDW with predicted bed scour depths of 0 to 10 cm and deeper than 10 cm during the 100-year high-flow event are shown in Figure 5-1. Net erosion occurs over approximately 18% (70 acres) of the LDW sediment bed, on an area basis, during a 100-year high-flow event. Bed-scour depths of 0 to 10 cm and deeper than 10 cm occur over about 12% and 6% (i.e., 48 acres and 22 acres) of the LDW bed area, respectively. BCM simulations were not performed on the results of the Scenario 5 simulation.

The total sediment mass balance for the 100-year high-flow event simulation is shown in Figure 5-2. This mass balance figure is also presented in the final STM (QEA 2008) as Figure E-15. Mass balances for bed sediment originating from the 0-to-10-cm and deeper-than-10-cm layers are presented in Figures 5-3 and 5-4, respectively. Of the total suspended sediment load transported downstream past RM 0.0 during the 100-year high-flow event (i.e., 211,600 MT, as shown in Figure 5-2), only about 4% and 2% of the total load was composed of bed sediment originating from the 0-to-10-cm and deeper-than-10-cm layers (i.e., 7,800 MT and 3,500 MT, as shown in Figures 5-3 and 5-4), respectively. The total mass of sediment eroded from the bed during the 100-year high-flow event was predicted to be about 52,200 MT, with approximately 80% and 20% of the total eroded mass originating from the 0-to-10-cm (42,100 MT) and deeper-than-10-cm layers (10,100 MT), respectively. About 78% of the sediment resuspended from the original bed (i.e., 40,900 MT) was predicted to be redeposited in the LDW during the 100-year high-flow event.

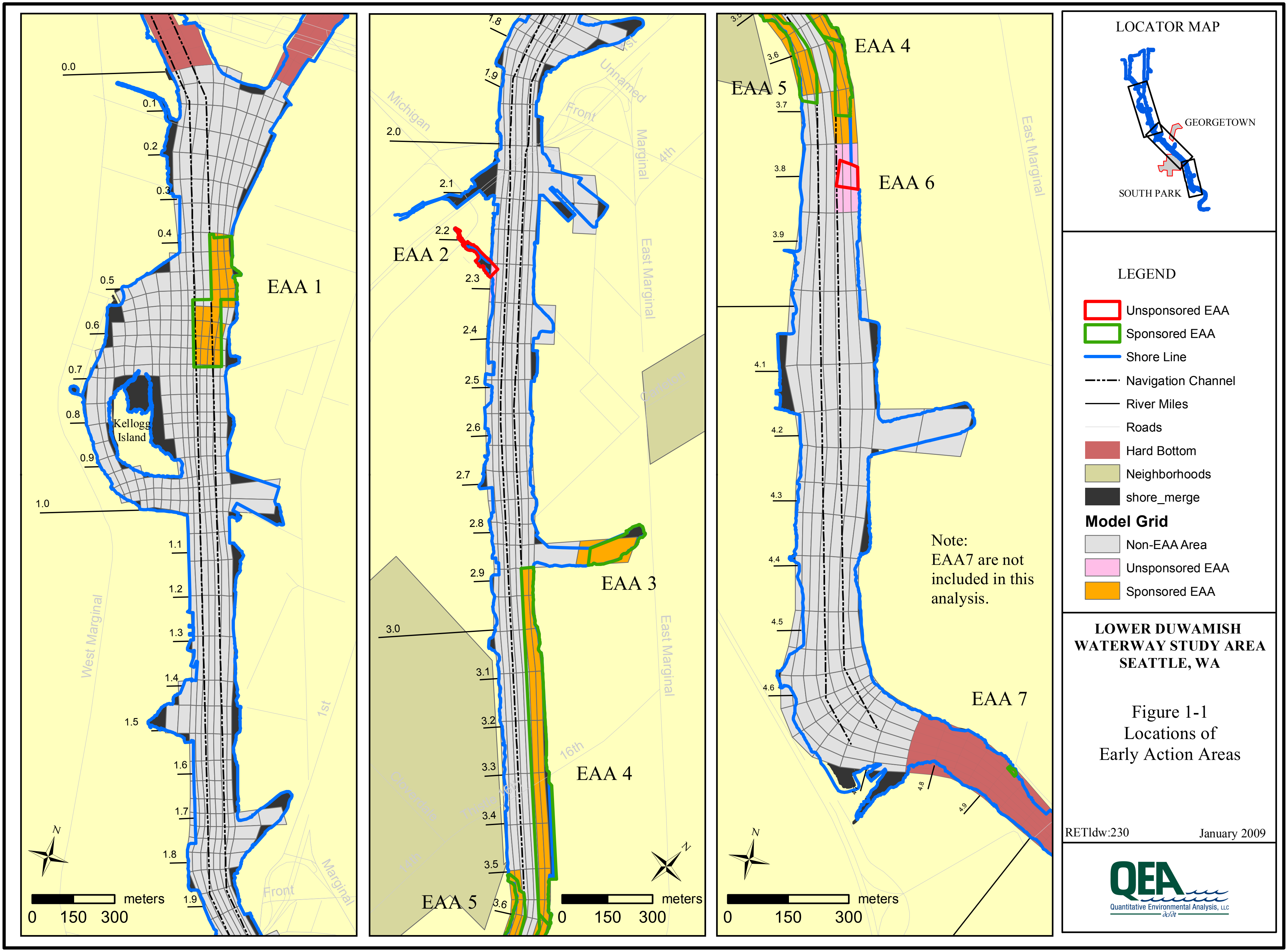
Many areas where scour in excess of 10 cm is predicted to occur have subsurface sediments that are below the Washington State sediment quality standards (SQS) or cleanup screening level (CSL). Figure 5-5 shows the areas where scour in excess of 10 cm is predicted to occur and 0- to 2-ft core data that exceeds the SQS or CSL. The 0- to 2-ft core data are shown because the maximum predicted depth of scour even using upper-bound erosion rate parameters is less than 2 feet.

The mass balance analysis shows that only a relatively small mass of the sediment load transported during a 100-year high-flow event is scoured from below 10 cm. Figure 5-5 indicates that of this small mass of sediment scoured from areas below 10 cm, only a few of these areas are above the SQS or CSL.

ATTACHMENTS

REFERENCE

Quantitative Environmental Analysis, LLC. 2008. *Lower Duwamish Waterway Sediment Transport Modeling Report. Final.* Prepared for the Lower Duwamish Waterway Group for submittal to the U.S. Environmental Protection Agency, Region 10, and Washington State Department of Ecology. Quantitative Environmental Analysis, LLC, Montvale, NJ. October 2008.



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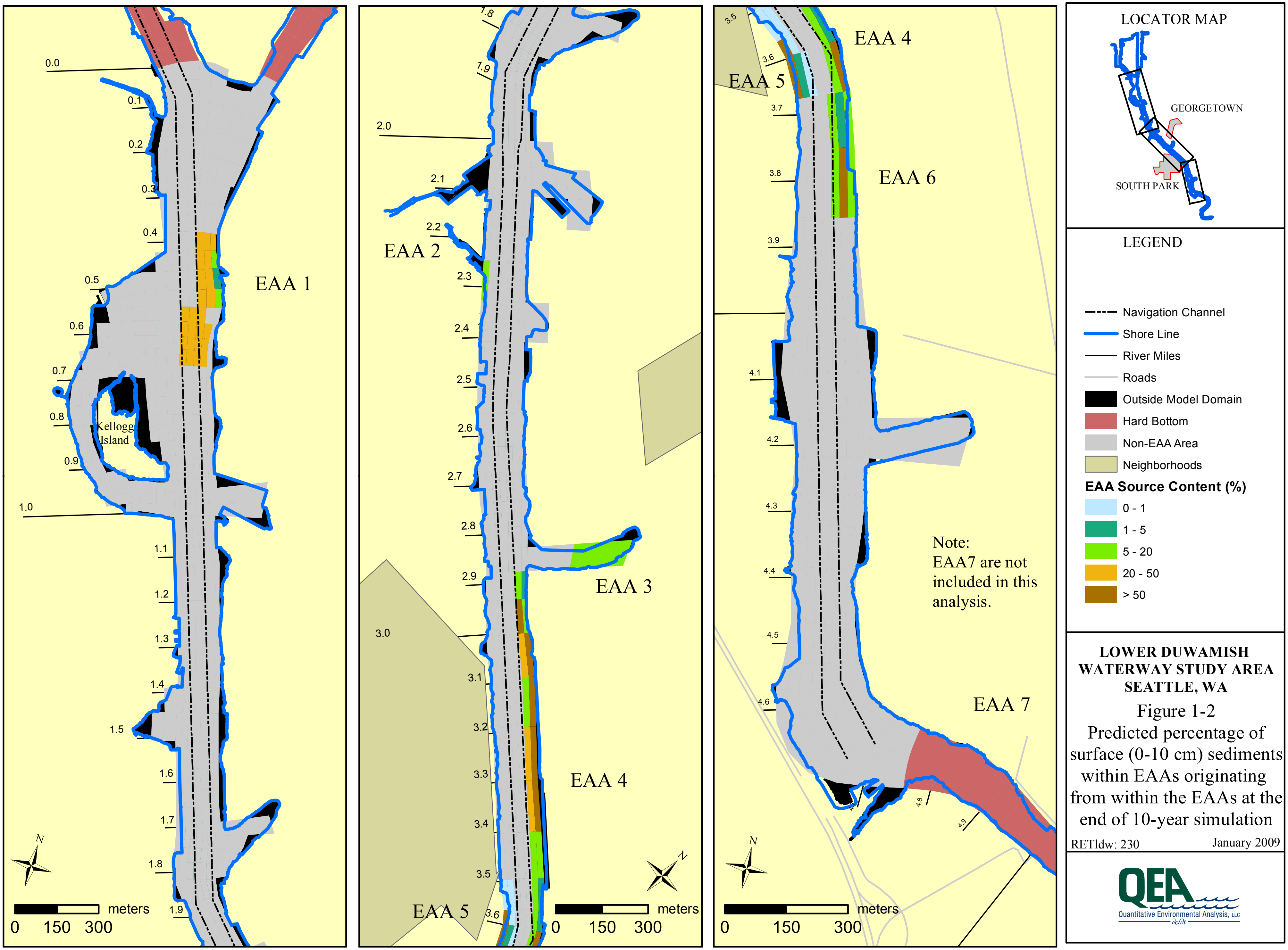

LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 1-2
Predicted percentage of surface (0-10 cm) sediments within EAAs originating from within the EAAs at the end of 10-year simulation

RETldw: 230 January 2009

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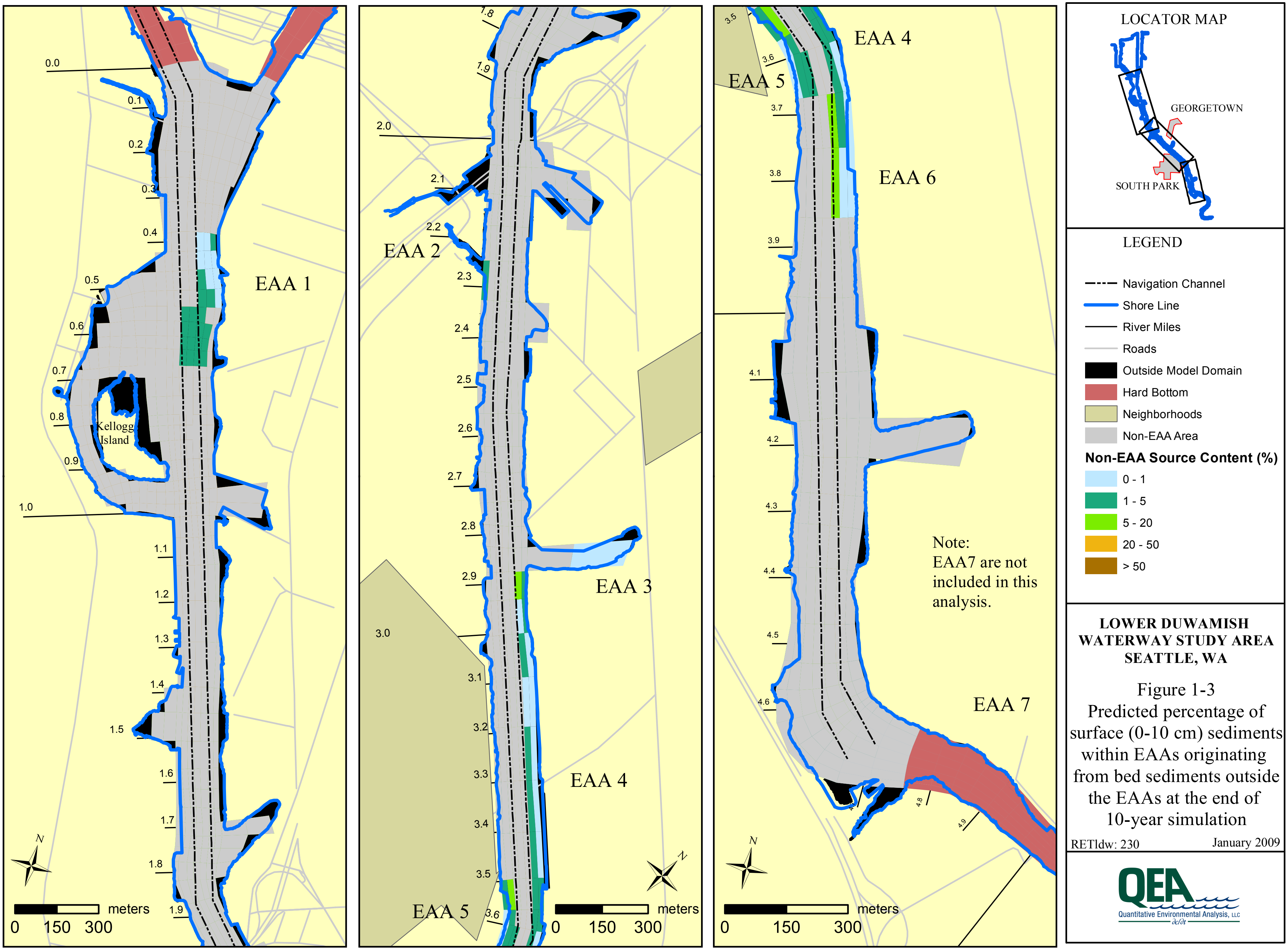

LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 1-3
Predicted 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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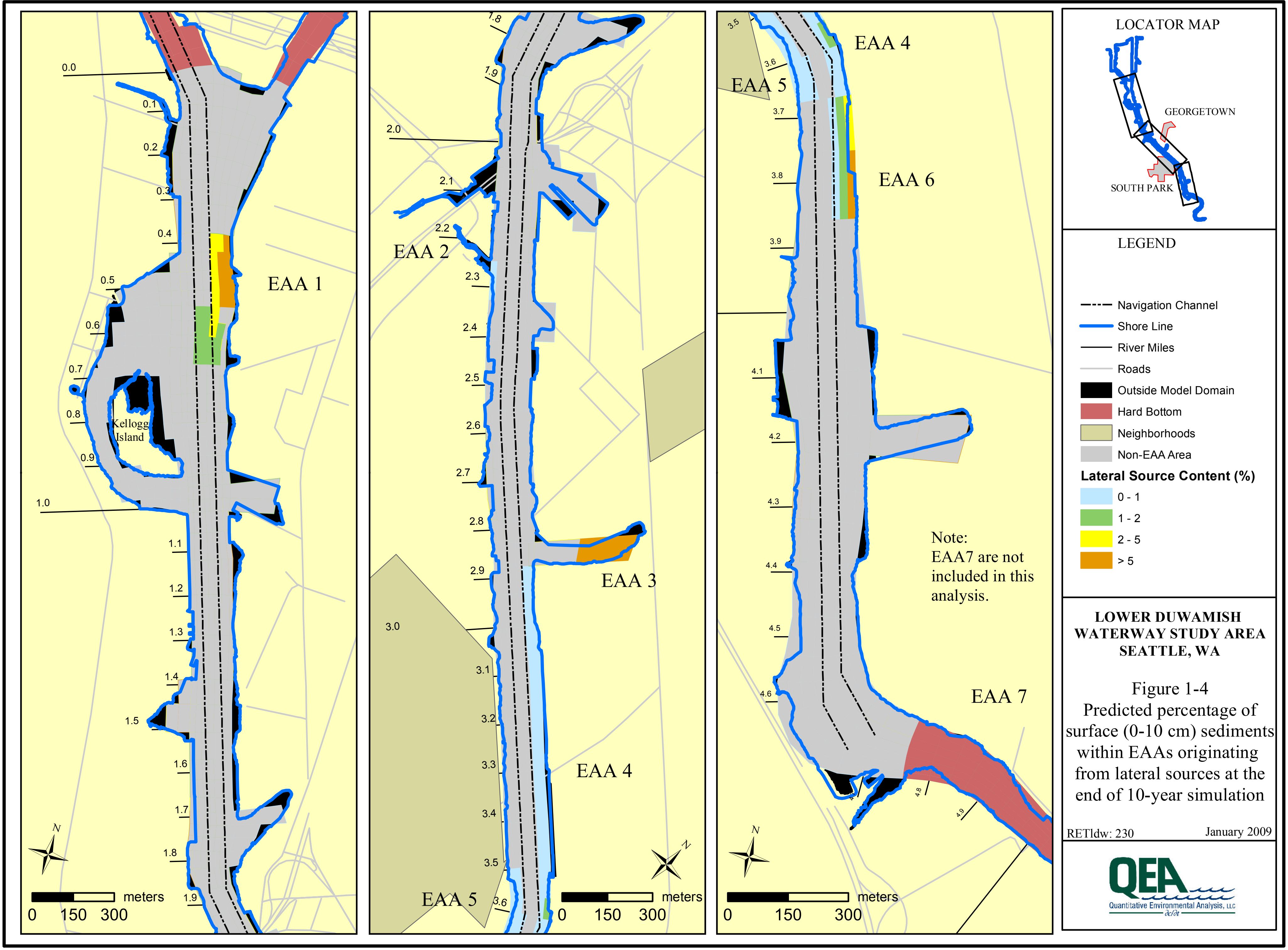

Figure 1-4
Predicted percentage of surface (0-10 cm) sediments within EAAs originating from lateral sources at the end of 10-year simulation

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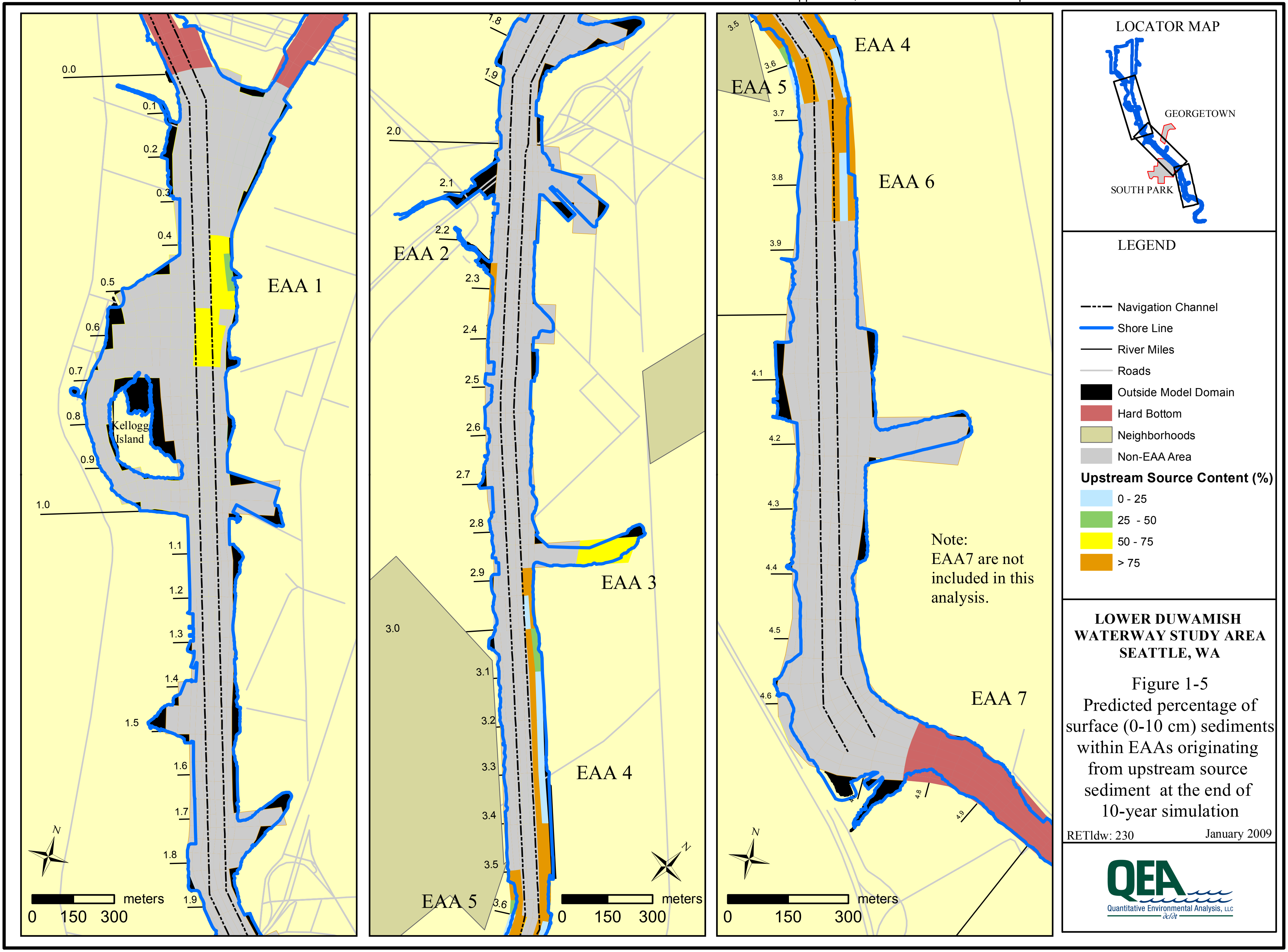

Figure 1-5
Predicted percentage of surface (0-10 cm) sediments within EAAs originating from upstream source sediment at the end of 10-year simulation

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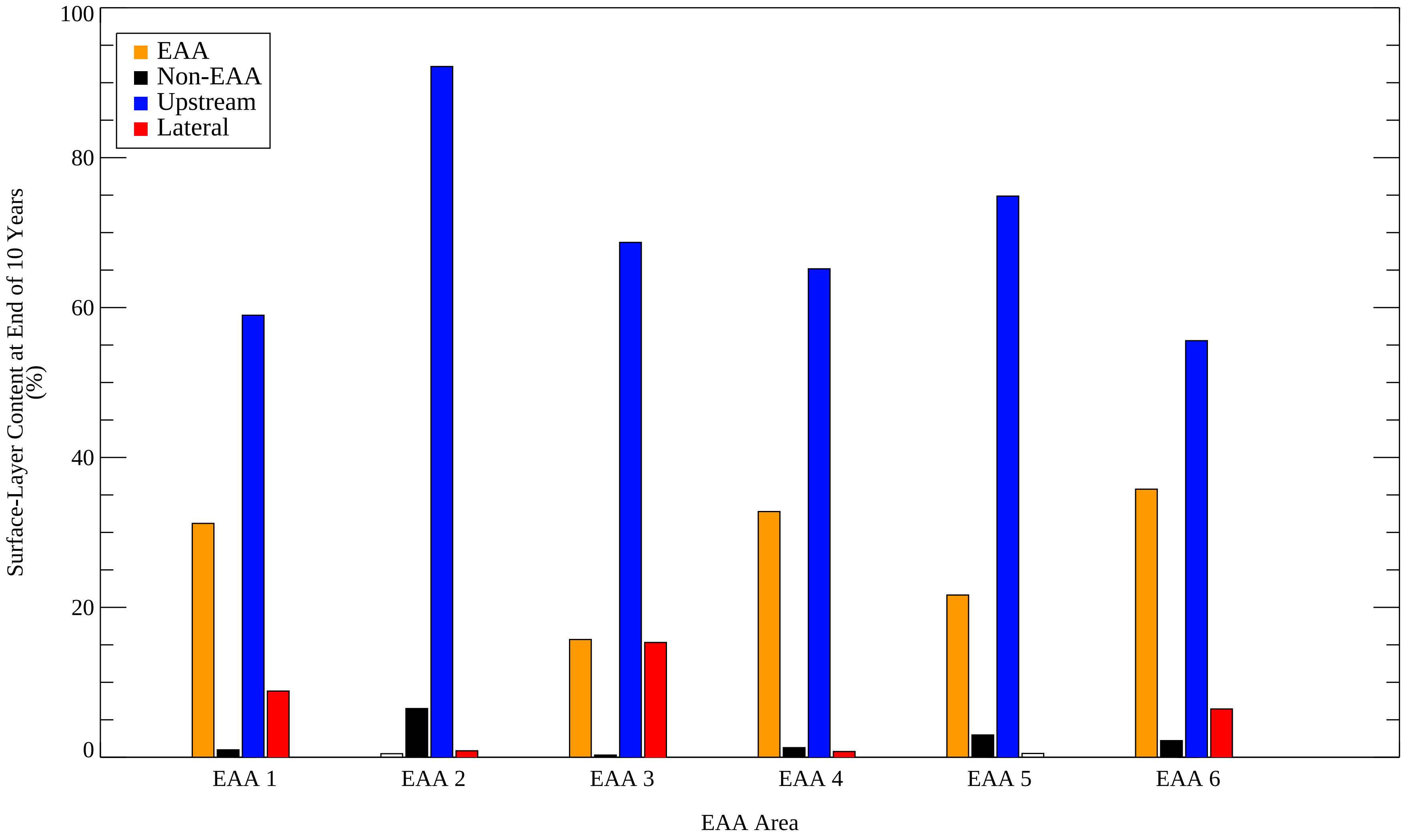
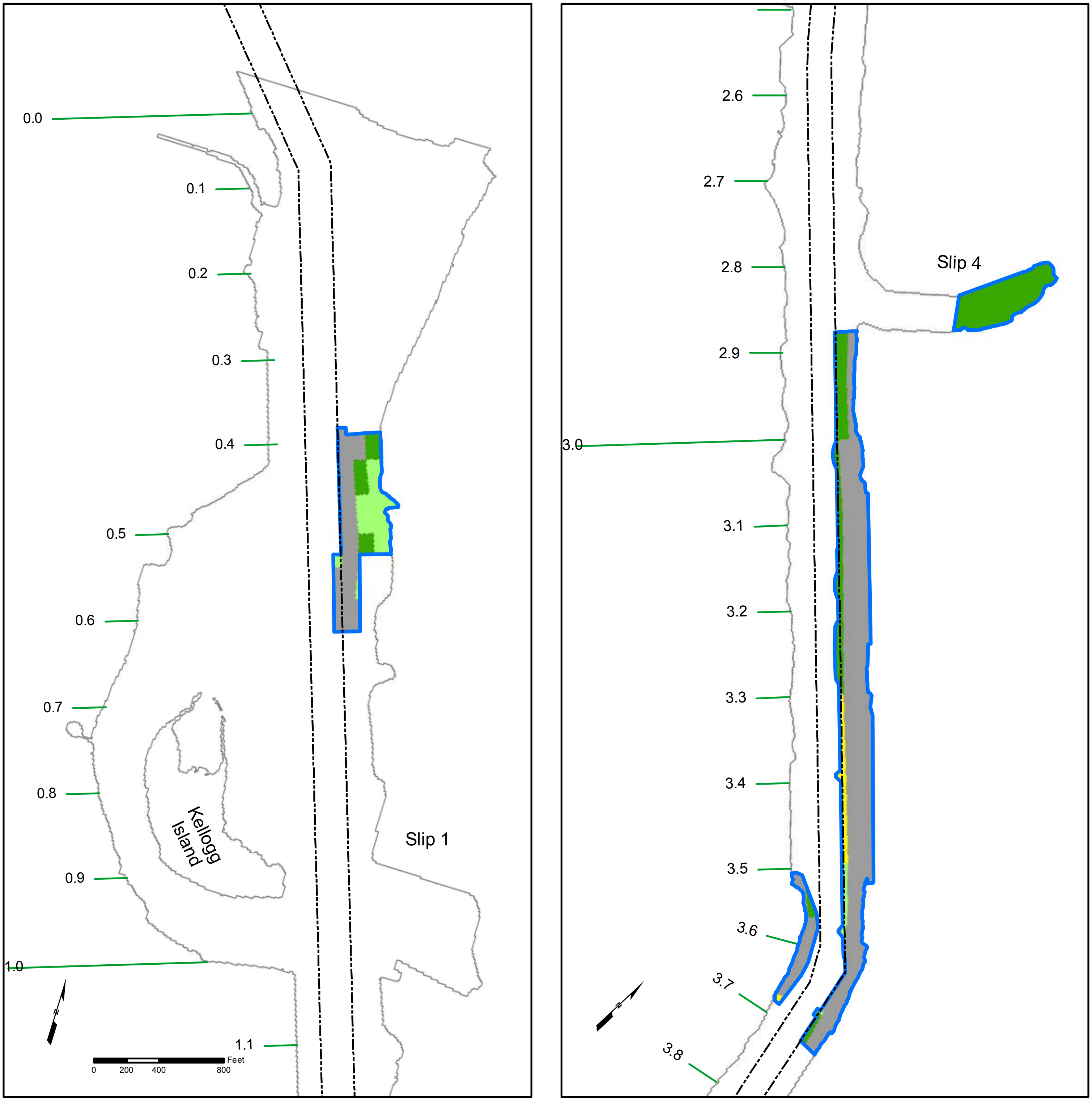
Figure 1-6. Comparison of surface-layer composition within different EAAs at end of 10-year simulation.



EAA 7 was not included in this analysis.



Notes:
1. Remediation was simulated in EAAs by changing the original baseline surface sediment concentration to the recommended post-remedy bed sediment replacement value (RV): 60 µg/kg dw.
2. 10 year model simulation for total PCBs were calculated using the recommended upstream input (35 µg/kg dw), the recommended lateral input (300 µg/kg dw), the RV for the bed sourced from the EAAs, and the reach-wide SWAC from sediment outside of the EAAs for the bed sourced from outside the EAAs. Those SWACs are as follows: Reach 1=271 µg/kg dw, Reach 2=435 µg/kg dw, and Reach 3=n/a (there are no EAAs in the STM footprint in Reach 3).

Legend

River Mile Marker
Navigation Channel
Early Action Area

Interpolated 10 Year Total PCB Concentration (µg/kg dw) in EAAs

- ≤ 60
- 60 - 100
- 100 - 240
- 240 - 480 (>SQS)
- 480 - 720
- 720 - 1,300
- > 1,300 (>CSL)

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Final Feasibility Study
60150279-14.49

Recontamination of EAAs: 10 Year Total PCB Surface Sediment Concentrations

DATE: 10/31/12 | DWRN:mvi/SEA | Revision: 0

FIGURE 1-7

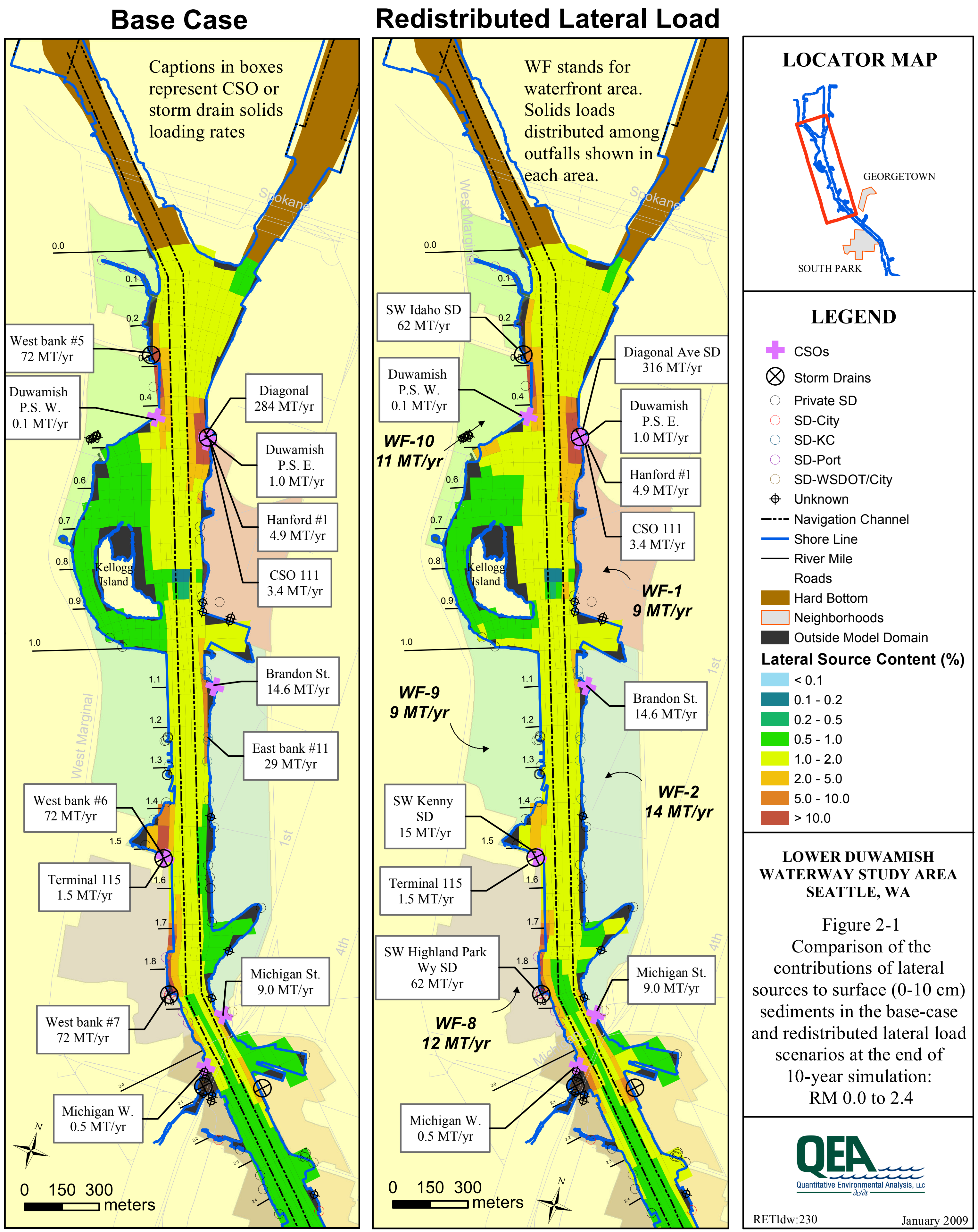

Figure 2-1
Comparison of the contributions of lateral sources to surface (0-10 cm) sediments in the base-case and redistributed lateral load scenarios at the end of 10-year simulation: RM 0.0 to 2.4

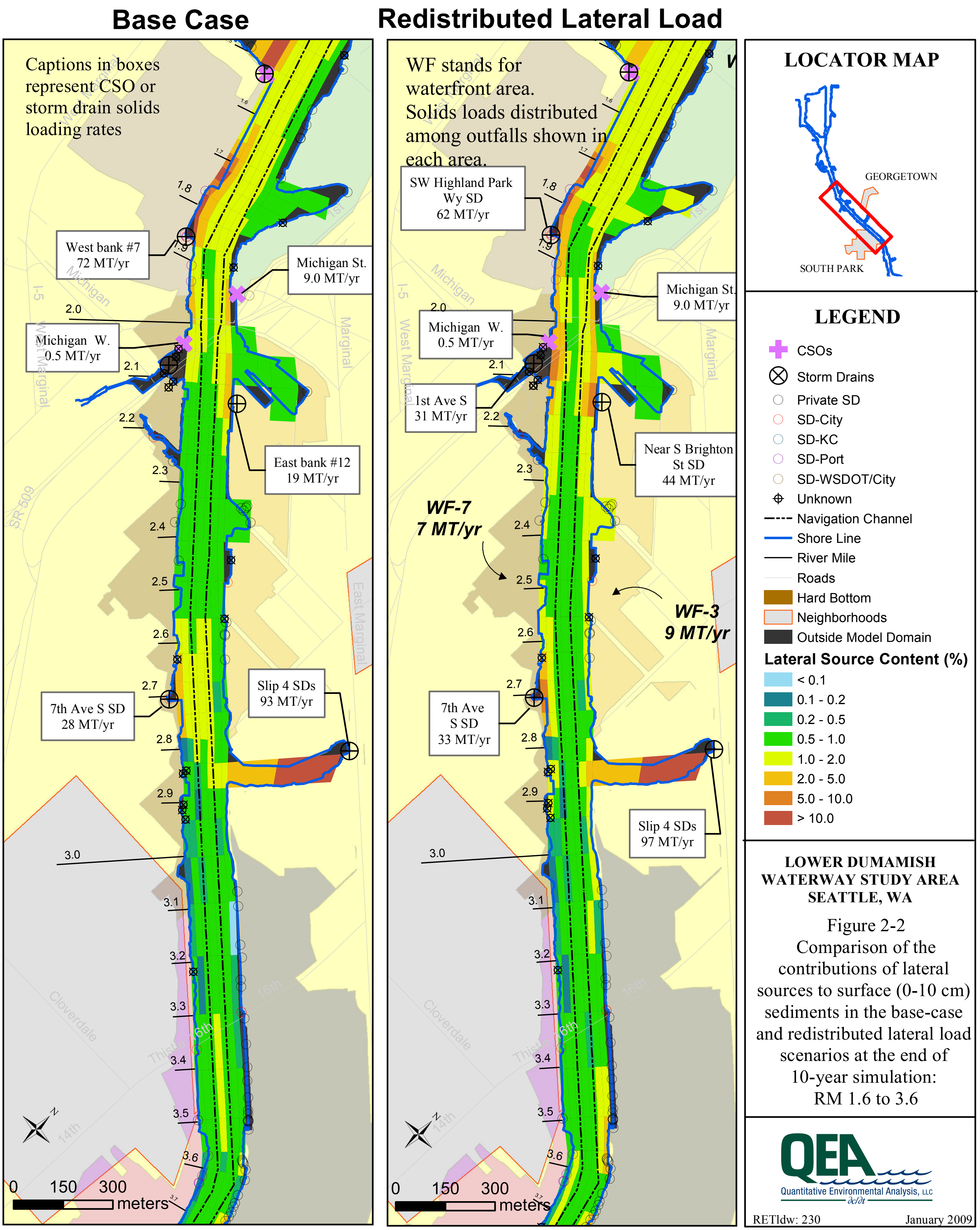

Figure 2-2
Comparison of the contributions of lateral sources to surface (0-10 cm) sediments in the base-case and redistributed lateral load scenarios at the end of 10-year simulation:
RM 1.6 to 3.6

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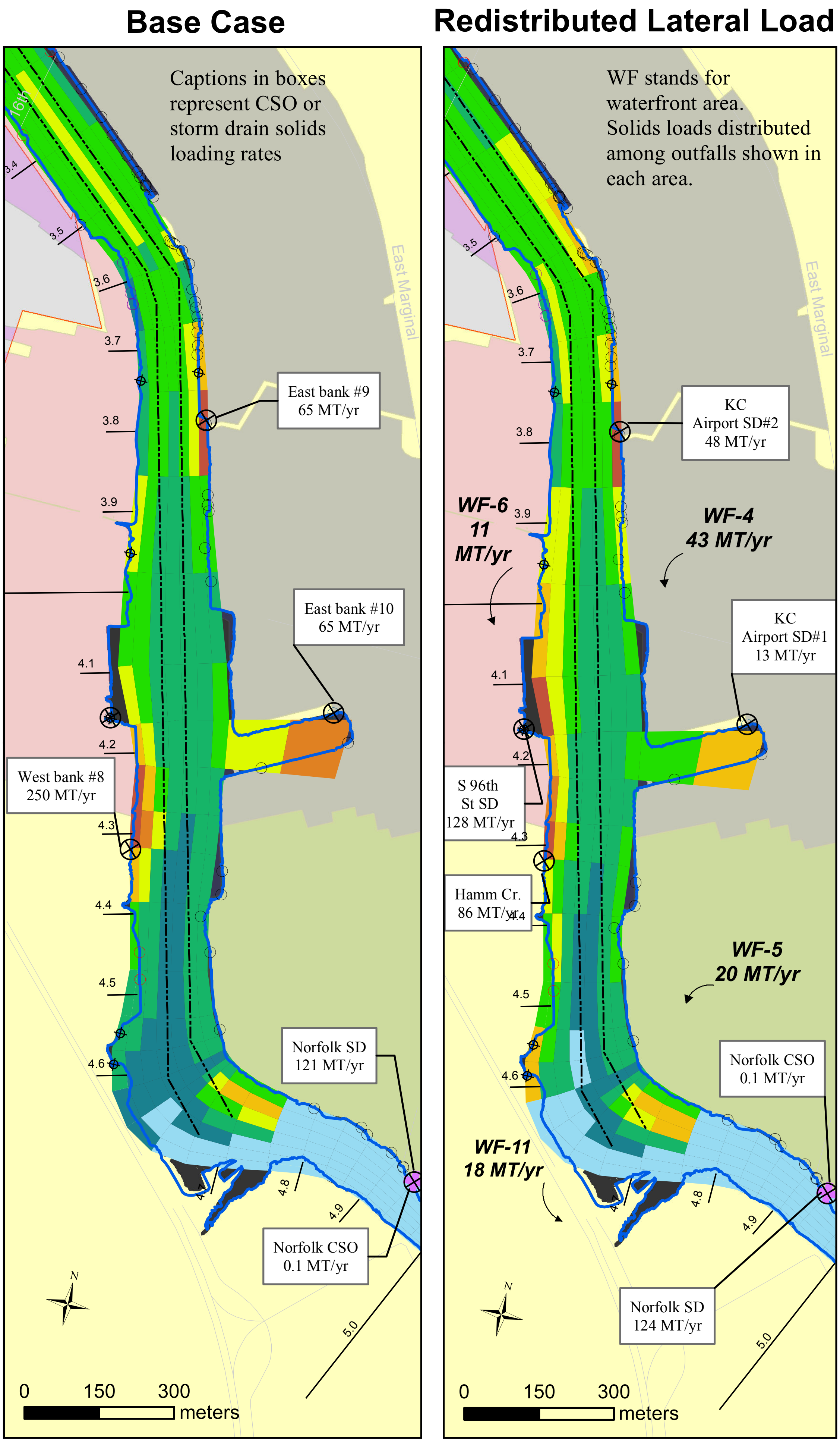

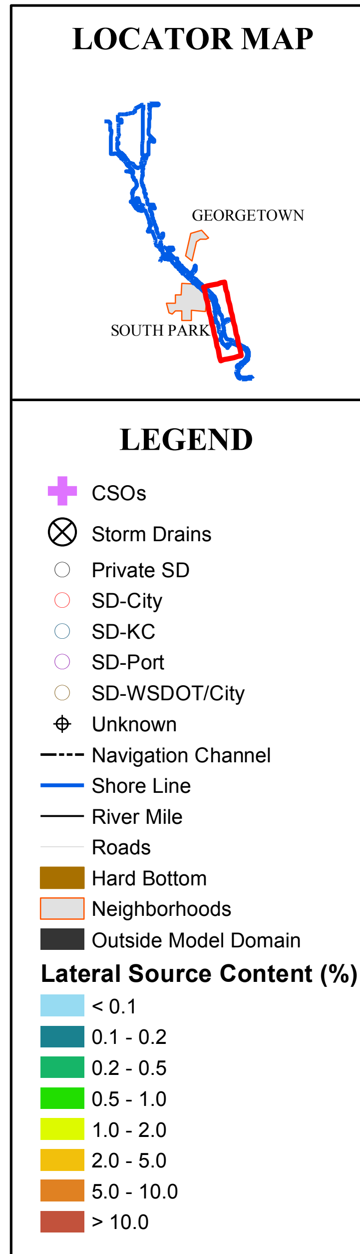

LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 2-3
Comparison of the contributions of lateral sources to surface (0-10 cm) sediments in the base-case and redistributed lateral load scenarios at the end of 10-year simulation: RM 3.5 to 4.75

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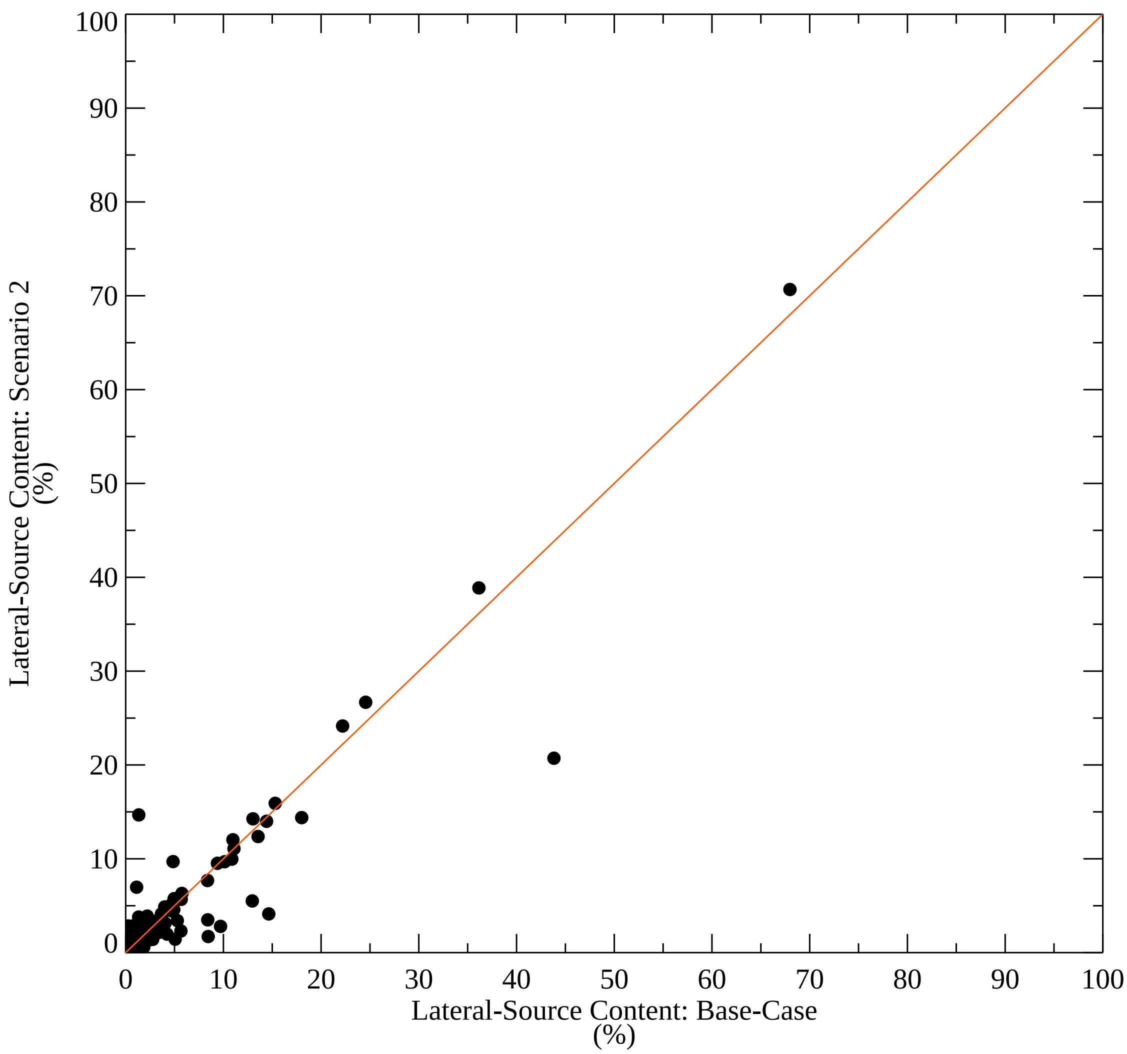
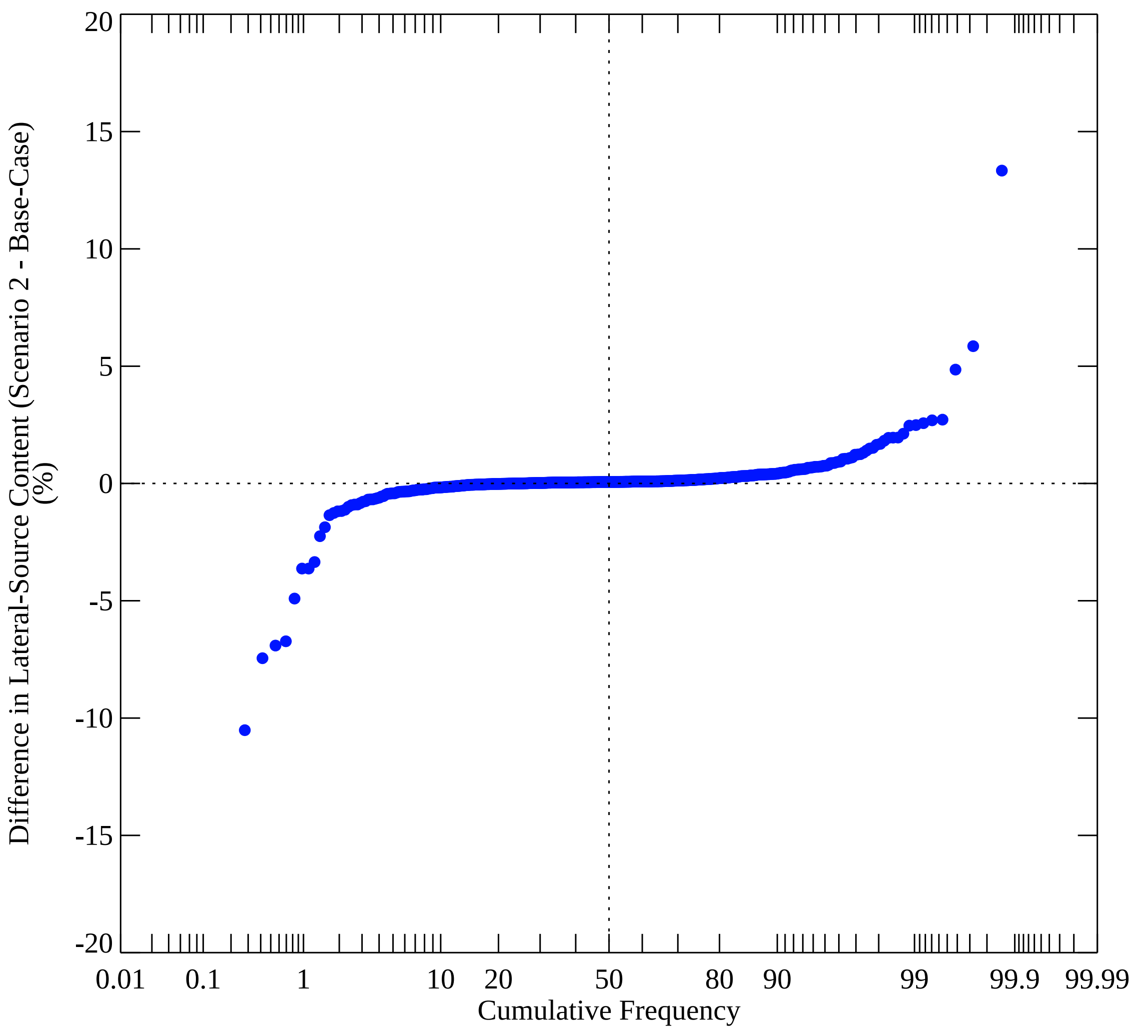
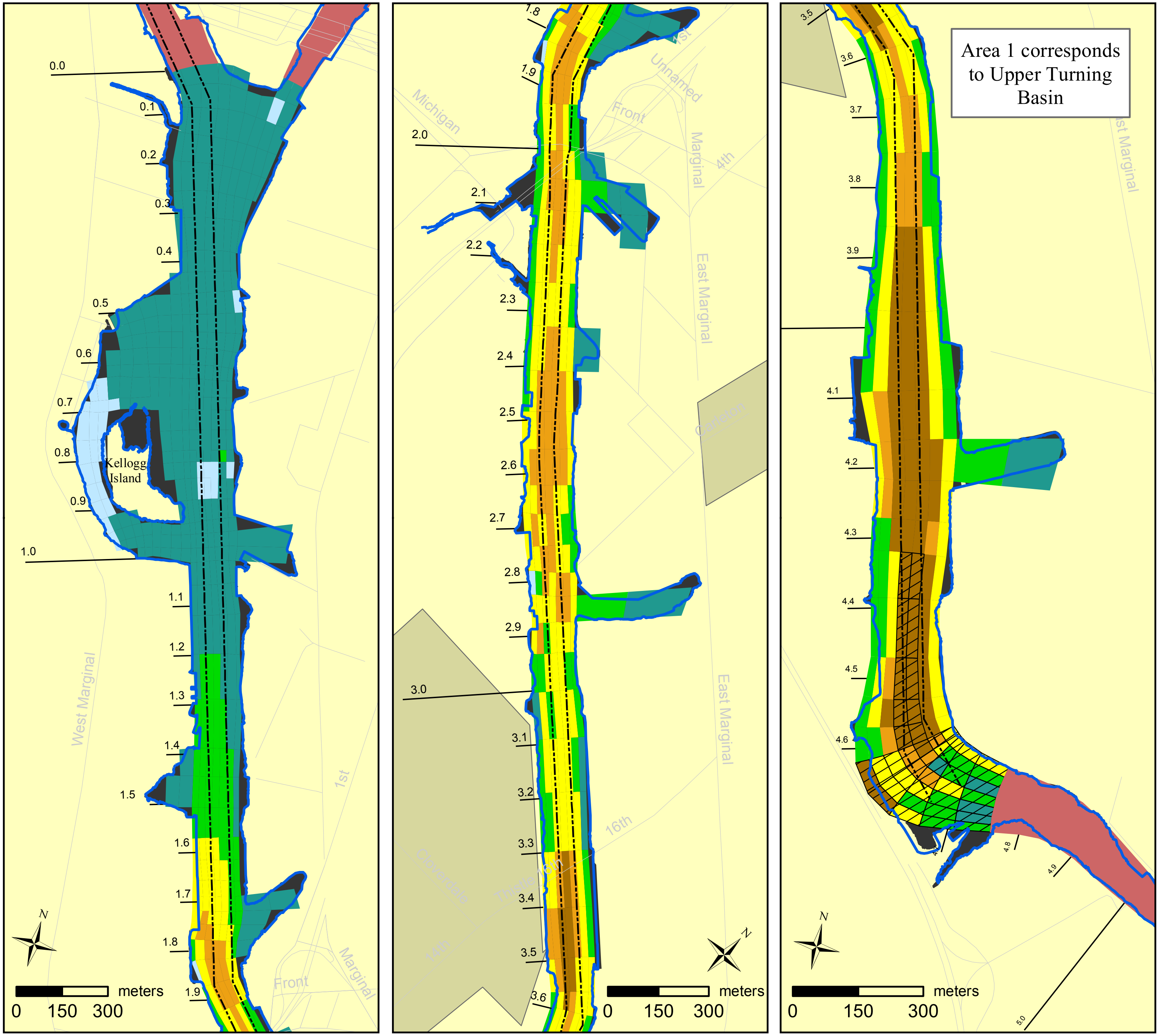
Figure 2-4 Cell-by-cell comparison of base-case and redistributed lateral load contributions to surface (0-10 cm) sediments at the end of 10-year simulation.



Total number of cells compared is 720.

Figure 2-5 Cumulative frequency distribution of absolute difference between base-case and redistributed lateral load contributions to surface (0-10 cm) sediments at the end of 10-year simulation.





LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 3-1.
Predicted percentage of surface (0-10 cm) sediments resuspended from Upper Turning Basin and re-deposited in other LDW areas at the end of 10-year simulation.

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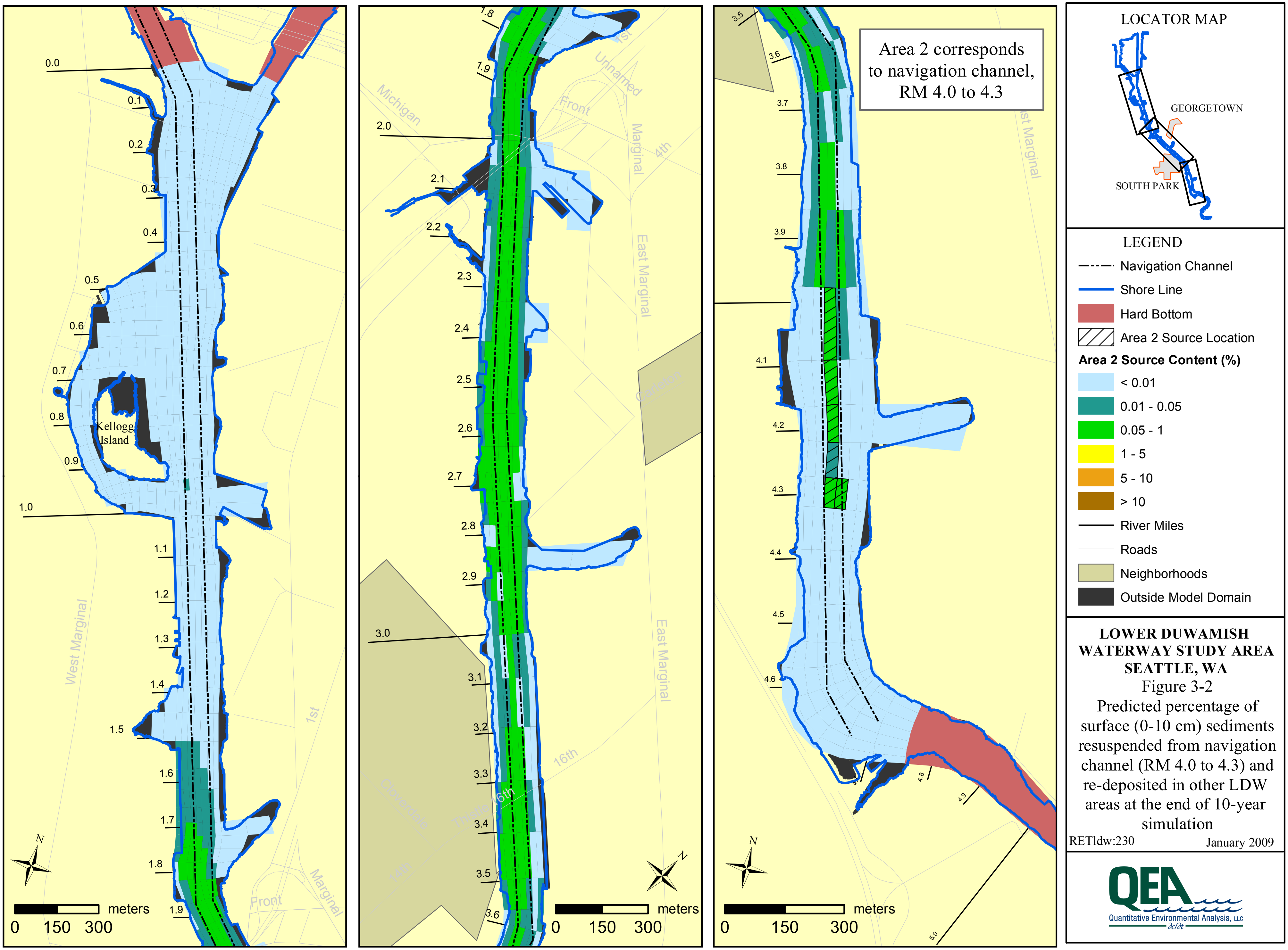

LOWER DUWAMISH WATERWAY STUDY AREA
SEATTLE, WA
Figure 3-2
Predicted percentage of surface (0-10 cm) sediments resuspended from navigation channel (RM 4.0 to 4.3) and re-deposited in other LDW areas at the end of 10-year simulation

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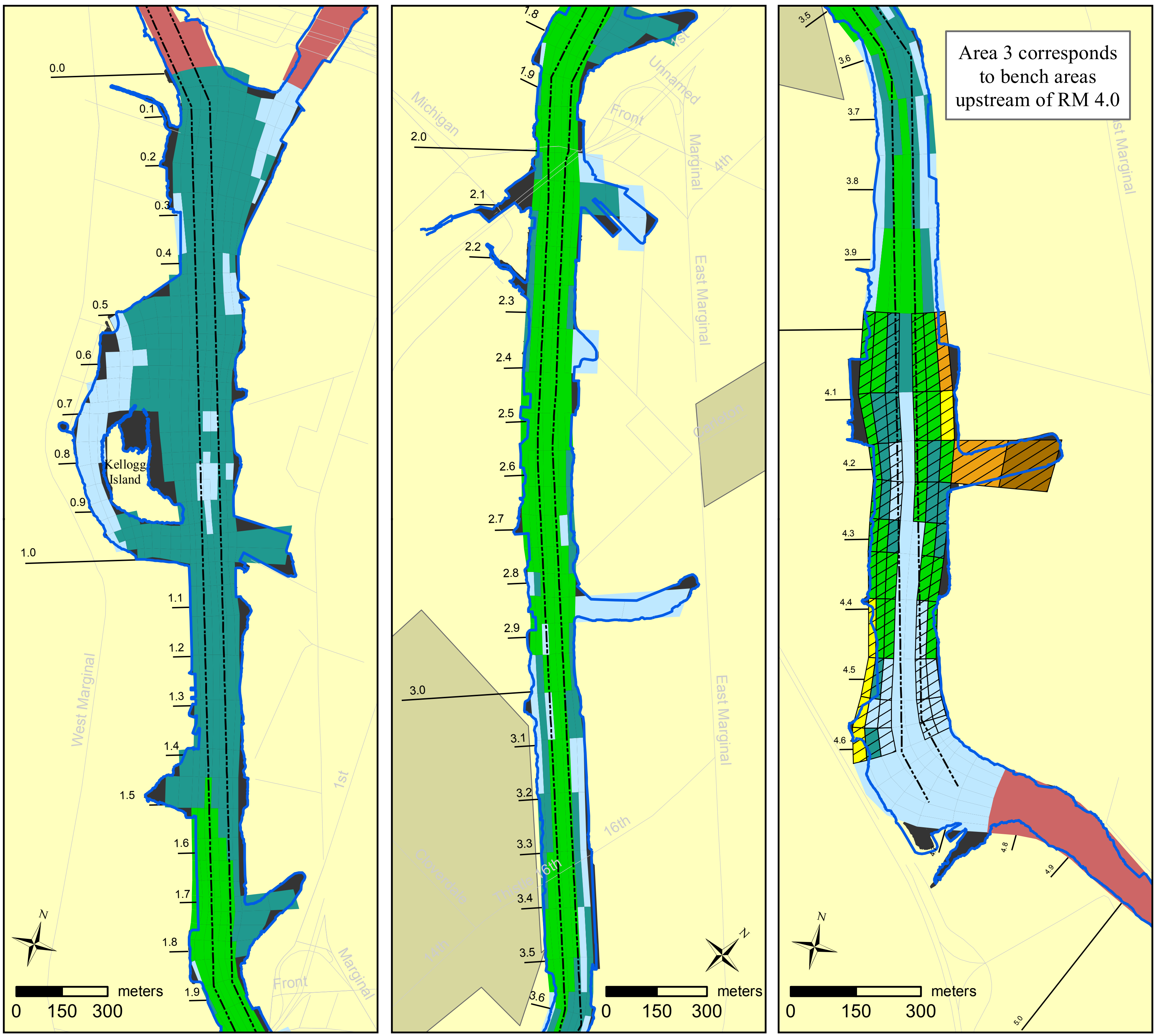

LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 3-3

Predicted percentage of surface (0-10 cm) sediments resuspended from bench areas upstream of RM 4.0 and re-deposited in other LDW areas at the end of 10-year simulation

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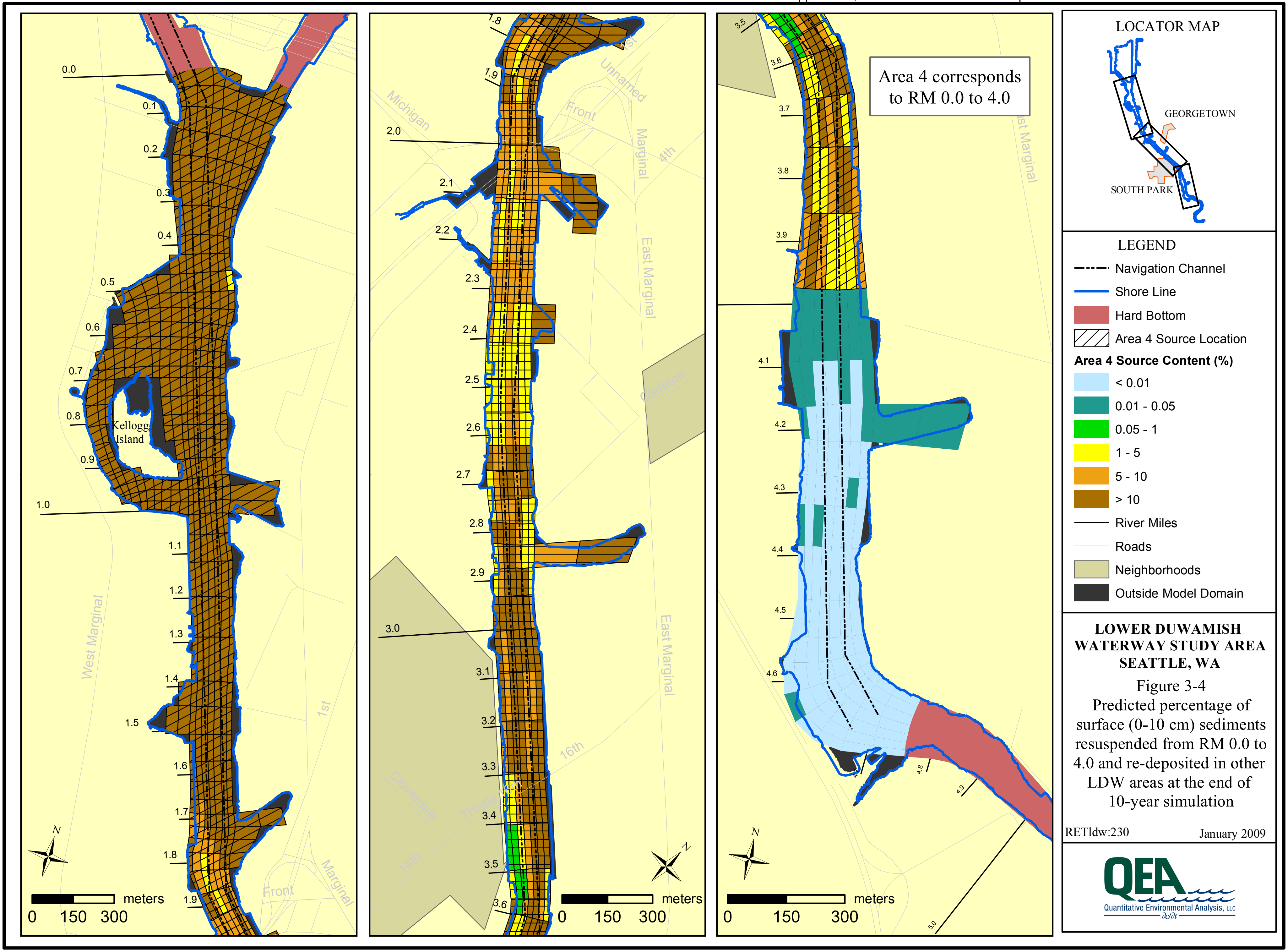

LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 3-4
Predicted 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

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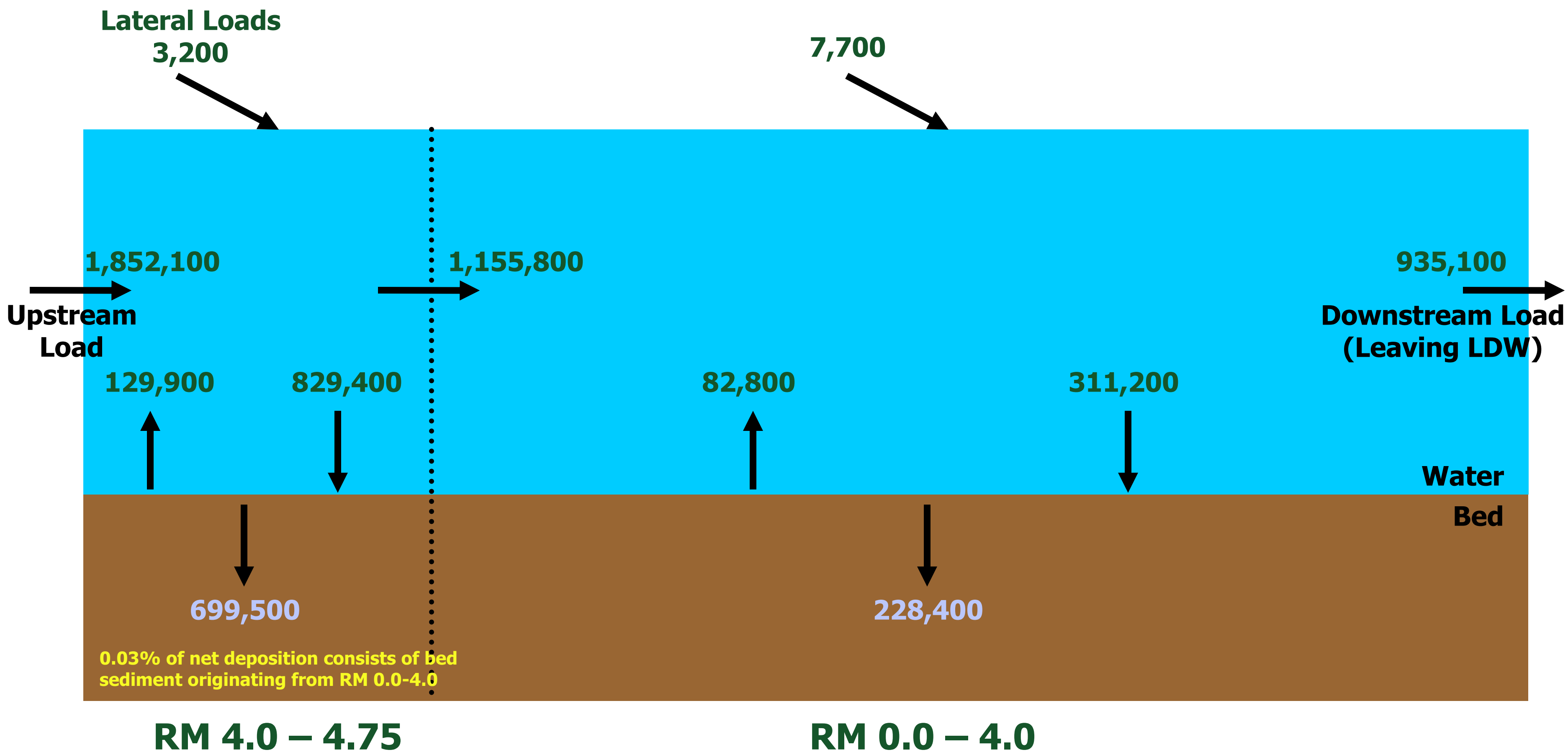
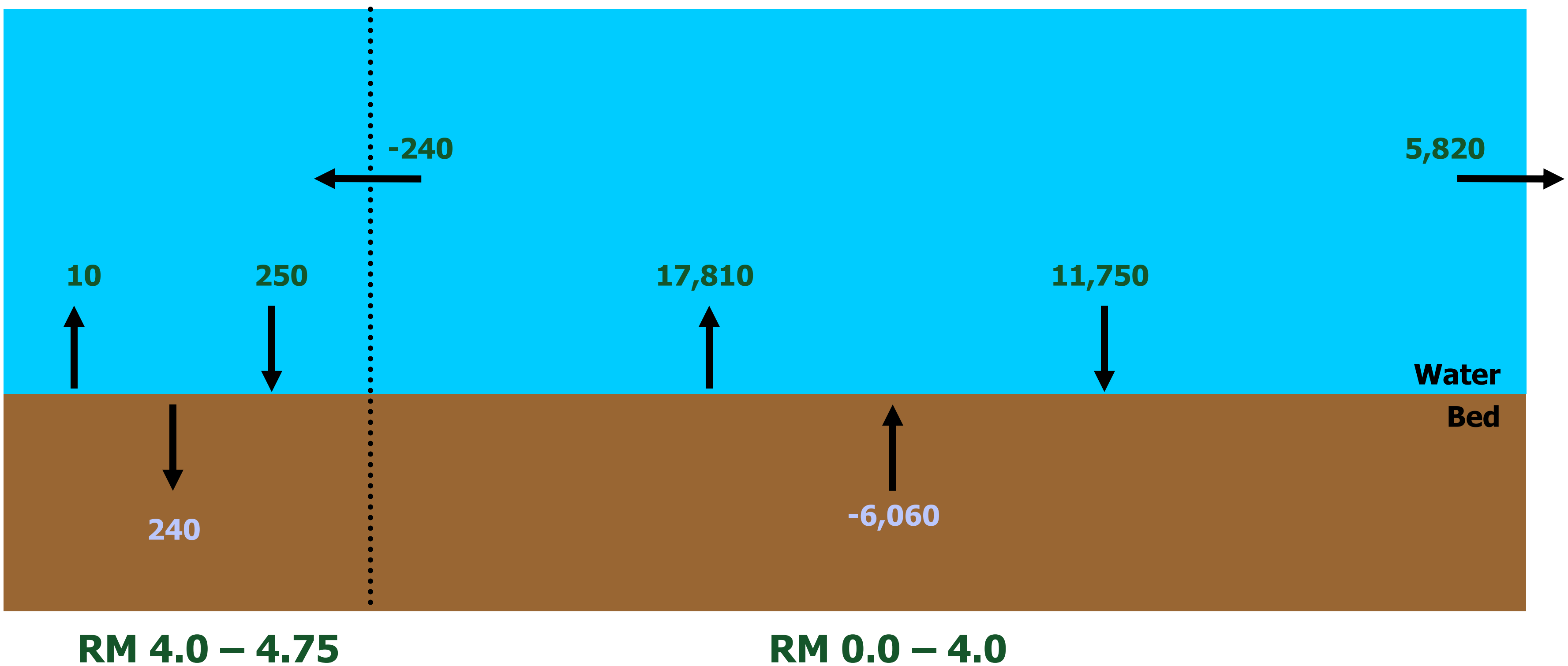
Figure 3-5 Total sediment mass balance for Scenario 3 simulation for 10-year period

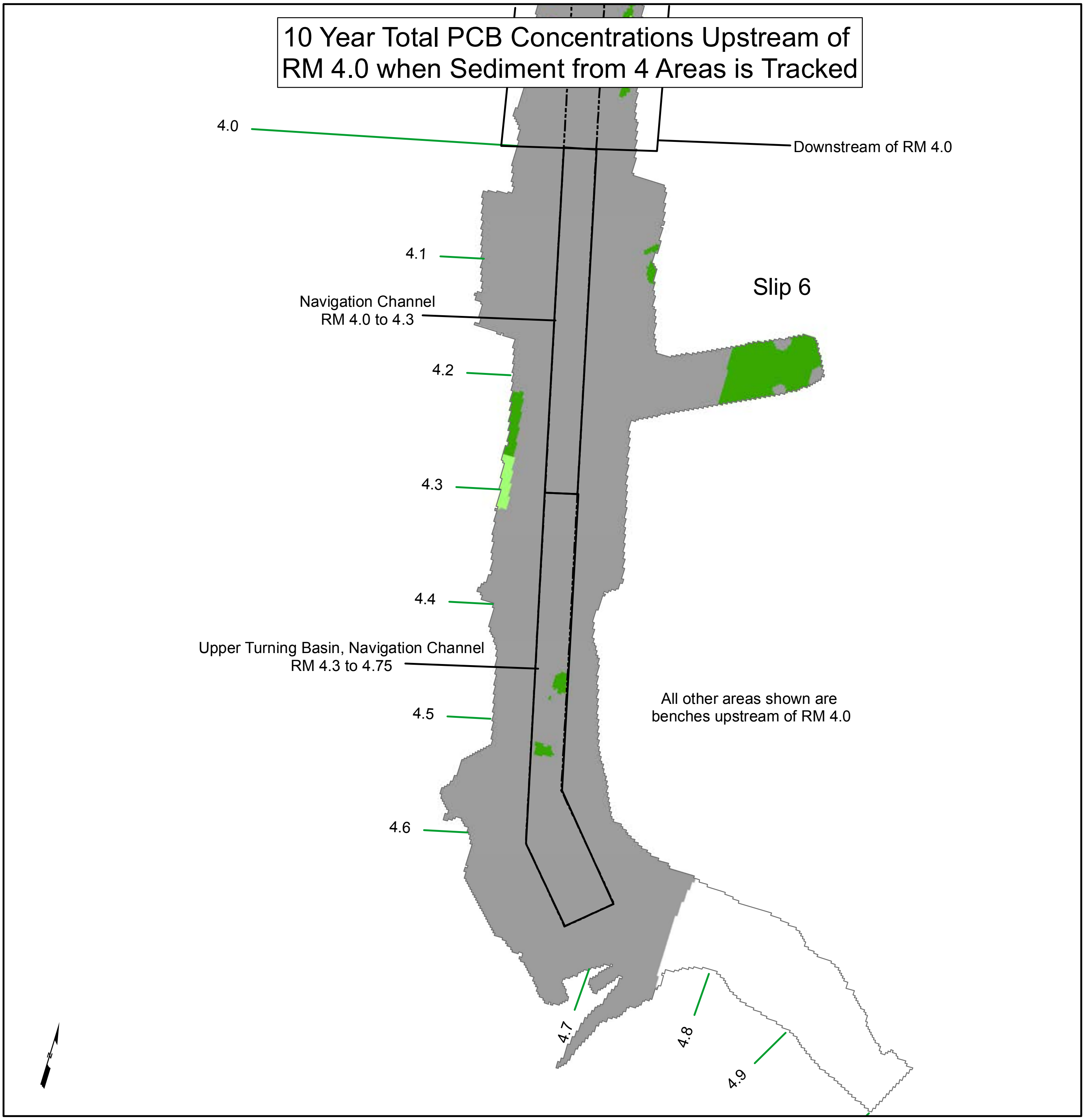


Notes:
Sediment mass units are in metric tons.
Mass balance results are rounded to the nearest 100 metric tons.

Figure 3-6 Mass balance for bed sediment originating from RM 0.0 to 4.0 for 10-year period



Notes:
Sediment mass units are in metric tons.
Mass balance results are rounded to the nearest 10 metric tons.



Notes:
1. Special Scenario 3 tracks movement of surface sediment from 4 areas into the Upper Turning Basin, downstream of RM 4.0, benches upstream of RM 4.0, navigation channel from RM 4.0 to 4.3, and navigation channel from 4.3 to 4.75 (Upper Turning Basin).
2. The recommended BCM input parameters were used: upstream = 300 µg/kg dw, lateral = 35 µg/kg dw.
3. Bed sediment input parameters for sediment originating from outside of the area being modeled were set to the FS baseline SWAC for those external areas. For example, in the Upper Turning Basin sediment migrating from the following areas was assigned the following input parameters: navigation channel RM 4.0 to 4.3 = 48 µg/kg dw; Upper Turning Basin = baseline value of interpolated cell; benches upstream of RM 4.0 = 54 µg/kg dw; and downstream of RM 4.0 = 474 µg/kg dw.

Legend

Interpolated Total PCB Concentration (µg/kg dw)

- ≤ 60
- > 60 - 100
- > 100 - 240
- Area From Which Bed Sediment is Tracked
- River Mile Marker
- Navigation Channel

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Special Scenario 3: 10 Year Total PCB Surface Sediment Concentrations

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FIGURE 3-7

LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 4-1
Delineation of Reaches 1, 2, and 3 for Scenario 4 simulation

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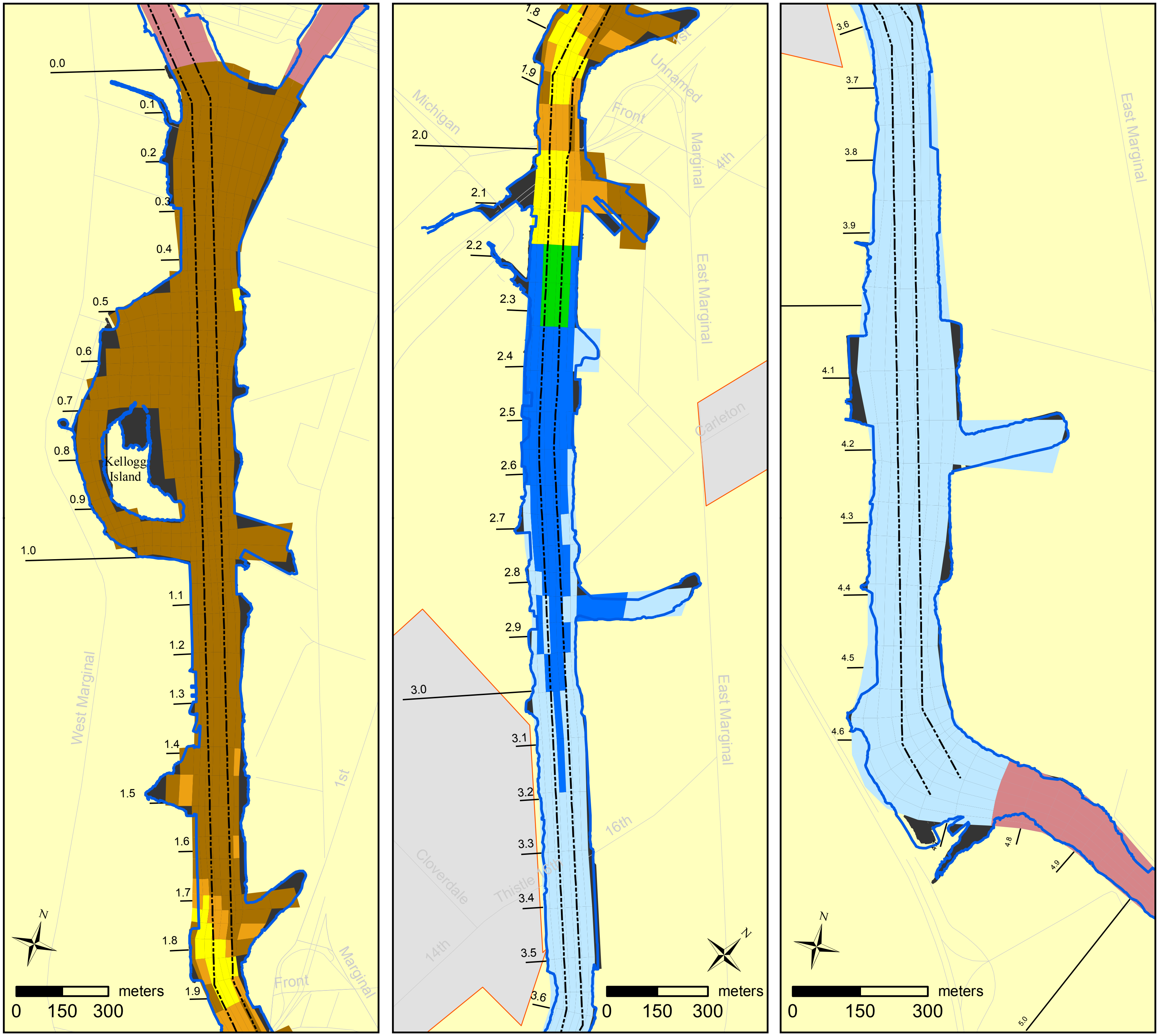

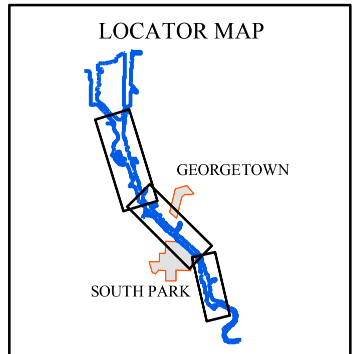

LEGEND

Reach 1 Bed Source Content (%)

- < 0.01
- 0.01 - 0.05
- 0.05 - 1
- 1 - 5
- 5 - 10
- > 10
- Navigation Channel
- Shore Line
- River Mile
- Roads
- Neighborhoods
- Outside Model Domain
- Hard Bottom

LOWER DUMAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 4-2
Predicted percentage of surface (0-10 cm) sediments originating from Reach 1 at the end of 10-year simulation

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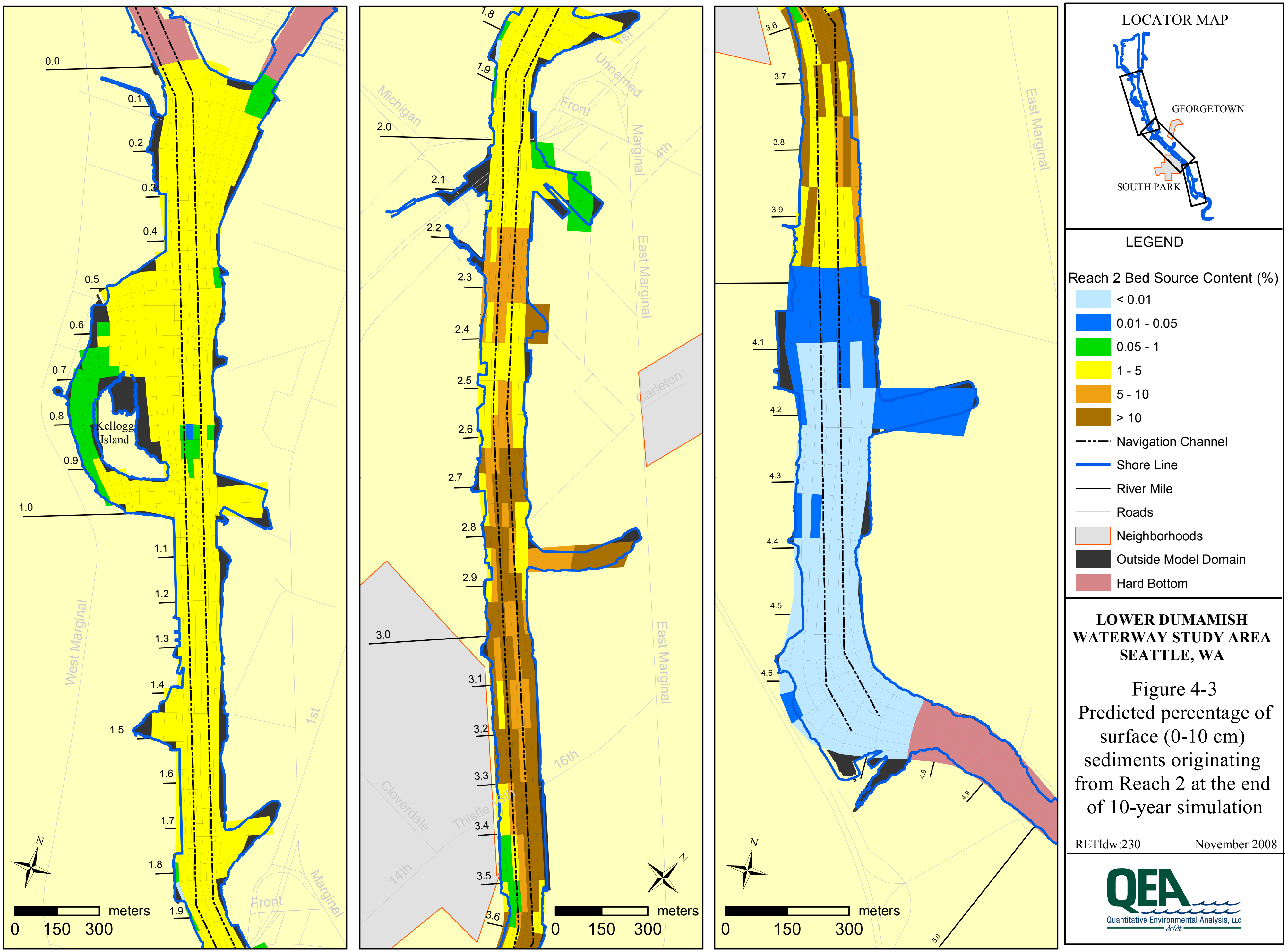

LOWER DUMAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 4-3
Predicted percentage of surface (0-10 cm) sediments originating from Reach 2 at the end of 10-year simulation

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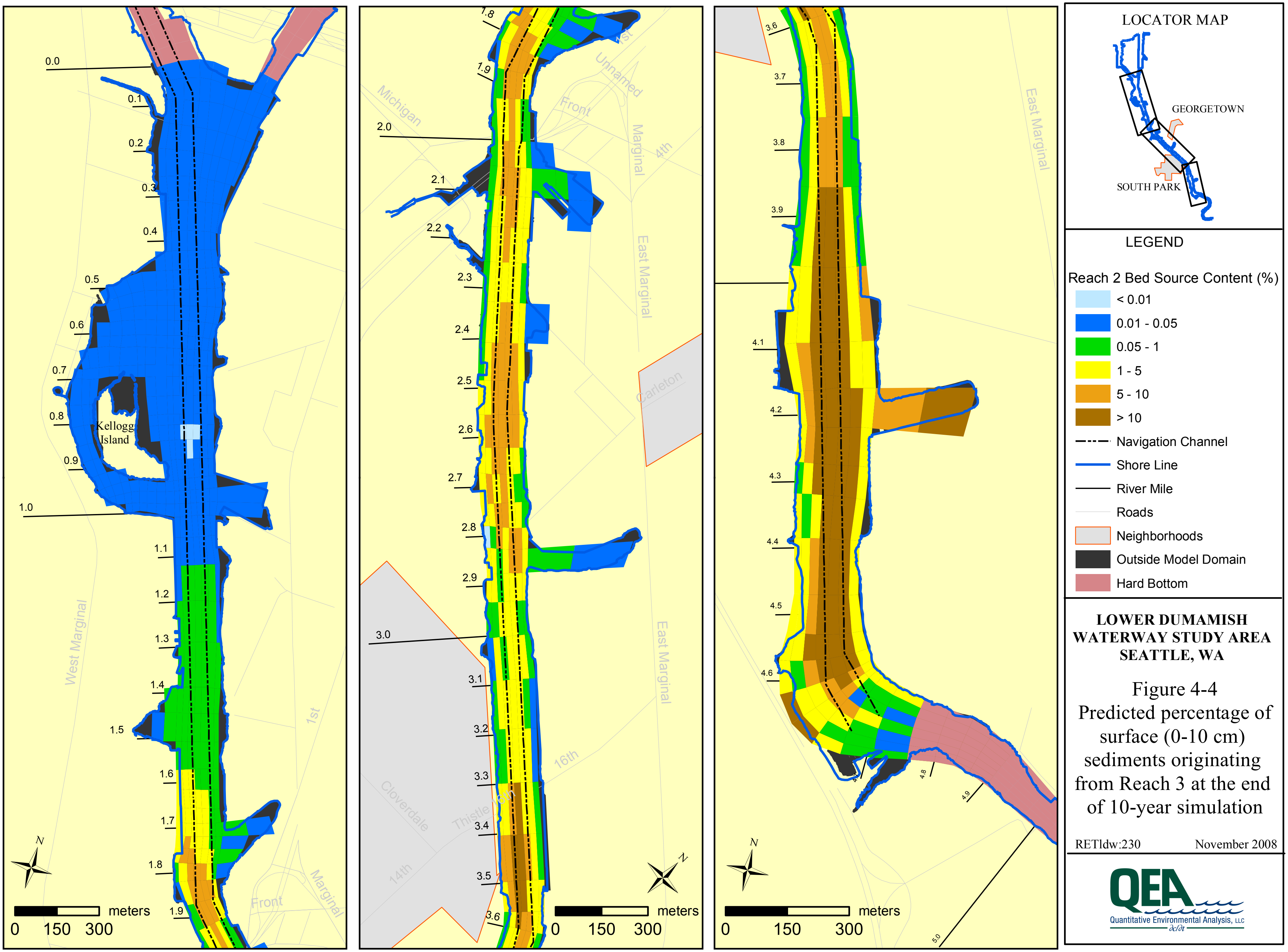

LOWER DUMAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 4-4
Predicted percentage of surface (0-10 cm) sediments originating from Reach 3 at the end of 10-year simulation

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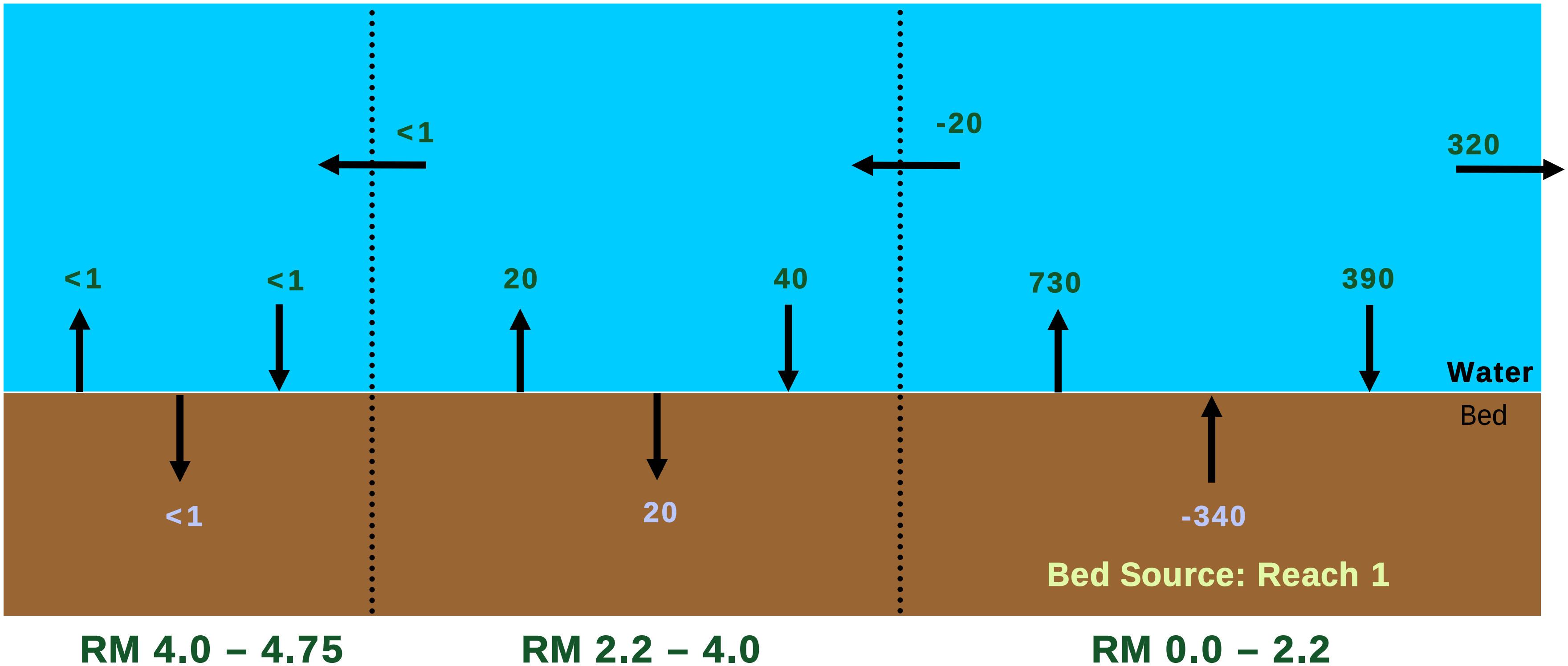
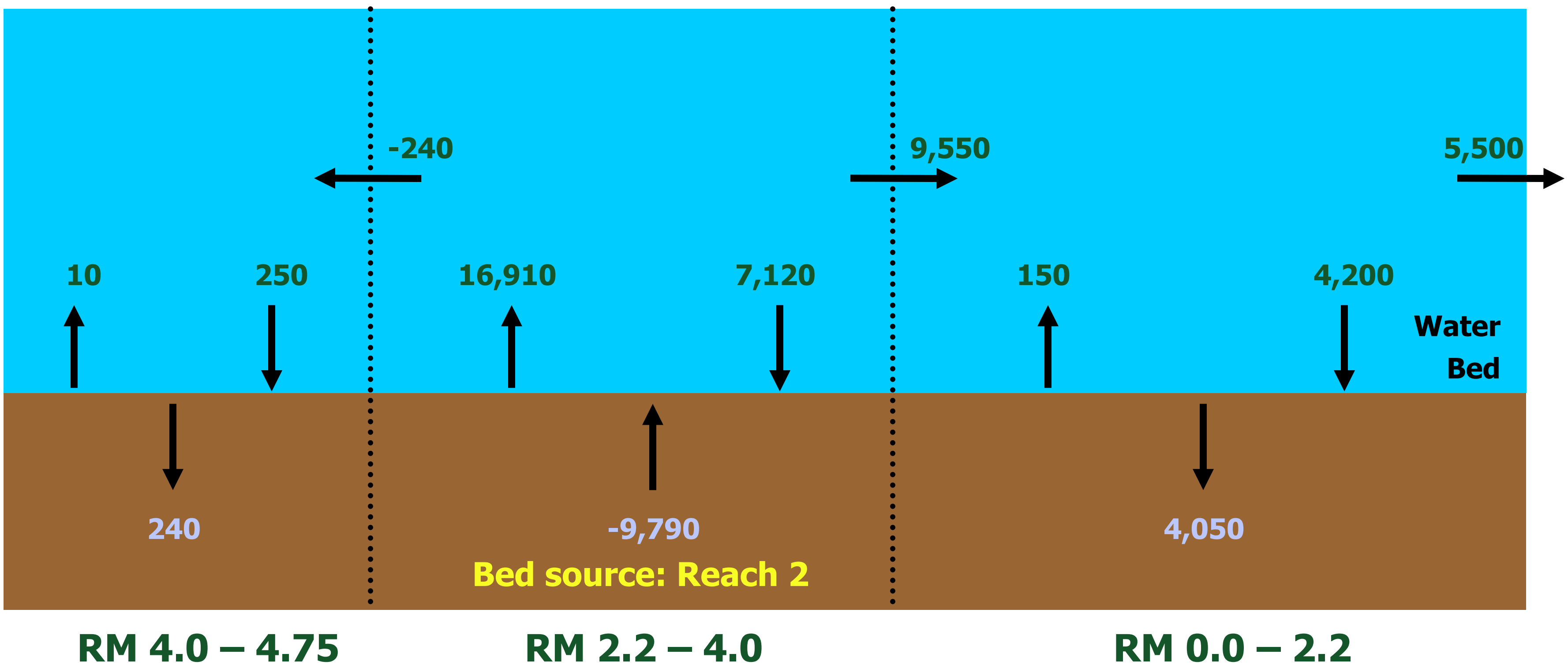
Figure 4-5 Mass balance for bed sediment originating from Reach 1 (RM 0.0 to 2.2) for 10-year period



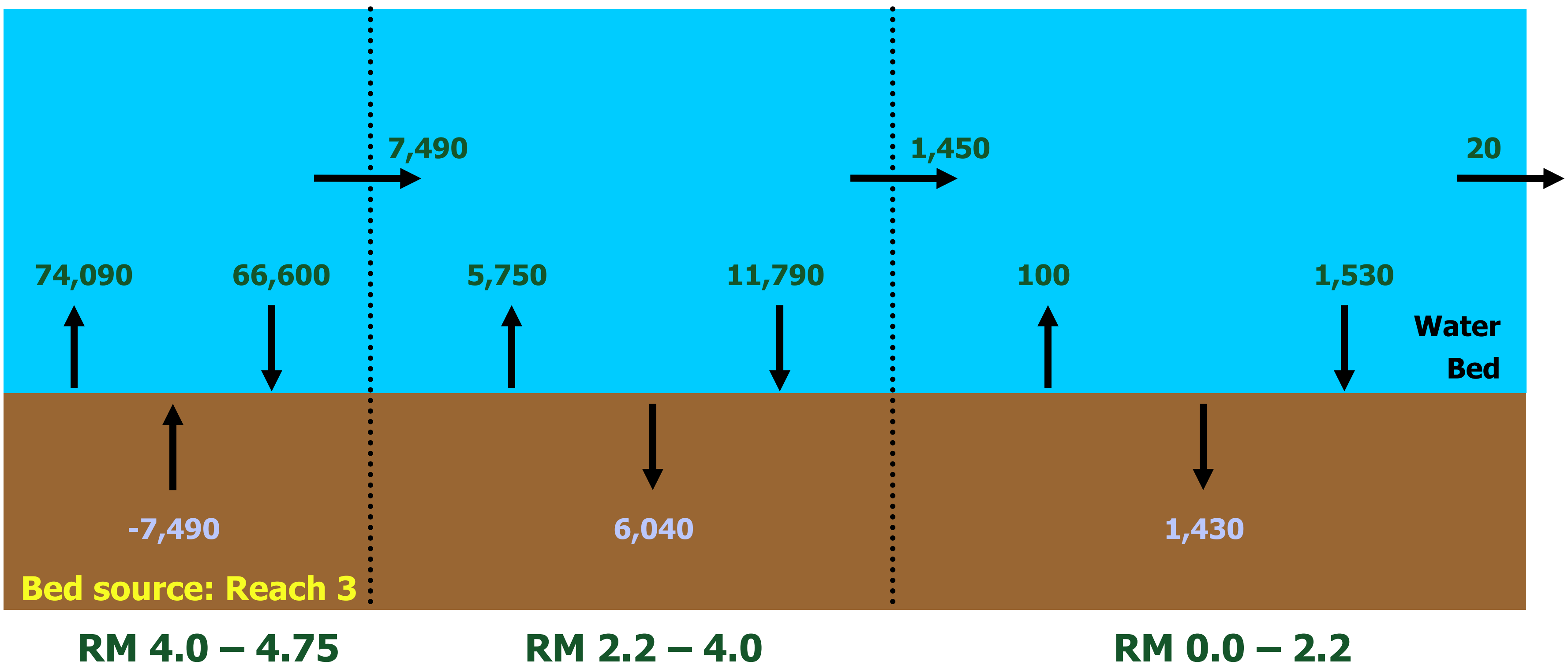
Notes:
Sediment mass units are reported in metric tons.
Mass balance results are rounded to the nearest 10 metric tons.

Figure 4-6 Mass balance for bed sediment originating from Reach 2 (RM 2.2 to 4.0) for 10-year period



Notes:
Sediment mass units are in metric tons.
Mass balance results are rounded to the nearest 10 metric tons.

Figure 4-7 Mass balance for bed sediment originating from Reach 3 (RM 4.0 to 4.8) for 10-year period



Notes:
Sediment mass units are in metric tons.
Mass balance results are rounded to the nearest 10 metric tons.

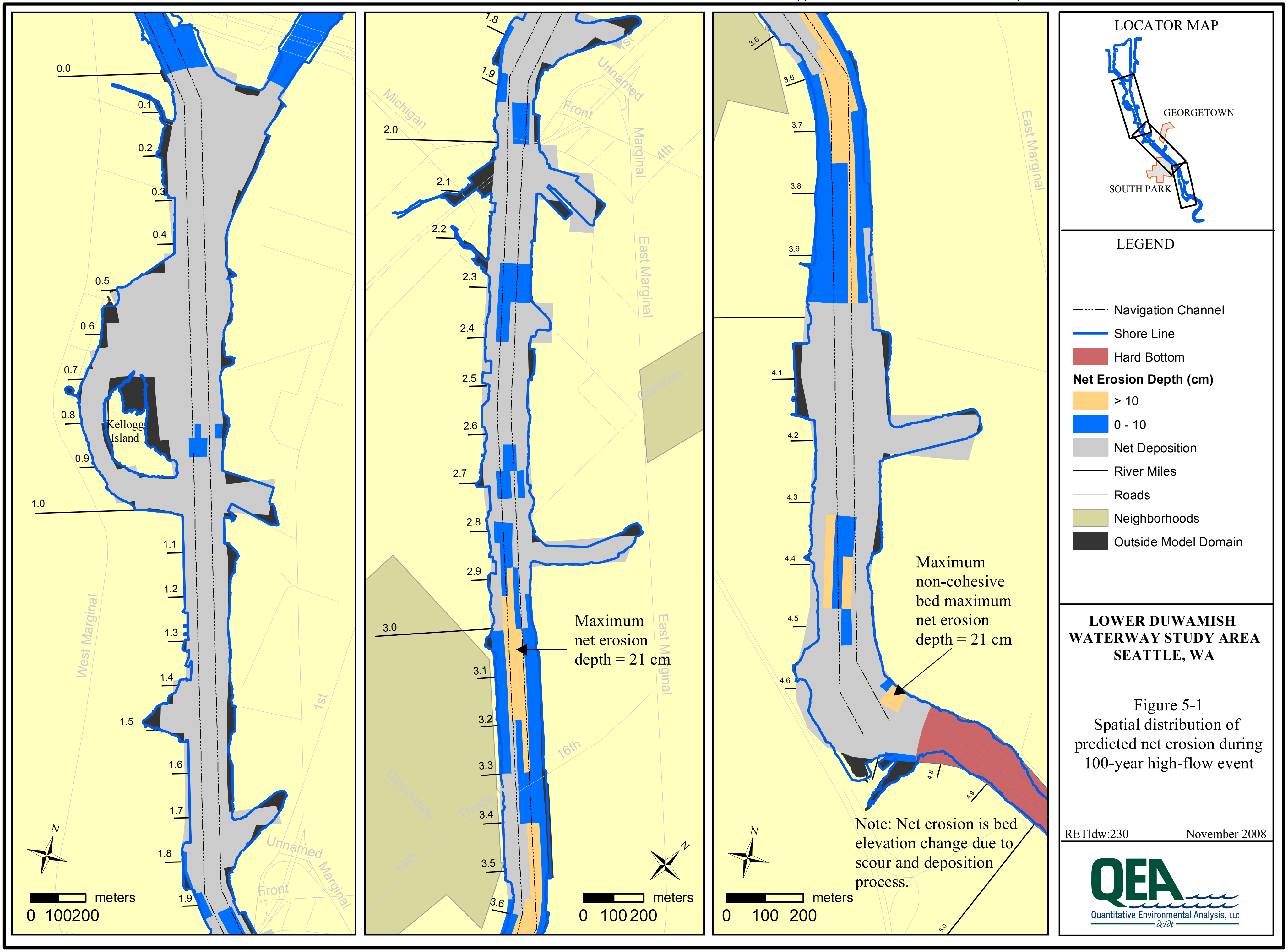


Figure 5-1
Spatial distribution of predicted net erosion during 100-year high-flow event

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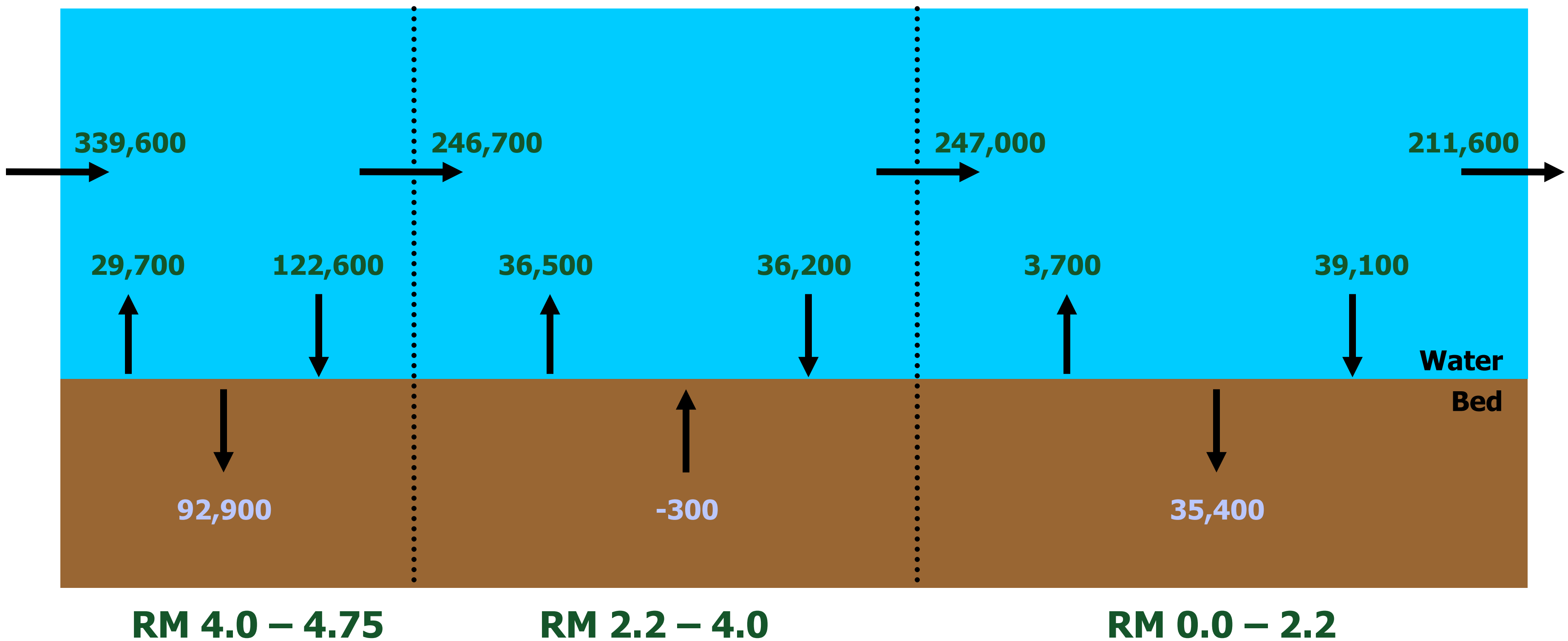
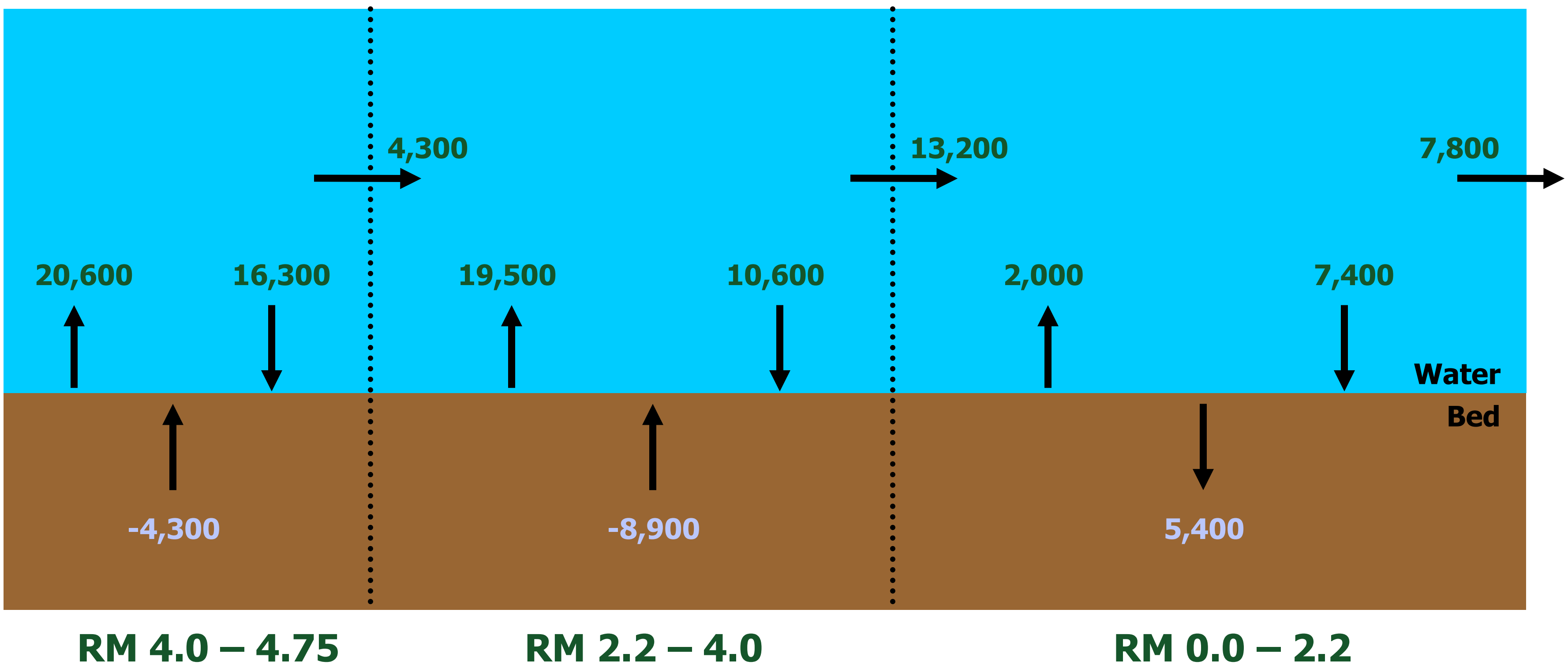
Figure 5-2 Total sediment mass balance for 100-year high-flow event simulation



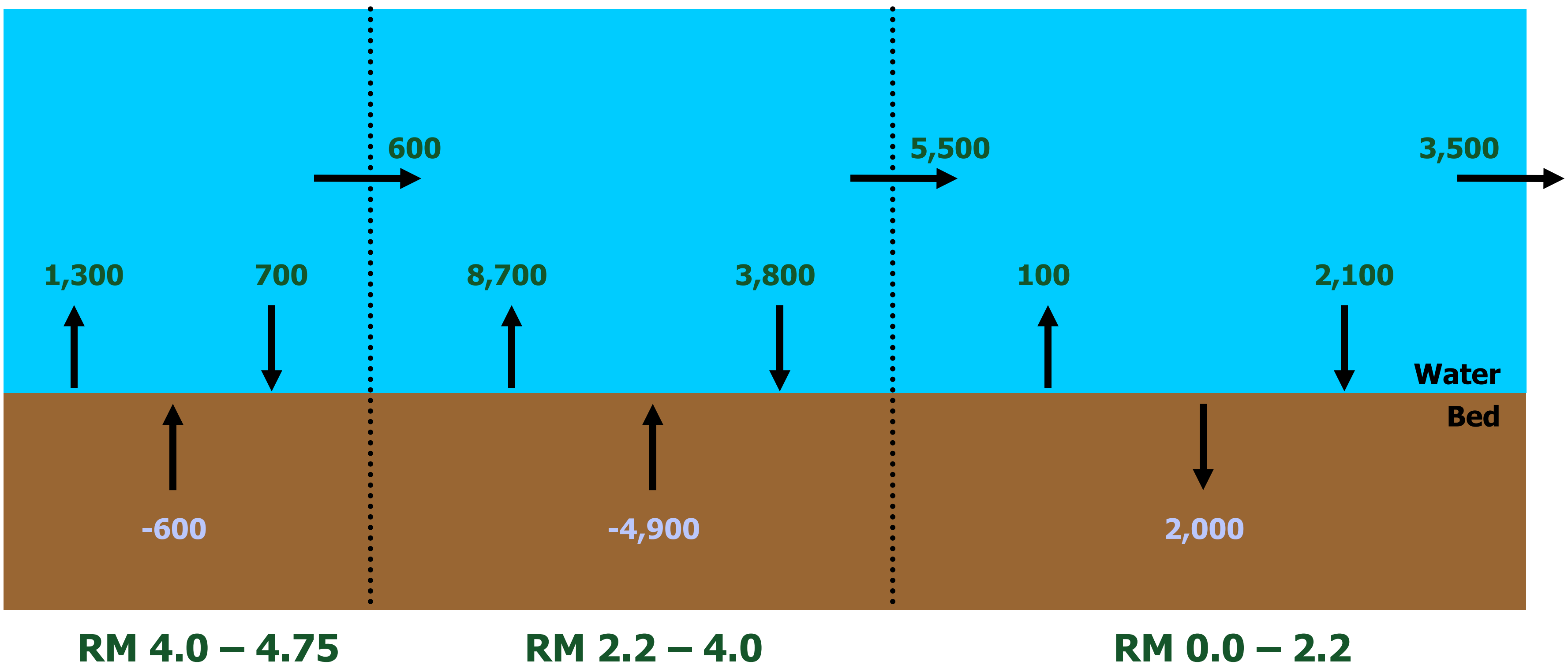
Notes:
Sediment mass units are in metric tons.
Mass balance results are rounded to the nearest 100 metric tons.

Figure 5-3 Mass balance for bed sediment originating from 0-to-10-cm layer during 100-year high-flow event simulation

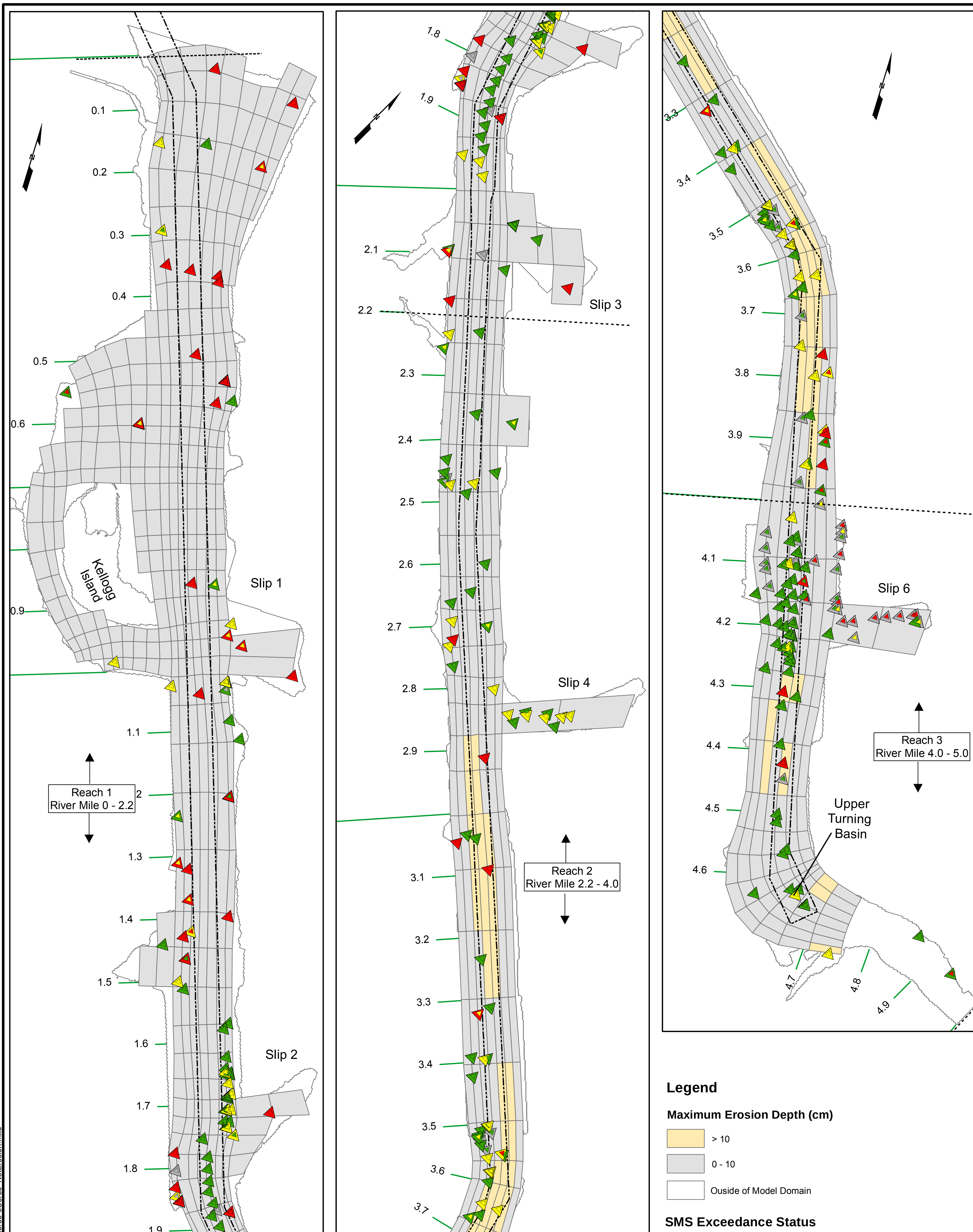


Notes:
Sediment mass units are in metric tons.
Mass balance results are rounded to the nearest 100 metric tons.

Figure 5-4 Mass balance for bed sediment originating from deeper-than-10-cm layer during 100-year high-flow event simulation



Notes:
Sediment mass units are in metric tons.
Mass balance results are rounded to the nearest 100 metric tons.



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

0 200 400 800 Feet

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.

AECOM

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

Lower Duwamish Waterway
Final Feasibility Study
60150279-14.49

DATE: 10/31/12 | DWRN:MVI/sea | Revision: 1

Subsurface Sediment SMS Exceedance Locations with > 10 cm Erosion Depth During 100-year High-flow Event

FIGURE 5-5

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Part 5: LDW STM and BCM Bed-tracking Scenario Simulation (Scenario 6)

MEMORANDUM (REVISED)

To:	Sediment Transport Modeling Group and Lower Duwamish Waterway Group	**Date:**	August 5, 2011
From:	C. Kirk Ziegler, Mike Riley, Anchor QEA; Anne Fitzpatrick, AECOM	**Project:**	RETldw
Cc:	Files		
Re:	LDW STM and BCM Bed-tracking Scenario Simulation (Scenario 6)		

The Lower Duwamish Waterway (LDW) sediment transport model (STM) is being used to track the fate and transport of sediments from three sources: 1) upstream (i.e., Green River); 2) original bed; and 3) lateral (i.e., combined sewer overflows [CSOs], storm drains, and streams). Temporal changes in the relative amounts of sediment from these three sources in the surface layer (top 10 cm) of the bed are calculated by the STM in each grid cell within the study area. There are 727 grid cells (in the horizontal plane) in the LDW, with the grid spanning bank-to-bank from river mile (RM) 0.0 up to RM 4.8. The areal sizes of the grid cells in this region range from 0.1 to 4 acres, with the median area of a grid cell being 0.5 acre. These results are used in the bed composition model (BCM) to calculate changes in bed sediment chemical concentrations and to evaluate the effectiveness of various remedial alternatives for the feasibility study (FS).

A limitation of the STM output is that the bed source content does not differentiate between the original bed and bedded material originating from other areas (i.e., “distal” sediment) that is resuspended from one grid cell and transported and redeposited in another grid cell. A limitation of the BCM is that bed-source sediment within a specific grid cell is assigned the same chemical concentration throughout the entire simulation period. The BCM cannot incorporate the potential effects of bed-source sediment eroded from other grid cells and subsequently transported to and redeposited in a specific grid cell. The bed-source sediment from other grid cells (i.e., “distal” sediment) may have a different chemical concentration than bed-source sediment in the grid cell (i.e., “local” sediment) where the distal sediment is redeposited.

The potential effects of this limitation of the BCM on model calculations were evaluated using the STM in diagnostic mode. The bed model in the STM was modified such that in addition to tracking the bed-source content, the local and distal components of the bed-source material were tracked by the model. This scenario simulation required modification of the STM bed model as described below. After modification of the bed model, the STM was used to conduct a 10-year simulation and track spatial and temporal changes in the composition of local and distal bed-source sediment within the cohesive bed area of the LDW.

MODIFICATION OF STM BED MODEL

The fraction of total bed-source sediment in the surface layer (top 10-cm) of the bed for sediment size class k ($f_{10,bed,k}$) is the sum of two components of bed-source sediment:

$$f_{10,bed,k} = f_{10,local,k} + f_{10,distal,k} \quad (1)$$

where $f_{10,local,k}$ is the fraction of local bed-source sediment and $f_{10,distal,k}$ is the fraction of distal bed-source sediment for size class k in the top 10-cm layer. Similarly, the fraction of total bed-source sediment in the parent-bed layer ($f_{PB,bed,k}$) may be decomposed into two components:

$$f_{PB,bed,k} = f_{PB,local,k} + f_{PB,distal,k} \quad (2)$$

where $f_{PB,local,k}$ is the fraction of local bed-source sediment and $f_{PB,distal,k}$ is the fraction of distal bed-source sediment for size class k in the parent-bed layer.

Constructing a mass balance for the top 10-cm layer for total bed-source sediment for size class k ($M_{10,bed,k}$) results in the following equation:

$$^{n+1}M_{10,bed,k} = {}^{n}M_{10,bed,k} - E_{bed,k} + D_{bed,k} + f_{PB,bed,k}E_{total,k} - f_{10,bed,k}\, D_{total,k} \quad (3)$$

where $E_{bed,k}$ is the mass of total bed-source sediment for size class k eroded during one time step, $D_{bed,k}$ is the mass of total bed-source sediment for size class k deposited during one time step, $E_{total,k}$ is the total mass of class k sediment eroded during one time step, and $D_{total,k}$ is the total mass of class k sediment deposited during one time step. The superscripts n and n+1 refer to time periods in the calculation.

Constructing a mass balance for the top 10-cm layer for local bed-source sediment for size class k ($M_{10,local,k}$) yields:

$$^{n+1}M_{10,local,k} = {}^{n}M_{10,local,k} - (f_{10,local,k} / f_{10,bed,k}) E_{bed,k} + f_{PB,local,k} E_{total,k} - f_{10,local,k}\, D_{total,k} \qquad (4)$$

Similarly, a mass balance for the top 10-cm layer for distal bed-source sediment for size class k ($M_{10,distal,k}$) yields:

$$^{n+1}M_{10,distal,k} = {}^{n}M_{10,distal,k} - (f_{10,distal,k} / f_{10,bed,k}) E_{bed,k} + D_{bed,k} + f_{PB,distal,k} E_{total,k} - f_{10,distal,k}\, D_{total,k} \qquad (5)$$

It is assumed that deposited bed-source sediment is composed entirely of distal material (i.e., eroded local sediment is not redeposited in the same grid cell). Note that the summation of Equations 4 and 5 produces Equation 3. Similar mass balance equations were developed for the parent-bed layer.

LIMITATIONS OF BED-TRACKING SIMULATION

The bed-tracking simulation has provided useful information on the potential for and extent of bed-source sediment to be eroded and redeposited within the LDW. However, the limitations of this analysis need to be acknowledged. First, it was assumed that bed-source sediment that is deposited in a specific grid cell is completely composed of distal material and that local material is not redeposited in the same grid cell after it is eroded. This assumption results in an over-estimation of the amount of material transported between grid cells. However, it is likely that, generally, the over-estimation due to this assumption is relatively minor. The second, and most important, limitation of this analysis is that the origin of distal sediment that is deposited within a specific grid cell cannot be determined. In some cases, the distal sediment will have originated in close proximity (i.e., immediately adjacent grid cells), whereas in other situations, the distal sediment will have come from a grid cell located 2 or 3 miles upstream. This situation would make it difficult to assign the appropriate chemical concentration to the distal sediment if these results were used in the BCM.

RESULTS OF STM BED-TRACKING SIMULATION

A 10-year simulation, corresponding to the first 10 years of the 30-year simulation presented in the STM report (QEA 2008), was conducted for this analysis. The STM was used to track sediment originating from three sources: 1) original bed sediments (total, local, and distal); 2) upstream source sediments (i.e., Green River); and 3) lateral source sediments (i.e., storm drains, CSOs, streams). Five variables were tracked by the bed model. The lateral loads were specified using the distributed approach (see Part 4 Scenario 2 of this appendix) so as to more realistically represent the transport of lateral source sediments in the STM.

Spatial distributions of local and distal bed-source sediment in the surface layer (top 10 cm) of the bed at the end of the 10-year period are presented in Figures 1 and 2, respectively. Local and distal bed-source sediments were tracked only in the cohesive bed of the study area. The non-cohesive bed area in the vicinity of the Upper Turning Basin was not included in this analysis and that area is denoted on these two figures. Generally, Reaches 2 (RM 2.2 to 4.0) and 3 (RM 4.0 to 4.8) contain relatively higher amounts of distal sediment than local sediment, which is consistent with the dynamic erosion and deposition characteristics of these two reaches. Reach 1 (RM 0 to 2.2) generally contains more local sediment than distal sediment, which is expected because of the minor amount of erosion that occurs in this reach.

The results of diagnostic analyses of the STM bed model were presented in Appendix F of the STM report (QEA 2008). For example, Figures F-59 through F-74 showed temporal changes in bed elevation and bed composition at 16 grid cell locations, which represent a range of net depositional environments. To evaluate the temporal variation in local and distal bed-source composition at these 16 locations (see Figure 3, which is a reproduction of Figure F-58 in of the STM report [QEA 2008]), a similar analysis was conducted for the 10-year bed-tracking simulation. Figures 4 through 19 show temporal changes in bed elevation and bed composition in the top 10-cm layer for the 10-year period at these 16 locations. Generally, the local bed-source content tends to continuously decrease, whereas the distal bed-source content increases during the first few years and then levels out at an approximately constant value.

APPLICATION OF THE BED-TRACKING ANALYSIS IN THE BCM

The bed-tracking analysis provides a breakdown of sediment that settles in a STM cell from one of two sources: 1) sediment that is resuspended and resettled in the same STM cell and

2) bedded material originating from other areas (distal sediment). For the BCM, the distal sediment is essentially another sediment source. This additional sediment source can be represented in the BCM by including a fourth term in the BCM equation. The standard BCM equation is:

$$C_{(time)} = C_{lateral} * f_{lateral} + C_{river} * f_{river} + C_{bed} * f_{bed} \quad (6)$$

Where $C_{lateral}$, C_{river}, and C_{bed} represent the contaminant concentrations associated with sediment from the lateral inflows, upstream, and original bed sediment, respectively. The $f_{lateral}$, f_{river}, and f_{bed} variables represent the fractions of sediment at each BCM grid cell associated with those same sources of sediment.

In the distal sediment BCM version, the equation becomes:

$$C_{(time)} = C_{lateral} * f_{lateral} + C_{river} * f_{river} + C_{bed} * f_{bed} + C_{distal} * f_{distal} \quad (7)$$

Where C_{distal} refers to the contaminant concentration associated with distal sediment and f_{distal} refers to the fraction of distal sediment at each BCM grid cell. The fraction of distal sediment is an output from the STM bed-tracking simulation and, therefore, the only additional input needed is the contaminant concentration associated with the distal sediment fraction.

The contaminant concentration associated with the distal sediment input was computed separately as an average for each reach based on the reach-average fraction of sediment settling from each reach. This reach average fraction for each reach is taken from the simulation of sediment movement between reaches (Part 4, Scenario 4 of this appendix). The PCB concentration associated with the distal sediment input for a reach is computed as the mass-weighted average concentration based on the mass of sediment that settles in a reach from all three reaches and the Post-Alternative 1 spatially-weighted average concentration (SWAC) at Year 0 in each reach. For example, the distal input for Reach 1 is computed as:

The $SWAC_1$, $SWAC_2$, and $SWAC_3$ are the post-Alternative 1 (Year 0) SWACs in each reach. This is an approximation that does not strictly conserve chemical 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.

RESULTS OF BCM BED-TRACKING SIMULATION

The BCM results from the bed-tracking analysis are shown in Table 1 (Year 0 and Year 10 following completion of the early action areas under Alternative 1). For comparison, results from the base-case BCM are also shown. Both the bed-tracking analysis and the BCM base case simulate natural recovery following completion of early actions with the assumption that no further action takes place over the simulation period.

This analysis indicates that accounting for bed sediment movement in the BCM produces either no change or a slightly lower total PCB SWAC at the end of 10 years, both on a site-wide and reach-wide basis. Compared to the base case, the bed-tracking PCB SWACs are the same in Reaches 1 and 3, and 6% lower in Reach 2. The change in calculated SWAC is approximately 1% lower site-wide.

The changes are small because throughout the LDW, resuspended 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 sediment mass balance in Reaches 1, 2, and 3, respectively. 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 average concentration of the resuspended bed sediment is generally lower than in the receiving cells in the other reaches. Overall, this simulation shows that redistribution of existing bed sediment has a minor effect on recovery predictions, except in Reach 2 where the approach used in the BCM base-case analysis likely underestimates natural recovery compared to a model that actually tracks the movement and concentration of individual sediment particles.

ATTACHMENTS

REFERENCES

AECOM 2009. *Draft Feasibility Study, Lower Duwamish Waterway, Seattle, Washington.* Prepared for the Lower Duwamish Waterway Group for submittal to the U.S. Environmental Protection Agency, Region 10, and Washington State Department of Ecology. AECOM, Seattle, WA. April 24, 2009.

QEA 2008. *Lower Duwamish Waterway Sediment Transport Modeling Report. Final.* Prepared for the Lower Duwamish Waterway Group for submittal to the U.S. Environmental Protection Agency, Region 10, and Washington State Department of Ecology. Quantitative Environmental Analysis, LLC, Montvale, NJ. October 2008.

Table 1 Comparison of Year 10 Total PCB SWACs between the Bed-Tracking Scenario and STM Base Case

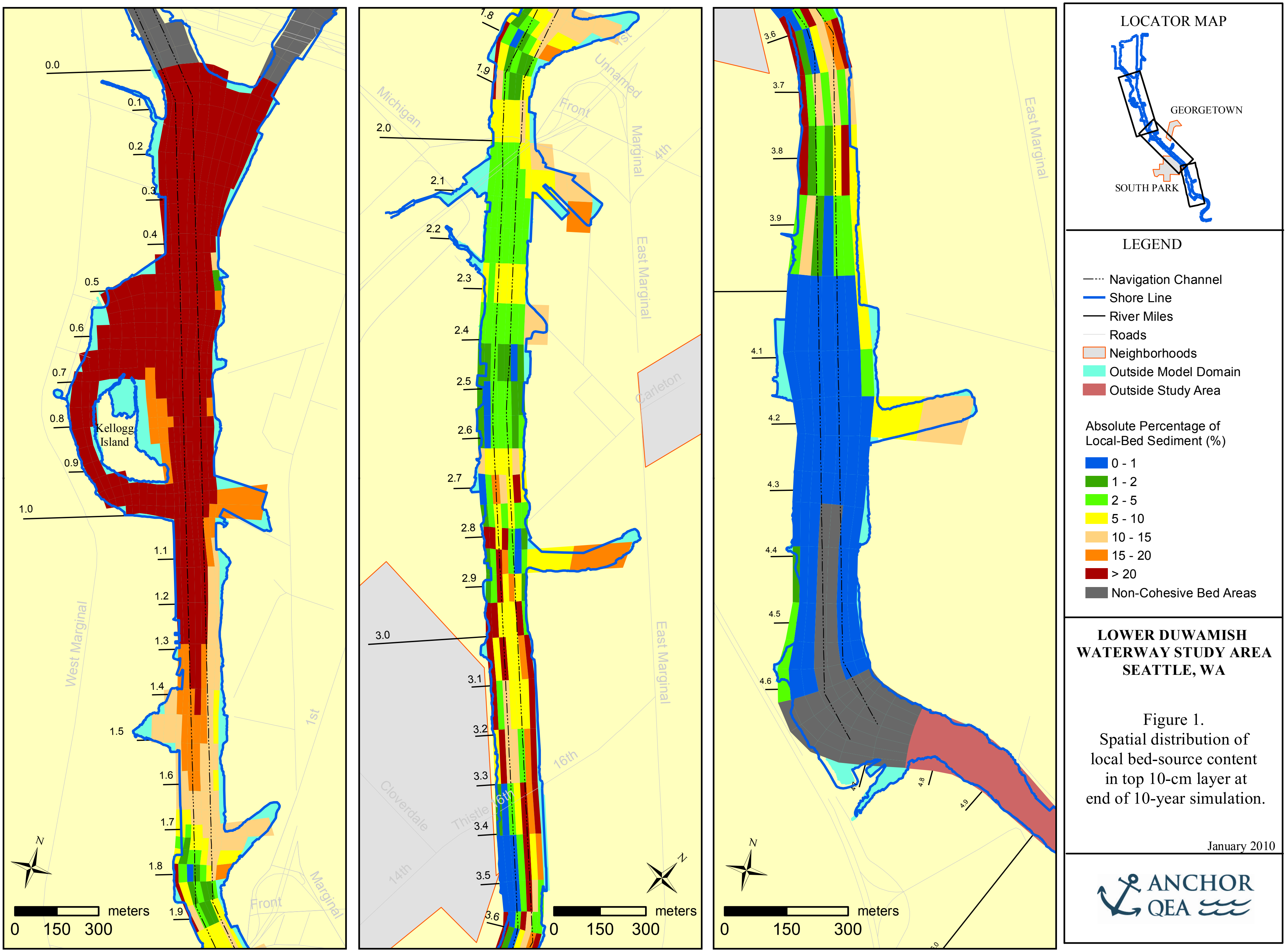
Scenario	Total PCB SWACs (µg/kg dw)			
	Site-wide	Reach 1	Reach 2	Reach 3
Post-Alternative 1 Bed-Tracking Results				
Year 0	180	190	220	57
Year 10 STM Base Case	73	84	67	40
Year 10 modified STM Bed-Tracking Scenario with resuspended bed variable	72	84	63	40
Distal Sediment Concentration Input Values to the Analysis				
Distal Bed (µg/kg dw) – reach-wide post-Alternative 1 mass-weighted SWAC	n/a	176	117	57

Shaded Cell = Greatest difference between bed-tracking and STM base case

Notes:

1. The distal input refers to sediments originating from the initial bed that resuspend and settle in a different STM model cell over time, as opposed to original bed sediments that are not eroded over time (remain in place) The distal input to the sediment bed for each reach is computed as the mass-weighted average total PCB concentration based on the mass of sediment that settles in a reach from all three reaches and the beginning (Year 0) Post-Alternative 1 SWAC in each reach.
2. The chemical input values used in this bed-tracking analysis include:
   a) Local Bed_c = Baseline IDW value in unremediated areas, or post-remedy bed sediment replacement value for total PCBs of 60 µg/kg dw in remediated areas (EAA footprints).
   b) Distal Bed_c = Reach-wide Post-Alternative 1 Mass-Weighted SWAC.
   c) $Upstream_c$ = Mid BCM input value of 35 µg/kg dw.
   d) $Lateral_c$ = Mid BCM input value of 300 µg/kg dw.
3. Three scenario results are shown. Year 0 - immediately after completion of the EAAs under Alternative 1; Year 10 – ten years after completion of the EAAs under Alternative1, assuming only recovery over the 10-year period (shown for comparison as the "STM base case"); and Year 10 modified – ten years after completion of the EAAs under Alternative 1, modified to track movement and reach-average concentration of the distal sediment fraction.
4. See text for calculation equations.

BCM = bed composition model; EAA = early action area; IDW = inverse distance weighting; µg/kg dw = micrograms per kilogram dry weight; n/a = not applicable; PCB = polychlorinated biphenyl; STM = sediment transport model; SWAC = spatially-weighted average concentration



LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 1.
Spatial distribution of local bed-source content in top 10-cm layer at end of 10-year simulation.

January 2010

ANCHOR QEA

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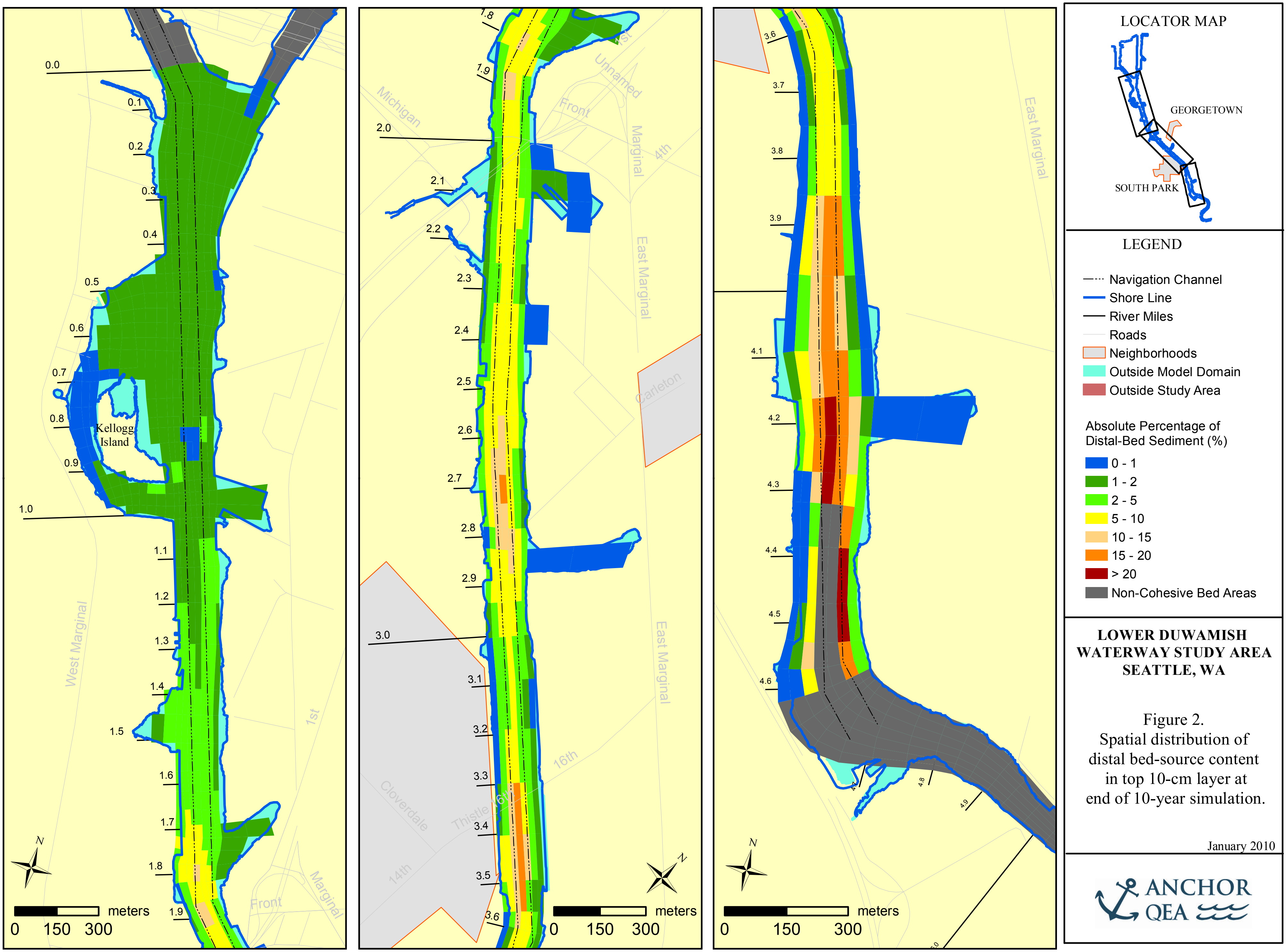

LOWER DUWAMISH WATERWAY STUDY AREA
SEATTLE, WA

Figure 2.
Spatial distribution of distal bed-source content in top 10-cm layer at end of 10-year simulation.

January 2010

ANCHOR QEA

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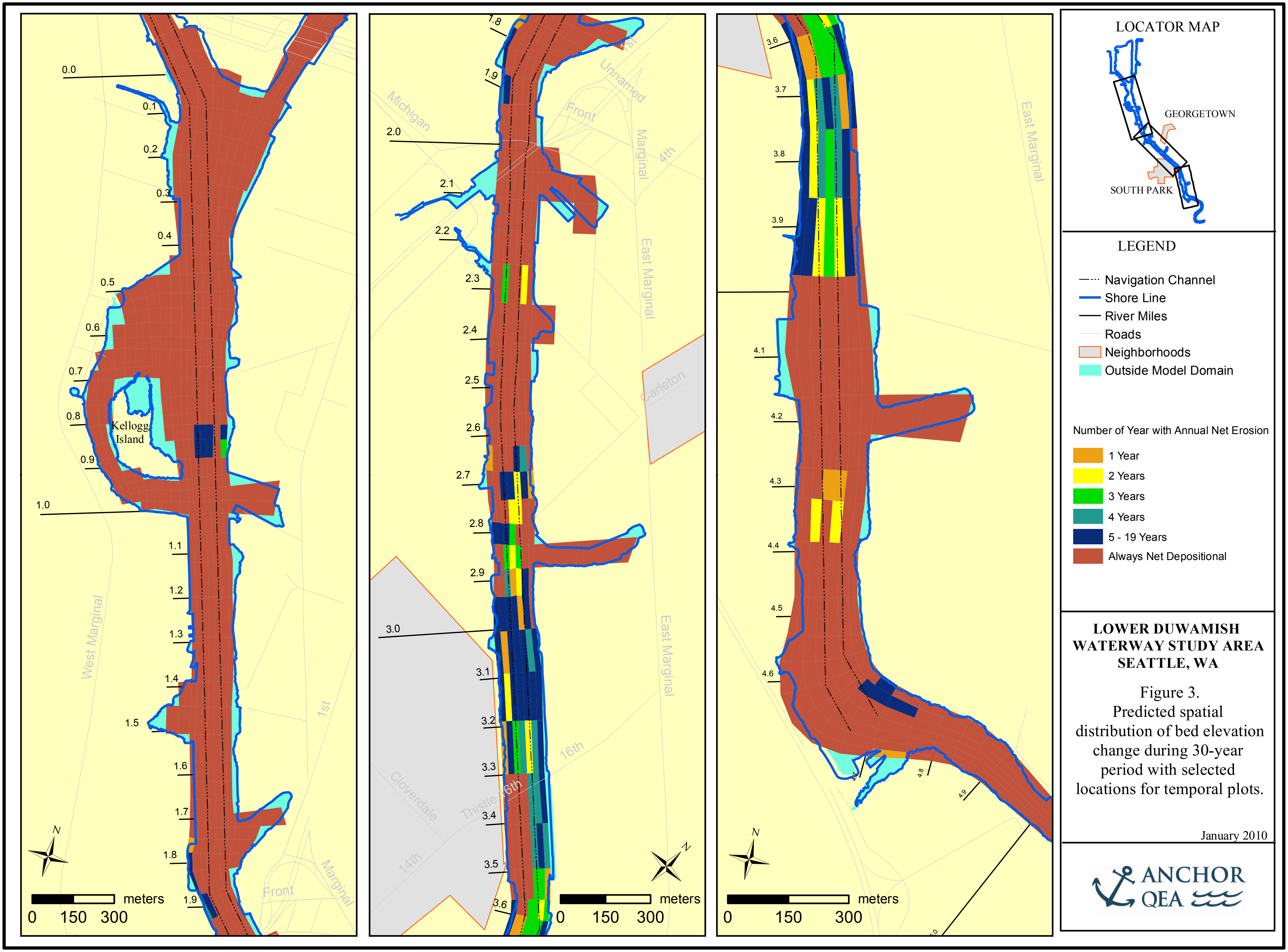

LOWER DUWAMISH WATERWAY STUDY AREA SEATTLE, WA

Figure 3.
Predicted spatial distribution of bed elevation change during 30-year period with selected locations for temporal plots.

January 2010

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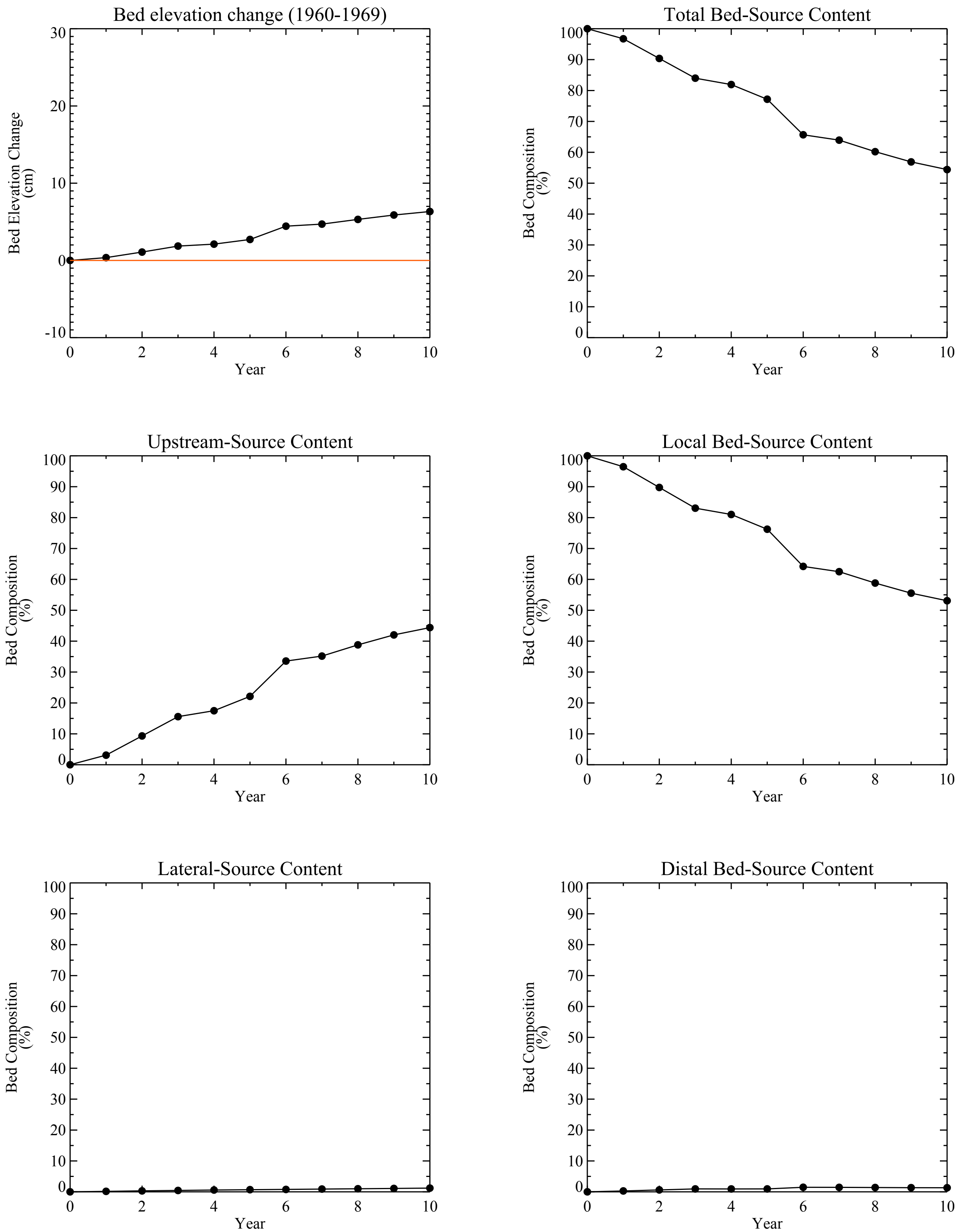

Figure 4. Temporal variation of bed elevation change and bed composition at grid cell: (18, 349), RM 0.20, East Bench.

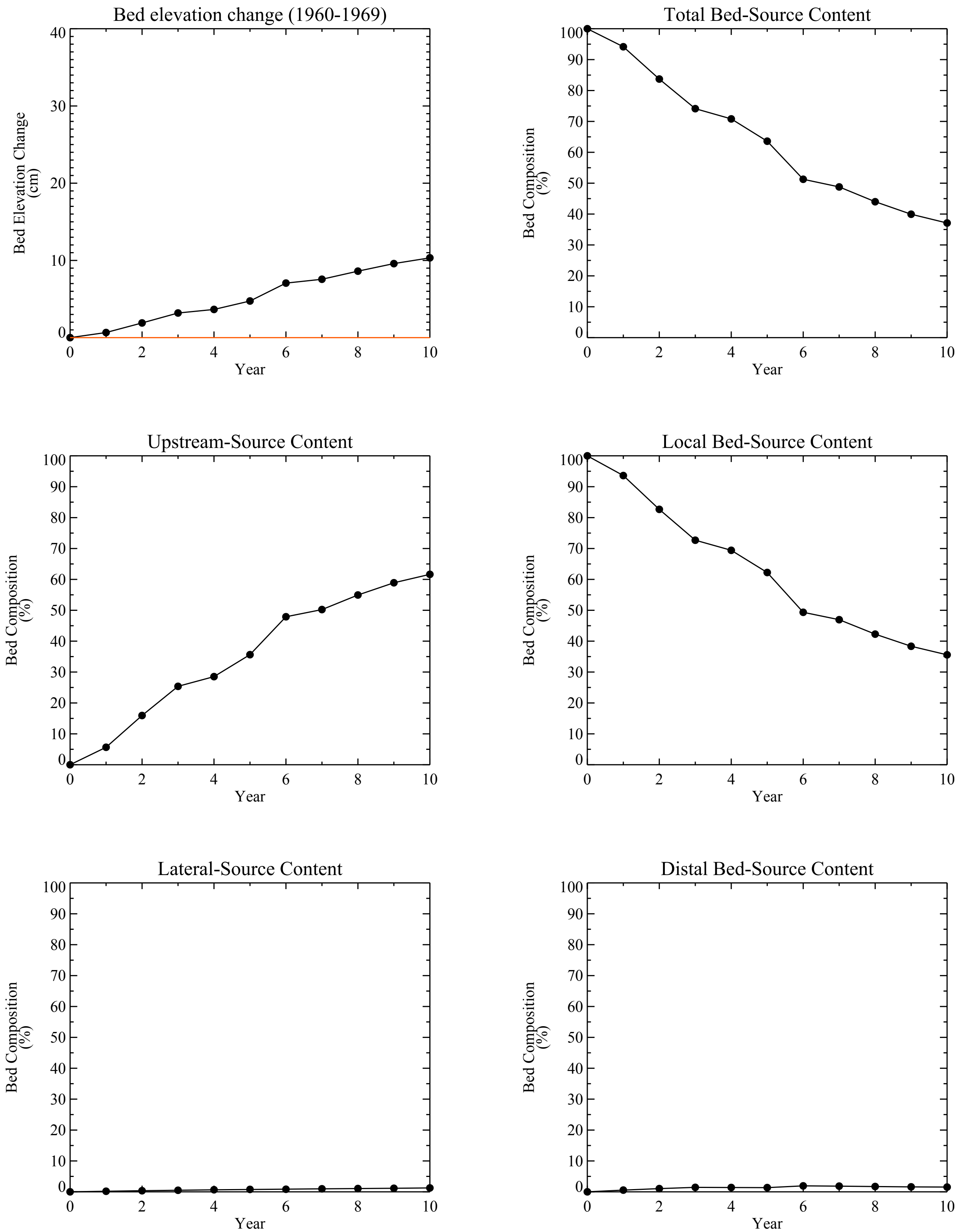

Figure 5. Temporal variation of bed elevation change and bed composition at grid cell: (13, 349), RM 0.17, Navigation Channel.

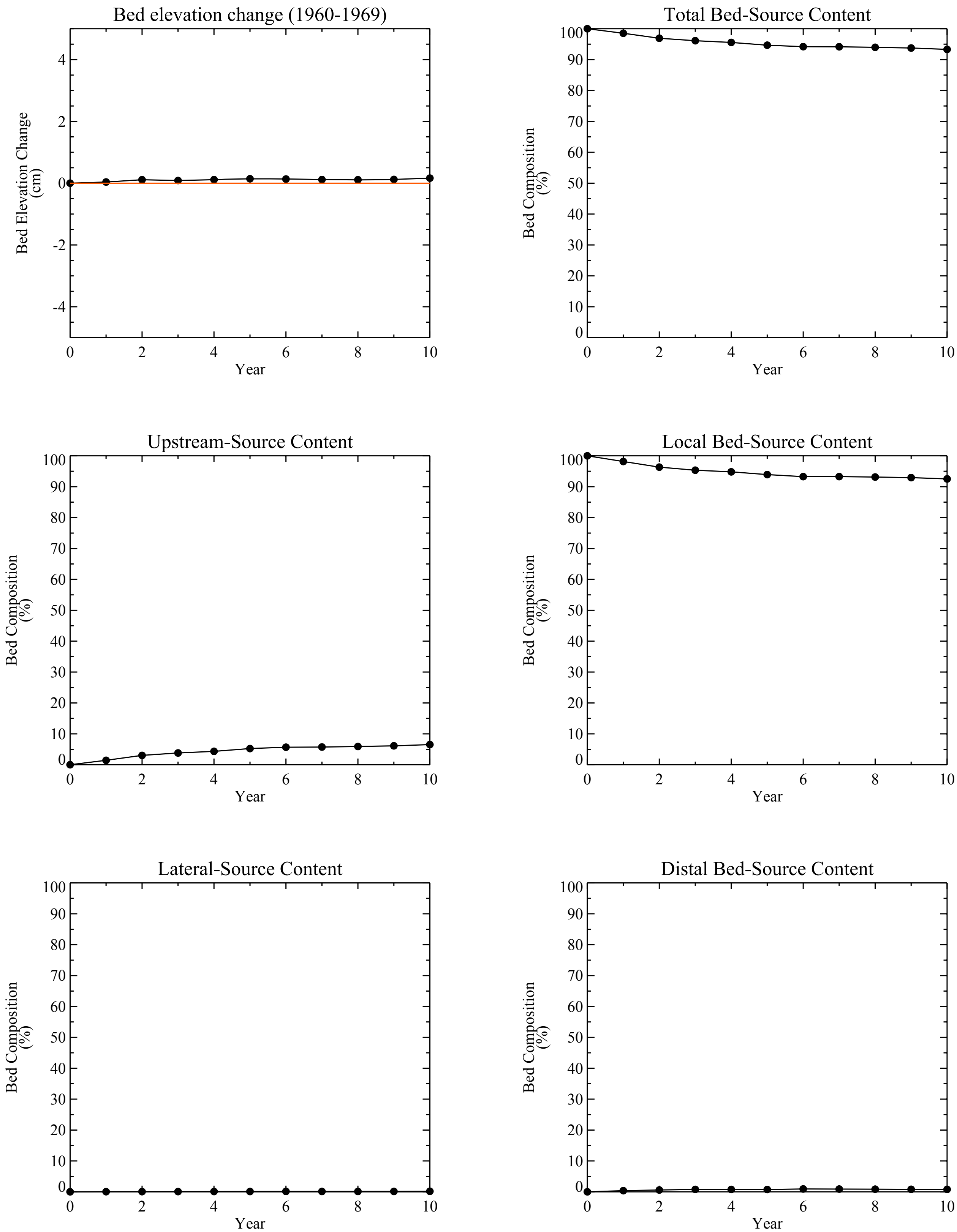

Figure 6. Temporal variation of bed elevation change and bed composition at grid cell: (14, 333), RM 0.82, Navigation Channel.

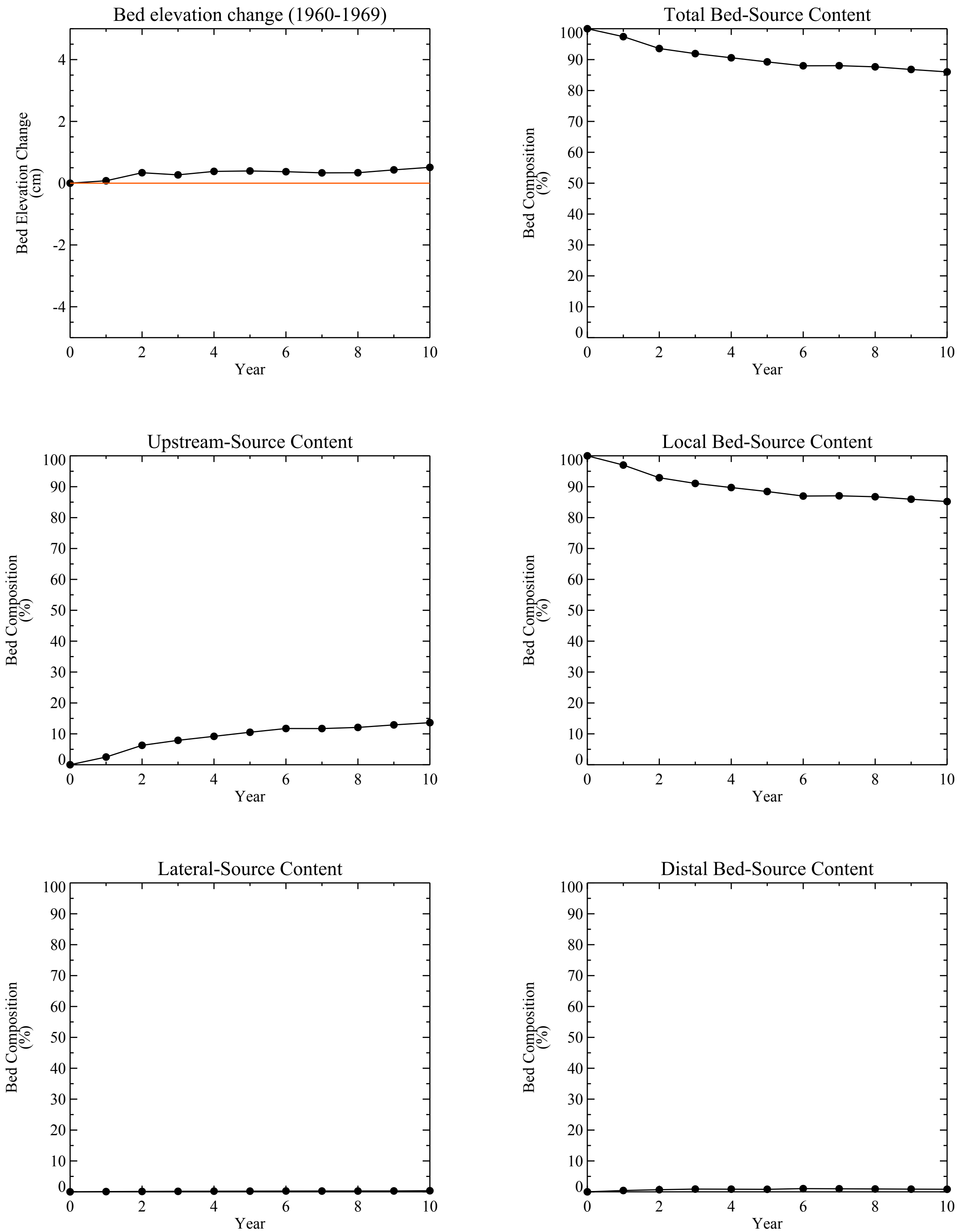

Figure 7. Temporal variation of bed elevation change and bed composition at grid cell: (14, 332), RM 0.86, Navigation Channel.

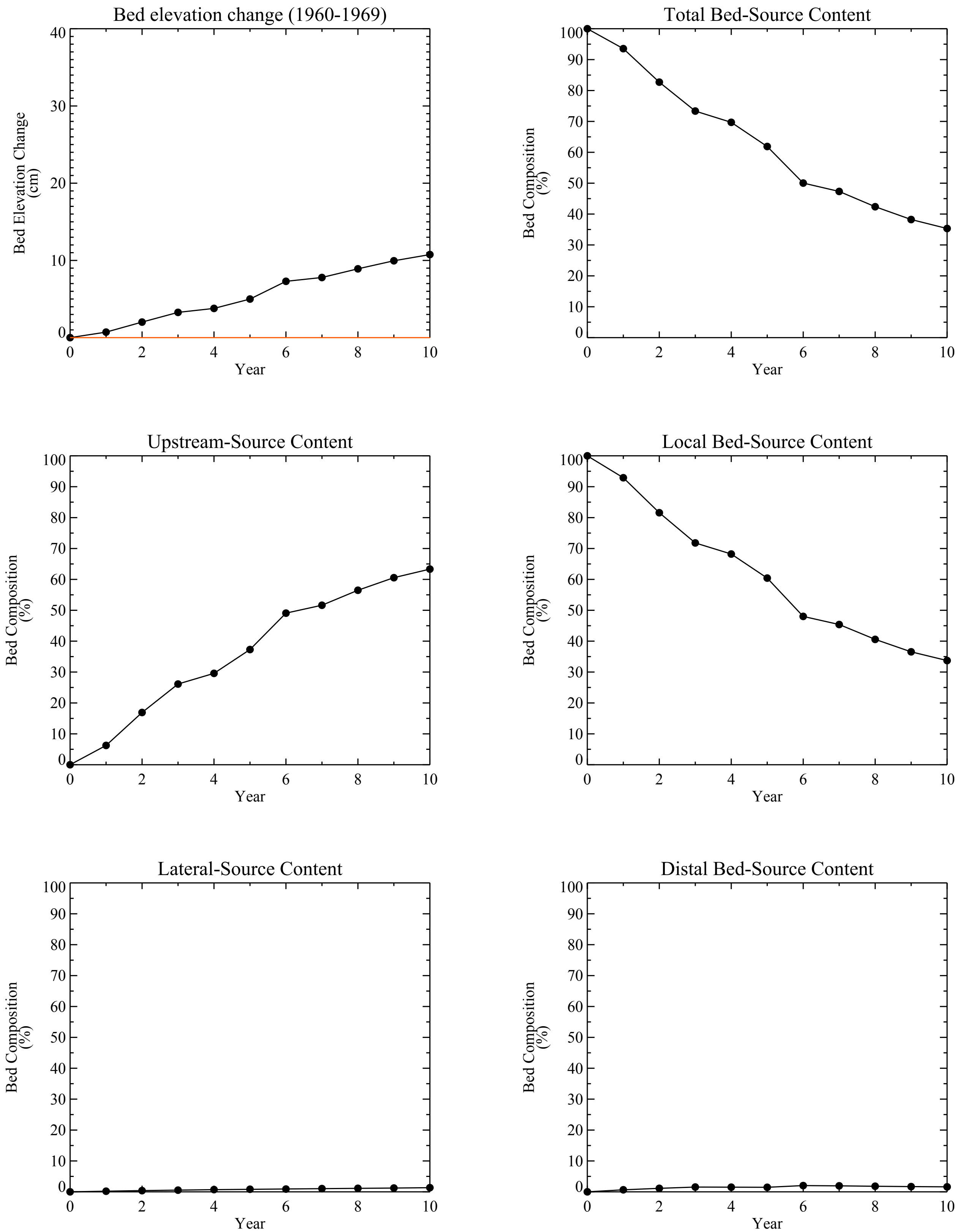

Figure 8. Temporal variation of bed elevation change and bed composition at grid cell: (14, 330), RM 0.94, Navigation Channel.

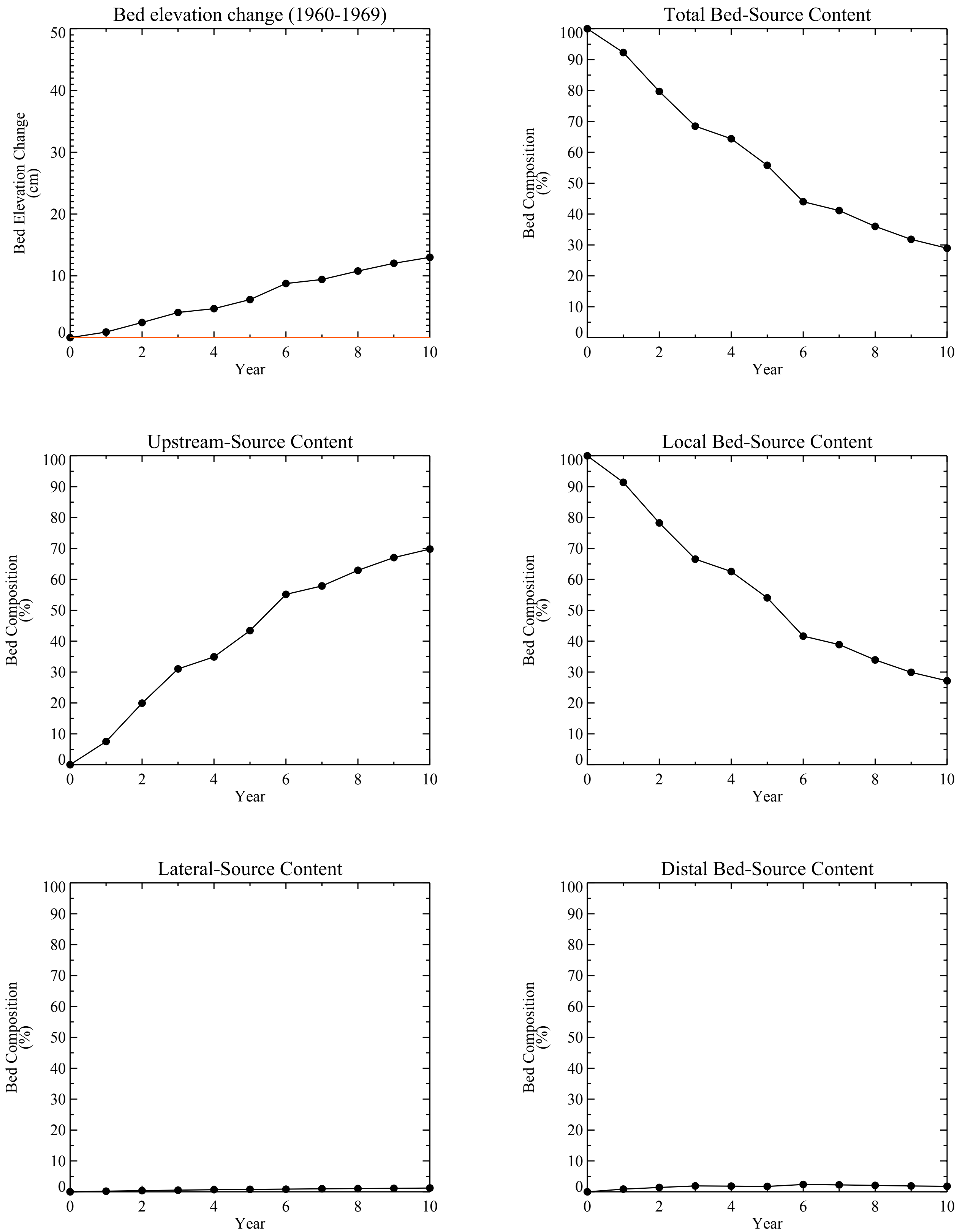

Figure 9. Temporal variation of bed elevation change and bed composition at grid cell: (14, 324), RM 1.2, Navigation Channel.

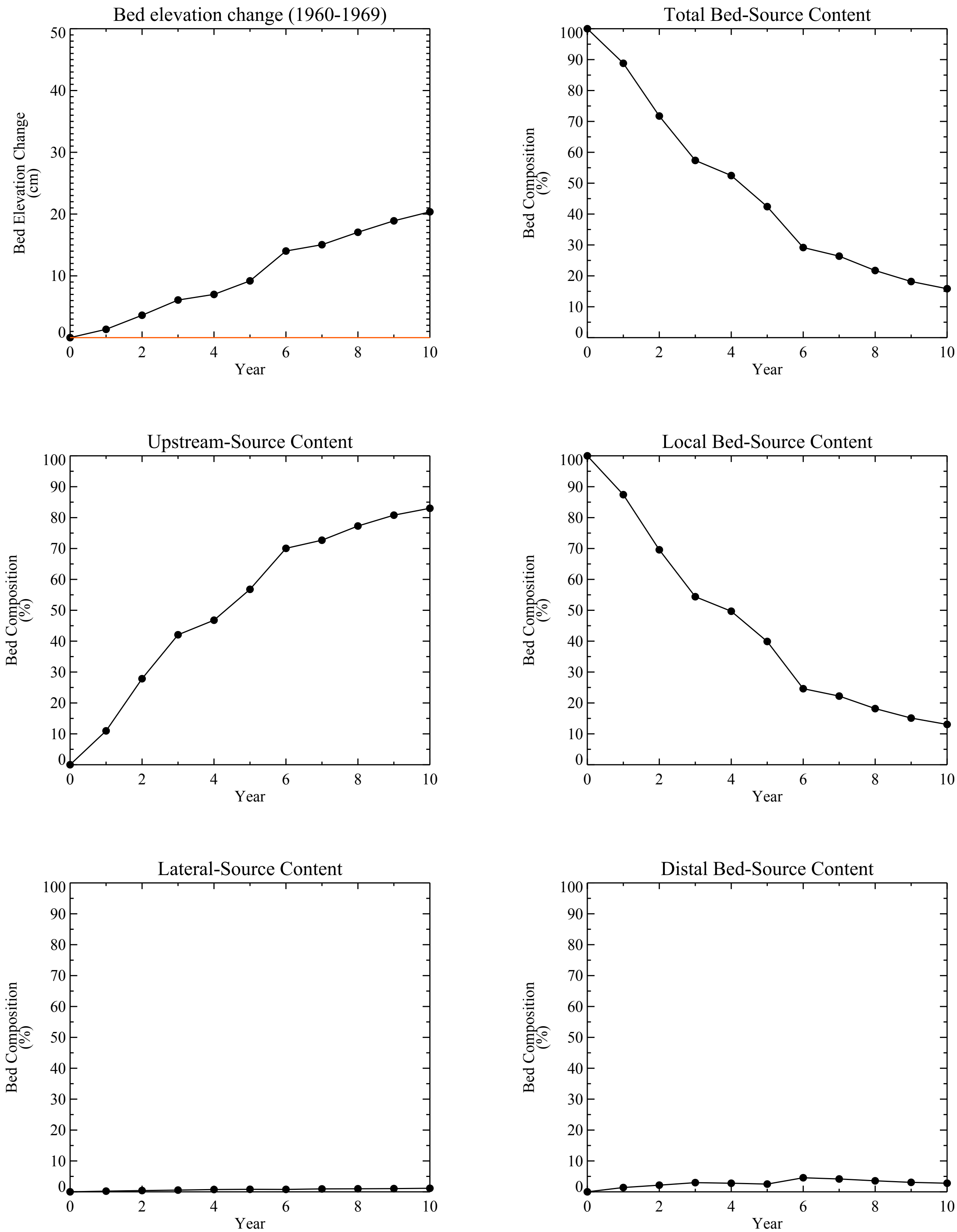

Figure 10. Temporal variation of bed elevation change and bed composition at grid cell: (15, 319), RM 1.6, Navigation Channel.

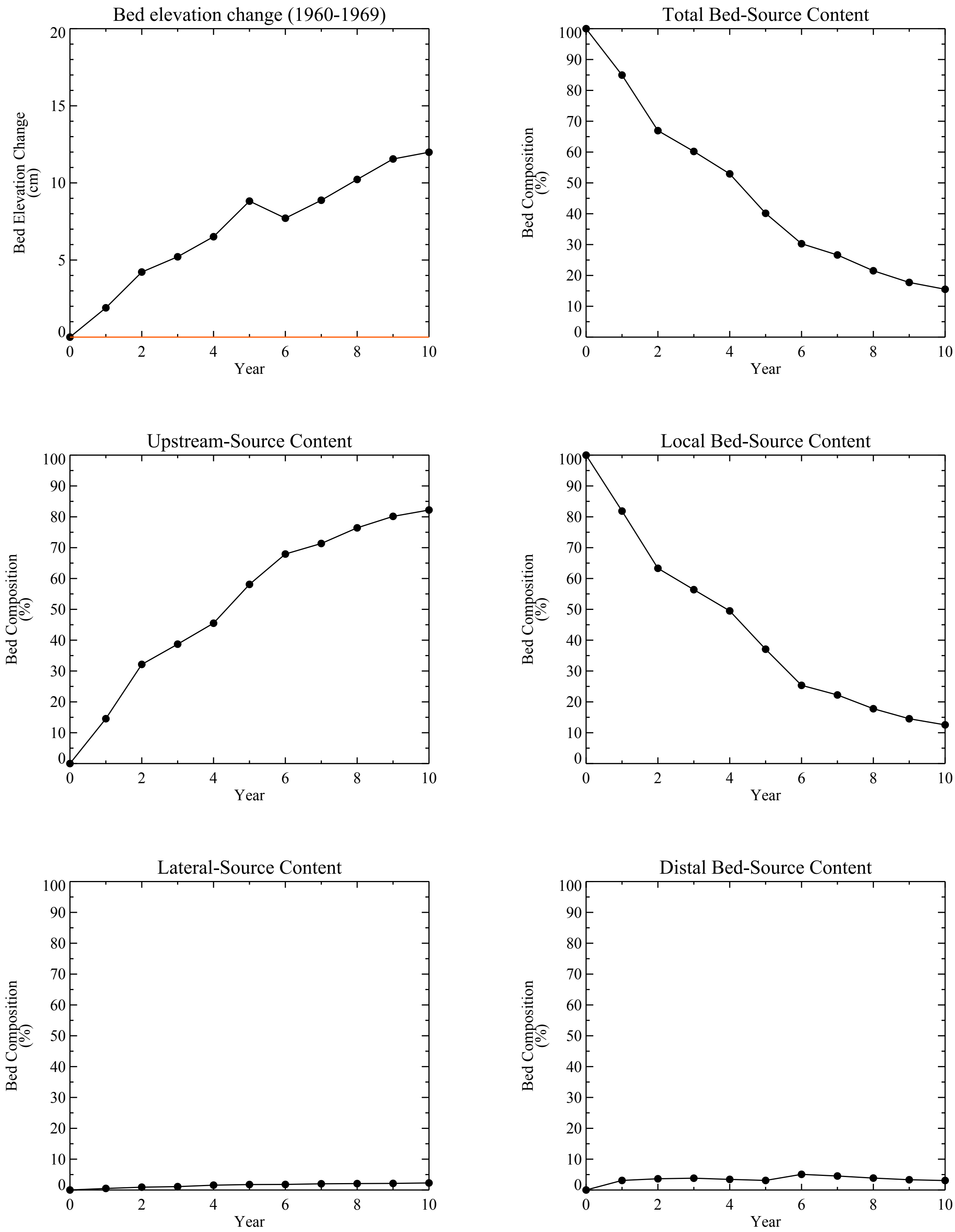

Figure 11. Temporal variation of bed elevation change and bed composition at grid cell: (12, 311), RM 1.9, West Bench.

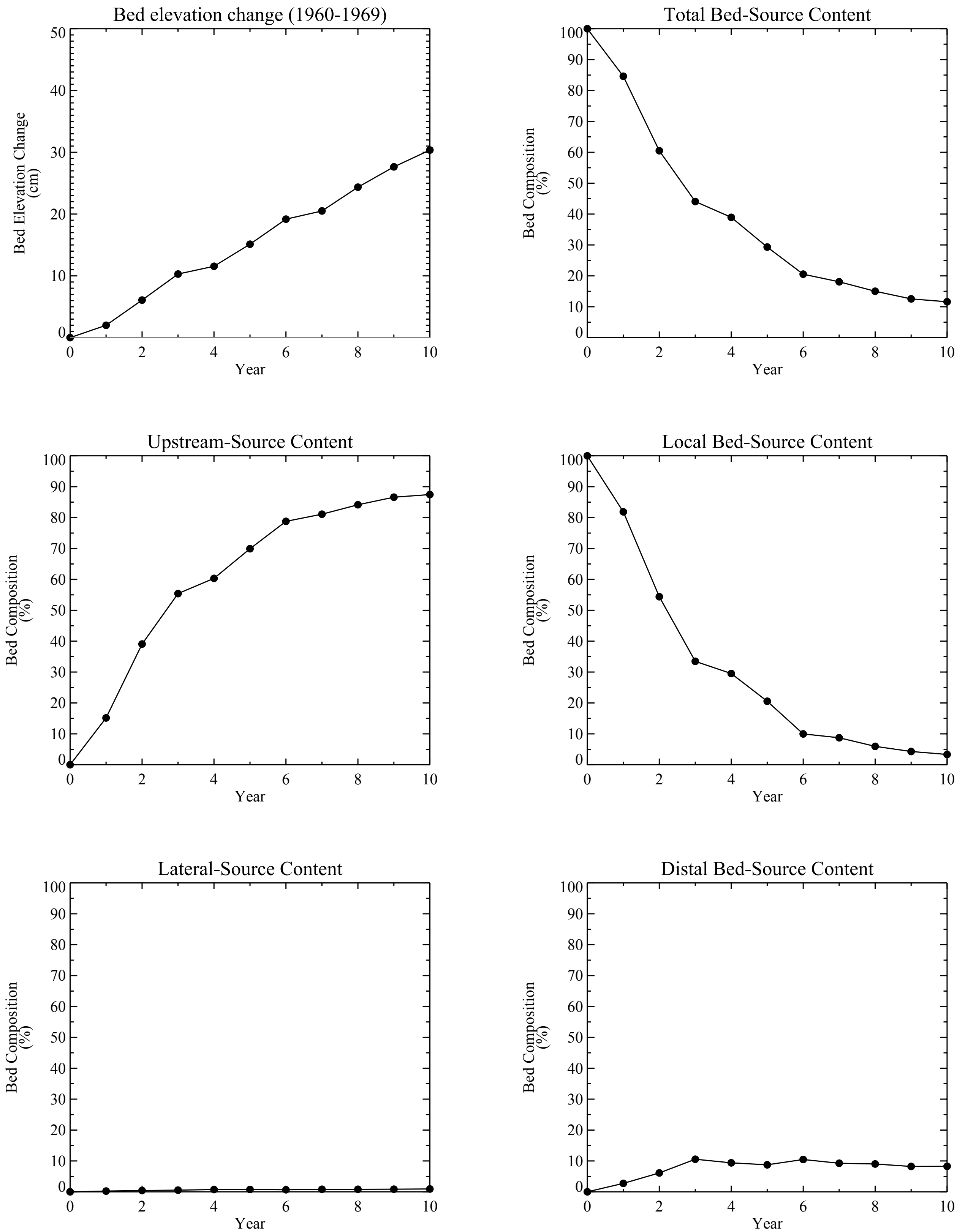

Figure 12. Temporal variation of bed elevation change and bed composition at grid cell: (14, 308), RM 2.1, Navigation Channel.

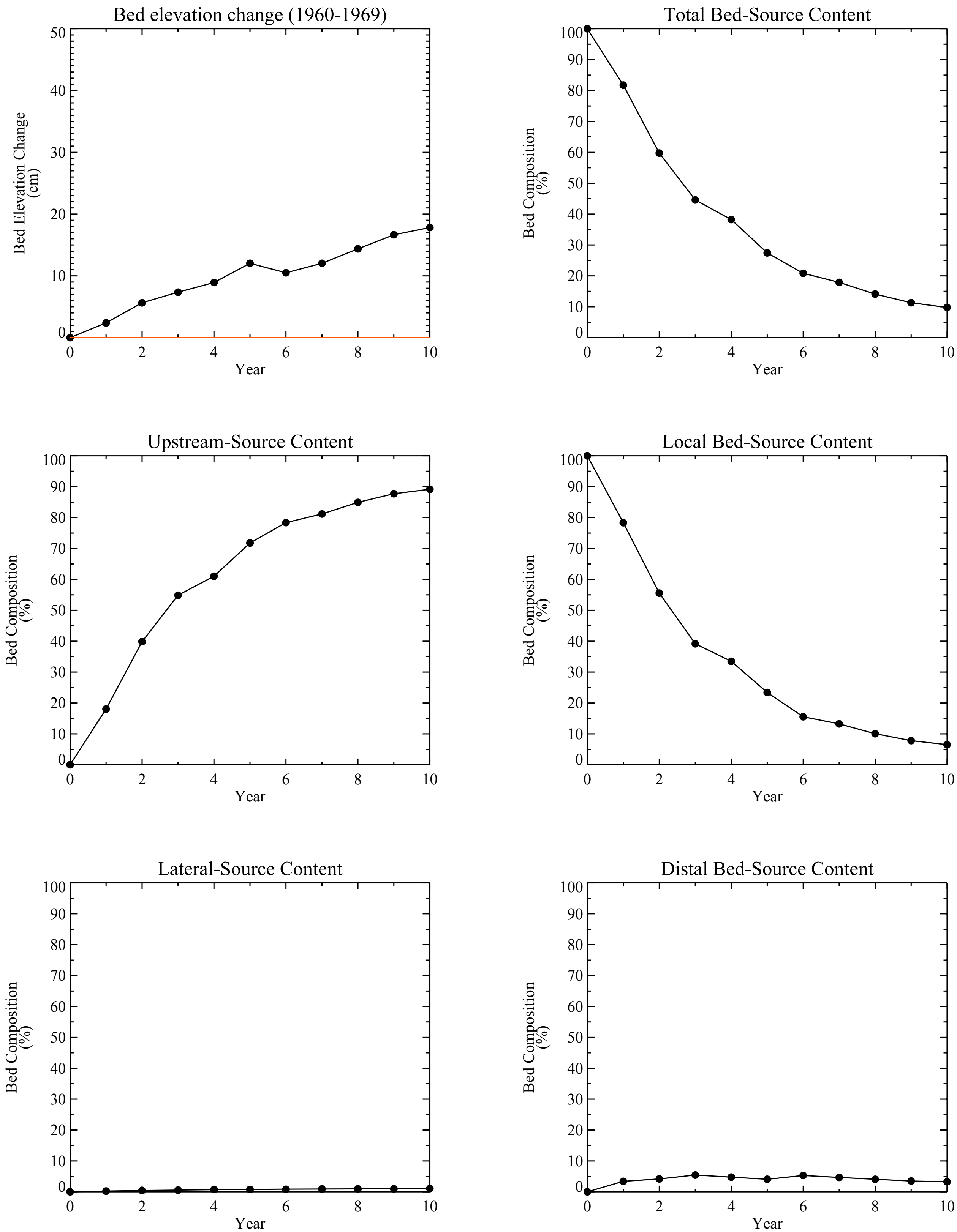

Figure 13. Temporal variation of bed elevation change and bed composition at grid cell: (16, 305), RM 2.3, East Bench.

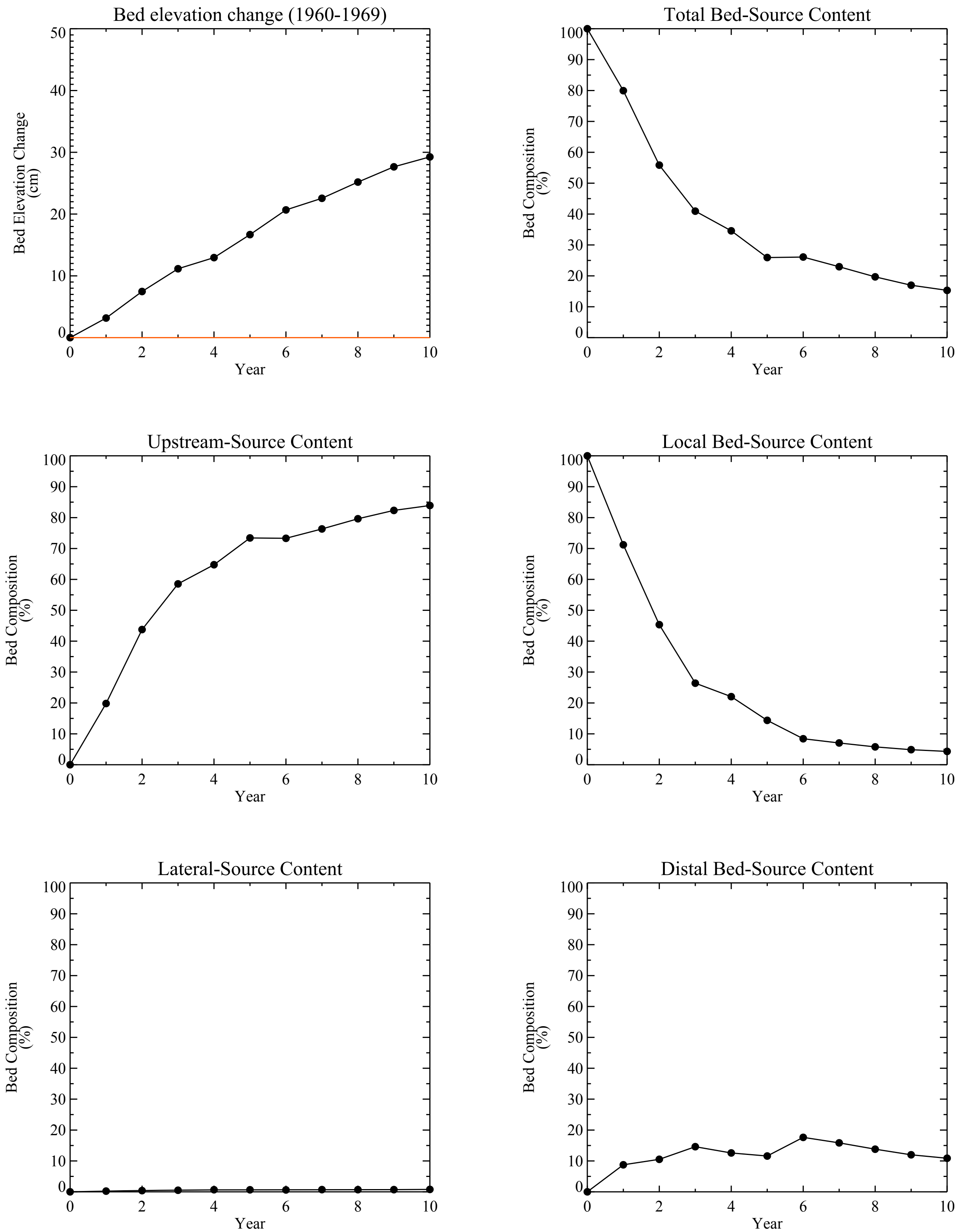

Figure 14. Temporal variation of bed elevation change and bed composition at grid cell: (14, 301), RM 2.6, Navigation Channel.

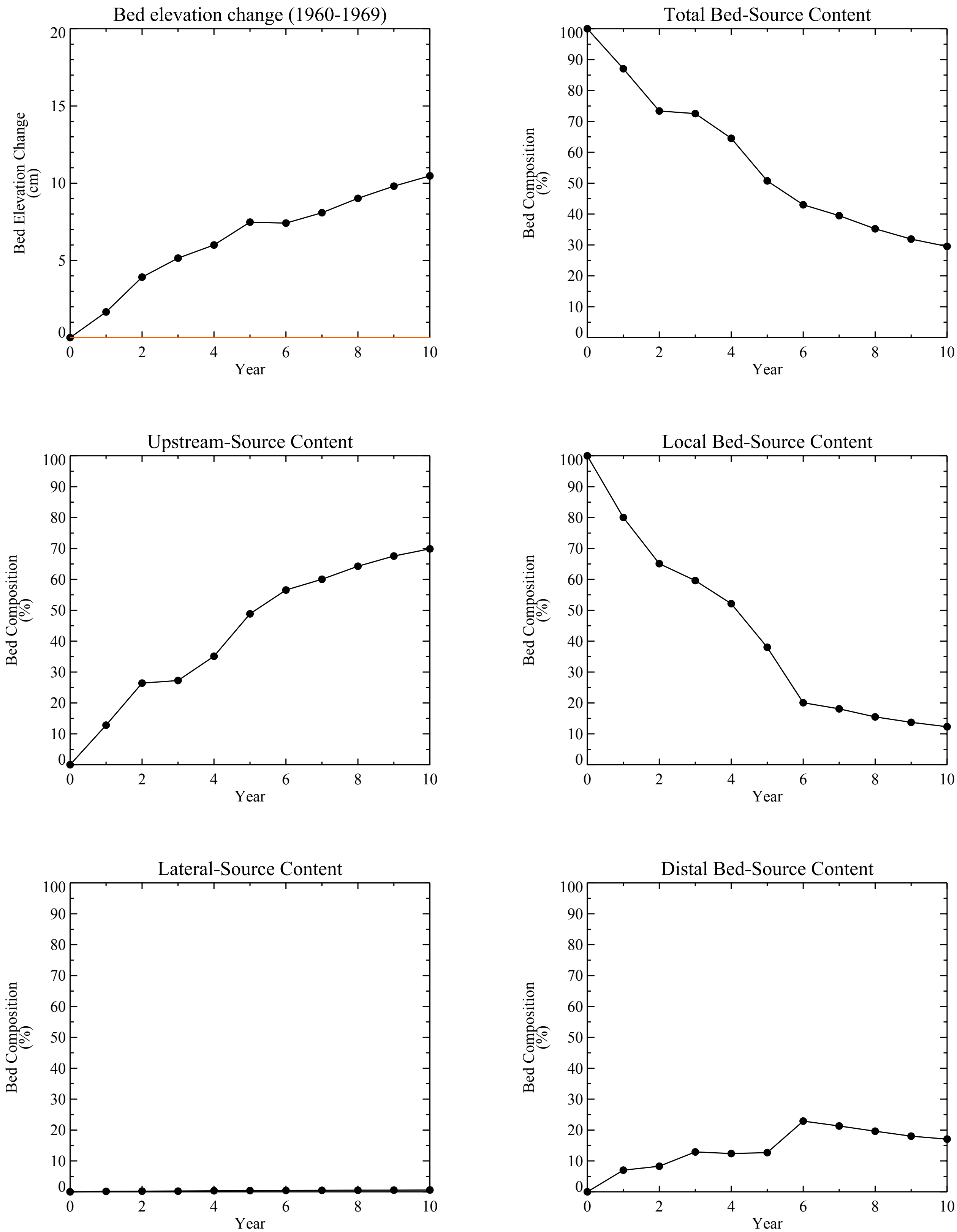

Figure 15. Temporal variation of bed elevation change and bed composition at grid cell: (14, 299), RM 2.7, Navigation Channel.

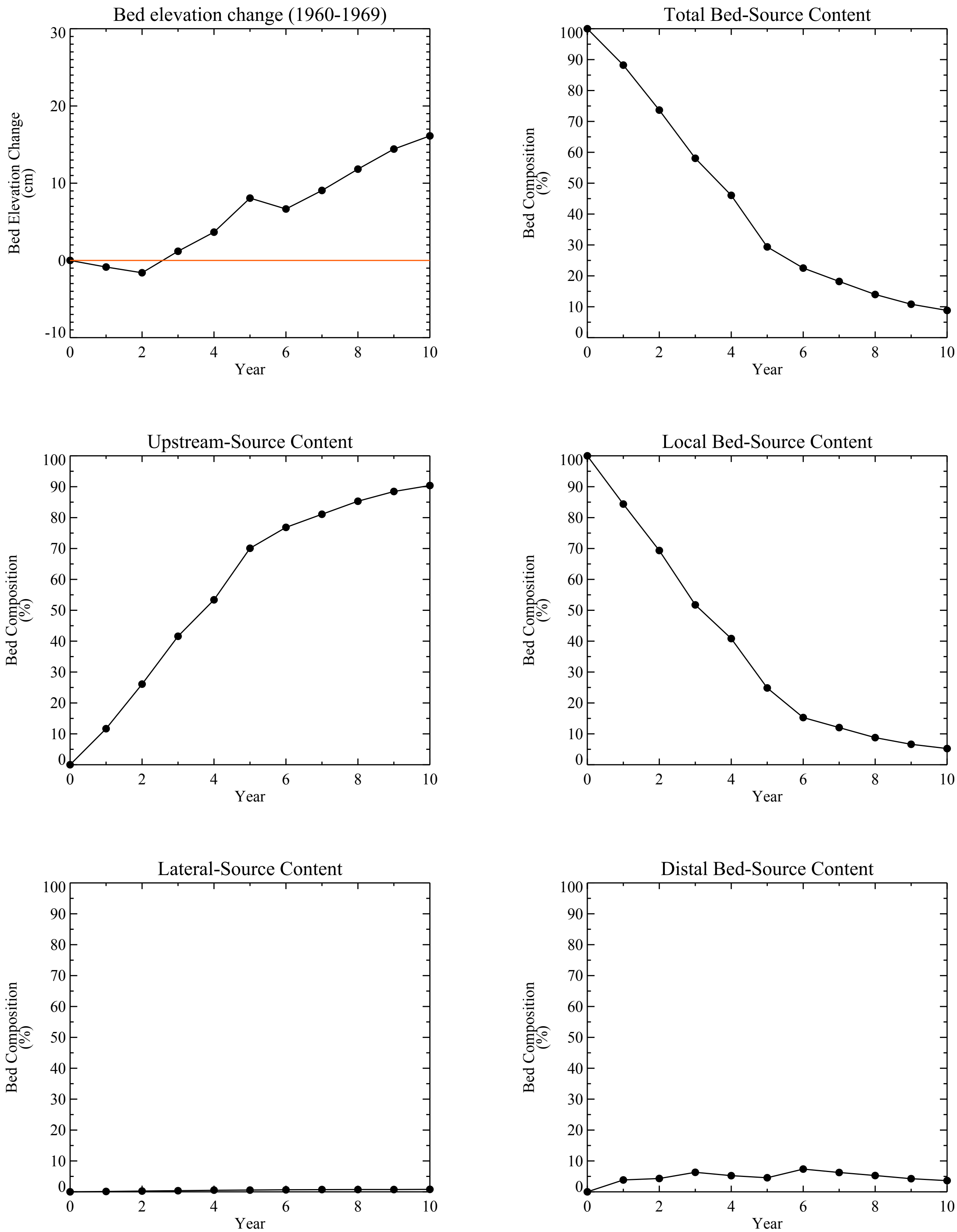

Figure 16. Temporal variation of bed elevation change and bed composition at grid cell: (15, 292), RM 3.1, Navigation Channel.

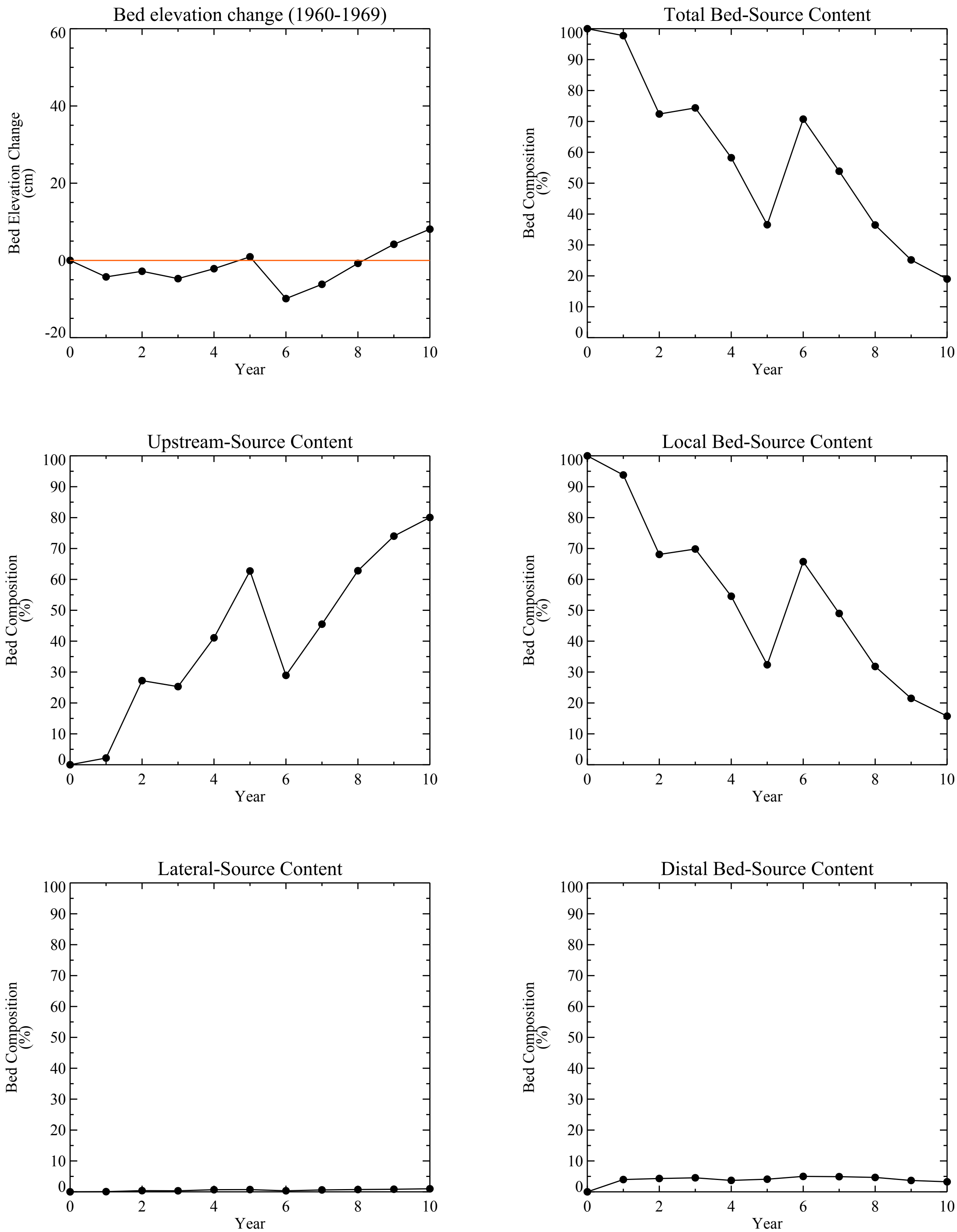

Figure 17. Temporal variation of bed elevation change and bed composition at grid cell: (16, 286), RM 3.6, East Bench.

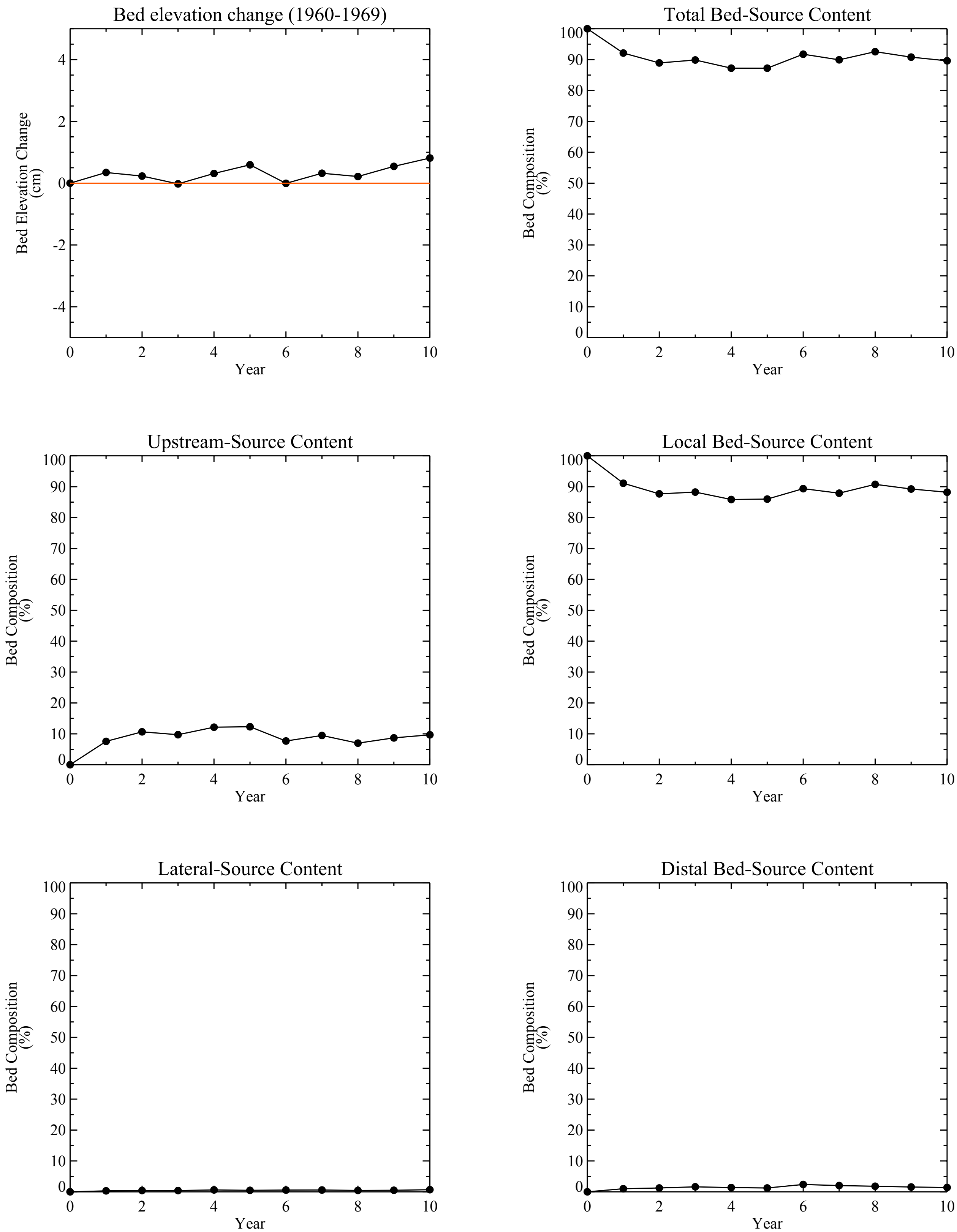

Figure 18. Temporal variation of bed elevation change and bed composition at grid cell: (17, 286), RM 3.6, East Bench.

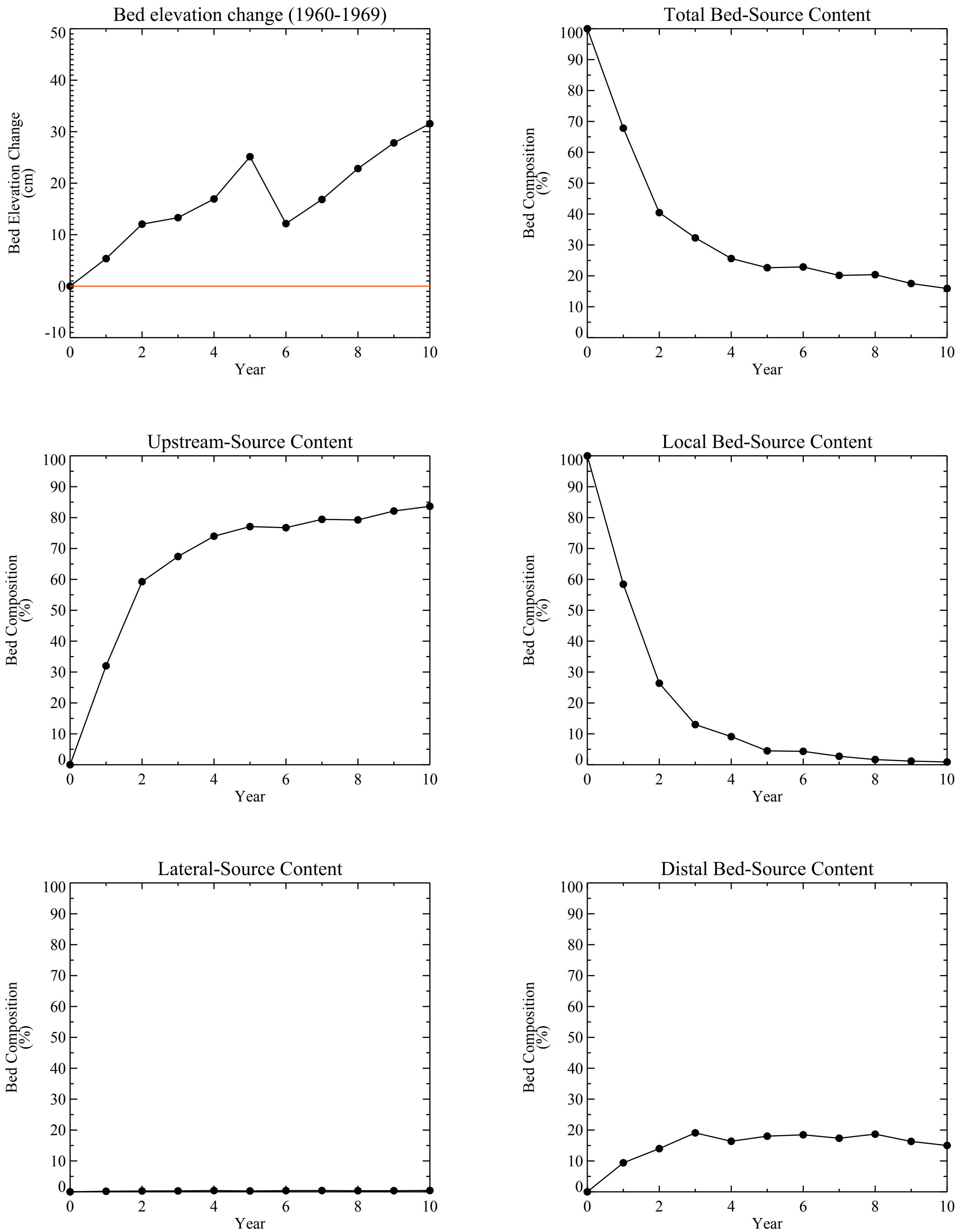

Figure 19. Temporal variation of bed elevation change and bed composition at grid cell: (14, 283), RM 3.9, Navigation Channel.

Part 6: Effects of STM Bounding Simulations on BCM Results

ANCHOR QEA

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MEMORANDUM

To:	Sediment Transport Modeling Group	**Date:**	October 15, 2010
From:	C. Kirk Ziegler, Anchor QEA, and AECOM	**Project:**	RETldw
Cc:	LDWG, Files		
Re:	Effects of STM Bounding Simulations on BCM Results		

Results from the sediment transport model (STM) are being used in the bed composition model (BCM) to evaluate various remedial alternatives in the Lower Duwamish Waterway (LDW). The effects on STM predictions due to uncertainty in model inputs were investigated by varying five model inputs: upstream sediment load, class 1A/1B settling speed, class 2/3 particle diameter, erosion rate parameters, and effective bed roughness. A complete description of that analysis is provided in Appendix D of the Final STM report (QEA 2008). The effects of model-input uncertainty in STM predictions on BCM results were evaluated by using lower- and upper-bound STM simulations in the BCM and comparing those results to results using the base-case STM simulation.

Ten-year simulations, corresponding to the first ten years of the 30-year simulation presented in the final STM report (QEA 2008), were conducted for this analysis. The STM was used to track sediment originating from three sources: 1) original bed sediment; 2) upstream loads (i.e., Green River); and 3) lateral loads (i.e., storm drains, combined sewer overflows [CSOs], streams). The lateral loads were specified using the distributed approach (see Part 4 Scenario 2 of this appendix) so as to more realistically represent the transport of those sediment sources in the STM.

The ranges of model inputs used in the base-case and bounding simulations (i.e., upper- and lower-bound) are listed in Table 1. Of the 32 simulations conducted in the STM uncertainty analysis (QEA 2008), four simulations were selected as reasonable bounding simulations for this BCM uncertainty analysis based on a review of the spatial-scale analyses (see Figures D-101 through D-132 of the STM report [QEA 2008]): runs 19 and 20 for lower-bounds; and runs 9 and 26 for upper-bounds. Runs 9 and 20 are the maximum reasonable bounding simulations, while runs 19 and 26 are the reasonable bounding simulations. The average difference between predicted and estimated net sedimentation rates (NSRs) for runs 20 and

9 were about -1 and +1 cm/yr, respectively, whereas the average difference in NSRs for runs 19 and 26 were approximately -0.5 and +0.5 cm/yr, respectively. The average difference for the base-case simulation was about 0.0 cm/yr. A summary of the model inputs for these four bounding simulations is provided in Table 2. The primary differences between the lower-bound (runs 19 and 20) and upper-bound (runs 9 and 26) simulations were the upstream sediment load and class 1A/1B settling speed.

Table 1. Model input values for STM bounding simulations.

Model Input	Base-Case Value	Lower-Bound Value	Upper-Bound Value
Upstream sediment load for 10-yr simulation period (MT)	1,852,100	926,700	3,703,000
Class 1A/1B settling speed (m/day)	1.3/20	0.65/10	2.6/40
Effective bed roughness (range in µm)	360 to 1,280	300 to 930	420 to 1,630
Class 2/3 particle diameter (µm)	130/540	110/450	150/630

Note: Erosion rate parameters vary among sediment layers in the model. See QEA 2008, Appendix E for bounding values.

Table 2. Model-input bounding limits for STM bounding simulations.

Bounding Simulation	Upstream Sediment Load	Class 1A/1B Settling Speed	Class 2/3 Particle Diameter	Erosion Rate Parameters	Effective Bed Roughness
Run 20: max reasonable lower-bound	Lower	Upper	Upper	Upper	Lower
Run 19: reasonable lower-bound	Lower	Upper	Lower	Upper	Lower
Run 26: reasonable upper-bound	Upper	Lower	Upper	Upper	Lower
Run 9: max reasonable upper-bound	Upper	Lower	Lower	Lower	Lower

Results

Sediment mass balances for the base-case and bounding simulations are shown in Figures 1 through 5. For the lower-bound simulations, the net deposition in the LDW decreases, relative to the base-case simulation, due to the upstream sediment load decreasing by about 50%. However, the predicted trapping efficiency increases for the lower-bound simulations primarily because of the increase in class 1A/1B settling speed. Net deposition in the LDW increases for the upper-bound simulations because of the 100% increase in upstream sediment load, with the trapping efficiency decreasing mainly because of a lower class 1A/1B settling speed.

Average NSR values for different reaches of the LDW for the base-case and lower- and upper-bound simulations are presented in Table 3. Graphical comparisons of the average NSR values for the three reaches [Reach 1, river mile [RM] 0 to 2.2; Reach 2, RM 2.2 to 4.0; and Reach 3, RM 4.0 to 4.8] are shown in Figures 6 through 10, with Figure 9 showing the average value for Reaches 1 and 2 combined. The average NSR for Reach 3 is for the cohesive bed area within that reach. In Reach 1, relatively small differences in average NSR values (i.e., 0.1 cm/yr) occurred between the two lower-bound (runs 19 and 20) and two upper-bound (runs 9 and 26) simulations, with larger differences occurring in Reach 2. Combining Reaches 1 and 2 produces average NSR values for the bounding simulations that are about ± 0.5 and ± 1.0 cm/yr different from the base-case value.

Table 3. Average net sedimentation rates (NSR) for STM uncertainty simulations.

Simulation	Site-Wide NSR (cm/yr)	Reach 1 NSR (cm/yr)	Reach 2 NSR (cm/yr)	Reach 1-2 NSR (cm/yr)	Reach 3 NSR (cm/yr)
Run 20: maximum reasonable lower-bound	1.9	1.2	1.2	1.2	9.2
Run 19: reasonable lower-bound	2.1	1.3	1.7	1.4	9.7
Base Case	**3.3**	**1.6**	**2.5**	**1.9**	**17**
Run 26: reasonable upper-bound	4.3	2.1	3.0	2.4	24
Run 9: maximum reasonable upper bound	5.0	2.2	4.5	2.8	27

The net sedimentation rates from base-case and bounding STM simulations were used by AECOM in the BCM to estimate spatially-weighted average concentrations (SWACs) for total PCBs within 10 years following completion of Alternative 1: No Further Action (Completion of EAAs). The BCM input parameters proposed by the Lower Duwamish Waterway Group (LDWG) as representing the total PCB concentrations for upstream Green/Duwamish River solids, lateral source solids (from storm drains, CSOs, and creeks), and post-remedy bed sediment replacement values were varied between low, mid, and high values (Table 4).

Table 4. LDWG-proposed total PCB input parameters for the BCM[1]

	Low (µg/kg dw)	Mid (µg/kg dw)	High (µg/kg dw)
Upstream Green/Duwamish River Solids	5	35	82
Lateral Source Solids	200	500	1,000
Post-Remedy Bed Sediment Replacement	30	60	90

This produced a total of 15 predictions of total PCB SWACs in the three reaches of the LDW. The site-wide results are presented in Table 5, with the results for Reaches 1, 2, and 3 presented in Tables 6, 7, and 8, respectively. The effects of uncertainty in STM predictions on BCM results are graphically illustrated in Figures 11 through 14. The following conclusions were developed from these figures:

- Generally, the site-wide PCB SWACs for the two lower-bound and two upper-bound simulations are similar. Thus, it is recommended that the maximum reasonable bounding simulations (i.e., runs 20 and 9) be used for future analyses and reporting, and that the reasonable bounding simulations (i.e., runs 19 and 26) not be considered in future analyses or discussions.
- The STM base case with the low and high BCM total PCB input values (Table 4) resulted in a wider range in PCB SWACs compared to the BCM mid values applied to the STM bounding runs.
- The total PCB SWACs estimated using the BCM respond in a non-linear fashion to average NSR values estimated by the STM.

[1] Values in Table 4 were the proposed input values as of November 17, 2009, when the analysis presented here was conducted. Final BCM input parameters are essentially the same for upstream and post-remedy bed sediment replacement values, but lower lateral low and mid values were used in the FS (see FS Table 5-1a).

Table 5. Year 10 Post Alternative 1 Total PCB SWACs: Site-Wide

Simulation	Total PCB SWAC (µg/kg dw)		
	Using Low BCM Input Parameter Values	Using Mid BCM Input Parameter Values	Using High BCM Input Parameter Values
Run 20: maximum reasonable lower-bound	78	104	145
Run 19: reasonable lower-bound	75	101	144
Base Case	**49**	**77**	**122**
Run 26: reasonable upper-bound	36	65	110
Run 9: maximum reasonable upper-bound	32	62	109

Table 6. Year 10 Post Alternative 1 Total PCB SWACs: Reach 1

Simulation	Total PCB SWAC (µg/kg dw)		
	Using Low BCM Input Parameter Values	Using Mid BCM Input Parameter Values	Using High BCM Input Parameter Values
Run 20: maximum reasonable lower-bound	89	114	154
Run 19: reasonable lower-bound	91	116	156
Base Case	**61**	**88**	**132**
Run 26: reasonable upper-bound	46	74	118
Run 9: maximum reasonable upper bound	43	72	117

Table 7. Year 10 Post Alternative 1 Total PCB SWACs: Reach 2

Simulation	Total PCB SWAC (µg/kg dw)		
	Using Low BCM Input Parameter Values	Using Mid BCM Input Parameter Values	Using High BCM Input Parameter Values
Run 20: maximum reasonable lower-bound	88	115	155
Run 19: reasonable lower-bound	72	101	145
Base Case	**43**	**73**	**119**
Run 26: reasonable upper-bound	29	59	106
Run 9: maximum reasonable upper-bound	22	54	102

Table 8. Year 10 Post Alternative 1 Total PCB SWACs: Reach 3

Simulation	Total PCB SWAC (µg/kg dw)		
	Using Low BCM Input Parameter Values	Using Mid BCM Input Parameter Values	Using High BCM Input Parameter Values
Run 20: maximum reasonable lower-bound	15	46	95
Run 19: reasonable lower-bound	16	46	94
Base Case	**12**	**42**	**90**
Run 26: reasonable upper-bound	9	40	88
Run 9: maximum reasonable upper-bound	9	40	88

Ranges of total PCB SWACs predicted by the BCM for the base-case STM results and for the lower- and upper-bound STM results are presented in Table 9 and graphically illustrated in Figures 15 through 18. For the STM base-case results (first column in Table 9), the ranges correspond to the differences resulting from using the high and low BCM input parameter values for total PCBs. For the STM range results (columns 2 through 4 in Table 9) the difference is the maximum difference among the upper and lower bound runs.

Table 9. Range of total PCB SWACs for STM uncertainty simulations.

	Range in Total PCB SWACs (µg/kg dw)			
	STM Base-Case Varying Only the BCM Input Parameters	Over the Range of STM Uncertainty Results		
LDW Reach		Using the Low BCM Input Parameters	Using the Mid BCM Input Parameters	Using the High BCM Input Parameters
Site-Wide	73	46	42	36
Reach 1	71	48	44	39
Reach 2	76	66	61	53
Reach 3	78	7	6	7

Discussion

A non-linear relationship exists between average NSR values estimated by the STM and total PCB SWACs predicted by the BCM. This non-linearity is caused primarily by mixing in the surface (top 10 cm) layer of the bed due to erosion and deposition processes. As discussed in the STM report (QEA 2008), the relationship between half-time of bed-source content in the surface layer and NSR is non-linear and multi-valued (i.e., range of half-time values for a specific NSR value) (see Figure F-37 [QEA 2008]). The primary cause of this non-linear relationship is episodic erosion and deposition at the spatial scale of a grid cell.

The following simplified calculation will help illustrate this non-linear process. First, it is useful to note that NSR is determined by the difference between the gross deposition (D_g) and erosion (E_g) rates:

$$NSR = D_g - E_g$$

where D_g and E_g are calculated by the STM. Second, the rate of change (decrease) of bed-source content in the surface layer is affected by both the absolute value of NSR and the relative values of D_g and E_g. A simplified example of the effect of the relative values of D_g and E_g is shown in Figure 19. This example calculation makes the following assumptions: 1) a generic chemical is permanently bound to sediment particles; 2) change in bed concentration is only due to erosion and deposition processes; 3) initial bed concentration is 10 ppm; 4) depositing sediment is "clean" (i.e., concentration on depositing particles is 0 ppm); 5) surface layer is 10 cm thick; and 6) NSR is 0.5 cm/yr. Two different combinations of D_g and E_g, with the difference between the gross fluxes being 0.5 cm/yr for each combination, were used to calculate the change in bed concentration at a specific location over a 1-year period. For the lower values of D_g and E_g (left-hand panel in Figure 19), the bed concentration decreased by 9%, from 10 to 9.1 ppm. For the higher values of D_g and E_g (right-hand panel in Figure 19), the bed concentration decreased from 10 to 7.1 ppm, which corresponds to a much higher rate of change than for the situation with lower values of D_g and E_g. Thus, significant differences in the rate of change in sediment chemical concentrations can occur at two grid cells with the same NSR values but with different gross erosion and deposition fluxes.

Additional Results

Spatial distributions of estimated NSRs for the maximum reasonable bounding simulations as compared to the base-case simulation for Reaches 1, 2, and 3 are presented on Figures 20 through 22. Generally, the lower-bound simulation yielded lower NSR values than the base-case simulation and higher NSR values were estimated by the upper-bound simulation. The spatial distribution of differences in NSR values between the upper- and lower-bound simulations are shown in Figure 23.

Predicted total PCB concentrations for 10 years following completion of Alternative 1, using the mid PCB concentrations for input to the BCM, are compared for the base-case, lower-bound, and upper-bound STM simulations in Figures 24, 25, and 26. The comparisons shown on these figures illustrate the effects of STM sensitivity simulations on the spatial distributions of total PCB concentrations.

Spatial distributions of predicted total PCB concentrations for 10 years following completion of Alternative 1, using the base-case STM results, are compared for the low, mid, and high inputs to the BCM in Figures 27, 28, and 29. These results demonstrate the sensitivity of the BCM to variations in the PCB input parameters.

Conclusions

The results presented above demonstrate that:

- The range in total PCB SWACs attributable to STM uncertainty is similar using the low and mid BCM input parameter values for total PCBs, and lower using the high BCM input parameter values.
- For site-wide and Reach 1 averages, the range in total PCB SWACs attributable to STM uncertainty is about 40% lower than the range attributable to uncertainty in the BCM input parameter values. For Reach 2, the range in total PCB SWACs attributable to STM uncertainty is about 20% lower than the range attributable to uncertainty in the BCM input parameter values. For Reach 3, STM uncertainty results in minimal uncertainty in BCM predictions.

<u>Attachments</u>

<u>Reference</u>

QEA 2008. *Lower Duwamish Waterway Sediment Transport Modeling Report. Final.* Prepared for the Lower Duwamish Waterway Group for submittal to the U.S. Environmental Protection Agency, Region 10, and Washington State Department of Ecology. Quantitative Environmental Analysis, LLC, Montvale, NJ. October 2008.

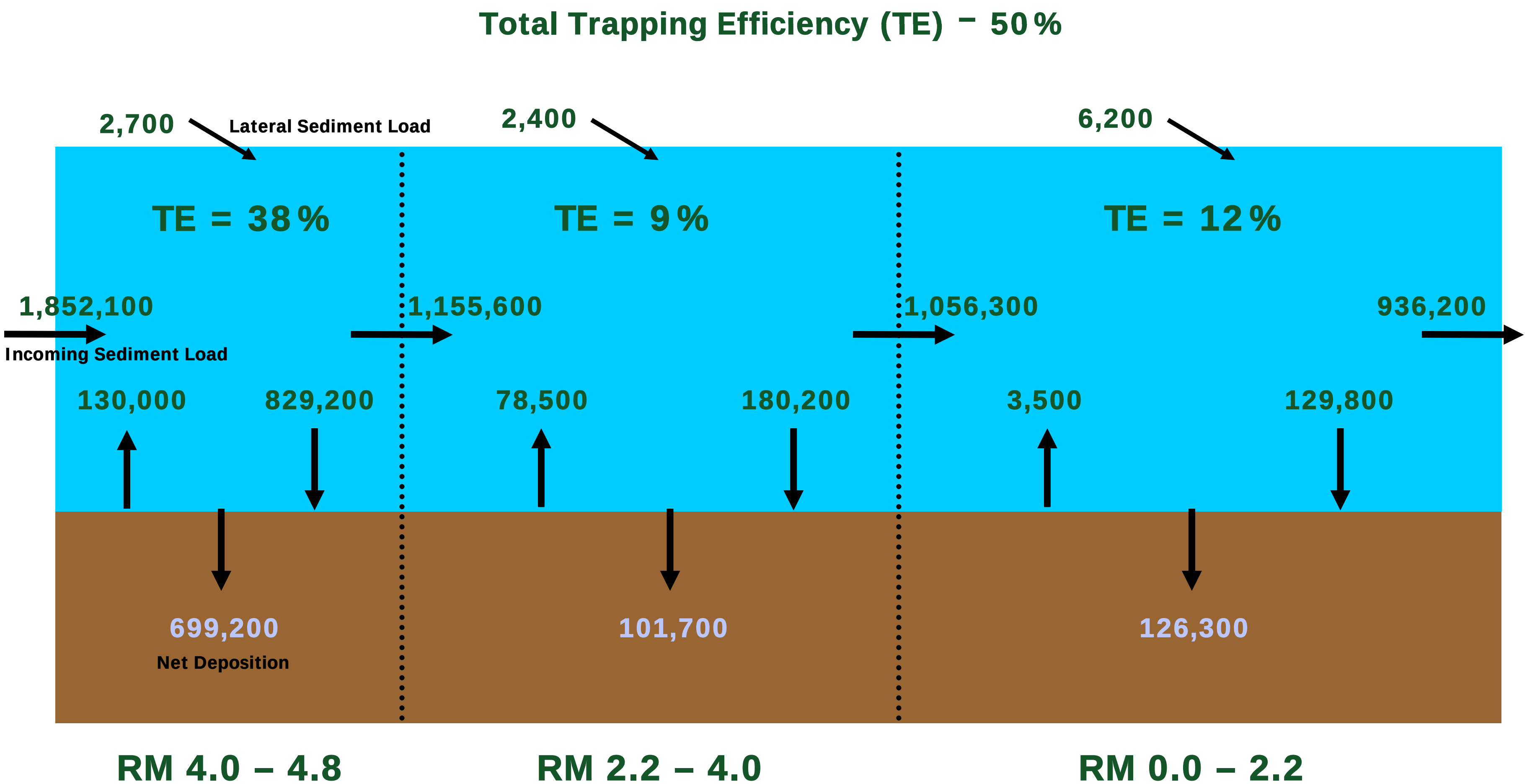


Figure 1. Sediment mass balance in the LDW (RM 0 – 4.8) for 10-year period: base case. Mass units are metric tons. Trapping efficiency is percentage of incoming sediment load that is deposited within a reach.

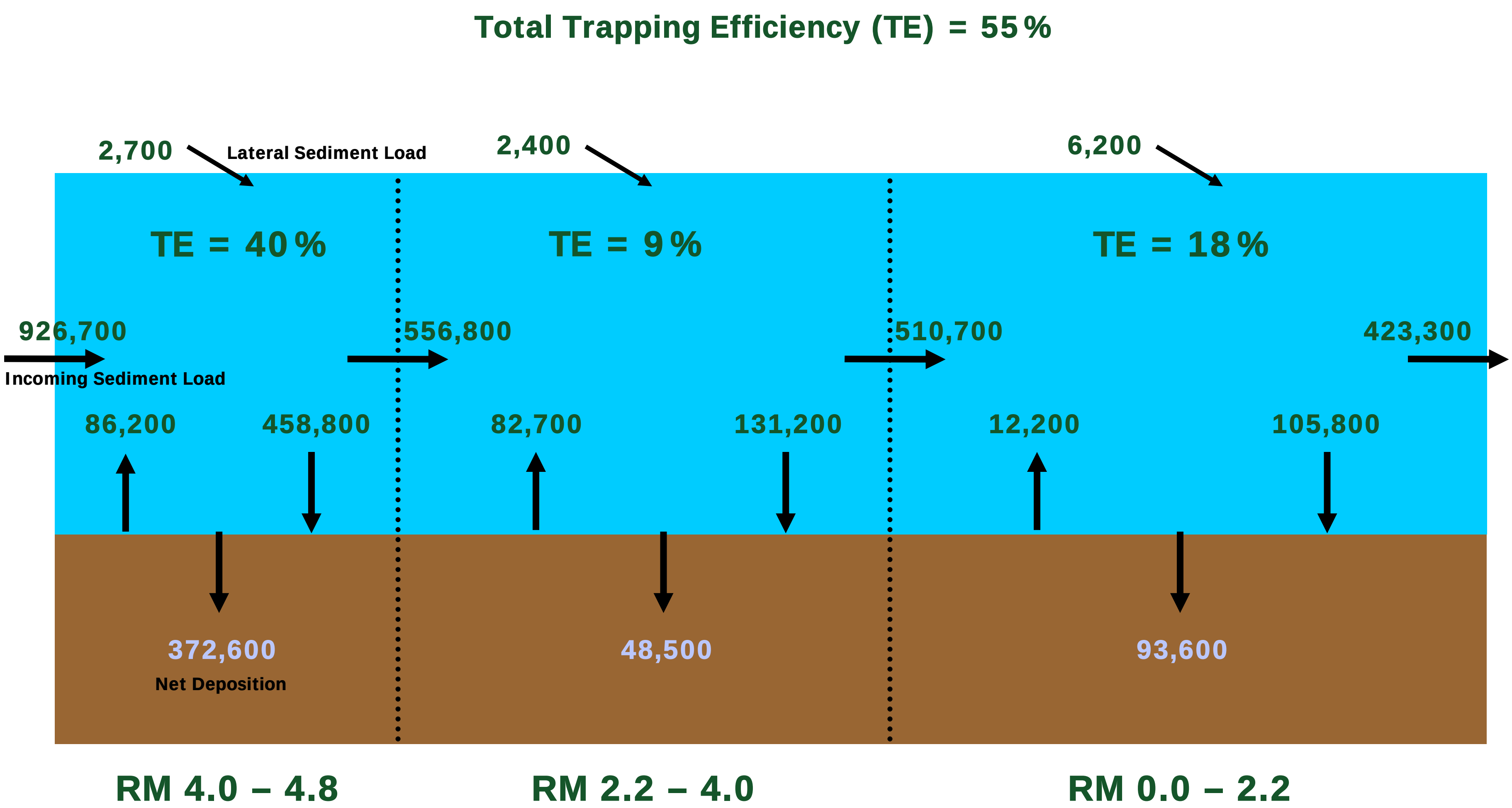


Figure 2. Sediment mass balance in the LDW (RM 0 – 4.8) for 10-year period: run 20, lower-bound 1. Mass units are metric tons. Trapping efficiency is percentage of incoming sediment load that is deposited within a reach.

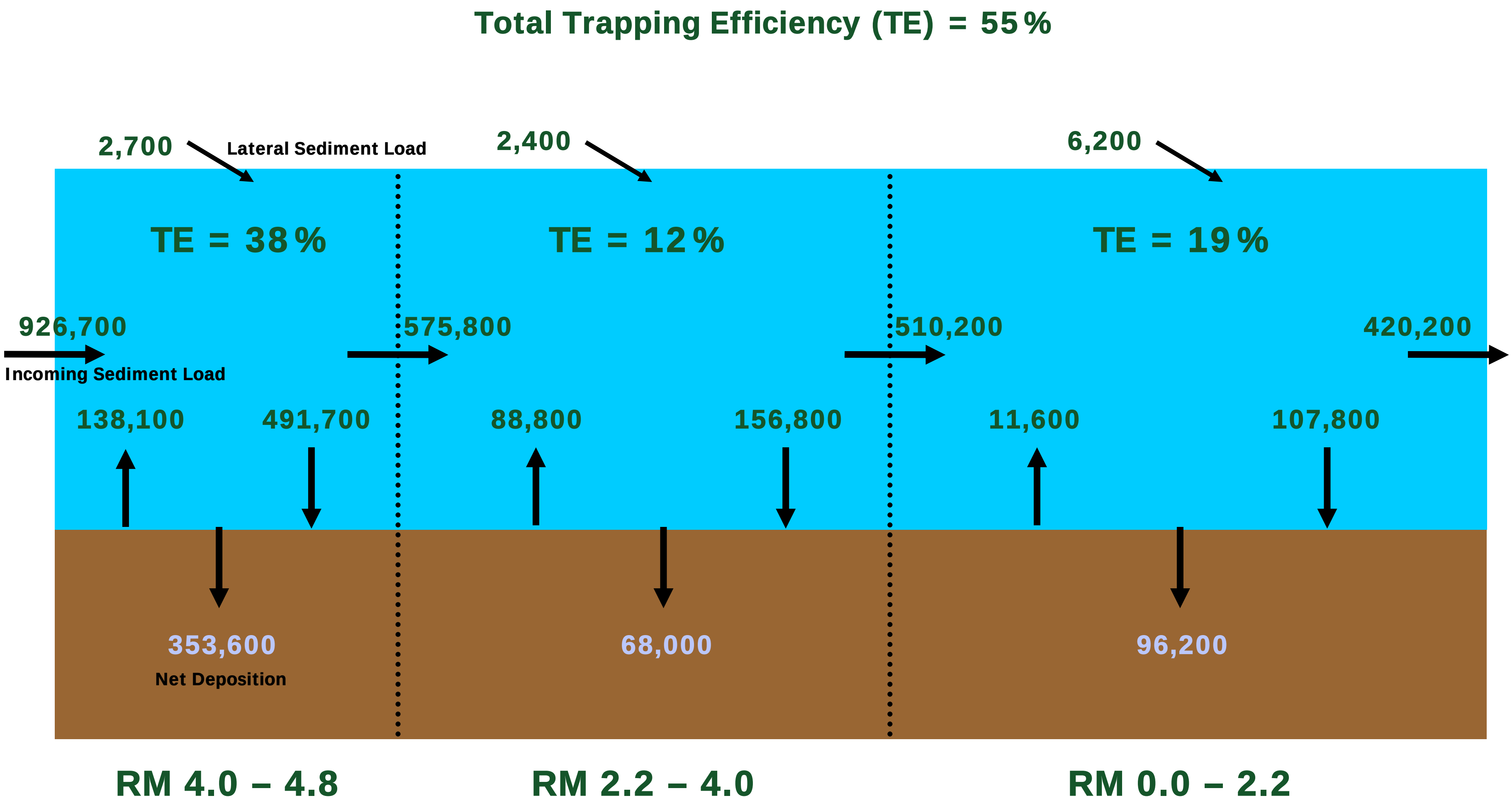


Figure 3. Sediment mass balance in the LDW (RM 0 – 4.8) for 10-year period: run 19, lower-bound 2. Mass units are metric tons. Trapping efficiency is percentage of incoming sediment load that is deposited within a reach.

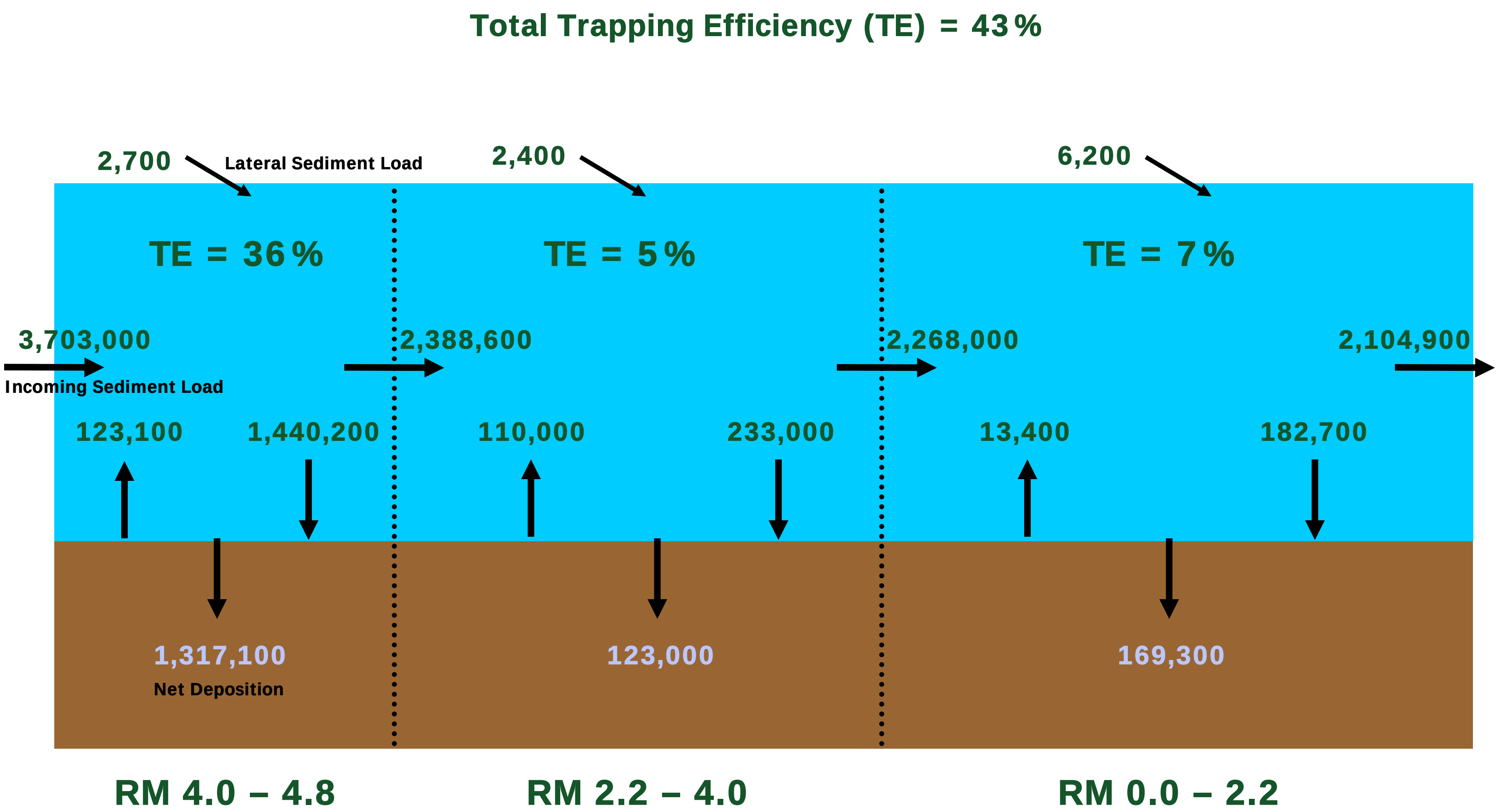


Figure 4. Sediment mass balance in the LDW (RM 0 – 4.8) for 10-year period: run 26, upper-bound 2. Mass units are metric tons. Trapping efficiency is percentage of incoming sediment load that is deposited within a reach.

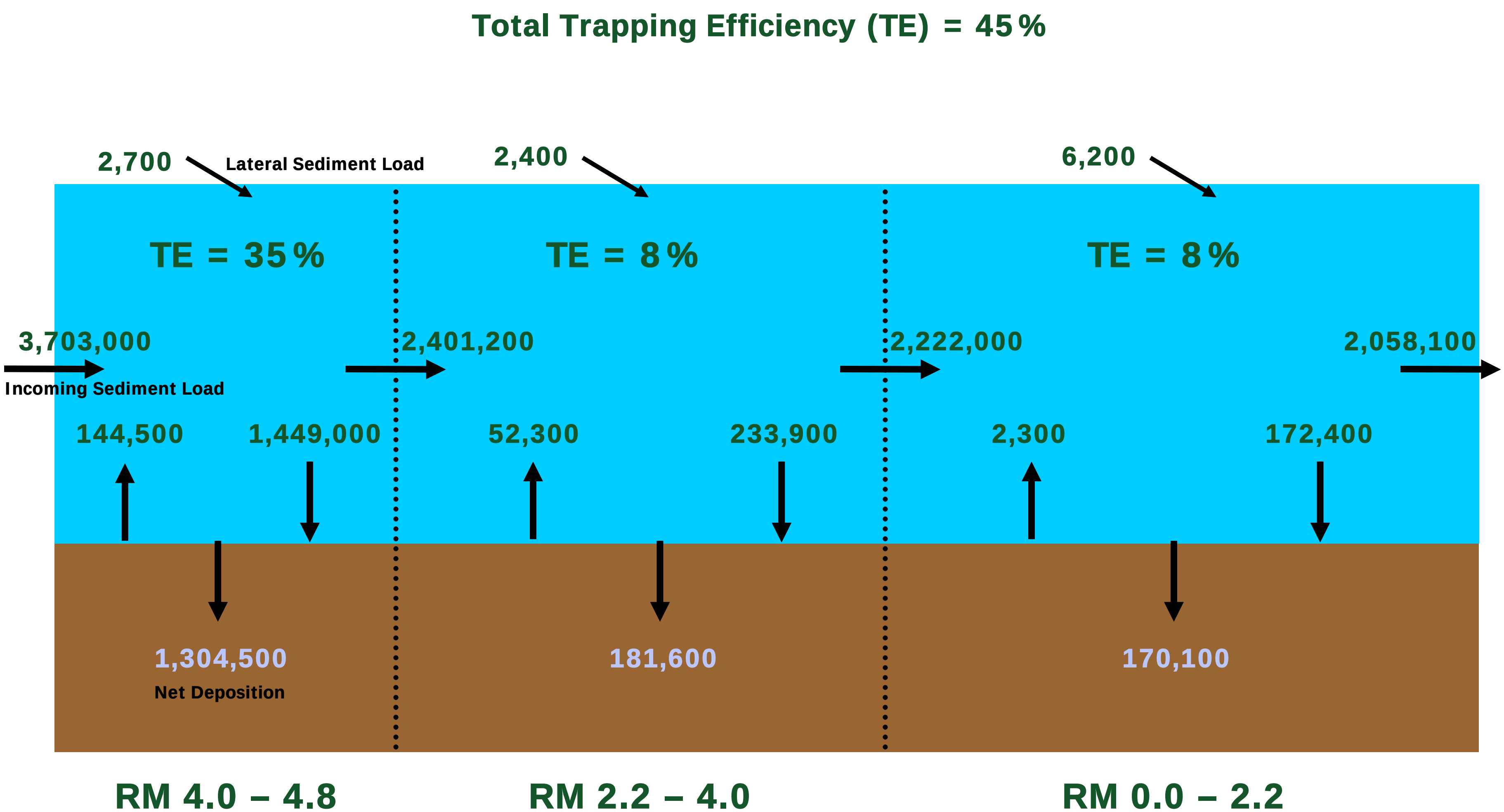


Figure 5. Sediment mass balance in the LDW (RM 0 – 4.8) for 10-year period, run 9, upper-bound 1. Mass units are metric tons. Trapping efficiency is percentage of incoming sediment load that is deposited within a reach.

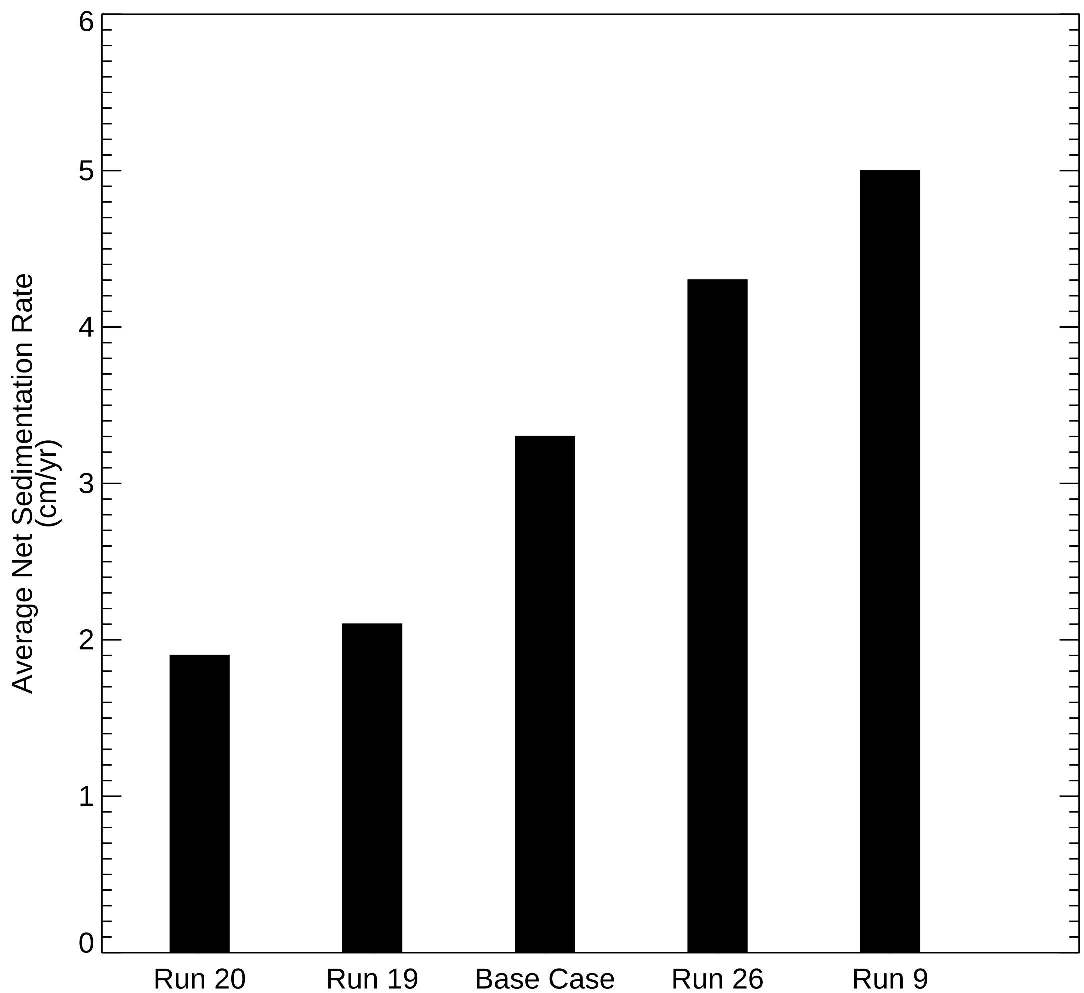


Figure 6. Estimated site-wide average net sedimentation rate.

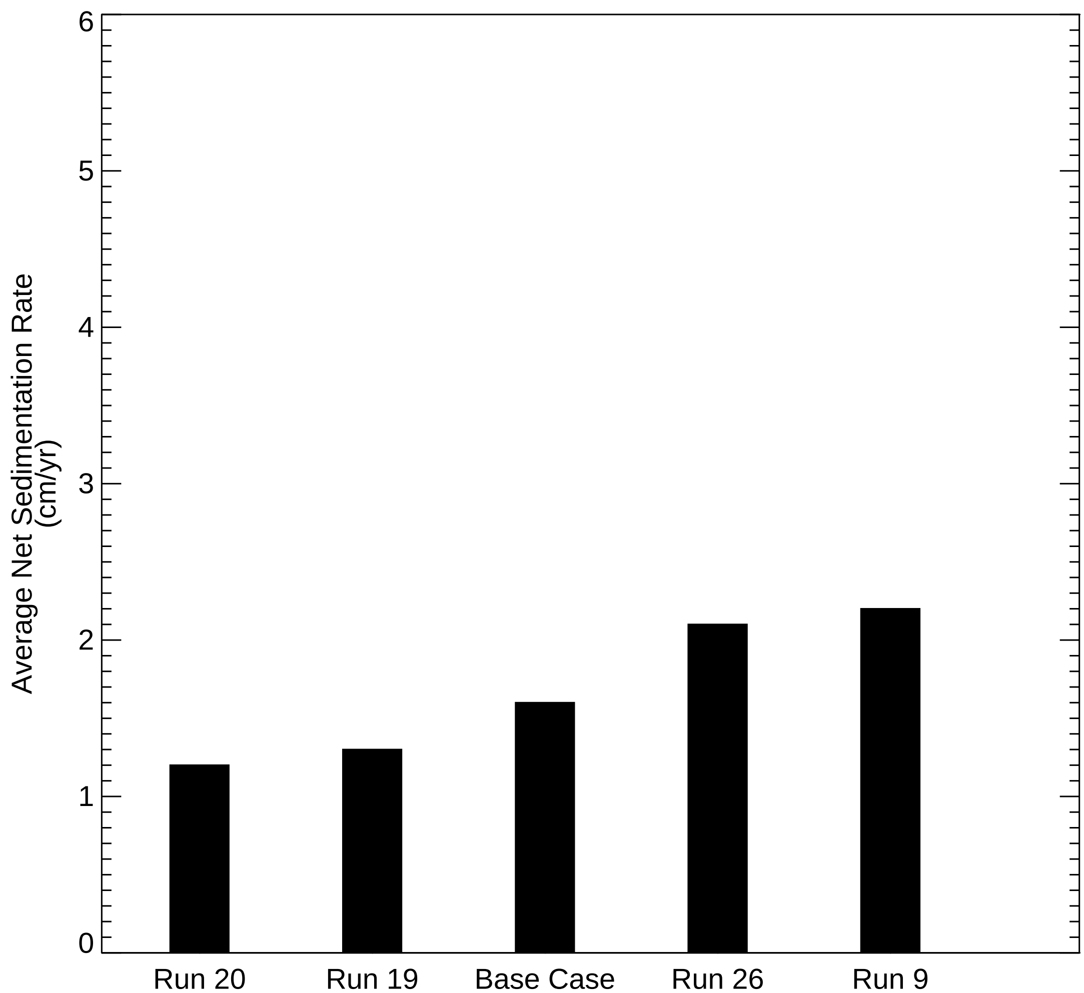


Figure 7. Estimated Reach 1 average net sedimentation rate.

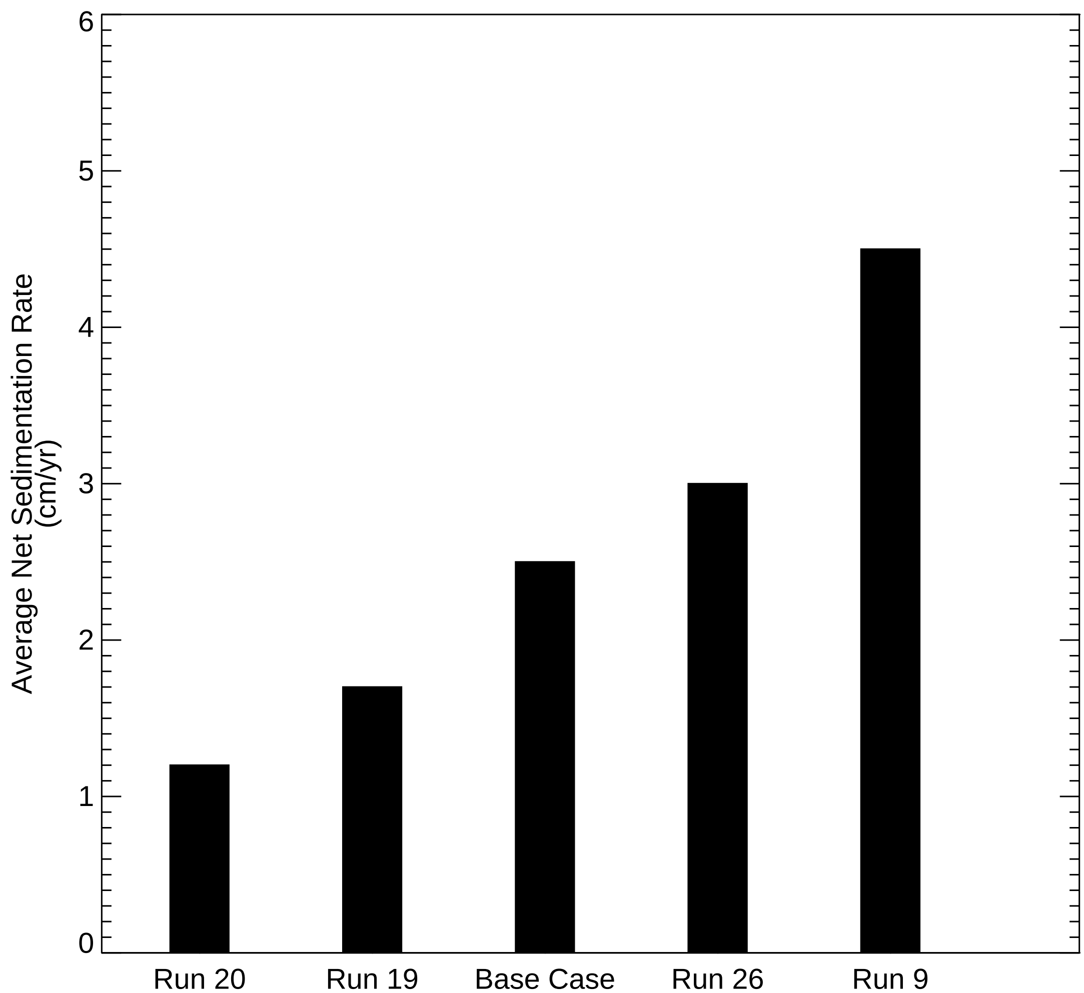


Figure 8. Estimated Reach 2 average net sedimentation rate.

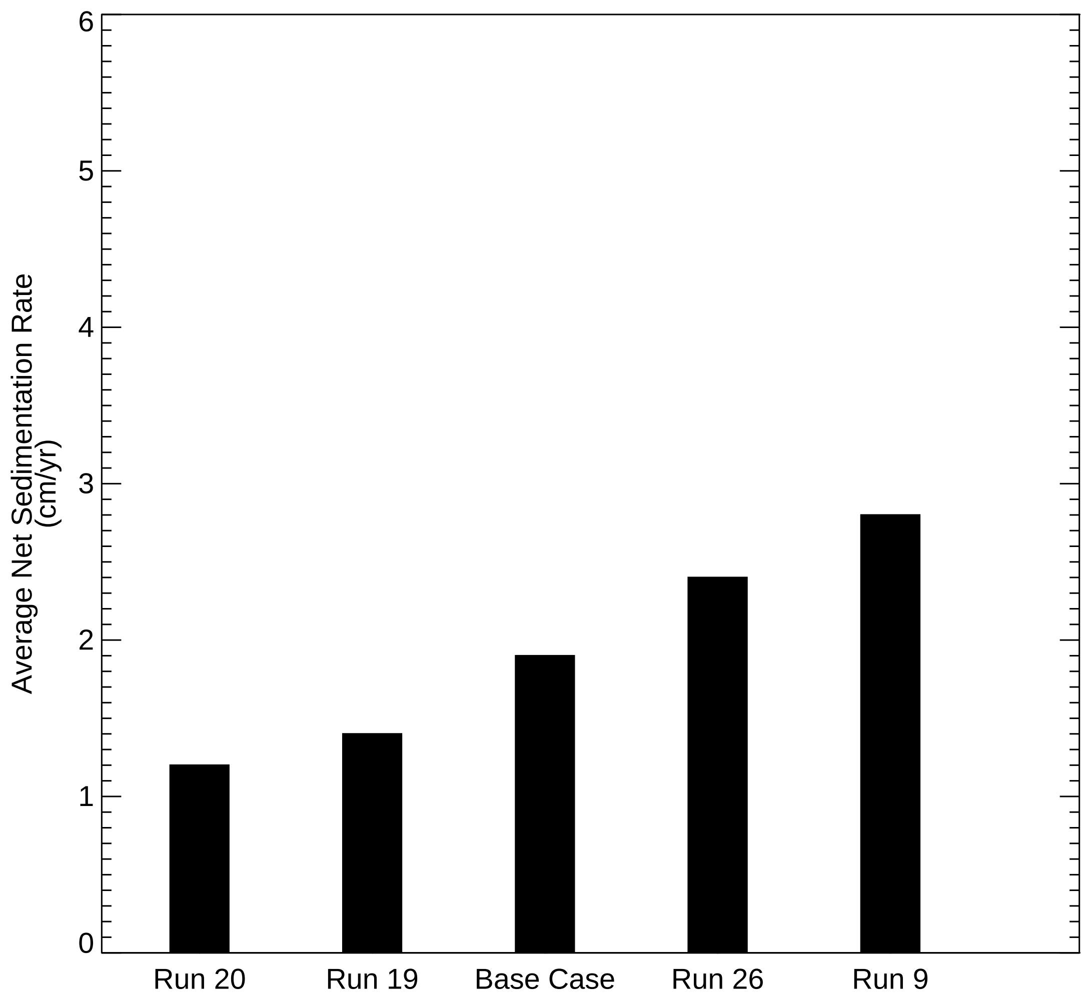


Figure 9. Estimated Reach 1 and 2 average net sedimentation rate.

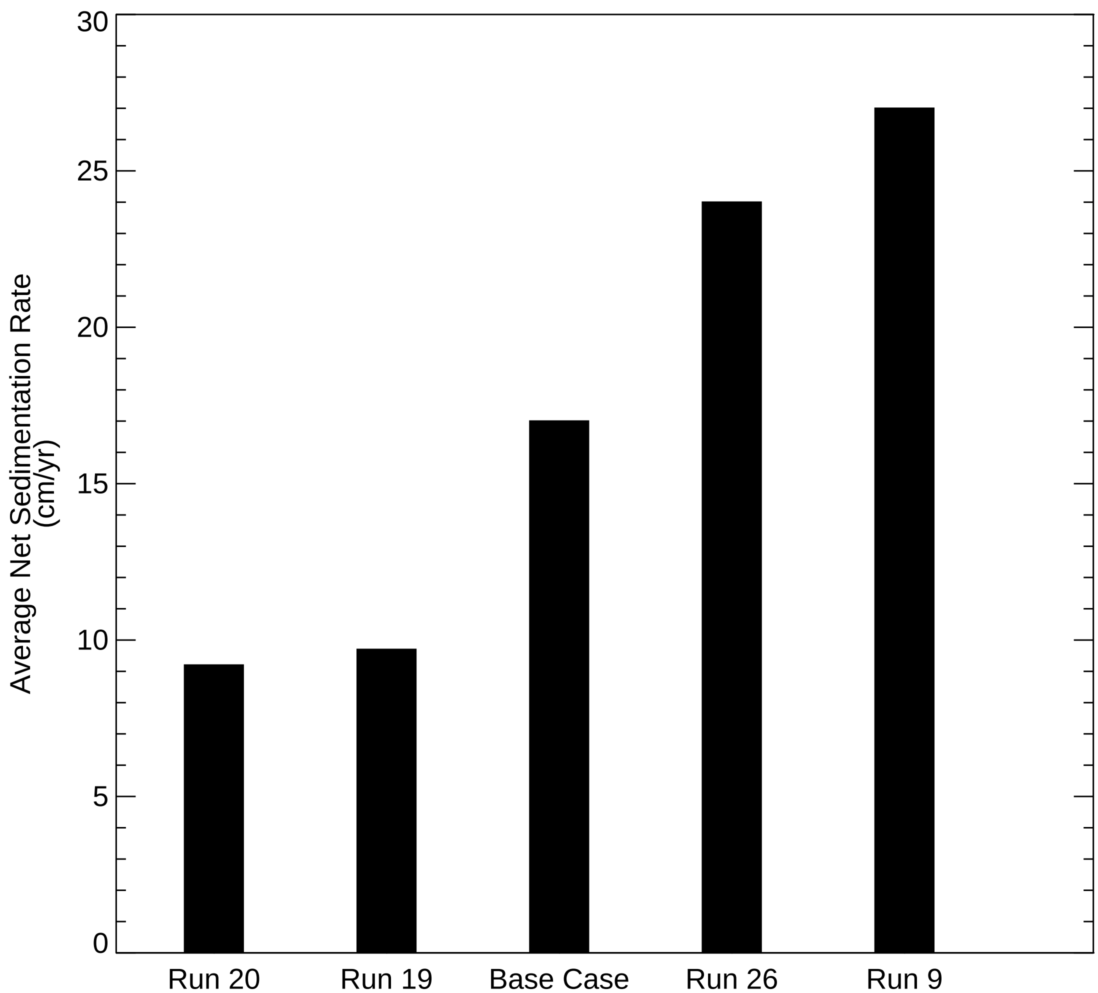


Figure 10. Estimated Reach 3 average net sedimentation rate (cohesive bed area).

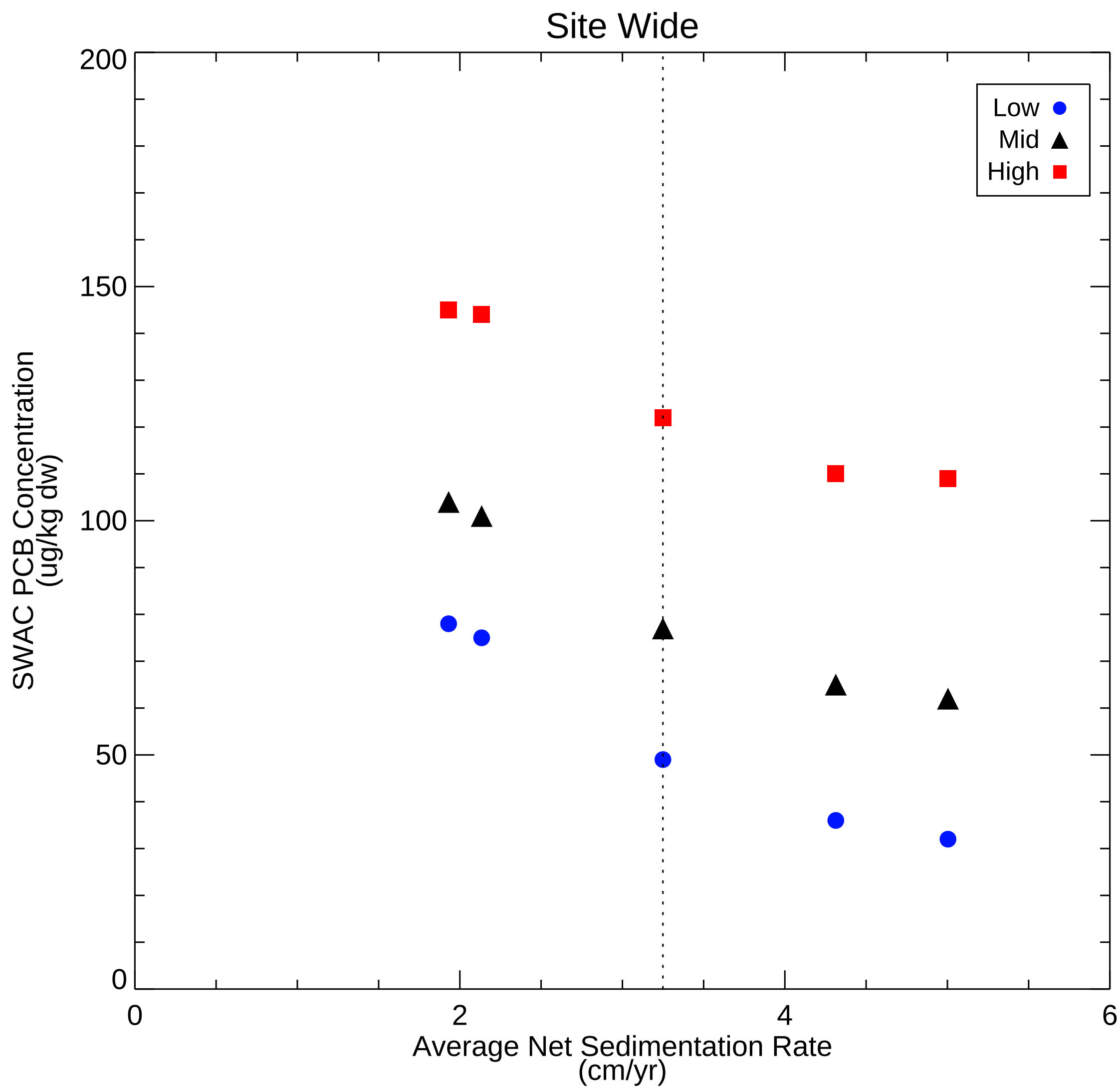


Figure 11. Year 10 Post Alt 1 (post-EAAs) distributed Lateral Load SWACs - Total PCBs.

Exploratory STM/BCM Analysis, last updated by AGF on November 20, 2009.

Dashed line represents base case sedimentation rate.

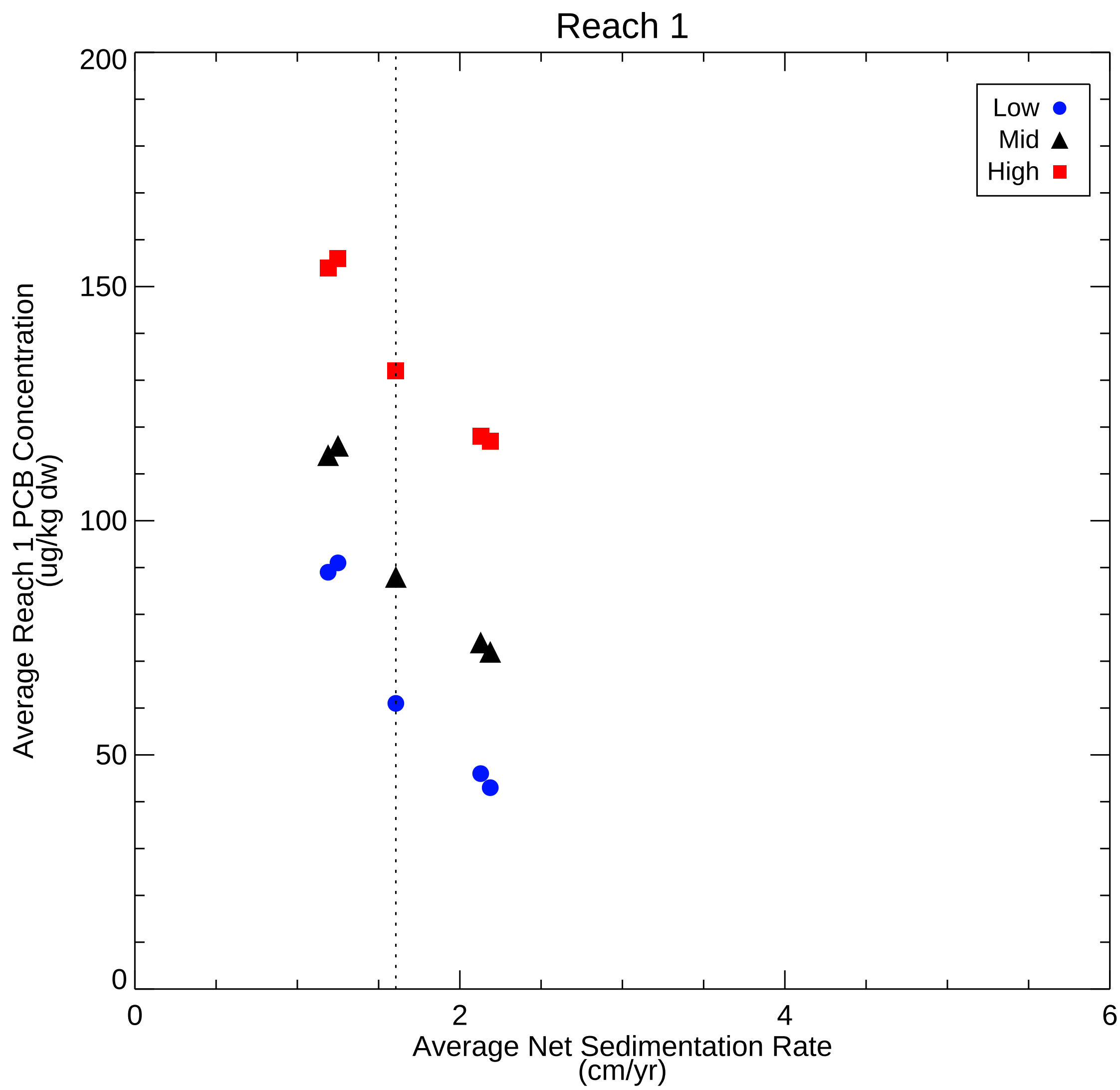


Figure 12. Year 10 Post Alt 1 (post-EAAs) distributed Lateral Load SWACs - Total PCBs.

Exploratory STM/BCM Analysis, last updated by AGF on November 20, 2009.

Dashed line represents base case sedimentation rate.

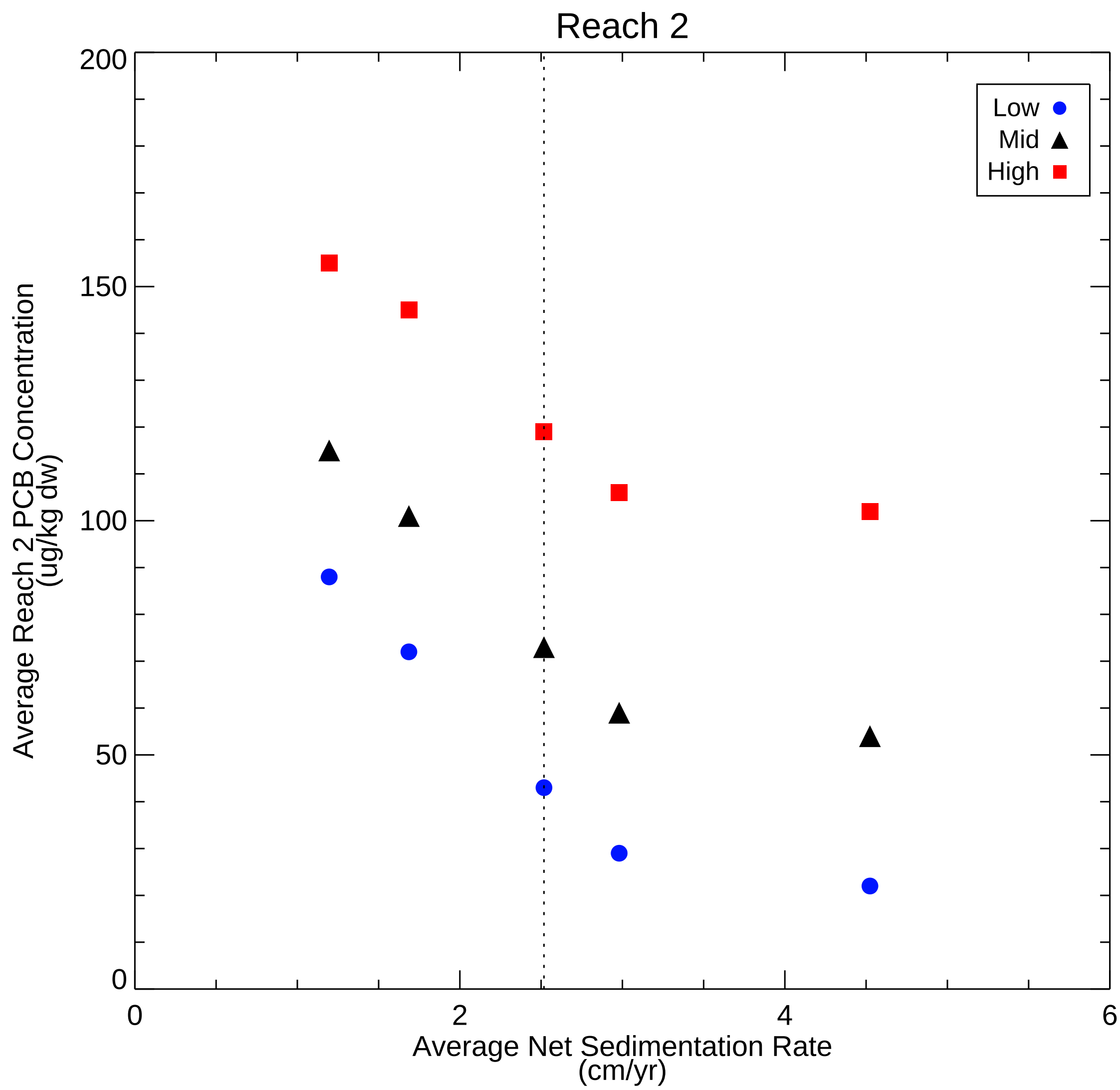


Figure 13. Year 10 Post Alt 1 (post-EAAs) distributed Lateral Load SWACs - Total PCBs.

Exploratory STM/BCM Analysis, last updated by AGF on November 20, 2009.

Dashed line represents base case sedimentation rate.

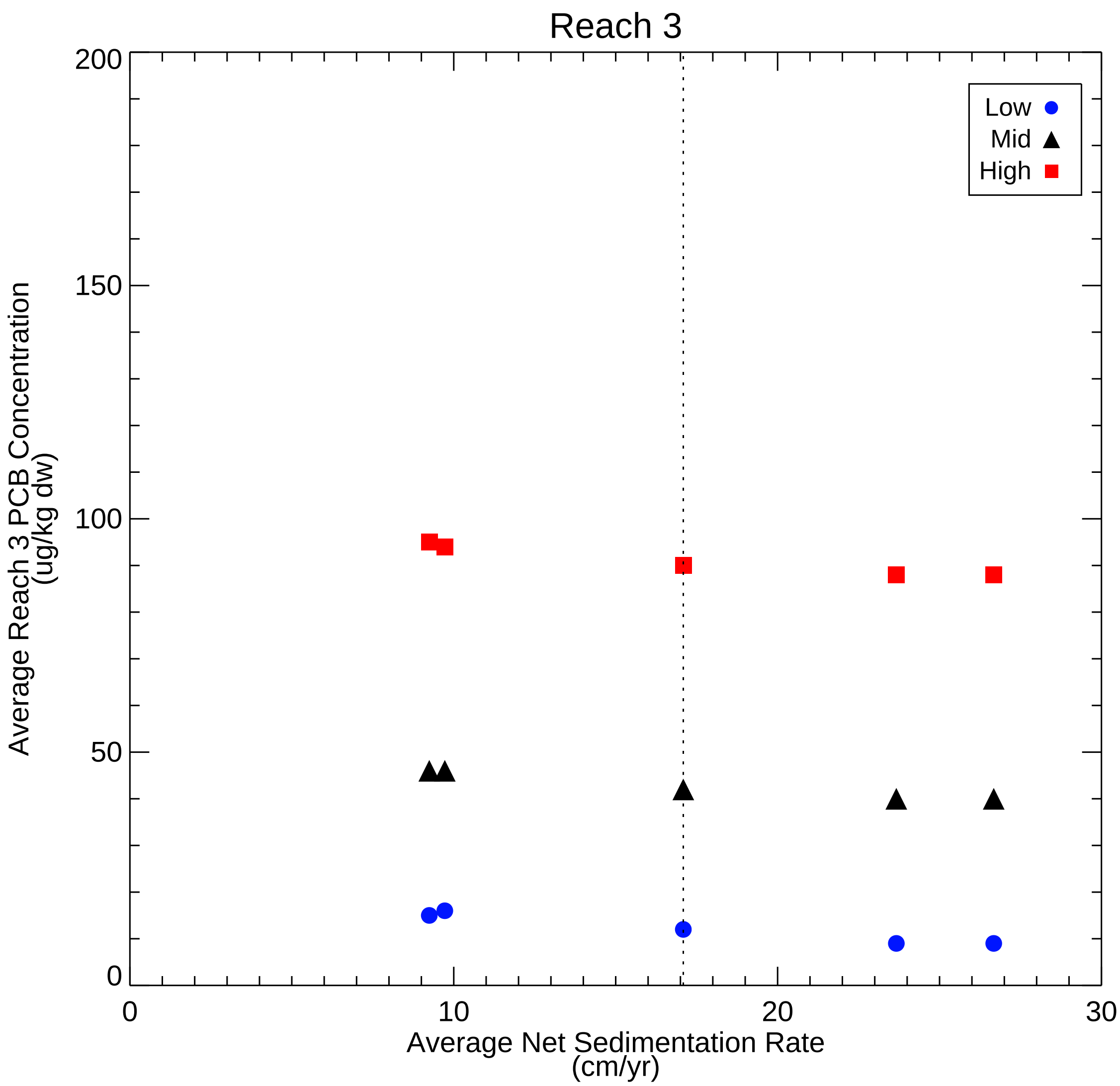


Figure 14. Year 10 Post Alt 1 (post-EAAs) distributed Lateral Load SWACs - Total PCBs.

Exploratory STM/BCM Analysis, last updated by AGF on November 20, 2009.

Dashed line represents base case sedimentation rate.

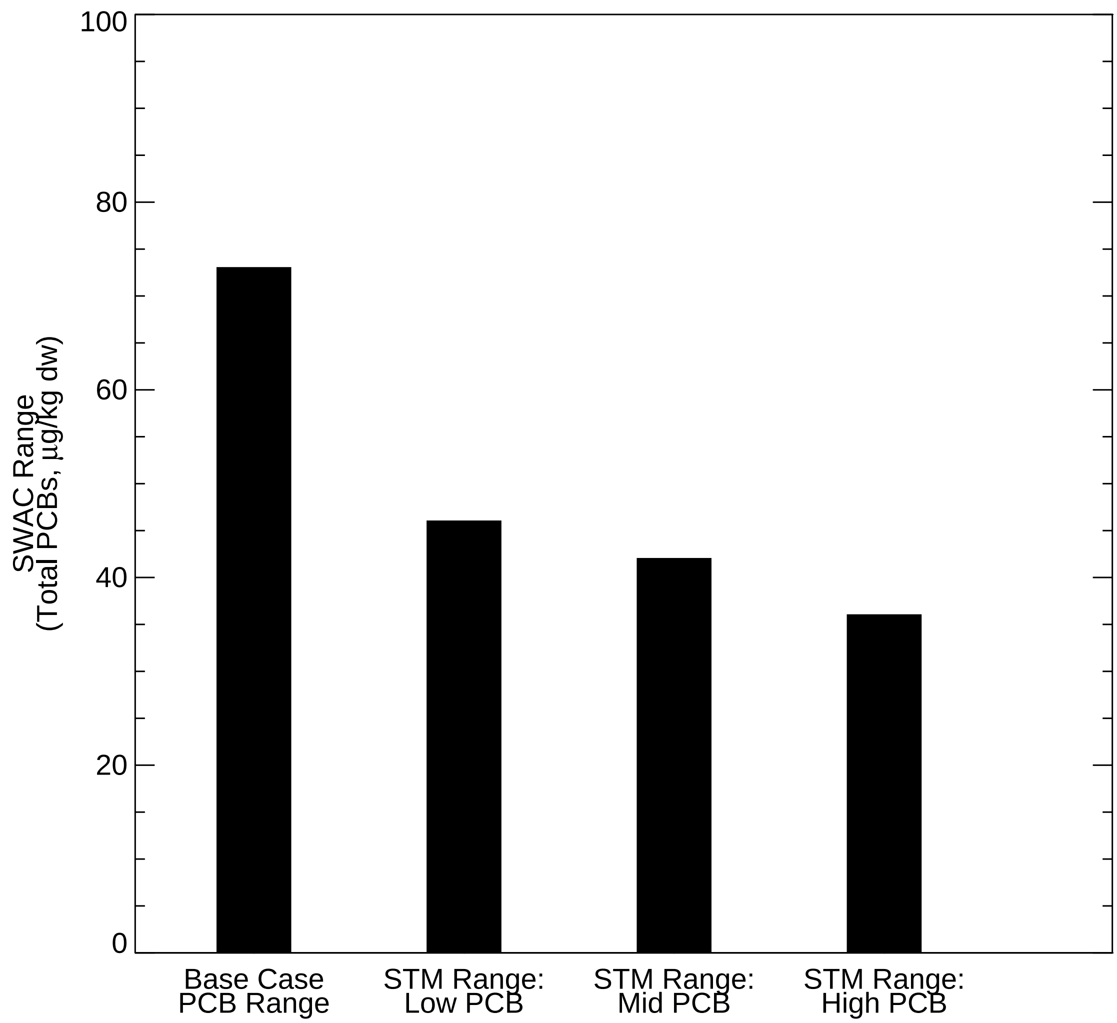


Figure 15. Estimated range of SWACs (total PCBs) in site-wide area.

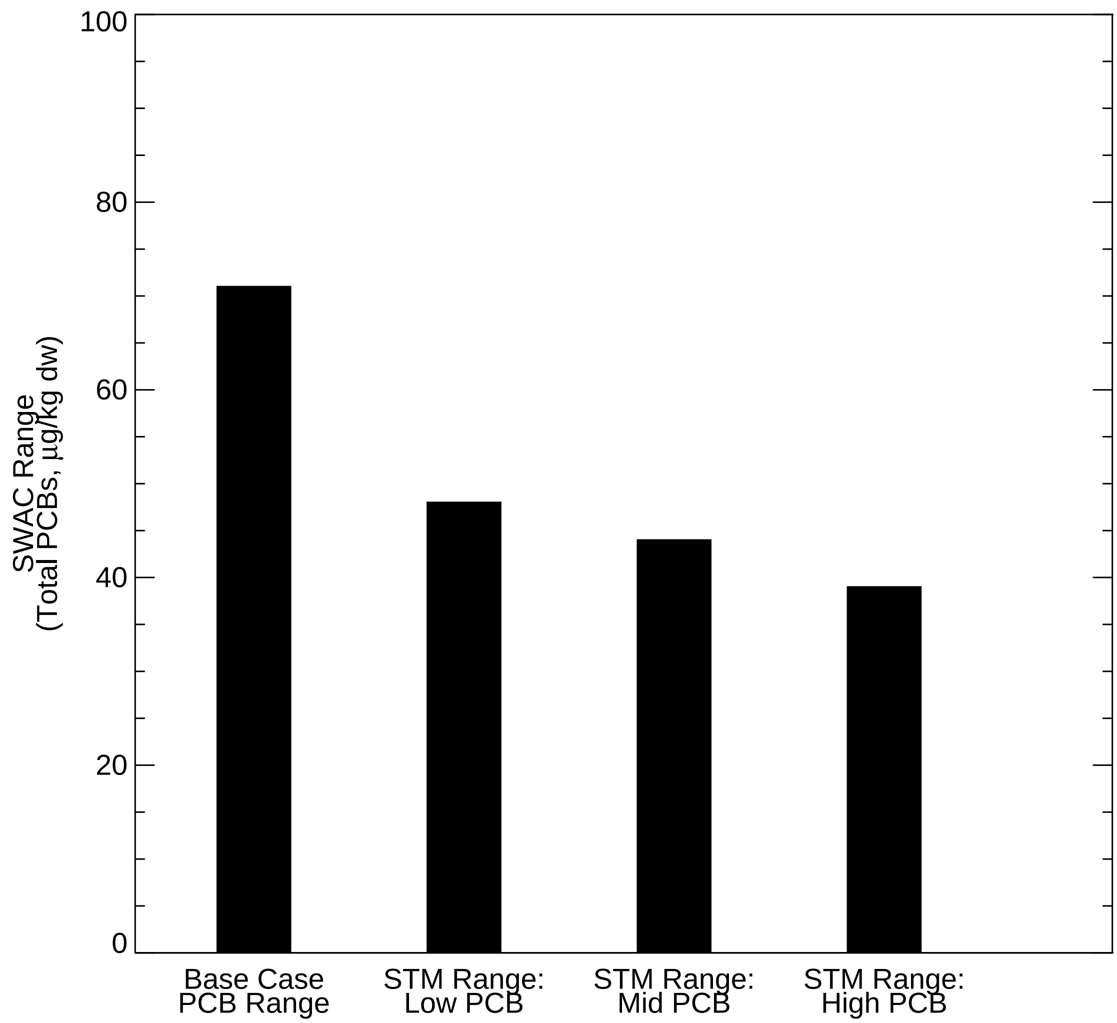


Figure 16. Estimated range of SWACs (total PCBs) in Reach 1.

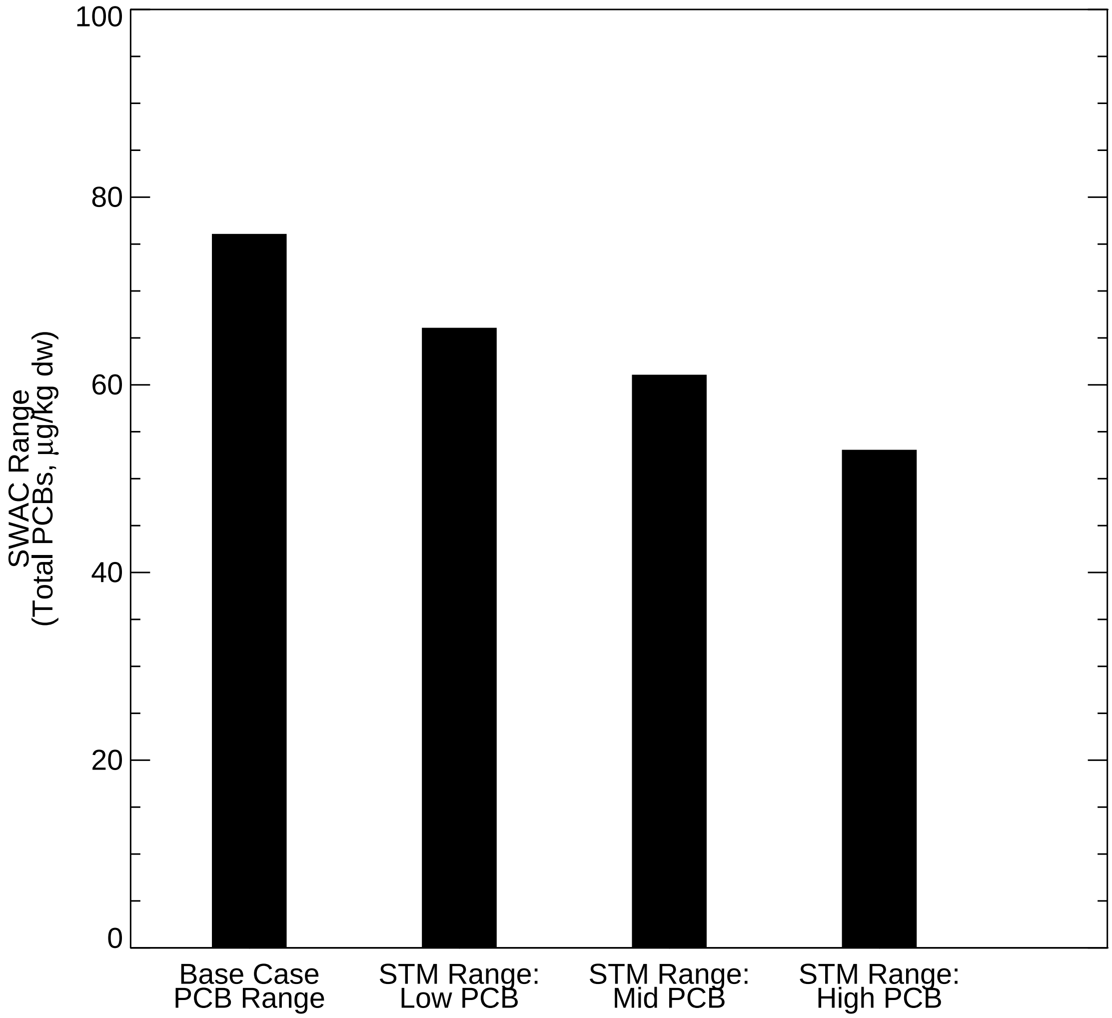


Figure 17. Estimated range of SWACs (total PCBs) in Reach 2.

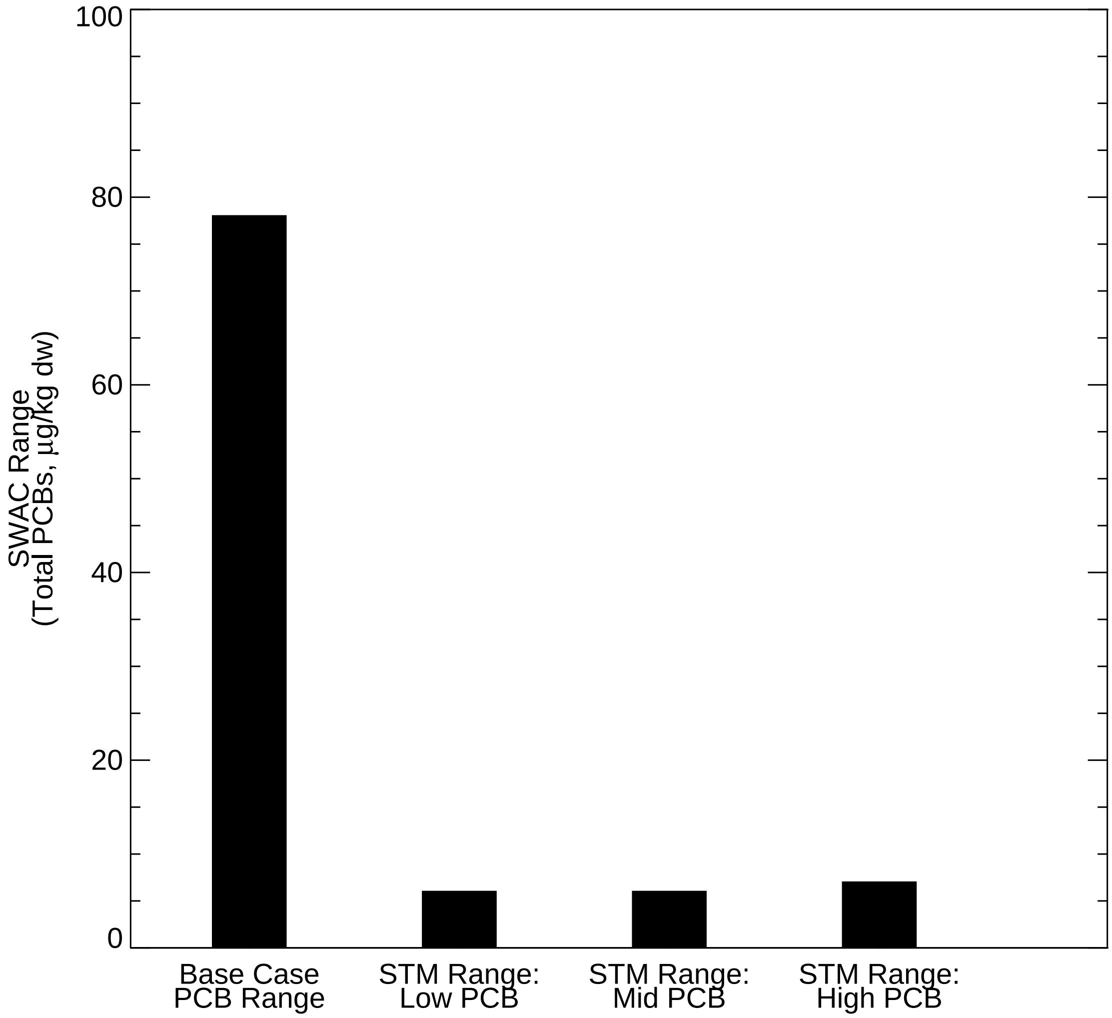
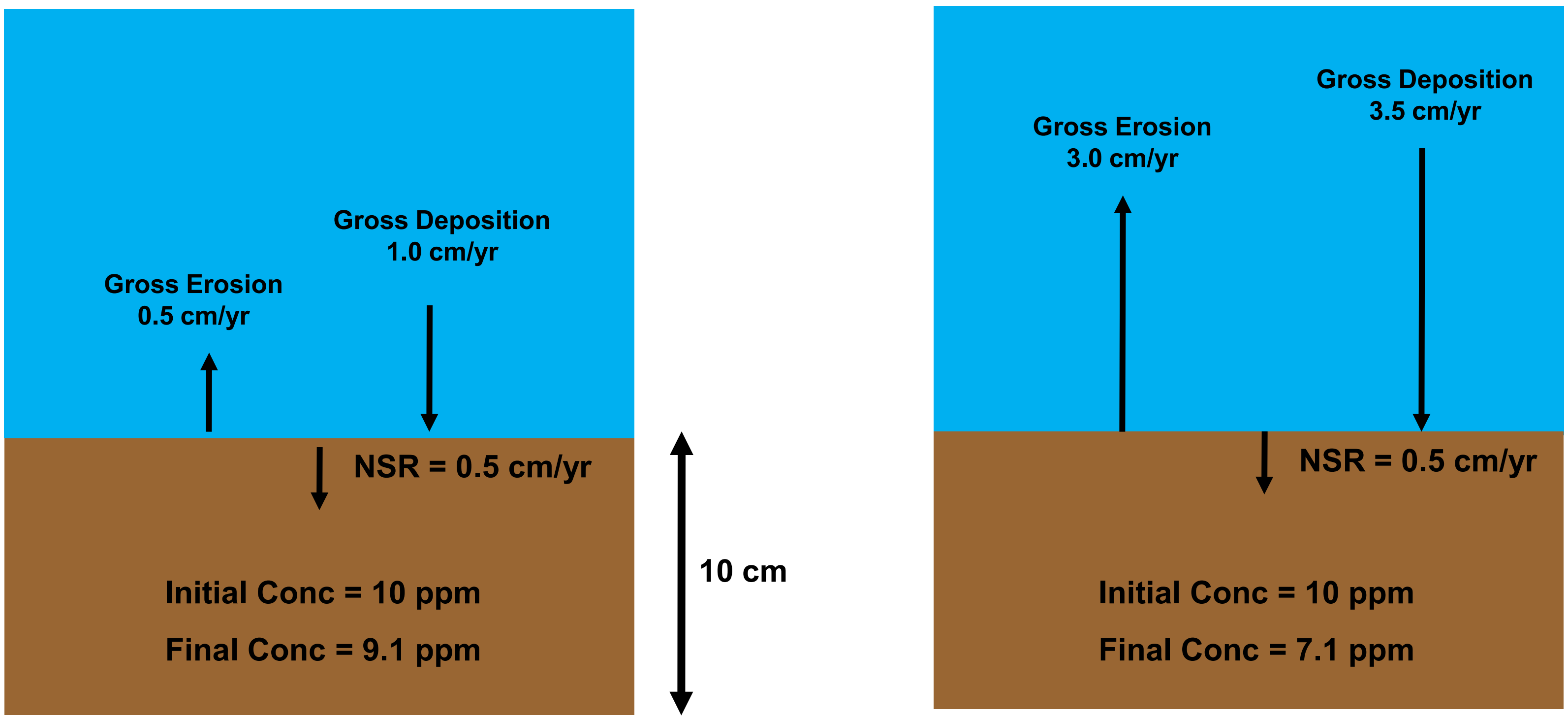
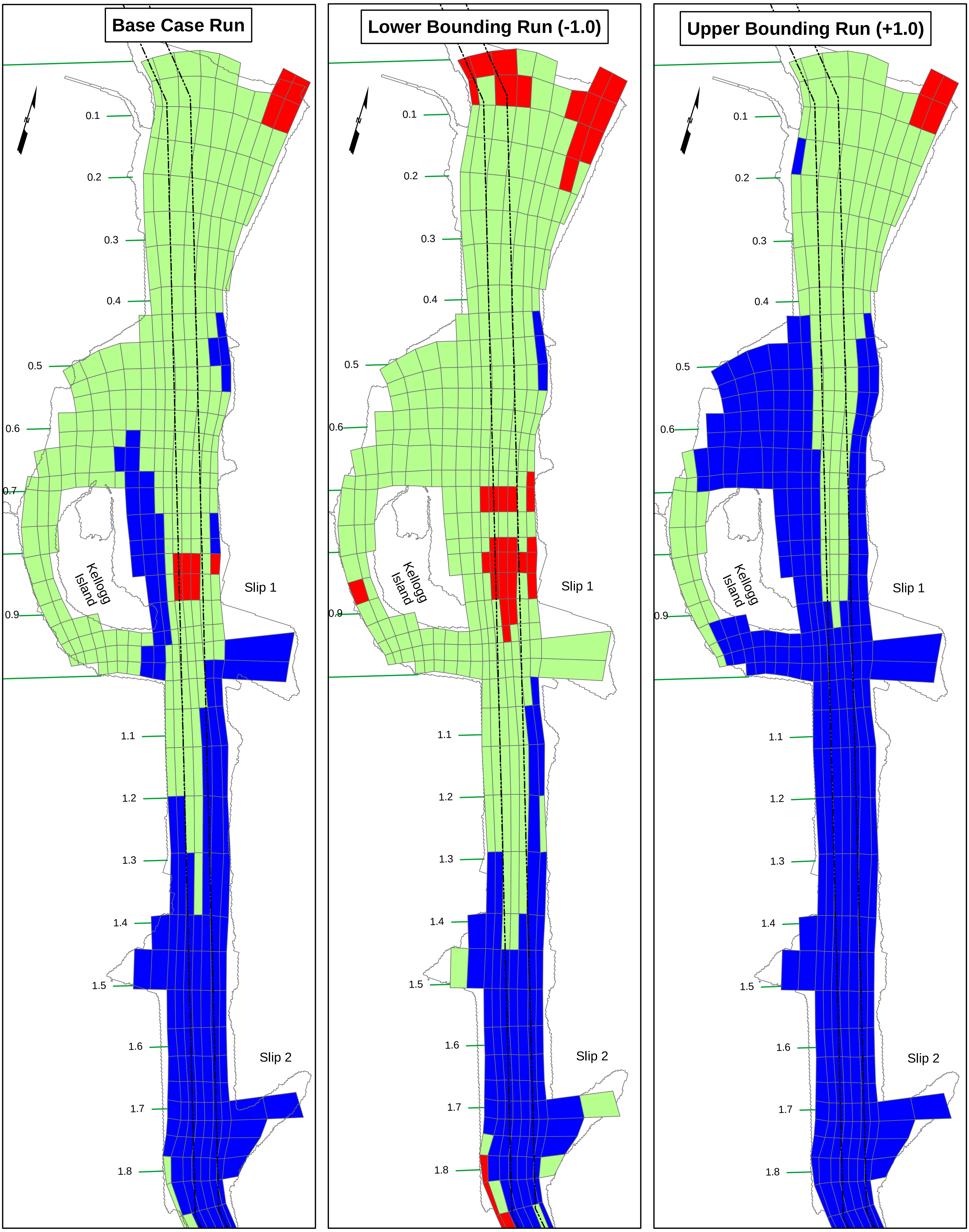


Figure 18. Estimated range of SWACs (total PCBs) in Reach 3.

Figure 19. Comparison of rate of bed concentration change due to differences in erosion-deposition conditions.





Notes:
1. New (11/16/09) reasonable STM runs showing net sedimentation at Year 10 (QEA):
   a. Redistributed lateral load Base Case: (No run #).
   b. Redistributed lateral load Lower bounding run: (-1.0 cm/yr); (run #20).
   c. Redistributed lateral load Upper bounding run: (+1.0 cm/yr); (run #9).

Legend

Net Sedimentation Rate (cm/yr)

- < 0.5
- 0.5 to 1.5
- > 1.5

- Outside of Model Domain
- Navigation Channel
- River Mile Marker

0 200 400 800 Feet

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60150279-14.46

Year 10 Net Sedimentation Rates for Redistributed Lateral Load Base Case, Upper, and Lower Bounding Runs: RM 0.0 to 1.9 (+/- 1.0 cm/yr)

DATE: 10/31/12 | DWRN:MVI/sea | Revision: 0

FIGURE 20

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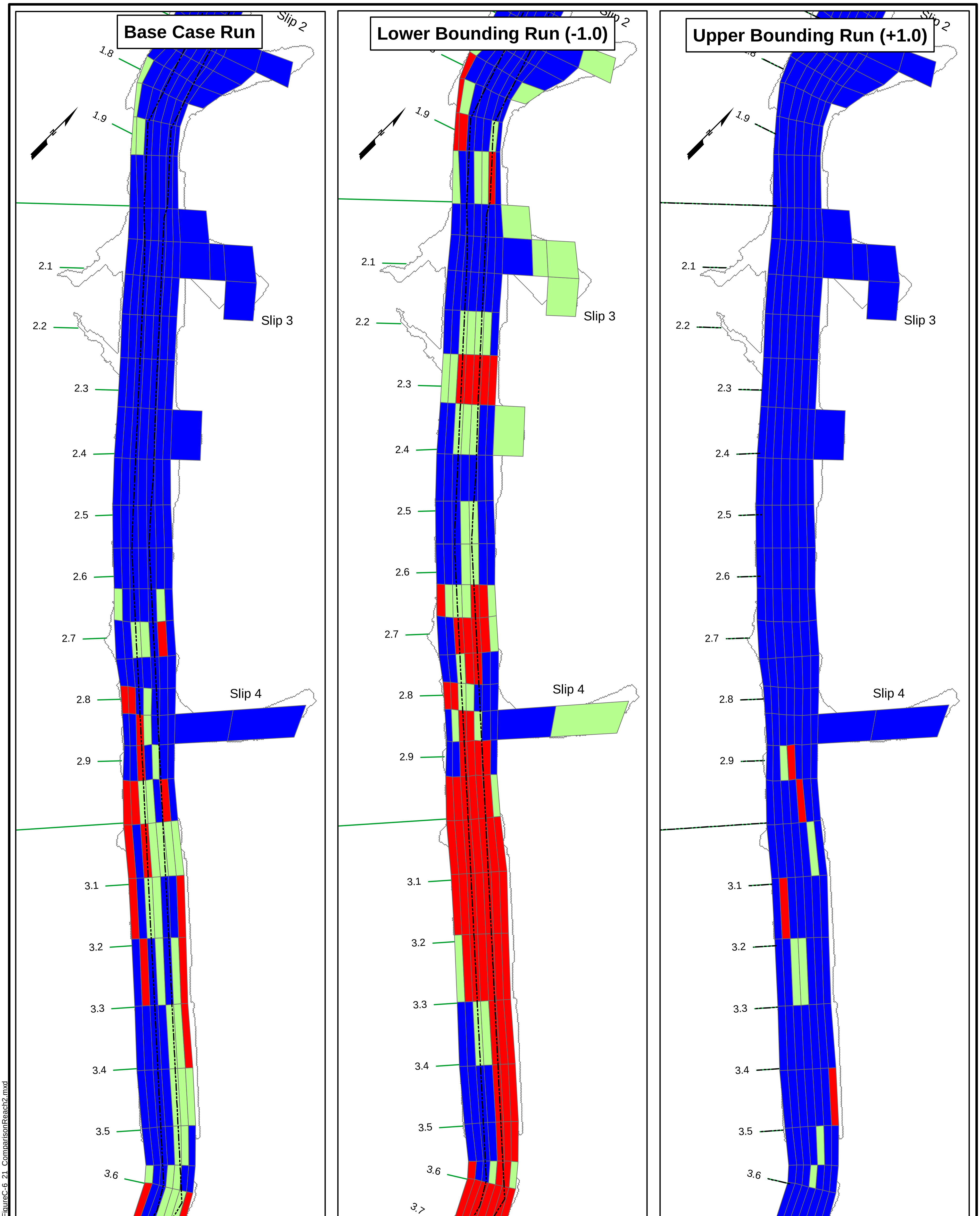

Notes:
1. New (11/16/09) reasonable STM runs showing net sedimentation at Year 10 (QEA):
   a. Redistributed lateral load Base Case: (No run #).
   b. Redistributed lateral load Lower bounding run: (-1.0 cm/yr); (run #20).
   c. Redistributed lateral load Upper bounding run: (+1.0 cm/yr); (run #9).

Legend

Net Sedimentation Rate (cm/yr)

- < 0.5
- 0.5 to 1.5
- > 1.5
- Outside of Model Domain
- Navigation Channel
- River Mile Marker

Feet
0 200 400 800

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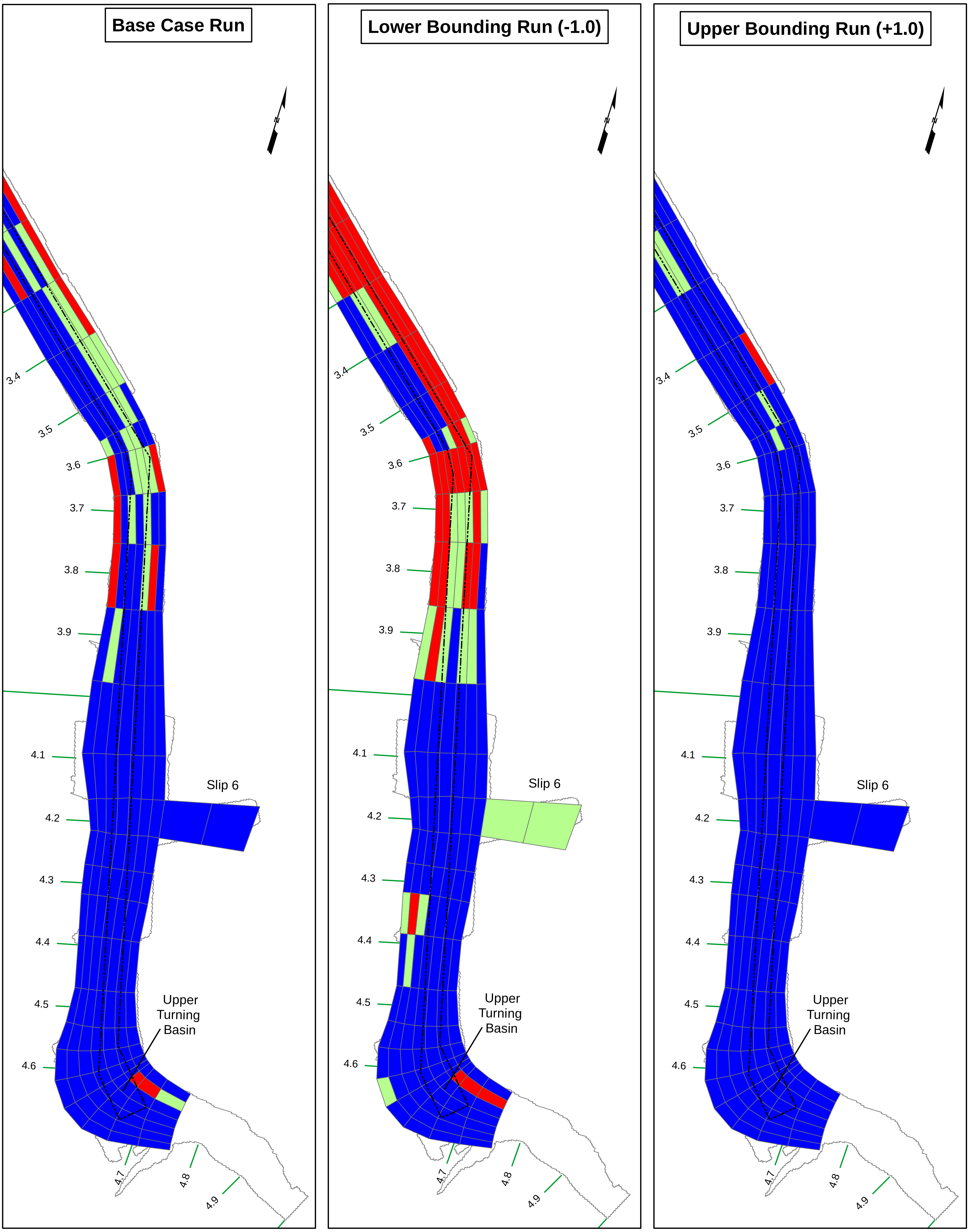
60150279-14.46

Year 10 Net Sedimentation Rates for Redistributed Lateral Load Base Case, Upper, and Lower Bounding Runs: RM 1.9 to 3.6 (+/- 1.0 cm/yr)

DATE: 10/31/12 | DWRN:MVI/sea | Revision: 0

FIGURE 21



Notes:
1. New (11/16/09) reasonable STM runs showing net sedimentation at Year 10 (QEA):
   a. Redistributed lateral load Base Case: (No run #).
   b. Redistributed lateral load Lower bounding run: (-1.0 cm/yr); (run #20).
   c. Redistributed lateral load Upper bounding run: (+1.0 cm/yr); (run #9).

Legend

Net Sedimentation Rate (cm/yr)

- < 0.5
- 0.5 to 1.5
- > 1.5
- Outside of Model Domain
- Navigation Channel
- River Mile Marker

0 200 400 800 Feet

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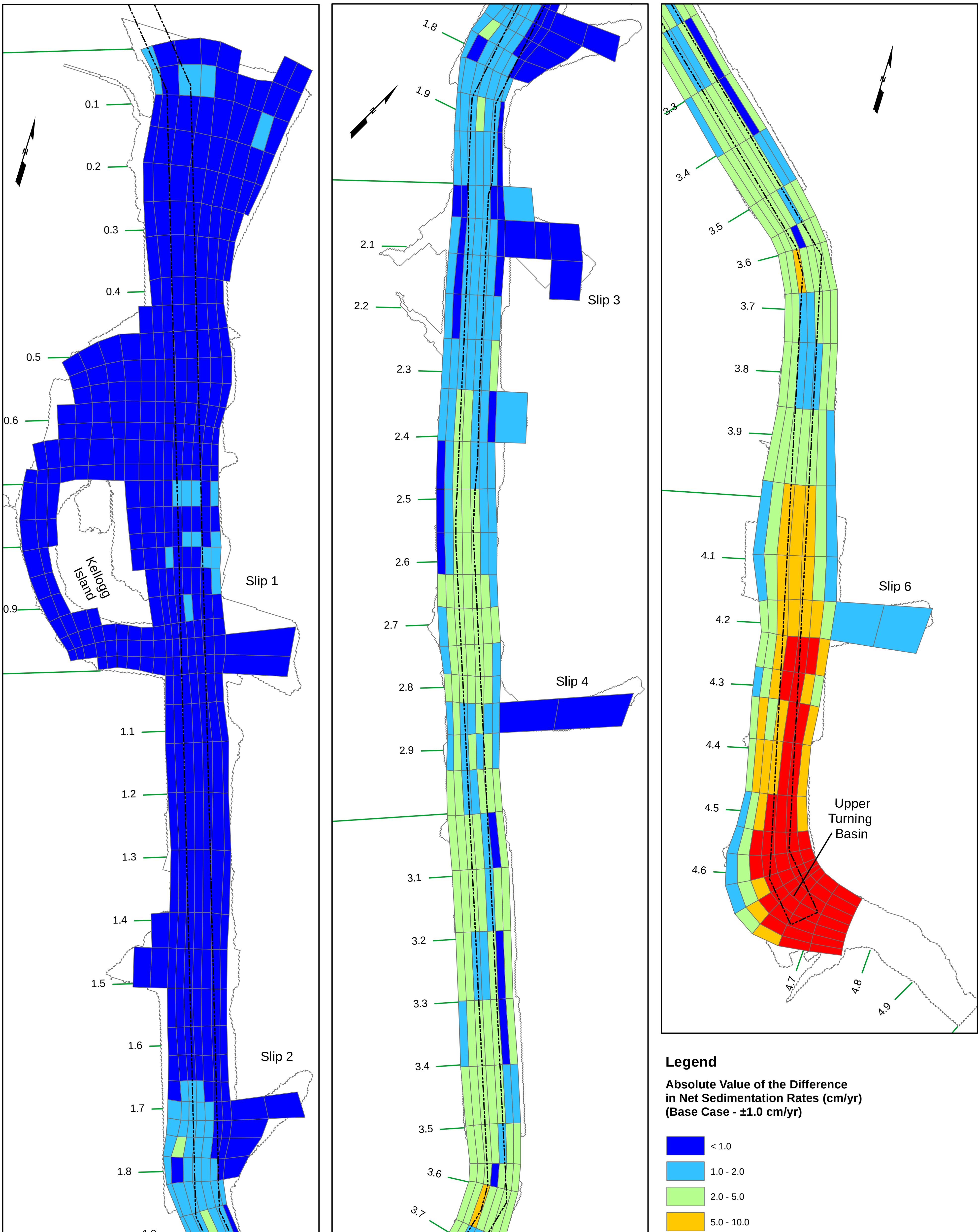
Final Feasibility Study
60150279-14.46

DATE: 10/31/12 | DWRN:MVI/sea | Revision: 0

Year 10 Net Sedimentation Rates for Redistributed Lateral Load Base Case, Upper, and Lower Bounding Runs: RM 3.6 to 5.0 (+/- 1.0 cm/yr)

FIGURE 22



Legend

Absolute Value of the Difference in Net Sedimentation Rates (cm/yr) (Base Case - ±1.0 cm/yr)

- < 1.0
- 1.0 - 2.0
- 2.0 - 5.0
- 5.0 - 10.0
- > 10.0
- Ouside of Model Domain
- Navigation Channel
- River Mile Marker

Notes:
1. New (11/16/09) reasonable STM runs showing net sedimentation at Year 10 (QEA):
   a. Redistributed lateral load Base Case: (No run #).
   b. Redistributed lateral load Lower bounding run: (-1.0 cm/yr); (run #20).
   c. Redistributed lateral load Upper bounding run: (+1.0 cm/yr); (run #9).
2. The difference between the reasonable bounding run sedimentation rate and the base case run sedimentation rate was calculated by subtracting the upper/lower sedimentation rate from the base case sedimentation rate in each cell and selecting the maximum absolute value of the difference between the two.

0 200 400 800 Feet

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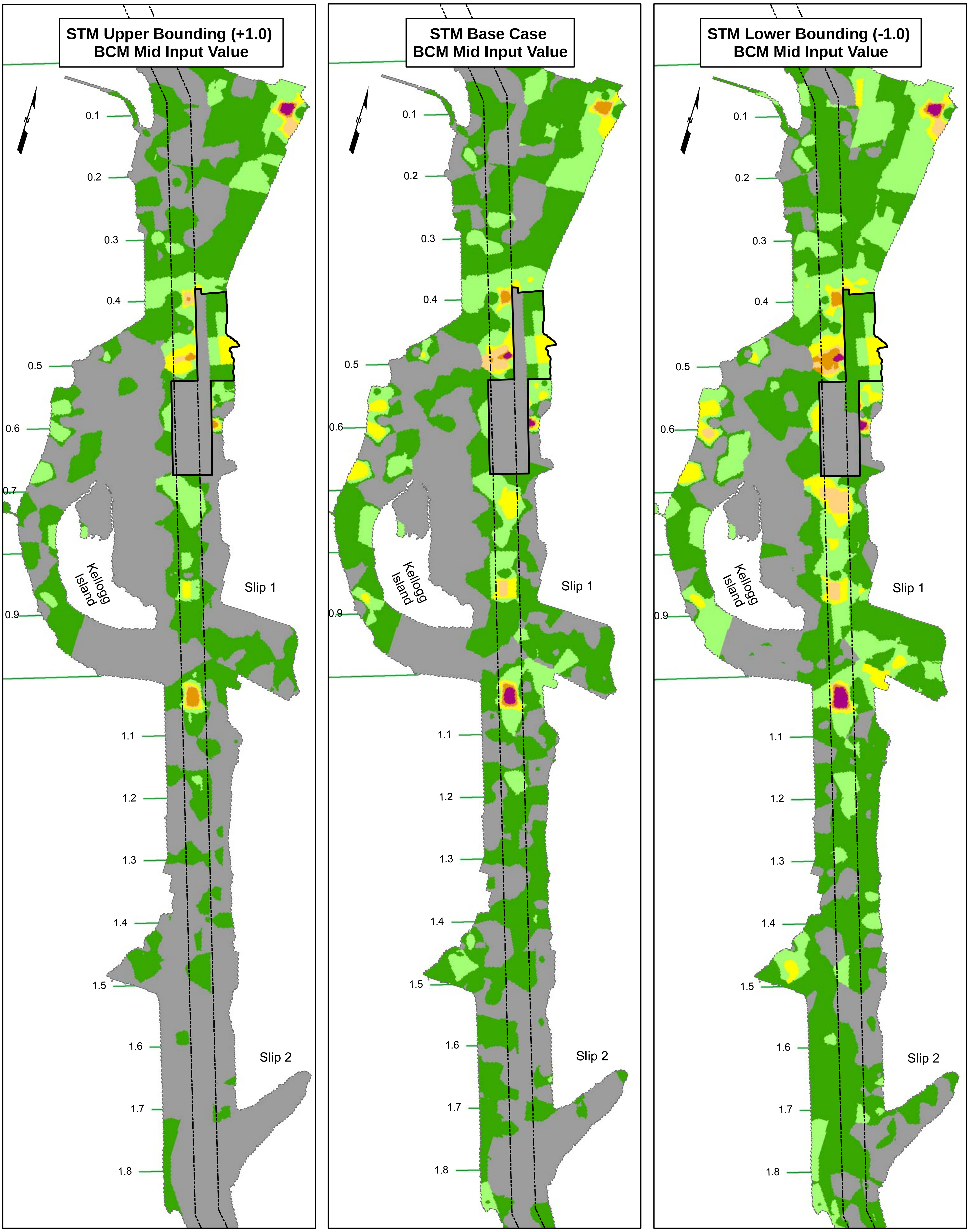
Lower Duwamish Waterway Final Feasibility Study 60150279-14.46			**Difference Between 10 Year Redistributed Lateral Load Base Case and Bounding Run Sedimentation Rates (+/- 1.0 cm/yr)**
DATE: 10/31/12	DWRN:MVI/sea	Revision: 0	**FIGURE 23**



Notes:

1. New (11/16/09) reasonable STM runs at Year 10 (QEA):
   a. Redistributed lateral load base case: (No run #).
   b. Redistributed lateral load lower bounding run: (-1.0 cm/yr); (run #20).
   c. Redistributed lateral load upper bounding run: (+1.0 cm/yr); (run #9).
2. Year 10 total PCB concentrations calculated for post alternative 1 (EAAs) using the following input parameters (µg/kg dw):
   a. Mid upstream: 35
   Mid lateral: 400
   Mid post-remedy bed sediment replacement value: 60
3. Alternative 1 (remediation of EAAs only) footprint is from December 2009. The alternative footprint was modified slightly for the Final FS.

Early Action Area
Outside of Model Domain
Navigation Channel
River Mile Marker

0 200 400 800 Feet

Legend

Year 10 Total PCB Concentration (µg/kg dw)

- ≤ 60
- > 60 - 120
- > 120 - 240
- > 240 - 480 (>SQS)
- > 480 - 720
- > 720 - 1,300
- > 1,300 (>CSL)

L:\Lower Duwamish FS\FS_Final_GIS\Oct2012\FS_GIS_MXDs_Oct12\Appendix C\C-6_24_ComparisonReach1Scenario2V2.mxd

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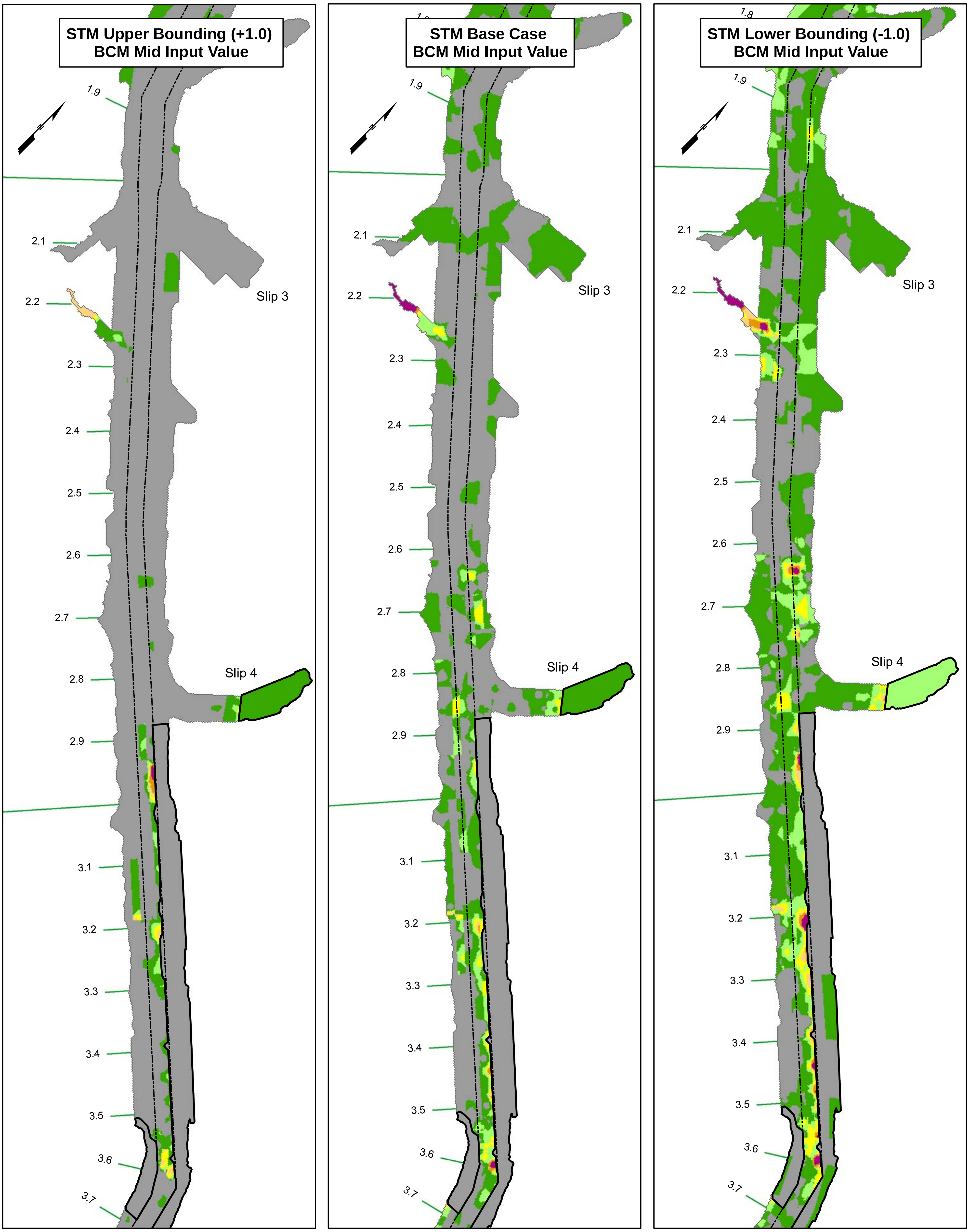
Year 10 Post Alternative 1 Total PCB Concentrations: STM Bounding Runs and BCM Mid Input Values (RM 0.0 to 1.9)

FIGURE 24



Notes:
1. New (11/16/09) reasonable STM runs at Year 10 (QEA):
   a. Redistributed lateral load base case: (No run #).
   b. Redistributed lateral load lower bounding run: (-1.0 cm/yr); (run #20).
   c. Redistributed lateral load upper bounding run: (+1.0 cm/yr); (run #9).
2. Year 10 total PCB concentrations calculated for post alternative 1 (EAAs) using the following input parameters (µg/kg dw):
   a. Mid upstream: 35
      Mid lateral: 400
      Mid post-remedy bed sediment replacement value: 60
3. Alternative 1 (remediation of EAAs only) footprint is from December 2009. The alternative footprint was modified slightly for the Final FS.

Early Action Area
Outside of Model Domain
Navigation Channel
River Mile Marker

Feet
0 200 400 800

Legend

Year 10 Total PCB Concentration (µg/kg dw)

- ≤ 60
- > 60 - 120
- > 120 - 240
- > 240 - 480 (>SQS)
- > 480 - 720
- > 720 - 1,300
- > 1,300 (>CSL)

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Year 10 Post Alternative 1 Total PCB Concentrations: STM Bounding Runs and BCM Mid Input Values (RM 1.9 to 3.6)

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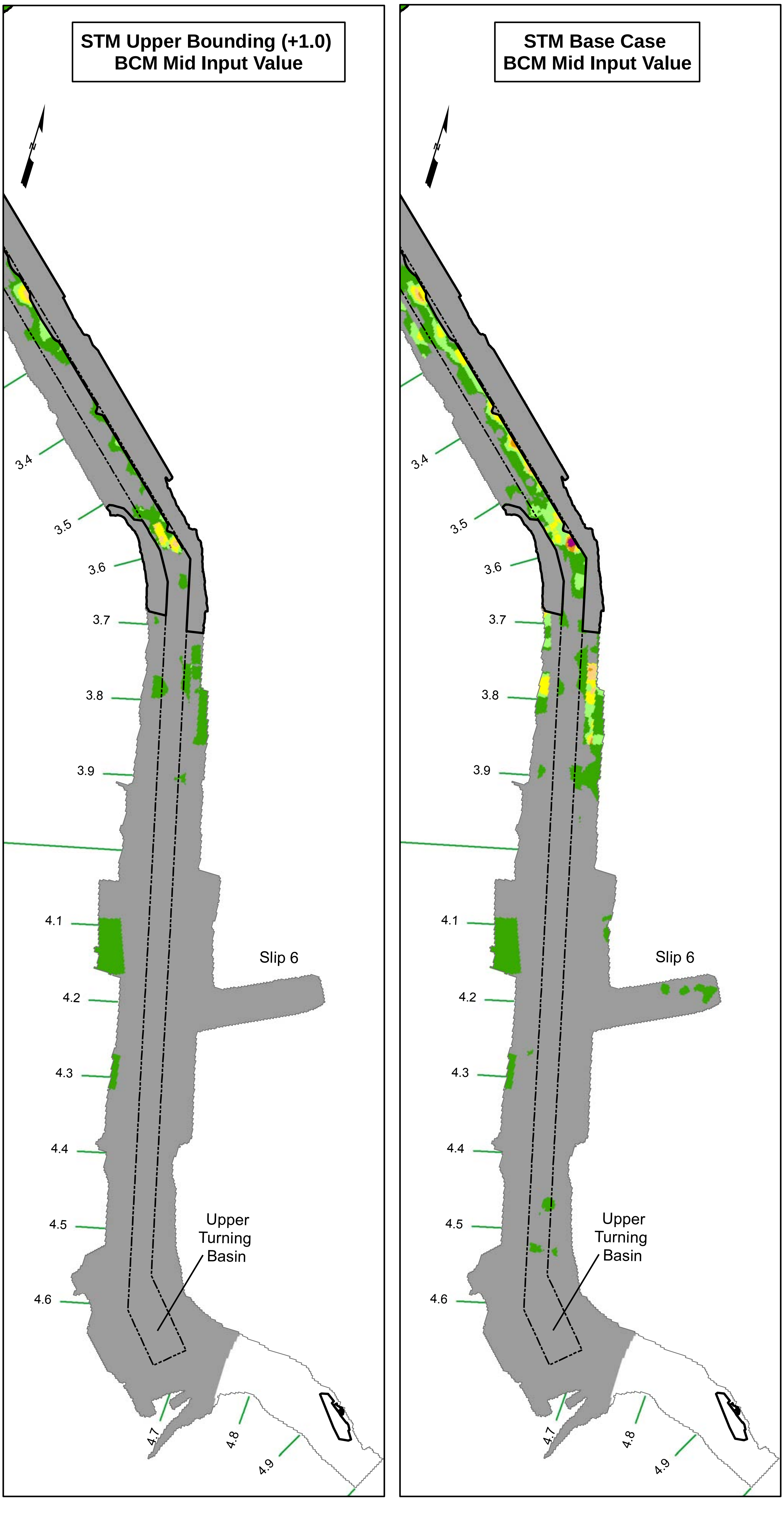
FIGURE 25

L:\Lower Duwamish FS\FS_Final_GIS\Oct2012\FS_GIS_MXDs_Oct12\Appendix C\FigureC-6_25_ComparisonReach2Scenario2V2.mxd



Notes:
1. New (11/16/09) reasonable STM runs at Year 10 (QEA):
   a. Redistributed lateral load base case: (No run #).
   b. Redistributed lateral load lower bounding run: (-1.0 cm/yr); (run #20).
   c. Redistributed lateral load upper bounding run: (+1.0 cm/yr); (run #9).
2. Year 10 total PCB concentrations calculated for post alternative 1 (EAAs) using the following input parameters (µg/kg dw):
   a. Mid upstream: 35
   Mid lateral: 400
   Mid post-remedy bed sediment replacement value: 60
3. Alternative 1 (remediation of EAAs only) footprint is from December 2009. The alternative footprint was modified slightly for the Final FS.

Legend

Year 10 Total PCB Concentration (µg/kg dw)

- ≤ 60
- > 60 - 120
- > 120 - 240
- > 240 - 480 (>SQS)
- > 480 - 720
- > 720 - 1,300
- > 1,300 (>CSL)

- Early Action Area
- Outside of Model Domain
- Navigation Channel
- River Mile Marker

Feet
0 200 400 800

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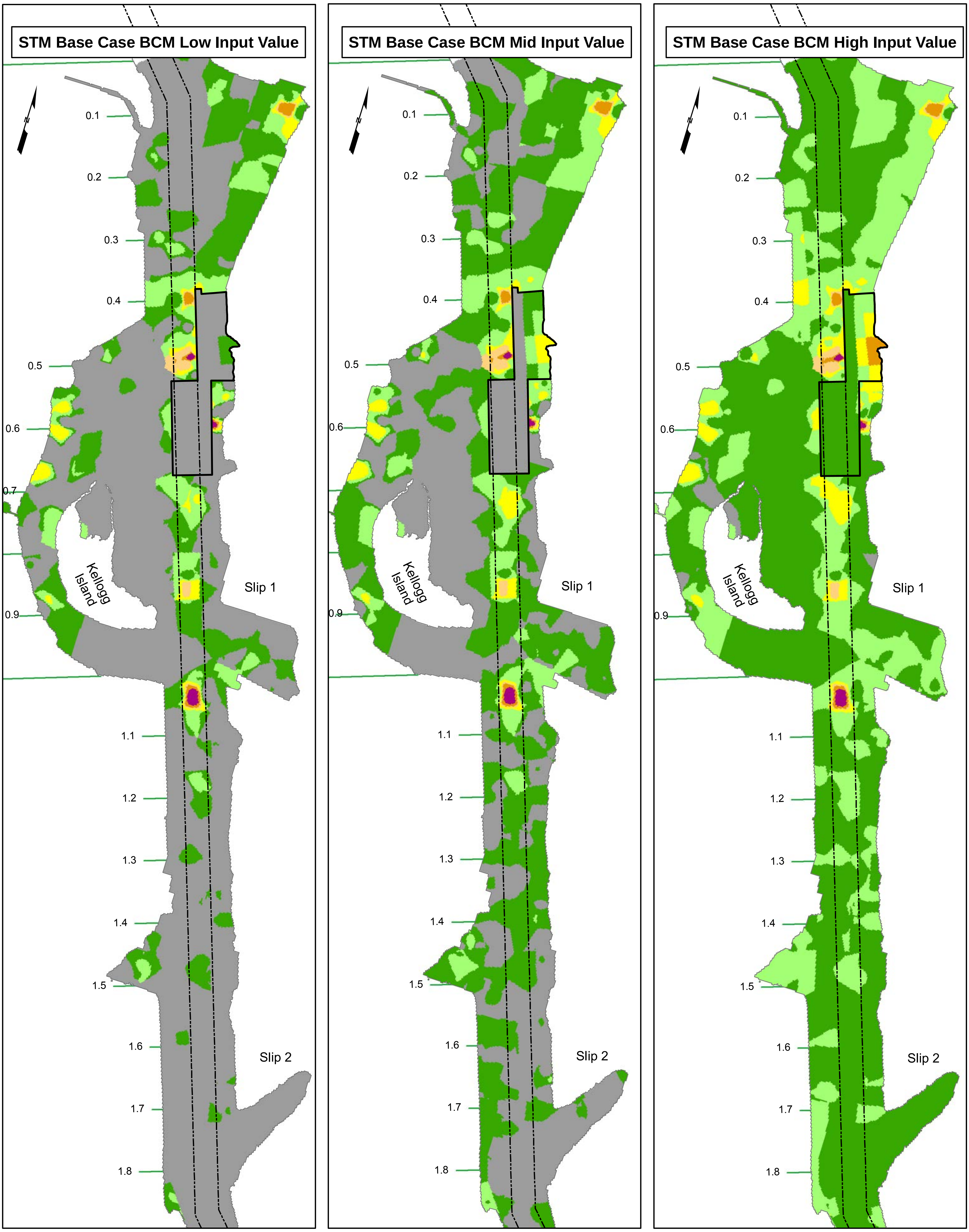
Year 10 Post Alternative 1 Total PCB Concentrations: STM Bounding Runs and BCM Mid Input Values (RM 3.6 to 5.0)

FIGURE 26

L:\Lower Duwamish FS\FS_Final_GIS\Oct2012\FS_GIS_MXDs_Oct12\Appendix C\FigureC-6_26_ComparisonReach3Scenario2V2.mxd



Notes:

1. New (11/16/09) reasonable STM runs at 10 years (QEA):
   a. Distributed lateral load base case: (No run #).
2. 10 Year total PCB concentrations calculated for post alternative 1 (EAAs) using the following input parameters (µg/kg dw):
   a. Low upstream: 5
      Low lateral: 100
      Low post-remedy bed sediment replacement value: 30
   b. Mid upstream: 35
      Mid lateral: 400
      Mid post-remedy bed sediment replacement value: 60
   c. High upstream: 80
      High lateral: 1000
      High post-remedy bed sediment replacement value: 90
3. Alternative 1 (remediation of EAAs only) footprint is from December 2009. The alternative footprint was modified slightly for the Final FS.

Early Action Area
Outside of Model Domain
Navigation Channel
River Mile Marker

0 200 400 800 Feet

Legend

Year 10 Total PCB Concentration (µg/kg dw)

- ≤ 60
- > 60 - 120
- > 120 - 240
- > 240 - 480 (>SQS)
- > 480 - 720
- > 720 - 1,300
- > 1,300 (>CSL)

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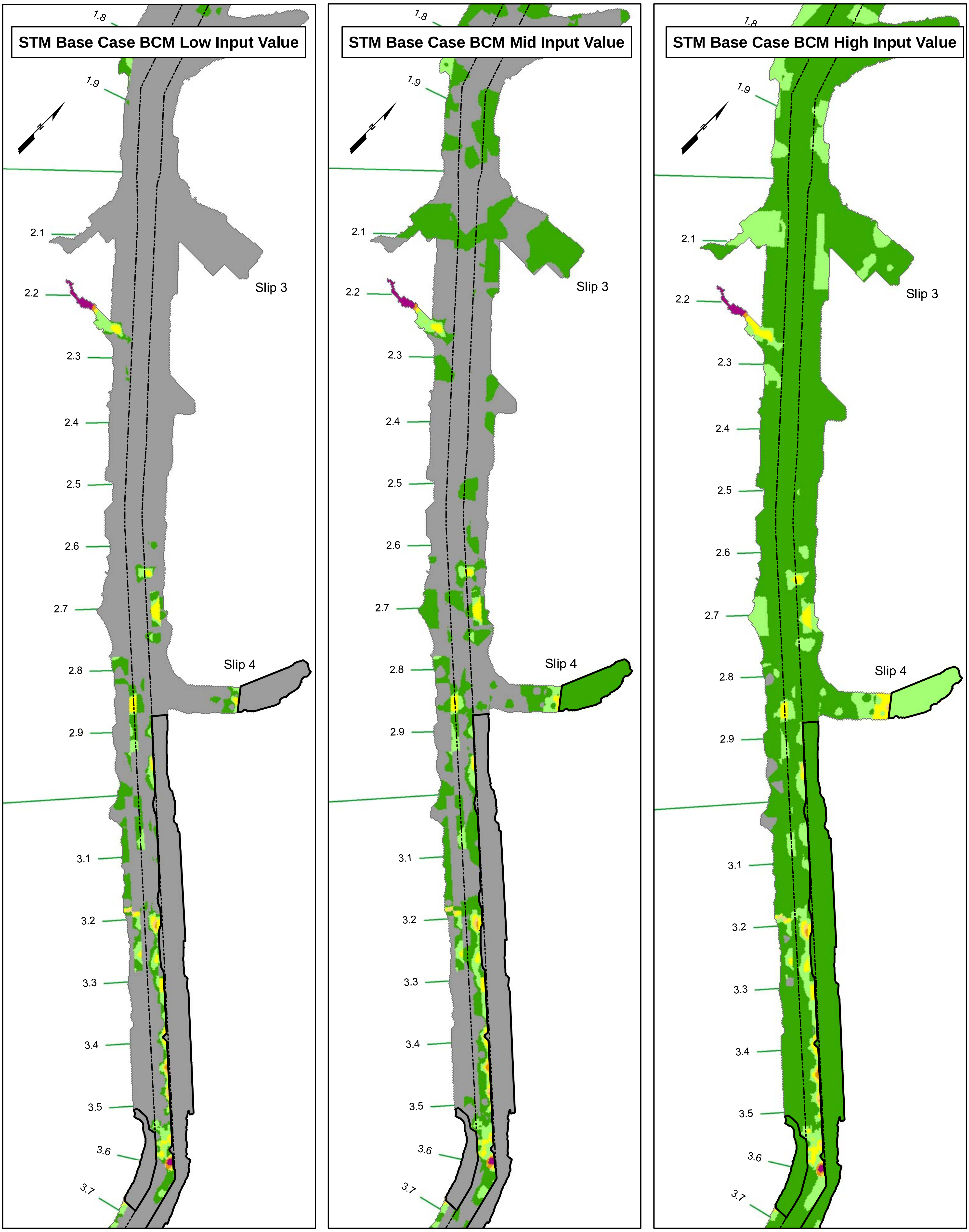
10 Year Post Alternative 1 Total PCB Concentrations: BCM Bounding Values and STM Base Case (RM 0.0 to 1.9)

FIGURE 27

L:\Lower Duwamish FS\FS_Final_GISOct2012\FS_GIS_MXDs_Oct12\Appendix C\C-6_27_ComparisonReach1Scenario1.mxd



Notes:
1. New (11/16/09) reasonable STM runs at Year 10 (QEA):
   a. Redistributed lateral load base case: (No run #).
2. Year 10 total PCB concentrations calculated for post alternative 1 (EAAs) using the following input parameters (µg/kg dw):
   a. Low upstream: 5
      Low lateral: 100
      Low post-remedy bed sediment replacement value: 30
   b. Mid upstream: 35
      Mid lateral: 400
      Mid post-remedy bed sediment replacement value: 60
   c. High upstream: 80
      High lateral: 1000
      High post-remedy bed sediment replacement value: 90
3. Alternative 1 (remediation of EAAs only) footprint is from December 2009. The alternative footprint was modified slightly for the Final FS.

Legend

Year 10 Total PCB Concentration (µg/kg dw)

- ≤ 60
- > 60 - 120
- > 120 - 240
- > 240 - 480 (>SQS)
- > 480 - 720
- > 720 - 1,300
- > 1,300 (>CSL)

- Early Action Area
- Outside of Model Domain
- Navigation Channel
- River Mile Marker

Feet
0 200 400 800

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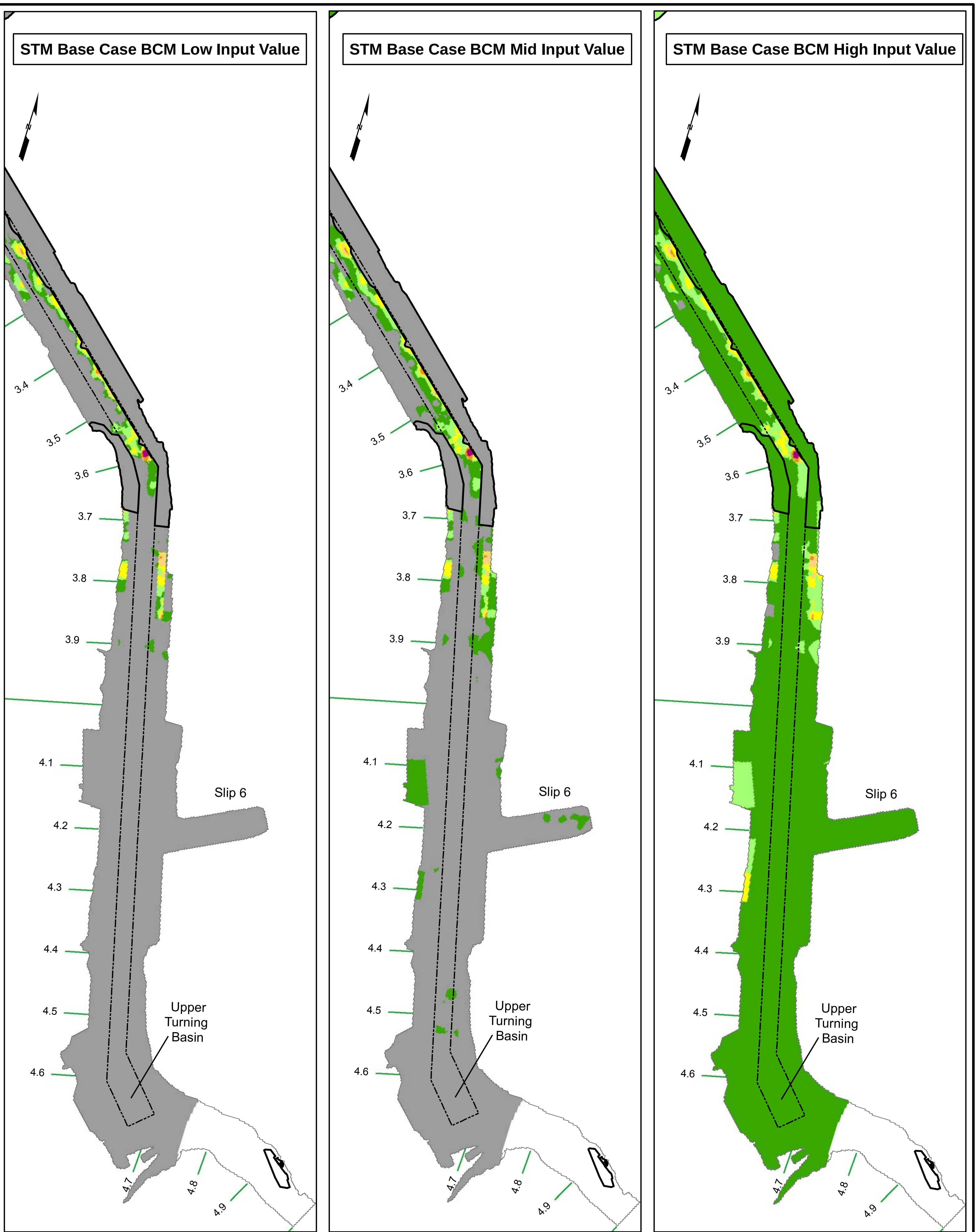
Year 10 Post Alternative 1 Total PCB Concentrations: BCM Bounding Values and STM Base Case (RM 1.9 to 3.6)

FIGURE 28

L:\Lower Duwamish FS\FS_Final_GIS\Oct2012\FS_GIS_MXDs_Oct12\Appendix C\FigureC-6_28_ComparisonReach2Scenario1.mxd



Notes:
1. New (11/16/09) reasonable STM runs at 10 years (QEA):
   a. Distributed lateral load base case: (No run #).
2. 10 year total PCB concentrations calculated for post alternative 1 (EAAs) using the following input parameters (µg/kg dw):
   a. Low upstream: 5
      Low lateral: 100
      Low post-remedy bed sediment replacement value: 30
   b. Mid upstream: 35
      Mid lateral: 400
      Mid post-remedy bed sediment replacement value: 60
   c. High upstream: 80
      High lateral: 1000
      High post-remedy bed sediment replacement value: 90
3. Alternative 1 (remediation of EAAs only) footprint is from December 2009. The alternative footprint was modified slightly for the Final FS.

0 200 400 800 Feet

Early Action Area
Outside of Model Domain
Navigation Channel
River Mile Marker

Legend

Year 10 Total PCB Concentration (µg/kg dw)

- ≤ 60
- > 60 - 120
- > 120 - 240
- > 240 - 480 (>SQS)
- > 480 - 720
- > 720 - 1,300
- > 1,300 (>CSL)

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10 Year Post Alternative 1 Total PCB Concentrations: BCM Bounding Values and STM Base Case (RM 3.6 to 5.0)

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FIGURE 29

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Part 7: Propeller-induced Riverbed Scour from Stationary Tugs

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AECOM

Memorandum

Date: April 23, 2009[1]

To: Lower Duwamish Waterway Group

From: AECOM and Mike Riley of SSPA

Subject: Propeller-induced Riverbed Scour from Stationary Tugs

Propeller-induced Riverbed Scour from Stationary Tugs

This analysis evaluates the potential for tug-induced bed scour within the Lower Duwamish Waterway (LDW). A prior analysis was conducted for the *Sediment Transport Analysis Report* (STAR; Windward and QEA 2008) that addressed scour potential for vessels in transit within the navigation channel. The STAR did not focus on the localized effects caused by complex vessel movements such as maneuvering, stopping and starting, and berthing activities. This analysis addresses scour potential induced by tugboats engaged in activities alongside berthing areas.

A number of methods were considered for this analysis. Among the methods reviewed were those used in the propeller wash analyses for stationary and maneuvering tugs conducted at Boeing Plant #2 where they used the Hamill et al. (1999), Verhey (1983) and Blaauw and Van de Kaa (1978) models and for the Duwamish/Diagonal cap where the Verhey model and Blaauw and Van de Kaa (1978) model were used. In addition, the U.S. Army Corps of Engineers (USACE) method presented by Maynord (2000), which was used in the STAR (Windward and QEA 2008), was also considered. The Maynord (2000), Verhey (1983), and Blaauw and Van de Kaa (1978) models have similar methodologies to define a velocity distribution behind the vessel caused by the propellers. All rely heavily on earlier work by Albertson (1948), which is based on jet theory coupled with site-specific empirical data.

Literature Review of Available Models

A literature review was conducted to investigate models that are capable of estimating the propeller-induced scour from stationary tug operation. The three models that are available for scour modeling of stationary vessels are the Hamill et al. model (1999), the Maynord model (2000), and the Verhey model (1983).

The Hamill et al. model calculates the maximum scour and its location behind the vessel. However, the model is not able to calculate erosion at any other location than where maximum scour occurs. The Hamill et al. model is not able to account for cohesive sediments and different sediment characteristics at different sediment layer depths. Furthermore, the Hamill et al. model has a specific range within which it is valid, when the distance between the sediment surface and the propeller tip (clearance C) is between $>0.5*D_p$ and $< 2.5*D_p$, where D_p is propeller diameter.

[1] Revised June 18, 2010 to be consistent with revisions to the FS requested by the agencies.

The Verhey model is only applicable for large grain sizes (0.1 m < d_s < 0.3 m) (Verhey 1983). Therefore, because LDW sediments typically have relatively small grain sizes, this model was ruled out. However, the Verhey model was used to estimate bottom velocities. The results were consistent with calculations using the Maynord model. This is to be expected, as the main structure of the equations in the two models are similar, since both models are based on previous work done by Albertson et al. (1948).

Considering the specific depth and grain size limitations of the Hamill et al. and Verhey models, the Maynord model was selected for use in the LDW. The Maynord model can be applied to the Sedflume data from the STAR and provide a more site-specific model that accounted for several sediment characteristics in different areas and for different sediment depths. Table 1 summarizes the input and output parameters for the Maynord and Hamill models. Table 2 summarizes the strengths and limitations associated with the models.

Table 1 Summary of Model Parameters for the Hamill et al. (1999) and Maynord (2000) Models

Model Parameters		Units	Model	
			Hamill (1999)	Maynord (2000)
Input Parameters				
Sediment and Water Properties	Water Depth	d [m]		X
	Density of Water	ρ_w [kg/m^3]	X	X
	Density of Sediments	d50 [m]	X	
	Average Stone Size	ρs [kg/m^3]	X	
Tug Parameters	Propeller Diameter	D_p [m]	X	X
	Propeller Rotational Speed	n [rps]	X	
	Propeller Tip Clearance	C [m]	X	
	Propeller Thrust Coefficient	Ct	X	
	Total Ship Power	hp		X
	Ship Speed	V_w [m/s]		X
	Propeller Configuration Open/Kort	—		X
	Distance Between Screws	W_p [m]		X
	Propeller Axis Depth	δ_p [m]		X
	Length of Tugboat	L_{tb} [m]		X
	Distance from Stern to Propeller	L_{set} [m]		X
	Vessels Stationary Operation Time	t [s]		X

Model Parameters		Units	Model	
			Hamill (1999)	Maynord (2000)
Output Parameters				
Output Parameters	Depth of Maximum Scour	E_m [mm]	X	C
	Location of Maximum Scour	X_{mu} [m]	X	C
	Bottom Velocity	V_{xp}, y_{cl} [m/s]		X
	Shear Stress	T_{peak} [Pa]		X
	Gross Erosion (at arbitrary channel location)	E_{gross} [cm/s]		X

Notes:

X = parameter is included in the model, C = computed from shear stress output from model and site-specific erosion characteristics of sediment.

Table 2 Strengths and Limitations for the Hamill (1999) and Maynord (2000) Models

	Hamill et al. (1999)	Maynord (2000)
Strengths/Weaknesses	Valid for sand and fine gravel	Valid for all grain sizes
	Not valid for cohesive sediments	Applicable for cohesive sediments
	Applicable when the propeller tip clearance C is 0.5*Dp<C< 2.5*Dp.	Able to account for site-specific sediment characteristics
	Determines the depth and location of the maximum scour	Determines the depth and location of scour at any riverbed location
	The bottom velocity does not have to be determined	Transitions between Zone 1 (jets still to merge) and Zone 2 (jets have merged) can sometimes be abrupt and therefore unrealistic
	Limited, if any, field verification of the model	Limited, if any, field verification of the model

The Maynord model is based on physical model studies and has, to our knowledge, undergone limited field verification. The model was developed for barge tows typically used on the upper Mississippi River-Illinois Waterway system, which are reasonably representative of the types and sizes of tugs and barges used on the LDW. For a more comprehensive description of the Maynord model limitations, see Maynord (2000) and the STAR, Chapter 3.

Background and Methods in the Maynord Model

The Maynord model was originally developed for use on the Upper Mississippi River-Illinois Waterway System. The study resulted in analytical/empirical methods that describe near-bed velocity and shear stress as a function of tow parameters. This model was used to calculate potential bed scour in the STAR and is applied here. The main difference between the analysis presented here and that in the STAR is that the present analysis does not include wake effects since the tug is assumed to be stationary.

Estimation of potential bed scour as a result of propeller wash-induced bed shear is determined through a series of calculation steps. These steps are:

1. Determine vessel parameters
2. Calculate maximum bottom velocity resulting from propeller wash
3. Calculate bed shear stress distribution
4. Calculate resulting potential bed scour.

For this scour analysis, the vessel parameters are based on two tugs operating in the LDW. The tug *Sea Valiant* was used for operations in the reach downstream of the First Avenue Bridge. Because the draft of the Sea Valiant is too deep to operate above the First Avenue Bridge, the *J.T. Quigg* was used to assess operations upstream of the bridge. Both tugs were referenced in the STAR and their general characteristics are presented below in Table 3.

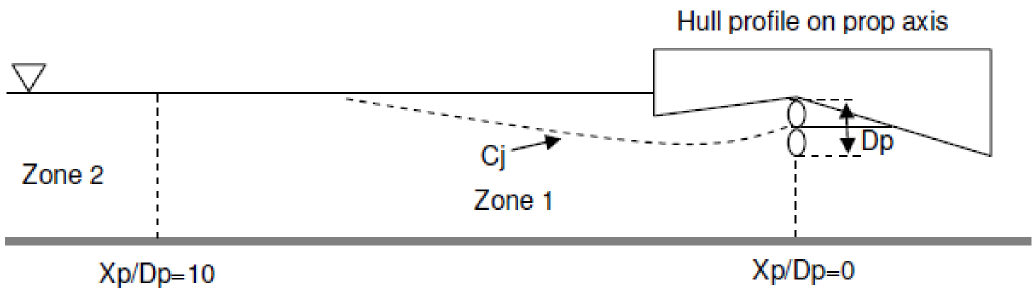
Table 3 Tug Characteristics for *J.T. Quigg* and *Sea Valiant*

Parameter		Ship	
		J.T. Quigg	***Sea Valiant***
Length of tugboat	L_{tb}	100 ft	128 ft
Tug draft depth	L_{tb}	12.3 ft	20 ft
Distance from stern to propeller	L_{set}	10 ft	13 ft
Distance between propellers	W_p	15 ft	19 ft
Propeller diameter	D_p	6.3 ft	9.3 ft
Propeller axis depth	δ_p	8 ft	8.5 ft
Type of propeller	O/K	Open-wheel	Kort nozzle
Total power	P_{hp}	3,000 hp	5,750 hp

Calculation of Maximum Bottom Velocity

For a twin-propeller tug, such as is used in the LDW, the area behind the vessel's propellers, located at X_p = 0, is divided into two distinct zones (Figure 1). In Zone 1, the propeller jet wash created by each propeller has yet to merge into one stream. This zone extends behind the propeller for a length of approximately 10 times the propeller diameter (D_p). The second zone, Zone 2, where the propeller jets have merged may be described as a single jet. Within Zone 2, the maximum jet velocity (C_j) is at the surface and the jet decays both laterally and vertically. The following is the methodology applied to both zones.

Figure 1 Zone Locations and a Maximum Jet Velocity Profile



Zone 1: X_p < 10 D_p

This zone is dominated by the central rudder effects; and the two propeller jets have not merged. The total bottom velocity distribution is determined by superposition of the velocity distribution of each propeller jet as described by Verhey (1983). Estimation of the spatial distribution of bottom velocity ^{Z1}V (X_p,Y_{cl}) caused by propeller wash is determined from the velocity increase in the water (V_2) as follows:

$$^{Z1}V(X_p,Y_{cl}) = 1.45\,V_2\left(\frac{X_p}{D_p}\right)^{-0.524}\left(\exp\left(-15.4\frac{R_1^2}{X_p^2}\right)+\exp\left(-15.4\frac{R_2^2}{X_p^2}\right)\right)$$

Where:

$$R_1^2 = \left(Y_{cl} - 0.5W_p\right)^2 + \left(H_p - C_j\right)^2$$
$$R_2^2 = \left(Y_{cl} + 0.5W_p\right)^2 + \left(H_p - C_j\right)^2$$

$$C_j = -\tan(12°)\left(X_p - 0.5\,L_{set}\right) + \frac{C_P\,g}{V_2^2\cos^2(12°)}\left(X_p - 0.5\,L_{set}\right)^2$$
$$C_j = -\left[0.213 - 1.05\left(\frac{C_p\,g}{V_2^2}\right)\left(X_p - 0.5L_{set}\right)\right]\left(X_p - 0.5\,L_{set}\right)$$

Where:

X_p= Distance behind the propeller [m] (see Figures 1 and 3)

D_p= Propeller diameter [m]

W_p= Distance between propellers [m]

L_{set}= Distance from ship stern to propeller [m]

H_p = Distance from center of propeller axis to channel bottom [m]

Y_{cl} = Lateral distance from ship centerline [m]

C_j = Vertical distance from propeller shaft to location of maximum velocity within the jet [m], Max C_j=δp

δp = Propeller depth [m]

g = acceleration of gravity [m/s^2]

C_p= 0.04 Kort nozzle propeller

$$C_p = 0.12\left(\frac{D_p}{H_p}\right)^{0.67}$$ (for open-wheel propeller)

$$V_2 = \frac{1.13}{D_O}\sqrt{\frac{T}{\rho_w}}$$

D_o = 0.71 D_p (for open-wheel propeller)

D_o = D_p (for Kort nozzle propeller)

T = Thrust [N]

ρ_w = Density of water [kg/m^3]

Estimation of propeller thrust is calculated using the Toutant (1982) equation:

$$EP = 23.57\,P_{hp}^{0.974} - 2.3V_w^2\,P_{hp}^{0.5}$$ (for open-wheel propeller)

$$EP = 31.82\,P_{hp}^{0.974} - 5.4V_w^2\,P_{hp}^{0.5}$$ (for Kort nozzles propeller)

Where:

EP= Effective Push (equivalent to thrust) from both propellers [pounds, converted to N]

P_{hp}= Total ship power [hp]

V_w= Ship speed relative to water, 0 for stationary vessels [m/s]

The Toutant equations were developed for tows operating in the upper Mississippi River-Illinois Waterway system, which as mentioned above are reasonably representative of the types and sizes of tugs and barges used on the LDW.

Figures 2 and 3 show the model nomenclature used for the propeller wash calculations in front and side views of the vessel relative to water depth, propeller placement, and vessel size.

Figure 2 Nomenclature for Parameters Used in the Maynord Model – Front View

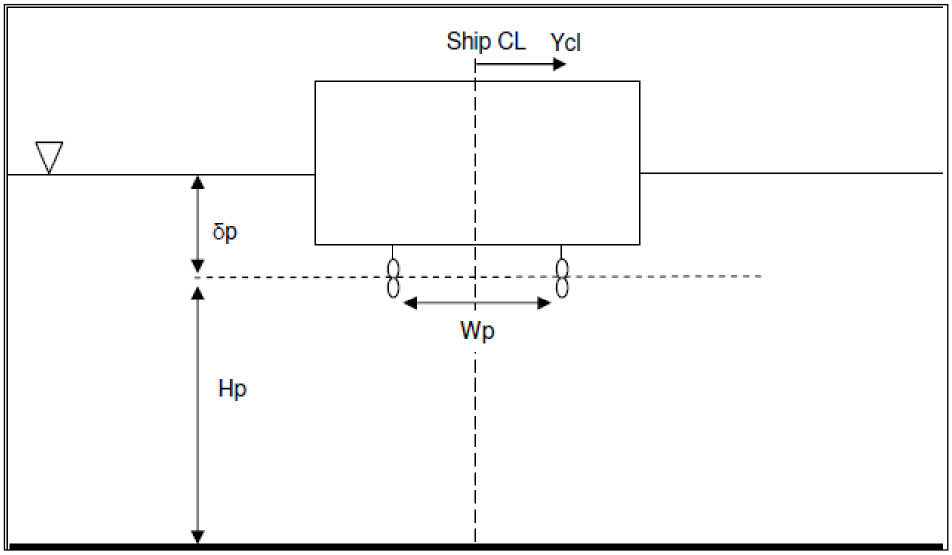
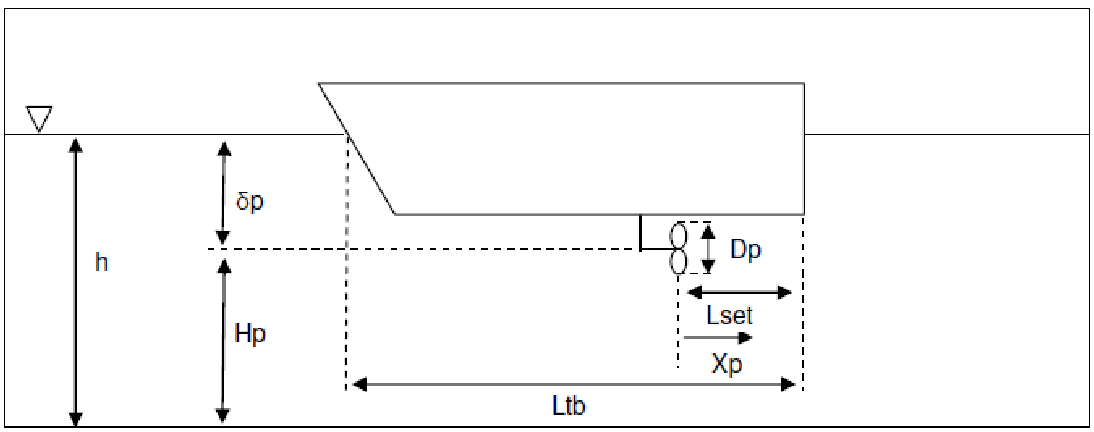


Figure 3 Nomenclature for Parameters Used in the Maynord Model – Side View



Zone 2: X_p > 10 D_p

Zone 2 is the region where the individual jets from the two propellers merged and therefore is represented by a single jet with maximum velocity at the surface. The bottom velocity distribution in Zone 2 is calculated by:

$$^{Z1}V(X_p, Y_{cl}) = 0.34 V_2 \left(\frac{D_p}{H_p}\right)^{0.93} \left(\frac{X_p}{D_p}\right)^{0.24} C_1\, EXP\left[-0.0178\frac{X_p}{D_p} - \frac{Y_{cl}^2}{2 C_{z2}^2\, X_p^2}\right]$$

Where:

C_1 = 0.66 for open-wheeled propeller; 0.85 for Kort nozzle propeller

$C_{Z\,2}$ = 0.84 $(X_p/D_p)^{-0.62}$

Calculation of Bed Shear Stress

Bed shear stress (τ) is calculated with the method prescribed by Maynord (2000) as presented below:

$$\tau = 0.5 \rho_w C_{fs} V_{prop}^2$$

Where:

C_{fs} = bottom friction factor for propeller wash, as described below

V_{prop} = bottom velocity due to propeller wash, as calculated previously.

The bottom friction factor for propeller wash is:

$$C_{fs} = 0.01 \left(\frac{D_p}{H_P} \right)$$

The equation for τ and C_{fs} was computed from a combination of propeller velocity and vessel wake velocity. Since the analysis here deals with maneuvering tugs, the wake effect is minimal. Maynord gives a separate analysis for C_{fs} from wake effects alone, which results in constant value for C_{fs}. The equation above is considered more appropriate as C_{fs} will increase in shallow water where H_p decreases.

Sediment Erosion Characteristics

Sediment cores collected in the LDW were analyzed for erosion rate parameters using a Sedflume analysis. A more detailed description of the sediment characteristics in the LDW is provided in the STAR. Table 4 displays the critical shear stresses for the Sedflume core groups A, B, and C, developed in the STAR.

Estimation of Bed Scour Due to Standing Tug

As discussed in the STAR, the various Sedflume cores were grouped according to erosion properties in the various sediment depth layers (0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, and 20-25 cm).

The gross erosion rate, E_{gross} (cm/s), is calculated as follows:

$$E_{gross} = A\tau^n \quad \text{for } \tau > \tau_{cr}$$

Where τ is shear stress (Pa) and τ_{cr} is critical shear stress (Pa). The parameters A and *n* are site-specific and calculated from the Sedflume analysis as discussed in Section 3 of the STAR.

Table 4 Critical Shear Stress, Average A and Average *n* Values at Different Depth Layers for the Sedflume Core Groups A, B, C and D

Depth Layer (cm)		Sedflume Cores			
		Group A	Group B	Group C	Group D
		Critical Shear Stress, τ_{cr} (Pa)			
1	0-5	0.16	0.24	0.63	—
2	5-10	0.56	0.49	0.34	1.6
3	10-15	1.4	0.35	0.79	—
4	15-20	1.4	0.67	0.49	—
5	20-25	1.3	2.4	1.3	—
		Average A (*10^-4)			
1	0-5	14	37	4.9	—
2	5-10	5.1	4.1	24	0.22
3	10-15	0.35	12	2.5	—
4	15-20	0.42	2.6	8.6	—
5	20-25	0.49	0.047	0.53	—
		***Average* n**			
1	0-5	1.5	2.5	3.4	—
2	5-10	2.8	2	2.9	3.3
3	10-15	3.2	2.3	4	—
4	15-20	2.8	2.4	3.1	—
5	20-25	3.3	3.6	2.5	—

The analysis was performed for various water depths (5 m and 7 m for *J. T. Quigg* and 7 m and 9 m for *Sea Valiant*) to provide hypothetical results for various bottom elevations that could be vulnerable to scour encountered in the LDW.

Gross erosion rates were calculated for when the tugs are operating at a low speed for different time periods (30 s, 1 min, 2 min, 5 min, 10 min, and 15 min). Further, the gross erosion rates were calculated for different magnitudes of applied ship power (15%, 35%, and 100% of maximum ship power).

Interviews were conducted with companies that use tugs in the LDW (Table 5) to gain an understanding of the type of ship operations and the different percentages of applied ship power used during the operations. Similarly, the duration time of the different berthing activities were based on interviews conducted with tug operators (Table 5). Consideration was also given to how stationary the berthing activities are considered to be, i.e. how long the tug is likely to operate over the same area.

Table 5 Estimated Percentage of Applied Power for Different Tugboat (1,000-5,000 hp) Activities

Activities	Western Towboat	Island Tug Barge	Harley Marine	Foss Maritime	Crowley Marine	Average	Operation Time
Nosing and holding tight to dock or barge	0-30%	10-15%	10-15%	20%	No Comment	15%	15 min
Holding barge/vessel in strong current	20-30%	20-50%	50%	30%	No Comment	35%	5 min
Emergency Operations	50-100%	—	100%	50-100%	No Comment	83%	5 min
Slowing barge/vessel down for berthing	50%	30-40%	5-10%	20-50%	No Comment	32%	5 min
Acceleration from berth/dock	25-50%	10-15%	50-60%	30-40%	No Comment	35%	5 min

Source: Emmons and Hernandez-White, personal communication, 2009

The bed shear stress caused by the propeller wash is applied to the bottom for the full time that the tug is standing. Where the applied shear stress is sufficient to initiate erosion ($\tau > \tau_{cr}$) then E_{gross} is calculated for the sediment layer. If sufficient bed stress is applied to remove all material from the surface sediment layer, the remaining shear stress is applied to the next layer. This is continued until either the full 25 cm is removed or the full time-period over which bed shear stress is applied has expired.

Downstream of the First Avenue Bridge, from river miles (RM) 0 to 2.0, *Sea Valiant* was used as its characteristics are typical of tugs operating in this part of the LDW. The smaller tug, the *J.T. Quigg*, was used for simulations in the shallower, upstream portion of the LDW from RM 2.0 to 3.8. Upstream from RM 3.8 the river becomes too shallow for the *J.T. Quigg* to operate. The areas most sensitive to erosion were identified and conservative estimates of scour depths for operation with the *Sea Valiant* and *J.T. Quigg* were made. These areas were identified by considering critical shear stress values for the different sediment layer depths for all bench areas of the river. The spatial extension of the bench areas was based on the groupings of sediments layers conducted in the STAR. The composition of each sediment group is provided below in Table 6.

Table 6 Riverbed Bench Areas, and their Associated Sediment Groups for Different Layer Depths

Sediment Layer depth (cm)	*Sea Valiant*	Sediment Group				*T.G. Quigg*	Sediment Group			
	Area 1	2	3	4	5	5	6	7	8	9
0-5	1C	1A	1B	1B	1B	1B	1B	1A	1A	1A
5-10	2D	2B	2C	2B	2A	2A	2A	2B	2D	2A
10-15	3B	3A	3B	3B	3A	3A	3A	3C	3C	3B
15-20	4C	4B	4C	4A	4A	4A	4B	4B	4A	4A
20-25	5B	5A	5A	5A	5A	5A	5A	5B	5A	5B

Mean critical shear stress values were calculated for all bench areas and then the area with lowest mean critical shear stress values upstream and downstream of the First Avenue Bridge were identified and considered to be the most susceptible areas for propeller-induced scour. Numerical results are presented in Table 7. Location of all areas, and their respective average critical shear stress, is presented on Figure 4 (Table B-8 and Figure B-26 to B-30 in Appendix B, STM; QEA 2008). The most vulnerable bench area downstream of the First Avenue Bridge was Bench Area 3 located between RM 0.8-1.3 and the corresponding area upstream of the bridge was Bench Area 6 located at RM 2.2-2.5 (Figure 4).

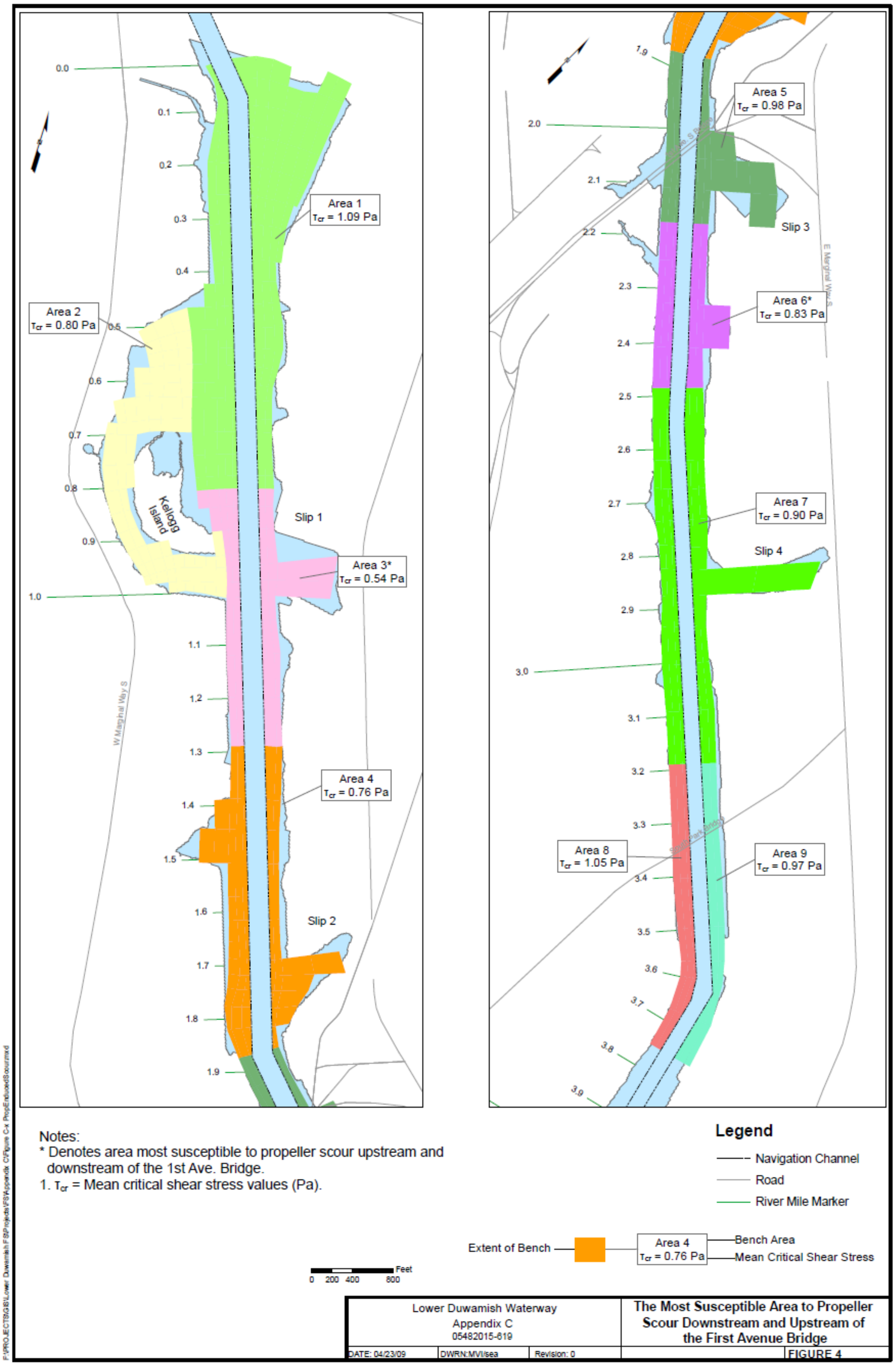
Table 7 Riverbed Bench Areas, and their Associated Critical Shear Stress Value for Different Layer Depths, and Mean Critical Shear Stress Values Calculated for Each Bench Area

Layer Depth (cm)	*Sea Valiant*	Critical Shear Stress [Pa]				*T.G. Quigg*	Critical Shear Stress [Pa]			
	Area 1	2	3	4	5	5	6	7	8	9
0-5	0.63	0.16	0.24	0.24	0.24	0.24	0.24	0.16	0.16	0.16
5-10	1.6	0.49	0.34	0.49	0.56	0.56	0.56	0.49	1.6	0.56
10-15	0.35	1.4	0.35	0.35	1.4	1.4	1.4	0.79	0.79	0.35
15-20	0.49	0.67	0.49	1.4	1.4	1.4	0.67	0.67	1.4	1.4
20-25	2.4	1.3	1.3	1.3	1.3	1.3	1.3	2.4	1.3	2.4
Average	1.09	0.80	0.54	0.76	0.98	0.98	0.83	0.90	1.05	0.97

Notes:

(shaded) Bench area most susceptible toward scour upstream and downstream of the First Avenue Bridge

Figure 4 The Most Susceptible Area to Propeller Scour Downstream and Upstream of the First Avenue Bridge



Results and Discussion

Tug simulations for *Sea Valiant* operating over the most erodible bench area downstream of the First Avenue Bridge are presented on Figures 5 and 6, where the water depths are 7 m and 9 m (22.96 ft and 29.52 ft), respectively.

Figure 5 Maximum Scour Depths for the Tug Sea Valiant at Water Depth of 7 m

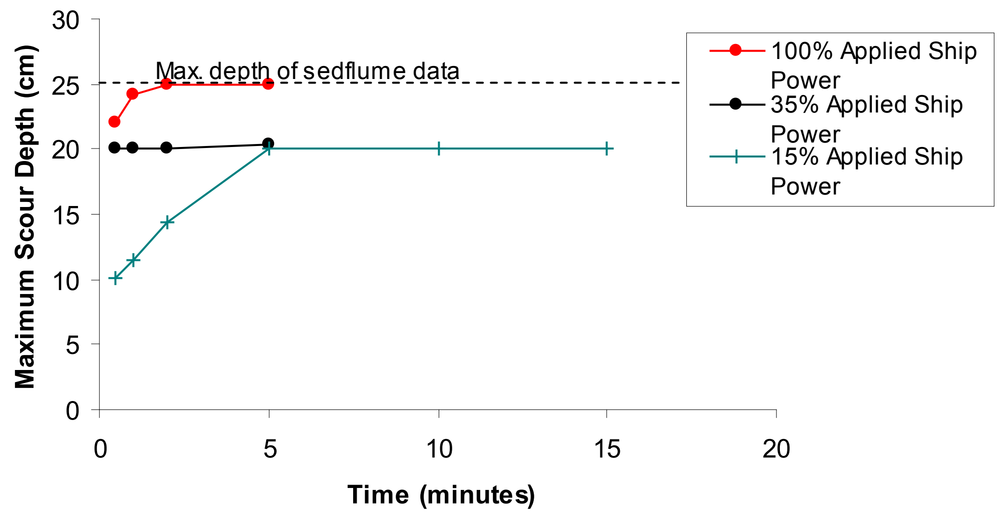
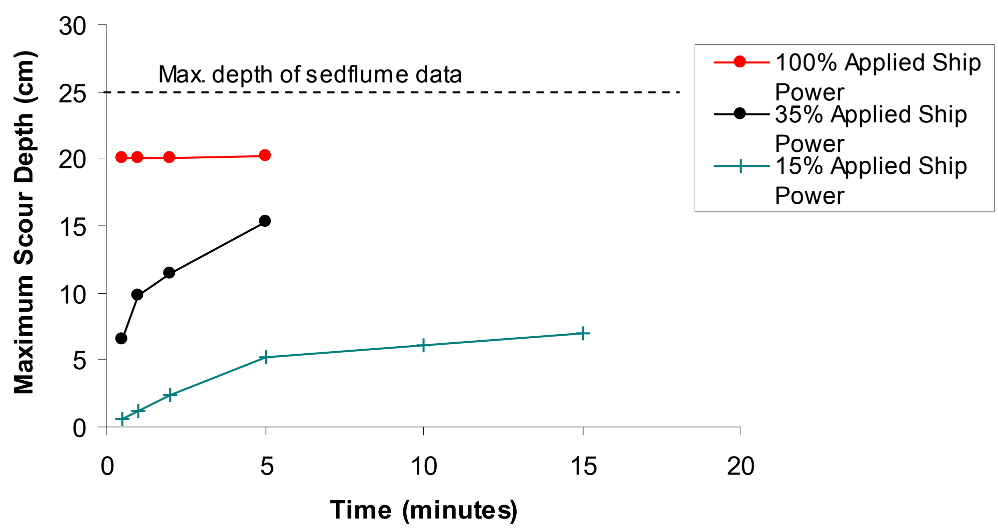


Figure 6 Maximum Scour Depths for the Tug *Sea Valiant* at Water Depth 9 m



At a water depth of 7 m, normal tug operations of the *Sea Valiant*, such as holding barge/vessel in strong current, slowing barge/vessel down for berthing, and acceleration from dock, causes scour to erode through the loose, upper sediment layers until it reaches a cohesive sediment layer at 20 cm (Figure 5). During emergency situations, the scour depth goes beyond 20 cm. However, emergency situations occur less frequently compared to other berthing activities (Emmons and Hernandez-White, personal communication, 2009).

The scour depth was also modeled for *Sea Valiant* operating in water depths of 9 m (Figure 6), where the erosion becomes less severe, demonstrating the effects of distance from the propeller to the bottom on shear stress and erosion. During normal tug activities, the more cohesive sediment layer (below 20 cm depth) is only reached during long operation times. Maneuvering with 35% applied ship power at 9 m water depth for 5 minutes a *Sea Valiant*-size tug is expected to cause scour that is 10 cm or deeper for an areal extent of approximately 270 m^2 behind the propellers.

Simulations for *J.T. Quigg* operating where the water depths are 5 m and 7 m (16.4 ft and 23.0 ft) over the most erodible bench area upstream of the First Avenue Bridge are presented on Figures 7 and 8, where the water depths are 5 m and 7 m, respectively. During emergency situations the scour reaches 25 cm within 1 minute (Figure 7).

Figure 7 Maximum Scour Depths for the Tug *J.T. Quigg* at Water Depth 5 m

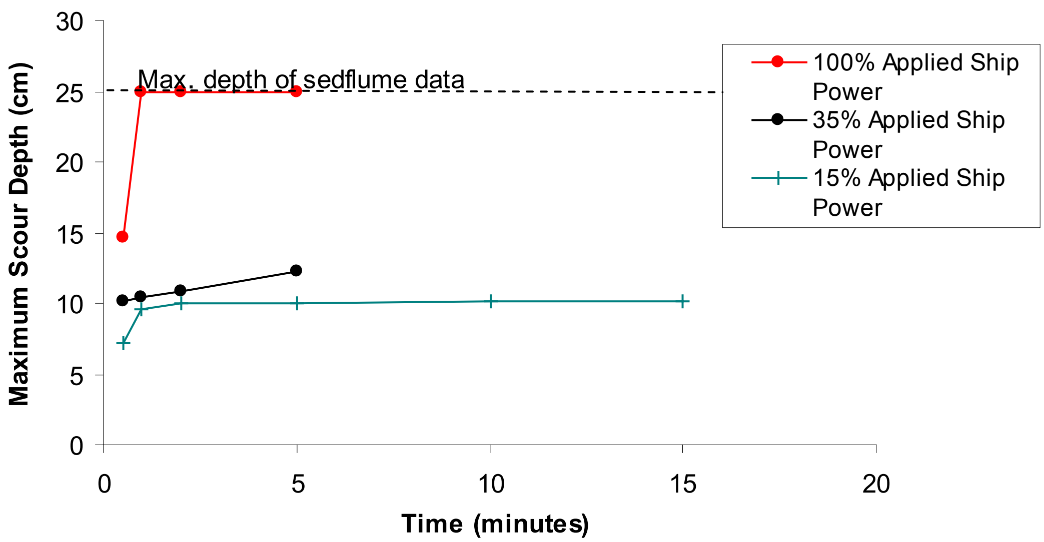
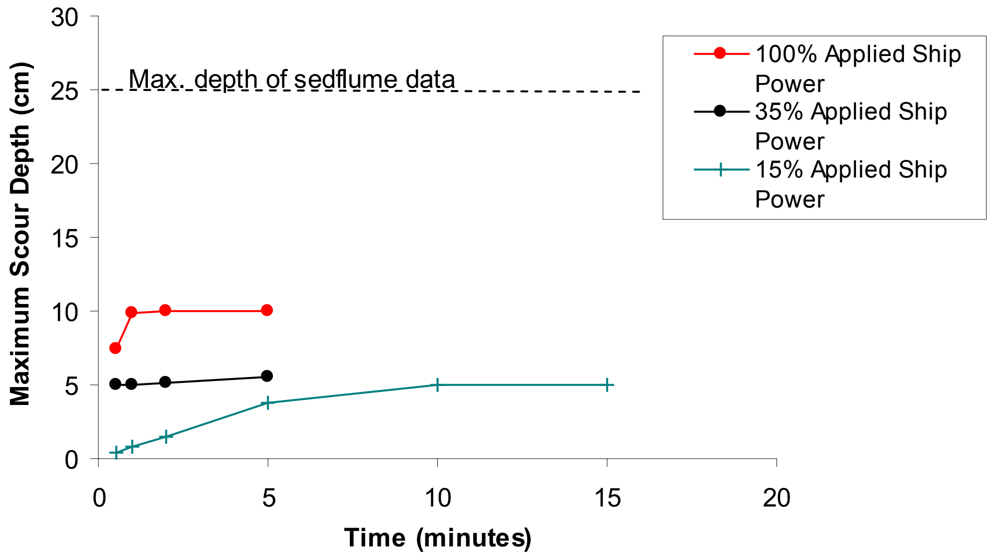


Figure 8 Maximum Scour Depths for the Tug *J.T. Quigg* at Water Depth 7 m



At a water depth of 5m, normal operations of the *J.T. Quigg* (not considering emergency situations) at shallow water depth, the erosion rate decreases at a layer depth of 10-15 cm, where the sediments appear to become more cohesive (Figure 7).

As anticipated, the scour depth decreases for operations of the *J.T. Quigg* at a water depth of 7 m (Figure 8). During normal berthing activities at this depth, the scour depth does not exceed 6 cm although it can reach 10 cm for emergency situations. Maneuvering with 35% applied ship power at a 7 m water depth a *J.T. Quigg*-size tug is expected to cause scour that is 5 cm or deeper (but not exceeding 10 cm) for an areal extent of approximately 300 m^2 behind the propellers.

Conclusion

When a *Sea Valiant*-size tug is conducting normal berthing activities (not considering emergency situations) over the most erodible area downstream of the First Avenue Bridge at a shallow water depth (7 m), erosion stops at a sediment layer depth of 20 cm where the sediments become more cohesive. During normal berthing activities at a water depth of 9 m, the scour depth reaches 20 cm for tug activities with lengthy operation times.

When a *J.T. Quigg*-size tug is conducting normal berthing activities over the most erodible area upstream of the First Avenue Bridge at a shallow water depth (5 m), the erosion rate decreases at a sediment layer depth of 10-15 cm where the sediments become more cohesive. During normal berthing activities at a water depth of 7 m, the scour depth does not exceed 6 cm.

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Part 8: Modeling Contaminant Transport through a Sediment Cap: Summary of Preliminary Work

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Memorandum

Date: October 15, 2010

To: Lower Duwamish Waterway Group

From: AECOM

Subject: Modeling Contaminant Transport through a Sediment Cap: Summary of Preliminary Work

Introduction

Capping is a technology component of all remedial alternatives being developed and evaluated for cleanup of contaminated sediments in the Lower Duwamish Waterway (LDW) Feasibility Study (FS). Gaining an FS-level understanding of how this technology is expected to perform under conditions within the LDW is an essential consideration in assessing its technical feasibility and effectiveness. One aspect of performance is whether and when contaminants originating from buried sediments or groundwater are predicted to emerge through the cap into the biologically active zone (BAZ)[1] and overlying water column (i.e., by diffusion and groundwater advection) at levels that constitute an unacceptable risk. To this end, porewater contaminant concentrations within a hypothetical sediment cap were modeled.

The modeling analysis was conducted in two ways:

1. A parameter sensitivity analysis was used to assess the relative importance of each model input parameter to capping effectiveness. In this analysis, the parameters were varied one at a time, keeping the rest of the parameters constant. The results of this analysis were used to select key parameters to be varied in the scenarios analysis.

2. The scenarios analysis was used to assess the viability of capping under a range of conditions potentially occurring in the LDW. Five parameters were varied and the remaining parameters were held constant. These five parameters were varied in 12 different combinations (i.e., the 12 scenarios) to make FS-level conclusions regarding capping effectiveness. These parameters included: organic carbon partitioning coefficient, Darcy velocity, depositional velocity, cap placement thickness, and fraction of organic carbon in the cap.

The modeling methods, input parameters, sensitivity analysis, and scenario results are described below.

Model Selection and Technical Approach

After reviewing several potential models, the Lampert and Reible model (2009) was selected for this exercise. This selection was made because the model accounts for: 1) advection, dispersion, and

[1] The BAZ is assumed to be the top 10 cm of the surface sediment.

diffusion; 2) sediment compaction resulting from cap placement; and 3) net sedimentation following cap placement. All of these processes are important in the LDW. Also, the model is a spreadsheet analysis and therefore easily manipulated for investigating various scenarios consistent with an FS-level analysis. A previous iteration of this model was employed at the Slip 4 Early Action Area (Integral 2006). The model was used to evaluate total PCBs because they are a key chemical of concern at the site, and because the analysis for PCBs can be generalized to be representative of other organic compounds, such as cPAHs (see discussion below).

Two small changes to the 2009 model were made to better represent the data and the conditions in the LDW. First, both the default Lampert and Reible spreadsheet model and the Slip 4 analysis used porewater concentration for the influent contaminant concentration below the cap. In the Slip 4 analysis, influent porewater concentrations were assumed equal to those concentrations measured in shoreline seeps. However, for the analysis presented here, very limited seep and porewater data were available to characterize the LDW, compared to the size of the potential capping footprint. Therefore, the influent porewater concentration beneath the cap was computed based on equilibrium partitioning with contaminant concentration in the underlying sediment. The partitioning coefficient (K_{oc}) was used to convert sediment concentration to influent porewater concentration for the model.

Second, the default Lampert and Reible spreadsheet model does not have a separate input for fraction of organic carbon (f_{oc}) of newly deposited sediment. Instead, the model assumes that the f_{oc} of newly deposited sediment is equal to the f_{oc} of capping material ($(f_{oc})_{eff}$). However, evidence in the LDW (Section 2) indicates that the f_{oc} of incoming sediment is closer to that in the BAZ ($(f_{oc})_{bio}$) than in the capping material (see Table 1). Therefore, new sediment was assumed to have the same f_{oc} as the BAZ ($(f_{oc})_{bio}$).

Input Parameters and Parameter Sensitivity Analysis

Model input parameters are listed in Table 1. Each parameter was varied with a low, mid, and high values (Table 1). Most of the mid parameter values are consistent with those used for the Slip 4 analysis (Integral 2006) and represent an estimate for average conditions in the LDW. The low and high parameter values represent an estimate for low and high conditions potentially occurring in the LDW. The basis for each parameter value is listed in Table 1.

The mid, low, and high parameter values used in the sensitivity analysis (Table 2) are the same as those in Table 1 with one significant exception: the depositional velocity (i.e., sedimentation rate) was set to zero for the mid values in Table 2. This change was made because of the finding that very small rates of sedimentation result in no contaminant breakthrough. In order to adequately compare the sensitivity of the other parameters, it was necessary to remove sedimentation from the analysis by setting depositional velocity to zero.

For the parameter sensitivity analysis, each parameter was varied one at a time while all the other variables were held constant at the mid values (see Table 2). Each parameter was varied from the mid to the low to the high value; the model results for each sensitivity run were recorded in the right-hand columns of Table 2. The results were reported as 1) breakthrough time,[2] and 2) maximum concentration that can be capped in steady state.[3]

The most sensitive parameters were the ones that showed the largest variance in the results, and included five key input parameters. These five parameters were retained for the scenarios analysis, and

[2] For this analysis, breakthrough time was defined as the time to reach 100 µg/kg dw PCBs in the BAZ.

[3] Steady state represents the conditions following breakthrough, generally 200 to 4,000 years into the future. For this analysis, the maximum concentration that can be capped was defined as the contaminant concentration that resulted in a BAZ concentration of 100 µg/kg dw PCBs.

were highlighted in blue in Table 2. These are: organic carbon partitioning coefficient, Darcy velocity, depositional velocity, cap placed thickness, and fraction of organic carbon in the cap.

Scenarios Analysis

Five key parameters were varied for the scenario analyses. Three of these parameters were varied to account for variations in waterway conditions: 1) Darcy velocity, 2) depositional velocity (net sedimentation rate), and 3) log K_{oc} values. These were used to evaluate capping in average (mid-range) waterway conditions and reasonable worst-case capping conditions, as shown in Table 3. The remaining two key design parameters were varied to evaluate potential cap design options: 1) a range of f_{oc} in capping material and 2) a range of cap thicknesses.

Finally, cap effectiveness was evaluated for two points of compliance: a 10-cm point of compliance for consistency with the benthic biologically active zone (BAZ) in the LDW, and a 45-cm point of compliance to address clamming direct contact risks in nearshore access areas. The point of compliance is 10 cm depth unless otherwise noted (average conditions).

In total, 12 different scenarios were selected to demonstrate various cap designs under various conditions:

1) Scenarios 1a and 1b: capping (3 ft sand) assuming sedimentation conditions consistent with empirical data of 1 cm/yr:
    a. Average mid conditions for all parameters
    b. Conditions unfavorable for capping (high or low parameter)
2) Scenarios 2a through 2c: capping with 3 ft sand assuming no sedimentation
    a. Average mid conditions for all parameters
    b. Conditions unfavorable for capping (high or low parameter)
    c. Conditions unfavorable for capping (raise to 1% f_{oc} in the cap)
3) Scenarios 3a and 3b: ENR with 0.5 ft sand assuming no physical mixing[4] assuming sedimentation conditions consistent with empirical data of 1 cm/yr
    a. Average mid conditions for all parameters
    b. Conditions unfavorable for capping
4) Scenarios 4a through 4c: ENR with 0.5 ft sand assuming no physical mixing and no sedimentation
    a. Average mid conditions for all parameters
    b. Average mid conditions for all parameters (raise to 2% f_{oc} in the cap)
    c. Conditions unfavorable for capping (raise to 2% f_{oc} in the cap)
5) Scenarios 5a and 5b: Capping with 3 ft sand assuming a 45-cm point of compliance for clamming areas[5] and no sedimentation
    a. Average mid conditions for all parameters
    b. Conditions unfavorable for capping (raise to 2% f_{oc} in the cap).

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4 ENR generally assumes that placed sand mixes with underlying sediment; therefore, this analysis is exploratory.

5 The standard point of compliance for the rest of the LDW is the BAZ, or the upper 10 cm of sediment.

Conditions considered unfavorable for capping include: high groundwater flow, low sedimentation, and low K_{oc}; and in some cases, low organic carbon in the sand cap (see Table 3 for exact input parameters). This modeling framework was used to estimate:

1) The maximum concentration that can be capped to maintain total PCB concentrations in BAZ sediments of less than 100 µg/kg dw in 100 years
2) The maximum concentration that can be capped to achieve total PCB concentration of less than the Water Quality Standard (WQS) of 0.03 µg/L PCBs in 100 years.

Results

Table 3 presents results of model runs for the twelve scenarios, which provide a range of results from expected conditions based on FS base assumptions to unfavorable conditions.

Scenarios 1a and 1b show that contaminant breakthrough is not expected to occur at concentrations above the assumed performance goals. This is true even where the assumed conditions are unfavorable (high groundwater flow, low sedimentation, and low K_{oc}), because the rate of sedimentation is still greater than the rate of contaminant front migration through the cap.

Scenarios 2a through 2c show that in the absence of sedimentation, capping is still feasible. However, a higher organic carbon cap may be necessary for a cap design life of 100 years. Higher organic carbon in the cap could be achieved through cap amendments or the use of capping material with higher organic carbon content (2% oc).

Scenarios 3a and 3b show that with sedimentation and thin sand placement (i.e., ENR without physical mixing), contaminant breakthrough is not expected to occur, even in conditions unfavorable to capping.

Scenarios 4a and 4b show that in the absence of sedimentation, thin sand placement is still feasible under average conditions, but a higher organic carbon in the sand layer may be necessary. Scenario 4c shows that the thin sand layer may not be feasible in conditions unfavorable for capping in the absence of sedimentation.

Scenarios 5a and 5b show that for the 45-cm clamming point of compliance direct contact scenario, capping is feasible, even in the absence of sedimentation. However, a higher organic carbon cap (2% oc) may be necessary for a cap design life of 100 years.

The modeling and results for total PCBs can be expanded to address cPAHs because the individual compounds that comprise the latter have K_{oc} values within or above the range used for total PCBs, as shown in Table 4.

Attachments

Table 1 Input Parameters for Analysis of PCB Transport through a Sediment Cap

Table 2 Parameter Sensitivity Analysis

Table 3 Cap Model Results for Select Scenarios

Table 4 K_{oc} Values for cPAHs and PCBs

References

Fabritz, J., J. Massmann, and D. Booth, 1998. *Development of a Three-Dimensional Numerical Groundwater Flow Model for the Duwamish River Basin*. Prepared for City of Seattle and King County for the Duwamish Basin Groundwater Pathways Study.

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Table 1 Input Parameters for Analysis of PCB Transport through Sediment Cap

Input Parameters			Input Values			
Parameter Description	Parameter Symbol	Units	Mid	Low	High	Basis
Contaminant Properties						
Organic Carbon Partition Coefficient	$\log K_{oc}$	log L/kg	5.9	5.0	6.5	Aroclor 1016: 5.03 - proxy for light Aroclors (MTCA); Aroclor 1260: 5.91 - common Aroclor at site, used in Slip 4 analysis (MTCA[a]); Aroclor 1260: 6.5 - high estimate[b]
Water Diffusivity	D_w	cm^2/s	5E-06	4E-06	6E-06	Low value: 4E-6 (model default)[c], 5E-6 (Slip 4)[a]
Cap Decay Rate	l_1	yr^{-1}	0	0	0	Assume no decay (Slip 4 estimate)[a]
Bioturbation Layer Decay Rate	l_2	yr^{-1}	0	0	0	Assume no decay (Slip 4 estimate)[a]
Sediment Properties						
Contaminant Concentration	$C_{0(dw)}$	µg/kg dw	2,600	1,300	6,500	CSL, 2xCSL, 5xCSL based on Sediment Management Standards
Contaminant Porewater Concentration	$C_{0(porewater)}$	µg/L	0.160	0.080	0.400	Calculated as C_o(dw)/(f_{oc}*K_{oc}) (partitioning equation). See sensitivity for C_o(dw)
Biological Active Zone fraction organic carbon	$(f_{oc})_{bio}$	unitless	0.02	0.01	0.04	1-4% based on conditions in the LDW (FS Section 2)
Colloidal Organic Carbon Concentration	r_{DOC}	mg/L	2.0	0.0	4.3	Low sensitivity. 0 mg/L (model default)[c], 4.3 mg/L (Slip 4 estimate)[a]
Darcy Velocity (positive is upwelling)	V	cm/yr	250	106	590	Location specific. Groundwater velocities for the STM: Reach 1:106 - 250 cm/yr, Reach 2: 230-250 cm/yr, Reach 3:260-590 cm/yr[d]
Depositional Velocity	V_{dep}	cm/yr	1.00	0.00	3.00	Not used in sensitivity analysis except to show no breakthrough predicted for very low sedimentation. Location specific deposition predictions from the STM: Reach 1: 1.0-2.0 cm/yr, Reaches 2 and 3: >3.0 cm/yr. 0 cm/yr is a very low estimate for the site.[e]
Bioturbation Layer Thickness	h_{bio}	cm	10	5	45	10 cm is the point of compliance for most of the river; 45 cm is the point of compliance and depth of clams in beaches and clamming areas (FS Section 3); 5 cm is a low estimate of BAZ thickness.
Porewater Biodiffusion Coefficient	D_{bio}^{pw}	cm^2/yr	100	50	200	Low sensitivity. 50 cm^2/yr (1/2x model estimate)[a], 100 cm^2/yr (model default)[c], 200 cm^2/yr (2x model default)[c]
Particle Biodiffusion Coefficient	D_{bio}^{p}	cm^2/yr	1.0	0.5	25.0	0.5 cm^2/yr (1/2x model default)[c], 1.0 cm^2/yr (model default)[c], 25 cm^2/yr (reasonable maximum estimate)
Cap Properties						
Cap Placed Thickness		cm	100	23	150	Design variable with low sensitivity, i.e., cap thickness does not greatly affect steady state BAZ concentration.
Cap Materials: Granular (G) or Consolidated Silty/Clay (C)			G	G	G	Assume granular cap
Cap Consolidation Depth	cm		0	0	0	Assume 0 cm (Slip 4 estimate)[a]
Underlying Sediment Consolidation Due to Cap Placement			23	10	30	Low sensitivity. 10 cm (about 1/2 Slip 4 estimate)[a], 23 cm (Slip 4 estimate)[a], 30 cm (reasonable maximum estimate)
Porosity	e	unitless	0.4	0.30	0.50	0.3 (low estimate), 0.4 (Slip 4 estimate)[a], 0.5 (high estimate)
Particle Density	ρ_P	g/cm^3	2.6	2.5	2.7	2.5 (low estimate), 2.6 (Slip 4 estimate)[a], 2.7 (high estimate)
Fraction Organic Carbon	$(f_{oc})_{eff}$	unitless	0.01	0.0010	0.0200	Key variable in cap design. 0.05% (1/2 MTCA assumption), 1% (Upper Turning Basin), 2% (high oc sand)
Boundary Layer Mass Transfer Coefficient	k_{bl}	cm/hr	0.75	0.60	0.90	0.60 cm/hr (low estimate), 0.75 (model default)[c], 0.9 (high estimate)

Sources:

a. Integral 2006. "Appendix D: Chemical Isolation Analysis," Lower Duwamish Waterway Slip 4 Early Action Area: Engineering Evaluation/Cost Analysis. Prepared for City of Seattle and King County. Integral Consulting, Inc., Mercer Island, Washington. 2006.

b. Mackay, D. W., W. Y. Shiu, K.C. Ma, S.C. Lee, 2006, *Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals.* CRC Press, Boca Raton, FL

c. Lampert, David J. and D. Reible 2009. "An Analytical Modeling Approach for Evaluation of Capping of Contaminated Sediments," *Soil and Sediment Contamination: An International Journal*, 18: 4, 470 - 488.

d. Fabritz, J., J. Massmann, and D. Booth 1998. *Development of a Three-Dimensional Numerical Groundwater Flow Model for the Duwamish River Basin.* Prepared for City of Seattle and King County for the Duwamish Basin Groundwater Pathways Study. 1998.

e. Sediment Transport Memo, Part 4 of this appendix.

Notes:

1. This analysis also applies to other compounds with similar K_{oc} values, such as cPAHs. See discussion in text.

oc = organic carbon

Table 2 Parameter Sensitivity Analysis

Input Parameters			Input Values[a]			Output 1) Time until Breakthrough (Years until 100 µg/kg of Contaminant Concentration Appears in the BAZ)			Output 2) Maximum Total PCB Concentration That Can Be Capped (µg/kg dw to Achieve 100 µg/kg dw in the BAZ under Steady State Conditions)[b]		
Parameter Description	**Parameter Symbol**	**Units**	**Mid**	**Low**	**High**	**Mid**	**Low**	**High**	**Mid**	**Low**	**High**
Contaminant Properties											
Contaminant	Contaminant		PCBs								
Organic Carbon Partition Coefficient	log K_{oc}	log L/kg	5.9	5.0	6.5	1,993	399	3,551	1,223	342	2,048
Colloidal Organic Carbon Partition Coefficient	log K_{DOC}	log L/kg	5.5	4.7	6.1	1,993	1,993	1,993	1,223	1,223	1,223
Water Diffusivity	D_w	cm^2/s	5E-06	4E-06	6E-06	1,993	2,000	1,986	1,223	1,223	1,223
Cap Decay Rate	l_1	yr^{-1}	0	0	0	1,993	1,993	1,993	1,223	1,223	1,223
Bioturbation Layer Decay Rate	l_2	yr^{-1}	0	0	0	1,993	1,993	1,993	1,223	1,223	1,223
Sediment Properties											
Contaminant Concentration	$C_{0(dw)}$	µg/kg	2,600	1,300	6,500	1,993	>2021	1,843	1,223	1,223	1,223
Contaminant Porewater Concentration	$C_{0(porewater)}$	µg/L	0.160	0.080	0.400	1,993	1,993	1,993	1,223	1,223	1,223
Biological Active Zone Fraction Organic Carbon	$(f_{oc})_{bio}$		0.02	0.01	0.04	1,993	1,876	>2021	1,223	818	1,670
Colloidal Organic Carbon Concentration	r_{DOC}	mg/L	2.0	0.0	4.3	1,993	3,375	1,355	1,223	1,223	1,223
Darcy Velocity, *V* (positive is upwelling)	V	cm/yr	250	106	590	1,993	4,597	853	1,223	2,781	563
Depositional Velocity	V_{dep}	cm/yr	0	0	0.05	1,993	1,993	no bt	1,223	1,223	no max
Bioturbation Layer Thickness	h_{bio}	cm	10	5	45	1,993	2,064	>1066	1,223	1,677	458
Porewater Biodiffusion Coefficient	D_{bio}^{pw}	cm^2/yr	100	50	200	1,993	1,993	1,993	1,223	1,222	1,226
Particle Biodiffusion Coefficient	D_{bio}^{p}	cm^2/yr	1.0	0.5	25.0	1,993	1,993	1,993	1,223	818	2,585
Cap Properties											
Depth of Interest	z	cm	10	5	15	1,993	1,993	1,993	1,223	1,223	1,223
Fraction Organic Carbon at Depth of Interest	$f_{oc}(z)$		0.02	0.010	0.040	1,993	>2021	1,876	1,223	1,223	1,223
Cap Placed Thickness		cm	100	23	150	1,993	>264	2,972	1,223	1,213	1,232
Cap Materials: Granular (G) or Consolidated Silty/Clay (C)			G	G	G	1,993	1,993	1,993	1,223	1,223	1,223
Cap Consolidation Depth			0	0	0	1,993	1,993	1,993	1,223	1,223	1,223
Underlying Sediment Consolidation Due to Cap Placement			23	10	30	1,993	1,993	1,993	1,223	1,223	1,223
Porosity	e		0.4	0.30	0.50	1,993	2,338	1,651	1,223	1,322	1,109
Particle Density	ρ_P	g/cm^3	2.6	2.5	2.7	1,993	1,916	2,070	1,223	1,198	1,247
Fraction Organic Carbon	$(f_{oc})_{eff}$		0.01	0.0010	0.0200	1,993	199	3,986	1,223	1,223	1,223
Boundary Layer Mass Transfer Coefficient	k_{bl}	cm/hr	0.75	0.60	0.90	1,993	1,993	1,993	1,223	1,111	1,316

Notes:

a. Mid-range values constitute the base case condition. Low-range and high-range parameter values constitute estimated possible low and high values for the LDW. Input values are identical to Table 1 except for sedimentation rate. Very low sedimentation results in no breakthrough; therefore, sedimentation must be set to zero to assess the sensitivity of the other parameters.

b. Steady state conditions occur following contaminant breakthrough, approximately 200 to 4,000 years into the future.

>[years] = output expressed as greater than because of analytical model limitations; BAZ = biological active zone; f_{oc} = fraction of organic carbon; no bt = no breakthrough predicted; no max = no maximum contamination concentration due to no predicted breakthrough

Shaded parameters are varied in the scenarios analysis in Table 3

Table 3 Cap Model Results for Select Scenarios

		Select Parameter Input Values for Scenario					Maximum Total PCB Concentration That Can Be Capped (µg/kg dw)	
	Scenario in Bedded Sediment	Darcy Velocity (cm/yr)	Depositional Velocity (cm/yr)	log K_{oc} (log L/kg)	Cap f_{oc} (%)	Cap Thickness (cm)	Goal: total PCBs of 100 µg/kg dw in the BAZ in 100 years	Goal: WQS of 0.03 µg/L Total PCBs in the BAZ in 100 years
1	***Scenarios for capping assuming sedimentation conditions consistent with empirical data***							
1a	Average conditions	250	1	6	1%	100	no maximum	no maximum
1b	High groundwater flow, low sedimentation, low K_{oc}, low oc cap	590	1	5	0.05%	100	no maximum	no maximum
2	***Scenarios for capping assuming no sedimentation***							
2a	Average conditions with no sedimentation	250	0	6	1%	100	no maximum	no maximum
2b	High groundwater flow, no sedimentation, low K_{oc}, low oc cap	590	0	5	0.05%	100	204	131
2c	High groundwater flow, no sedimentation, low K_{oc}, mid oc cap	590	0	5	1%	100	no maximum	no maximum
3	***Scenarios for ENR assuming no physical mixing and low level of sedimentation[a]***							
3a	Average conditions, 6-inch ENR layer	250	1	6	1%	15	no maximum	no maximum
3b	High groundwater flow, low sedimentation, low K_{oc}, low oc ENR layer	590	1	5	0.05%	15	no maximum	no maximum
4	***Scenarios for ENR assuming no physical mixing and no sedimentation[a]***							
4a	Average conditions with no sedimentation and 6-inch ENR	250	0	6	1%	15	1,213	5,919
4b	Average conditions with no sedimentation and 6-inch ENR	250	0	6	2%	15	no maximum	no maximum
4c	High groundwater flow, no sedimentation, low K_{oc}, high oc cap	590	0	5	2%	15	181	116
5	***Scenarios for capping assuming a 45-cm POC in clamming areas***							
5a	Average conditions with no sedimentation	250	0	6	1%	100	no maximum	no maximum
5b	High groundwater flow, no sedimentation, low K_{oc}	590	0	5	2%	100	no maximum	no maximum

Notes:

1. Model used mid-range parameters from Table 1, except as noted for Darcy velocity, sedimentation rate, log K_{oc}, cap f_{oc}, and cap thickness.

a. ENR generally assumes that placed sand mixes with underlying sediment, therefore the analysis is exploratory and may need to be refined during remedial design.

BAZ = biologically active zone; C_0 = porewater concentration of contaminant; ENR = enhanced natural recovery; f_{oc} = fraction of organic carbon; K_{oc} = organic carbon partitioning coefficient; oc = organic carbon; PCB = polychlorinated biphenyl; POC = point of compliance; WQS = water quality standard

Table 4 K_{oc} values for cPAHs and PCBs

Compound	CAS #	Log K_{oc}[a]
Benz[a]anthracene	56-55-3	5.56
Benzo[a]pyrene	50-32-8	5.99
Benzo[b]fluoranthene	205-99-2	6.08
Benzo[k]fluoranthene	207-08-9	6.08
Chrysene	218-01-9	5.60
Dibenz[a,h]anthracene	53-70-3	6.26
Indeno[1,2,3-cd]pyrene[2]	193-39-5	6.54
cPAH weighted average based on TEF		6.02
PCB-Aroclor 1016	12674-11-2	5.04
PCB-Aroclor 1260	11096-82-5	5.91
PCBs (generic mixture)	1336-36-3	5.49

Notes:

a. From Washington State Department of Ecology Cleanup Levels and Risk Calculation Database

CAS# = chemical abstracts service number; cPAH = carcinogenic polycyclic aromatic hydrocarbon; K_{oc} = organic carbon partitioning coefficient; PCB = polychlorinated biphenyl; TEF = Toxicity Equivalency Factor

Part 9: BCM Sensitivity – Sediment Particle Fractionation

AECOM

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MEMORANDUM

To:	Sediment Transport Modeling Group and Lower Duwamish Waterway Group	**Date:**	July 14, 2011
From:	C. Kirk Ziegler, Mike Riley, Anchor QEA Anne Fitzpatrick, AECOM	**Project:**	RETldw
Cc:	Files		
Re:	BCM Sensitivity – Sediment Particle Fractionation		

The concentrations assigned to upstream solids for bed composition model (BCM) base case calculations are the same for all four particle sizes simulated in the sediment transport model (STM). The particle size fractions that deposit in different portions of the Lower Duwamish Waterway (LDW) are not, however, the same (the percent fines increase downriver). Some studies on other sites have concluded that contaminant concentrations vary among different size fractions. The basic assumption on the difference in contaminant concentration is that concentrations may be higher on fine grain clay and silt sized particles than on sand-sized particles due to a larger surface area per unit mass and resulting higher organic carbon content (Hedges and Keil 1995).

The Lower Duwamish Waterway Group (LDWG) discussed grain-size and total polychlorinated biphenyl (PCB) concentration distribution analyses with the U.S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology (Ecology) in a meeting on October 1, 2009. Two approaches were used to assign total PCB concentrations to upstream and lateral source sediments. Based on the results presented, and the uncertainty in assigning concentrations by particle size, the decision at the October 1, 2009 meeting was not to fractionate chemical concentrations on STM/BCM sediment classes used in the feasibility study (FS).

However, it is important to understand the potential uncertainty associated with spatially-weighted average concentrations (SWACs) based on these model assumptions. In the subsequent meeting held on April 8, 2011, a third approach was added to this analysis to better understand the effects of grain size and organic carbon on total PCB SWACs. The following describes the three approaches used in the present analysis:

1. Assigning high BCM sensitivity total PCB values to the Class 1A and 1B sediments (clay/silt fractions) and low BCM sensitivity total PCB values to the Class 2 and 3 sediments (sand fractions) from both the upstream and lateral sources. Table 1 presents the grain size distributions for each of the four grain size classes used in the STM.
2. Assigning total PCB values to the upstream and lateral source sediments based on an expectation that smaller particle sizes will have higher organic carbon content and therefore have higher total PCB concentrations. Organic carbon content was assigned at 5, 2.5, 1.5, and 0.3 percent for Classes 1A, 1B, 2, and 3, respectively, while maintaining the same aggregate suspended load value as the BCM base case of 35 μg/kg dw.
3. Similar to Approach 2, but Classes 1A and 1B were assumed to have the same PCB concentration; and total PCB values on Class 2 and Class 3 were assigned based on 1.5 and 0.3 percent organic carbon content.

Using these approaches, the grain size/total PCB concentrations were developed (Table 2). The mid BCM input values used in the FS are shown for reference. The average total organic carbon content of LDW bed sediment is about 2 percent.

Table 1 Characteristics of Sediment Particle Size Classes

Sediment Size Class	Particle Size Range (μm)	Effective Particle Diameter (μm)
1A: clay, fine silt	< 10	5
1B: medium, coarse silt	10 – 62	20
2: fine sand	62 – 250	130
3: medium, coarse sand	250 – 2,000	540

Table 2 Total PCB Input Value for the Grain Size Fractionation Analysis

Sediment Source and Class	Percentage of Suspended Load by Mass	Total PCB Concentration Input Value (µg/kg dw)			
		FS mid BCM Value	Approach 1	Approach 2	Approach 3
Green/Duwamish (Upstream) Sediment					
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 suspended load		35	71	35	35
Lateral Source Sediment					
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 suspended load		300	757	300	300

Notes:

1. For Green/Duwamish sediment 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 BCM values are shown for reference when comparing input values for the three approaches.
3. Approach 3 has more PCB mass on 1A and 1B than in approach 2. Since in both cases, we are maintaining the same aggregate load of 35 µg/kg, the mass assigned to classes 2 and 3 must be reduced in approach 3 compared to approach 2.

Note that as a result of the high proportion of Class 1A and 1B particles in the upstream source sediment and the high total PCB concentration assigned to these sediment classes, Approach 1 results in an average total PCB concentration for upstream suspended sediment of 71 µg/kg dw, which is substantially higher than the mid BCM upstream input value used in the analysis in the draft final FS. Approaches 2 and 3 maintain the same average total PCB concentration for upstream suspended sediment as the BCM value used in the draft final FS, but assign that concentration by organic carbon and sediment composition of upstream and lateral source sediment to the different size classes.

RESULTS AND DISCUSSION:

Table 3 presents the results of these approaches after 10 years of natural recovery following completion of the EAAs (Post Alternative 1).

Table 3 Results of the Grain Size Fractionation Analysis

LDW Reach	Total PCB SWAC (µg/kg dw)			
	FS mid BCM 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

Approach 1 produces substantially higher SWACs than the FS BCM mid input value case (recommended input values). This is not surprising because the allocation of total PCBs to the different size fractions results in an increase in total PCB concentration from upstream and lateral source sediments.

Approach 2 produces slightly lower SWACs for all reaches. This is because the highest concentration is assigned to the Class 1A size fraction while the other size fractions have total PCB concentrations less than the value used in the FS. The Class 1A size fraction makes up 70% of the total suspended sediment load by mass entering the LDW; however, most of this material passes through the LDW without settling. Therefore, the sediment that does settle has an average total PCB concentration slightly less than the FS mid BCM input value.

Approach 3 produces SWAC values for the LDW site-wide and for Reaches 1 and 2 that are essentially the same as for the FS mid BCM input values. While the SWAC for Reach 3 is substantially lower due to the low total PCB concentration on Class 3 material, Class 3 is the size fraction that predominantly deposits in Reach 3.

Overall, the size fractionation of PCB concentration results in either lower predicted SWACs with time or essentially the same as in the current FS base case BCM analysis. The analysis shows that the approach used in the BCM base case analysis likely underestimates natural recovery over time compared to a BCM model in which contaminant concentrations are assigned by particle size.