100% Remedial Design Basis of Design Report

Appendix I
Engineered Cap Chemical Isolation Design Analysis

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ABBREVIATIONS

µg/kg	micrograms per kilogram
µg/L	micrograms per liter
cfs	cubic feet per second
cm	centimeter
cm/hr	centimeters per hour
cm/yr	centimeters per year
cm^2/s	square centimeters per second
cm^2/yr	square centimeters per year
COC	contaminant of concern
FNC	federal navigation channel
f_{OC}	fraction organic carbon
FS	Feasibility Study
g/cm^3	grams per cubic centimeter
K_d	equilibrium partition coefficient
K_{OC}	organic carbon partition coefficient
K_{OW}	octanol-water partition coefficient
L/kg	liters per kilogram
LDW	Lower Duwamish Waterway
mg/kg	milligrams per kilogram
MLLW	mean lower low water
OC	organic carbon
PCB	polychlorinated biphenyl
RAA	remedial action area
RAL	remedial action level
RD	remedial design
RI	remedial investigation
RM	river mile
ROD	*Record of Decision*
SMA	sediment management area
TOC	total organic carbon

1 Introduction

This appendix documents the chemical transport modeling conducted to evaluate engineered capping to address elevated polychlorinated biphenyls (PCBs) in the sediment at remedial action area (RAA) 14/15/16 (sediment management area [SMA] 12B) and RAA 27 (SMA 5)[1] (Figures I1-1a and I1-1b).

RAA 14/15/16 (SMA 12B) is located at river mile (RM) 3.6 within the subtidal zone. Elevated PCB concentrations were measured in this area during the Pre-Design Investigation Phase I, II, and III sampling programs (*Basis of Design Report* Appendix A and *Pre-Design Investigation Data Evaluation Report* [Anchor QEA and Windward 2022]). Partial dredging and engineered capping have been selected as the remedial technology for this SMA.

Final (100%) Remedial Design (RD) identified that the sediment cleanup remedy at RAA 27 (SMA 5) (Container Properties; RM 4.1E) extends up the adjacent bank. Chemistry data underneath the bank concrete debris and riprap armor could not be collected; however, chemistry data at the toe of the bank slope indicate that there is potential for contaminated sediment underneath at least part of the bank surface. The need for a cap in RAA 27 will not be confirmed until post-excavation sampling is conducted per the *Construction Quality Assurance Plan* (Volume II, Part I). Because there is uncertainty regarding whether sediment underneath the bank concrete debris and riprap armor material at RAA 27 (SMA 5) is contaminated, the conservative remedial technology of engineered capping will be applied to the bank portion of this RAA. The engineered cap would be applied only to the bank portion of RAA 27 (SMA 5), which is located approximately above +4 feet mean lower low water (MLLW; upper intertidal area); contaminated sediment in RAA 27 below +4 MLLW will be removed (SMA 6).

The modeling was conducted to evaluate a sediment cap to address elevated concentrations of PCBs in sediments. The modeling analyses described herein were performed in accordance with guidance on cap design set forth by the U.S. Environmental Protection Agency and U.S. Army Corps of Engineers (Palermo et al. 1998) and the Interstate Technology and Regulatory Council (ITRC 2014, 2023). The primary goal of this modeling was to simulate the transport of PCBs within an engineered cap to identify a chemical isolation layer configuration (i.e., thickness and composition) that will meet remedial action levels (RALs) set forth in the *Record of Decision* (ROD; EPA 2014) for a long period of time (e.g., 100 years).

[1] RAA 27 comprises SMA 5 and SMA 6. References to "RAA 27 (SMA 5)" in this document refer to the portion of RAA 27 where engineered capping analyses have been conducted (i.e., SMA 5).

Figure I1-1a
RAA 27 (SMA 5) Cap Area

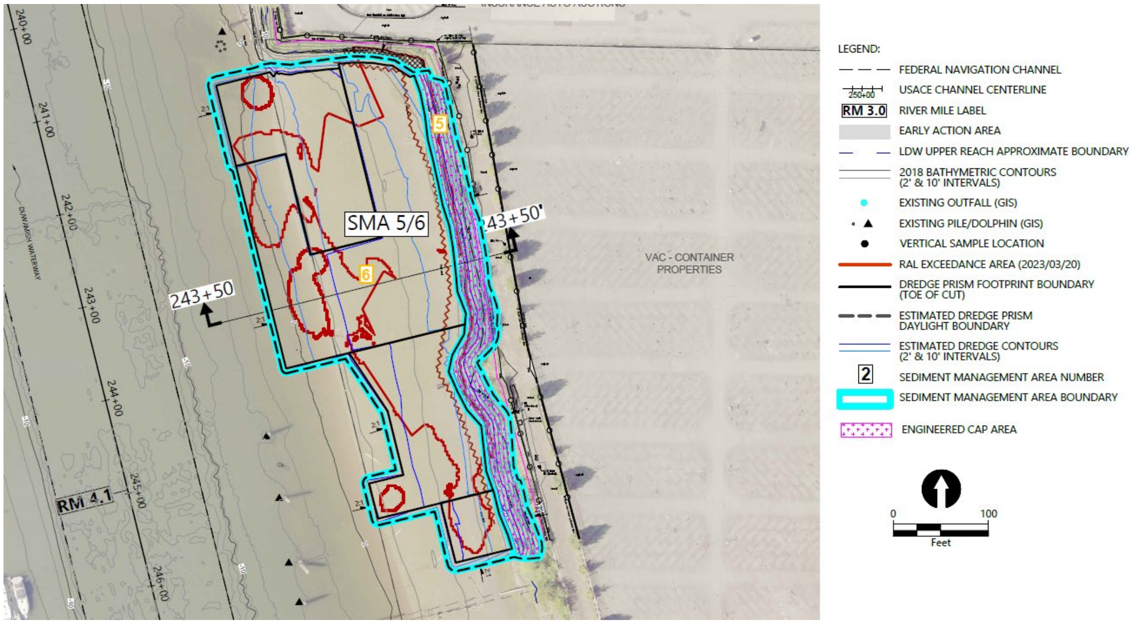
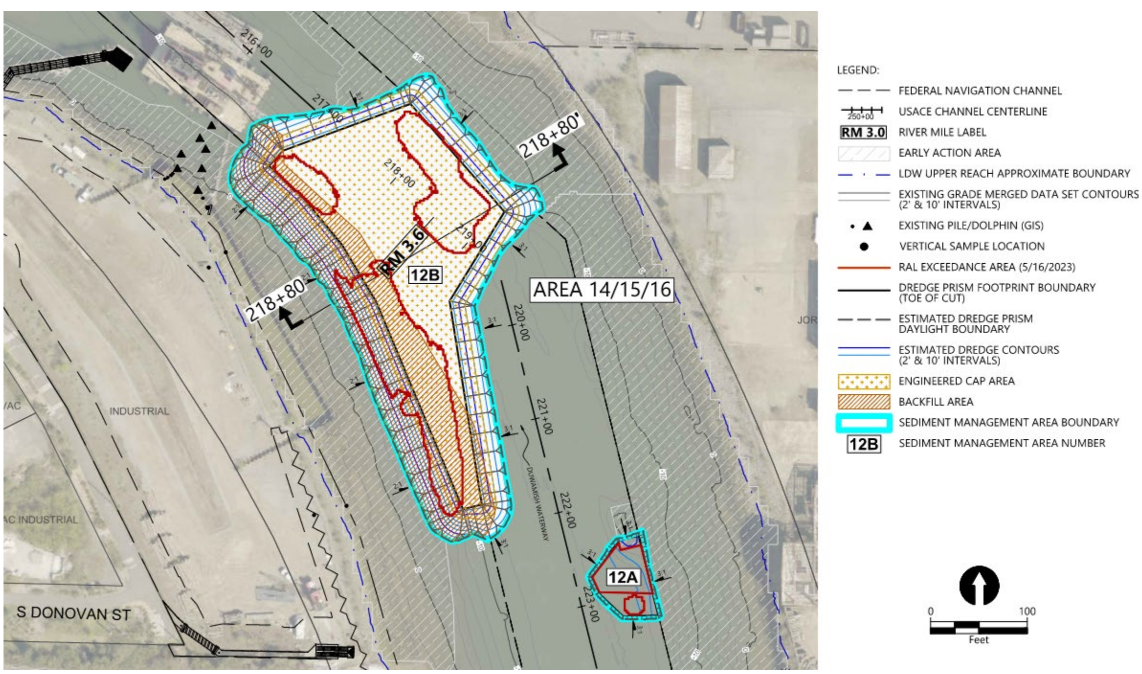


Figure I1-1b
RAA 14/15/16 (SMA 12B) Cap Area



2 Approach

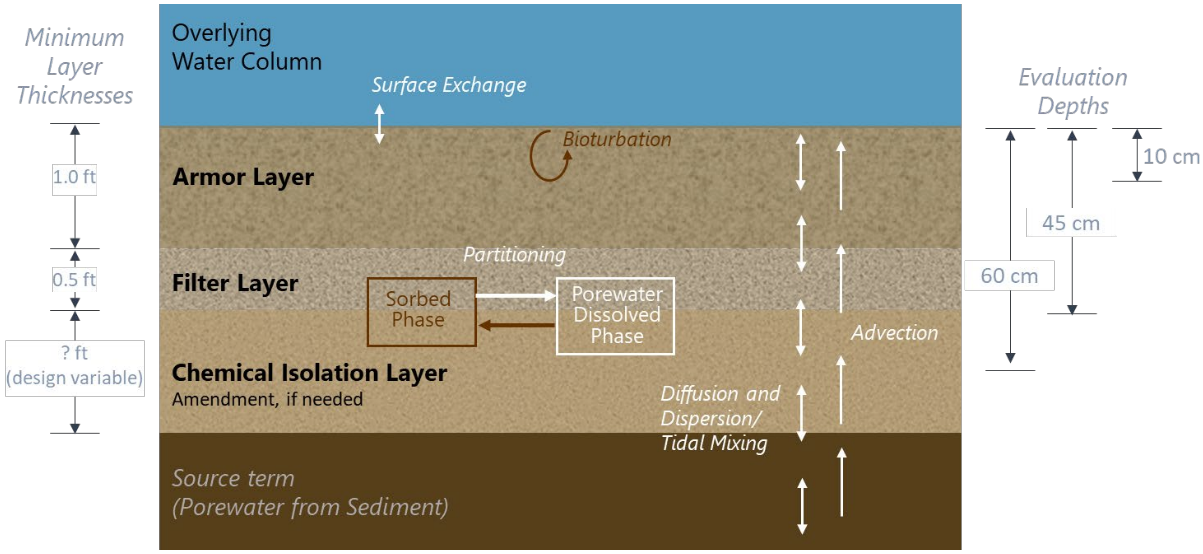
2.1 Model Framework

The one-dimensional model of chemical transport within sediment caps, CapSim (version 3.8; Reible 2017), was used for this evaluation. This model simulates the time-variable fate and transport of chemicals (dissolved and sorbed phases) under the processes of advection, diffusion/dispersion, biodegradation, bioturbation/bioirrigation, and exchange with the overlying surface water within a sediment cap. This model and its predecessor versions have been used to support the evaluation and design of sediment caps at numerous cleanup sites around the United States and internationally. Details on the model structure and underlying theory and equations are provided in Lampert and Reible (2009), Go et al. (2009), and Shen et al. (2018).

2.2 Simulation Approach

As shown in the schematic in Figure I2-1, the initial cap configuration for the two cap areas consists of a chemical isolation layer, overlain by a 6-inch-minimum-thickness filter layer and a 1-foot-minimum-thickness erosion protection (i.e., armor) layer. The armor layer is specified as a cobble and gravel layer. It is assumed that the interstitial spaces of the armor layer will become filled in from deposition at RAA 27 (SMA 5) and RAA 14/15/16 (SMA 12B) and from the addition of habitat material placed at RAA 27 (SMA 5). Nonetheless, a sensitivity analysis was conducted to evaluate cap model results with the armor layer excluded from the model domain.

Figure I2-1
Cap Layer Configuration and Processes Modeled



Notes:
The modeling approach conservatively ignored net sedimentation (i.e., addition of material on top of the armor stone, which would add thickness to the model domain), but does assume the armor layer will become infilled with depositing sediment. The model uses a porosity for the armor that assumes the infilling is complete at the beginning of the simulation, which is a reasonable assumption, given the relatively short time it will take for infilling to occur compared with the long-term simulation period of 100 years.
Consolidation of underlying sediments was not simulated; consolidation was assumed to be negligible due to dredging before material placement.

There are a total of 42 Lower Duwamish Waterway (LDW) contaminants of concern (COCs): 4 COCs based on risk to human health, 40 COCs based on risk to benthic invertebrates, and 1 COC for wildlife (i.e., river otters). In RAA 14/15/16 (SMA 12B) and RAA 27 (SMA 5), PCBs are the only COC to exceed the RAL. In RAA 27 (SMA 6), which is adjacent to RAA 27 (SMA 5), dioxins/furans, mercury, and phenol had one or more exceedances of the RAL. Due to lack of data within RAA 27 (SMA 5) and proximity of these sample locations to RAA 27 (SMA 5), these samples were also considered in the cap design evaluations for the cap in RAA 27 (SMA 5).

In the design of a cap, the chemicals that drive the design are those that have the highest concentrations relative to the design criteria (in this case, the RAL), requiring the greatest reduction in concentration to meet the RAL, and the chemicals that are the most mobile. These two considerations (required percent reductions and mobility) are considered together when selecting the COCs to evaluate at a site. PCBs require the greatest reduction in concentrations within RAA 14/15/16 (SMA 12B) and RAA 27 (SMA 5). Total PCB was evaluated as the driver COC based on observed exceedances of RALs in these areas. In RAA 27 (SMA 6), mercury and phenol exceeded the RAL only slightly (exceedance factors of 1.2 and 1.1, respectively). The maximum exceedance factor for PCBs of 17 was greater than the exceedance factor of dioxins/furans, which have a maximum exceedance factor of 13. In addition, PCBs are more mobile than dioxins/furans, indicating PCBs are the driving COC. Therefore, a remedy that addresses PCBs will also address reductions for dioxins/furans, mercury, and phenol. Thus, PCBs were evaluated in the modeling performed for RAA 14/15/16 (SMA 12B) and RAA 27 (SMA 5). PCBs were simulated as individual PCB homologs in the model to account for the differences in homolog mobility.[2]

Initial model simulations started with a chemical isolation layer thickness of 1 foot. If a 1-foot chemical isolation layer was not sufficient to maintain predicted PCB concentrations less than performance target concentrations in surface sediment, as discussed subsequently, then the model simulations were conducted iteratively, increasing thickness (or adding a sorptive amendment) until the performance targets were predicted to be met. Model simulations were conducted to identify the chemical isolation layer thickness required to maintain PCB concentrations less than performance target concentrations in surface sediment, as discussed subsequently.

2.3 Performance Targets

For the purposes of this evaluation, performance targets were set to the RALs. Consistent with Table 28 of the ROD (EPA 2014), the RALs are dependent on the location, elevation type (i.e., intertidal vs. subtidal), recovery category (e.g., erosion potential), and depth interval in the sediment. RAA 27 (SMA 5) is located in the intertidal zone within the Recovery Category 2 area. RAA 14/15/16 (SMA 12B) is located in the subtidal zone, mostly within the Recovery Category 1 area. The performance of the caps was evaluated against the PCB RALs applicable to human health as follows:

- **RAA 27 (SMA 5):** 12 milligrams per kilogram (mg/kg) organic carbon (OC) total PCB in 0 to 10 centimeters (cm); 65 mg/kg-OC in 0 to 45 cm.
- **RAA 14/15/16 (SMA 12B):** 12 mg/kg-OC total PCB in 0 to 10 cm. Because armoring will be placed in the cap areas to protect against erosion/scour, the subsurface criteria are not relevant in the subtidal zone.

[2] PCB concentrations were measured using an Aroclor-based method. To account for the range in mobility of the PCB congeners that make up an Aroclor, reported Aroclor PCB concentrations in sediment were converted to homolog concentrations based on the average fraction of each homolog group associated with each Aroclor developed from several published studies (Rushneck et al. 2004; Schulz-Bull et al. 1989; Frame et al. 1996; EPA 1995).

3 Model Inputs

The CapSim model uses several input parameters that describe chemical-specific properties, cap material properties, and chemical mass transfer rates. These input parameters were developed based on site-specific data, information from literature, and experience with cap design at other similar sites. A list of model input parameters, values used for this modeling assessment, and source(s) from which they were derived is provided in Table I3-1. More details describing certain key model inputs are provided in Sections 3.1 through 3.3.

Table I3-1
Input Parameter Values for the Chemical Isolation Cap Model

Model Input Parameter	Value	Data Source
Chemical-Specific Properties		
PCB porewater concentration	Table I3-3	Based on the maximum calculated total PCB porewater concentration (from sediment sample LDW22-SC782K and soil sample FRP-082911-002; see Table I3-3). Homolog concentrations were estimated from individual Aroclor concentrations based on composition reported in literature. Porewater concentrations were calculated based on bulk sediment PCB and TOC concentrations and equilibrium partition coefficients. The model assumes a fixed concentration at the bottom boundary of the model (i.e., infinite source). See Section 3.2 for more detail.
OC partition coefficients for PCB homologs, log K_{OC} (log L/kg)	Table I3-2	Based on partition coefficients developed as part of the Pre-Design Studies (Windward 2020). See Section 3.1 for more detail.
Molecular diffusivity (cm^2/s)	PCBs: 3.3E-06 to 6.5E-06	Calculated based on molecular weight using correlation from Schwarzenbach et al. (1993). The model calculates an effective diffusion coefficient using this chemical-specific input value for the molecular diffusivity and an empirical equation based on the cap material porosity using the approach developed by Millington and Quirk (1961).
Chemical biodegradation rate (per year)	0	Assumed no biodegradation.
Armor Layer Properties		
Thickness (cm)	30	Minimum armor layer thickness.
Total porosity	0.35	The armor layer consists of cobble and gravel. The porosity represents a typical value for these materials, assuming the interstitial spaces will become filled in from deposition at RAA 27 (SMA 5) and RAA 14/15/16 (SMA 12B), and the addition of habitat material at RAA 27 (SMA 5) (e.g., Domenico and Schwartz 1990).
Dry bulk density (g/cm^3)	1.69	Calculated based on typical particle density of 2.6 g/cm^3 and porosity of 0.35 (see previous row).

Model Input Parameter	Value	Data Source
Fraction OC of bioturbation zone (%)	1%	Assumed 1% within the 10-cm bioturbation zone based on experience from other sites and the assumption that over time, the interstitial spaces of the armor stone will fill in and the f_{OC} will increase toward levels similar to (but lower than) those of the current surface sediment, which averages 1.6%.
Fraction OC of cap material below bioturbation zone	0.1%	Represents the sorptive capacity of the cap material within the 10- to 30-cm depth interval. A lower-bound estimate typically used to represent quarry sand in which sorption to mineral fractions can also occur (Karickhoff 1984; EPA 2000). This is conservative in RAA 14/15/16 (SMA 12B), which may be filled in completely with depositional material having a higher fraction of OC.
Filter Layer Properties		
Thickness (cm)	15	Minimum thickness of 15 cm (6 inches).
Total porosity	0.35	Typical value for gravel (e.g., Domenico and Schwartz 1990).
Dry bulk density (g/cm^3)	1.56	Calculated based on typical particle density of 2.6 g/cm^3 and porosity of 0.4 for sand.
Fraction OC of cap material (%)	0.1%	A lower-bound estimate typically used to represent quarry sand in which sorption to mineral fractions can also occur (Karickhoff 1984; EPA 2000).
Chemical Isolation Layer Properties		
Thickness (cm)	30	Design variable. Started with a minimum thickness of 30 cm (12 inches) and increased as necessary to meet the performance targets.
Total porosity	0.4	Typical value for gravelly sand (e.g., Domenico and Schwartz 1990).
Dry bulk density (g/cm^3)	1.56	Calculated based on typical particle density of 2.6 g/cm^3 and porosity of 0.4 for gravelly sand.
Fraction OC of chemical isolation cap material (%)	Design variable	Represents sorptive capacity of the cap material. Started with a nominal value of 0.1%. If the PCB RAL was predicted not to be met with sand alone, this value was increased as necessary to represent an OC amendment needed to meet the PCB RAL.
Mass Transport Properties		
Boundary layer mass transfer coefficient (cm/hr)	0.3	Midpoint of range of values compiled from laboratory and field site measurements reported in the literature (e.g., Thibodeaux et al. 2001; Martinez et al. 2010; Erickson et al. 2005) and values calibrated as part of models (1D and system-wide) of sediment/water exchange at other sites (e.g., Anchor QEA and GZA 2015; Connolly et al. 2000; EPA 2006).
Groundwater seepage rate (cm/yr)	100, 400, and 800	Range of values estimated from MODFLOW model predictions developed by Fabritz et. al. (1998). See Section 3.3 for detail. RAA 27 (SMA 5) is located in the nearshore, so seepage rates in this area were set to 400 and 800 cm/yr. RAA 14/15/16 (SMA 12B) is located in the FNC; therefore, seepage rates in this area were set to 100 and 400 cm/yr.

Model Input Parameter	Value	Data Source
Net sedimentation rate (cm/yr)	0	Conservatively assumed no future net sedimentation in the model, which would add material on top of the armor stone, adding thickness to the model domain. Instead, the model assumes a porosity of armor stone based on the infilling of the interstitial spaces of the armor stone being complete at the beginning of the simulation, which is a reasonable assumption, given the relatively short time it will take for infilling to occur compared with the long-term simulation period of 100 years.
Dispersion length (cm)	Variable	Based on 20% of the model domain length (cap thickness). See Section 3.3 for detail.
Bioturbation zone thickness (cm)	10	The RI (Windward 2010) concluded that 10 cm can be reasonably estimated as the depth of bioturbation in the LDW.
Particle biodiffusion coefficient (cm^2/yr)	1	Parameter represents bioturbation rate applied to the particulate phase; order of magnitude estimate represents midpoint between freshwater rivers and intertidal areas (Thibodeaux and Mackay 2011).
Porewater biodiffusion coefficient (cm^2/yr)	100	Parameter represents bioturbation rate applied to dissolved phase. Typical cap modeling approach is to use 100 times the particle biodiffusion coefficient (see row above) (Reible 2012).
Consolidation (cm)	0	Consolidation is not expected to occur. In RAA 27 (SMA 5), sediments are currently consolidated because they are beneath riprap that will be replaced as part of the remedy in this area. In RAA 14/15/16 (SMA 12B), dredging of sediments will occur prior to placing a cap; therefore, no consolidation is expected.

Note:
cm: centimeter
cm/hr: centimeters per hour
cm/yr: centimeters per year
cm^2/s: square centimeters per second
cm^2/yr: square centimeters per year
FNC: federal navigation channel
f_{OC}: fraction organic carbon
g/cm^3: grams per cubic centimeter
K_{OC}: organic carbon partition coefficient
L/kg: liters per kilogram
LDW: Lower Duwamish Waterway
OC: organic carbon
PCB: polychlorinated biphenyl
RAA: remedial action area
RAL: remedial action level
RD: remedial design
RI: remedial investigation
SMA: sediment management area
TOC: total organic carbon

3.1 Partitioning Coefficients

Partitioning of chemicals between the dissolved and sorbed (i.e., cap material) phases is described in the model by the chemical-specific equilibrium partition coefficient (K_d). This approach assumes sorption follows a linear isotherm and is instantaneous (not rate-limited) and reversible. For organic compounds, such as PCBs, the partition coefficient is calculated in the model based on the customary K_d = fraction organic carbon (f_{OC})*organic carbon partition coefficient (K_{OC}) approach (e.g., Karickhoff 1984), where K_{OC} is the compound's OC partition coefficient and f_{OC} is the OC fraction of the solid phase (i.e., cap material).

For PCBs, model simulations were performed at the homolog level to represent the range of chemical mobility associated with the congeners that make up the total. Log K_{OC} values for each homolog group were calculated from the empirical relationship developed from the data collected as part of the Pre-Design Studies ($\log K_{OC} = 0.77 \times \log K_{OW} + 1.5$) using the K_{OW} values from Hawker and Connell (1988) (Windward 2020). Windward (2020) confirmed that effects from black carbon on partitioning within site sediments were minimal; therefore, these site-specific partition coefficients were used to represent partitioning onto sediments as well as sand cap material. Log K_{OC} values by homolog group are shown in Table I3-2.

Table I3-2
Partitioning Coefficients Used in the Cap Model

Chemical Name	OC Partition Coefficient, Log K_{OC} (log L/kg)
PCB-Mono	5.1
PCB-Di	5.4
PCB-Tri	5.8
PCB-Tetra	6.1
PCB-Penta	6.4
PCB-Hexa	6.7
PCB-Hepta	7.0
PCB-Octa	7.3
PCB-Nona	7.5
PCB-Deca	7.8

Notes:
K_{OC}: organic carbon partition coefficient
L/kg: liters per kilogram
OC: organic carbon
PCB: polychlorinated biphenyl

3.2 Porewater Concentrations

The porewater concentration input defines the source term in the cap model and corresponds to the contaminant concentrations present in the porewater immediately beneath the cap. Porewater was not sampled in RAA 27 (SMA 5) and RAA 14/15/16 (SMA 12B); therefore, PCB concentrations in sediment porewater were calculated from measured sediment concentrations using the equilibrium partitioning coefficients discussed in Section 3.1. Although the lack of measured porewater data presents an uncertainty in the model, the availability of site-specific partition coefficients, as discussed in Section 3.1, reduces that uncertainty.

Vertical core interval sediment concentrations collected from RAA 27 (SMA 5), as well as the soil samples collected from 5 feet or more below the ground surface along the shoreline riverbank (adjacent to Container Properties) (AMEC 2012), were used for the evaluation of the cap in this area. Conservatively, simulations were conducted using the maximum calculated porewater concentrations, which were from soil sample FRP-082911-002 from Location SL-01 at a depth from 5 to 7 feet below ground surface.

In RAA 14/15/16 (SMA 12B), sediment samples within the RAA from depths below an elevation of -21 feet MLLW[3] were used in the evaluation of the cap in this area. Conservatively, simulations were conducted using the maximum OC-normalized PCB concentration, which was from sample LDW22-SC782K from Location LDW22-SC782 at a depth from approximately 11 to 12 feet below the current ground surface (2 to 3 feet below the post-dredge surface).

PCB concentrations were measured using an Aroclor-based method. To account for the range in mobility of the PCB congeners that make up an Aroclor, reported Aroclor PCB concentrations in sediment were converted to homolog concentrations based on the average fraction of each homolog group associated with each Aroclor developed from several published studies (Rushneck et al. 2004; Schulz-Bull et al. 1989; Frame et al. 1996; EPA 1995). Sediment PCB concentrations are shown in Table I3-3 for reference. The sediment PCB homolog concentrations were then converted to porewater concentrations using the log K_{OC} values listed in Table I3-2. The porewater concentrations used in the model evaluations are provided in Table I3-3.

Table I3-3
Porewater Concentrations Used in the Cap Model

Chemical Name	RAA 27 (SMA 5) Maximum PCB Concentration[1]		RAA 14/15/16 (SMA 12B) Maximum PCB Concentration[1]	
	Sediment (µg/kg)[2]	Porewater (µg/L)	Sediment (µg/kg)[2]	Porewater (µg/L)
PCB-Mono	2.2E-02	7.6E-05	2.9E-01	1.3E-04
PCB-Di	6.0E-01	9.0E-04	9.5E+00	1.8E-03
PCB-Tri	4.2E+00	2.8E-03	1.4E+02	1.2E-02
PCB-Tetra	6.9E+01	2.0E-02	4.9E+02	1.8E-02
PCB-Penta	2.2E+02	3.1E-02	7.1E+02	1.3E-02
PCB-Hexa	1.1E+02	8.0E-03	4.4E+02	4.1E-03
PCB-Hepta	1.2E+01	4.6E-04	1.6E+02	7.8E-04
PCB-Octa	8.5E-01	1.5E-05	3.1E+01	7.2E-05
PCB-Nona	4.4E-02	4.9E-07	2.9E+00	4.1E-06
PCB-Deca	3.8E-04	2.3E-09	2.1E-01	1.6E-07
Total PCB[3]	4.2E+02	6.3.E-02	2.0E+03	4.9E-02

Notes:
1. Concentrations are shown to two significant figures.
2. Sediment concentrations estimated from Aroclor PCBs are provided for reference.
3. Total PCB is included for reference only; total PCB was not simulated with the model. PCBs were simulated by homolog group, and results were summed to calculate total PCBs for comparison with RALs.

µg/kg: micrograms per kilogram
µg/L: micrograms per liter
PCB: polychlorinated biphenyl

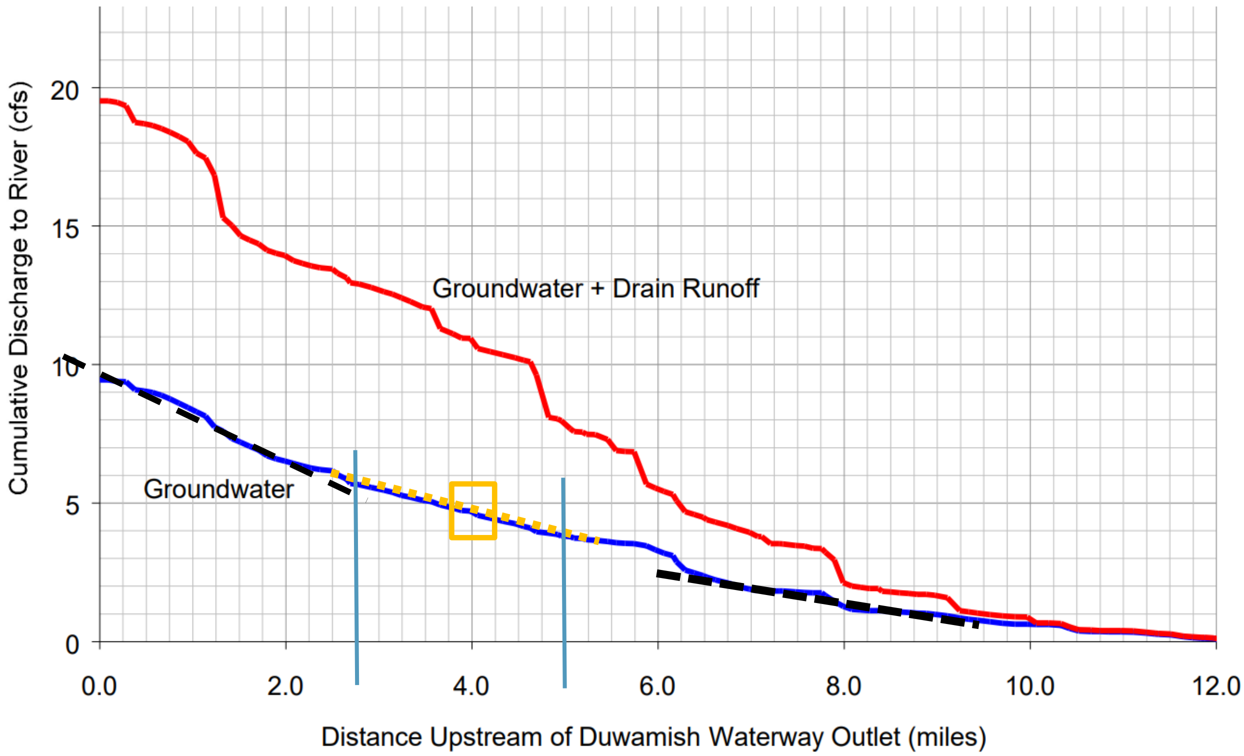
[3] Dredge depth in this SMA is to -23 MLLW. Including data from -21 MLLW and deeper is conservative.

SMA: sediment management area
RAA: remedial action area
RAL: remedial action level

3.3 Groundwater Seepage and Dispersion

Direct measurements of groundwater seepage rates in the project area were not available. Therefore, seepage rates were estimated from the groundwater flow modeling study documented by Fabritz et. al. (1998). In this study, a 3D model of the Duwamish River Basin was developed using the U.S. Geological Survey MODFLOW framework. As part of that study, predicted cumulative discharge to LDW was presented as a function of location along 12 miles of river (see Figure I3-1, which is adapted from Figure 11 of Fabritz et al. [1998]). To estimate the seepage rate in the cap design areas, the change in cumulative discharge with distance in the project area, as shown in Figure I3-1, was reviewed. The increase in discharge with distance appears to differ somewhat among three sections of the river. Discharge is predicted to be the greatest from the river outlet to RM 2.75, as illustrated by the steeper slope shown in Figure I3-1. The slope becomes flatter from RM 2.75 to RM 5; the cap areas are located between RMs 3.6 and 4.1 (identified by the yellow rectangle in Figure I3-1). The flatter slope from RMs 6 to 9.5 suggests lower discharge to the LDW in this area.

Figure I3-1
Cumulative Discharge to the Lower Duwamish Waterway Predicted by MODFLOW Model



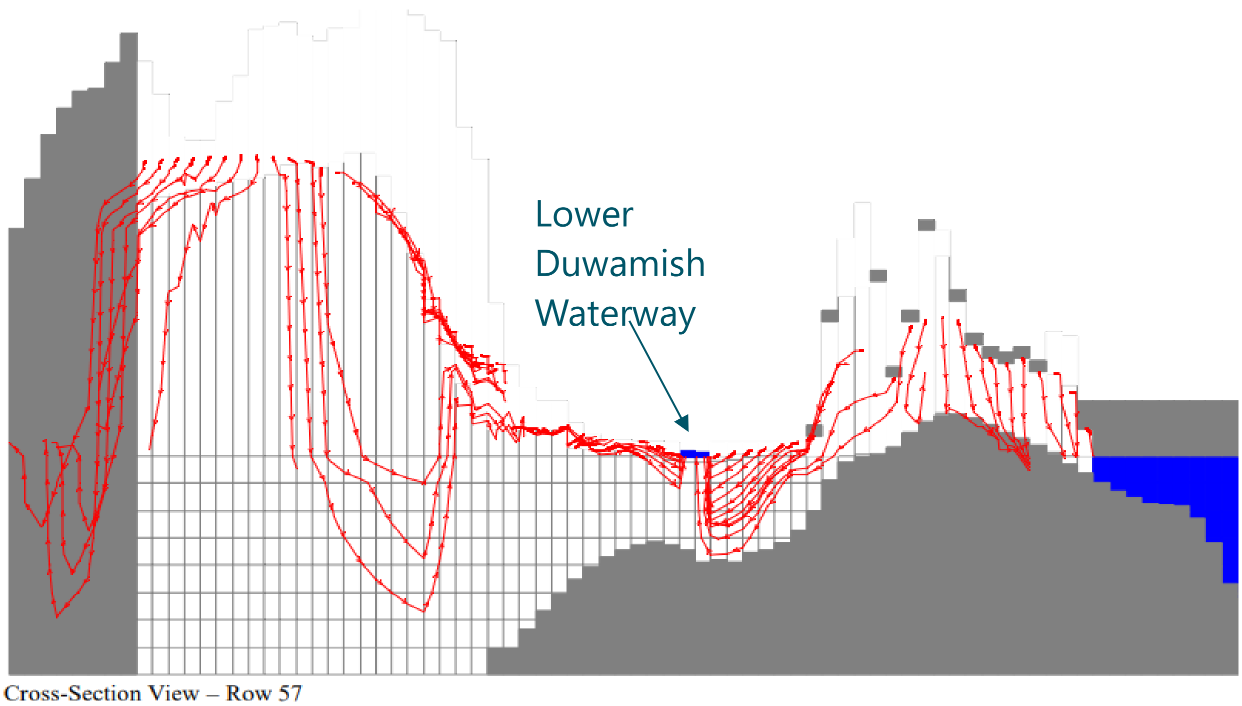
Notes:
Source: Fabritz et. al. (1998), Figure 11
The dashed lines, vertical blue lines, and yellow box were not part of original figure.
Dashed lines represent the three general discharge patterns observed in the river (based on change in slope). The yellow dashed line represents the consistent change in discharge over the portion of the river where the cap design area is located. The cap design area is represented by the yellow box. Seepage was calculated as the change in cumulative discharge between the two vertical blue lines (2.25 miles).

Within the portion of the waterway where the cap design area is located, discharge changes by 2 cubic feet per second (cfs) over 2.25 miles (11,880 feet), as illustrated by the yellow dotted line in Figure I3-1. The LDW is approximately 400-feet wide in this section. The Darcy flux can therefore be calculated as the change in discharge over a specified distance (2 cfs), divided by surface area, which equals the specified distance (11,880 feet) multiplied by the width of the river (400 feet). The resulting Darcy flux is approximately 400 centimeters per year (cm/yr).

This calculation assumes the flow to the river is distributed evenly across its width. Figure I3-2, which is adapted from Figure 8 of Fabritz et. al. (1998), shows a cross section view of the river near the cap design area, with model-predicted groundwater flow paths. Based on this figure, the majority of the flow is expected to discharge in the nearshore areas. Thus, the Darcy flux closer to the center of the channel could be closer to 100 cm/yr or less, whereas closer to shore within the cap design area, the

Darcy flux could be closer to 800 cm/yr (assuming the majority of flow discharges to half the area along shore). Because of the uncertainty and spatial variability associated with the estimated value of 400 cm/yr, the model simulations were conducted using values of 400 and 800 cm/yr in RAA 27 (SMA 5), which is located in the nearshore area, and 100 and 400 cm/yr in RAA 14/15/16 (SMA 12B), which are located in the federal navigation channel (FNC). Each of these values are considered equally valid in the absence of site-specific measurements.

Figure I3-2
Flow Paths to Lower Duwamish Waterway Predicted by MODFLOW Model



Note:
Source: Fabritz et. al. (1998), Figure 8

Darcy fluxes assumed in cap design evaluations in other portions of the LDW range from 56.8 to 590 cm/yr, as shown in Table I3-4, which are generally consistent with the range considered here.

Table I3-4
Seepage Rates Assumed for Modeling Conducted for Cap Design at Other Nearby Sites

Site	Assumed Seepage Rate (cm/yr)	Reference
EMJ Jorgensen	250	USACE 2016
Duwamish Diagonal	56.8	Anchor Environmental 2003
Slip 4 100% Design	312	Integral Consulting Inc. 2007
LDW FS	250 (106 – 590)	AECOM 2010

Notes:
cm/yr: centimeters per year
FS: feasibility study
LDW: Lower Duwamish Waterway

The water levels in the LDW are influenced by tidal fluctuations. At low tides, seepage rates could be greater than the daily average, and at high tides, seepage rates could be lower than the daily average. Extreme conditions, such as king tides, would result in even lower seepage rates compared to the long-term average.

Dissolved phase transport within the cap may be influenced by tidal fluctuations in the LDW, which can result in daily reversals in hydraulic gradient and advective flow. Representing such tidal mixing with a dispersion coefficient is a common approach in groundwater modeling (e.g., La Licata et al. 2011). Dispersivity values for flow in porous media over relatively short distances are typically in the range of 1% of the domain length (consistent with typical value used in cap modeling [Reible 2012]), whereas those associated with large-scale groundwater plumes are on the order of 10% (Gelhar et al. 1992; Neuman 1990).

The hydrodynamic dispersivity was set to a higher value of 20% of the cap thickness to represent hydraulic gradient variations and reversals from tidal fluctuations as a dispersion process. This dispersivity value (i.e., 20% of domain length) is consistent with values used in the final cap designs conducted at other tidally influenced sites, such as the Former Portland Gas Manufacturing Site (located on the Lower Willamette River just upstream of Portland Harbor, Oregon), where dispersivity was estimated based on the comparative strengths of tidal signals in hourly seepage meter measurements (Appendix C of Anchor QEA 2020), and Gloucester Harbor, Massachusetts, where dispersivity was derived from model calibrations to vertical profiles of salinity in porewater (Anchor QEA and GZA 2015; Reidy et al. 2015).

4 Model Results

Modeling was conducted to evaluate the effectiveness of four cap configurations in meeting the RALs that apply to sediment in the intertidal portion RAA 27 (SMA 5) and within Recovery Category 2 and RAA 14/15/16 (SMA 12B), which is mostly within Recovery Category 1. Model-predicted concentrations for the 100-year simulation period were compared to the RALs to evaluate the performance of the cap, including whether concentrations were predicted to exceed the RALs (and if so, when). Model results indicate that a 30-cm gravelly sand chemical isolation layer (with no amendment) is more than sufficient to maintain model-predicted total PCB concentrations less than the RALs for more than 100 years for each cap area under the two seepage rates evaluated. The chemical isolation layer configuration and model-predicted total PCB concentrations in the top 10 cm and top 45 cm of the cap are summarized in Table I4-1.

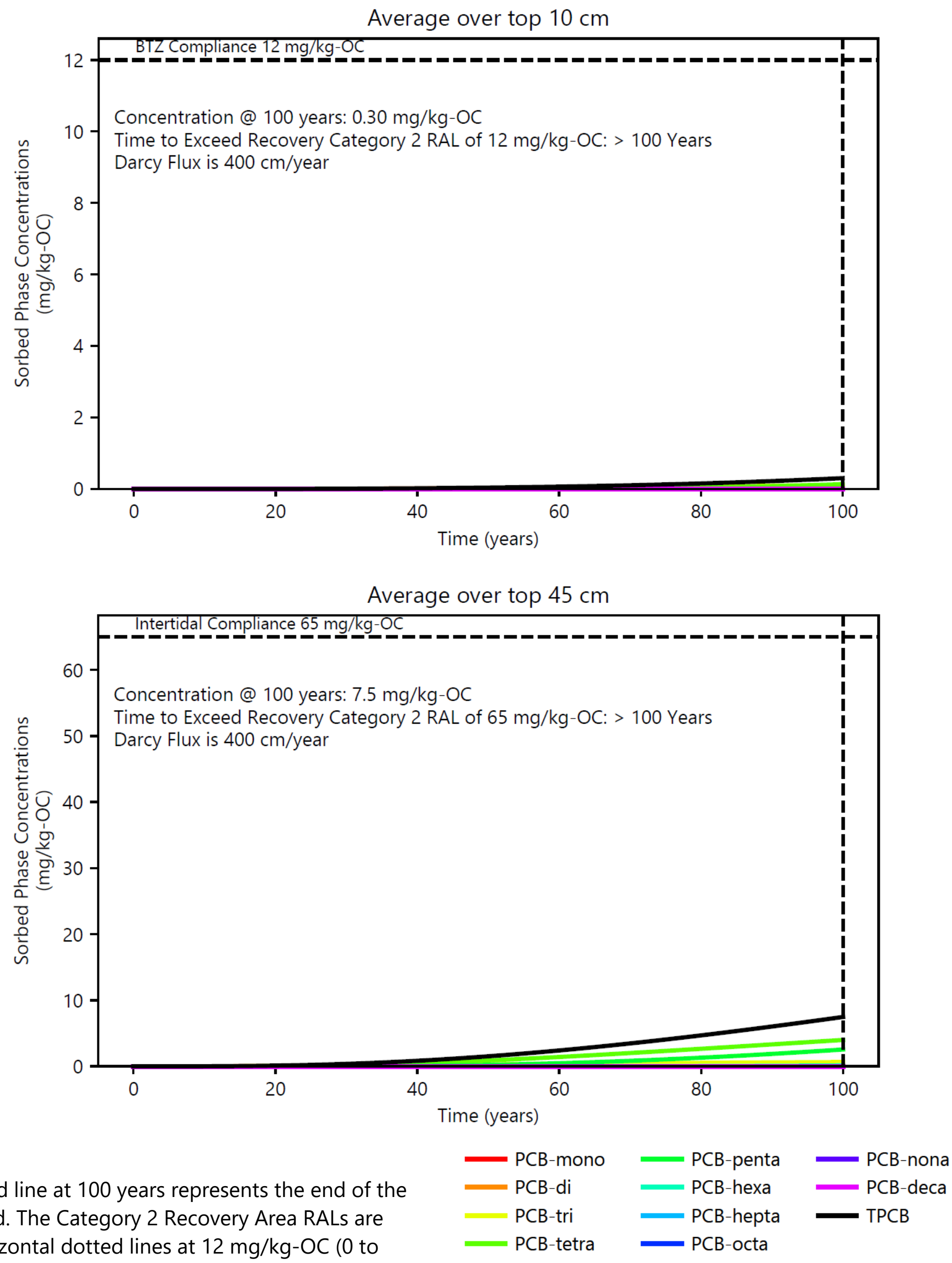
Table I4-1
Summary of Model Scenarios and Model Results

Area	Chemical Isolation Layer	Amendment	Seepage Rate (cm/yr)	Model-Predicted Total PCB Concentration at End of 100 Year Simulation (mg/kg-OC)[1]	
				Top 10 cm (RAL = 12 mg/kg-OC)	Top 45 cm (RAL = 65 mg/kg-OC)
RAA 27 (SMA 5)	30 cm gravelly sand	None	400	0.30	7.5
			800	2.4	24
RAA 14/15/16 (SMA 12B)	30 cm gravelly sand	None	100	0.0085	NA
			400	0.71	NA

Notes:
1. Results are shown to two significant figures.
cm: centimeter
cm/yr: centimeters per year
mg/kg: milligrams per kilogram
NA: not applicable
OC: organic carbon
PCB: polychlorinated biphenyl
RAA: remedial action area
RAL: remedial action level
SMA: sediment management area

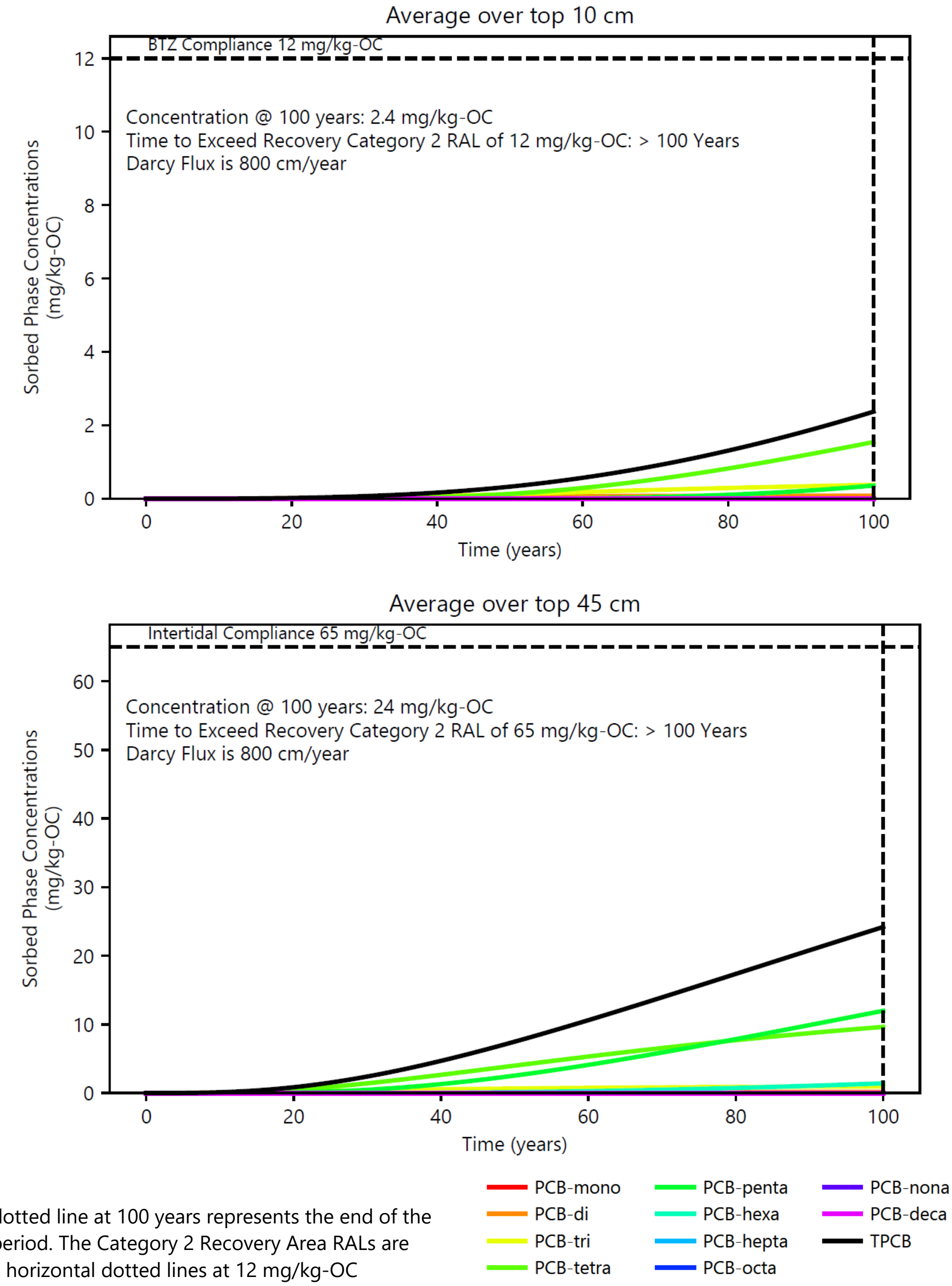
At the highest simulated seepage rate of 800 cm/yr, model-predicted total PCB concentrations within the top 10 cm and top 45 cm of the cap at RAA27 (SMA 5) at 100 years are factors of 5 and 2.7 times lower than the RALs, respectively. Model-predicted total PCB concentrations within the top 10 cm of the cap at RAA 14/15/16 (SMA 12B) at 100 years are a factor of 17 times lower than the RAL at the highest seepage rate of 400 cm/yr. Model-predicted concentrations for the 100-year simulation period are shown in Figures I4-1a, I4-1b, I4-2a, and I4-2b. These figures show the model-predicted PCB concentrations within the cap over time. In addition to total PCB, the individual homologs that contribute to the total PCB concentration are shown.

Figure I4-1a
Temporal Profile of PCBs Within the Surface of the RAA 27 (SMA 5) Cap (400 cm/yr Darcy Flux)



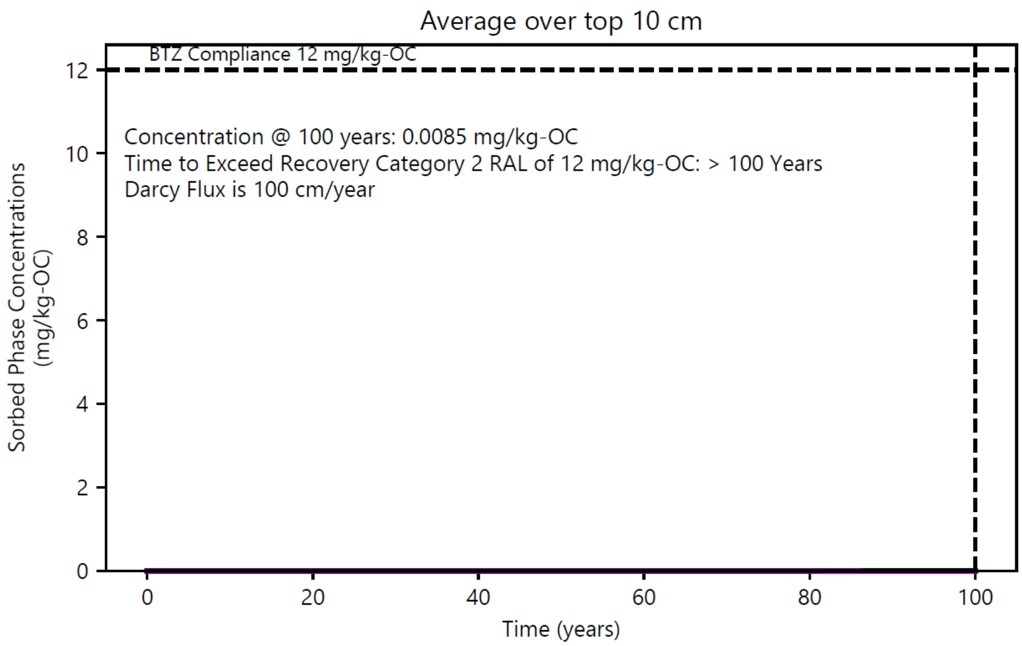
Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 2 Recovery Area RALs are shown as the horizontal dotted lines at 12 mg/kg-OC (0 to 10 cm) and 65 mg/kg-OC (0 to 45 cm)

Figure I4-1b
Temporal Profile of PCBs Within the Surface of the RAA 27 (SMA 5) Cap (800 cm/yr Darcy Flux)



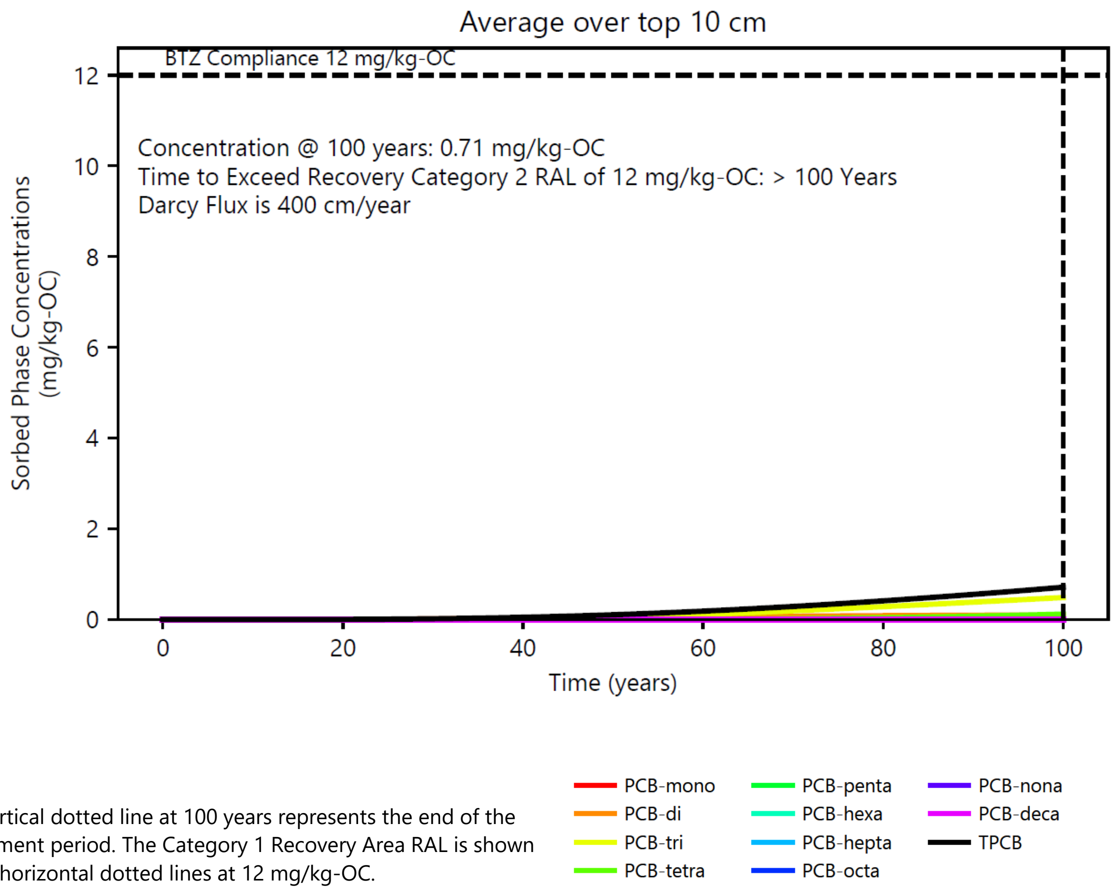
Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 2 Recovery Area RALs are shown as the horizontal dotted lines at 12 mg/kg-OC (bioturbation zone) and 65 mg/kg-OC (intertidal zone).

Figure I4-2a
Temporal Profile of PCBs Within the Surface of the RAA 14/15/16 (SMA 12B) Cap (100 cm/yr Darcy Flux)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 1 Recovery Area RAL is shown as the horizontal dotted lines at 12 mg/kg-OC.

Figure I4-2b
Temporal Profile of PCBs Within the Surface of the RAA 14/15/16 (SMA 12B) Cap (400 cm/yr Darcy Flux)

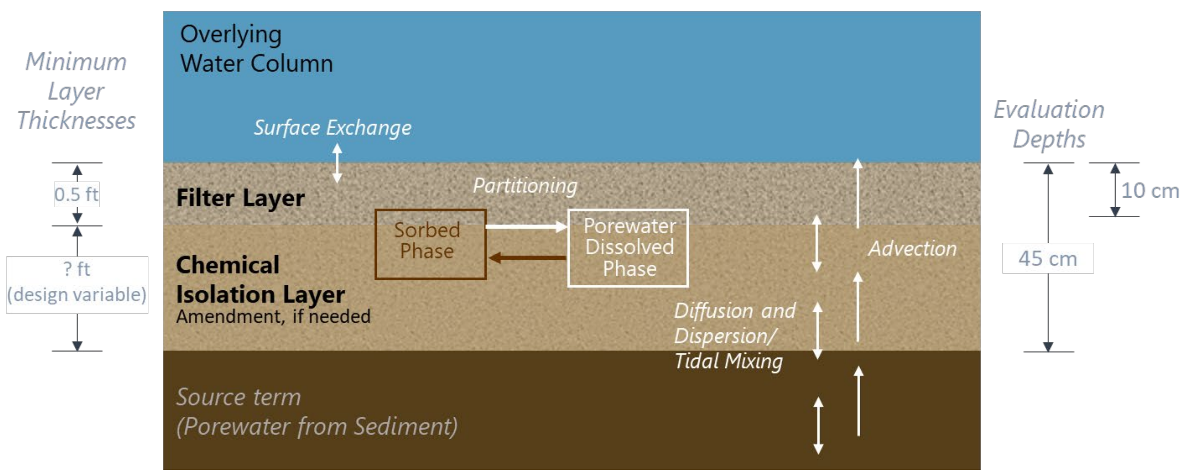


Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 1 Recovery Area RAL is shown as the horizontal dotted lines at 12 mg/kg-OC.

5 Sensitivity Analysis

The modeling described in the previous sections included the cobble and gravel armor stone within the model domain, based on the assumption that interstitial spaces would fill in over time in SMA 5 and SMA 12B depositional intertidal and subtidal areas. Upon cap placement, the armor stone will have large pore spaces that do not provide much attenuation. The SMA 5 cap will receive a thin layer of sand (habitat material) over the armor layer, which will fill in the interstitial spaces of the armor stone. In addition, based on visual observations of the existing riprap slope (at SMA 5) that has filled in with sands and silts, it is expected that within a few years, the interstitial spaces of the armor stone will fill in with depositing sediment. The interstitial spaces in SMA 12B will fill in at a shorter time frame than SMA 5 because SMA 12B is located within the subtidal area in the waterway and the top of the cap will be at a deeper elevation than surrounding areas. The time it takes to fill in, however, is uncertain; therefore, the model results discussed in Section 4, which were based on a cap configuration that assumed the interstitial spaces of the armor stone are filled in, may not be conservative and may overestimate the armor layer sorptive capacity. To evaluate this uncertainty, the modeling was repeated with the armor layer excluded from the model domain. Figure I5-1 shows a schematic of the cap model domain and the processes simulated for this sensitivity analysis.

Figure I5-1
Modeled Cap Configuration and Processes Modeled



Notes:
Consolidation of underlying sediments was not simulated; consolidation was assumed to be negligible due to dredging before material placement.
cm: centimeter

The model inputs used for this sensitivity analysis were consistent with those described in Section 3, with the following exceptions:

- The armor layer was excluded from the model domain.

- Bioturbation was not simulated.
- Surface exchange is expected to occur at the interface between the filter layer and interstitial space of the armor layer, therefore it was simulated at the top of the filter layer.

As with the modeling presented in Section 4, model-predicted concentrations over the 100-year sensitivity analysis simulation period were compared to the RALs to evaluate the performance of the cap, including whether concentrations were predicted to exceed the RALs (and if so, when). The chemical isolation layer configuration and model-predicted total PCB concentrations in the top 10 cm and top 45 cm of the cap from the sensitivity analysis are summarized in Table I5-1.

Table I5-1
Summary of Sensitivity Analysis Model Scenarios and Model Results

Area	Chemical Isolation Layer	Amendment	Seepage Rate (cm/yr)	Model-Predicted Total PCB Concentration (mg/kg-OC)[1]	
				Top 10 cm (RAL = 12 mg/kg-OC)	Top 45 cm (RAL = 65 mg/kg-OC)
RAA 27 (SMA 5)[2]	30 cm gravelly sand	None	400	11	63
			800	33 (exceeds RAL in 51 years)	90 (exceeds RAL in 53 years)
	45 cm gravelly sand	None	800	16 (exceeds RAL in 86 years)	54
	60 cm gravelly sand	None	800	7.6	18
RAA 14/15/16 (SMA 12B)	30 cm gravelly sand	None	100	0.69	NA
			400	9.2	NA

Notes:
1. Results are shown to two significant figures.
2. The SMA 5 cap design includes a thin layer sand cover over the armor layer, which will infill the armor interstitial spaces and is expected to remain over time. In addition to excluding the armor layer (and infill from sedimentation), the sensitivity analysis results for SMA 5 exclude the sand cover and represents a worst-case scenario.

cm: centimeter
cm/yr: centimeters per year
mg/kg: milligrams per kilogram
NA: not applicable
OC: organic carbon
PCB: polychlorinated biphenyl
RAA: remedial action area
RAL: remedial action level
SMA: sediment management area

Model results indicate that a 30-cm gravelly sand chemical isolation layer (with no amendment) is more than sufficient to maintain model-predicted total PCB concentrations less than the RAL for more than 100 years in RAA 14/15/16 (SMA 12B) under the two seepage rates evaluated. In RAA 27

(SMA 5), model results indicated that a 30-cm gravelly sand layer was sufficient to maintain model-predicted total PCB concentrations less than the RALs for more than 100 years at the seepage rate of 400 cm/yr. At the upper-end seepage rate of 800 cm/yr and a chemical isolation layer thickness of 30 cm, model results indicated that predicted total PCB concentrations exceeded the RAL in 51 years (Table I5-1). A 60-cm-thick chemical isolation layer was found to be needed to maintain total PCB concentrations less than the RALs for more than 100 years.

Due to visual evidence of sands and silts present on the steep bank face of SMA 5 embedded within the riprap armor layer and covering much of the riprap, it is expected that SMA 5 experiences deposition. As such, it is expected that there will be deposition of sediment in the intertidal portion of the SMA 5 cap. Although it is acknowledged that the armor layer will not fill in immediately from deposition after construction, the placement of habitat material on top of the armor stone in SMA 5 as part of construction will fill in the interstitial spaces of the armor stone. Results from the sensitivity analysis that excluded the armor layer from the model domain indicate that the model-predicted total PCB concentrations within the top 10 cm of the filter layer (i.e., under the armor layer) are predicted to exceed the surface RAL in 51 years. However, with the armor layer and the placement of sand habitat material that will fill in the armor interstitial spaces, attenuation is expected, and the surface RAL would not be exceeded within 100 years.

6 Summary

Chemical transport modeling was conducted to evaluate the performance of caps in RAA 14/15/16 (SMA 12B) and RAA 27 (SMA 5) to maintain concentrations less than the RAL for more than 100 years. Modeling indicates that a 1-foot gravelly sand chemical isolation layer within RAA 14/15/16 (SMA 12B) and RAA 27 (SMA 5) is predicted to meet the PCB RAL for more than 100 years. Some uncertainties in the modeling include the use of calculated porewater concentrations using sediment data and site-specific partition coefficients and seepage rates based on MODFLOW results with no quantification of spatial differences between nearshore and mid-channel seepage rates. Although these uncertainties exist, these simulations are still considered conservative. Examples of the conservative assumptions include the following:

- The cap thickness represented in the modeling is based on the thinnest cap thicknesses (though it could be as thick as 4 feet in some areas due to overplacement allowances).
- Maximum PCB concentrations within the cap area were assumed for the source term.
- Net sedimentation atop the armor layer, which would increase the thickness of the model domain, was ignored.

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