100% Remedial Design Basis of Design Report

Appendix K
Chemical Fate and Transport Modeling to Support Evaluations of Buried Contamination, ENR/AC Pilot, and Area-Specific Technology Locations

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TABLES

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ABBREVIATIONS

µg/L	micrograms per liter
AC	activated carbon
BODR	*Basis of Design Report*
cm	centimeter
cm/yr	centimeters per year
COC	contaminant of concern
Ecology	Washington State Department of Ecology
ENR	enhanced natural recovery
ENR/AC Pilot Study	pilot study to evaluate enhanced natural recovery amended with activated carbon
EPA	U.S. Environmental Protection Agency
FNC	federal navigation channel
f_{OC}	fraction organic carbon
g/cm^3	grams per cubic centimeter
GAC	granular activated carbon
K_{OC}	organic carbon partition coefficient
LDW	Lower Duwamish Waterway
MLLW	mean lower low water
mg/kg	milligrams per kilogram
N/A	not applicable
OC	organic carbon
PCB	polychlorinated biphenyl
RAA	remedial action area
RAL	remedial action level
RAO	remedial action objective
RD	remedial design
ROD	*Record of Decision*
TOC	total organic carbon

1 Introduction and Approach

This appendix describes chemical transport modeling conducted to support the contaminated sediment remedial design (RD) for the upper reach of the Lower Duwamish Waterway (LDW). The purpose of this modeling was to evaluate the transport potential of dissolved phase polychlorinated biphenyls (PCBs) in the following areas and circumstances:

- Areas of contamination buried beneath cleaner sediment that does not require remedial action (i.e., sediment with concentrations less than remedial action levels [RALs])
- Areas where a thin layer of sand/gravel or sand/gravel amended with activated carbon (AC) was placed over contaminated sediment as part of a pilot study to evaluate enhanced natural recovery amended with AC (referred to as the ENR/AC Pilot Study)
- Structural offset areas, where an area-specific technology in the form of a sandy gravel cover will be used

Section 2 of this appendix discusses the transport potential of dissolved phase PCBs in areas not requiring remedial action (i.e., areas without RAL exceedances) but where contamination is potentially buried beneath cleaner surface sediments adjacent to remedial action areas (RAAs). This evaluation addressed two specific sediment core locations, per U.S. Environmental Protection Agency (EPA) input, and two conservative representative locations where there is potential for buried contamination outside of the adjacent RAAs. This section also describes two sensitivity analyses that were conducted—the first to understand the impact of sedimentation and the second to identify the maximum theoretical buried contamination concentration that could exist without resulting in an exceedance of the RAL at the surface within 100 years.

Section 3 presents a similar evaluation of the ENR/AC Pilot Study area to assess the long-term effectiveness of a sand cover to attenuate contaminants and maintain concentrations at the surface within project remedial targets. The information presented in Sections 2 and 3 was presented to the EPA in a meeting on July 19, 2022.

Section 4 presents modeling that was conducted to evaluate whether a sandy gravel cover could address RAL exceedances at two locations adjacent to existing structures where dredging and enhanced natural recovery (ENR) technology cannot be used. Two locations adjacent to existing structures (RAA 24/25/26) have PCB concentrations that exceed the surface RAL ENR upper limit (three times the RAL). Dredging cannot occur at these locations due to their proximity to structures and risk of structural failure (area known as a dredge offset). Per the *Record of Decision* (ROD; EPA 2014), in areas with structural or access restrictions (e.g., under-pier areas and in the vicinity of dolphins or pilings, bulkheads, and riprapped or engineered shorelines), a location-specific cleanup technology can be applied. A sandy gravel cover was evaluated as an area-specific technology for these two locations in RAA 24/25/26, including the need for amendment.

The one-dimensional model of chemical transport within sediment caps, CapSim (version 3.8; Reible 2017),[1] was used for these evaluations. Although this model was initially developed to support design of sediment caps, it also can be used to simulate transport within uncapped sediments. 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 vertical column of sediment and cap material (if present). Details on the model structure and underlying theory and equations are provided in Lampert and Reible (2009), Go et al. (2009), the EPA/U.S. Army Corps of Engineers capping guidance (Appendix B of Palermo et al. 1998), and Shen et al. (2018).

[1] A newer version of CapSim is available; however, the functionality of the model used in these evaluations has not changed in the newer version.

2 Buried Contamination Evaluation

For the purposes of this evaluation, buried contamination is defined as sediment having contaminant of concern (COC) concentrations greater than the surface RAL that is buried beneath 60 centimeters (cm; 2 feet) or more of sediment with concentrations less than RALs in subtidal areas or that is buried beneath 45 cm (1.5 feet) or more of sediment with concentrations less than surface RALs in intertidal areas. Areas and COCs meeting this definition of buried contamination in the upper reach are limited to PCBs, with the lone exception of arsenic in RAA 18, which was deferred (see Section 6.1.3 of the BODR) and not included in the upper reach design. Therefore, this buried contamination evaluation focused on PCBs. The evaluation presented in this section assesses whether buried contamination is likely to migrate to the surface, resulting in exceedances of the RAL (a total PCB concentration of 12 milligrams per kilogram [mg/kg] organic carbon [OC]) within the surface sediment (0 to 10 cm). This evaluation did not assess physical processes that may result in exposure of the buried contamination (e.g., scour).[2] A number of factors can affect the transport of contaminants within subsurface and surface sediment and influence the resulting concentrations over time in the surface sediment (i.e., top 10 cm). Two key factors that affect the potential for buried contamination to recontaminate surface sediment over the long term due to chemical migration through the sediments are as follows:

1. The magnitude of the buried contaminant concentrations
2. The depth below the surface at which such concentrations are present

Higher PCB concentrations present in buried sediments have a greater potential to result in an increase in concentrations in the surface sediment over the long term due to upward transport (i.e., driven by groundwater seepage) as compared with lower PCB concentrations that are buried. Likewise, elevated PCB concentrations present closer to the surface have a greater potential to result in an increase in concentrations in the surface sediment as compared to those same concentrations buried more deeply.

Several core profiles and buried contamination scenarios were evaluated with the model. These core profiles are based on PCB concentrations in sediment within the federal navigation channel (FNC) that are considered conservatively high concentrations. The core profiles evaluated are as follows:

- Two specific core profiles having buried contamination of PCBs: LDW21-SC572 and LDW21-SC554 (Figure K2-1). Core LDW21-SC572 is located in RAA 14/15/16 (Figure 6-2c of the Final [100%] RD *Basis of Design Report* [BODR]) and Core LDW21-SC554 is located between RAA 4/5/6 and 12 (Figure 6-2b of the BODR). These two cores were selected because

[2] EPA's 2014 ROD anticipates that subsurface buried contamination will remain in some areas, subject to the specific criteria defined in the ROD (EPA 2014). EPA's determination was based on a variety of analyses in the Feasibility Study, including the potential for scour from river flows and vessels. Therefore, EPA's ROD already accounts for likely exposure of buried contamination from potential scour associated with physical processes.

they represented worst-case buried contamination core profiles as discussed with EPA. LDW21-SC572 had an elevated PCB concentration at a depth of 30 cm (when overlying shoal sediment depth is conservatively ignored; see footnote in Table K2-2), and LDW21-SC554 had the highest buried PCB concentration, observed at a depth greater than 4 feet. Values for PCB concentration, total organic carbon (TOC), dry bulk density, and porosity used in the model for these locations were based on the samples from each depth interval at each core location.

- Two generalized core profile scenarios were developed to be representative of potential buried contamination adjacent to the following: 1) RAA 1/2/3, as shown in Figure 6-2a of the BODR; and 2) RAA 14/15/16, as shown in Figure 6-2c of the BODR. The generalized core profiles for RAA 1/2/3 and RAA 14/15/16 are shown in Figures K2-2 and K2-3, respectively. These generalized core profiles were used to conservatively simulate buried contamination immediately beneath surface sediment that may be adjacent to those RAAs. They were configured to simulate 60 cm (2 feet) of sediment (below RAL concentrations) on top of the buried contamination as well as a worst-case thickness of 30 cm (1 foot; i.e., shorter distance) of surface sediment (below RAL concentrations) on top of the buried contamination (see panels on right side of Figures K2-2 and K2-3). The 30-cm thickness represents a hypothetical worst-case scenario in which some removal of the cleaner surface material may have occurred. This scenario is more conservative than the 60-cm thickness because it assumes the buried contamination is closer to the surface (i.e., shorter distance for contaminants to travel to the surface).

Concentrations associated with the layers of sediment for the generalized core profiles were based on shallow subsurface (0 to 60 cm) and deep subsurface (all depths beneath the shallow subsurface) sediment samples within and adjacent to the two groups of areas evaluated. Both maximum and average PCB concentrations from these local areas were evaluated to cover a range of conditions that may be observed in the generalized profiles. For the maximum scenario, the TOC, dry bulk density, and porosity associated with the sample that produced the maximum PCB concentration were used. For the average scenario, the TOC, dry bulk density, and porosity values were based on the average values from the samples that made up the average PCB concentration.

Figure K2-1
Sediment Profiles of Cores 572 and 554

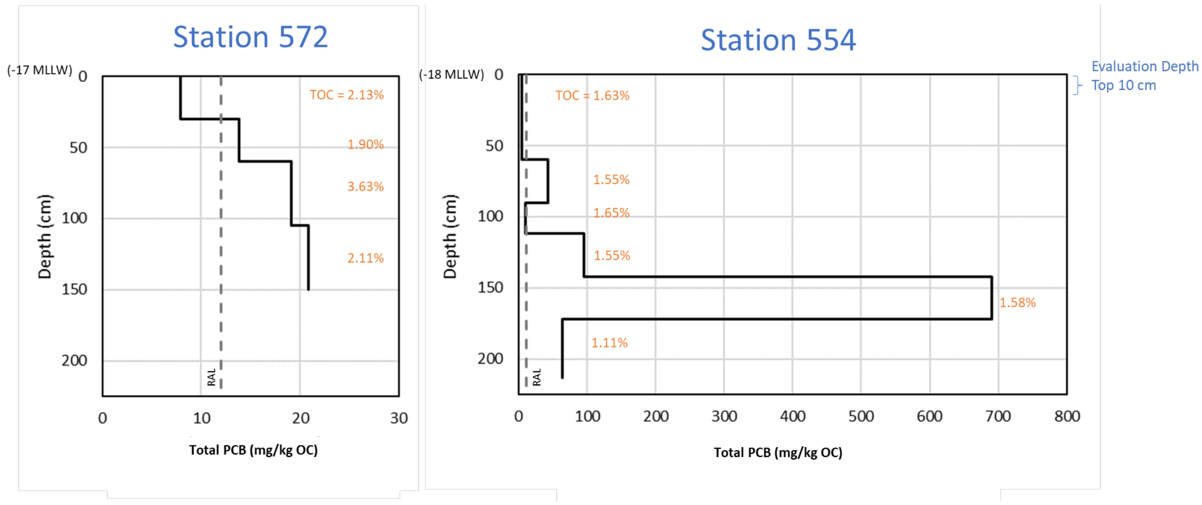


Figure K2-2
Generalized Core Profiles for RAA 1/2/3

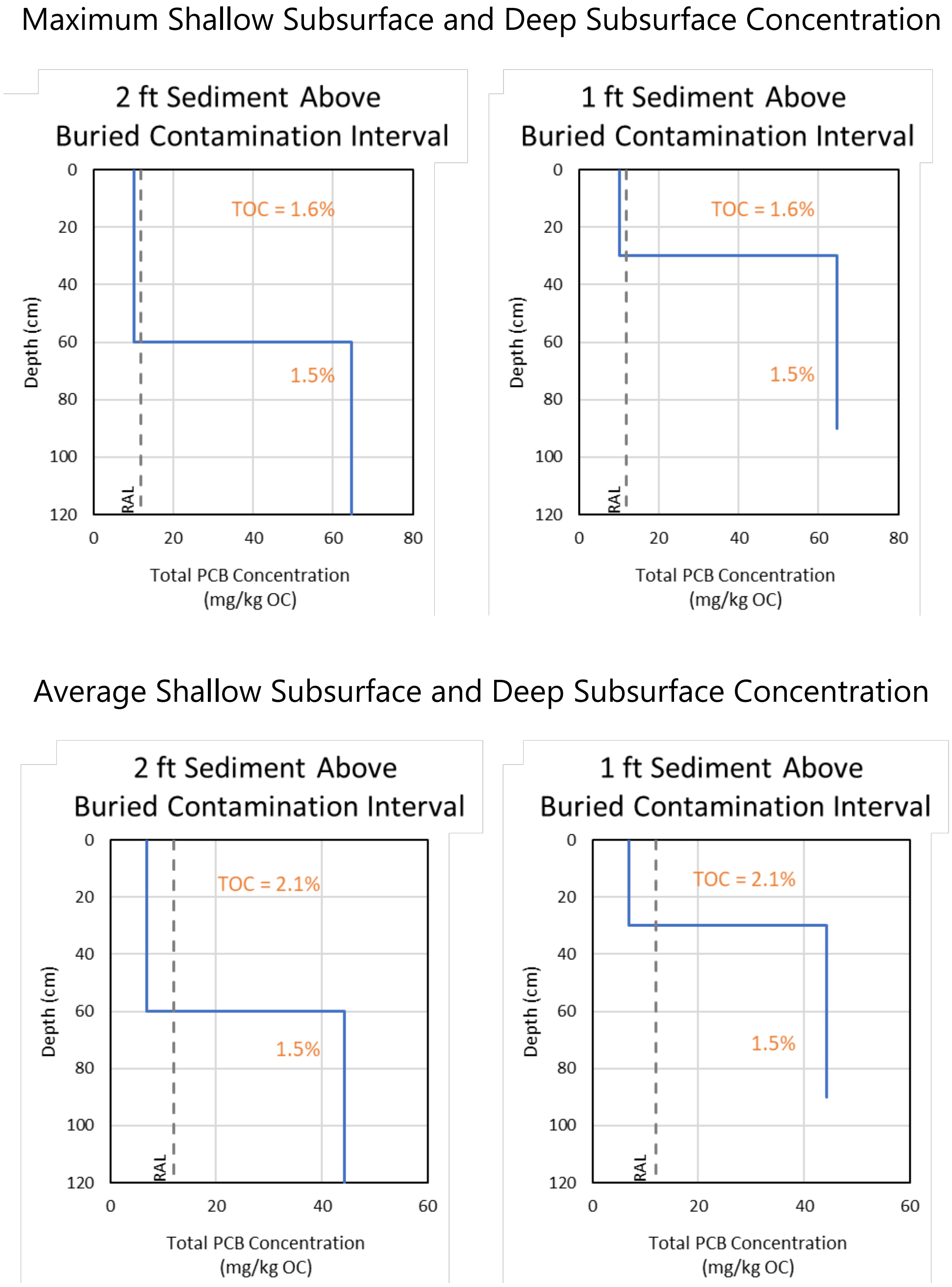
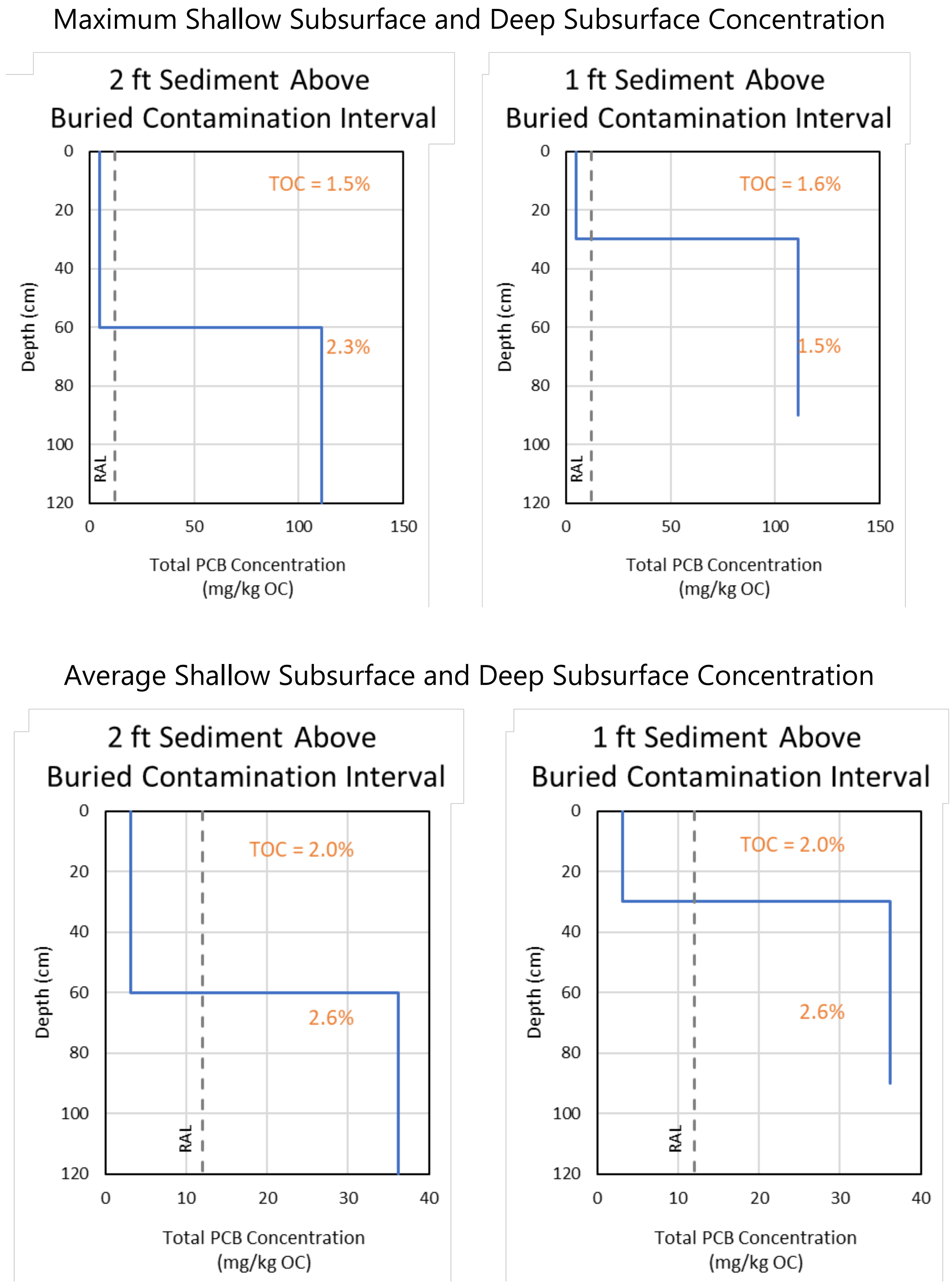


Figure K2-3
Generalized Core Profile for RAA 14/15/16



2.1 Buried Contamination Model Inputs

The model uses several input parameters that describe chemical-specific properties, sediment properties, and chemical mass transfer rates. Chemical-specific properties (e.g., molecular diffusivity and OC partition coefficients), bioturbation properties (depth and biodiffusion coefficients), reaction rates, and sedimentation (conservatively ignored), are consistent with the values used for the cap design modeling described in BODR Appendix I. As described in BODR Appendix I, the groundwater seepage rate (Darcy flux) in the upper reach is estimated to average 400 centimeters per year (cm/yr) and range from 100 cm/yr in the center of the channel up to 800 cm/yr nearshore. Because the areas being evaluated for buried contamination are located within the FNC and are not nearshore, this evaluation considered Darcy fluxes of 100 cm/yr and 400 cm/yr. A sensitivity analysis was conducted for the full range of groundwater seepage rates, including 800 cm/yr, to identify the maximum concentration that could exist in the LDW upper reach deep subsurface sediments before resulting in a RAL exceedance in surface (0 to 10 cm for intertidal and subtidal areas) and in the shallow subsurface (0 to 45 cm in the intertidal zone; Section 2.3.1).

A listing of model input parameters that differ from those reported in BODR Appendix I are provided in Table K2-1. These inputs describe the scenario-specific characteristics of the sediment simulated with the model and include initial PCB concentrations (converted to porewater concentrations by homolog group[3] based on partition coefficients, consistent with the cap design modeling), porosity, dry bulk density, and fraction organic carbon (f_{OC}). Initial total PCB sediment concentrations for the sediments evaluated with the model are also presented in Figures K2-1 through K2-3 and in Table K2-2.

[3] 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).

Table K2-1
Buried Contamination Modeling Input Parameter Values

Core Location	Depth Interval (cm)	PCB Homolog Porewater Concentration (µg/L)										Porosity	Dry Bulk Density (g/cm³)	f_{OC}
		Mono	Di	Tri	Tetra	Penta	Hexa	Hepta	Octa	Nona	Deca			
LDW21-SC554	0 to 60	6.5E-06	7.5E-05	4.6E-04	7.2E-04	5.7E-04	2.8E-04	8.0E-05	8.0E-06	4.6E-07	1.9E-08	0.66	0.90	0.016
	60 to 90	4.8E-05	3.1E-04	1.4E-03	2.3E-03	3.1E-03	3.0E-03	1.1E-03	1.2E-04	6.9E-06	2.8E-07	0.63	0.95	0.016
	90 to 112	1.4E-05	1.7E-04	1.1E-03	1.7E-03	1.2E-03	5.5E-04	1.5E-04	1.5E-05	8.4E-07	3.4E-08	0.65	0.92	0.017
	112 to 142	1.8E-04	3.0E-03	2.2E-02	2.7E-02	1.1E-02	2.5E-03	4.0E-04	3.5E-05	2.0E-06	8.4E-08	0.59	1.07	0.016
	142 to 172	7.6E-04	5.3E-03	2.5E-02	4.3E-02	5.3E-02	4.8E-02	1.7E-02	1.8E-03	1.0E-04	4.3E-06	0.59	1.06	0.016
	172 to 213	1.0E-04	1.6E-03	1.1E-02	1.5E-02	7.3E-03	2.2E-03	4.5E-04	4.3E-05	2.5E-06	1.0E-07	0.54	1.19	0.011
LDW21-SC572	0 to 30	9.5E-06	1.0E-04	6.2E-04	9.8E-04	8.2E-04	4.4E-04	1.3E-04	1.3E-05	7.7E-07	3.1E-08	0.67	0.86	0.021
	30 to 60	1.8E-05	2.4E-04	1.5E-03	2.3E-03	1.6E-03	6.5E-04	1.6E-04	1.6E-05	9.0E-07	3.6E-08	0.64	0.94	0.019
	60 to 105	3.0E-05	4.5E-04	3.1E-03	4.1E-03	2.2E-03	7.1E-04	1.5E-04	1.4E-05	8.0E-07	3.3E-08	0.56	1.14	0.036
	105 150	2.8E-05	3.9E-04	2.5E-03	3.7E-03	2.4E-03	9.3E-04	2.2E-04	2.2E-05	1.2E-06	5.0E-08	0.58	1.09	0.021
RAA 1/2/3 (maximum)	Surface[1]	1.2E-05	1.2E-04	7.0E-04	1.1E-03	9.1E-04	6.2E-04	2.1E-04	2.1E-05	1.2E-06	5.0E-08	0.67	0.85	0.016
	Subsurface[2]	7.7E-05	1.0E-03	6.6E-03	1.1E-02	8.5E-03	2.9E-03	5.9E-04	5.5E-05	3.2E-06	1.3E-07	0.65	0.92	0.015
RAA 1/2/3 (average)	Surface[1]	8.9E-06	1.0E-04	6.2E-04	9.3E-04	7.0E-04	3.8E-04	1.1E-04	1.1E-05	6.7E-07	2.7E-08	0.67	0.86	0.021
	Subsurface[2]	5.4E-05	6.7E-04	4.2E-03	6.6E-03	5.2E-03	2.2E-03	5.6E-04	5.5E-05	3.2E-06	1.3E-07	0.61	1.01	0.015
RAA 14/15/16 (maximum)	Surface[1]	7.0E-06	9.2E-05	6.1E-04	8.3E-04	4.9E-04	2.2E-04	6.2E-05	6.2E-06	3.6E-07	1.5E-08	0.60	1.03	0.015
	Subsurface[2]	1.7E-04	2.5E-03	1.7E-02	2.4E-02	1.4E-02	4.1E-03	7.3E-04	6.6E-05	3.8E-06	1.5E-07	0.66	0.893	0.023
RAA 14/15/16 (average)	Surface[1]	4.7E-06	6.4E-05	4.3E-04	5.8E-04	3.4E-04	1.4E-04	3.8E-05	3.8E-06	2.2E-07	8.9E-09	0.60	1.05	0.020
	Subsurface[2]	5.3E-05	7.8E-04	5.3E-03	7.4E-03	4.3E-03	1.4E-03	2.9E-04	2.7E-05	1.6E-06	6.4E-08	0.63	0.96	0.026

Notes:

1. Generalized core profiles were configured to simulate the surface as 2 feet of cleaner sediment on top of the buried contamination (i.e., depth interval of 0 to 60 cm) as well as 1 foot of cleaner surface sediment (i.e., 0 to 30 cm).
2. The generalized core profiles were configured to have 60 cm of sediment beneath the surface. For the case where the surface represents the 2 feet of cleaner material, the subsurface interval is 60 to 120 cm. For the case where the surface represents the 1 foot of cleaner material, the subsurface interval is 30 to 90 cm.

µg/L: micrograms per liter
cm: centimeter
f_{OC}: fraction organic carbon
g/cm³: grams per cubic centimeter
PCB: polychlorinated biphenyl
RAA: remedial action area

2.2 Buried Contamination Model Results

The purpose of this buried contamination modeling was to evaluate whether buried contamination has the potential to recontaminate surface sediments (0 to 10 cm) in the FNC to a concentration greater than the RAL in the future (i.e., over a 100-year simulation) through dissolved phase transport driven by groundwater seepage (as well as diffusion/dispersion and bioturbation). Conservatively, sedimentation was ignored in this evaluation, despite the fact that sedimentation in the FNC is ongoing, necessitating periodic maintenance dredging. Model-predicted concentrations in the top 10 cm (surface) of the sediment were compared to the surface (0 to 10 cm) RAL to evaluate whether buried contamination could result in RAL exceedances in the surface sediment within 100 years. PCB homologs were modeled separately to account for differences in transport properties and summed to calculate total PCB concentrations for comparison to the total PCB RAL of 12 mg/kg OC. Model-predicted total PCB concentrations in the top 10 cm of the sediment are shown in Table K2-2 for both Darcy flux values evaluated.

Table K2-2
Buried Contamination Model Results: Model-Predicted Concentrations in Top 10 cm of Sediment at Year 100

Area	Scenario		Properties			Model-Predicted Surface Sediment (top 10 cm) Total PCB Concentration at Year 100 (mg/kg OC)	
	PCB Concentration Statistic Modeled	Surface Layer Thickness (feet)	Model Layer	Depth from Mudline (feet)	Initial Total PCB Concentration (mg/kg OC)	100 cm/yr Darcy Flux	400 cm/yr Darcy Flux
Specific Core Profiles							
Core 554	A (-18 to -20 feet MLLW)	2	1	0–2	5.28	3.5	3.7
	B (-20 to -21 feet MLLW)		2	2–3	42.8		
	C (-21 to -22 feet MLLW)		3	3–3.7	11.0		
	D (-22 to -23 feet MLLW)		4	3.7–4.7	95.5		
	E (-23 to -24 feet MLLW)		5	4.7–5.7	690		
	F (-24 to -25 feet MLLW)		6	5.6–7	63.7		
Core 572*	C (-17 to -18 feet MLLW)	2	1	3.6–4.6	7.93	5.7	6.0
	D (-18 to -19 feet MLLW)		2	4.6–5.6	13.8		
	E (-19 to -20 feet MLLW)		3	5.6–6.6	19.2		
	G (-21 to -22 feet MLLW)		4	7.5–8.5	20.9		

Area	Scenario		Properties			Model-Predicted Surface Sediment (top 10 cm) Total PCB Concentration at Year 100 (mg/kg OC)	
	PCB Concentration Statistic Modeled	Surface Layer Thickness (feet)	Model Layer	Depth from Mudline (feet)	Initial Total PCB Concentration (mg/kg OC)	100 cm/yr Darcy Flux	400 cm/yr Darcy Flux
Generalized Core Profiles							
RAA 1/2/3	Maximum	2	1	0–2	10.2	7.0	7.3
			2	2–4	64.6		
	Maximum	1	1	0–1	10.2	6.9	7.6
			2	1–3	64.6		
	Average	2	1	0–2	6.97	4.9	5.1
			2	2–4	44.2		
	Average	1	1	0–1	6.97	4.9	5.2
			2	1–3	44.2		
RAA 14/15/16	Maximum	2	1	0–2	4.75	3.1	3.3
			2	2–4	111		
	Maximum	1	1	0–1	4.75	3.1	4.0
			2	1–3	111		
	Average	2	1	0–2	3.18	2.2	2.3
			2	2–4	36.2		
	Average	1	1	0–1	3.18	2.2	2.4
			2	1–3	36.2		

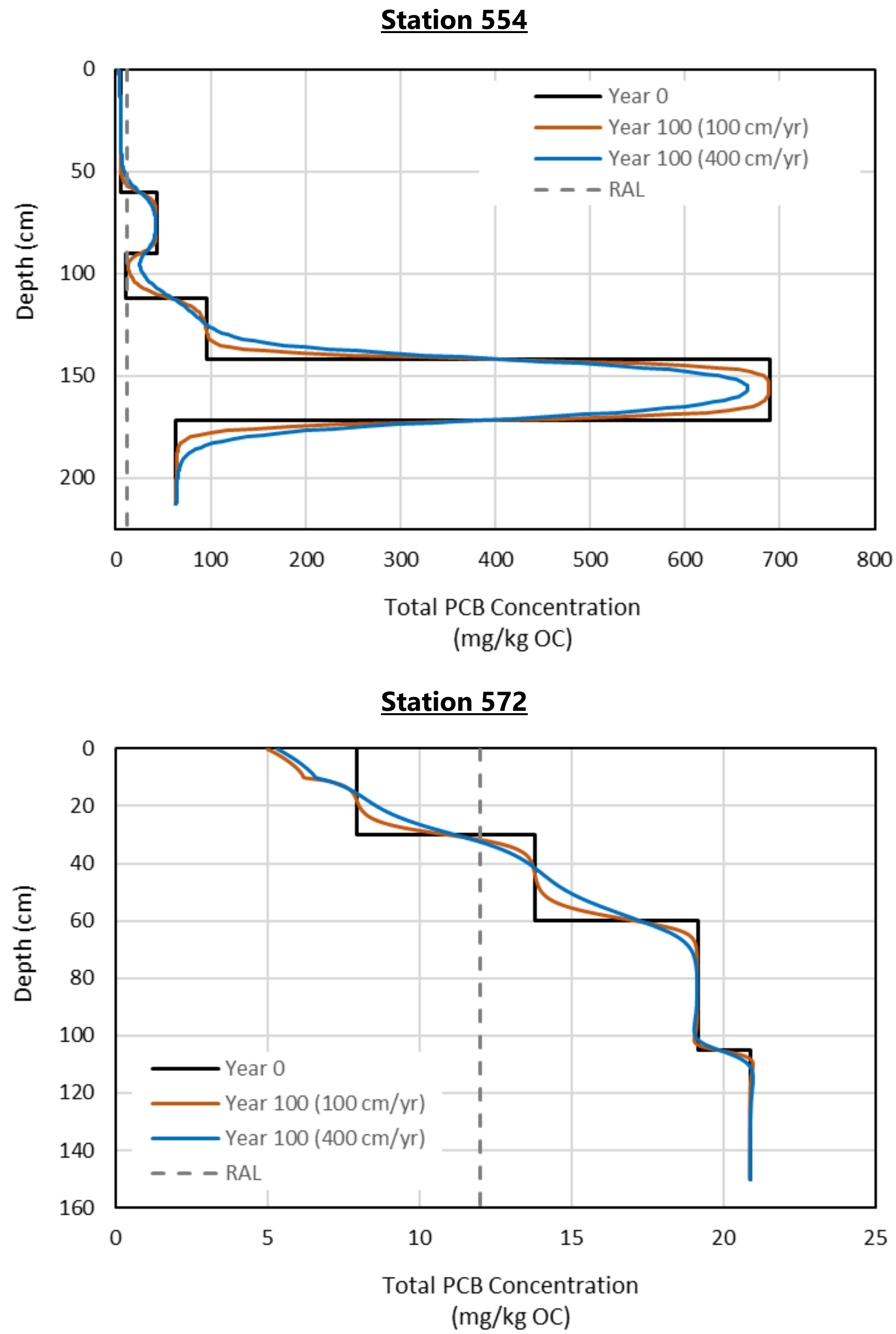
Notes:
Core 572 is within a shoal area and is a location within the FNC where the bed elevation is higher than the authorized navigation depth, Intervals A and B are shoal intervals and include sediment from elevation -13.4 to -17 MLLW; these shoal intervals did not exceed PCB RAL of 12 mg/kg OC.

cm: centimeter
cm/yr: centimeters per year
mg/kg: milligrams per kilogram
MLLW: mean lower low water
OC: organic carbon
PCB: polychlorinated biphenyl
RAA: remedial action area
RAL: remedial action level
.

Model results in Table K2-2 show that PCB concentrations in the top 10 cm of the sediment are predicted to remain less than the surface RAL of 12 mg/kg OC for more than 100 years in all scenarios. Because buried contamination beneath 30 or 60 cm of sediment that is less than the surface RAL results in concentrations in the top 0 to 10 cm that remain below the surface RAL, these results also indicate that a 45-cm shallow subsurface layer that is less than the RALs would also result in the surface (top 10 cm) remaining below the surface RAL of 12 mg/kg OC for more than 100 years at groundwater seepage rates of 100 and 400 cm/yr. Because PCBs partition relatively strongly to sediments, they do not migrate quickly through the sediments in dissolved phase; therefore, contamination that is buried beneath cleaner sediment remains buried.

An example of this predicted lack of migration is shown for Core 554 in Figure K2-4. The black line represents the initial concentrations in sediment (Year 0). The orange and blue lines represent the concentrations predicted at Year 100 for the Darcy fluxes of 100 and 400 cm/yr, respectively. Although the PCBs are predicted to migrate upward to a very slight extent, the transport is not significant enough to impact the surface sediments. The model also predicts some smoothing of vertical concentrations gradients due to the processes of diffusion and dispersion.

Figure K2-4
Depth Profiles at Stations 554 and 572 at Year 0 and Year 100



As shown in Figure K2-4, PCB concentrations at the bottom of the two cores are greater than the surface RAL (i.e., depth of contamination is unbounded). Uncharacterized PCB concentrations below the core depth are not likely to impact concentrations at the surface within a 100-year time frame. As shown by the model-predicted PCB concentrations at 100 years presented in Figure K2-4 for both seepage rates evaluated, even at depths of 140 cm from the surface, it is predicted that the PCBs will not have migrated to the surface within this time frame. In addition, the sensitivity analysis described in Section 2.3.1 identifies the maximum PCB concentrations that could theoretically exist at a depth of 1 to 2 feet below the surface and still not result in an exceedance of the RAL at the surface. Those theoretical maximum concentrations are within the range, or greater than, the concentrations observed at Stations 554 and 572 but modeled to be closer to the surface (i.e., less travel distance). Thus, elevated PCB concentrations at depths greater than characterized by these cores are expected to remain buried long term.

2.3 Sensitivity Analyses

In addition to evaluating a range of concentrations and a range of Darcy fluxes, two additional sensitivity analyses were conducted. The first sensitivity analysis was conducted to predict the maximum PCB concentration that could exist beneath the shallow subsurface in the FNC before resulting in a RAL exceedance in the surface (0 to 10 cm) sediment. The second sensitivity analysis evaluated the impact of sedimentation on the model results. These two sensitivity analyses are discussed in the following subsections.

2.3.1 Hypothetical Maximum Subsurface Concentration

Additional modeling was conducted to identify the maximum concentration that could exist in the LDW upper reach deep subsurface sediments before resulting in a RAL exceedance in surface (0 to 10 cm for intertidal and subtidal areas) and in the shallow subsurface (0 to 45 cm in the intertidal). Starting with the generalized core profiles from RAA 1/2/3, and assuming the maximum concentration in the shallow subsurface (10.2 mg/kg OC), the deep subsurface concentration represented in the model was increased iteratively until the total PCB concentration predicted in the surface sediment (top 10 cm) was just below the PCB RAL of 12 mg/kg OC and, in the intertidal area, a PCB RAL of 65 mg/kg OC in the shallow subsurface (0 to 45 cm). Generalized core profiles, assuming 2 feet (60 cm), 1.5 feet (45 cm), and 1 foot (30 cm) of sediment (below RAL concentrations) on top of the buried contamination, were evaluated. Darcy fluxes of 100 and 400 cm/yr were assumed in the subtidal areas, and Darcy fluxes of 400 and 800 cm/yr were assumed in the intertidal areas.

EPA's Estimation Programs Interface Suite for Microsoft Windows indicates a wide range of solubility limits for PCB Aroclor mixtures, although it could be as high as 100 micrograms per liter (µg/L) for the Aroclors detected in site sediments. The current maximum subsurface porewater total PCB concentration from the generalized core profiles evaluated (Area 1, 2, and 3 maximum) is 0.03 µg/L; 100 µg/L is just over 3,000 times the current maximum subsurface total PCB concentration from the generalized core profile). Thus, modeling did not consider total PCB porewater concentrations greater than 100 µg/L, which corresponds to a dry weight concentration of almost 3,000 mg/kg.

Consistent with the modeling discussed in Sections 2.1 and 2.2, sedimentation was ignored. Through this modeling, it was determined that, in the subtidal areas, PCB concentrations beneath the surface could be as high as 3,000 times the current maximum subsurface total PCB concentration from the generalized core profiles when assuming a 100 cm/yr Darcy flux and 2-foot thickness of sediment (not exceeding RALs) on top of the buried contamination. This concentration is close to solubility limits for PCB Aroclors (i.e., theoretical maximum dissolved phase concentration). The maximum concentration that could be present in buried contamination was predicted to be 10 times greater than the current concentration when assuming a Darcy flux of 400 cm/yr and only 1 foot of cleaner sediment on top of the buried contamination, which is considered a worst-case scenario. In the intertidal area, the maximum PCB concentration that could be present in buried contamination was predicted to be 130 mg/kg OC assuming 1 foot of cleaner sediment on top of the buried contamination or 452 mg/kg OC assuming 1.5 feet of cleaner sediment on top of the buried contamination. The results are shown in Table K2-3.

Table K2-3
Results of Hypothetical Maximum Subsurface Concentration Sensitivity Analysis

Sediment Thickness Above Buried Contamination Interval[1]	Averaging Depth (cm)	Subsurface Sediment Total PCB Concentration (mg/kg OC)		
		100 cm/yr Darcy Flux[2]	400 cm/yr Darcy Flux	800 cm/yr Darcy Flux[3]
Subtidal Zone				
2 feet	0–10	>193,800 mg/kg OC (> 3,000X Area 1, 2, 3 Maximum Porewater)	>25,800 mg/kg OC (>400X Area 1, 2, 3 Maximum Porewater)	N/A
1 foot	0–10	>38,800 mg/kg OC (>600X Area 1, 2, 3 Maximum Porewater)	>650 mg/kg OC (>10X Area 1, 2, 3 Maximum Porewater)	N/A
Intertidal				
1.5 feet	0–10	N/A	>5,430 mg/kg OC (>84X Area 1, 2, 3 Maximum Porewater)	>711 mg/kg OC (>11X Area 1, 2, 3 Maximum Porewater)
1.5 feet	0–45	N/A	>711 mg/kg OC (>11X Area 1, 2, 3 Maximum Porewater)	>452 mg/kg OC (>7X Area 1, 2, 3 Maximum Porewater)
1 foot	0–10	N/A	>650 mg/kg OC (>10X Area 1, 2, 3 Maximum Porewater)	>194 mg/kg OC (>3X Area 1, 2, 3 Maximum Porewater)
1 foot	0–45	N/A	>130 mg/kg OC (>2X Area 1, 2, 3 Maximum Porewater)	>130 mg/kg OC (>2X Area 1, 2, 3 Maximum Porewater)

Notes:
Value in parenthesis is factor above maximum subsurface sediment concentration from RAA 1/2/3.

1. 2-foot thickness represents sediment above buried contamination in the subtidal zone. 1.5-foot thickness represents sediment above buried contamination in the intertidal zone. 1-foot thickness represents a hypothetical worst-case scenario, in which some removal of the cleaner surface material may have occurred.
2. 100 cm/yr Darcy flux not relevant to the intertidal areas.
3. 800 cm/yr Darcy flux not relevant to the subtidal areas.

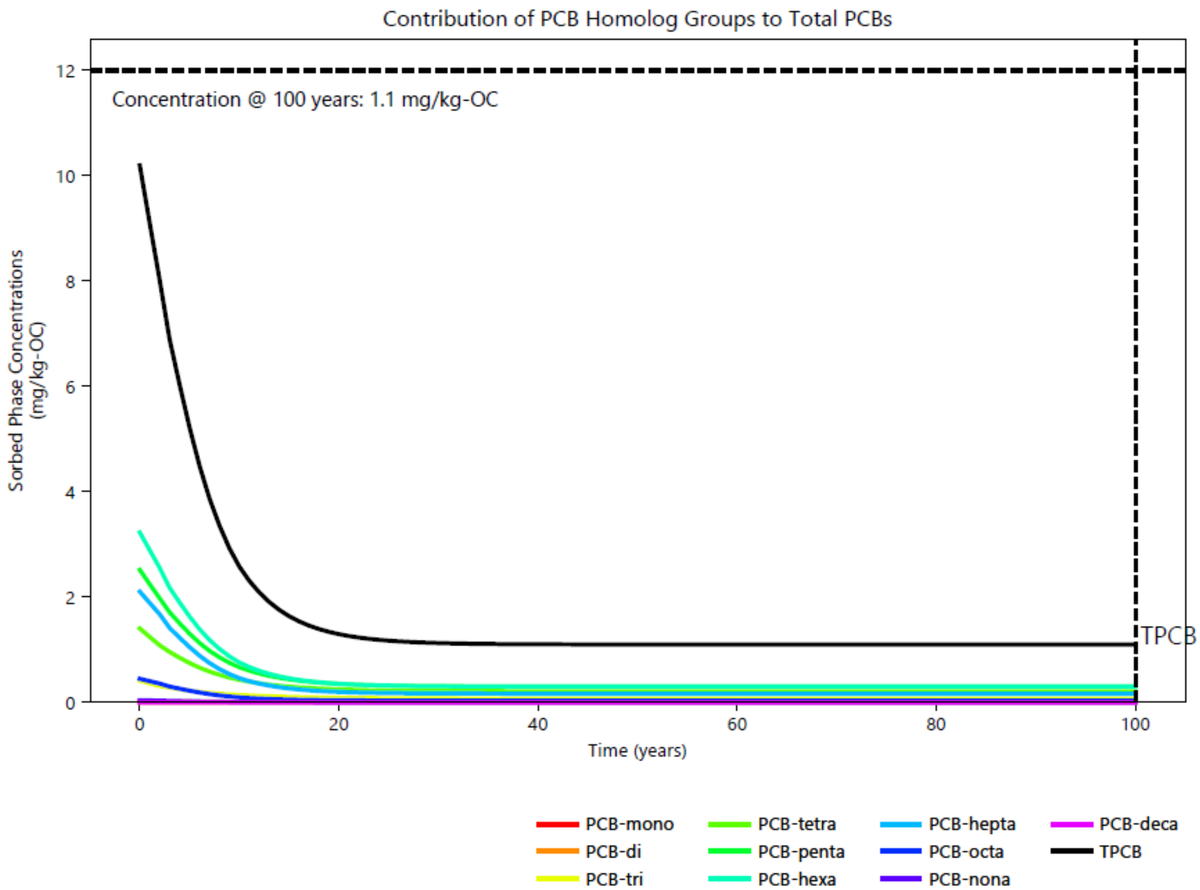
cm: centimeter
cm/year: centimeters per year
mg/kg: milligrams per kilogram
N/A: not applicable
OC: organic carbon
PCB: polychlorinated biphenyl
RAA: remedial action area

2.3.2 Sedimentation Sensitivity Analysis

The modeling discussed in Sections 2.1 and 2.2 ignored the effects of future net sedimentation. Although no net sedimentation was assumed, based on feasibility study evaluations (AECOM 2012), it is expected that sedimentation will occur in the future. In addition, it is known that sedimentation occurs in the LDW upper reach. Therefore, a sensitivity analysis was conducted to evaluate the effects of sedimentation on the model results. Starting with the generalized core profile for RAA 1/2/3, using the maximum concentration in the surface and subsurface and a Darcy flux of 400 cm/yr, the modeling was repeated, with the inclusion of net sedimentation. Sedimentation rates in intertidal and subtidal areas were estimated to range from 0.2 to greater than 2 cm/yr (AECOM 2012). Sedimentation rates in the FNC exceed 2 cm/yr (AECOM 2012). For this evaluation, a sedimentation rate of 1 cm/yr was assumed. The total PCB concentration of the depositing sediment was assumed to be 1.1 mg/kg OC for this sensitivity analysis. This is consistent with the incoming PCB concentrations measured upstream in the Green River (e.g., 20 micrograms per kilogram PCB and 1.8% TOC; Windward 2020).

Model results for this sensitivity analysis are shown in Figure K2-5. Model-predicted concentrations within the top 10 cm of the sediment decrease for approximately 20 years, until reaching a steady-state concentration of 1.1 mg/kg OC (i.e., the value specified for the depositing sediment). These results show that the exclusion of sedimentation from the base case modeling is conservative and that even a low amount of sedimentation would produce a situation in which the surface sediment concentrations are controlled by the concentrations of the depositing sediment and that upward transport from buried contamination would be negligible. If total PCB concentrations depositing on sediments in this area end up being greater than 1.1. mg/kg due to potentially uncontrolled PCB sources, then the surface sediments would equilibrate to those higher concentrations. This is an important consideration for setting expectations during long-term monitoring.

Figure K2-5
Temporal Profile of Model-Predicted PCB Concentrations Within the Top 10 cm of Sediment, Assuming Sedimentation



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The RAL is shown as the horizontal dotted line at 12 mg/kg OC.
The Darcy flux is 400 cm/year.

3 ENR/AC Pilot Area Evaluation

ENR consists of the placement of a thin cover layer of clean sand or sand/gravel atop contaminated sediment to accelerate natural recovery processes. ENR immediately provides a new surface substrate of clean sediments and reduces contaminant concentrations in surface sediments more quickly than would happen by natural sedimentation processes alone. Under order amendment with EPA and the Washington State Department of Ecology (Ecology), LDWG performed a pilot study (ENR/AC Pilot Study) to assess whether ENR material amended with AC was more effective than ENR alone in reducing the bioavailability of PCBs in contaminated sediments of the LDW. Pilot study construction occurred in late 2016 through early 2017, and monitoring of three pilot study plots continued through 2020.

Results from 3 years of monitoring indicate that the application of ENR material alone resulted in decreases in baseline PCB bioavailability of approximately 90% or more in many cases (Wood et al. 2021). The study did not show measurable differences between ENR and ENR amended with AC, except for minor differences in intertidal plot. EPA and Ecology concluded there is no clear benefit in adding AC to ENR material in the LDW. Therefore, AC amendment was not included in ENR as part of the Final (100%) RD. Although the 3-year monitoring results are favorable, PCB concentrations in sediments beneath the placed ENR layer are greater than the upper limit for ENR in some samples of the intertidal plot. Therefore, contaminant transport modeling was conducted to evaluate the long-term effectiveness of the ENR layer in the ENR/AC Pilot area to maintain PCB concentrations in the surface sediments (top 10 cm) at levels less than the surface PCB RAL of 12 mg/kg OC.

3.1 ENR Model Inputs

The model was configured to simulate the placed cover material, which was, on average, 30 cm of sand/gravel overlying the surface sediment.

Chemical-specific properties (e.g., molecular diffusivity and OC partition coefficients), bioturbation properties (depth and biodiffusion coefficients), and reactions used in the ENR modeling were consistent with the values used for the buried contamination evaluations discussed in Section 2 and the cap modeling described in BODR Appendix I. As described in BODR Appendix I, the Darcy flux in the upper reach is estimated to average 400 cm/yr and range from 100 cm/yr in the center of the channel up to 800 cm/yr nearshore. The pilot study areas are located in different energy conditions and water depths, so the full range of Darcy fluxes (100 cm/yr to 800 cm/yr) was considered for these evaluations.

Human health remedial action objectives (RAOs) are applied on an area-wide basis; therefore, the average PCB concentration in sediments beneath the cover material in the sand/gravel only pilot plots (41.9 mg/kg OC) was used to represent the source of PCBs to the surface sediments in the modeling. Benthic RAOs are applied on a point-by-point basis; therefore, the maximum concentration (107 mg/kg OC, nearly 9 times the surface RAL) was also evaluated to demonstrate the effectiveness of ENR in this location, even though some sediment samples in the original surface concentrations exceeded the ROD ENR upper limit of 3 times the RAL. Pre-placement surface sediment concentrations within the pilot study areas and concentrations in the sediment immediately beneath the ENR cover material that were measured post-placement were used for this evaluation. The sediment PCB concentrations, f_{OC}, and site-specific partition coefficients were used to estimate the porewater concentrations beneath the ENR layer (i.e., source term to the model), consistent with the cap design modeling presented in BODR Appendix I. A listing of PCB homolog concentrations used for model inputs is provided in Table K3-1.

Table K3-1
Porewater Concentrations Representing the Source Term for ENR Modeling

Chemical Name	Concentration of Porewater Beneath Cover (µg/L)	
	Average	Maximum
PCB-Mono	1.2E-04	4.8E-05
PCB-Di	1.6E-03	5.4E-04
PCB-Tri	9.8E-03	2.5E-03
PCB-Tetra	1.7E-02	5.4E-03
PCB-Penta	1.5E-02	5.9E-03
PCB-Hexa	5.0E-03	2.2E-03
PCB-Hepta	9.8E-04	4.3E-04
PCB-Octa	9.0E-05	3.9E-05
PCB-Nona	5.1E-06	2.2E-06
PCB-Deca	2.1E-07	8.9E-08

Notes:
µg/L: micrograms per liter
ENR: enhanced natural recovery
PCB: polychlorinated biphenyl

3.2 ENR Model Results

Model-predicted PCB concentrations within the surface of the ENR Layer (0 to 10 cm) throughout the 100-year simulations were compared to the total PCB surface RAL (12 mg/kg OC). Model results indicate that PCB concentrations in the surface of the ENR layer are predicted to remain less than the RAL for more than 100 years for both the average and maximum concentrations measured beneath the ENR pilot area plot (both subplots) and for each of the three Darcy flux values simulated

(Table K3-2). Thus, the use of ENR in the ENR/AC pilot plot will be protective even for concentrations that exceed the ROD ENR upper limit.

Table K3-2
ENR Model Results: Model-Predicted Concentrations in Top 10 cm of ENR Layer Within ENR/AC Pilot Study Intertidal Plot at Year 100

Scenario	Measured PCB Concentrations in Sediment Beneath ENR Layer (mg/kg OC)	Model-Predicted PCB Concentration in the Top 10 cm of the ENR Layer at Year 100 (mg/kg OC)		
		100 cm/yr Darcy Flux	400 cm/yr Darcy Flux	800 cm/yr Darcy Flux
Average	41.9	0.07	1.3	3.7
Maximum	107	0.25	4.0	11

Notes:
cm: centimeter
cm/yr: centimeters per year
ENR: enhanced natural recovery
mg/kg: milligrams per kilogram
OC: organic carbon
PCB: polychlorinated biphenyl

For the sensitivity analysis scenario that used the upper-bound seepage rate of 800 cm/yr combined with the maximum measured PCB concentration beneath the ENR layer, model-predicted concentrations at 100 years approach the RAL of 12 mg/kg OC. As such, these results suggest that seepage rates greater than 800 cm/yr could potentially result in an exceedance of the RAL in less than 100 years; however, this would be offset by deposition from natural recovery in these areas. The results of this evaluation ignore the impacts of future sedimentation. As described in Section 2.3.2, sedimentation, even at a modestly low rate, can have a large impact on the future surface sediment concentrations. Therefore, the results of this evaluation are conservative and represent a worst-case scenario. In addition, the ENR/AC Pilot Study intertidal plot area will be included in the long-term monitoring plan for the site.

4 Area-Specific Technology Evaluation of Cover in Dredge Offset Areas

At sample locations IT627 and SS646 (RAA 24/25/26), which are within dredge offset areas, an area-specific technology in the form of a sandy gravel cover will be applied to address PCB RAL exceedances.

Chemical fate and transport modeling was conducted to evaluate the composition (thickness and amendment needs, if any) of a cover to maintain PCB concentrations less than the surface PCB RAL of 12 mg/kg OC for more than 100 years at each of these two locations. The model was configured to simulate a 15-cm-thick sandy gravel cover overlying the surface sediment, which is considered a minimum cover thickness that would be applied. The simulations were conducted in an iterative manner, increasing the thickness of the cover, and adding a sorptive amendment represented in the model by TOC, as necessary, to meet the RAL long term. When simulating the addition of amendments to the cover, the amendment was assumed to be present throughout the full thickness of the cover (i.e., carbon-based amendment blended with the sandy gravel).

4.1 Cover Model Inputs

Chemical-specific properties (e.g., molecular diffusivity and OC partition coefficients), bioturbation properties (depth and biodiffusion coefficients), and reactions used in the modeling of the sandy gravel cover were consistent with the values used for the cap modeling described in BODR Appendix I. Location-specific values were developed for porewater concentrations in the sediments beneath the cover (discussed in the next paragraph), and the porosity and bulk density of the cover material, which were assumed to be 0.35 and 1.69 grams per cubic centimeter (g/cm^3), respectively, based on typical geotechnical characteristics of a sandy gravel cover. As described in BODR Appendix I, the Darcy flux in the upper reach is estimated to average 400 cm/yr and range from 100 cm/yr in the center of the channel to 800 cm/yr nearshore. Locations IT627 and SS646 are located closer to shore, so Darcy fluxes of 400 cm/yr and 800 cm/yr were used for these evaluations.

The surface sediment concentrations measured in these areas were used to represent the source of PCBs to the cover. The sediment PCB concentrations, f_{OC}, and site-specific partition coefficients were used to estimate the porewater concentrations beneath the cover (i.e., source term to the model), consistent with the cap design modeling presented in BODR Appendix I. A listing of the PCB homolog porewater concentrations is provided in Table K4-1.

Table K4-1
Porewater Concentrations Representing the Source Term to the Cover in Dredge Offset Areas

Chemical Name	Concentration of Porewater Beneath Cover (µg/L)	
	Location IT627	Location SS646
PCB-Mono	1.1E-04	1.4E-04
PCB-Di	1.0E-03	1.1E-03
PCB-Tri	3.0E-03	3.0E-03
PCB-Tetra	2.0E-02	1.9E-02
PCB-Penta	3.2E-02	3.2E-02
PCB-Hexa	1.1E-02	1.3E-02
PCB-Hepta	1.6E-03	2.6E-03
PCB-Octa	1.3E-04	2.4E-04
PCB-Nona	7.3E-06	1.4E-05
PCB-Deca	2.8E-07	5.4E-07

Notes:
µg/L: micrograms per liter
PCB: polychlorinated biphenyl

4.2 Cover Model Results

Model-predicted PCB concentrations within the surface of the cover (0 to 10 cm) were compared to the total PCB surface RAL (12 mg/kg OC) throughout the 100-year simulations. Table K4-2 shows the range of cover configurations (thickness and amendment content) and the time before the surface sediment PCB RAL of 12 mg/kg OC is predicted to be exceeded for each configuration. Model results indicate that at both locations, a 12-inch cover with 1% TOC or a 6-inch cover with 1.5% TOC would be sufficient to maintain the PCB concentration in the surface of the cover at values less than the 12 mg/kg OC RAL for more than 100 years for both Darcy flux scenarios.

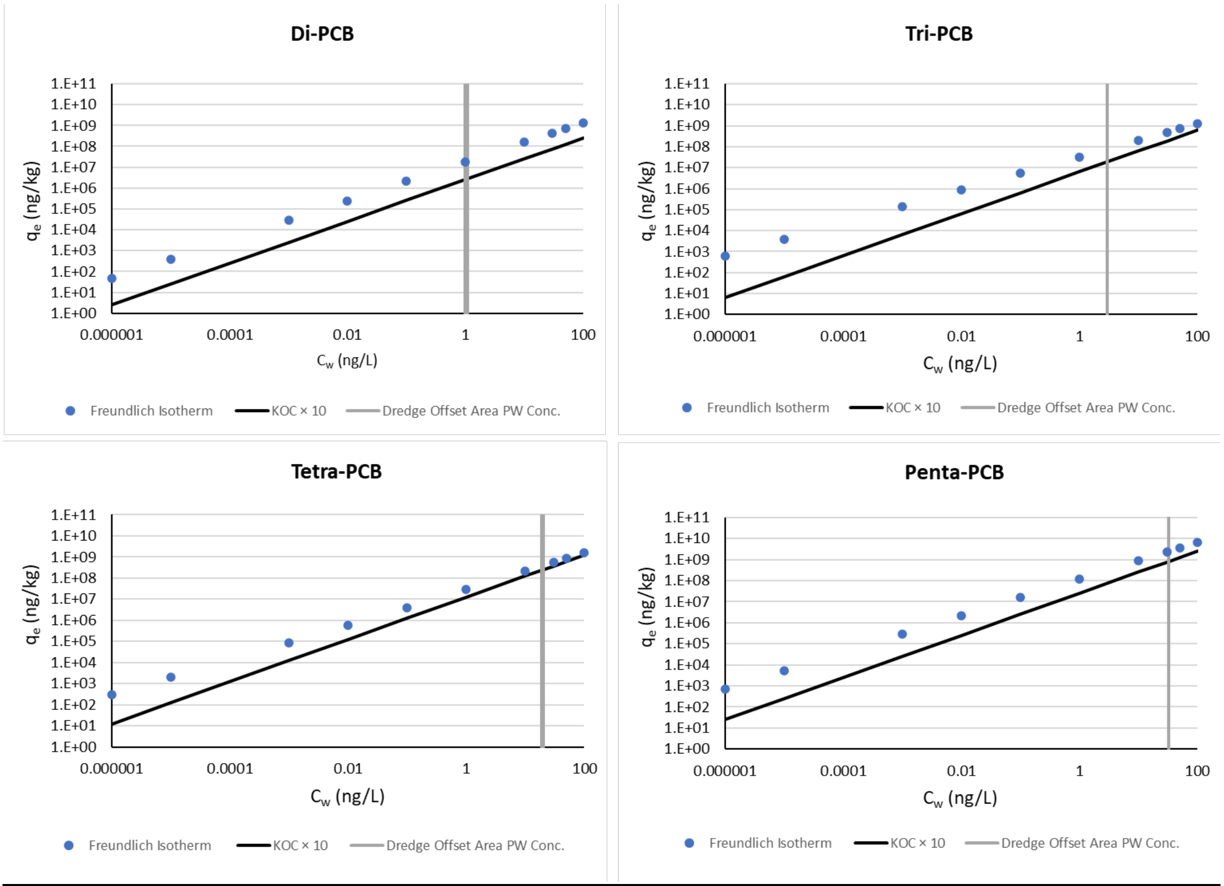
Table K4-2
ENR Model Results: Model-Predicted Concentrations in Top 10 cm of Cover Material at Year 100

Scenario	Measured PCB Concentrations in Sediment Beneath Cover (mg/kg OC)	Thickness of Cover (cm)	Amendment	Predicted Time to Exceed Surface PCB RAL of 12 mg/kg OC (years)	
				400 cm/yr Darcy Flux	800 cm/yr Darcy Flux
IT627	191	15	None	87	41
		15	1% TOC	>100	95
		15	1.5% TOC	>100	>100
		30	None	>100	94
		30	1% TOC	>100	>100
SS646	214	15	None	84	40
		15	1% TOC	>100	95
		15	1.5% TOC	>100	>100
		30	None	>100	94
		30	1% TOC	>100	>100

Notes:
cm: centimeter
cm/yr: centimeters per year
mg/kg: milligrams per kilogram
OC: organic carbon
PCB: polychlorinated biphenyl
RAL: remedial action level
TOC: total organic carbon

Amendments such as granular activated carbon (GAC) could be added to the cover material to achieve the equivalent of 1% to 1.5% TOC within the cover. GAC has been shown to be at least 10 times more sorptive than other forms of TOC for PCBs (McDonough et al. 2008; Arp et al. 2009; Hale et al. 2010). Studies have also shown that sorption of PCBs to GAC can often be a nonlinear process described by a Freundlich isotherm (Reible and Lampert 2014). However, as a reasonable simplification, the evaluation described herein was based on the linear isotherm parameter for TOC (i.e., organic carbon partition coefficient [K_{OC}]) multiplied by a scale factor of 10 based on the literature findings. This simplification is also conservative. For example, the linear isotherm, represented by $K_{OC} \times 10$, is compared to the Freundlich isotherm parameters for PCBs sorbed to dissolved organic matter-loaded AC presented by McDonough et al. (2008). As shown in Figure K4-1, at a given dissolved phase PCB concentration, the loading of PCBs to AC using the McDonough et al. (2008) Freundlich isotherm (blue dots) is greater than that calculated based on the $K_{OC} \times 10$ linear isotherm (presented by the black line), particularly for the concentration range measured in the offset areas (shown by the vertical gray line).

Figure K4-1
Comparison of Freundlich Isotherm and Linear Isotherm



Notes:
Freundlich isotherm from McDonough et al. 2008
K_{OC} x 10 uses K_{OC} values from BODR Appendix I, Table I3-2

In addition, literature studies of nonlinear PCB sorption to GAC appear to be primarily conducted for a small number of individual PCB congeners, whereas the evaluations conducted to evaluate a cover in the dredge offset areas were conducted on a homolog basis to capture the range in mobility for the full spectrum of PCB congeners at the site. Thus, the linear isotherm (i.e., K_{OC} × 10 approach) was used to estimate the GAC dose required to meet the RALs. Although modeling indicates that 0.1% to 0.15% by weight GAC would be sufficient to meet the RALs for more than 100 years (Table K4-2), a conservative minimum dose of 1% GAC by weight is recommended to ensure even distribution of GAC throughout the cover; this will provide greater sorptive capacity than the required 1% to 1.5% TOC (0.1% to 0.15% GAC). In addition, the construction specifications (100% RD Volume III) will require 2% GAC by weight as an additional conservative measure during construction to account for any loss of GAC during placement. The results of this evaluation also ignore the impacts of future sedimentation. As described in Section 2.3.2, sedimentation, even at a modestly low rate, can have a large impact on the future surface sediment concentrations. Therefore, the results of this evaluation are conservative.

5 Conclusions

Evaluations were conducted to evaluate transport potential of dissolved phase PCBs in areas of contamination buried beneath cleaner sediment, areas where thin layer of sand/gravel were placed over contaminated sediment as part of the ENR/AC Pilot Study, and dredge offset areas, where an area-specific technology in the form of a sandy gravel cover will be used. The results showed that for each of these scenarios, model-predicted PCB concentrations within the surface of the sediment or cover (0 to 10 cm) are expected to remain less than the surface RAL for more than 100 years.

The results of these evaluations ignore the impacts of future sedimentation. As described in Section 2.3.2, sedimentation, even at a modestly low rate, can have a large impact on the future surface sediment concentrations. Therefore, the results of this evaluation are conservative and represent a worst-case scenario. Further, should long-term monitoring results show areas with higher PCB concentrations within the surface, it should be considered that the elevated PCB concentrations may be due to sediments depositing on the sediments/cover material due to uncontrolled PCB sources rather than from chemical transport from subsurface layers.

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