Appendix G
Engineered Cap Chemical Isolation Design Analysis

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ABBREVIATIONS

95% UCL	95% upper confidence limit of the mean
µg/L	micrograms per liter
BODR	*Basis of Design Report*
Boeing	The Boeing Company
cfs	cubic feet per second
CIL	chemical isolation layer
cm	centimeter
cm/hr	centimeters per hour
cm/yr	centimeters per year
cm^2/s	square centimeters per second
$cm^2/year$	square centimeters per year
COC	contaminant of concern
EPA	U.S. Environmental Protection Agency
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
OC	organic carbon
PAH	polycyclic aromatic hydrocarbons
PCB	polychlorinated biphenyl
RAA	remedial action area
RAL	remedial action level
RD	remedial design
RI	remedial investigation
RM	river mile
ROD	*Record of Decision*
TOC	total organic carbon
USACE	U.S. Army Corps of Engineers
ZVI	zero valent iron

1 Introduction

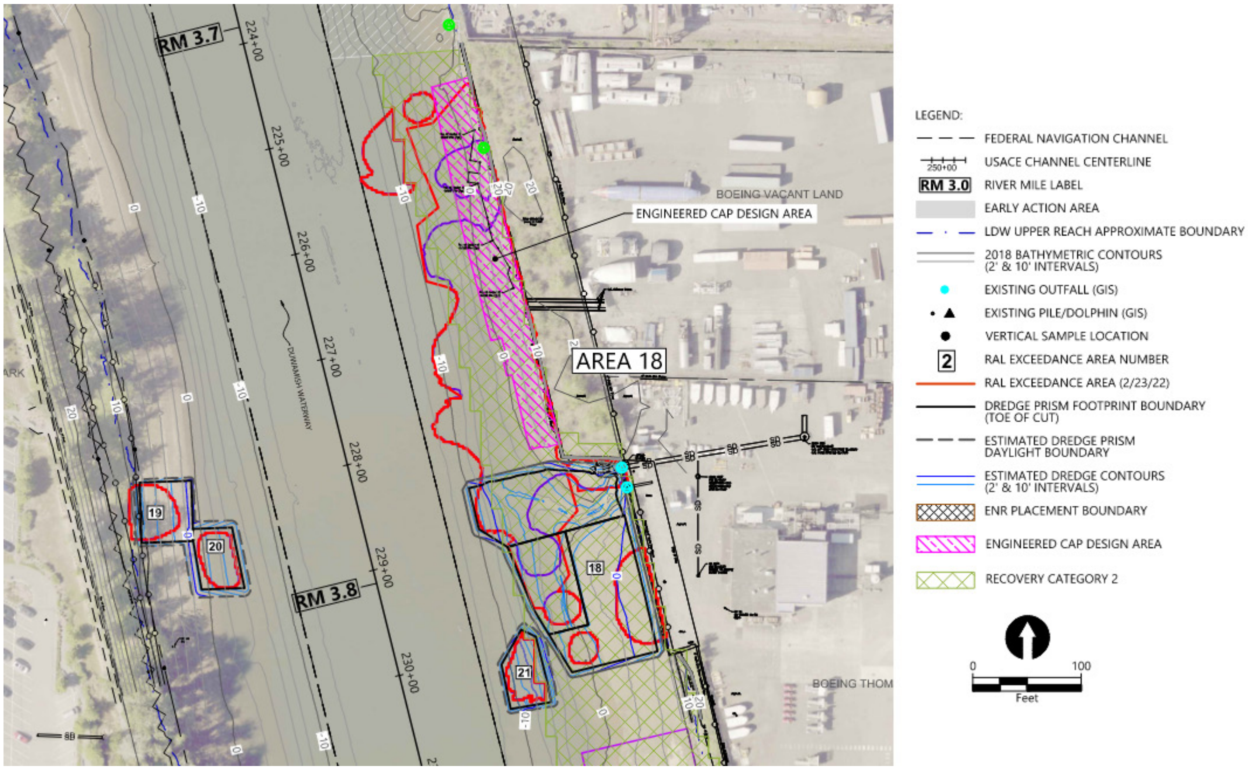
The engineered capping option for the northern portion of Remedial Action Area (RAA) 18 was not carried forward for the Intermediate (60%) Remedial Design (RD) as discussed in Section 6.1.3 of the Intermediate (60%) Remedial Design *Basis of Design Report* (BODR). However, chemical transport modeling to address potential engineered capping at RAA 18 was retained, and this analysis is presented in this appendix as representative of intertidal areas with similar range of groundwater and contaminant conditions for polychlorinated biphenyls (PCBs) and arsenic and within a Recovery Category 2 area. This evaluation is discussed in Section 2. As discussed in Section 2.2 of the BODR, Intermediate (60%) RD identified that the sediment cleanup remedy at RAA 27 (Container Properties; river mile [RM] 4.1E) extends up the adjacent bank. Chemistry data underneath the bank debris and armoring materials 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 would not be confirmed until post-excavation sampling is conducted per the Construction Quality Assurance Plan. Because there is uncertainty regarding whether sediment underneath the bank debris and armor material at RAA 27 is contaminated, the conservative remedial technology of engineered capping will be applied to the bank portion of this RAA. The RAA 27 capping evaluation is discussed in Section 3.

2 Example Cap Evaluation

The example cap area (RAA 18) is located between RMs 3.7 and RM 3.8, between the federal navigation channel and an existing deteriorated bulkhead along the eastern bank of the Lower Duwamish Waterway (LDW) adjacent to the Boeing Isaacson Thompson Model Toxics Control Act Site and Port of Seattle sliver property (see Figure G-1).

The modeling was conducted to evaluate a sediment cap to address elevated concentrations of PCBs and arsenic 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 (EPA) and U.S. Army Corps of Engineers (USACE; Palermo et al. 1998) and the Interstate Technology and Regulatory Council (ITRC 2014). The primary goal of this modeling was to simulate the transport of PCBs and arsenic within an engineered cap to identify a chemical isolation layer configuration (i.e., thickness and composition) that could 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).

Figure G-1
Engineered Cap Example Design Area (RAA 18)



2.1 Approach

2.1.1 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).

2.1.2 Simulation Approach

As shown in the schematic on the left of Figure G-2, caps in clamming areas (including intertidal areas) need to include a clam habitat layer on top of the cap erosion protection layer, which in turn is on top of the chemical isolation layer. Combined layers can support more than one function (e.g., chemical isolation and erosion protection requirements can sometimes be met with a single layer of material). Therefore, for the purposes of the example design, the model domain was simplified, such that the entire simulated cap thickness was represented as a layer of granular material having geotechnical properties that are representative of both the chemical isolation material and the erosion protection material[1] (i.e., porosity and dry bulk density; see schematic on the right of Figure G-2).

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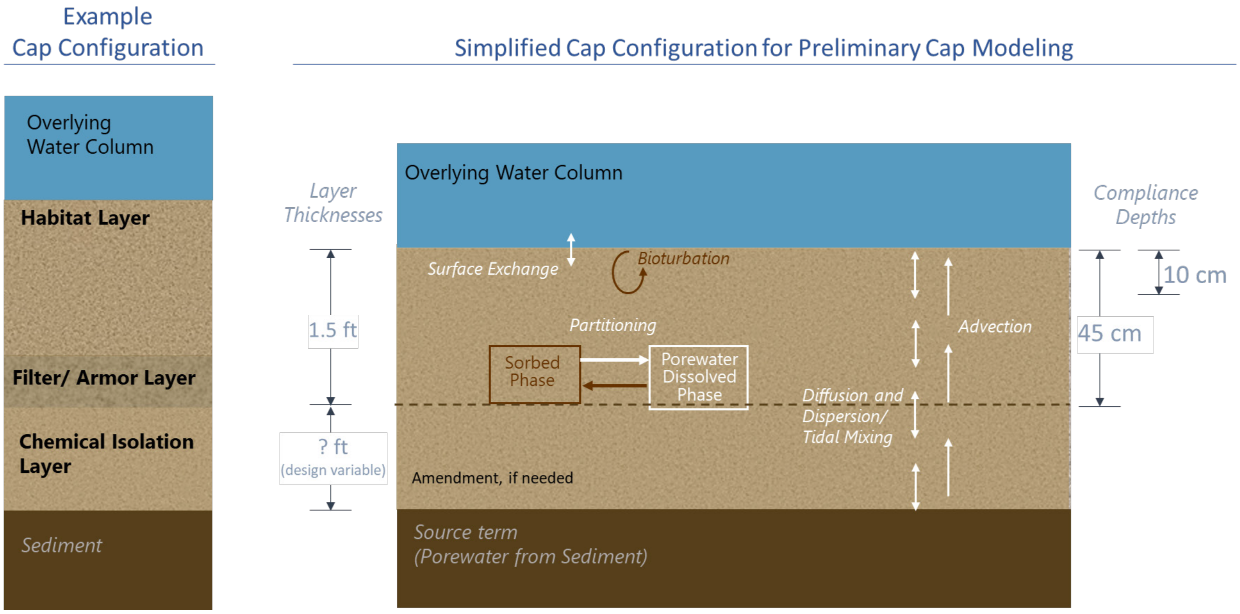
[1] The key geotechnical parameters for cap design, porosity and bulk density, do not vary significantly between the typical materials that are used for chemical isolation and erosion protection.

Figure G-2
Cap Layer Configuration and Processes Modeled



Notes:
The modeling approach conservatively ignored net sedimentation.
Consolidation of underlying sediments was not simulated; consolidation was assumed to be minimal where dredging occurs before material placement. This assumption will be revisited in future phases of design.

There are a total of 42 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). RAL exceedances in RAA 18 surface (0 to 10 centimeters [cm]) sediment were reported for PCBs, arsenic, benzo(a,h)anthracene, benzo(a)pyrene, chrysene, benzo(g,h,i)perylene, dibenzo(a,h)anthracene, fluoranthene, indeno(1,2,3-cd)pyrene, phenanthrene, carcinogenic polycyclic aromatic hydrocarbons, total high-molecular-weight polycyclic aromatic hydrocarbons, total benzofluoranthenes, and butyl benzyl phthalate. 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. Of the organic compounds, PCBs require the greatest reduction in concentrations. The maximum PCB concentration exceeds the RAL by a factor of 9. Butyl benzyl phthalate and polycyclic aromatic hydrocarbon (PAH) exceedances in the top 10 cm are less than 2 times greater than the RAL; the exceptions are indeno (1,2,3-cd)pyrene and benzo(g,h,i)perylene, which exceed the RAL by 2.8 and 2.9 times, respectively. In addition to having the highest factor of RAL exceedance, the dominant PCBs[2] are just as, or more mobile than, the PAHs, which have the next highest factor of exceedance. Log k_{OC} values for the PCB homologs range from 5.1 log liter per kilogram (L/kg) to 7.8 log L/kg, with tri, tetra, and penta having the largest contribution to total PCB (log k_{OC} of 5.8, 6.1, and 6.4 log L/kg, respectively) compared with the log k_{OC} of Indeno(1,2,3-cd)pyrene (6.6 log L/kg) and benzo(g,h,i)perylene (6.4 log L/kg). Therefore, a remedy that addresses a factor of 9 times reduction in PCBs will also address reductions for these chemicals. In this example cap design, total PCBs and arsenic were evaluated as the driver COCs based on observed exceedances of RALs in this area. PCBs were simulated as individual PCB homologs in the model to account for the differences in homolog mobility. Model simulations were conducted to identify the cap thickness and composition (i.e., sorptive amendment content, if any, in the portion of the cap beneath the 45-cm depth) required to maintain PCB and arsenic concentrations less than performance target concentrations in surface sediment, as discussed subsequently.

2.1.2.1 Performance Target Concentrations

For the purposes of this evaluation, performance targets for the example cap design evaluation 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. The example cap design area is located within the Recovery Category 2 area and fully within the intertidal zone. Therefore, the performance of the example cap was evaluated based on meeting the PCB and arsenic RALs that apply to sediment in the intertidal portion of the example cap design area and within Recovery Category 2 as follows:

- **PCBs:** 12 milligrams per kilogram (mg/kg) organic carbon (OC) total PCB in 0 to 10 cm; 65 mg/kg OC in 0 to 45 cm
- **Arsenic:** 57 mg/kg in 0 to 10 cm; 28 mg/kg in 0 to 45 cm (Note: The Remedial Action Objective 3 cleanup level for arsenic is 57 mg/kg.)

2.1.2.2 Cap Thickness and Compliance Intervals Considered

Four total cap thicknesses were evaluated: 2 feet, 2.5 feet, 3.5 feet, and 4.5 feet. For each cap thickness evaluated, compliance with performance targets was assessed in the top 10 cm and top 45 cm of the simulated cap material as per the targets discussed in the previous section. If necessary to meet performance targets, the lower portion of the cap (i.e., the cap material below a depth of 45 cm) was simulated to contain an amendment. The amendment content was considered a design

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[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).

variable in such cases. The upper 10 cm of the model domain was used for the bioturbation zone, where mixing by benthic activity was simulated.

2.2 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 G-1. More details describing certain key model inputs are provided in Sections 2.2.1 through 2.2.3.

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

Model Input Parameter	Value	Data Source
Chemical-Specific Properties		
PCB porewater concentration	See Table G-3.	Based on bulk sediment PCB concentrations from Samples SD-507-0020 and SD-507-0060,[1] which represent the maximum and 95% UCL total PCB concentrations from the example cap design area, respectively. 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 Sections 2.2.1 and 2.2.2 for more detail.
Arsenic porewater concentration	See Table G-3.	Based on the maximum and 95% UCL arsenic concentrations in sediment from the example cap design area.[1] Porewater concentrations were calculated based on bulk sediment arsenic concentrations and partition coefficients. The model assumes a fixed concentration at the bottom boundary of the model (i.e., infinite source). See Sections 2.2.1 and 2.2.2 for more detail.
OC partition coefficients for PCB homologs, log K_{OC} (log L/kg)	See Table G-2.	Based on partition coefficients developed as part of the Pre-Design Studies (Windward 2020). See Section 2.2.1 for more detail.
Partition coefficient for arsenic, log K_d (log L/kg)	See Table G-2.	Values based on literature; separate values used for sorption to sand material versus sand amended with ZVI, with K_d calculated as a function of ZVI content for the latter. See Section 2.2.1 for more detail.

Model Input Parameter	Value	Data Source
Molecular diffusivity (cm^2/s)	PCBs: 3.3E-06 to 6.5E-06 Arsenic: 1.2E-05	For PCB homologs, calculated based on molecular weight using correlation from Schwarzenbach et al. (1993). For arsenic, calculated based on molar volume using correlation from Hayduk and Laudie (1974). 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.
Upper Portion of Cap (top 45 cm)		
Thickness (cm)	45	Based on the depth interval used for target sediment concentration.
Total porosity	0.4	Typical value for 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 sand.
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 f_{OC} will increase toward levels similar to (but lower than) that of the current surface sediment, which is 1.6%.
Fraction OC of cap material below bioturbation zone	0.1%	Represents the sorptive capacity of the cap material within the 10- to 45-cm depth interval. A lower-bound estimate typically used to represent quarry sand where sorption to mineral fractions can also occur (Karickhoff 1984; EPA 2000).
Lower Portion of Cap (below 45 cm)		
Thickness (cm)	15 to 120 cm	Design variable. Multiple cap thicknesses evaluated, ranging from 2 feet (60 cm) to 4.5 feet (137 cm). Thickness of the lower portion of the cap (below 45 cm) ranged from 15 cm to 90 cm.
Total porosity	0.4	Typical value for 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 sand. Value adjusted to account for quantity of ZVI added to address arsenic, as necessary. Dry bulk density of ZVI was 2.92 g/cm^3.
Fraction OC of cap material (%)	Design variable	Represents sorptive capacity of the cap material. Started with a nominal value of 0.1%. If the PCB RAL was not met with sand alone, this value was increased as necessary to represent an OC amendment 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).

Model Input Parameter	Value	Data Source
Groundwater seepage rate (cm/yr)	400 and 800	Range of values estimated from MODFLOW model predictions developed by Fabritz et. al. (1998). See Section 2.2.3 for detail. This value may be refined in 60% RD based on additional evaluations.
Net sedimentation rate (cm/yr)	0	Conservatively assumed no future net sedimentation.
Dispersion length (cm)	Variable	Based on 20% of the model domain length (cap thickness). See Section 2.2.3 for detail.
Bioturbation zone thickness (cm)	10	The RI (Windward 2010) concluded that 10 cm can be reasonably estimated as 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 not simulated in this phase of design; parameter may be updated in the 60% RD phase.

Note:

1. These data are included in the design dataset, which is described in detail in the *Pre-Design Investigation Data Evaluation Report* (Anchor QEA and Windward 2022).

95% UCL: 95 percent upper confidence limit of the mean
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
f_{OC}: fraction organic carbon
g/cm^3: grams per cubic centimeter
K_d: equilibrium partition coefficient
K_{OC}: organic carbon partition coefficient
L/kg: liters per kilogram
LDW: Lower Duwamish Waterway
OC: organic carbon
PCB: polychlorinated biphenyl
RAL: remedial action level
RD: remedial design
RI: remedial investigation
TOC: total organic carbon
ZVI: zero valent iron

2.2.1 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 arsenic, K_d values were defined for two potential cap materials.

Site-specific partitioning data were not available for arsenic. Arsenic partitioning onto sand or sediment was based on the mean log K_d value reported for sediment by Allison and Allison (2005) of 2.4 log L/kg. As necessary, the modeling evaluation considered amendment of sand cap material to limit transport of arsenic, which was represented in the model as a sorption term. For the purposes of this evaluation, zero valent iron (ZVI) was the assumed amendment. The log K_d value used to simulate the sorption of arsenic onto ZVI was set to 3.6 log L/kg (Nikolaidis et al. 2003). When simulating sand amended with ZVI, a weighted average K_d to represent the effective strength of sorption to ZVI, accounting for the percent by weight ZVI in the bulk mixture, was used in the model.

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 × 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 G-2.

Table G-2
Partitioning Coefficients Used in the Cap Model

Chemical Name	OC Partition Coefficient, Log K_{OC} (log L/kg)	Partition Coefficient, Log K_d (log L/kg)
Arsenic (Sand)	--	2.4
Arsenic (ZVI)	--	3.6
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	--

Note:
--: not relevant
K_d: equilibrium partition coefficient
K_{OC}: organic carbon partition coefficient
L/kg: liters per kilogram
OC: organic carbon
PCB: polychlorinated biphenyl
ZVI: zero valent iron

2.2.2 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 the example cap design area; therefore, PCB and arsenic concentrations in sediment porewater were calculated from vertical core interval sediment concentrations collected from the example cap design area using the equilibrium partitioning coefficients discussed in Section 2.2.1. For this evaluation, all data collected from within the example cap design area were used. Simulations were conducted using both the maximum and 95% upper confidence limit of the mean (95% UCL) concentrations, which were calculated using ProUCL.

2.2.2.1 Arsenic

For arsenic, the maximum sediment concentration (1,100 mg/kg from Sample LDW-SS114-010 [0 to 10 cm]) and the 95% UCL (347 mg/kg[3] [sample count = 59]) were selected for modeling. These sediment concentrations were converted to porewater using the log K_d of 2.4 log L/Kg listed in Table G-2. Because of the uncertainty in arsenic species present at the Site (i.e., dissolved or precipitated form), the porewater concentration derived from literature partition coefficients was compared to the range in dissolved groundwater concentrations measured in monitoring wells on the adjacent Boeing Isaacson Thompson Site and Port of Seattle Sliver property (Landau Associates 2020).

The estimated porewater concentration of arsenic in the example cap design area sediments was within the range measured in groundwater from monitoring wells located along the shoreline (Note: Dissolved concentrations in groundwater are greater in monitoring wells further from shore in the upland direction, suggesting attenuation is occurring as groundwater moves towards the LDW). As presented in the Boeing Isaacson Thompson Site feasibility study (FS), alkaline conditions in groundwater may increase arsenic mobility. Arsenic concentrations in porewater depend on multiple factors, including pH, dissolved oxygen, redox conditions, and other geochemical characteristics. This means the arsenic concentrations in porewater may be different from those reported in groundwater for adjacent upland wells.

Pathway or geochemical studies of arsenic have not been performed in the example cap design area, so it is not known whether the arsenic precipitates out of solution before entering the biological active zone of the sediments. Because of large tidal variations in the LDW, it is reasonable to assume that dissolved oxygen is present in the surface sediment porewater, which could cause arsenic to precipitate out of solution and become immobile. That said, because supporting data are not available, this evaluation conservatively assumed the arsenic is mobile throughout the full thickness of the sediment layer (and within the simulated cap). Until additional data can be collected to better characterize the geochemical conditions and porewater concentrations of arsenic at the Site, the concentrations used in this evaluation are considered representative (but are recognized as uncertain).

2.2.2.2 PCBs

For PCBs, the sediment samples with OC-normalized PCB concentrations equal to the maximum (sample SD-507-0020 [61 to 91 cm depth interval], with a total PCB concentration of 110 mg/kg OC) and 95% UCL (23.6 mg/kg OC[4] [sample count = 63]) were selected for use in the model. The total PCB concentration associated with sample SD-507-0060 was equal to the 95% UCL; therefore, the Aroclor composition of this sample was used to represent the 95% UCL. PCB concentrations were measured using an Aroclor-based method. To account for the range in mobility of the PCB

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[3] ProUCL selected statistic for arsenic: 95% Chebyshev (Mean, Sd) UCL
[4] ProUCL selected statistic for total PCBs: 95% KM Approximate Gamma UCL

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). The sediment PCB homolog concentrations were then converted to porewater concentrations using the log K_{OC} values listed in Table G-2.

The porewater concentrations used in the model evaluations are provided in Table G-3.

Table G-3
Porewater Concentrations Used in the Cap Model

Chemical Name	Maximum (µg/L)	95% UCL (µg/L)
Arsenic	4.3E+03	1.4E+03
PCB-Mono	1.3E-04	3.3E-05
PCB-Di	1.9E-03	4.7E-04
PCB-Tri	1.2E-02	3.2E-03
PCB-Tetra	2.1E-02	4.5E-03
PCB-Penta	1.6E-02	2.7E-03
PCB-Hexa	4.6E-03	9.7E-04
PCB-Hepta	6.5E-04	2.2E-04
PCB-Octa	5.4E-05	2.1E-05
PCB-Nona	3.0E-06	1.2E-06
PCB-Deca	1.2E-07	4.9E-08
Total PCB[1]	5.6.E-02	1.2.E-02

Notes:

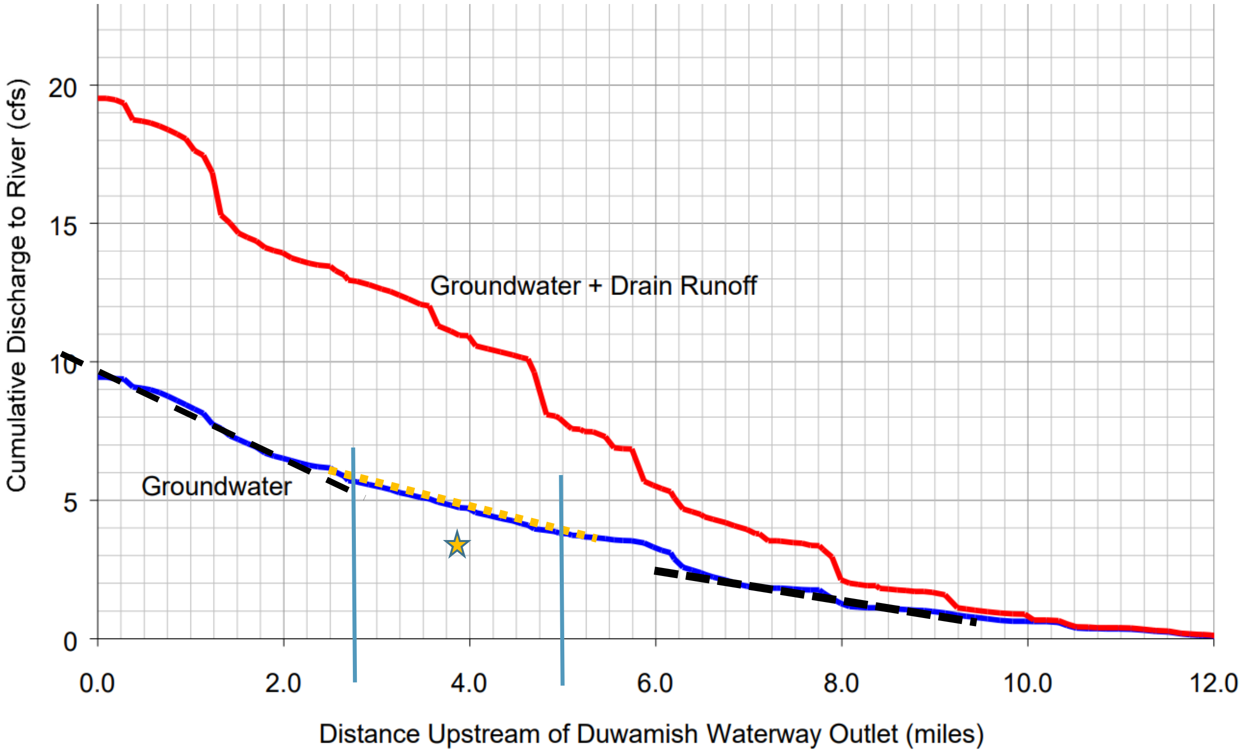
1. Total PCB is included for reference only; total PCB was not simulated with the model. PCBs were simulated by homolog group, and results were summed to calculate total PCBs for comparison with RALs.

µg/L: micrograms per liter
95% UCL: 95 percent upper confidence limit of the mean
PCB: polychlorinated biphenyl
RAL: remedial action level

2.2.3 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 G-3, which is adapted from Figure 11 of Fabritz et al. [1998].) To estimate the seepage rate in the example cap design area, the change in cumulative discharge with distance in the project area, as shown in Figure G-3, 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 G-3. The slope becomes flatter from RM 2.75 to RM 5; the example cap design area is located between RMs 3.6 and 3.7 (identified by a star on Figure G-3). The flatter slope from RMs 6 to 9.5 suggests lower discharge to the LDW in this area.

Figure G-3
Cumulative Discharge to the Lower Duwamish Waterway Predicted by MODFLOW Model

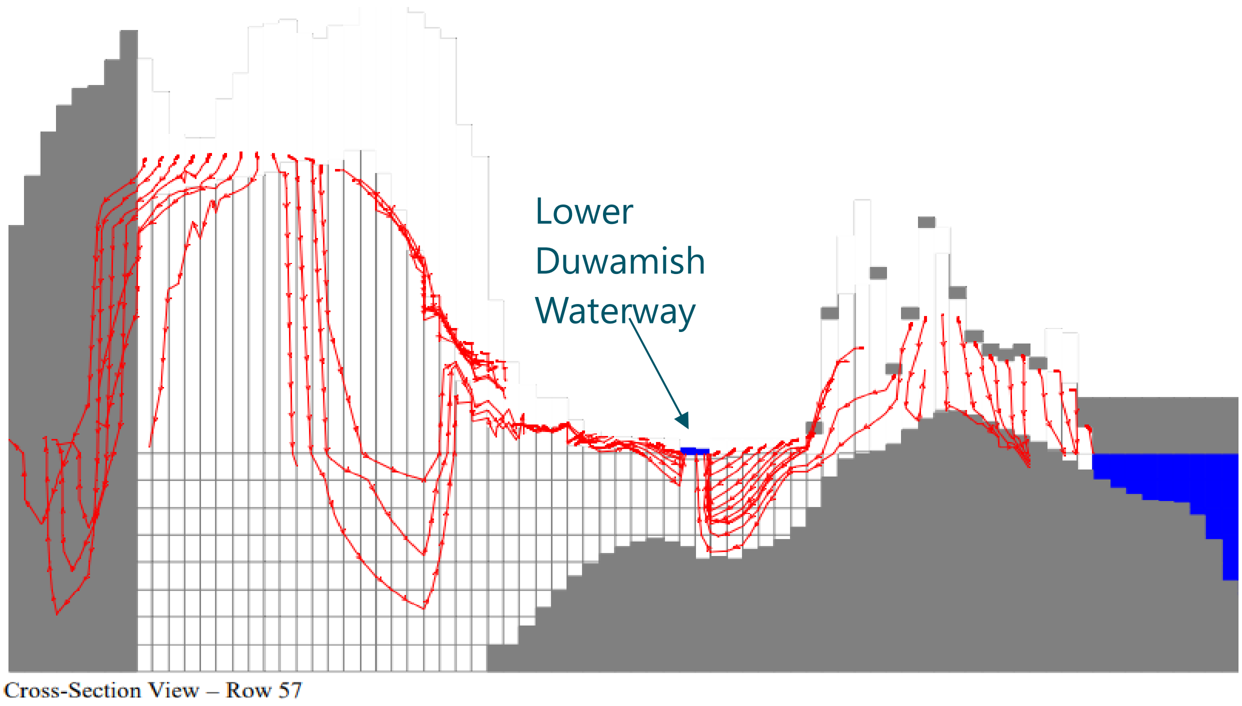


Notes:
Source: Fabritz et. al. (1998), Figure 11
The dashed lines, vertical blue lines, and star were not part of original figure.
Dashed lines represent the three general discharge patterns observed in the river (based on change in slope). The yellow dashed line represents the consistent change in discharge over the portion of the river where the example cap design area is located. The example cap design area is represented by the star. 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 example 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 G-3. 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 G-4, which is adapted from Figure 8 of Fabritz et. al. (1998), shows a cross section view of the river near the example 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 example 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). Model simulations were therefore conducted using values of 400 and 800 cm/yr, both of which are considered equally valid in the absence of Site-specific measurements. Site-specific measurements are recommended for refining this value in the future.

Figure G-4
Flow Paths to Lower Duwamish Waterway Predicted by MODFLOW Model



Notes:
Source: Fabritz et. al. (1998), Figure 8
The example cap design area is located to the right of the LDW in this diagram.

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 G-4, which are generally consistent with the range considered here.

Table G-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	June 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

Dissolved phase transport within the cap may also be influenced by tidal fluctuations in the LDW, which can result in daily reversals in hydraulic gradient and advective flow. Representing 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).

In this example capping evaluation, 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).

2.3 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 of the example cap design area and within Recovery Category 2. Cap thicknesses of 2 feet (Scenario 1), 2.5 feet (Scenario 2), 3.5 feet (Scenario 3), and 4.5 feet (Scenario 4) were evaluated. The caps were evaluated under two seepage rates—400 cm/yr and 800 cm/yr—and for two calculated porewater concentrations—maximum and 95% UCL—for both PCBs and arsenic.

Model-predicted concentrations over the 100-year simulation period are provided in the attached Figures G-5 though G-20 for each scenario simulated. These figures show predicted increases in concentrations in the 0- to 10-cm (top panel) and 0- to 45-cm (bottom panel of the cap) ranges over time in some cases. For PCBs, in addition to total PCB, the individual homologs that contribute to the total PCB concentration are shown.

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). Table G-5 shows the results with respect to which scenarios resulted in a predicted RAL exceedance and the time at which the RAL was predicted to be exceeded, if applicable.

Table G-5
Model-Predicted Time to Exceed the RALs for Four Cap Thicknesses Evaluated

Depth of Interest (cm)	RAL	Predicted Time to Exceed RALs (Years)[1]							
		Scenario 1 2 feet Cap (0.5 foot CIL)		Scenario 2 2.5 feet Cap (1 foot CIL)		Scenario 3 3.5 feet Cap (2 feet CIL)		Scenario 4 4.5 feet Cap (3 feet CIL)	
		400 cm/yr	800 cm/yr	400 cm/yr	800 cm/yr	400 cm/yr	800 cm/yr	400 cm/yr	800 cm/yr
PCBs – 95% UCL									
0 to 10	12 mg/kg OC	100+	100+	100+	100+	100+	100+	100+	100+
0 to 45	65 mg/kg OC	100+	100+	100+	100+	100+	100+	100+	100+
PCBs– Maximum									
0 to 10	12 mg/kg OC	100+	100+	100+	100+	100+	100+	100+	100+
0 to 45	65 mg/kg OC	100+	100+	100+	100+	100+	100+	100+	100+
Arsenic – 95% UCL									
0 to 10	57 mg/kg	29	14	40	18	62	27	88	37
0 to 45	28 mg/kg	8	4	14	7	25	13	37	19
Arsenic – Maximum									
0 to 10	57 mg/kg	18	9	24	12	35	17	47	22
0 to 45	28 mg/kg	4	2	9	5	17	9	26	13

Notes:
1.100+ indicates predicted concentrations were lower than RAL throughout the 100-year simulation.
95% UCL: 95 percent upper confidence limit of the mean
cm: centimeter
cm/yr: centimeters per year
CIL: chemical isolation layer
mg/kg: milligrams per kilogram
OC: organic carbon
PCB: polychlorinated biphenyl
RAL: remedial action level

For simulations of PCBs using both the 95% UCL and the maximum calculated porewater concentrations, model results indicate that concentrations in the cap surface were not predicted to exceed the RALs within the 100-year simulations. Thus, for PCBs, a 2-foot sand cap was predicted to be sufficient to meet the RALs for more than 100 years for each Darcy flux evaluated (see Table G-5 and Figures G-5a G-5b, G-9a, and G-9b).

For arsenic, the RAL of 28 mg/kg in the 0- to 45-cm depth interval is the more stringent of the two criteria. For simulations using the 95% UCL concentration as the source term, arsenic concentrations were predicted to exceed the RAL within 4 to 37 years, depending on cap thickness and Darcy flux (see Figures G-13 through G-16). For simulations using the maximum concentration as the source term, arsenic concentrations were predicted to exceed the RAL within 2 to 26 years, depending on cap thickness and Darcy flux (see Figures G-17 through G-20).

Cap configurations were simulated with the addition of 10% by weight ZVI in the lower portion of the cap (below 45 cm, identified as the CIL thickness in Table G-6). Table G-6 shows the predicted times for arsenic RAL exceedances in these scenarios with the simulated ZVI amendment. Temporal profiles of arsenic within the top 10 cm and top 45 cm of the cap for these scenarios are shown in Figures G-21 through G-28.

Table G-6
Model-predicted Time to Exceed the RALs for Four Cap Thicknesses Evaluated Assuming 10% by Weight ZVI in Lower Portion of the Cap (CIL)

Depth of Interest (cm)	RAL	Time to Exceed RALs (years)							
		Scenario 1 **2 feet Cap** **(0.5 foot CIL)**		**Scenario 2** **2.5 feet Cap** **(1 foot CIL)**		**Scenario 3** **3.5 feet Cap** **(2 feet CIL)**		**Scenario 4** **4.5 feet Cap** **(3 feet CIL)**	
		400 cm/yr	**800 cm/yr**	**400 cm/yr**	**800 cm/yr**	**400 cm/yr**	**800 cm/yr**	**400 cm/yr**	**800 cm/yr**
Arsenic – 95% UCL									
0 to 10	57 mg/kg	39	18	63	29	100+	53	100+	79
0 to 45	28 mg/kg	13	7	26	13	54	27	84	42
Arsenic – Maximum									
0 to 10	57 mg/kg	24	12	38	18	68	32	100+	47
0 to 45	28 mg/kg	8	4	18	9	39	20	61	30

Notes:
Cap configuration with no ZVI amendment predicted to meet RALs for more than 25 years.
95% UCL: 95% upper confidence limit of the mean
cm: centimeter
cm/yr: centimeters per year
CIL: chemical isolation layer
mg/kg: milligrams per kilogram

RAL: remedial action level
ZVI: zero valent iron

Using the 95% UCL arsenic concentration in sediment beneath the cap, model results indicate that a 3.5-foot (Scenario 3) cap with 10% by weight ZVI in the lower 2 feet of the cap is predicted to meet the RAL of 57 mg/kg in the top 10 cm of the cap for more than 100 years at the seepage rate of 400 cm/yr and 53 years at the seepage rate of 800 cm/yr seepage rate. An additional foot of ZVI amended sand (Scenario 4) increases the time to exceed the RAL to 79 years for the 800 cm/yr seepage rate. A 4.5-foot cap (Scenario 4) with 10% by weight ZVI in the lower 3 feet of the cap is predicted to meet the RALs for at least 25 and 40 years, respectively, based on the 95% UCL arsenic concentration in sediment beneath the cap and considering both values for seepage rate. For the more stringent RAL of 28 mg/kg in the top 45 cm of the cap, model results indicate that a 4.5-foot (Scenario 4) cap with 10% by weight ZVI in the lower 3 feet of the cap is predicted to meet the RAL for 42 to 84 years, depending on the seepage rate.

Using the maximum arsenic concentration in sediment beneath the cap, a 4.5-foot cap (Scenario 4) with 10% ZVI by weight in the lower 3 feet of the cap is predicted to meet RAL of 57 mg/kg in the top 10 cm of the cap for 47 to more than 100 years depending on the seepage rate. A 4.5-foot cap (Scenario 4) with 10% ZVI by weight is predicted to meet RAL of 28 mg/kg in the top 45 cm of the cap for 30 and 60 years at seepage rates of 800 cm/yr and 400 cm/yr, respectively. If a remedial area is addressed using an engineered cap, additional data collection may be needed to better understand the mobility of arsenic within a remedial area in order to refine the evaluations.

2.4 Summary

Chemical transport modeling was conducted to evaluate the performance of a range of cap thicknesses considered for example cap design area in the LDW. Modeling indicates that for PCBs, a 2-foot sand cap is predicted to meet the PCB RALs for more than 100 years. For arsenic, a cap thickness of 3.5 feet amended with 10% ZVI by weight in the lower cap horizon is predicted to meet the arsenic RALs for 27 to more than 100 years for the 95% UCL calculated porewater concentrations and for 20 to 68 years for the maximum calculated porewater concentrations. A cap thickness of 4.5 feet amended with 10% ZVI by weight in the lower cap horizon is predicted meet the arsenic RALs for 42 to more than 100 years for the 95% UCL calculated porewater concentrations and for 30 to greater than 100 years for the maximum calculated porewater concentrations. These simulations are conservative and ignored net sedimentation, which would enhance the performance of the cap.

3 RAA 27 Engineered Cap Evaluation

The modeling was conducted to evaluate a sediment cap in RAA 27 to address elevated concentrations of PCBs in bank sediments. The modeling analyses described herein were performed in accordance with guidance on cap design set forth by EPA and USACE (Palermo et al. 1998) and the Interstate Technology and Regulatory Council (ITRC 2014). 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 could meet RALs set forth in the ROD (EPA 2014) for a long period of time (e.g., 100 years).

3.1 RAA 27 Model Approach and Inputs

The model framework and approach for the RAA 27 cap evaluation are consistent with those used in the example cap evaluation documented in Section 2. With the exception of PCB concentrations in sediment, all the model inputs are consistent with those used for the modeling described in Section 2.

As described in Section 2.2.2, 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; therefore, PCB concentrations in sediment porewater were calculated from sediment using the equilibrium partitioning coefficients discussed in Section 2.2.1. Vertical core interval sediment concentrations collected from RAA 27, as well as the soil samples collected from 5 feet or more below the ground surface along the shoreline riverbank (adjacent to Container Properties) were used for the evaluation. 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). The sediment PCB homolog concentrations were then converted to porewater concentrations using the log K_{OC} values listed in Table G-2.[5]

Conservatively, simulations were conducted using the maximum calculated porewater concentrations, which was from sample FRP-082911-002 from Location SL-01 at a depth from 5 to 7 feet below ground surface. The porewater concentrations used in the model evaluations are provided in Table G-7.

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[5] As discussed in Section 2.2.2, porewater were calculated from OC normalized sediment PCB concentrations using a partitioning theory. Total organic carbon (TOC) was not measured in the soil samples collected along the shoreline at the adjacent Container Properties; therefore, the average TOC measured in the nearby sediment samples was used in the calculation of porewater.

Table G-7
Porewater Concentrations Used in the Cap Model for RAA 27

Chemical Name	Maximum (µg/L)
PCB-Mono	7.6E-05
PCB-Di	9.0E-04
PCB-Tri	2.8E-03
PCB-Tetra	2.0E-02
PCB-Penta	3.1E-02
PCB-Hexa	8.0E-03
PCB-Hepta	4.6E-04
PCB-Octa	1.5E-05
PCB-Nona	4.9E-07
PCB-Deca	2.3E-09
Total PCB[1]	6.3.E-02

Notes:

2. 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/L micrograms per liter
PCB: polychlorinated biphenyl
RAA: remedial action area
RAL: remedial action level

3.2 RAA 27 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 and within Recovery Category 2. Cap thicknesses of 2 feet (Scenario 1), 2.5 feet (Scenario 2), 3.5 feet (Scenario 3), and 4.5 feet (Scenario 4) were evaluated. The caps were evaluated under two seepage rates—400 cm/yr and 800 cm/yr—for the maximum calculated PCB porewater concentrations.

Model-predicted concentrations over the 100-year simulation period are provided in the attached Figures G-29 though G-32 for each scenario simulated. These figures show predicted increases in concentrations in the 0- to 10-cm (top panel) and 0- to 45-cm (bottom panel of the cap) ranges over time in some cases. For PCBs, in addition to total PCB, the individual homologs that contribute to the total PCB concentration are shown. 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 total PCB concentrations are predicted to remain less than the RALs for more than 100 years for all scenarios evaluated.

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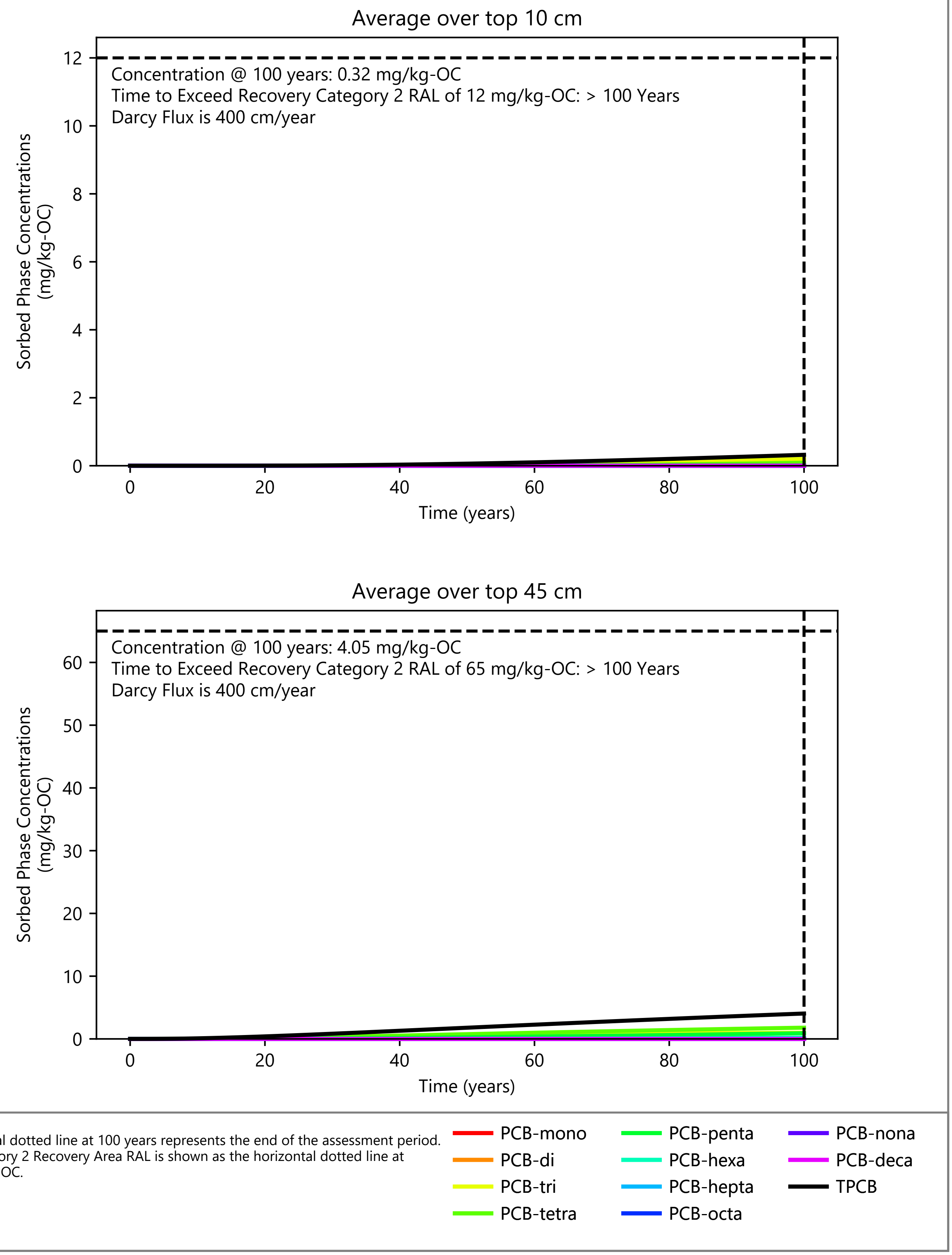
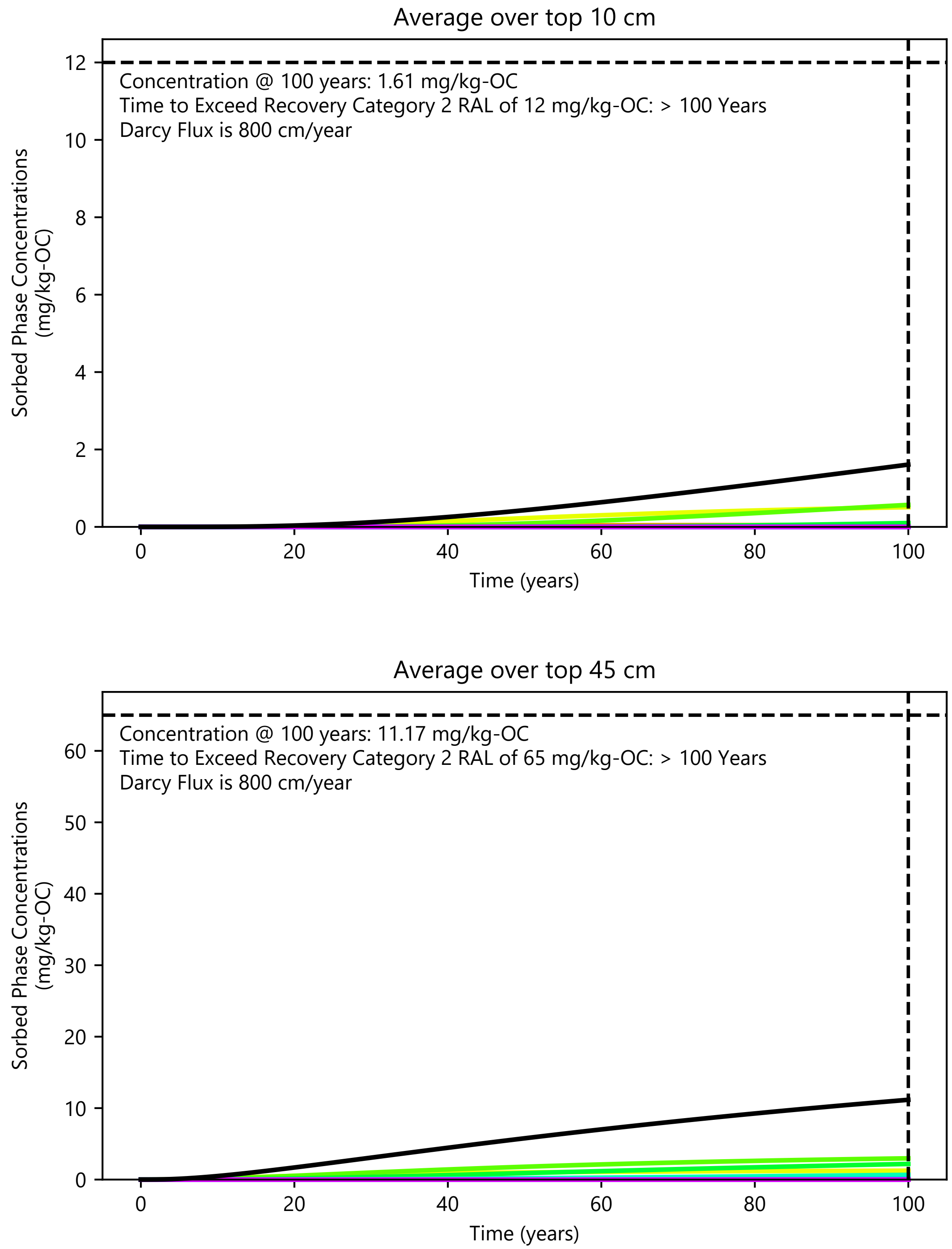
Figures G-5 to G-32



Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

Figure G-5a
Temporal Profile of PCBs Within the Surface of the Scenario 1 Cap
(400 cm/yr Darcy Flux and 95% UCL PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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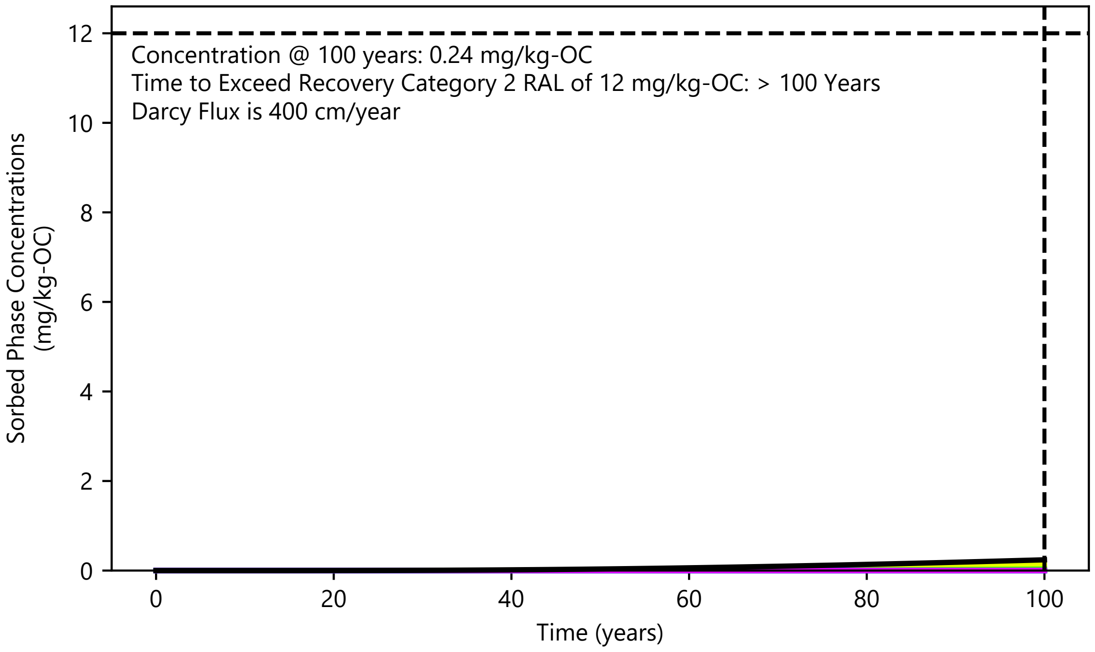
Figure G-5b

Temporal Profile of PCBs Within the Surface of the Scenario 1 Cap (800 cm/yr Darcy Flux and 95% UCL PCB Concentration)

Average over top 10 cm



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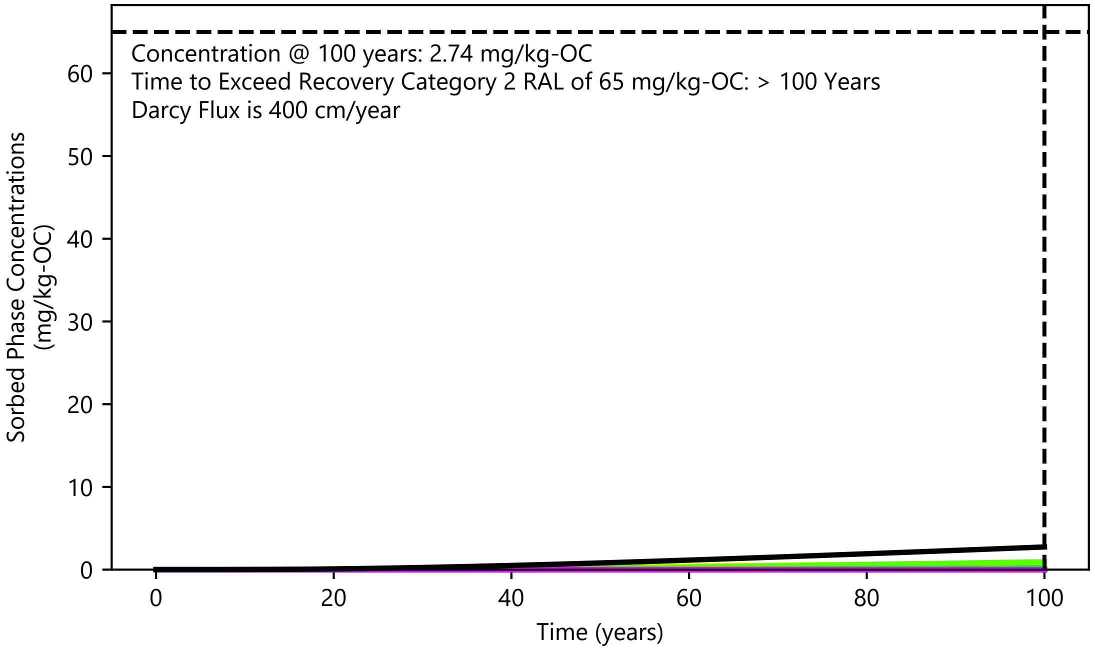

Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
12 mg/kg-OC.

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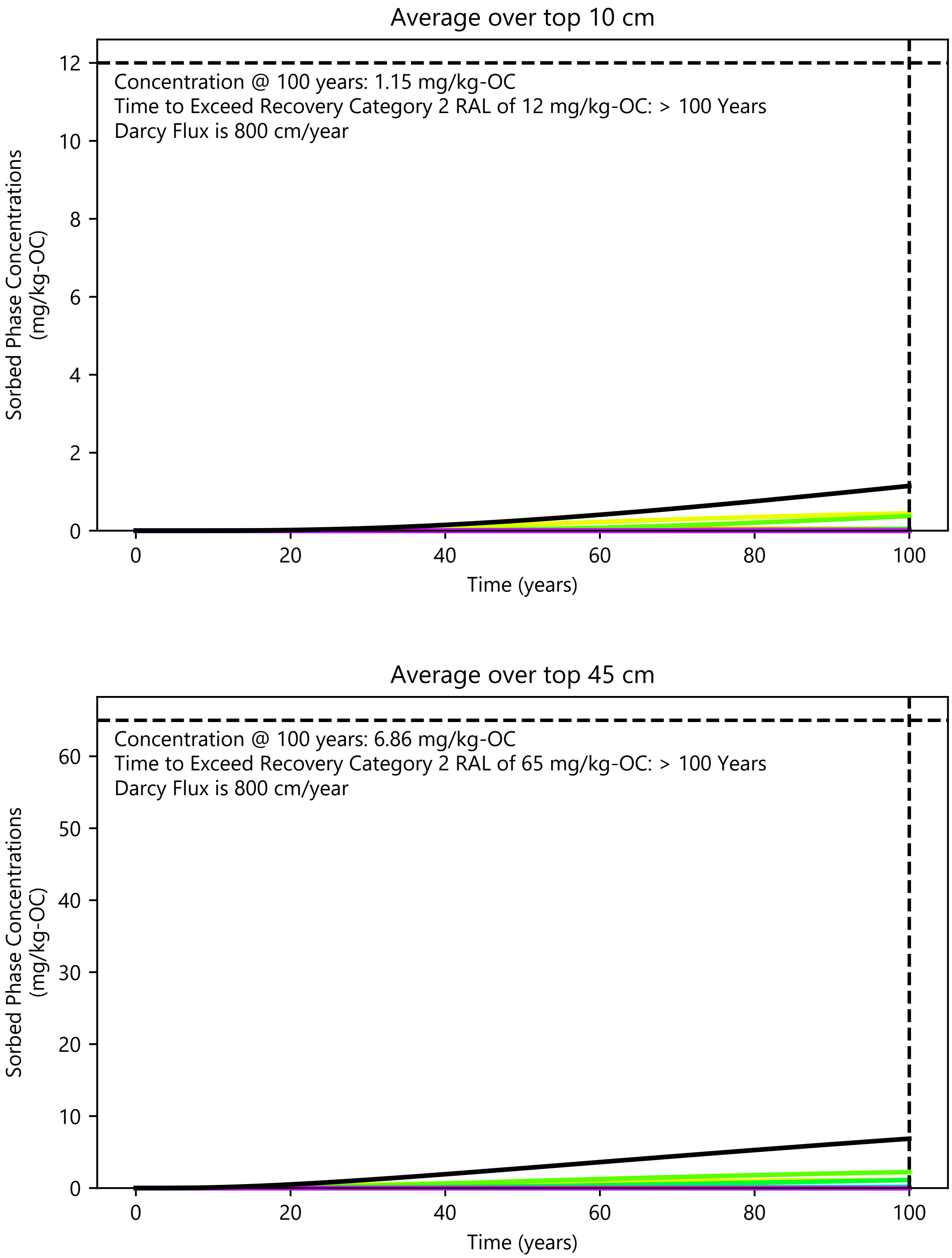
Figure G-6a
Temporal Profile of PCBs Within the Surface of the Scenario 2 Cap (400 cm/yr Darcy Flux and 95% UCL PCB Concentration)

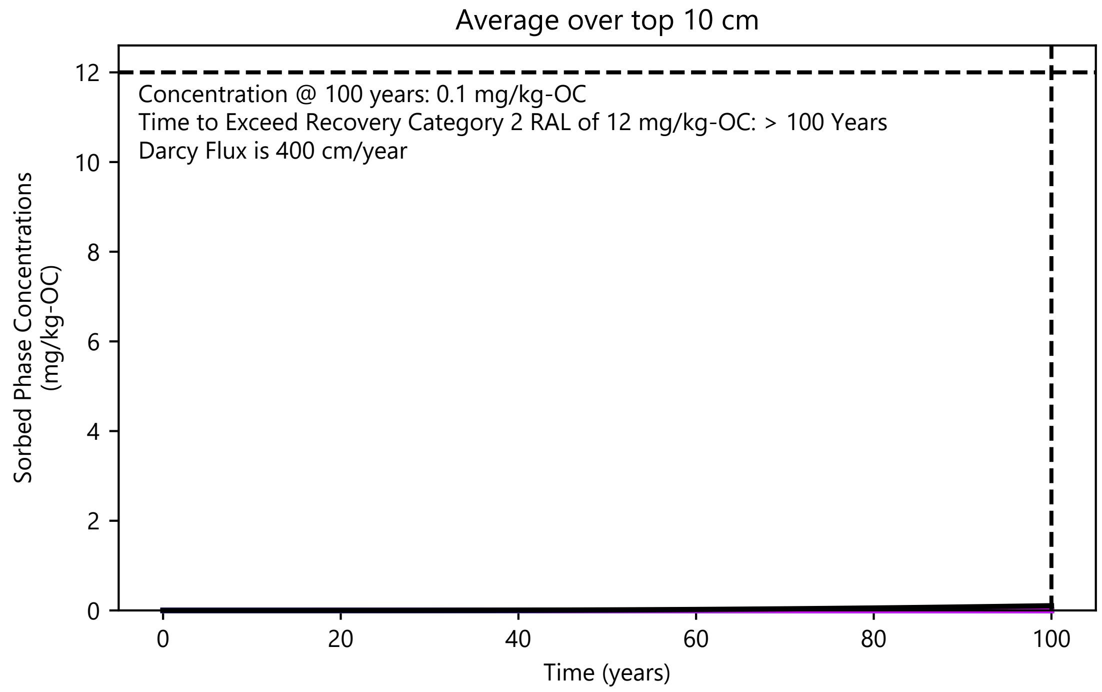
Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach

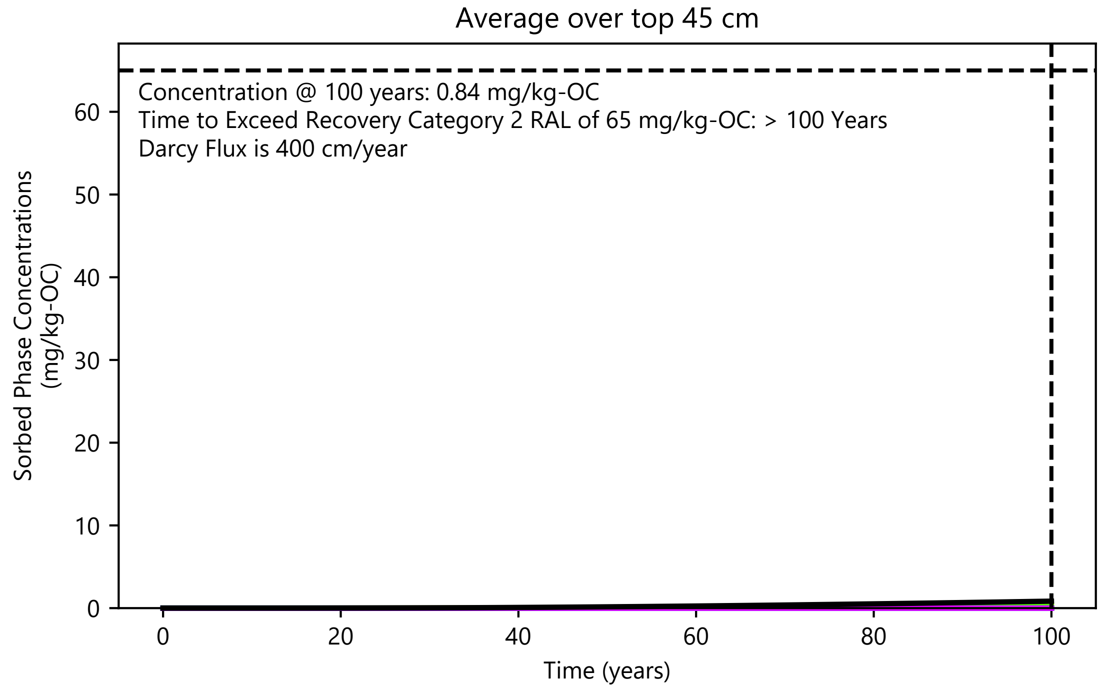


Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

Figure G-6b

Temporal Profile of PCBs Within the Surface of the Scenario 2 Cap (800 cm/yr Darcy Flux and 95% UCL PCB Concentration)





Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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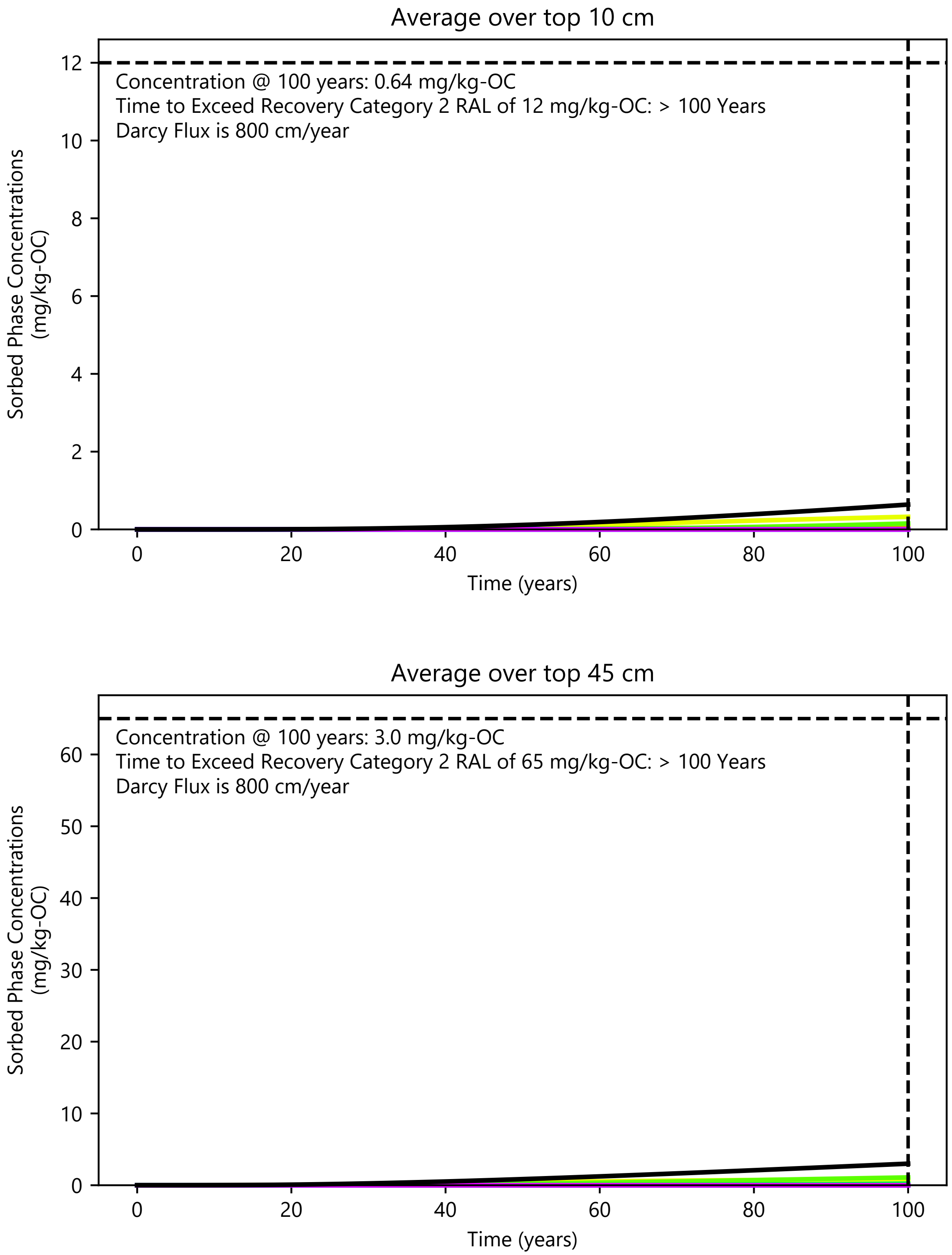
Figure G-7a
Temporal Profile of PCBs Within the Surface of the Scenario 3 Cap (400 cm/yr Darcy Flux and 95% UCL PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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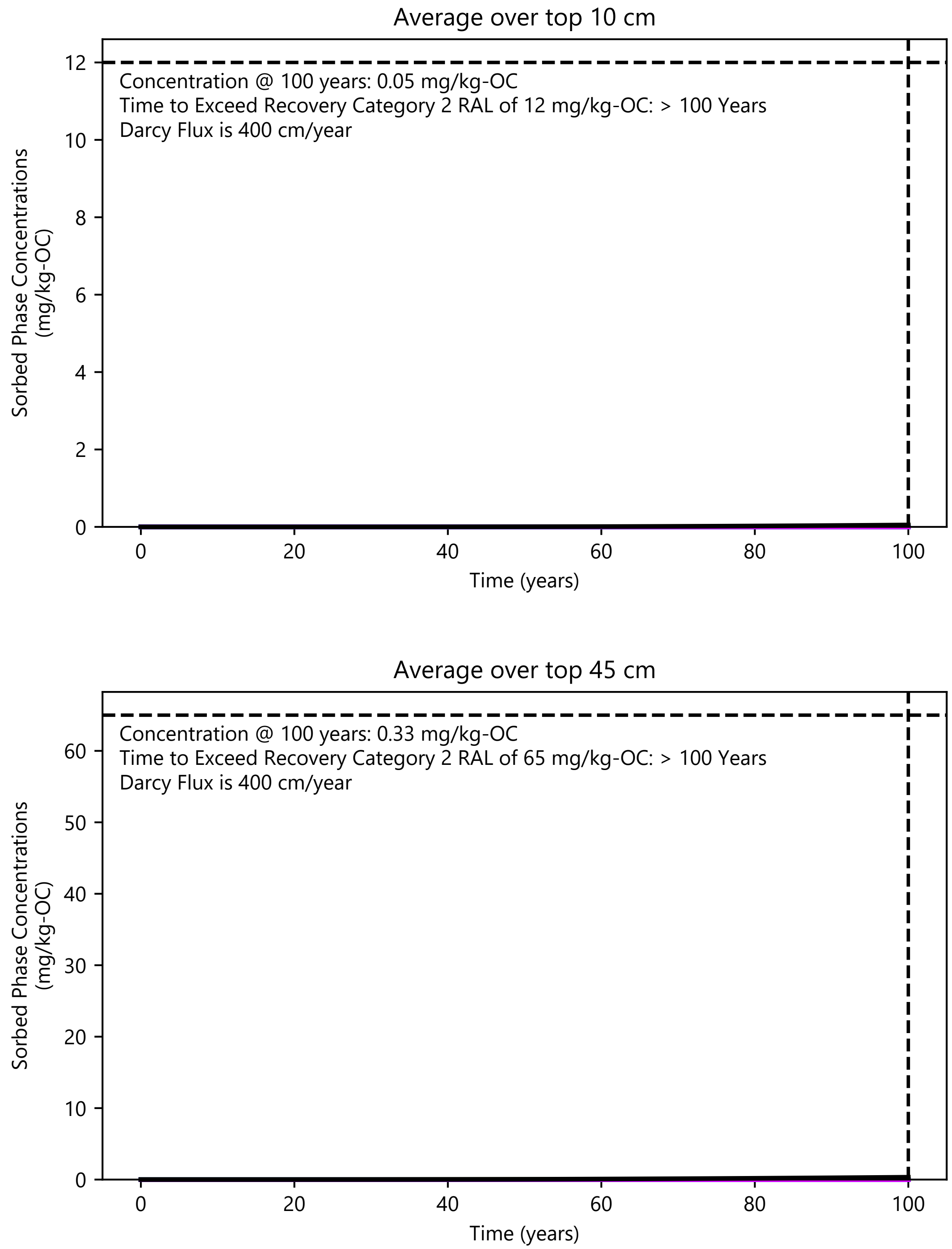
Figure G-7b

Temporal Profile of PCBs Within the Surface of the Scenario 3 Cap (800 cm/yr Darcy Flux and 95% UCL PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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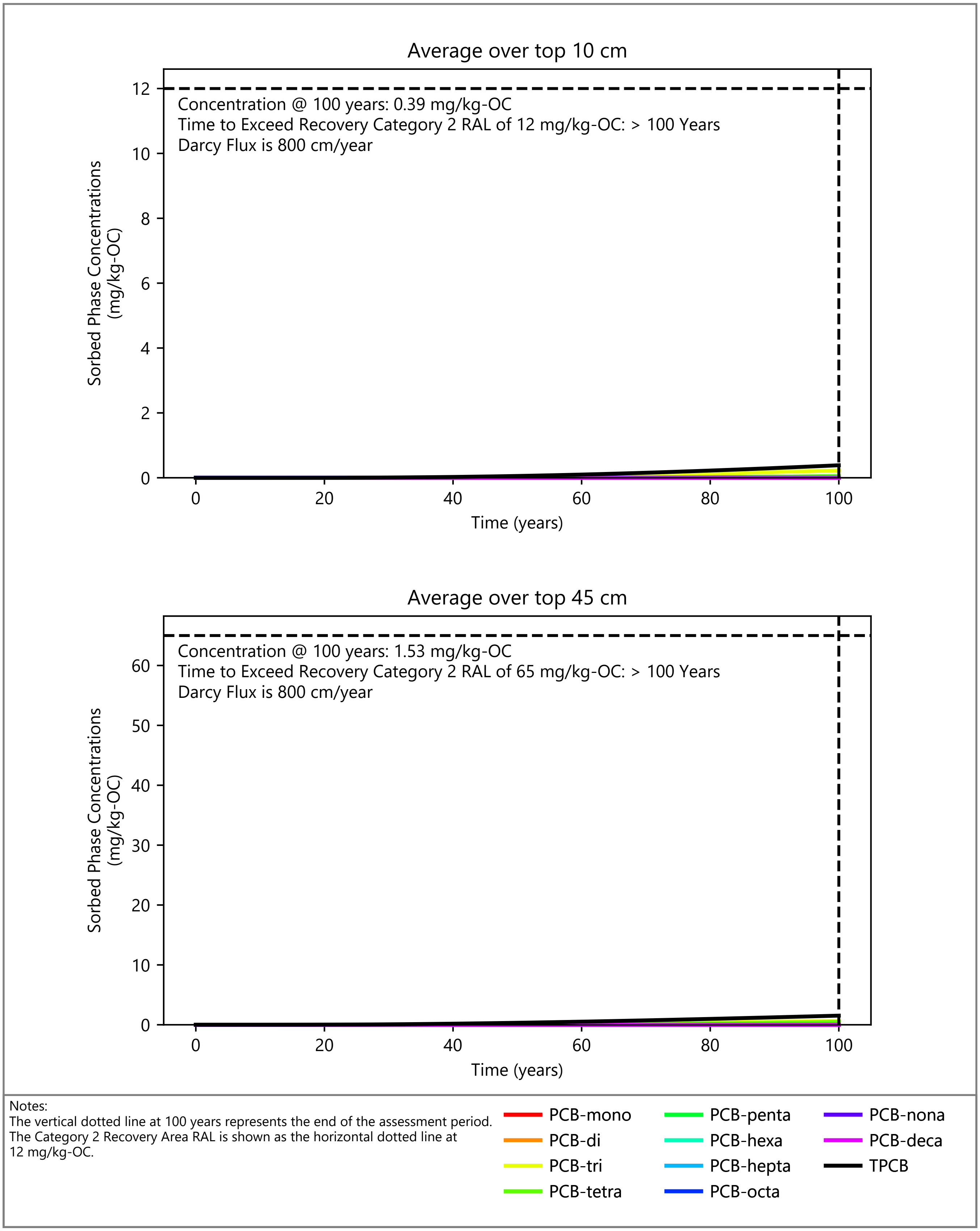
Figure G-8a
Temporal Profile of PCBs Within the Surface of the Scenario 4 Cap (400 cm/yr Darcy Flux and 95% UCL PCB Concentration)

Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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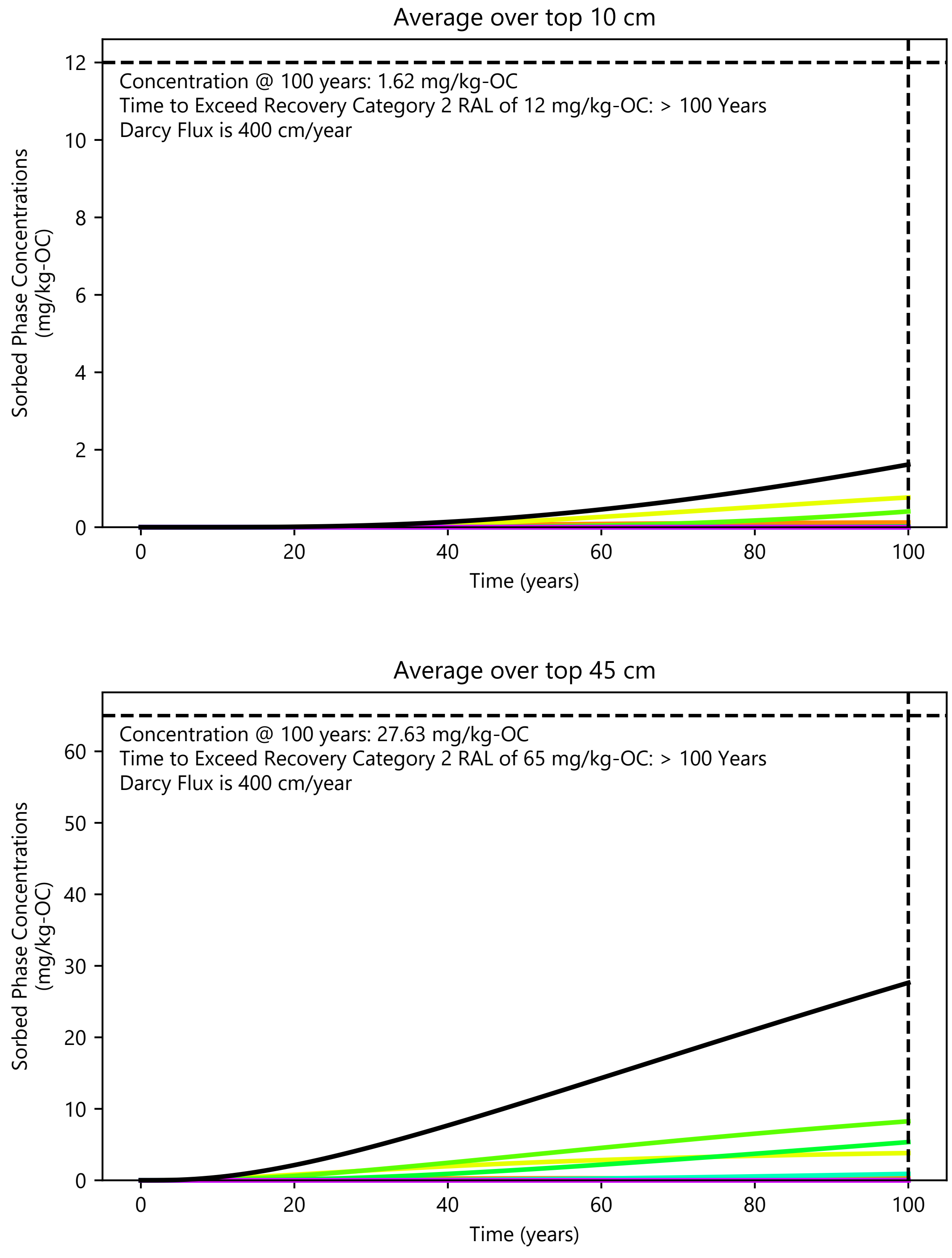
Figure G-8b
Temporal Profile of PCBs Within the Surface of the Scenario 4 Cap (800 cm/yr Darcy Flux and 95% UCL PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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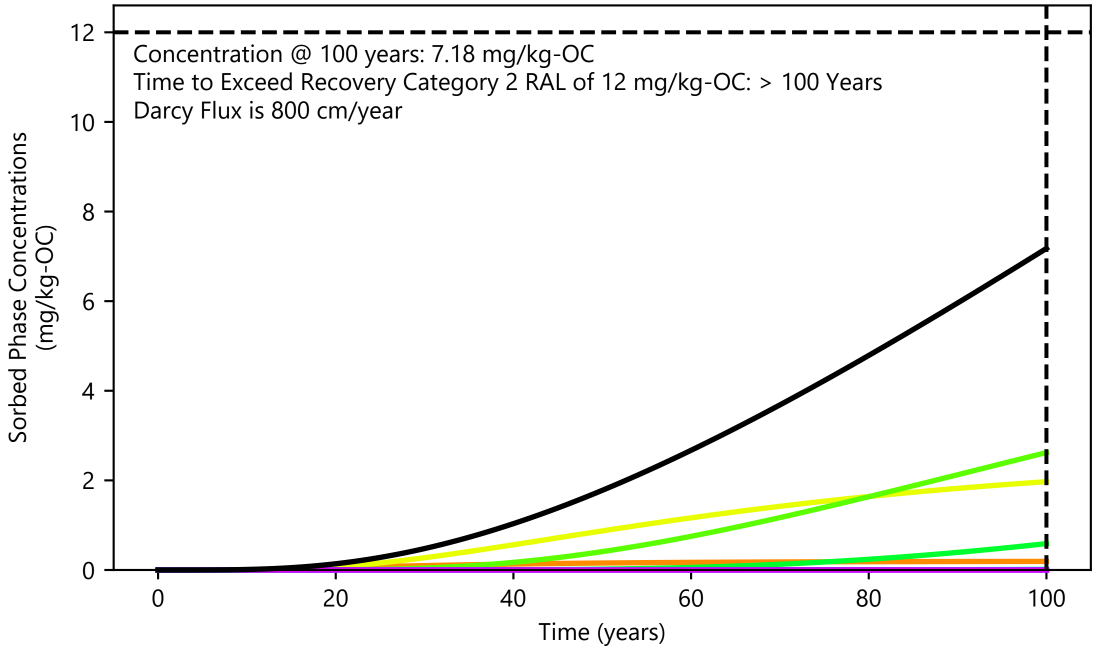
Figure G-9a

Temporal Profile of PCBs Within the Surface of the Scenario 1 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)

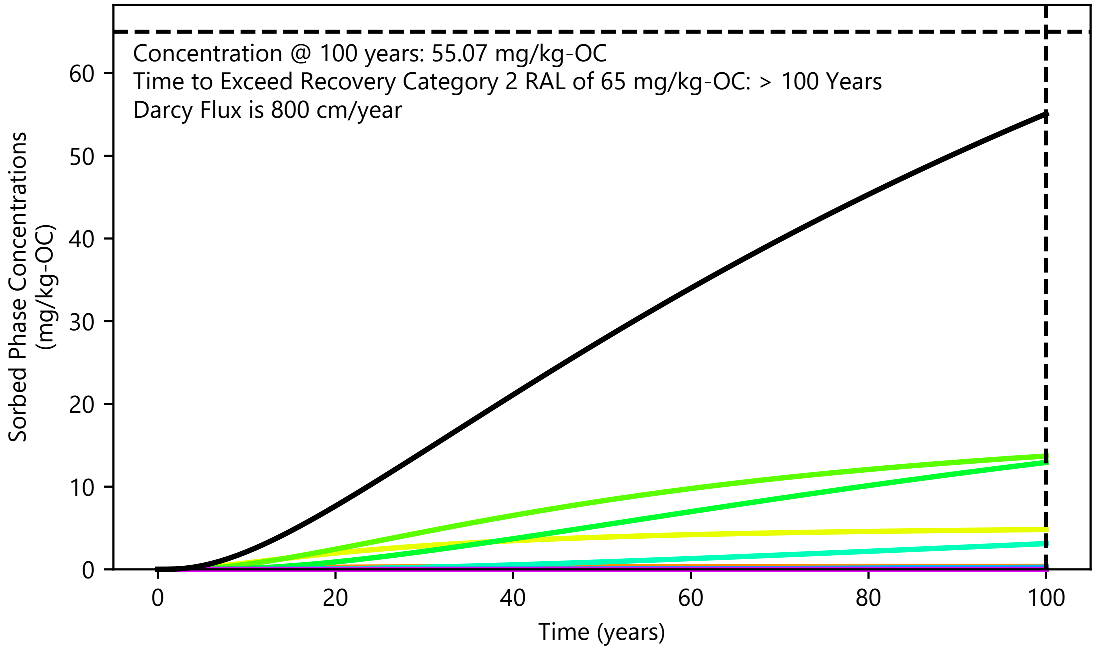
Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach

Average over top 10 cm



Concentration @ 100 years: 7.18 mg/kg-OC
Time to Exceed Recovery Category 2 RAL of 12 mg/kg-OC: > 100 Years
Darcy Flux is 800 cm/year

Average over top 45 cm



Concentration @ 100 years: 55.07 mg/kg-OC
Time to Exceed Recovery Category 2 RAL of 65 mg/kg-OC: > 100 Years
Darcy Flux is 800 cm/year

Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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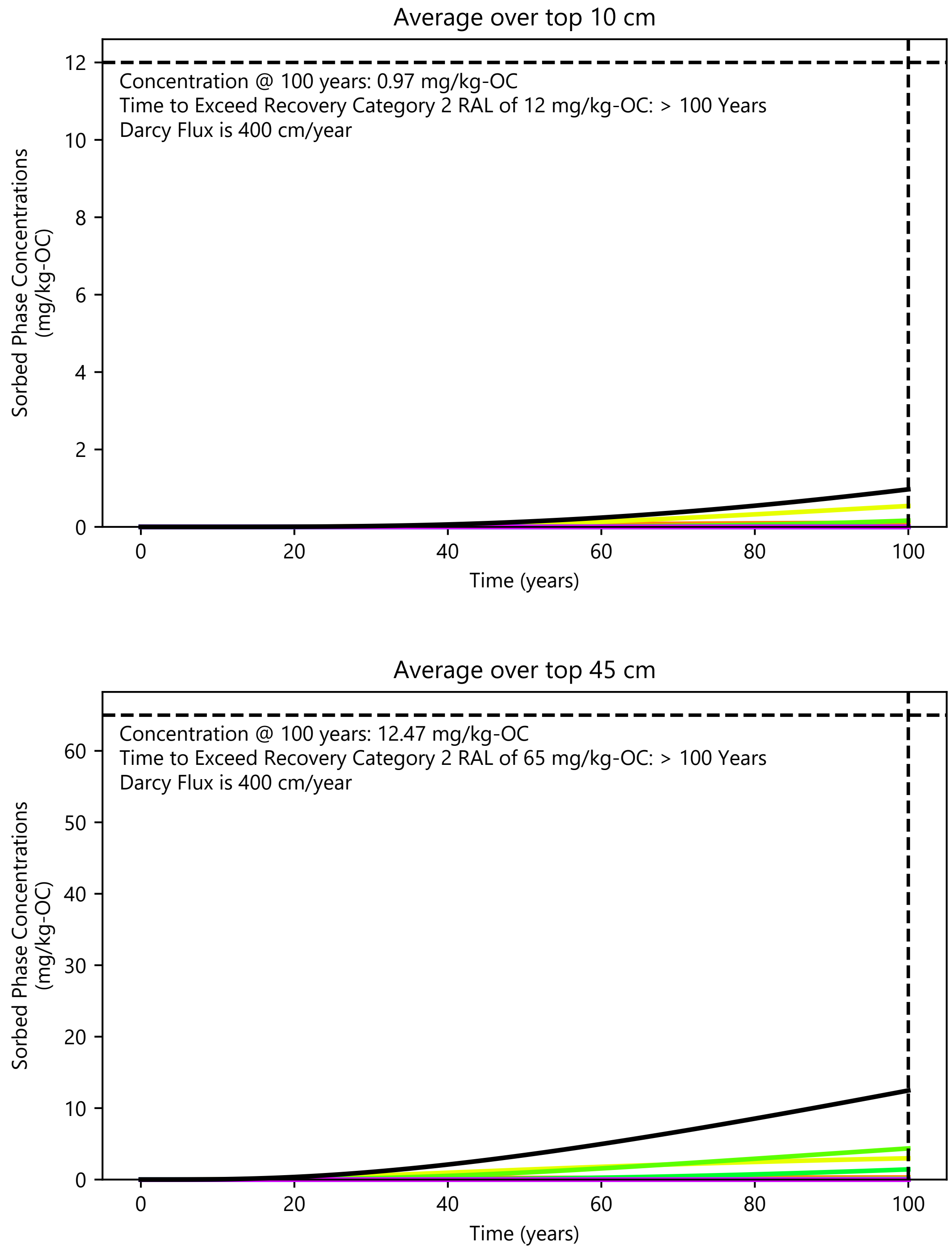
Figure G-9b

Temporal Profile of PCBs Within the Surface of the Scenario 1 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)

Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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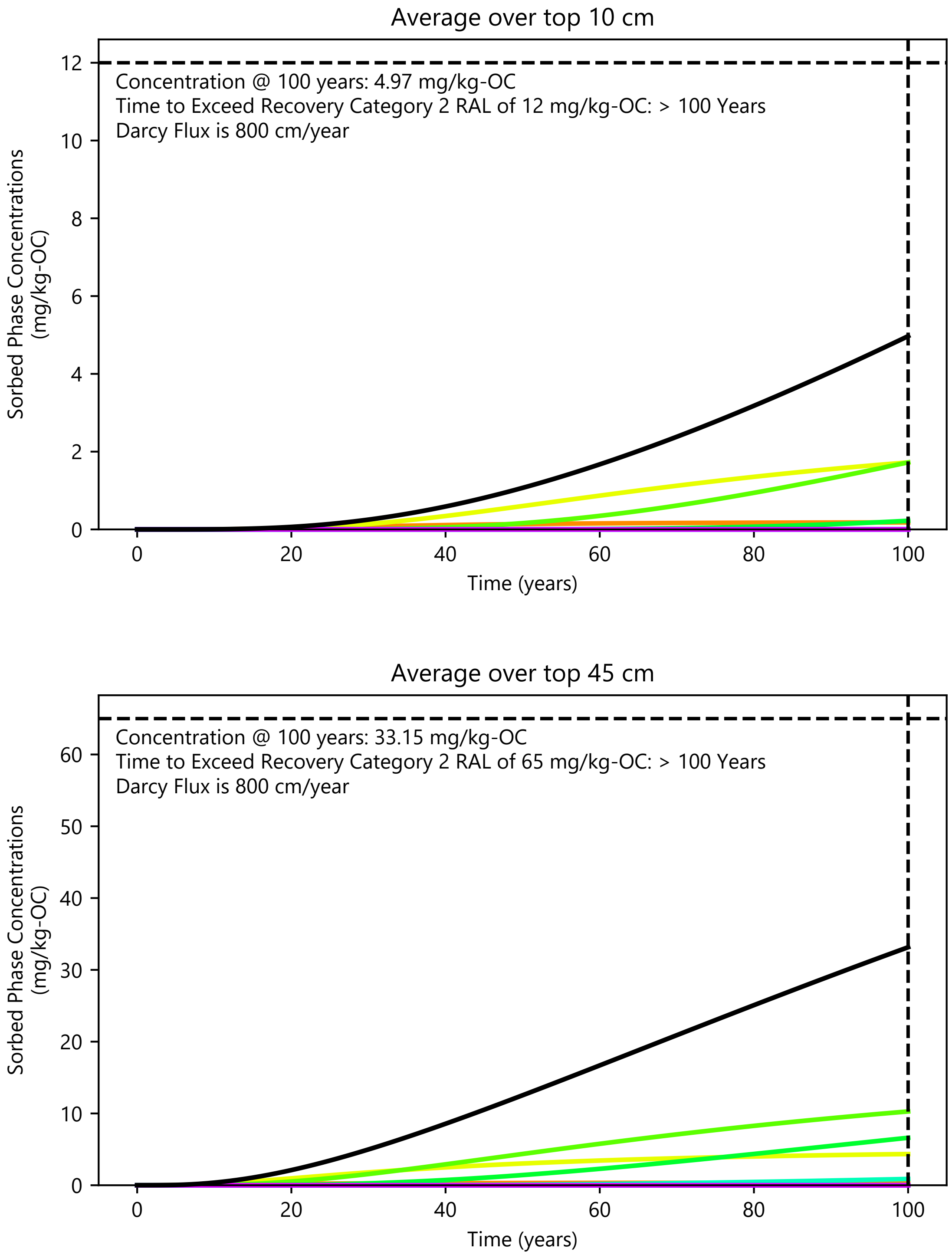
Figure G-10a
Temporal Profile of PCBs Within the Surface of the Scenario 2 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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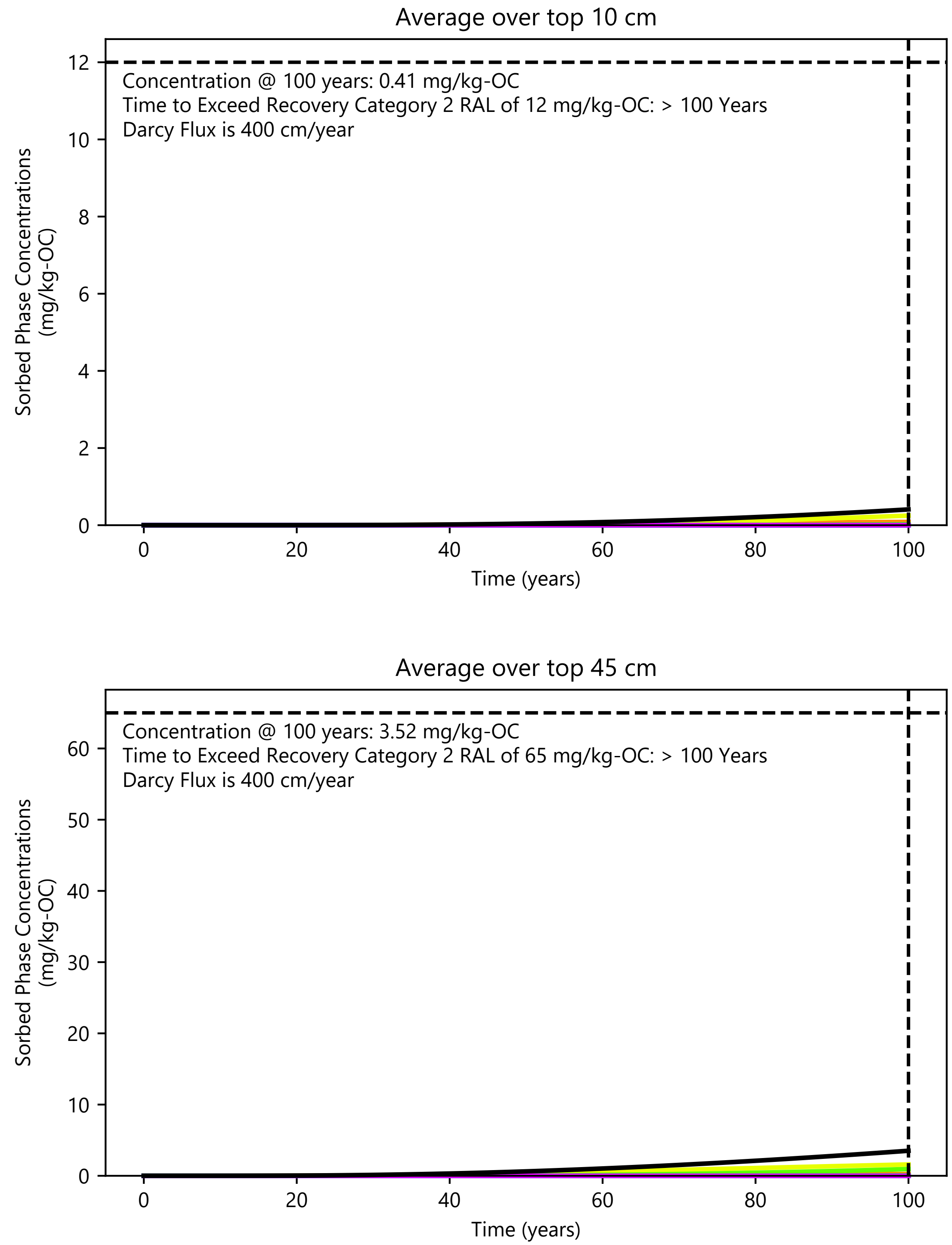
Figure G-10b
Temporal Profile of PCBs Within the Surface of the Scenario 2 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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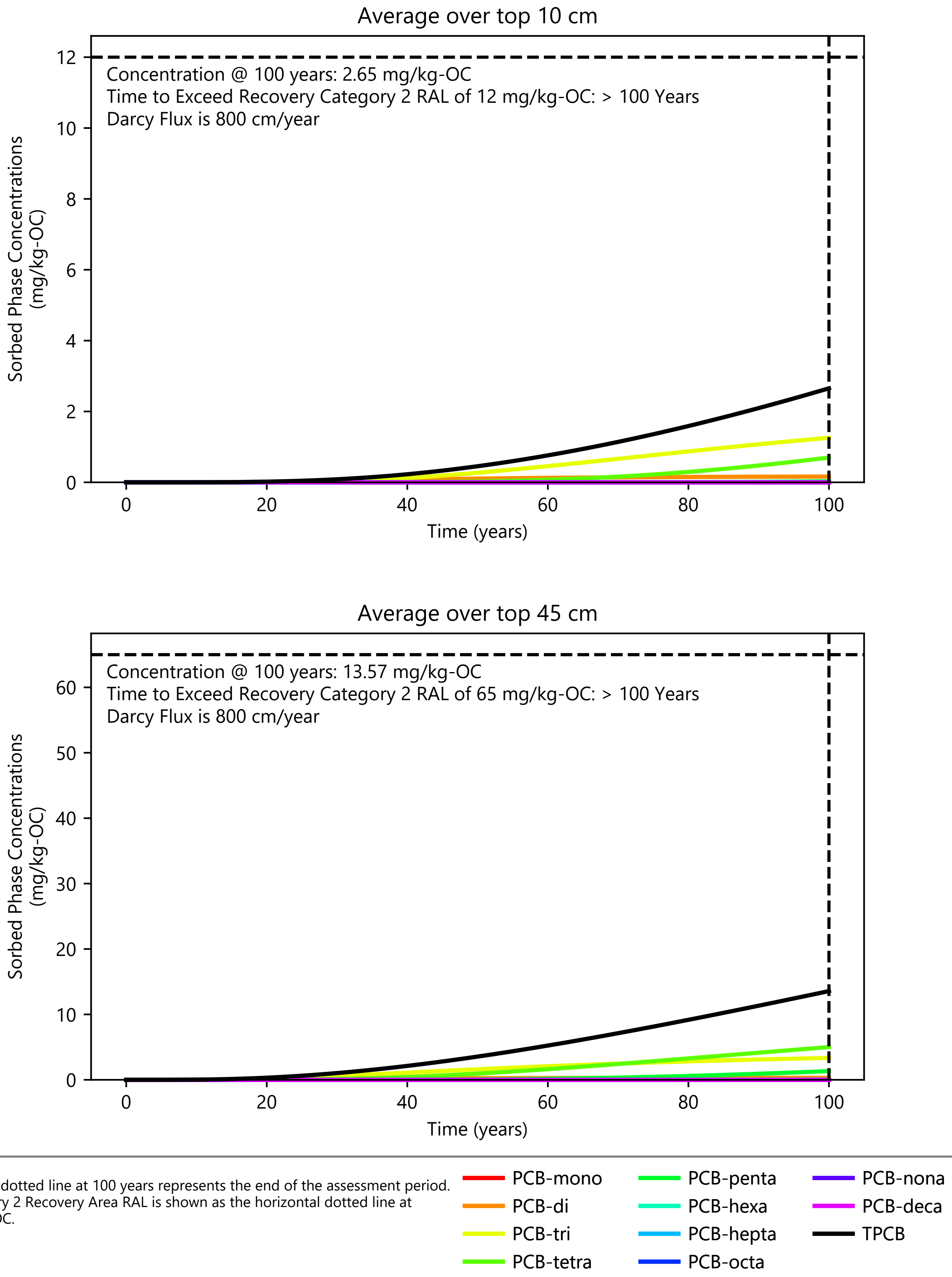
Figure G-11a
Temporal Profile of PCBs Within the Surface of the Scenario 3 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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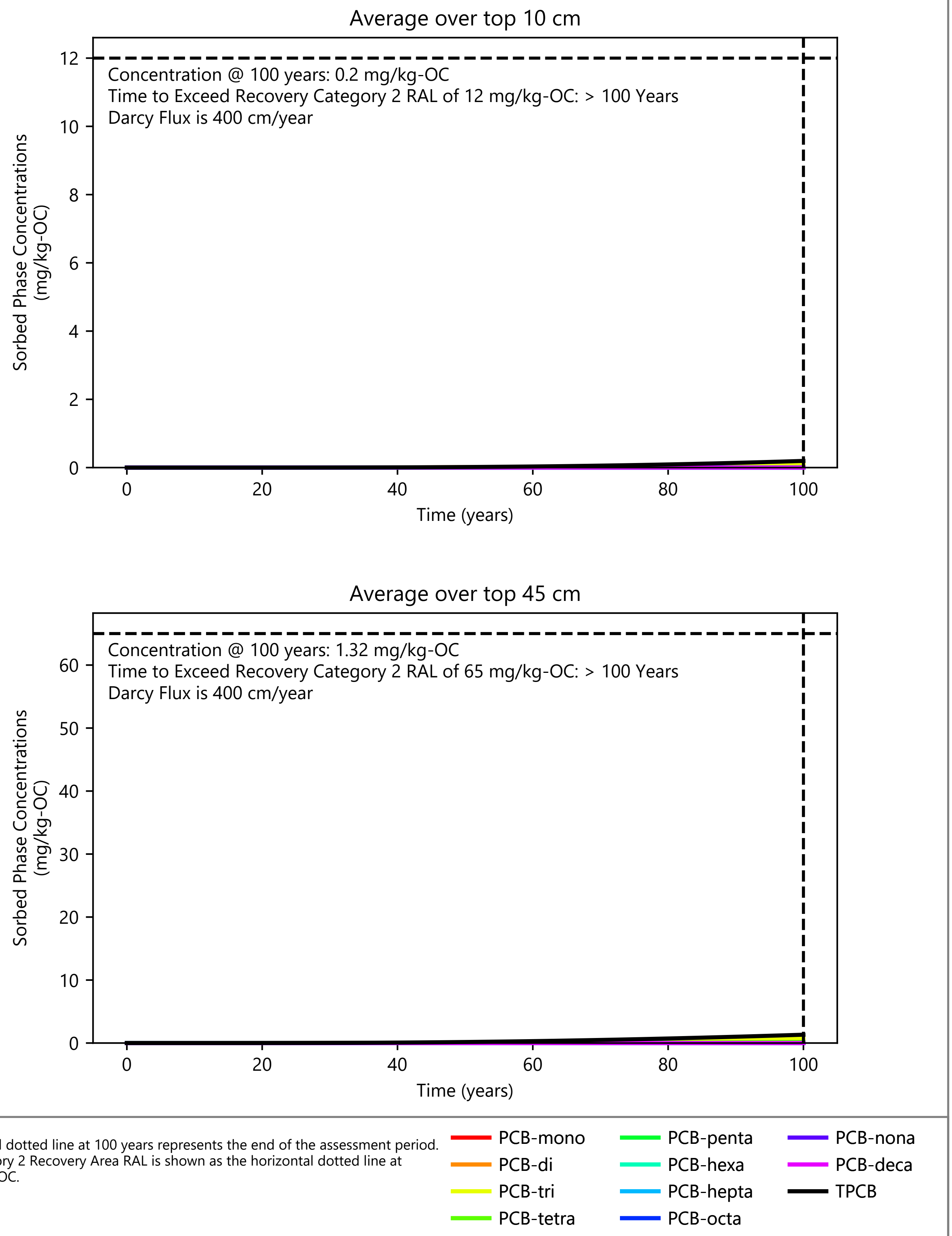
Figure G-11b
Temporal Profile of PCBs Within the Surface of the Scenario 3 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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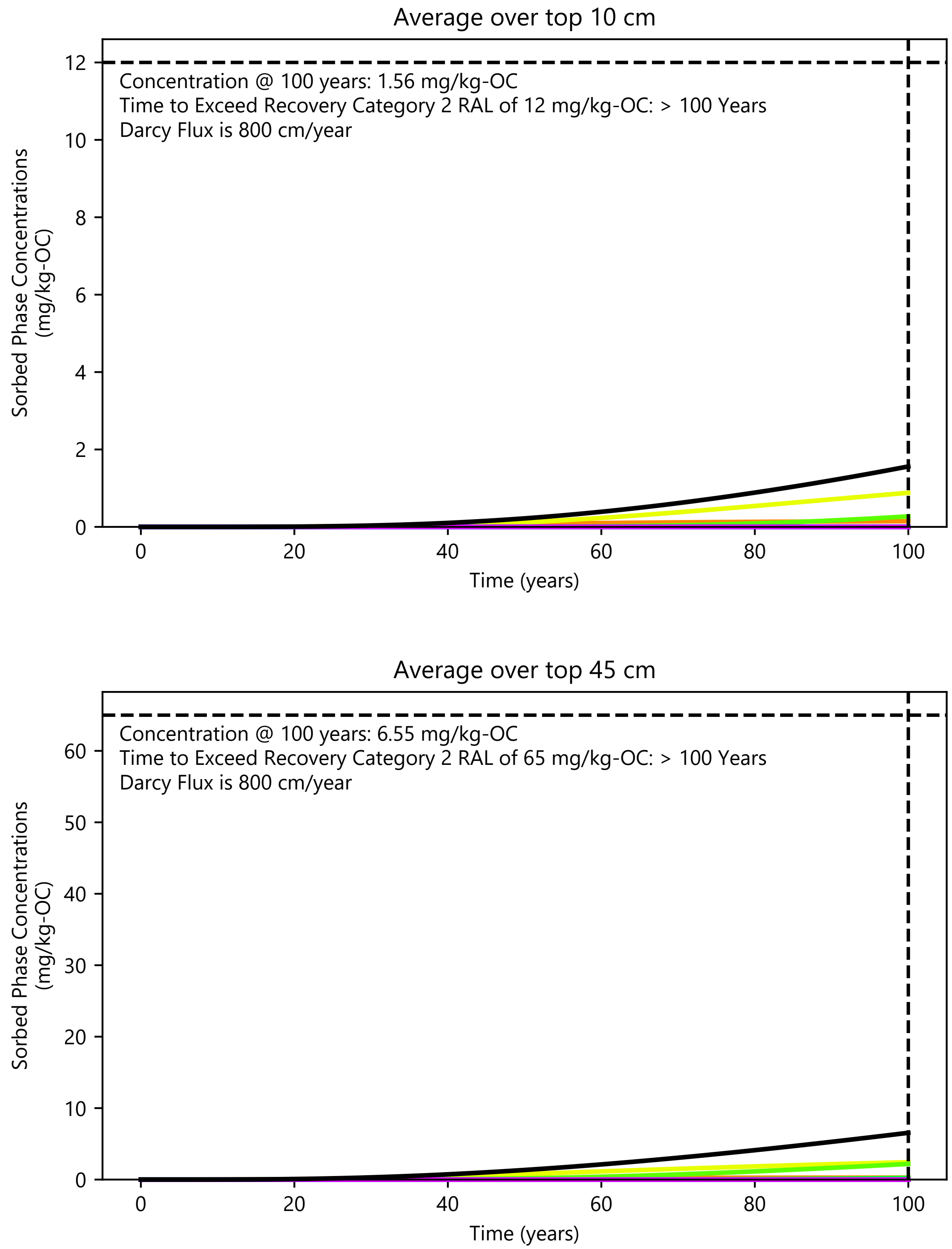
Figure G-12a
Temporal Profile of PCBs Within the Surface of the Scenario 4 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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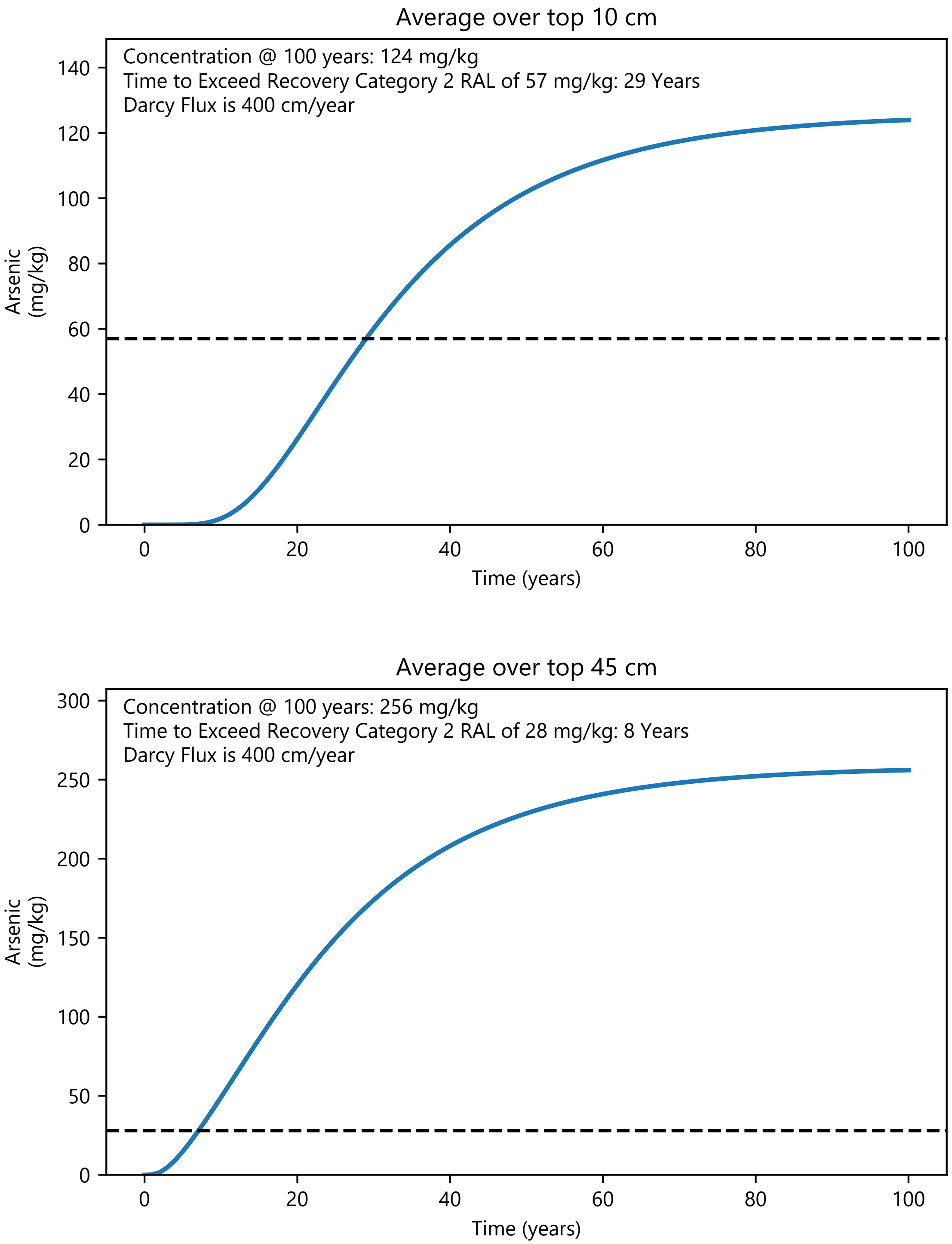
Figure G-12b

Temporal Profile of PCBs Within the Surface of the Scenario 4 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)

Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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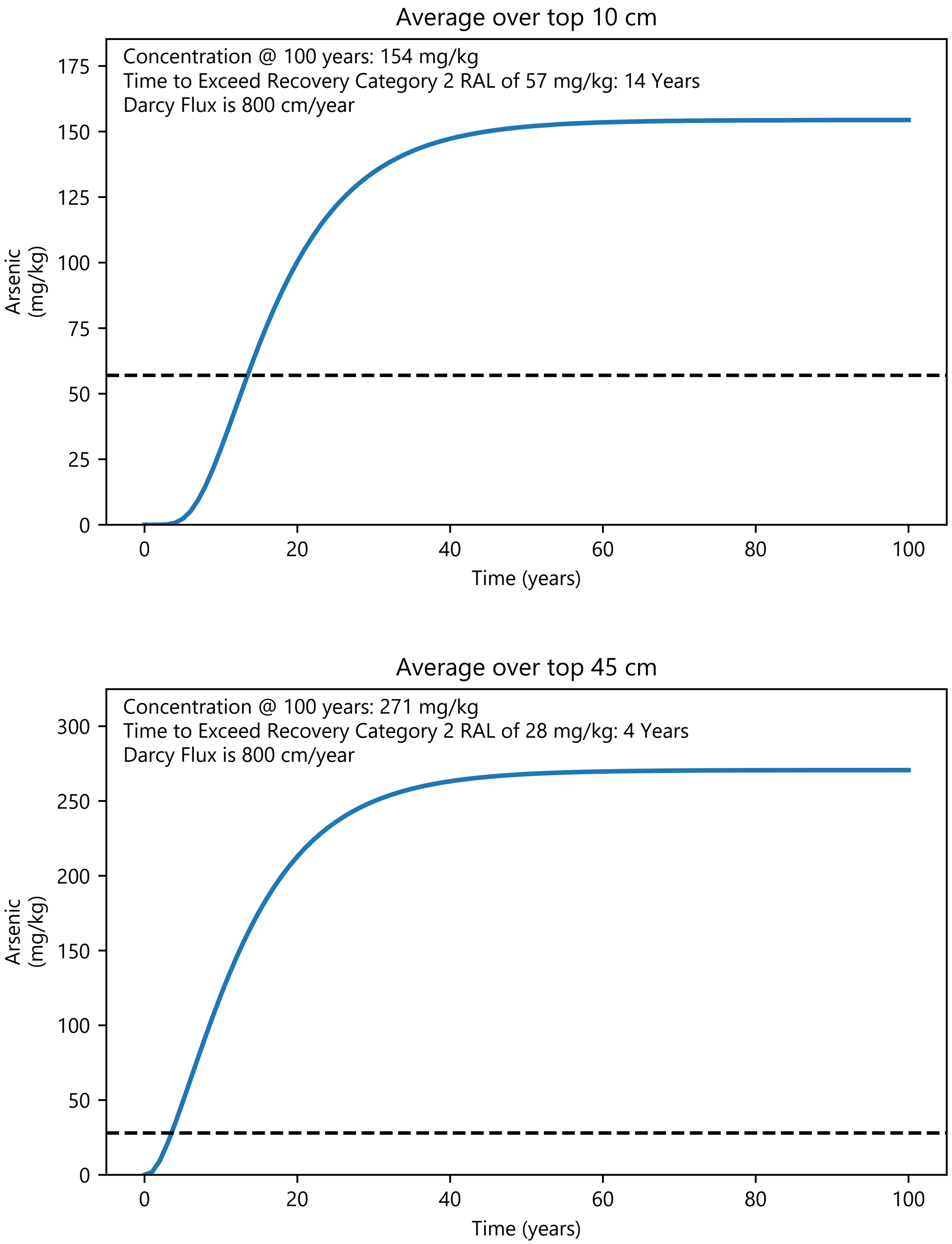
Figure G-13a
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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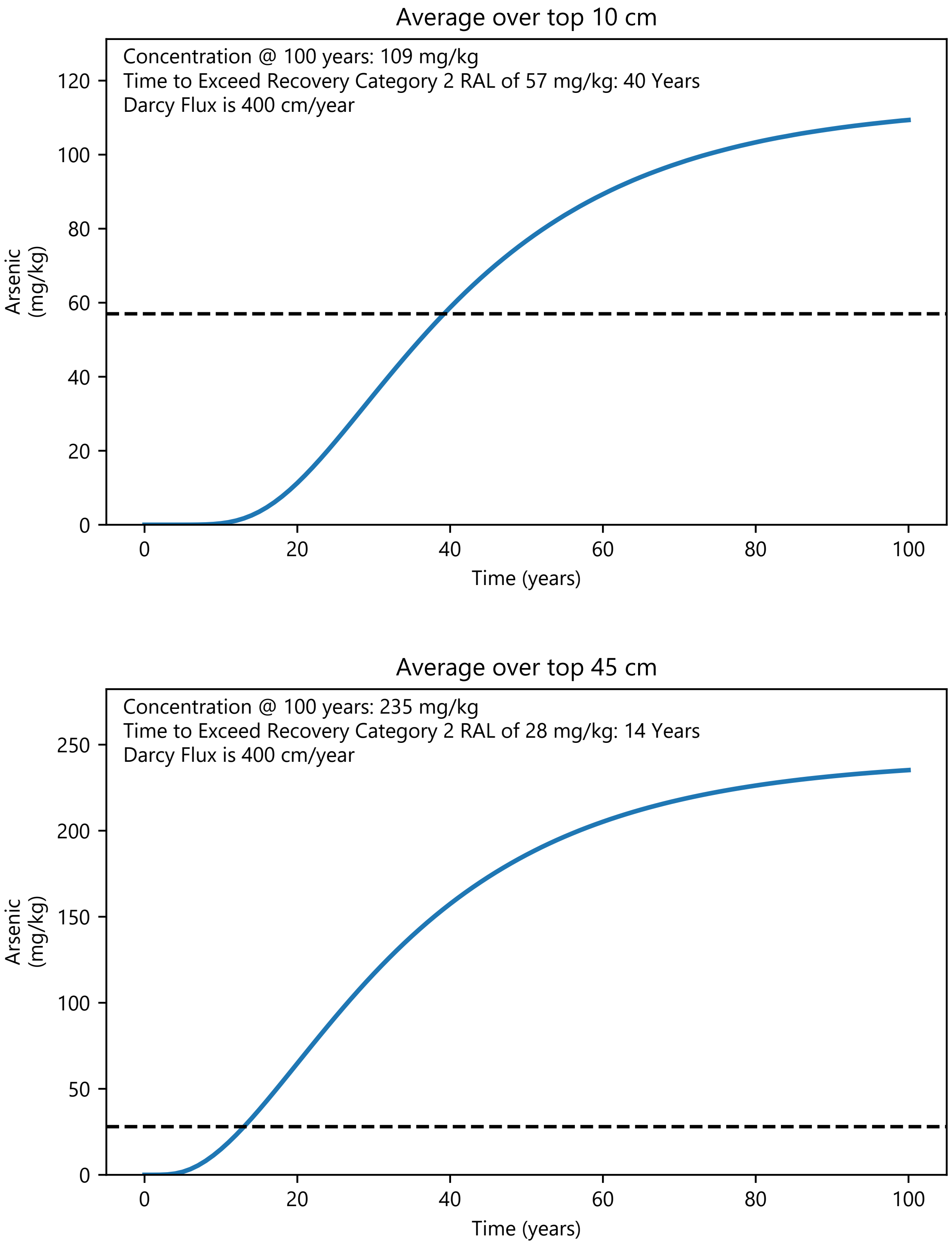
Figure G-13b
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)


Average over top 10 cm

Concentration @ 100 years: 109 mg/kg
Time to Exceed Recovery Category 2 RAL of 57 mg/kg: 40 Years
Darcy Flux is 400 cm/year

Average over top 45 cm

Concentration @ 100 years: 235 mg/kg
Time to Exceed Recovery Category 2 RAL of 28 mg/kg: 14 Years
Darcy Flux is 400 cm/year

Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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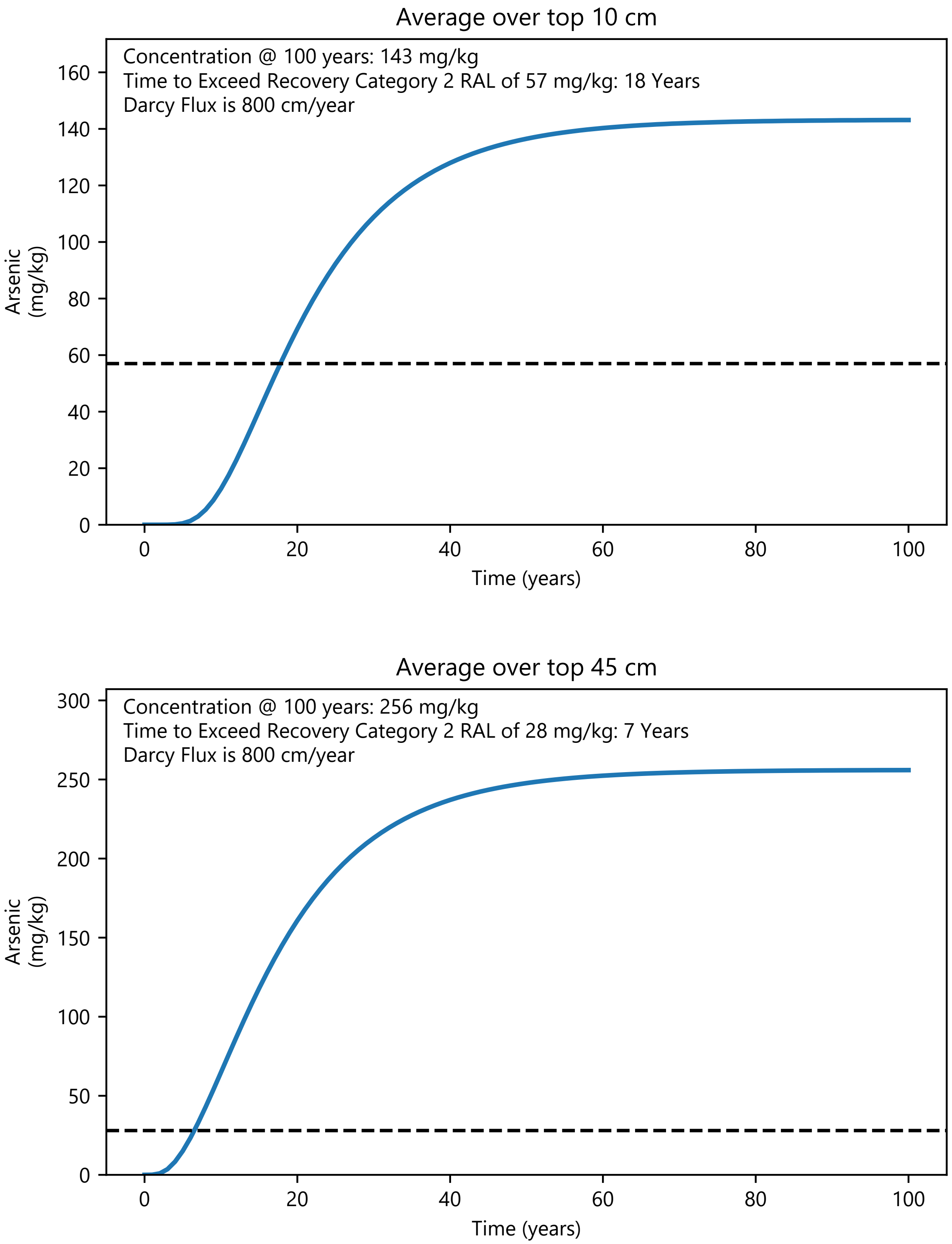
Figure G-14a
Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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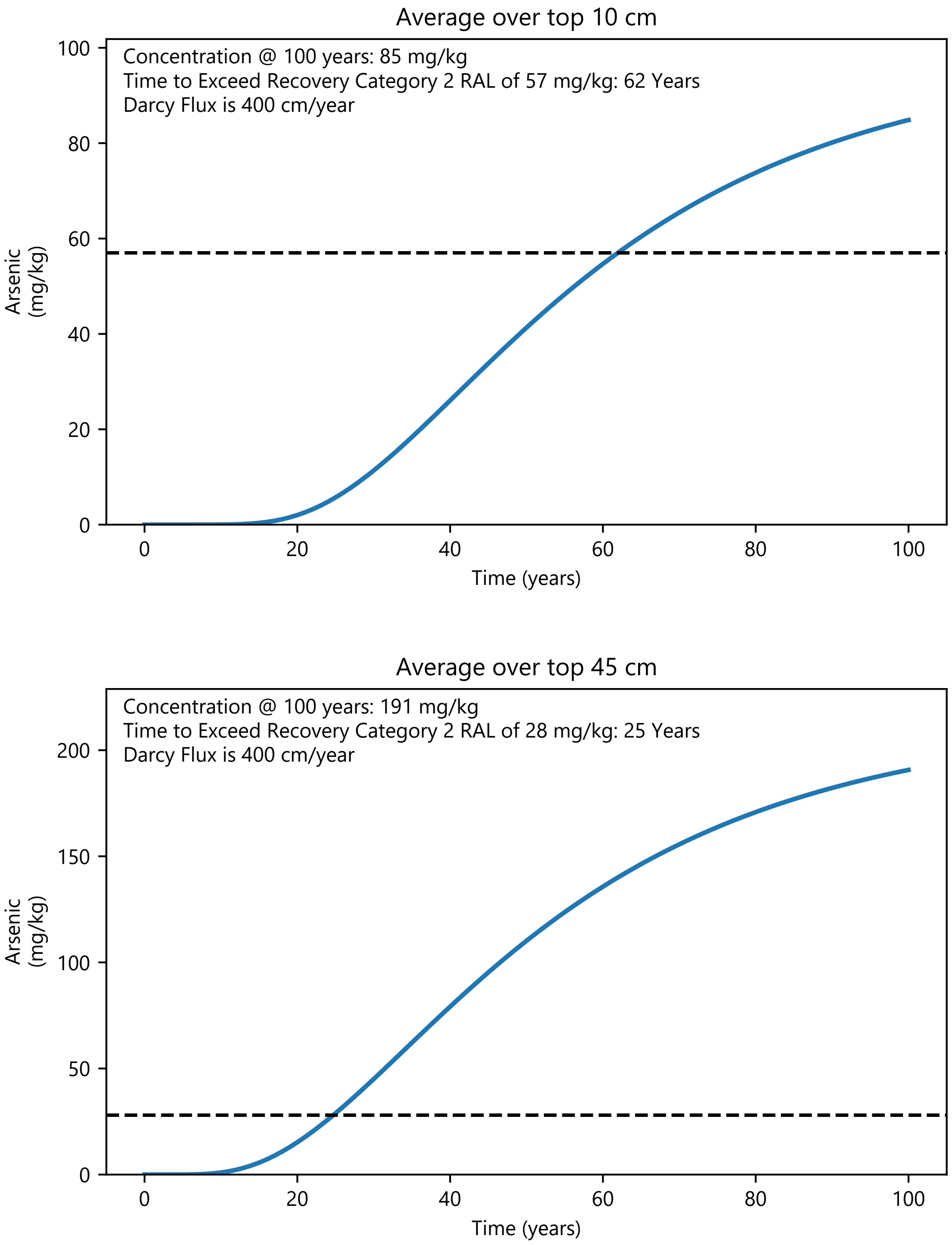
Figure G-14b
Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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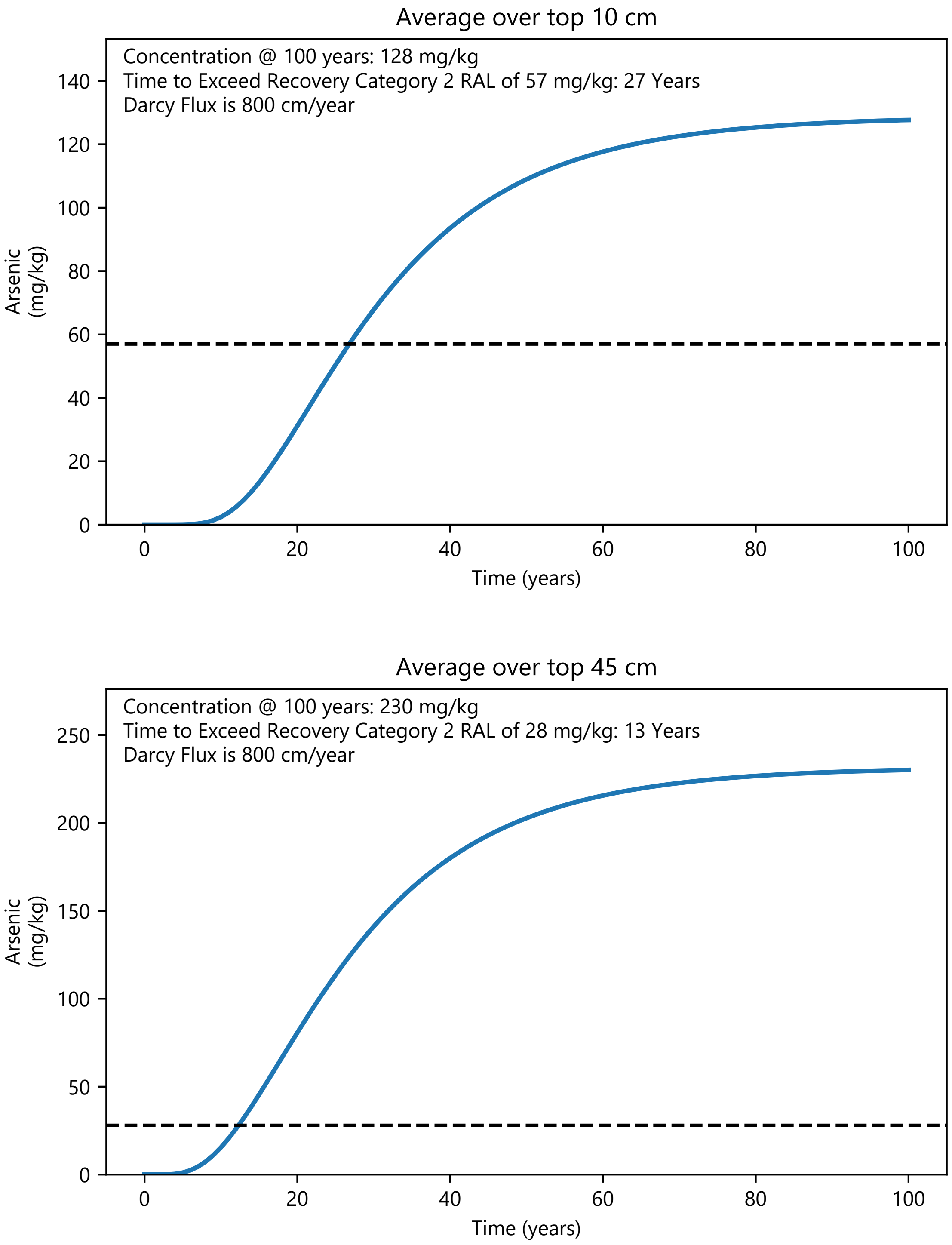
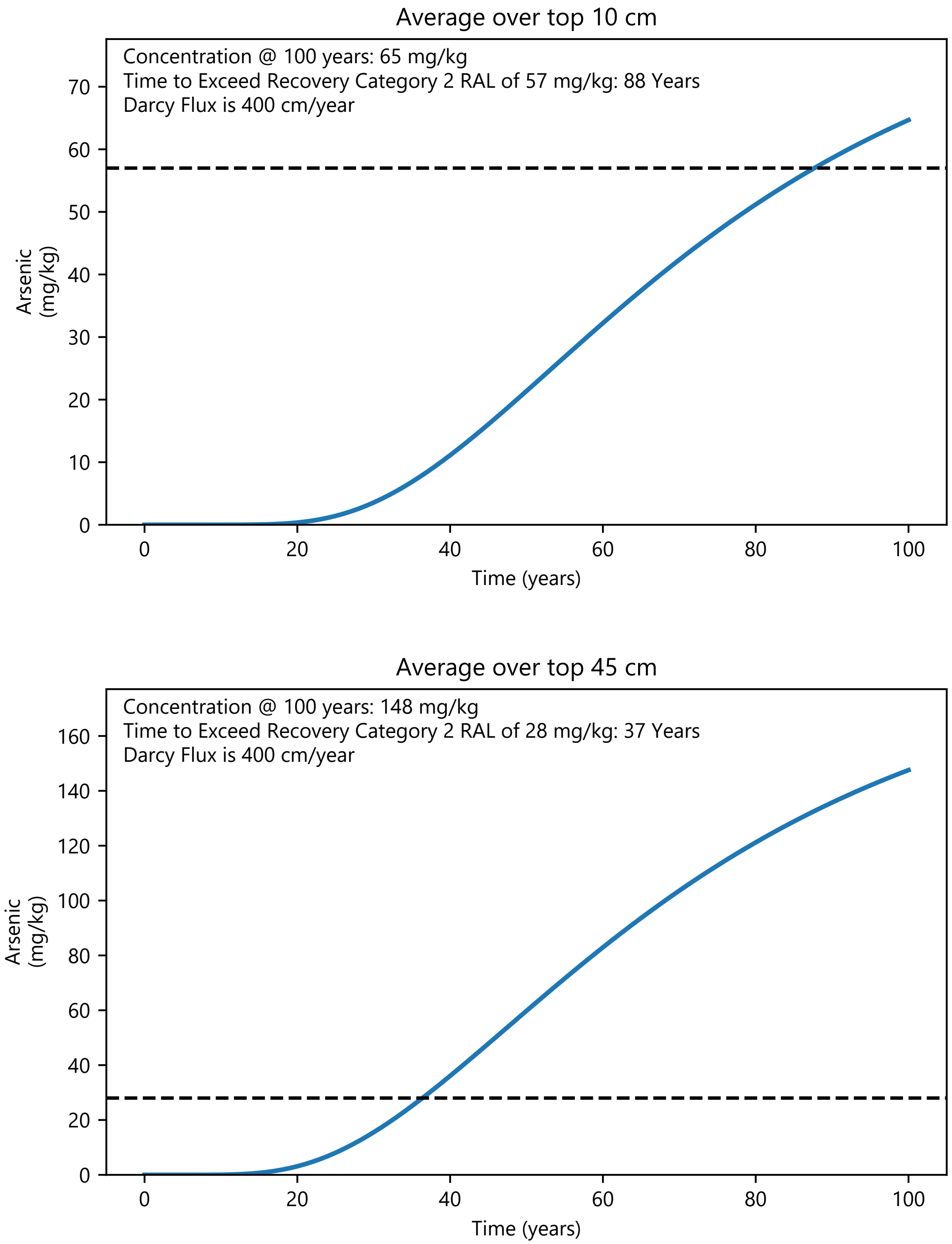
Figure G-15a
Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI
(400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



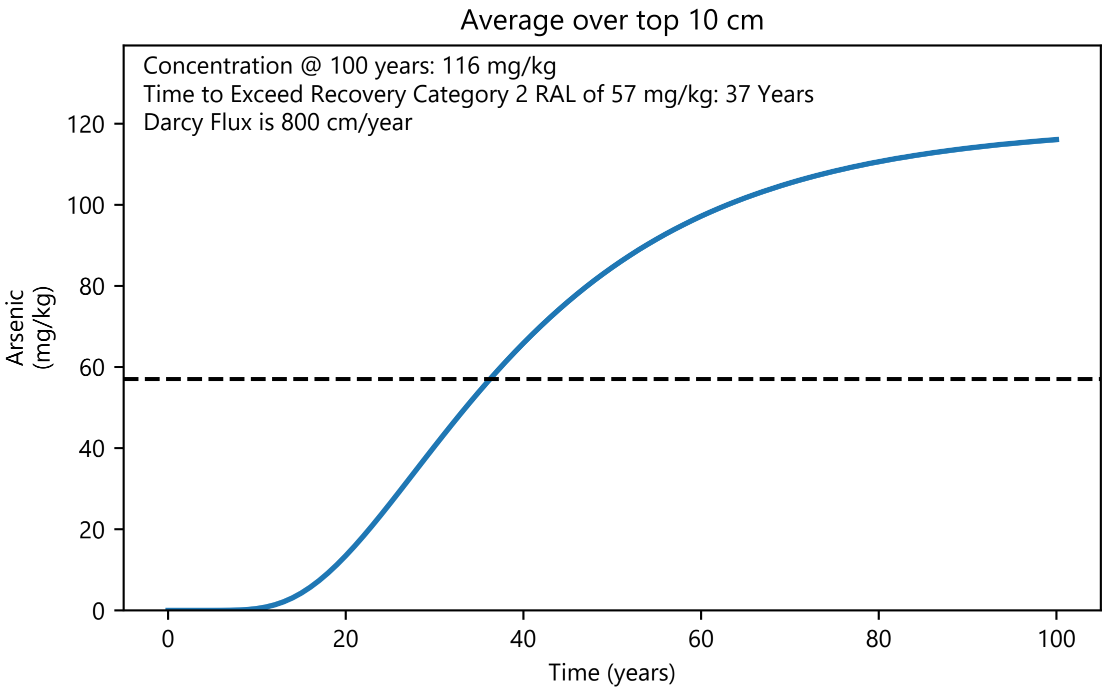
Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

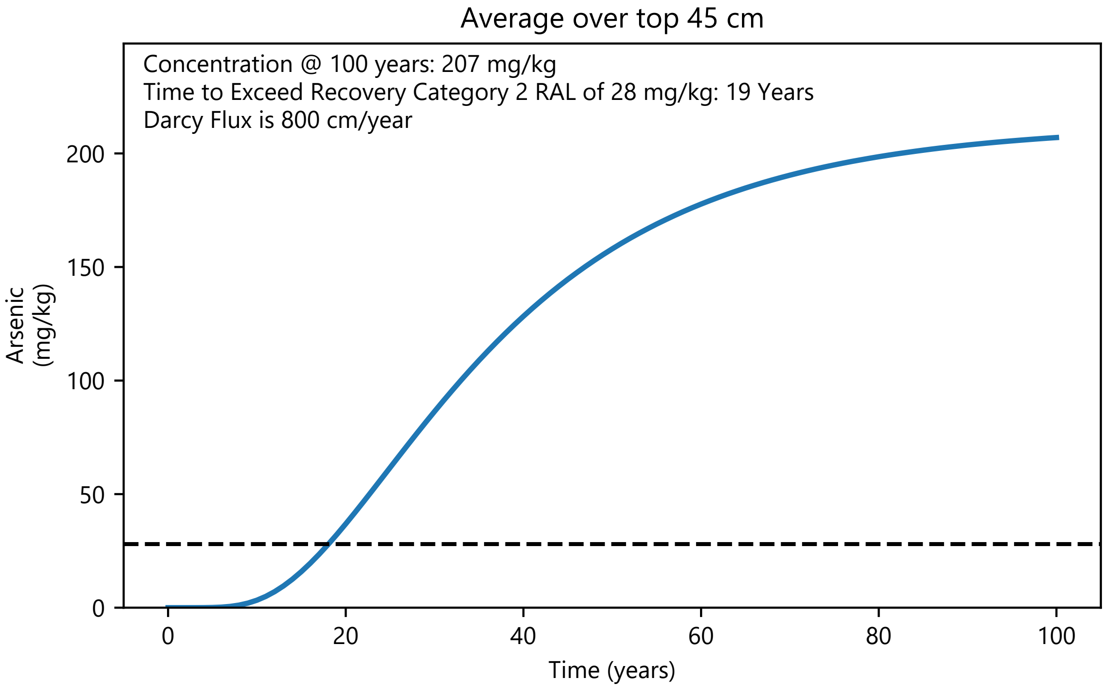
Figure G-15b
Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

Figure G-16a
Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)

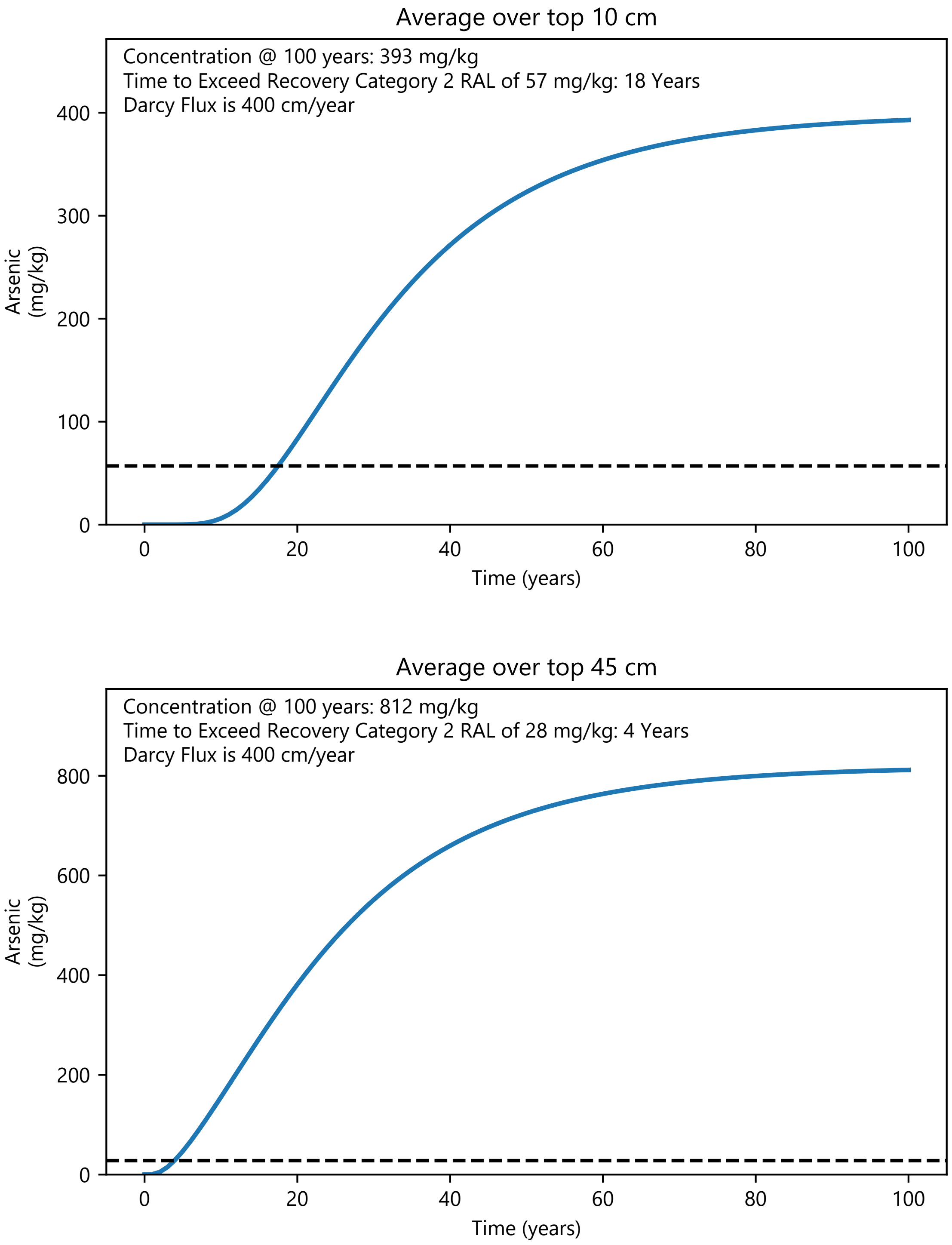




Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

Figure G-16b

Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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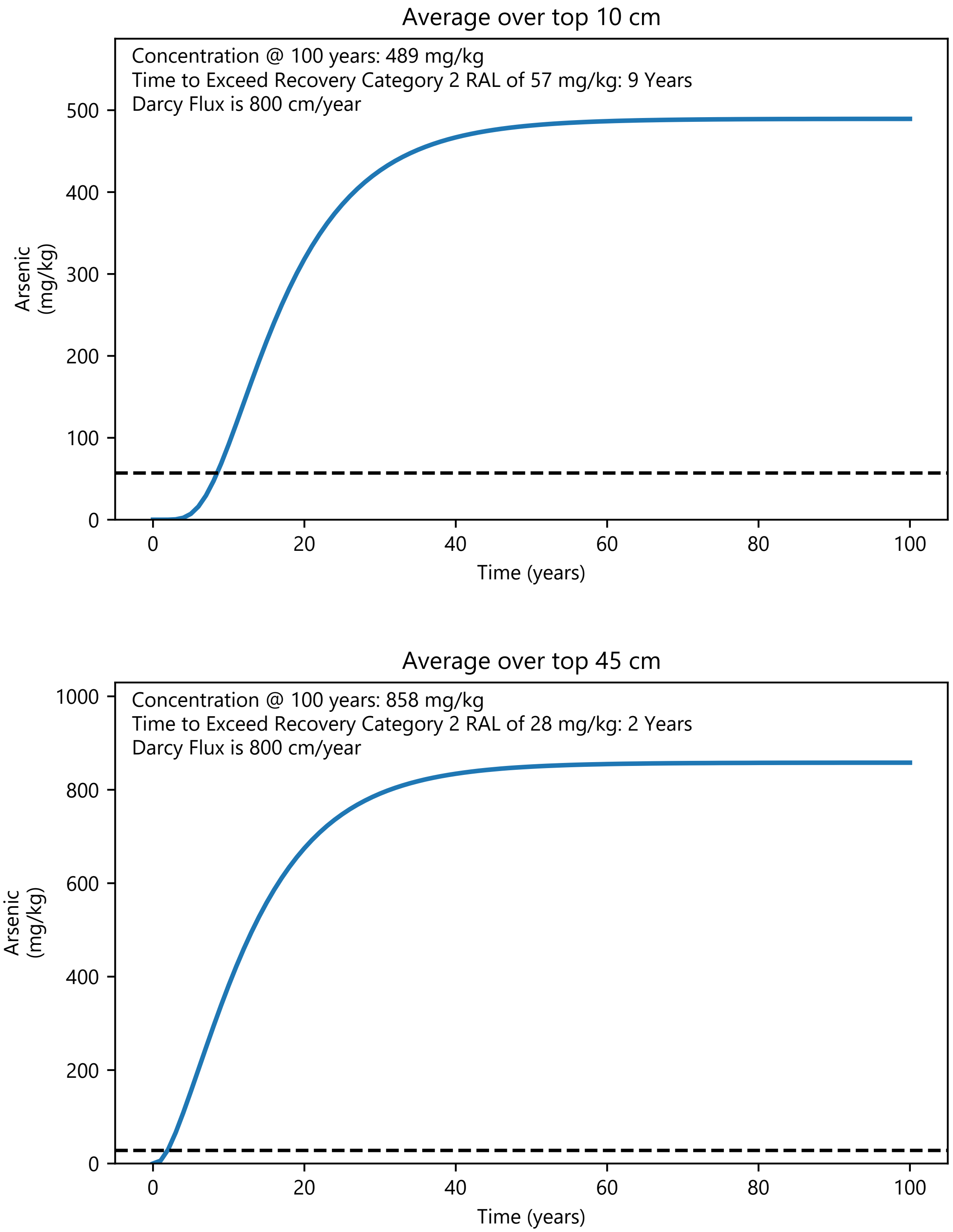
Figure G-17a
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Concentration @ 100 years: 489 mg/kg
Time to Exceed Recovery Category 2 RAL of 57 mg/kg: 9 Years
Darcy Flux is 800 cm/year

Concentration @ 100 years: 858 mg/kg
Time to Exceed Recovery Category 2 RAL of 28 mg/kg: 2 Years
Darcy Flux is 800 cm/year

Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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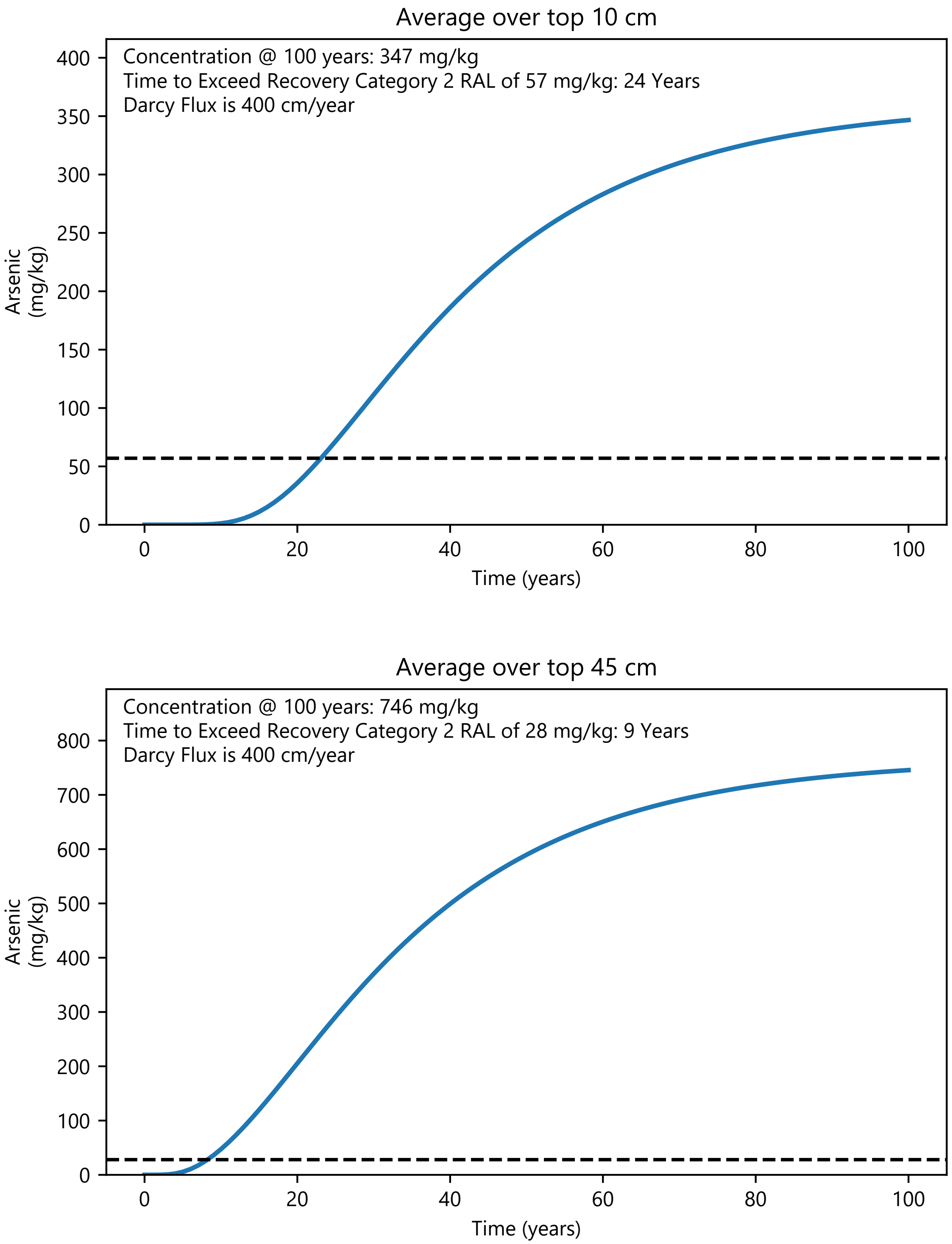
Figure G-17b
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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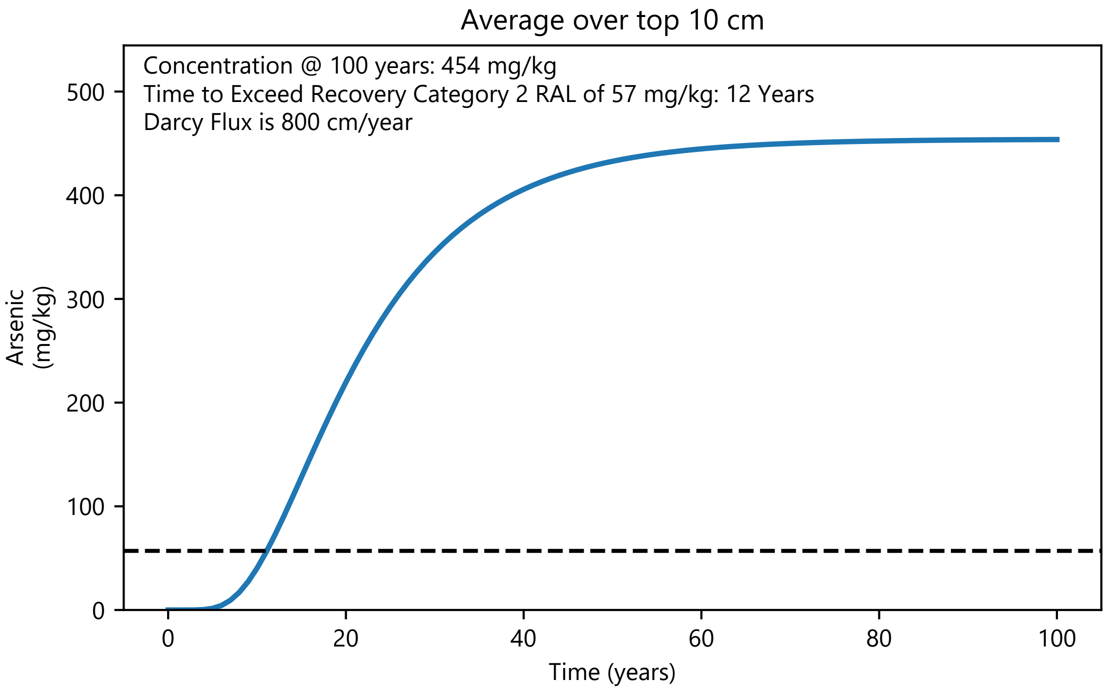
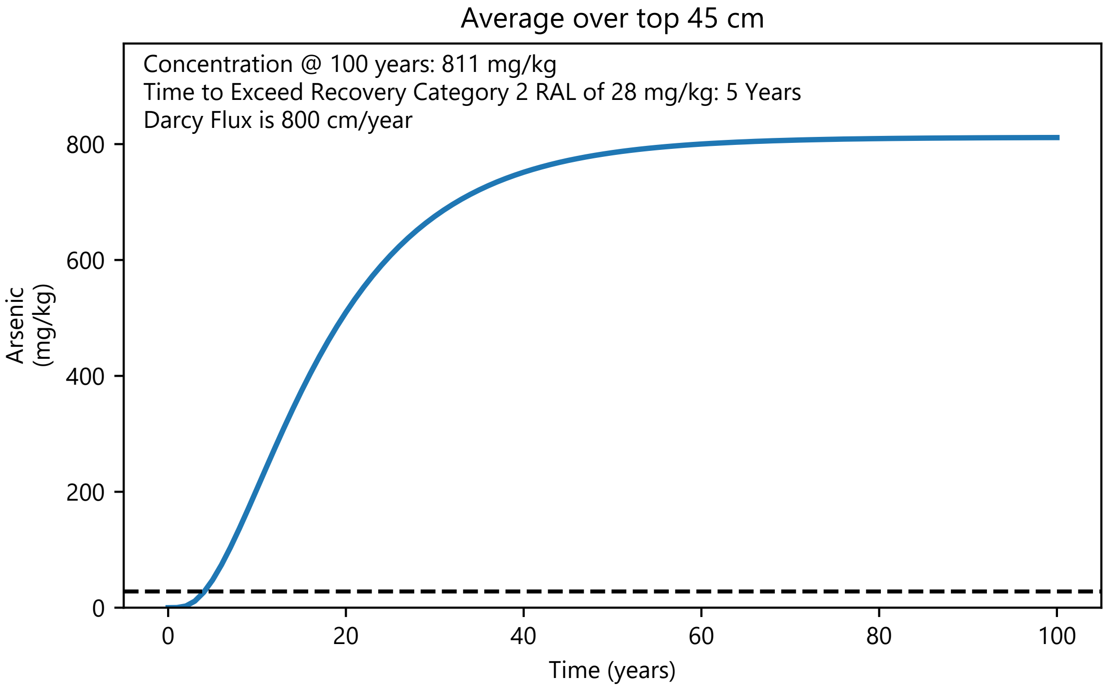
Figure G-18a
Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)





Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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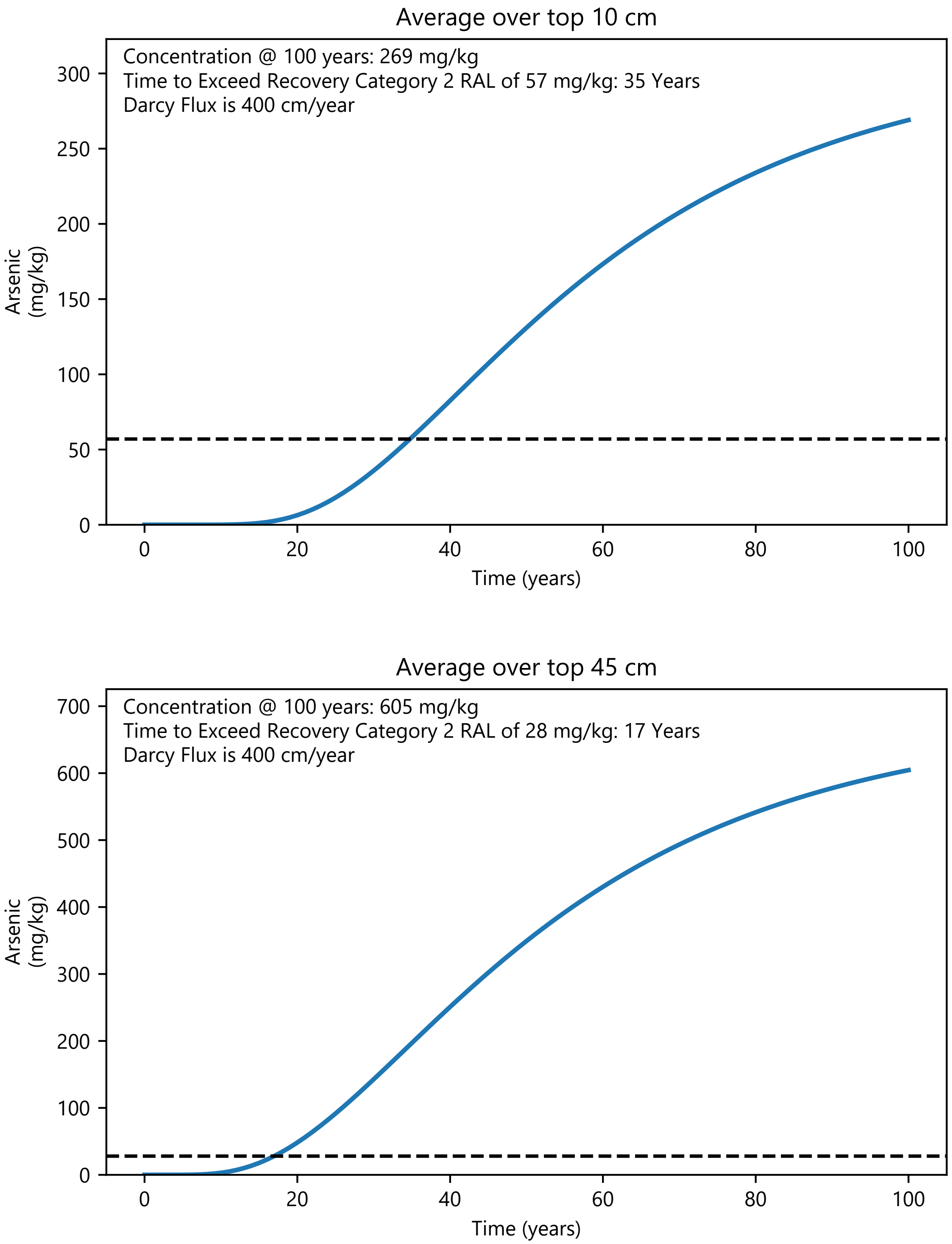
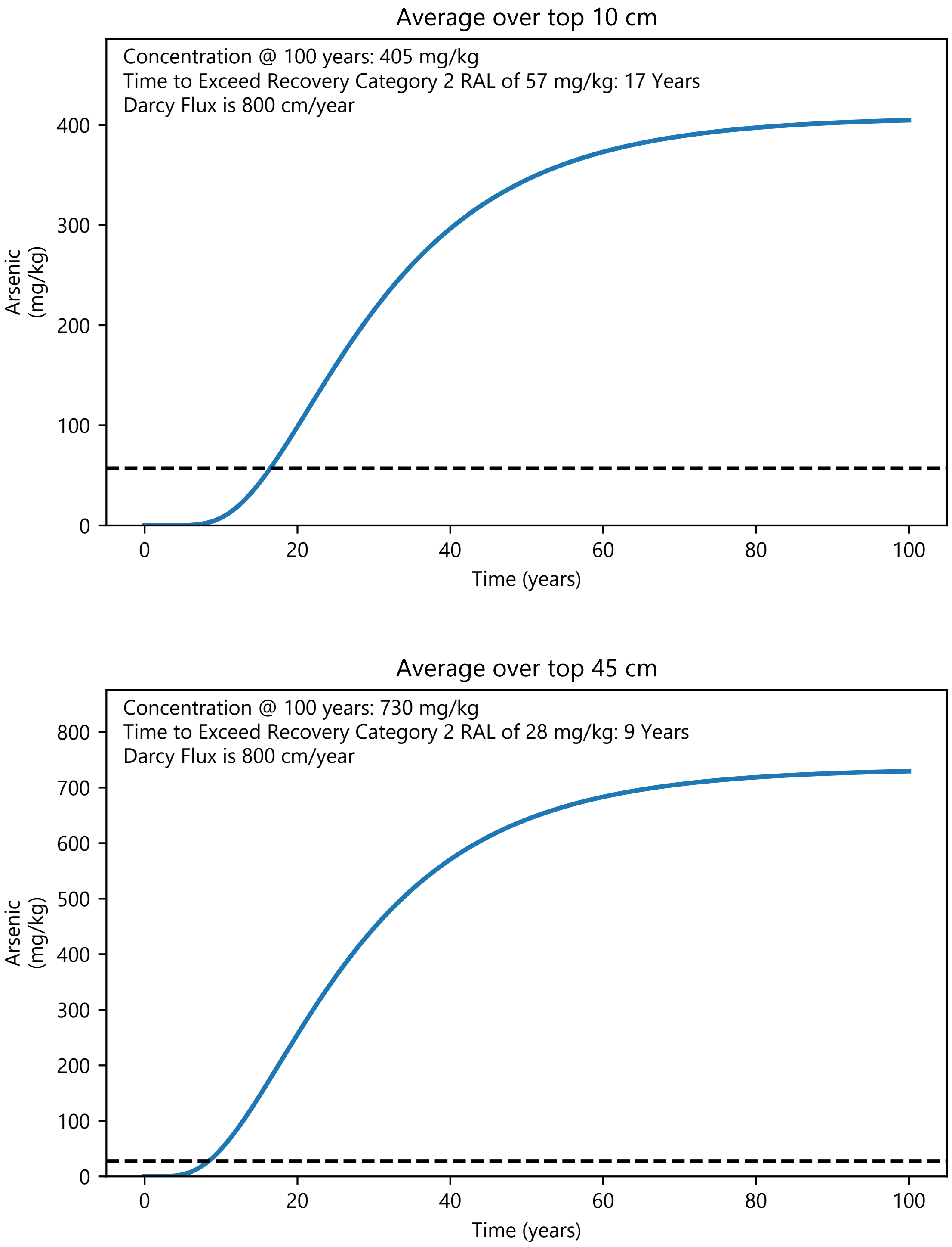
Figure G-18b
Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

Figure G-19a

Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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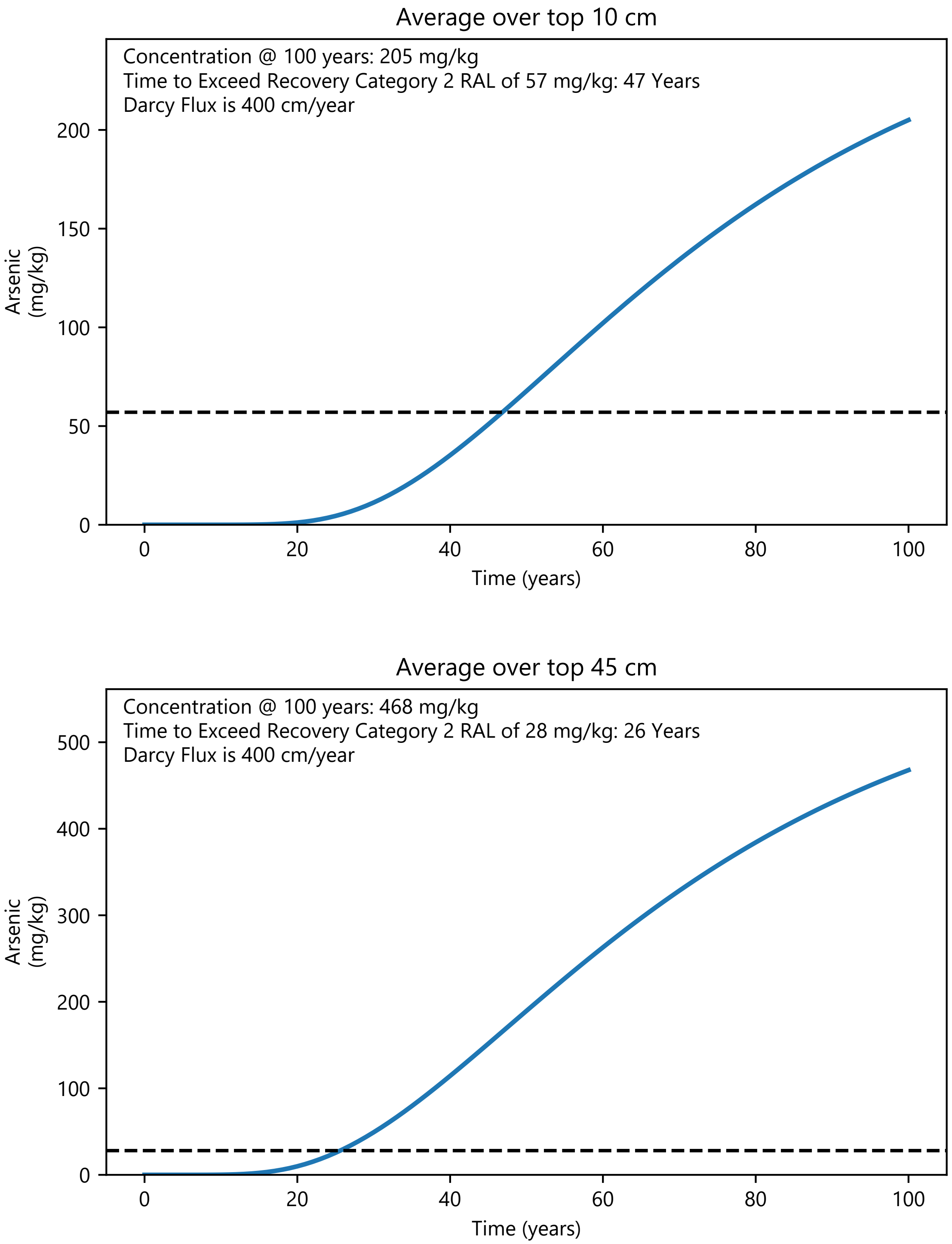
Figure G-19b
Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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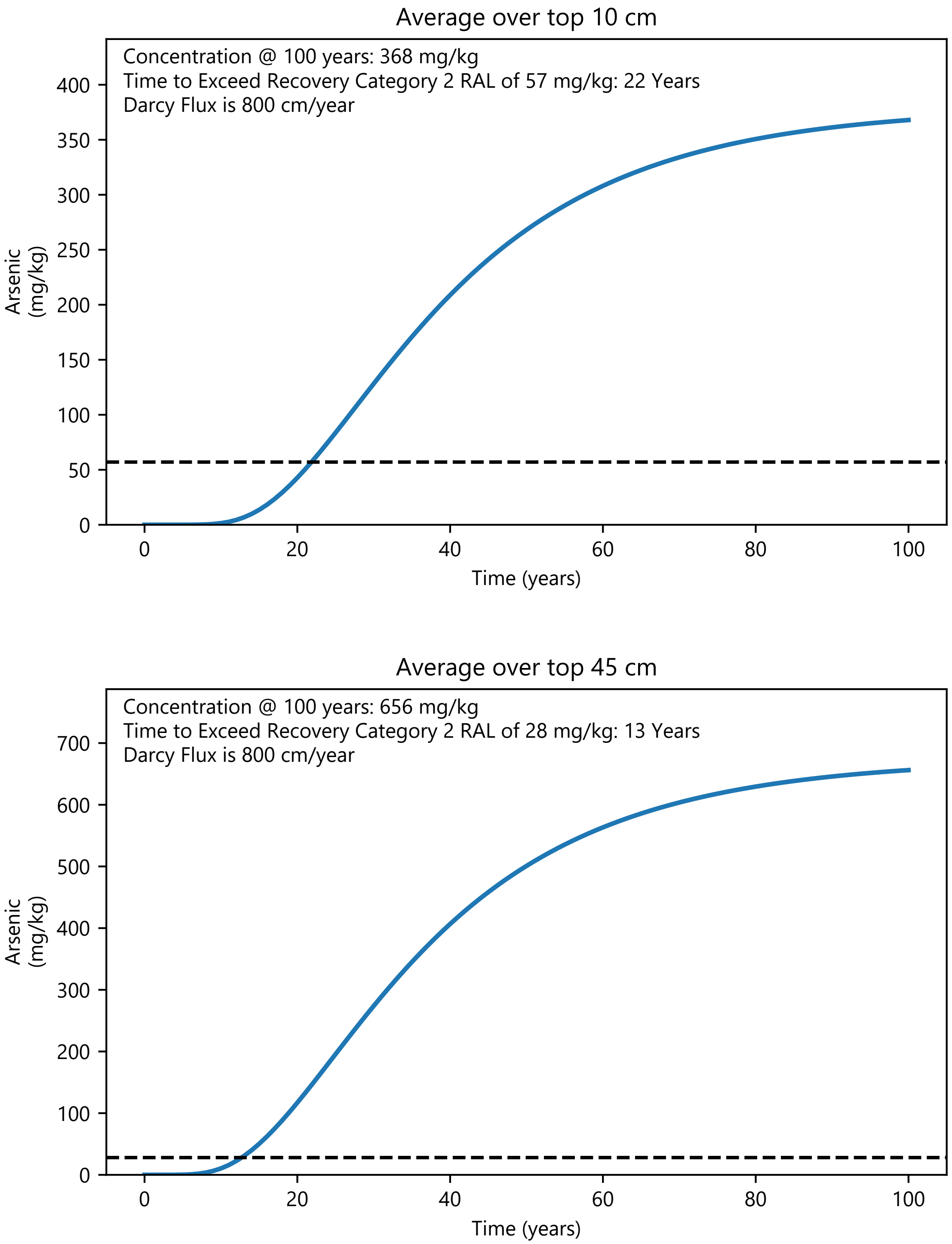
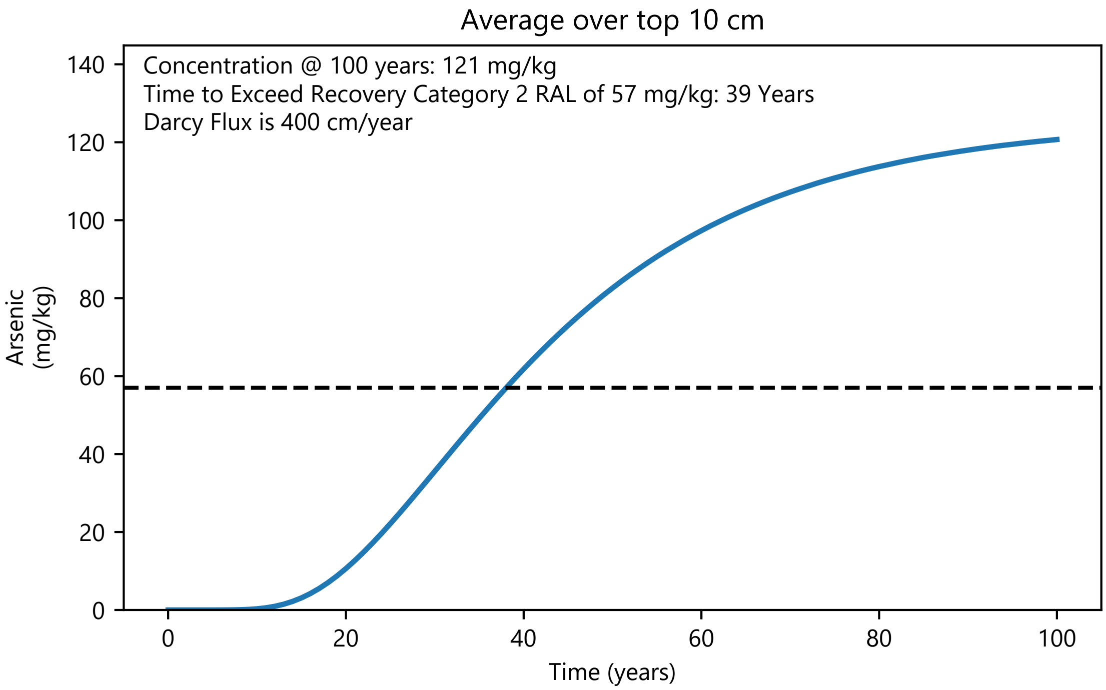
Figure G-20a
Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)

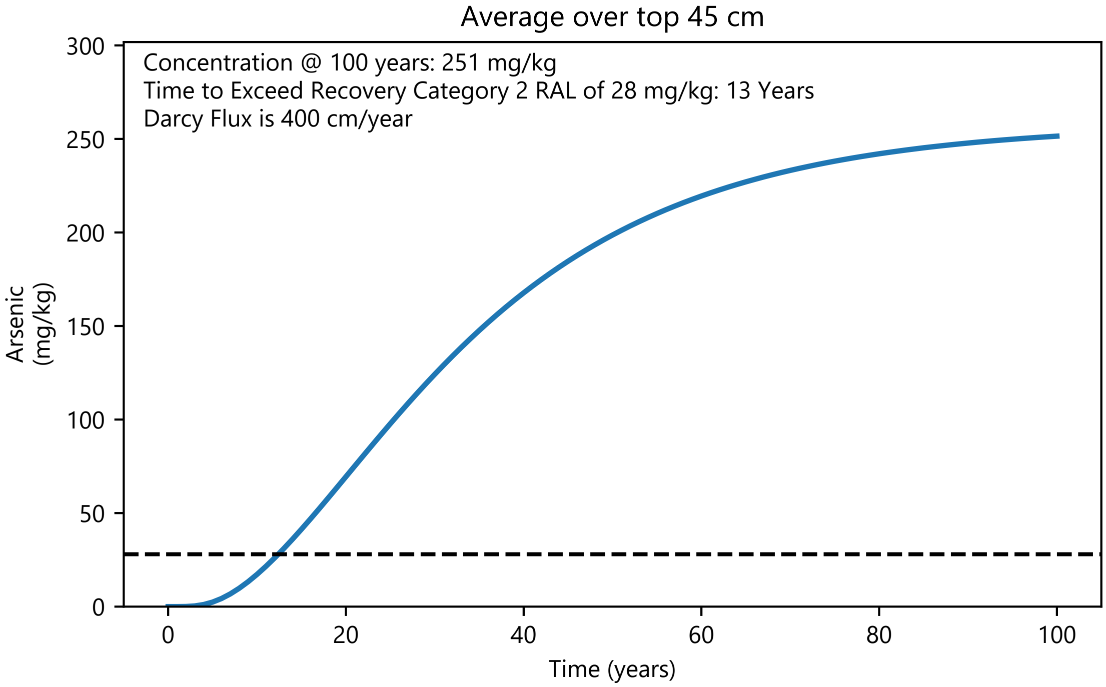
Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

Figure G-20b
Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)





Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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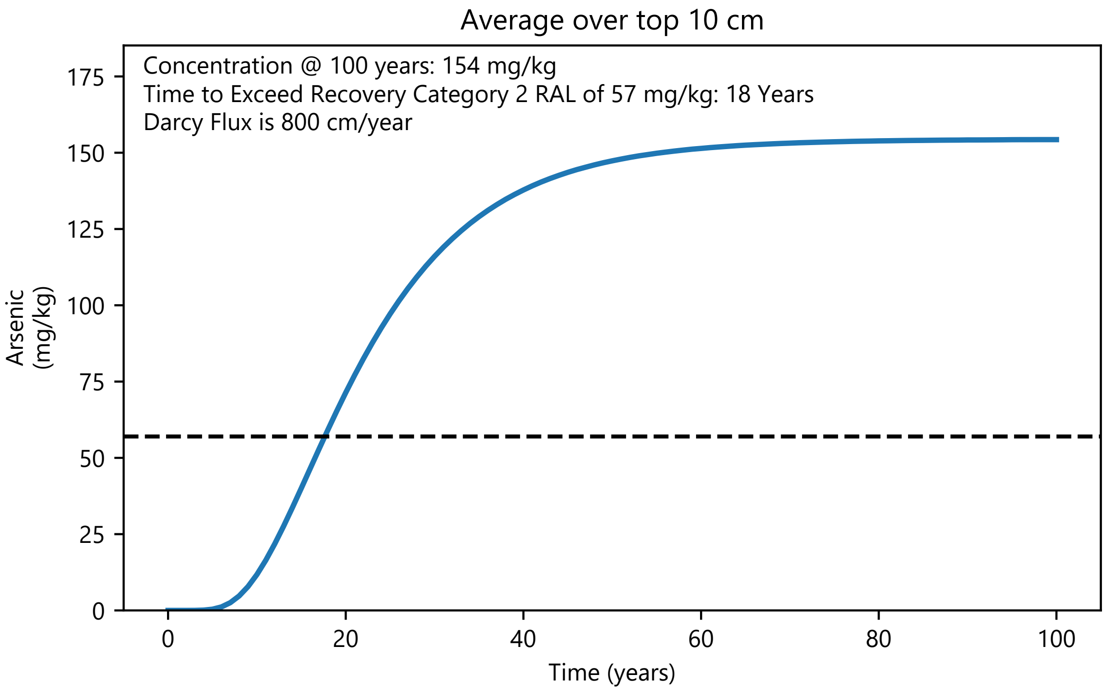
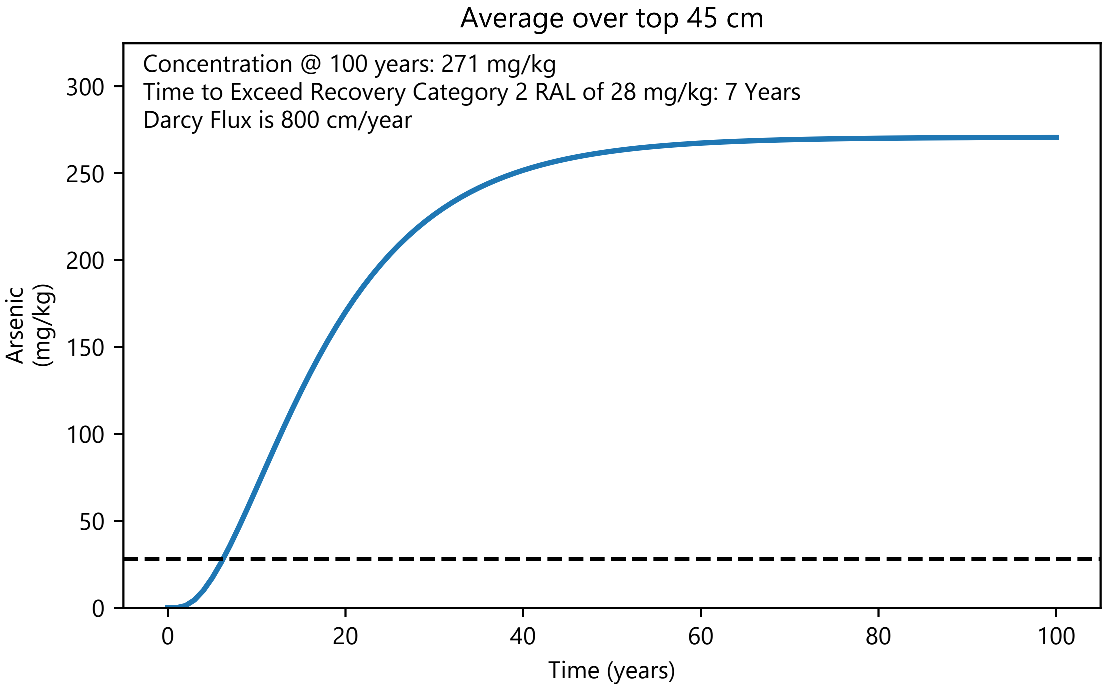
Figure G-21a
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)





Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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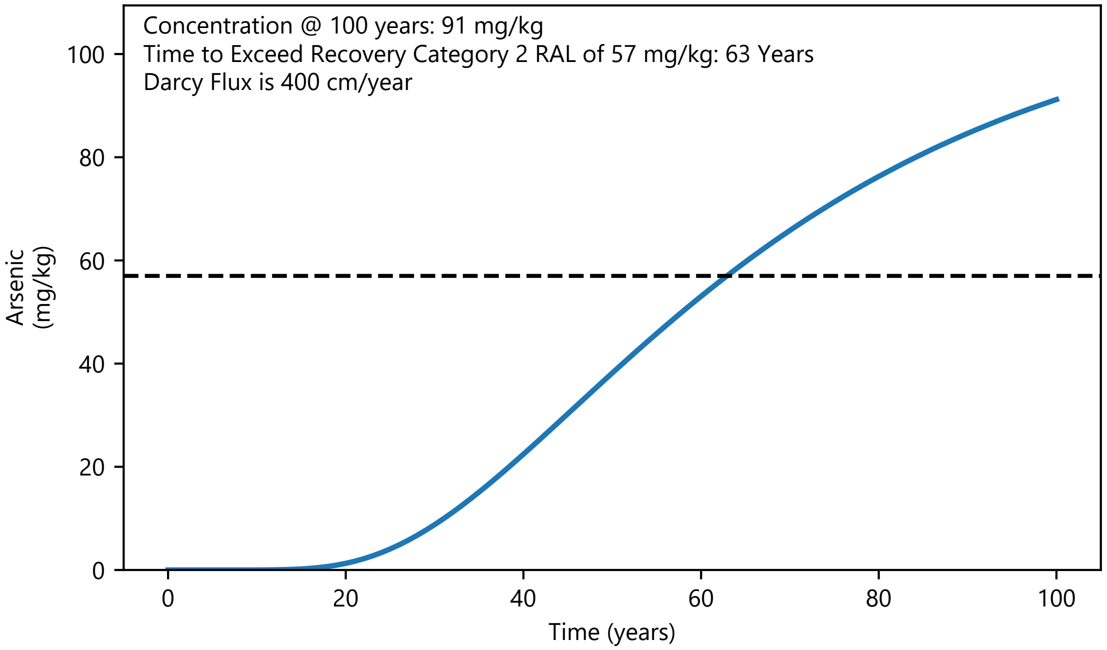
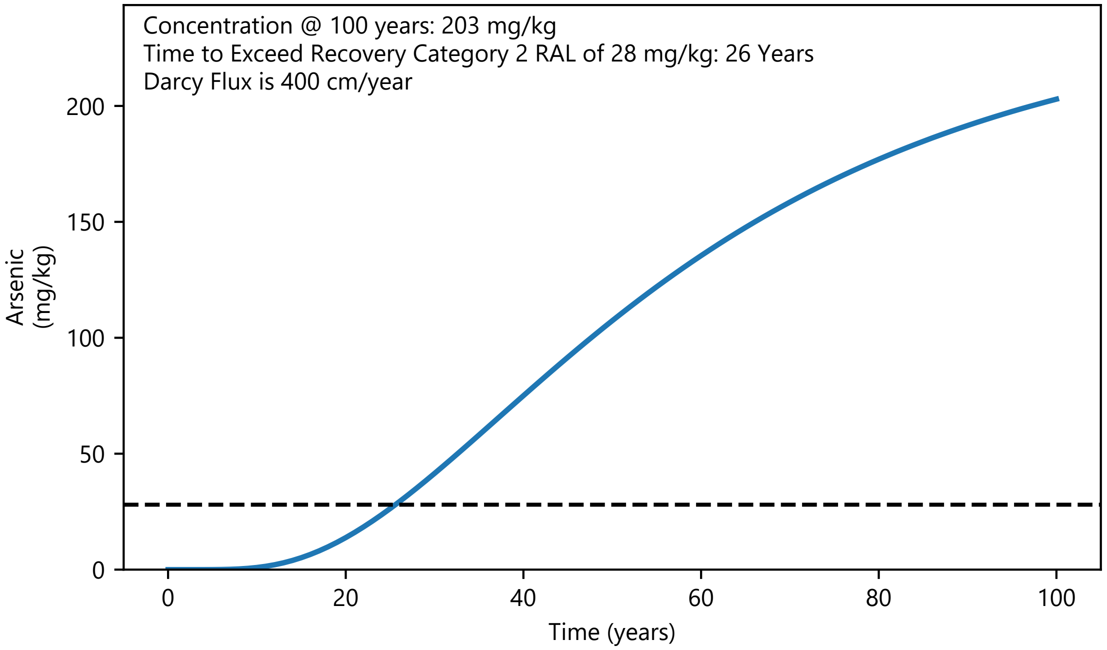
Figure G-21b
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)

Average over top 10 cm



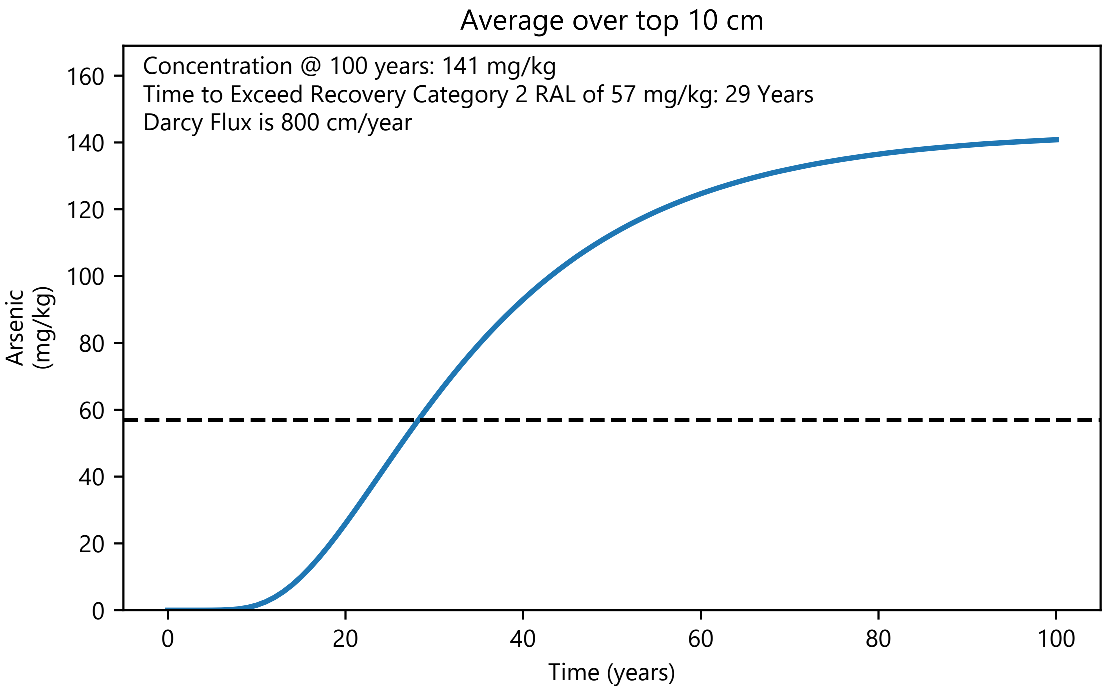
Average over top 45 cm



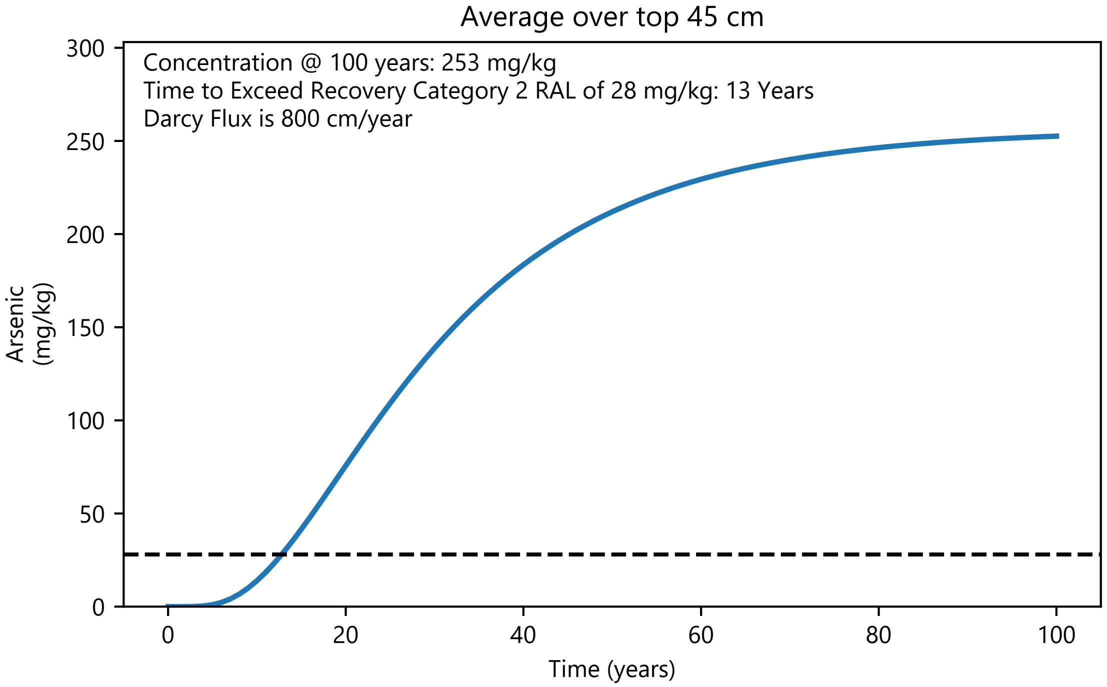
Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

Figure G-22a
Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)

Average over top 10 cm



Average over top 45 cm



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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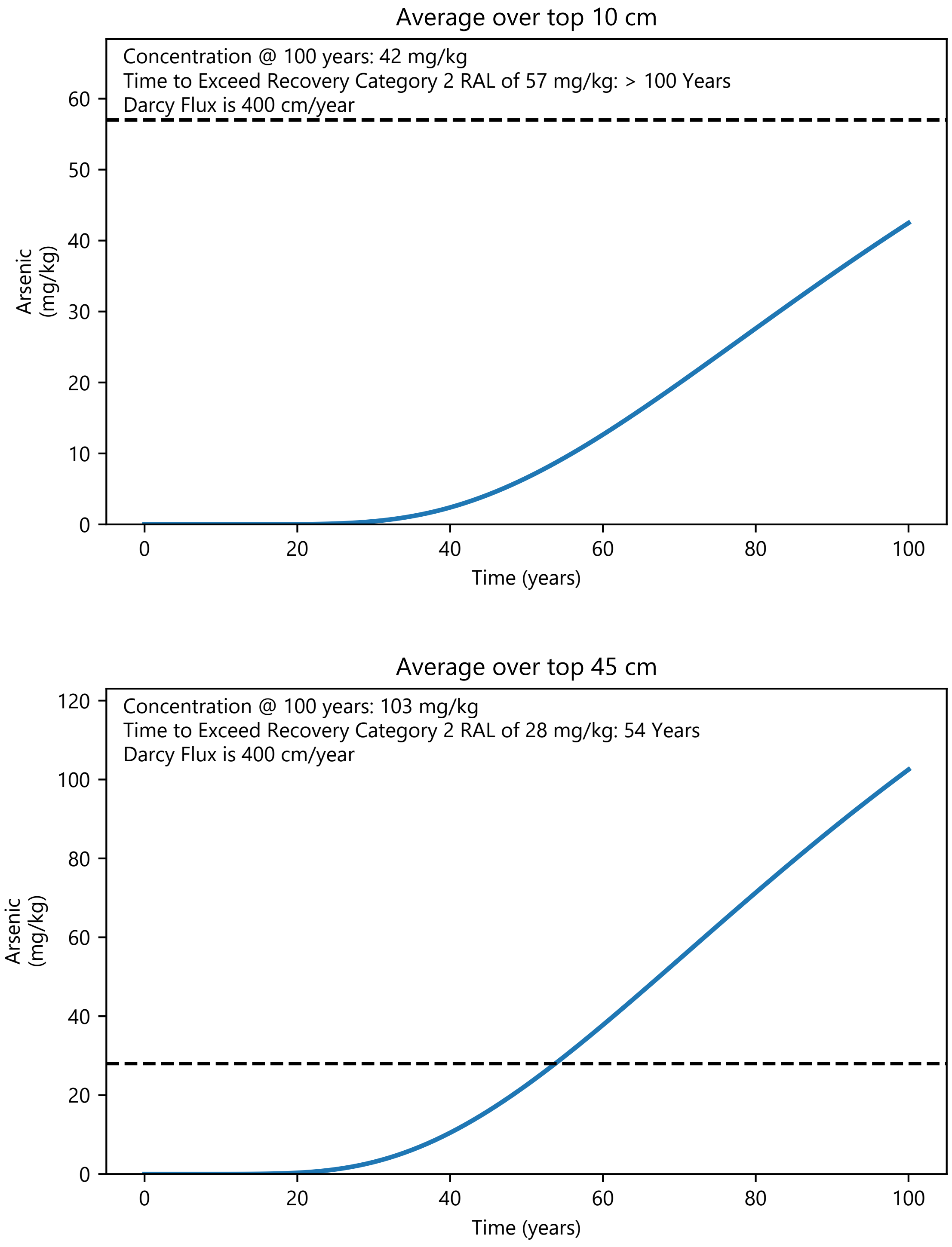
Figure G-22b
Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)

Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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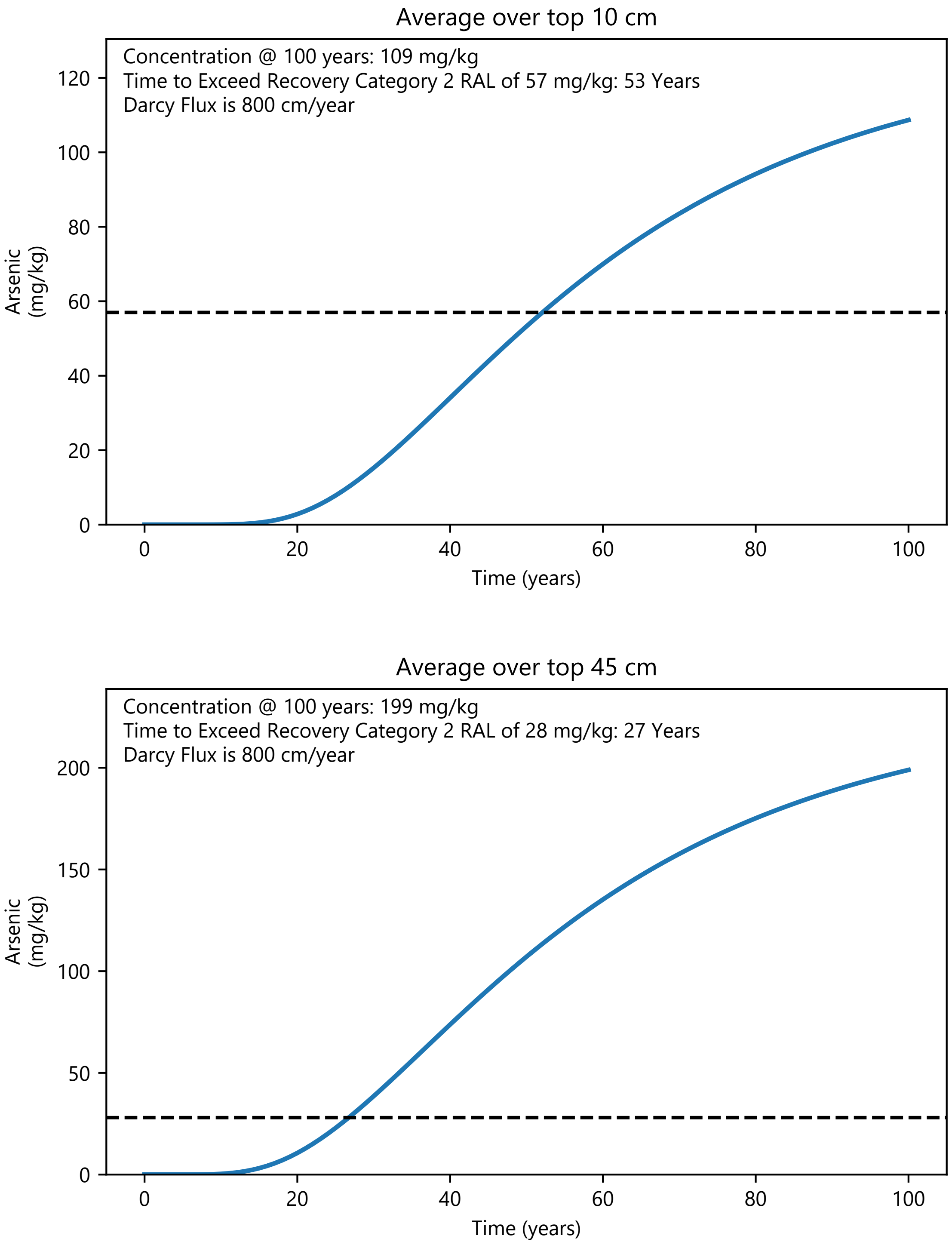
Figure G-23a

Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI (400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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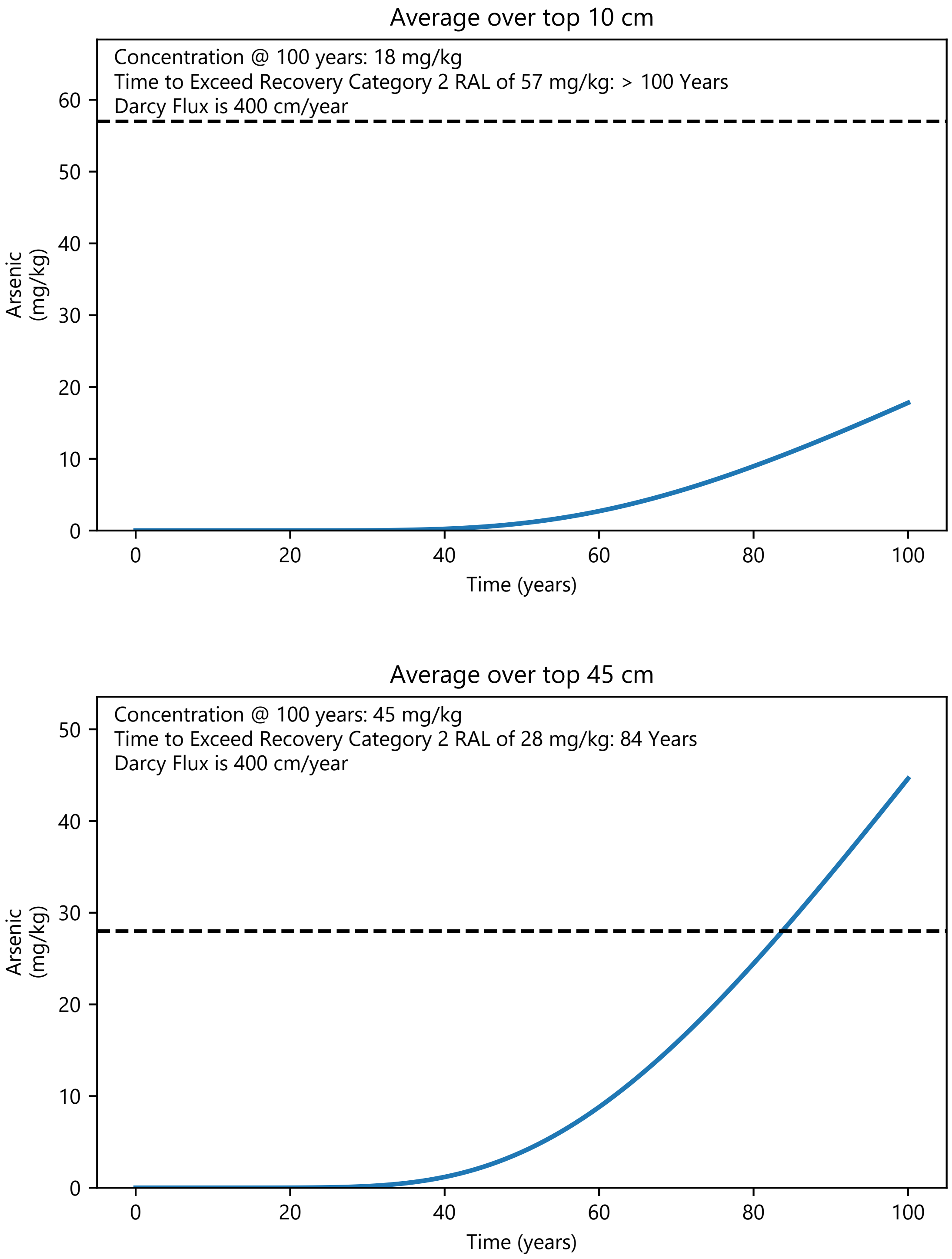
File Path: \\athena\Syracuse\Projects\Lower Duwamish Waterway\MODEL\BODR\CapSim_3-8\python\CapSim_Plots_Batch.py

Figure G-23b
Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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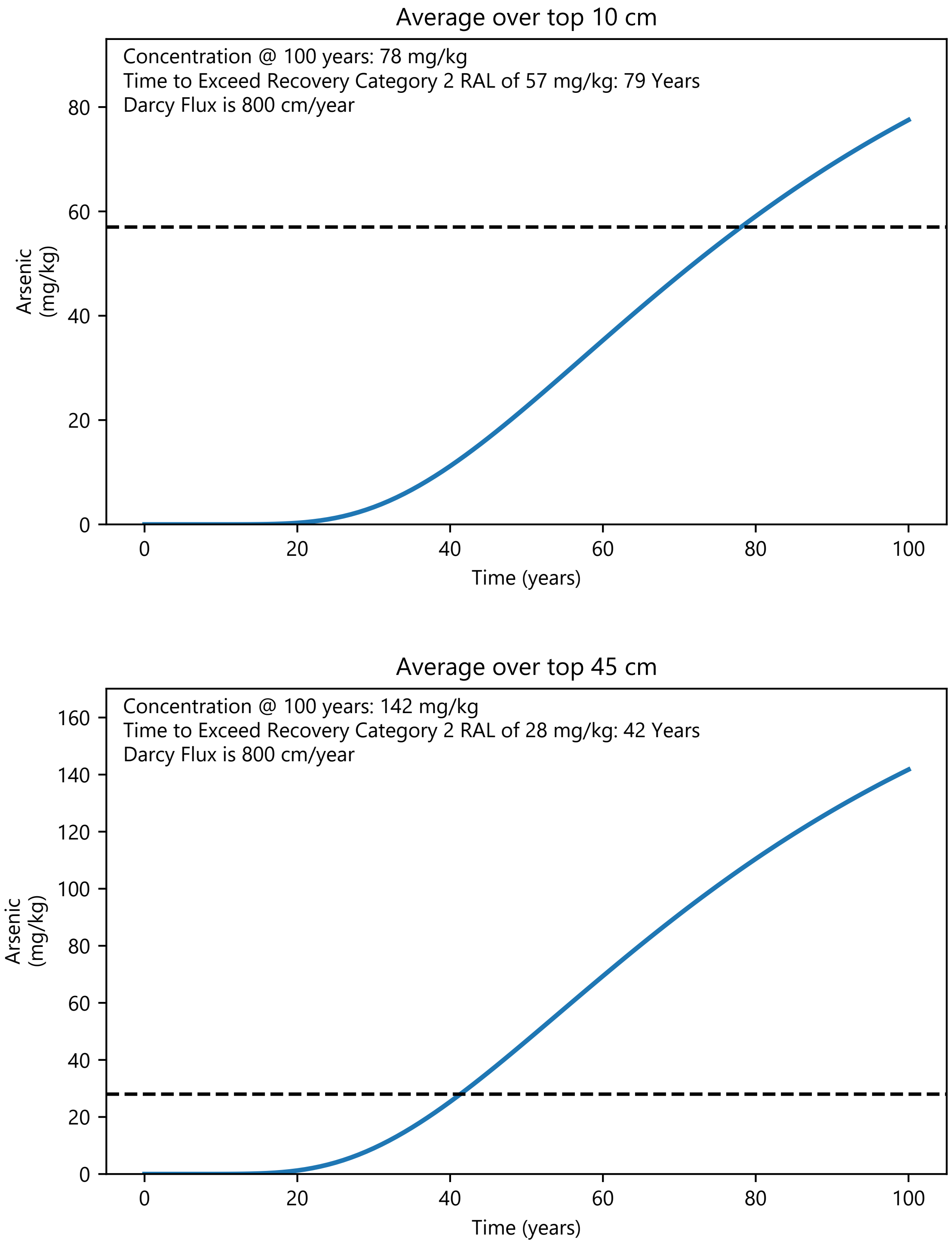
Figure G-24a
Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (400 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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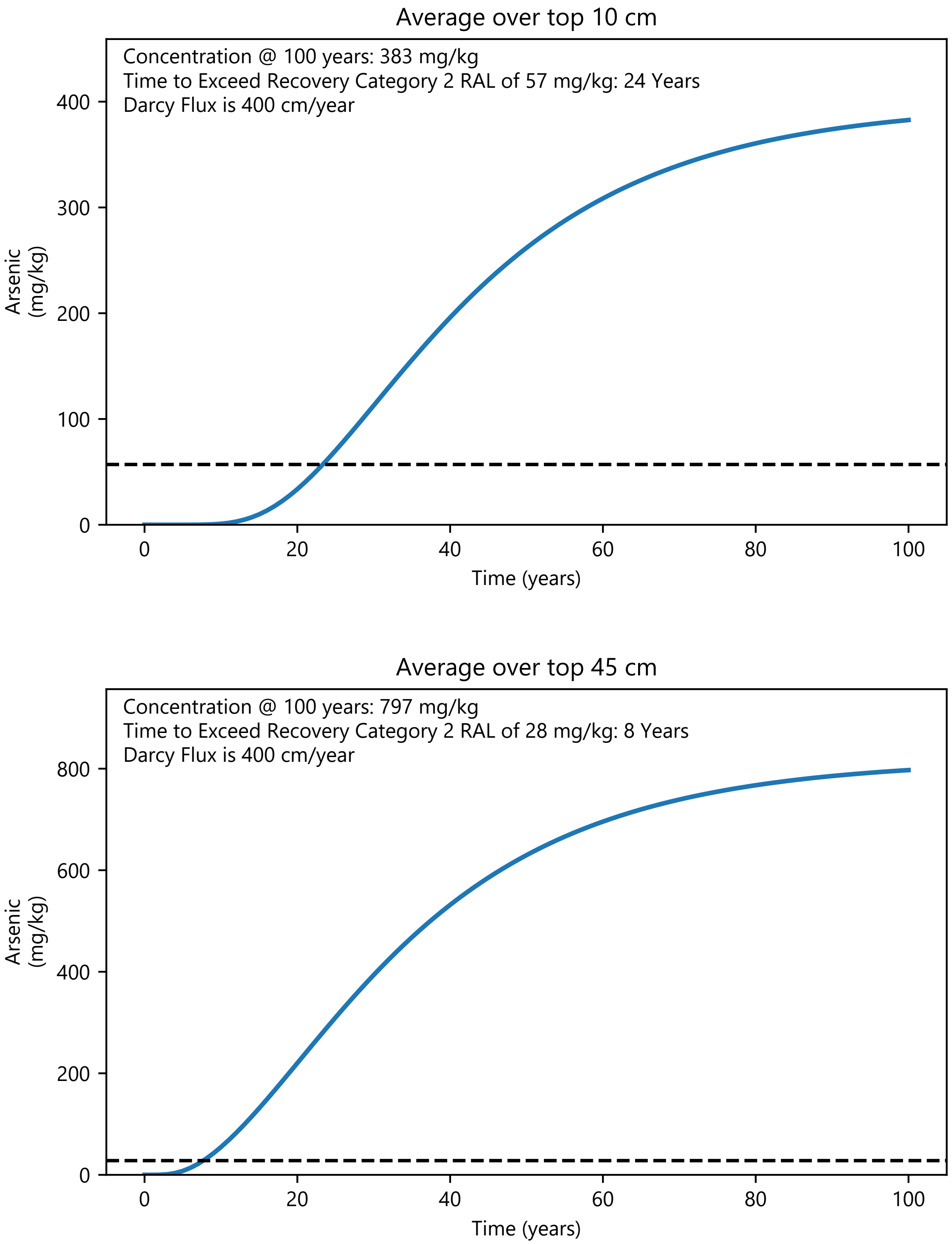
Figure G-24b
Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (800 cm/yr Darcy Flux and 95% UCL Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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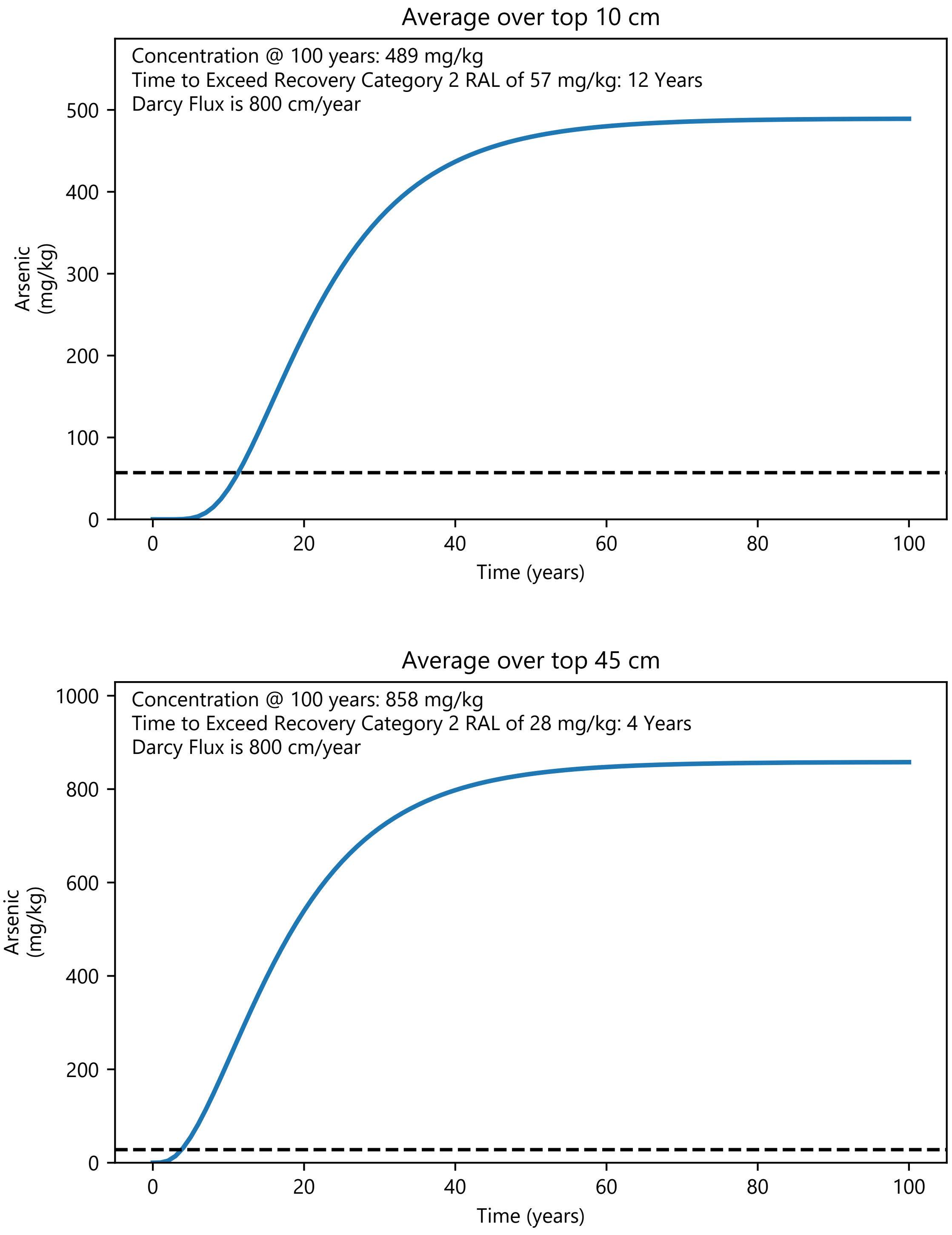
Figure G-25a
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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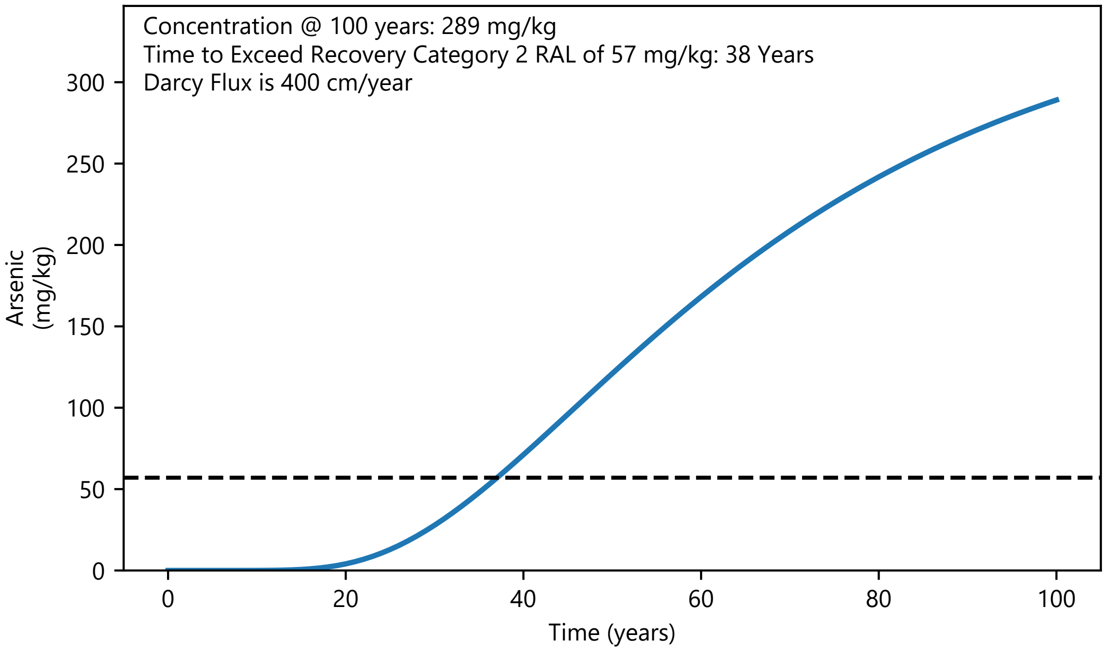
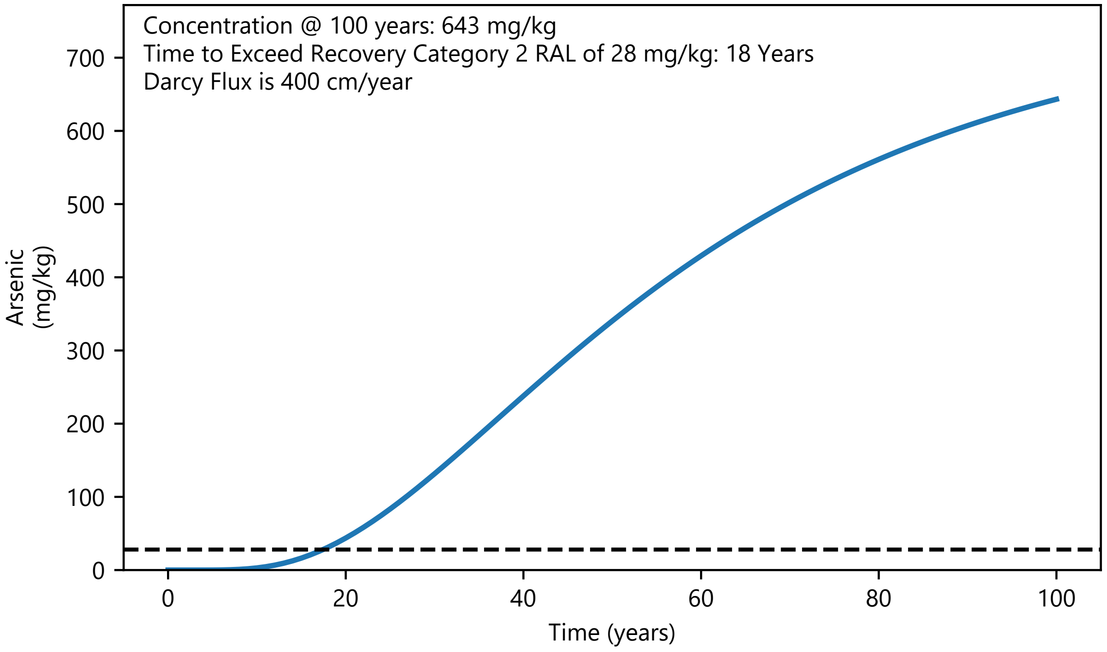
Figure G-25b
Temporal Profile of Arsenic Within the Surface of the Scenario 1 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)

Average over top 10 cm



Average over top 45 cm



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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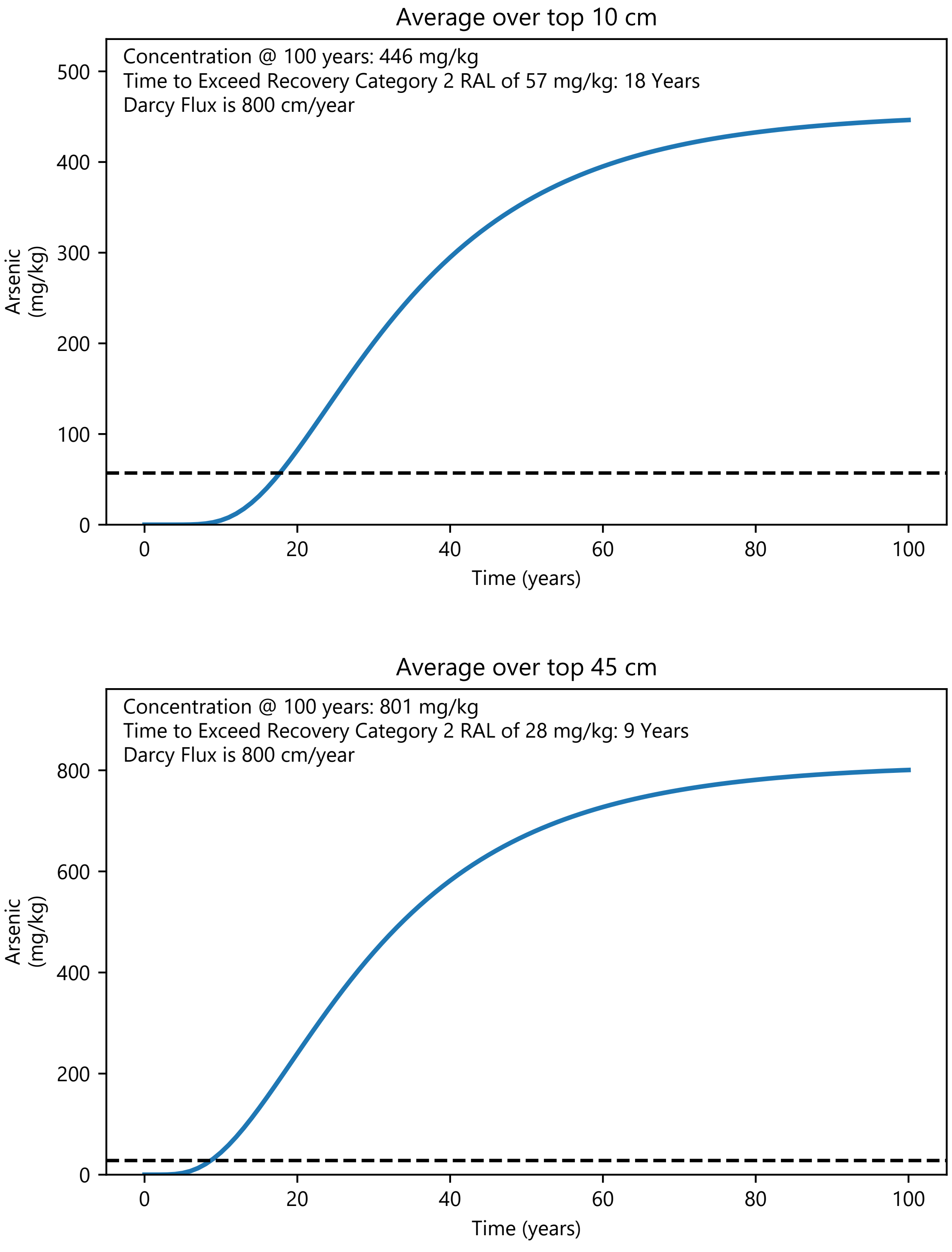
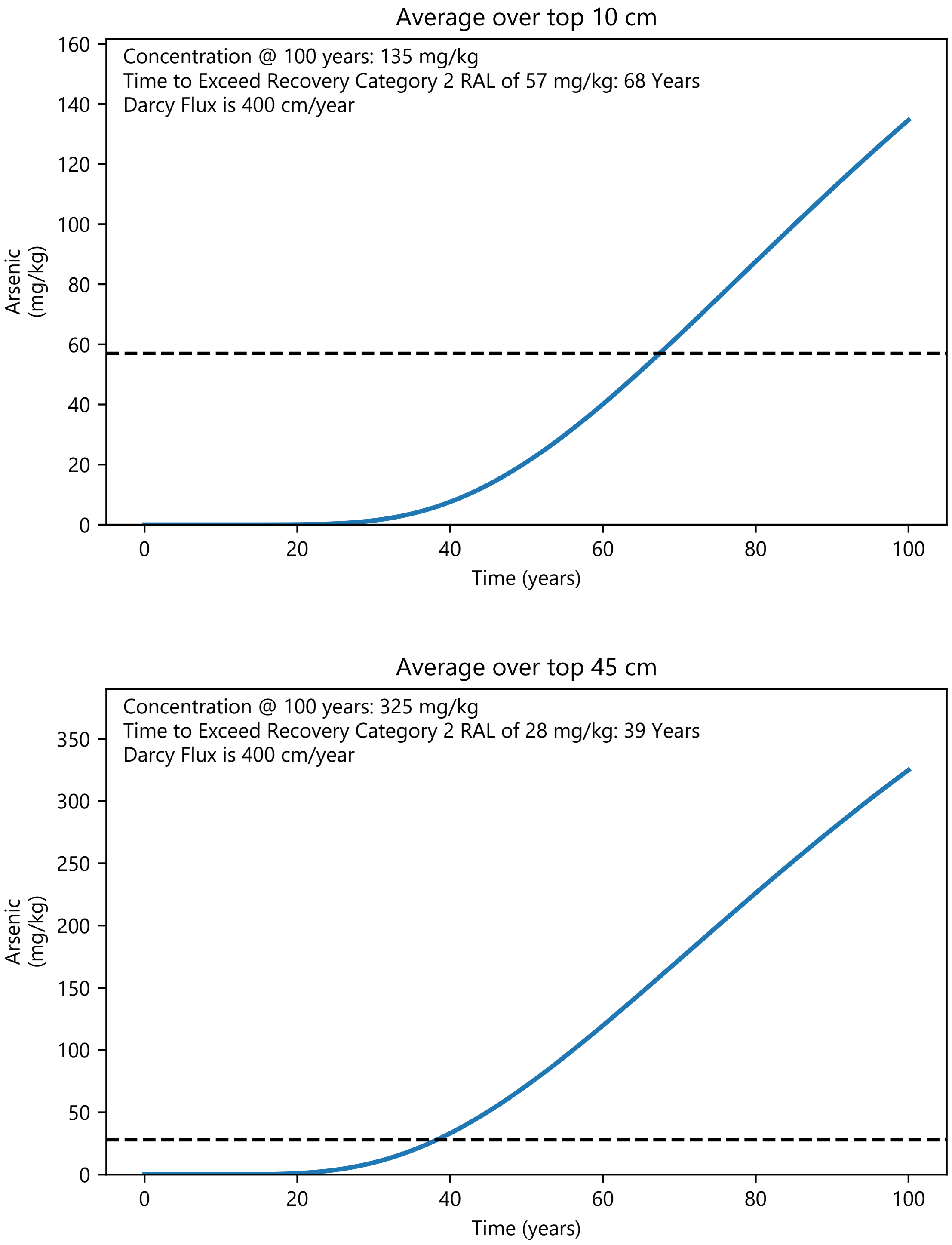
Figure G-26a

Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

Figure G-26b
Temporal Profile of Arsenic Within the Surface of the Scenario 2 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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File Path: \\athena\Syracuse\Projects\Lower Duwamish Waterway\MODEL\BODR\CapSim_3-8\python\CapSim_Plots_Batch.py

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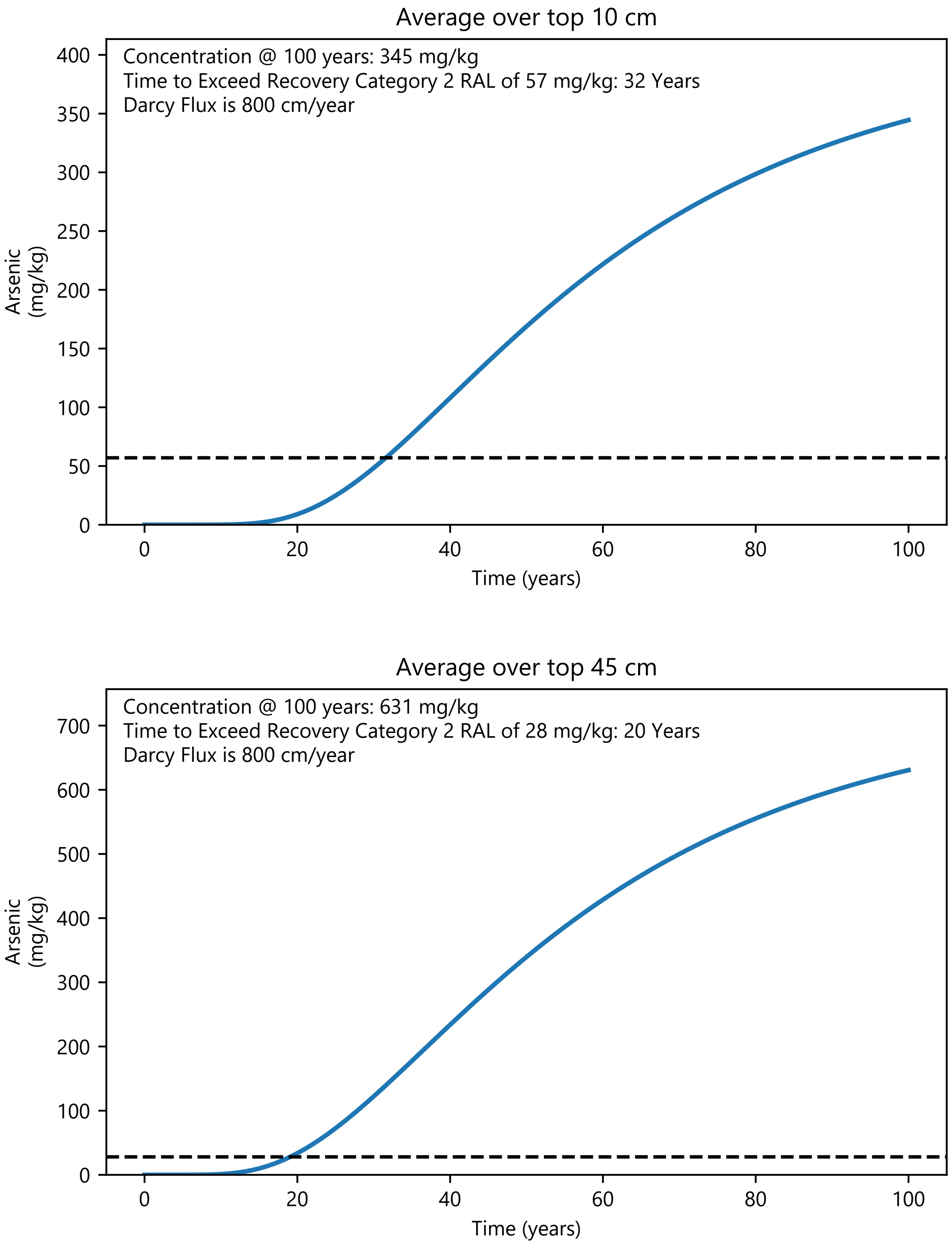
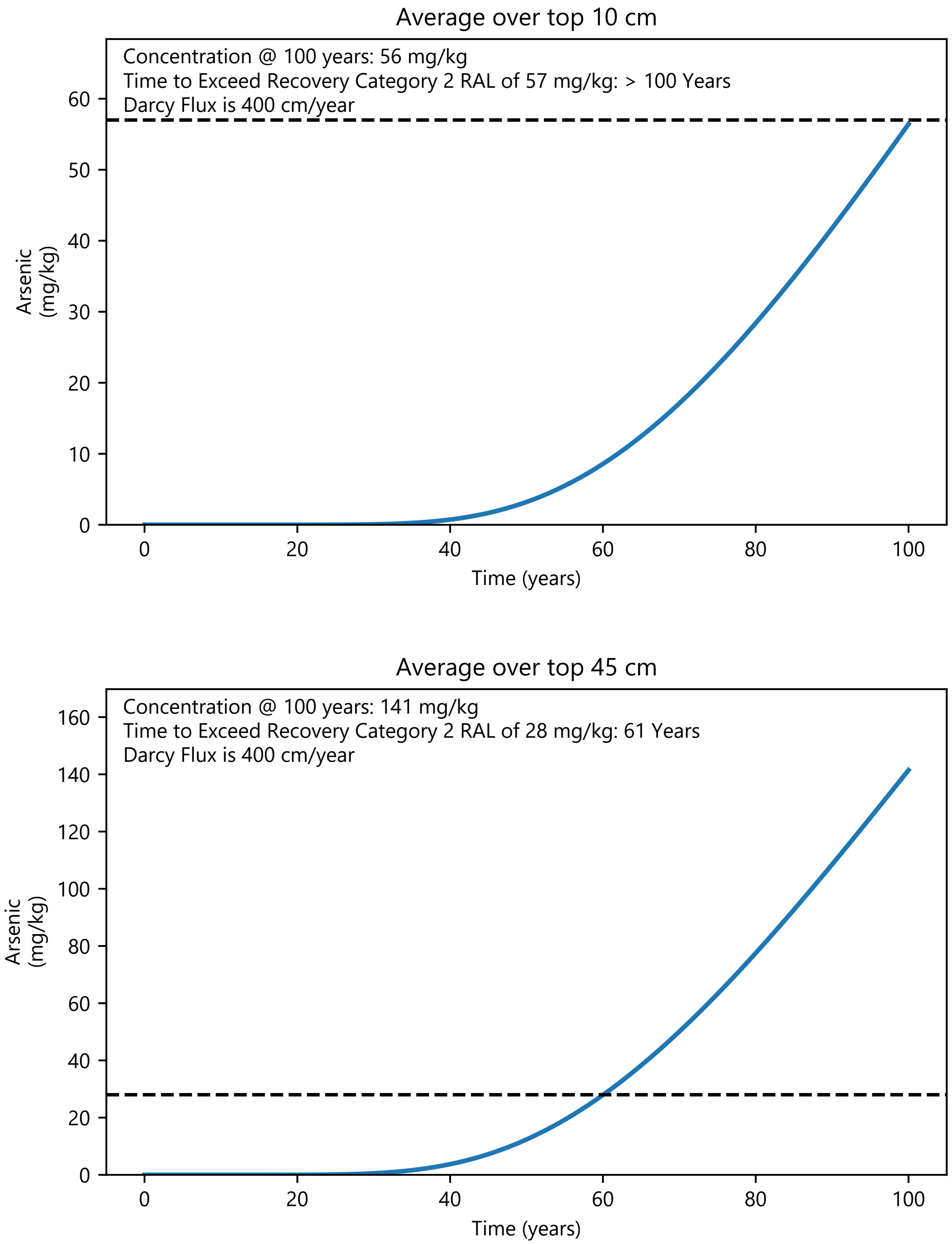
Figure G-27a
Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

Figure G-27b
Temporal Profile of Arsenic Within the Surface of the Scenario 3 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)


Average over top 10 cm

Concentration @ 100 years: 56 mg/kg
Time to Exceed Recovery Category 2 RAL of 57 mg/kg: > 100 Years
Darcy Flux is 400 cm/year

Average over top 45 cm

Concentration @ 100 years: 141 mg/kg
Time to Exceed Recovery Category 2 RAL of 28 mg/kg: 61 Years
Darcy Flux is 400 cm/year

Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
57 mg/kg (top panel) and 28 mg/kg (bottom panel)

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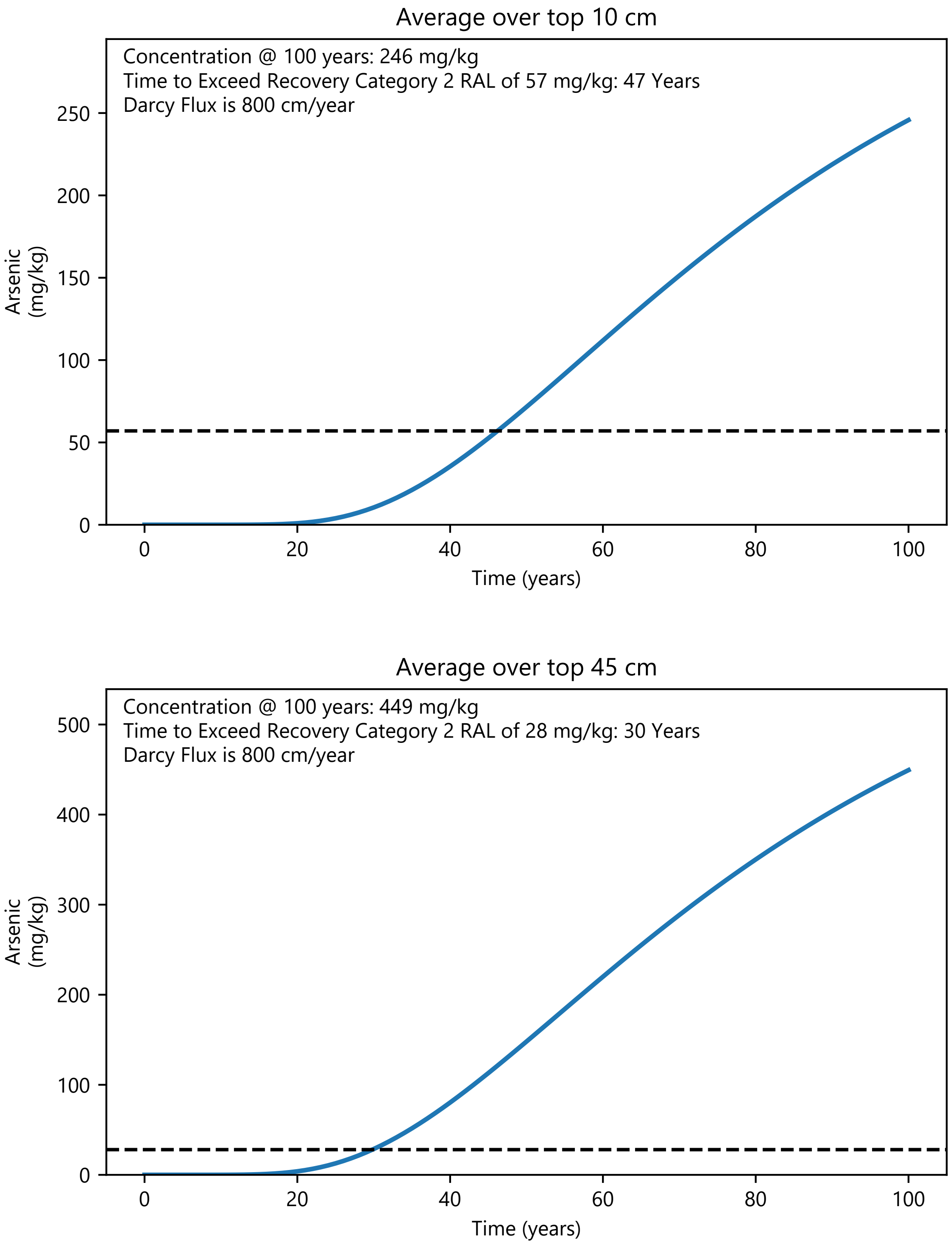
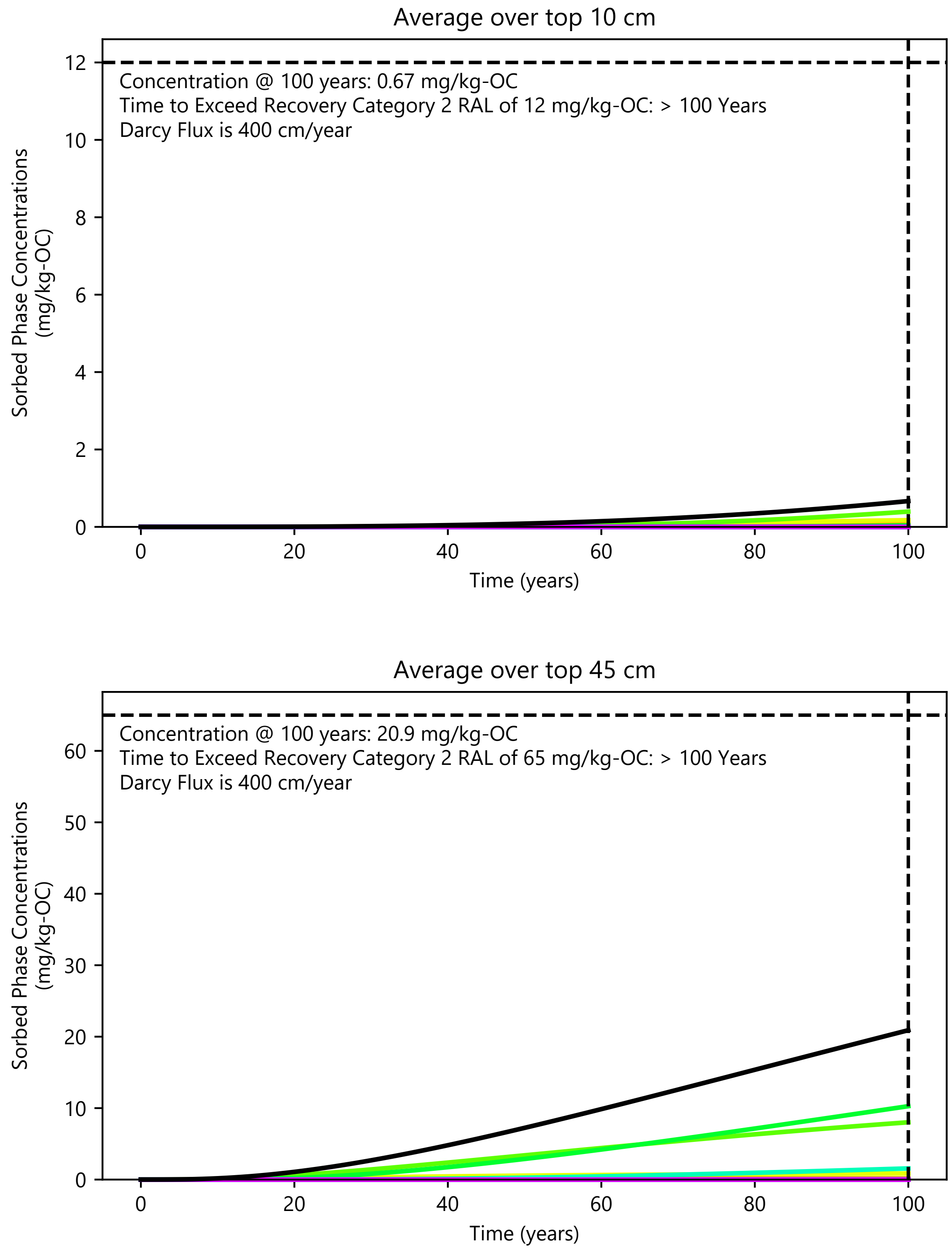
Figure G-28a
Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (400 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 57 mg/kg (top panel) and 28 mg/kg (bottom panel)

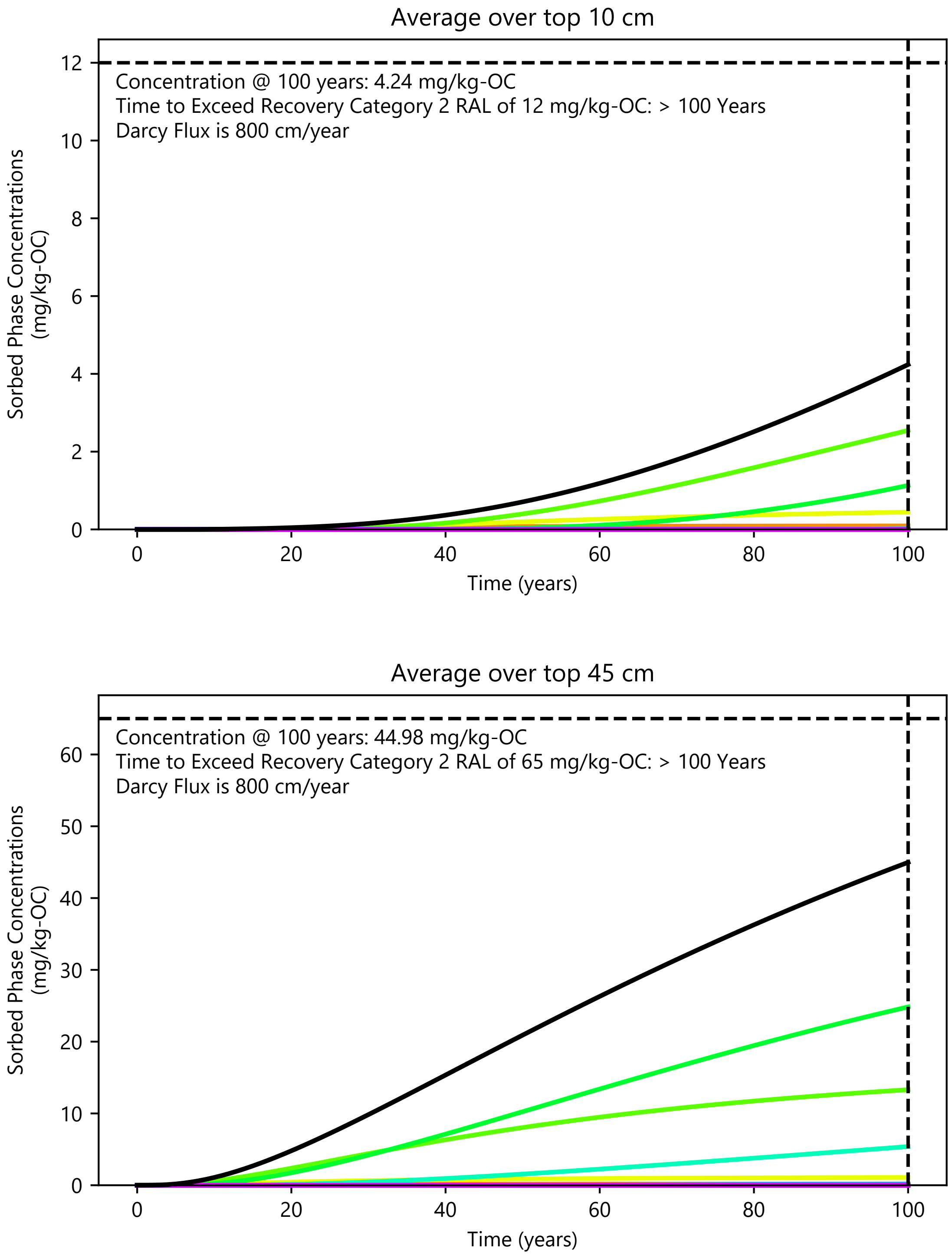
Figure G-28b
Temporal Profile of Arsenic Within the Surface of the Scenario 4 Cap with 10% ZVI (800 cm/yr Darcy Flux and Maximum Arsenic Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at
12 mg/kg-OC.

Figure G-29a

Temporal Profile of PCBs Within the Surface of the Scenario 1 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)



Concentration @ 100 years: 4.24 mg/kg-OC
Time to Exceed Recovery Category 2 RAL of 12 mg/kg-OC: > 100 Years
Darcy Flux is 800 cm/year

Concentration @ 100 years: 44.98 mg/kg-OC
Time to Exceed Recovery Category 2 RAL of 65 mg/kg-OC: > 100 Years
Darcy Flux is 800 cm/year

Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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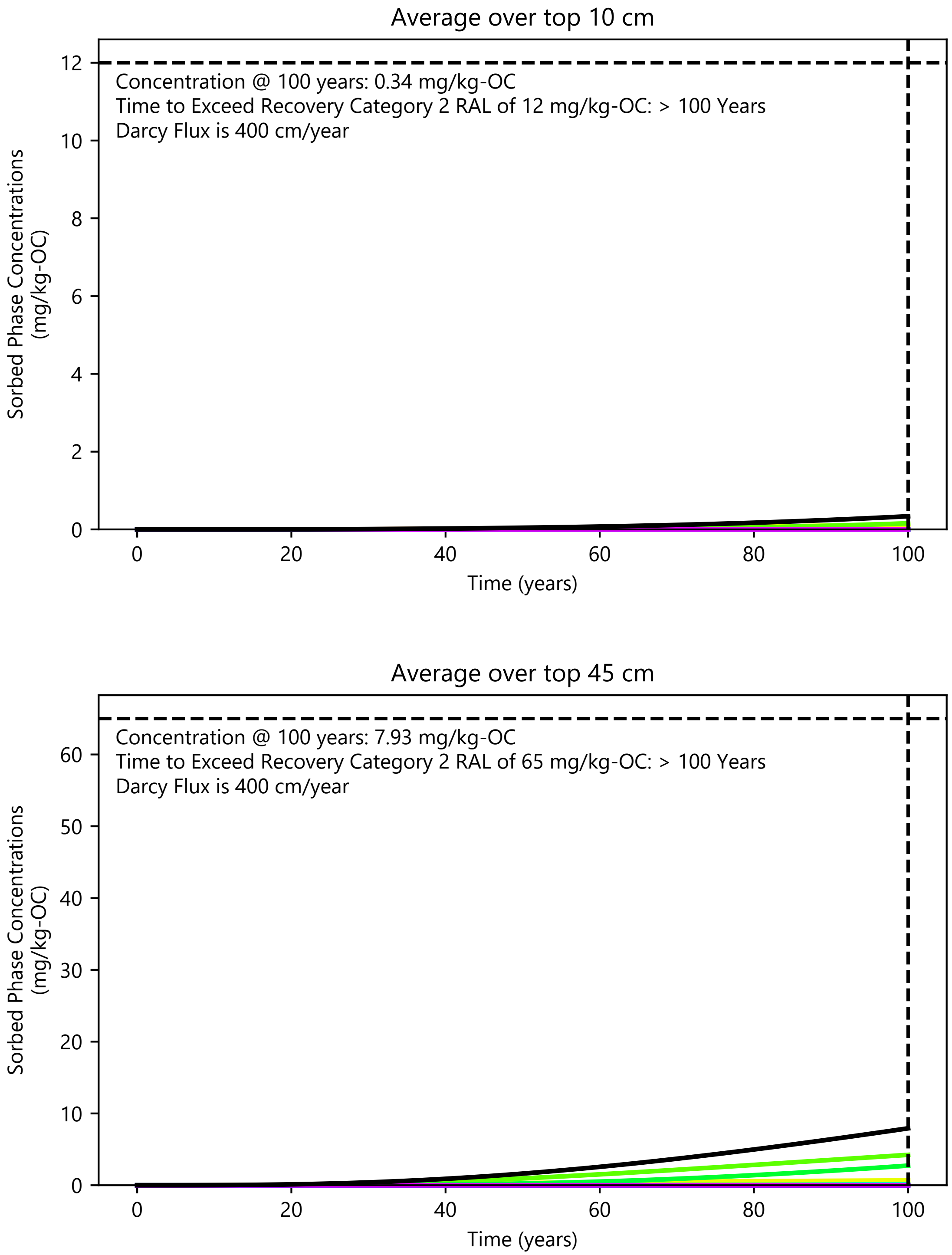
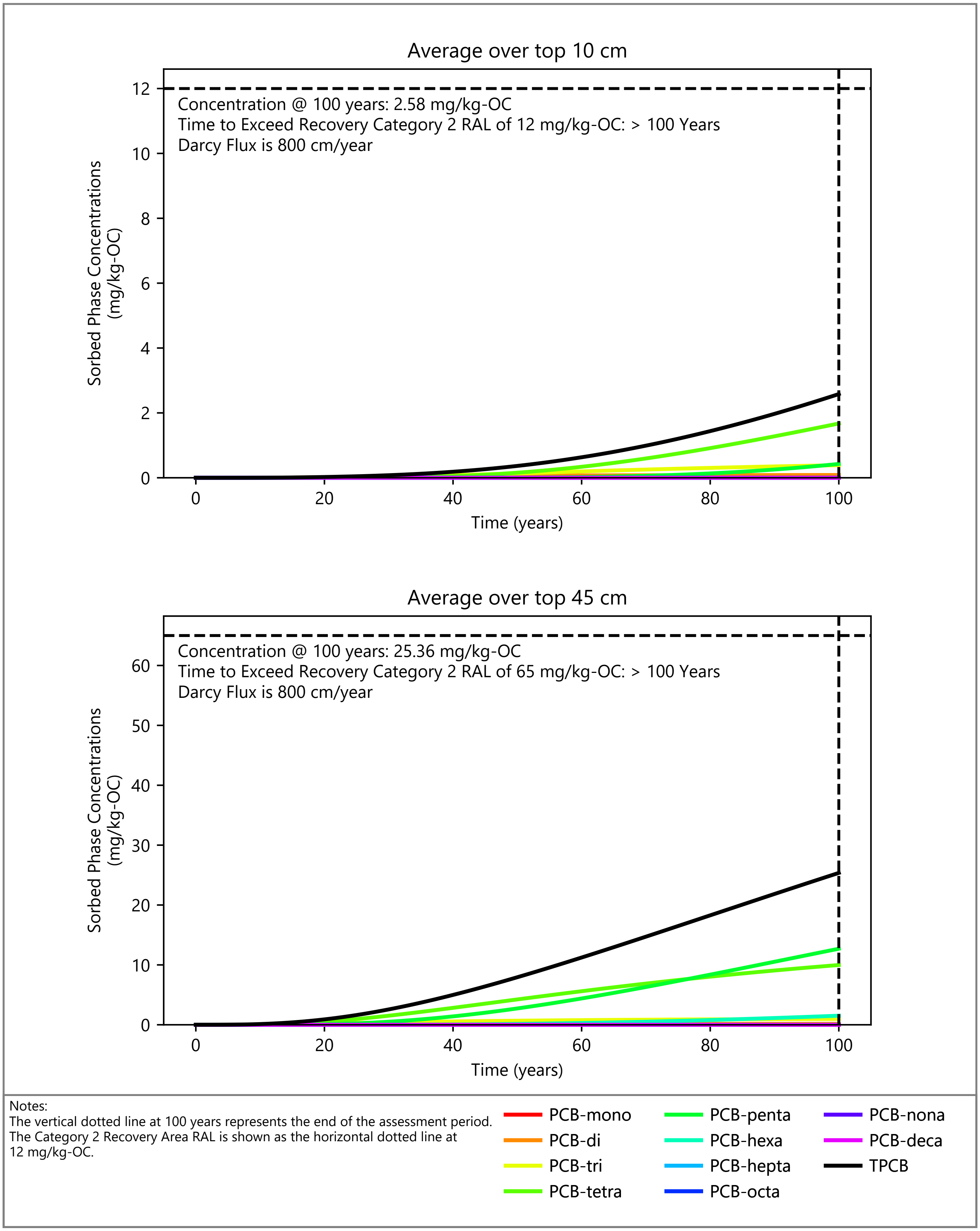
Figure G-29b
Temporal Profile of PCBs Within the Surface of the Scenario 1 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)



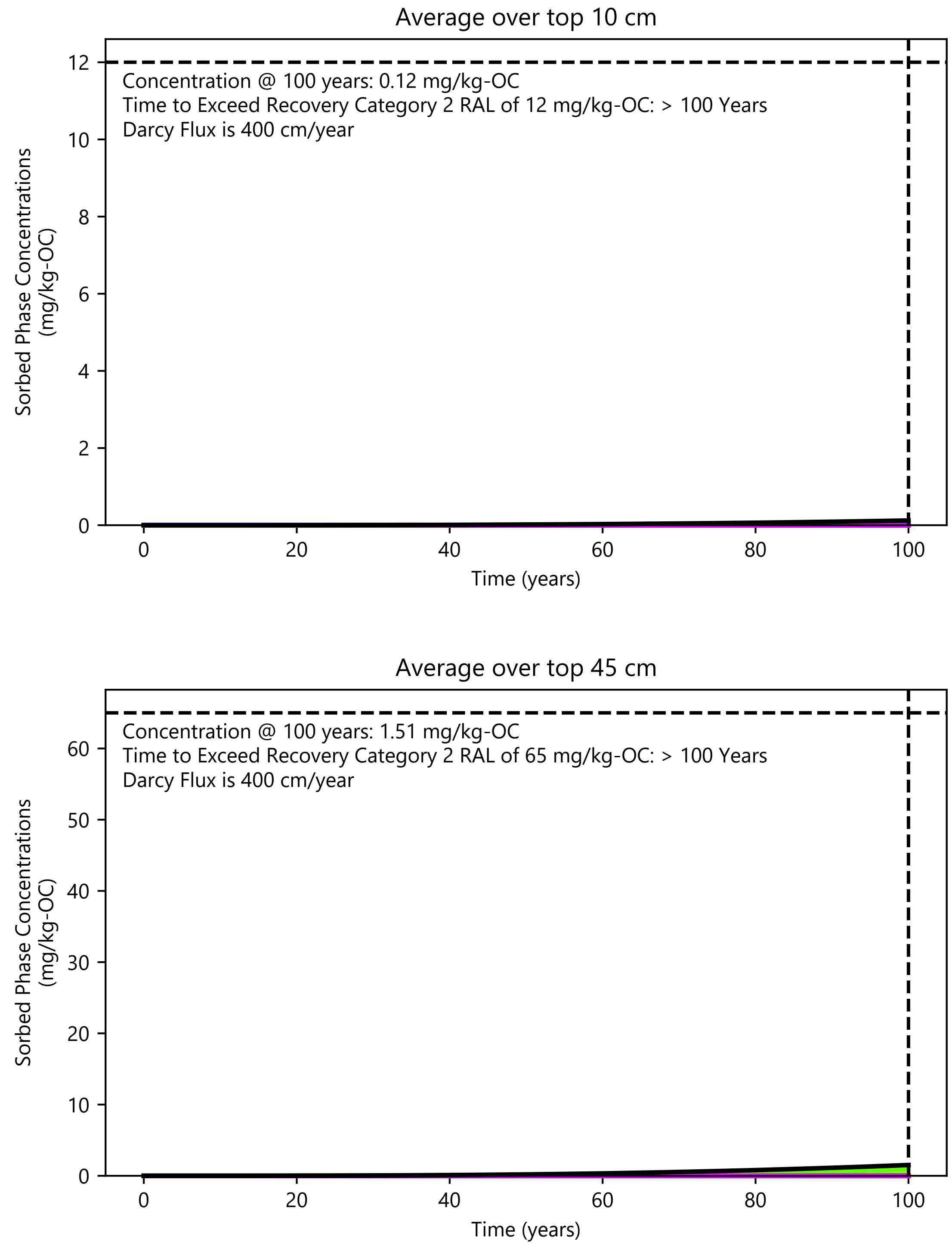
Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

Figure G-30a
Temporal Profile of PCBs Within the Surface of the Scenario 2 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

Figure G-30b
Temporal Profile of PCBs Within the Surface of the Scenario 2 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period. The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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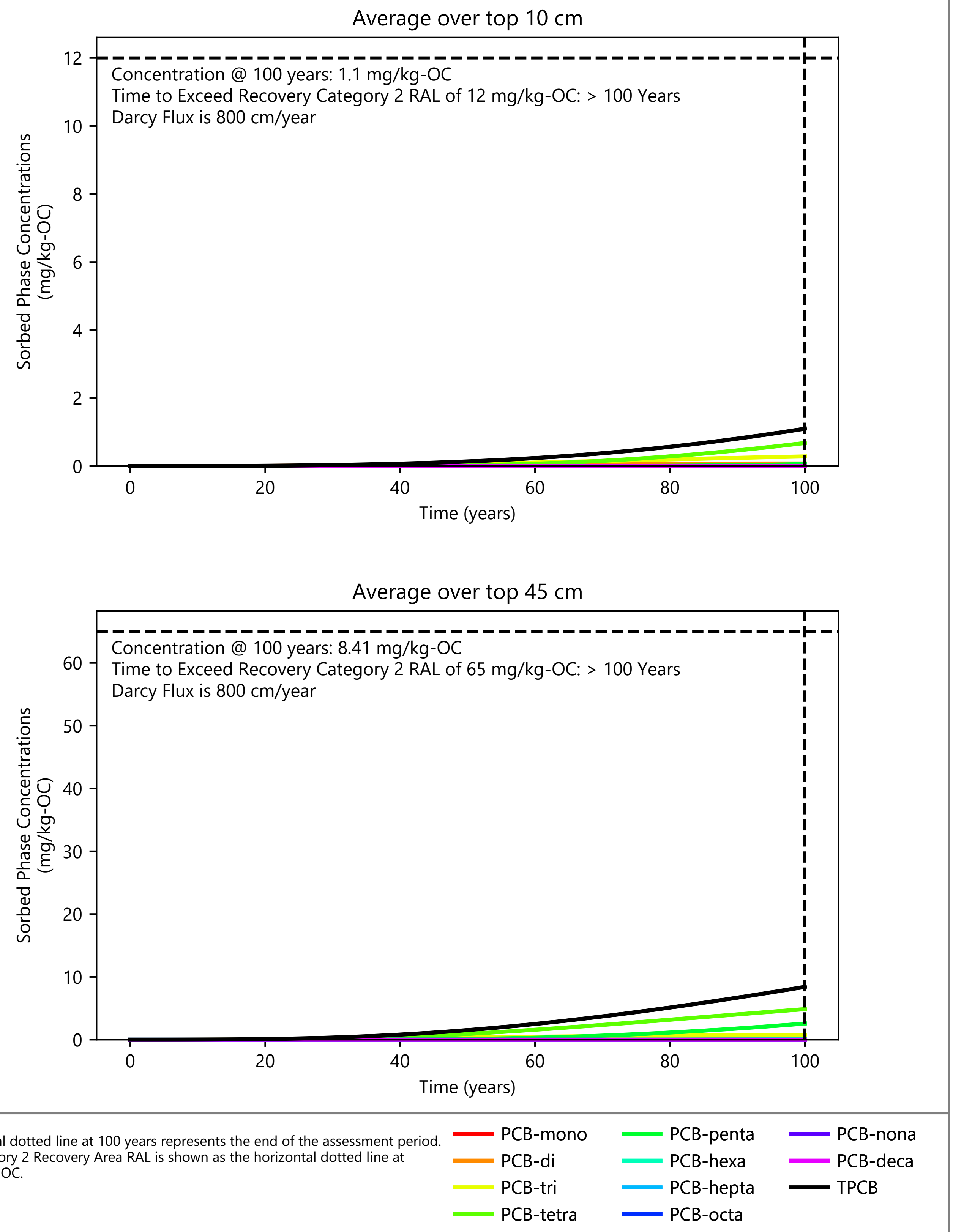
Figure G-31a
Temporal Profile of PCBs Within the Surface of the Scenario 3 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)

Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach


Average over top 10 cm

Concentration @ 100 years: 1.1 mg/kg-OC
Time to Exceed Recovery Category 2 RAL of 12 mg/kg-OC: > 100 Years
Darcy Flux is 800 cm/year

Average over top 45 cm

Concentration @ 100 years: 8.41 mg/kg-OC
Time to Exceed Recovery Category 2 RAL of 65 mg/kg-OC: > 100 Years
Darcy Flux is 800 cm/year

Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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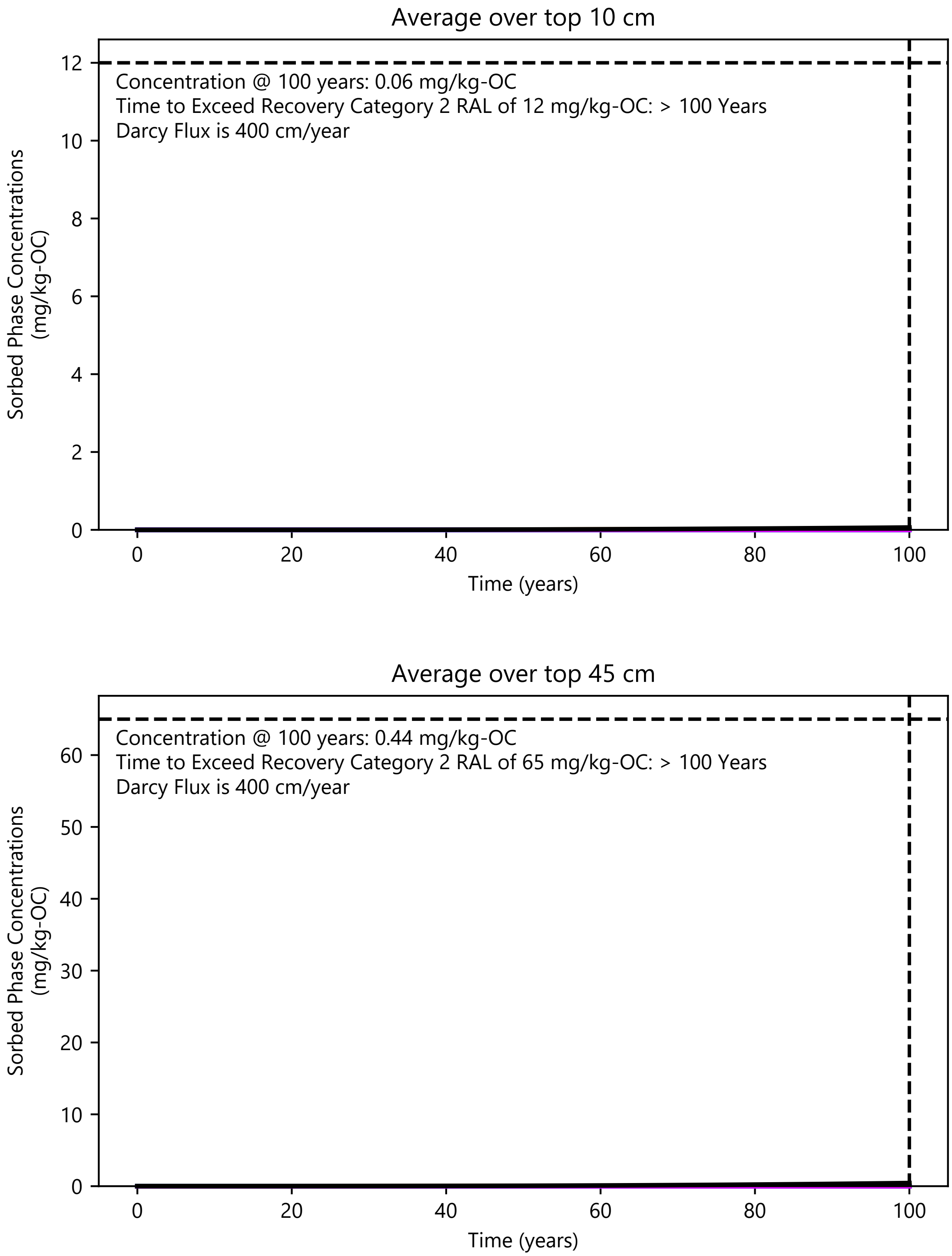
Figure G-31b
Temporal Profile of PCBs Within the Surface of the Scenario 3 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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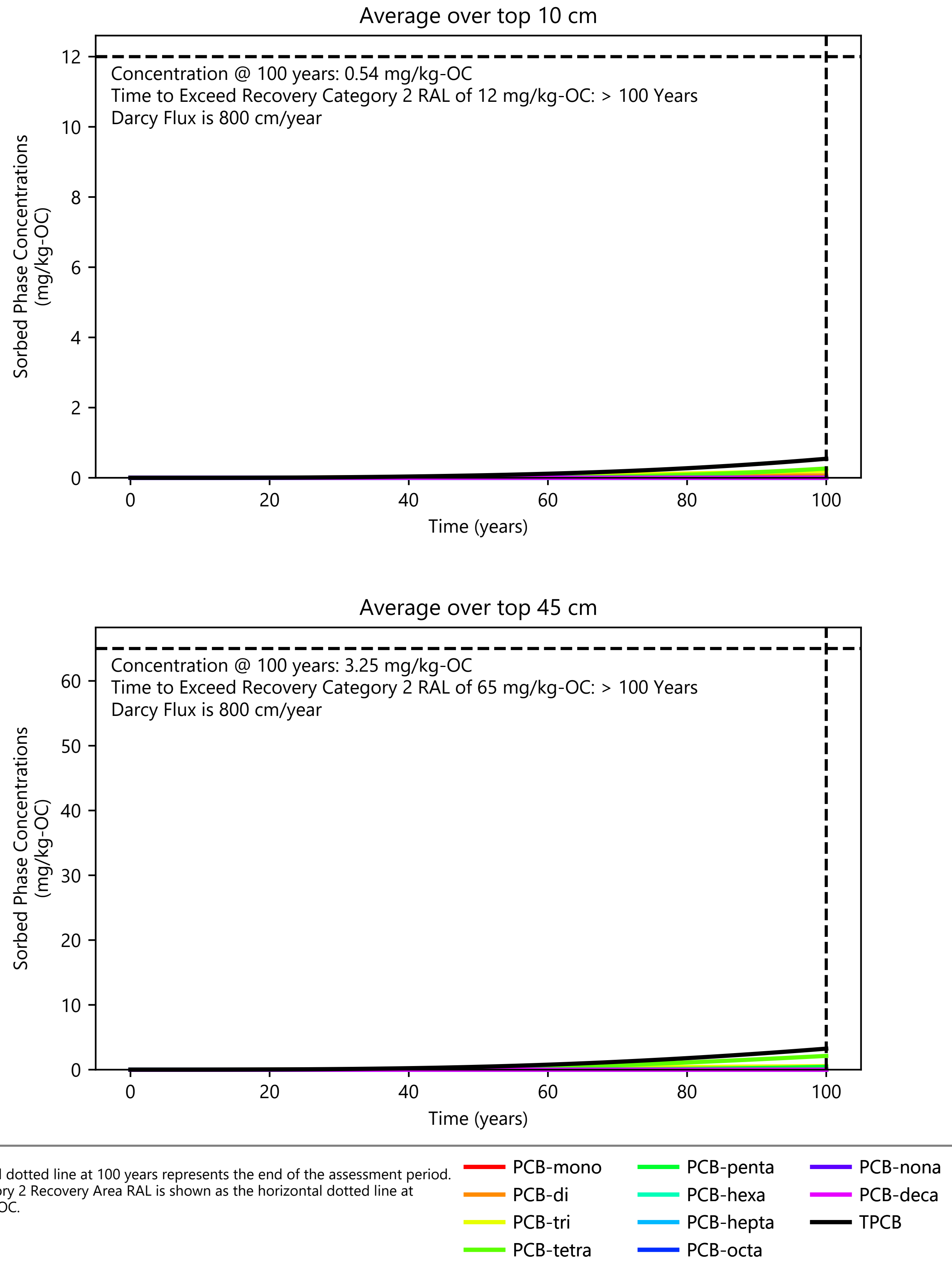
Figure G-32a
Temporal Profile of PCBs Within the Surface of the Scenario 4 Cap (400 cm/yr Darcy Flux and Maximum PCB Concentration)

Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach



Notes:
The vertical dotted line at 100 years represents the end of the assessment period.
The Category 2 Recovery Area RAL is shown as the horizontal dotted line at 12 mg/kg-OC.

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Figure G-32b
Temporal Profile of PCBs Within the Surface of the Scenario 4 Cap (800 cm/yr Darcy Flux and Maximum PCB Concentration)

Engineered Cap Chemical Isolation Design Analysis
Lower Duwamish Waterway Upper Reach