Ambient PCB reduction through use of activated carbon in the Lower Duwamish Waterway

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Abstract

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Decades of industrial activity along the Lower Duwamish Waterway have resulted in significant pollution of the sediments, water, and aquatic life in the area. Through the U. S. Environmental Protection Agency's (EPA) Superfund Program, the Lower Duwamish Waterway is being remediated for numerous Contaminants of Concern, including Polychlorinated Biphenyls (PCBs). The Record of Decision, published in November 2014, identified Enhanced Natural Recovery as one remedial technology slated for implementation to help reduce through sequestration dissolved (and therefore readily bioavailable) concentrations of contaminants in the waterway. As part of the implementation, activated carbon is proposed as an amendment to Enhanced Natural Recovery pending the results of design phase pilot testing. A hydrophobic organic contaminant mass transfer model, developed by Luthy, Choi, and Cho (2013), was utilized to predict PCB concentration reductions in sediment pore water for three PCB congeners. The model relied upon a series of parameters specific to sediment characteristics, properties of the activated carbon, and kinetic characteristics specific to the PCB congener modeled. A combination of Lower Duwamish Waterway-specific parameters and default parameters set in the model was used. Model results predicted a 69% reduction in PCB 180 concentrations over a one year period under the most probable scenario for activated carbon. Similar porewater reductions of 68% and 81% were predicted for the PCB 153 and PCB 101 congeners, respectively. The mass transfer model was then applied to field data from Puget Sound Naval Shipyard, another sediment site with PCB contamination where activated carbon was placed by the U.S. Navy in 2012 as part of remedial efforts at the site.

Results from the model were compared to actual concentration reductions seen at Puget Sound Naval Shipyard at the ten month post construction period. The model closely predicted a PCB 180 concentration reduction of measured reduction seen at the site. However, model results for PCB 153 and 101 under predicted actual reductions but fell within the 95% confidence intervals of the observed mean results. The results of this predictive modeling have implications for remedy implementation in the Lower Duwamish Waterway.

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Chapter 1. Introduction

Activated carbon (AC) has long been used as a technology to remove organic contaminants from air and water. Air purifiers, such as gas masks and water treatment systems use activated carbon as a component to sequester contaminants. Activated carbon is a product of coal and other biomass sources, such as coconut shells. It has a high specific surface area (~1000 m^2/g), which makes it effective at sorbing hydrophobic contaminants. Its effectiveness and low cost make it a preferred technology for use in air and water purification processes (Beckingham & Ghosh, 2011). In those traditional applications, AC is contained in a vessel and can be thermally regenerated when sorptive capacity is exhausted.

Application of loose activated carbon in sediment remediation is a more recent approach to its use as a sequestering agent for contaminants. Various lab studies as well as field scale implementation of activated carbon as a remedial technology have been conducted in recent years to help demonstrate its effectiveness. In this application, amendment of sediment with AC represents an attempt to shift the storage capacity of sediment solids for hydrophobic contaminants upwards in relation to the storage capacity of the water column.

Predictive modeling can help to elucidate potential contaminant reductions at a reduced cost and timeframe relative to full scale field studies or even lab studies. A mass transfer model developed by Luthy, Choi, and Cho (2013) is one tool for predicting the effectiveness of activated carbon to reduce contaminant concentrations while accounting for site specific conditions that may influence activated carbon effectiveness.

While activated carbon has been used for remediation of sediments in several pilot scale and full scale scenarios to evaluate effectiveness, these studies have shown that unique site specific characteristics can influence contaminant reduction potential. The objective of this study is to apply the mass transfer model developed by Luthy, Choi, and Cho to predict potential reduction in PCB concentrations using parameters specific to the Lower Duwamish Waterway Superfund Site and the likely remediation techniques to be used for activated carbon application and to identify implications for AC remediation options.

A related objective of this study is to assess the predictive quality of this mass transfer model by retrospectively evaluating another contaminated sediment site in Washington State where activated carbon has already been implemented as a remediation tool. To achieve this objective, the mass transfer model was used to predict concentration reductions at Puget Sound Naval Shipyard in Bremerton, Washington, where activated carbon was applied by the U.S. Navy in 2012. For the predictive modeling, site specific parameters for Puget Sound Naval Shipyard were applied. The predicted results were compared to actual results from the site collected at ten months post construction.

Chapter 2. Background and Significance

Lower Duwamish Waterway Superfund Project

Decades of industrial activity along the Lower Duwamish Waterway have resulted in significant pollution of the sediments, water, and aquatic life in the area. Through the U. S. EPA's Superfund Program, the Lower Duwamish Waterway is being remediated for numerous Contaminants of Concern, including PCBs, polycyclic aromatic hydrocarbons (PAHs), dioxins/furans, and arsenic. Based on the Remedial Investigation and Feasibility Study conducted by the Potentially Responsible Parties and under the guidance of the EPA, the EPA identified a preferred remedy in the Proposed Plan released in February of 2013. This plan was then finalized in the Record of Decision in November 2014. In the Record of Decision, EPA identified a plan that would actively remediate 156 acres of contaminated sediments (Figure 1) through dredging, capping, or Enhanced Natural Recovery (ENR). The ENR locations as shown in green in Figure 1 are the candidate sites for AC application.

An additional 29 acres would be remediated through the cleanup of Early Action Areas; sites identified for expedited cleanup due to high concentrations of contaminants in the waterway. 256 acres would be designated for Monitored Natural Recovery. Monitored Natural Recovery relies on naturally occurring deposition of cleaner upstream sediment that mix with the contaminated sediment to reduce overall contaminant concentrations over time. The current estimated cost of the preferred plan is $342 million and would take approximately seven years to construct. (U.S EPA, 2014)

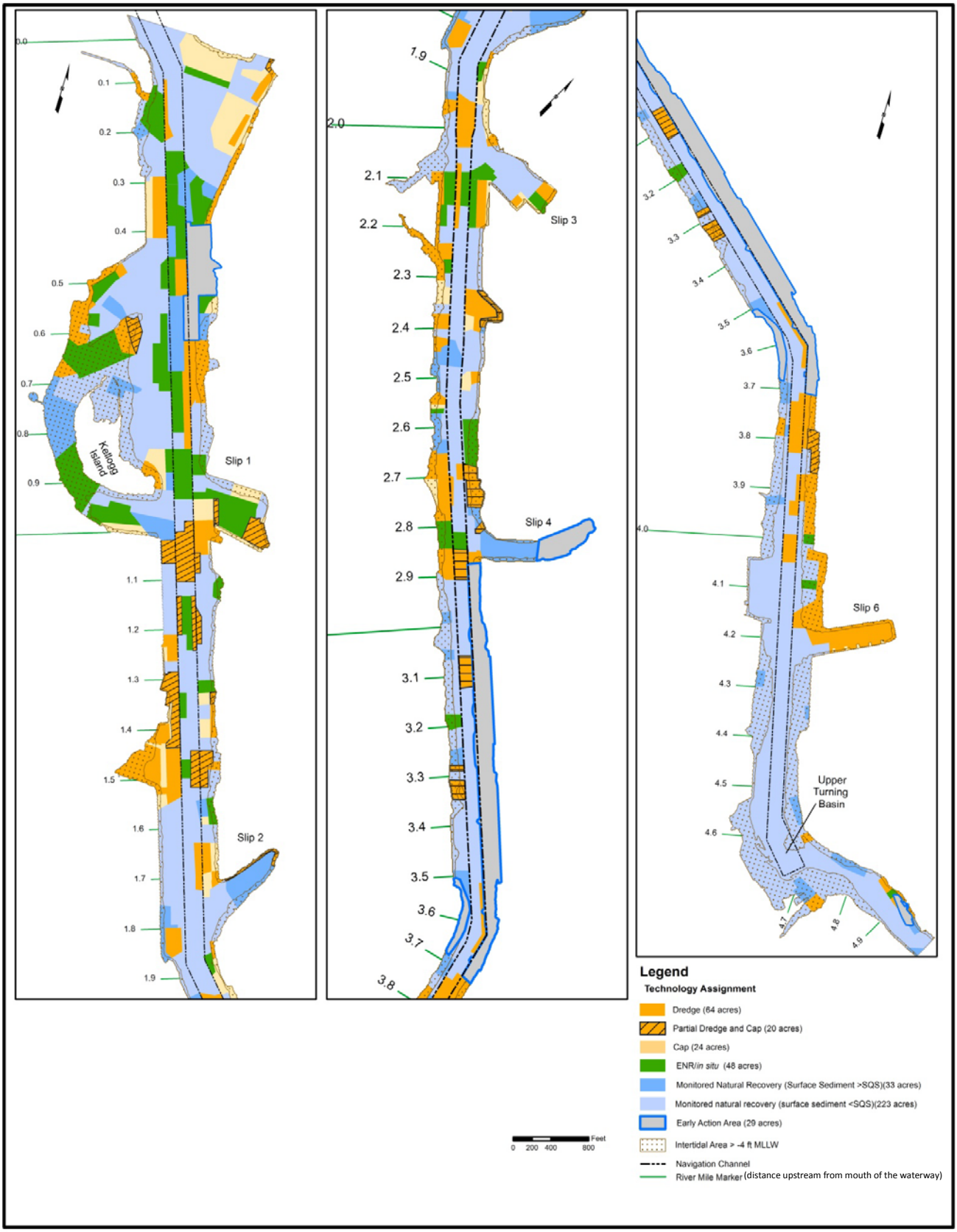

Figure 1. Lower Duwamish Waterway Superfund Site Selected Remedy (Source: U.S EPA, 2014)

Of the 156 acres proposed for active remediation, approximately 49 acres are designated for Enhanced Natural Recovery. Enhanced Natural Recovery involves placement of a nominal six to nine inches of clean sand atop contaminated sediments. The purpose of the sand is not to provide a complete isolation barrier over the contamination, as is the intent of a traditional engineered cap, but to reduce contaminant concentrations in the surface substrate to facilitate recolonization of the benthic community and accelerate natural processes of sediment deposition for long term isolation (U.S. EPA, 2013). For the Lower Duwamish Waterway, the EPA has restricted the areas where ENR is assumed to be most effective based on contaminant concentrations in existing sediment. Per the Record of Decision, ENR can only be implemented in intertidal areas with little to no scour and contaminant concentrations that do not exceed three times the Sediment Cleanup Objective (SCO) in the top ten cm and 1.5 times the Cleanup Screening Level (CSL) in the top 45 cm. The SCO and CSL are standards specified by the Washington State Department of Ecology's Sediment Management Standards, Chapter 173-204 WAC, which guide cleanup work, navigation dredging, and discharge into freshwater and marine environments in the State of Washington (WA State Department of Ecology, 2015). The SCO and CSL for total PCBs as aroclors in marine sediments is 12 and 65 mg/kg OC, respectively.

As part of Enhanced Natural Recovery in the Lower Duwamish Waterway, the EPA has identified an opportunity to incorporate an amendment to further sequester contaminants. A final decision regarding addition of an amendment will be made once pilot testing is conducted to determine the engineering feasibility and success of the amendment to further sequester contaminants, thus decreasing the contaminant concentration in the porewater and rendering the contaminant less bioavailable. The amendment being considered by EPA for incorporation into the ENR layer is activated carbon. Activated carbon sequesters hydrophobic organic contaminants through absorption of the contaminant to the activated carbon particle.

Design of the pilot test is currently being developed by the Lower Duwamish Waterway Group with the EPA serving as the regulating agency. The Lower Duwamish Waterway Group consists of four Potentially Reliable Parties identified for the Superfund cleanup. Those Potentially Responsible Parties include the Boeing Company, Port of Seattle, King County, and the City of Seattle. Implementation of the pilot test is tentatively scheduled for winter of 2016. There are four primary objectives of the pilot study. Those

objectives are outlined in the second amendment to the administrative order on consent for the remedial investigation/ feasibility study for the Lower Duwamish Waterway. The objectives are:

1) Verify that Enhanced Natural Recovery amended with activated carbon can be successfully applied in the Lower Duwamish Waterway by monitoring physical placement success (uniformity of coverage and percent of carbon in a placed layer);
2) Evaluate performance of Enhanced Natural Recovery amended with activated carbon compared to Enhanced Natural Recovery alone in locations with a range of PCB concentrations;
3) Assess potential impacts to the benthic community in Enhanced Natural Recovery amended with activated carbon compared to Enhanced Natural Recovery alone; and
4) Assess changes in PCB bioavailability in Enhanced Natural Recovery amended with activated carbon compared to Enhanced Natural Recovery alone.

At present, three one acre plot locations have been selected for implementation of ENR (Figure 2). Half of each plot will consist of a six to nine inch sand type layer and the other half will consist of a combined sand and activated carbon mixture to compare relative effectiveness. These plots are placed throughout intertidal and subtidal areas subject to a range of scour and erosional forces. Concentrations of total PCBs as Aroclors for these plot range between 100 and 3,300 µg/kg dry weight. The pilot study is being designed to achieve an 80 to 90 percent reduction in PCB porewater concentrations based on previous published literature.

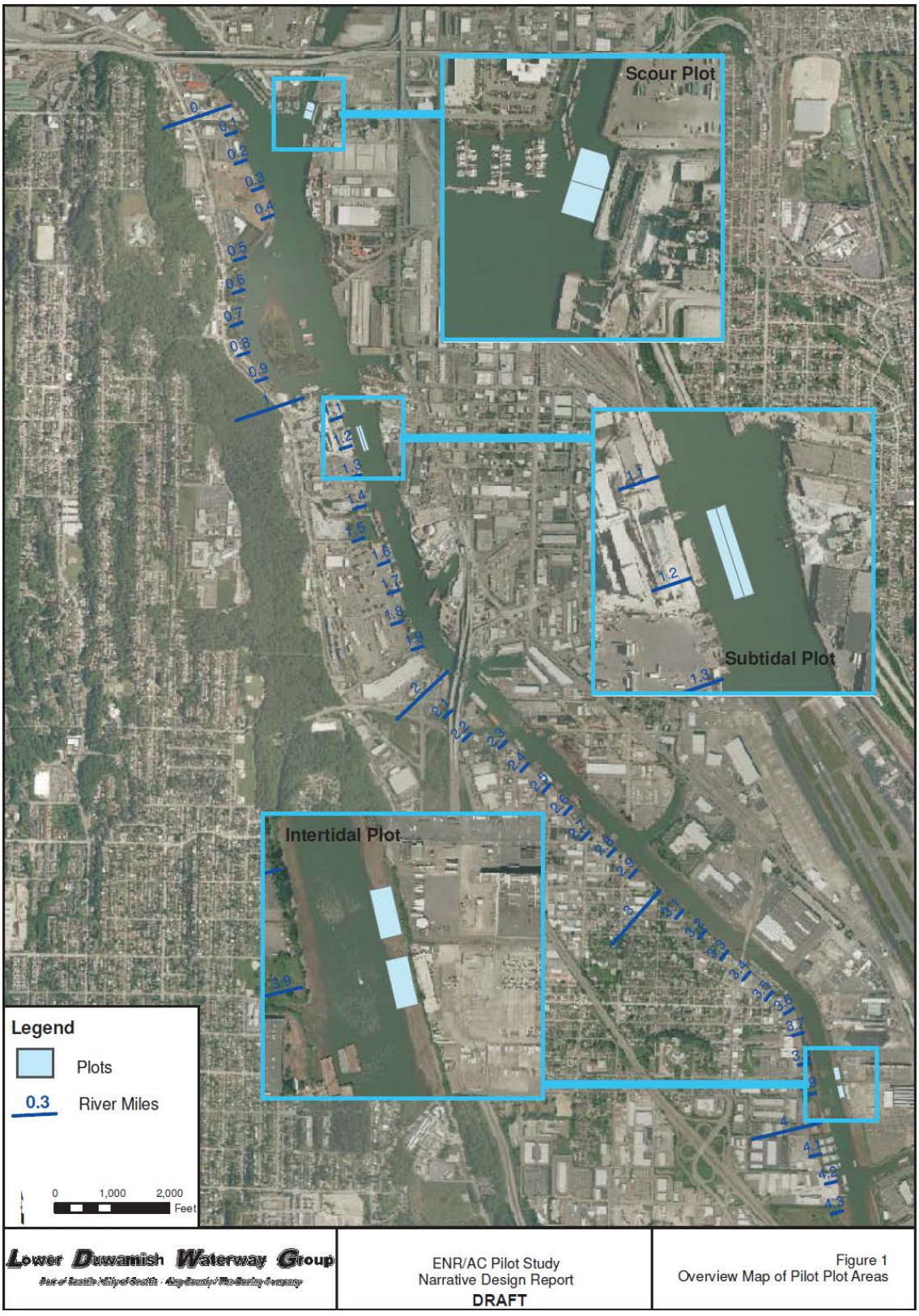

Figure 2. Locations for ENR pilot study in the Lower Duwamish Waterway (Source: Lower Duwamish Waterway Group, 2015)

While many laboratory and field studies have been done to determine contaminant reductions in porewater and aquatic organisms, the primary data gap remaining is a quantitative understanding of the potential risk reduction if activated carbon is applied to Enhanced Natural Recovery Areas in the Lower Duwamish Waterway. The Remedial Action Objectives (RAOs) for the Lower Duwamish Waterway are primarily focused on reduction of risk. The four RAOs identified in the Record of Decision (U.S EPA, 2014) are:

> RAO 1: Reduce to protective levels the human health risks associated with consumption of contaminated Lower Duwamish Waterway resident fish and shellfish by adults and children with the highest potential exposure.
>
> RAO 2: Reduce to protective levels the human health risks from direct contact (skin contact and incidental ingestion) to contaminated sediments during net fishing, clamming, and beach play.
>
> RAO 3: Reduce to protective levels the risks to benthic invertebrates from exposure to contaminated sediments.
>
> RAO 4: Reduce to protective levels the risks to crabs, fish, birds, and mammals from exposure to contaminated sediment, surface water, and prey.

Numerical criteria associated with these RAOs are presented in Table 1. As PCBs are one of the primary risk drivers for the Lower Duwamish Waterway, the success of activated carbon to sequester PCBs in areas designated for Enhanced Natural Recovery could potentially help meet all four RAOs. Prior to full scale implementation of activated carbon amendment in the Lower Duwamish Waterway, a prediction of the possible risk reduction could assist in future risk management decisions.

Table 1. Numerical cleanup criteria for PCBs for the Lower Duwamish Superfund Site.

		Intertidal Sediments				**Subtidal Sediments**			
		High Scour Areas		Low/Moderate Scour Areas		High Scour Areas		Low/Moderate Scour Areas	
	Action Level	Top 4 inches	Top 1.5ft	Top 4 inches	Top 1.5ft	Top 4 inches	Top 2ft	Top 4 inches	Top 2ft
Total PCBs (mg/kg OC)	**Remedial Action Level**	12	12	12	65	12	12	12	195
	Upper Limit for ENR	-	-	36	97	-	-	36	195

Properties of activated carbon

Activated carbon is a microporous adsorbent produced from various carbonaceous materials. Commercially available activated carbon is sourced from a variety of materials including, wood, coal, and coconut shells. There are both physical and chemical interactions that play a role in activated carbon's strong adsorptive properties. The microporous structure of activated carbon provides a high surface area, resulting in distinctive adsorption properties. The molecular scale structure of activated carbon consists of hexagonal layers of carbon atoms ordered in parallel stacks. Within this carbon matrix, oxygen, hydrogen, and nitrogen atoms are present, either in the form of single atoms or functional groups. Of these atoms, the presence of oxygen dominates. Functional groups are chemically connected to the carbon atoms with unsaturated valences. These functional groups lend to adsorptive capacity of the activated carbon. Modification of these functional groups though heat treatment, oxidation, or impregnation can be made to further refine the adsorptive properties. (Karanfil & Kilduff, 1999) .

Some forms of organic carbon, particularly black carbon in the form of soot, charcoal, and coke, possess a strong binding affinity for hydrophobic organic contaminants. (Beckingham & Ghosh, 2011)PCB

compounds in water adsorb to activated carbon with a high affinity and nearly irreversibly. The specific congeners studied prefer AC to water with an equilibrium ratio of 10 million to 1 and prefer AC over sediment with an equilibrium ratio of about 1,000-10,000 to 1.

Concept and importance of bioavailability and influence of activated carbon

Evaluation of human health and ecological risk at contaminated sediment sites is typically based on bulk sediment concentration. Reliance on bulk sediment concentrations to asses risk includes implicit assumptions regarding sediment-water partitioning. The distribution (and bioavailability) of hydrophobic organic contaminants in sediments is heavily influenced by the presence of organic carbon. The type of organic carbon can also influence bioavailability.

Benthic organisms can be exposed to contaminants via ingestion of both sediment and porewater. Filter feeding benthos may also be exposed via the surface water immediately above the sediment surface. The presence of carbon in sediment can decrease contaminant exposure via these ingestion routes through increased binding of the contaminants to sediment and decreased flux to porewater and surface water. This has implications throughout the food web for predators that consume benthos and surface water. Decreases in benthos tissue concentration as well as decreased surface water concentrations reduce uptake in the pelagic food web as well as mammalian predators. This further influences human health risk from consumption of seafood. Figure 3 illustrates how the addition of activated carbon to sediment reduces contaminant uptake though reduction of bioaccumulation and decreased flux of dissolved contaminants.

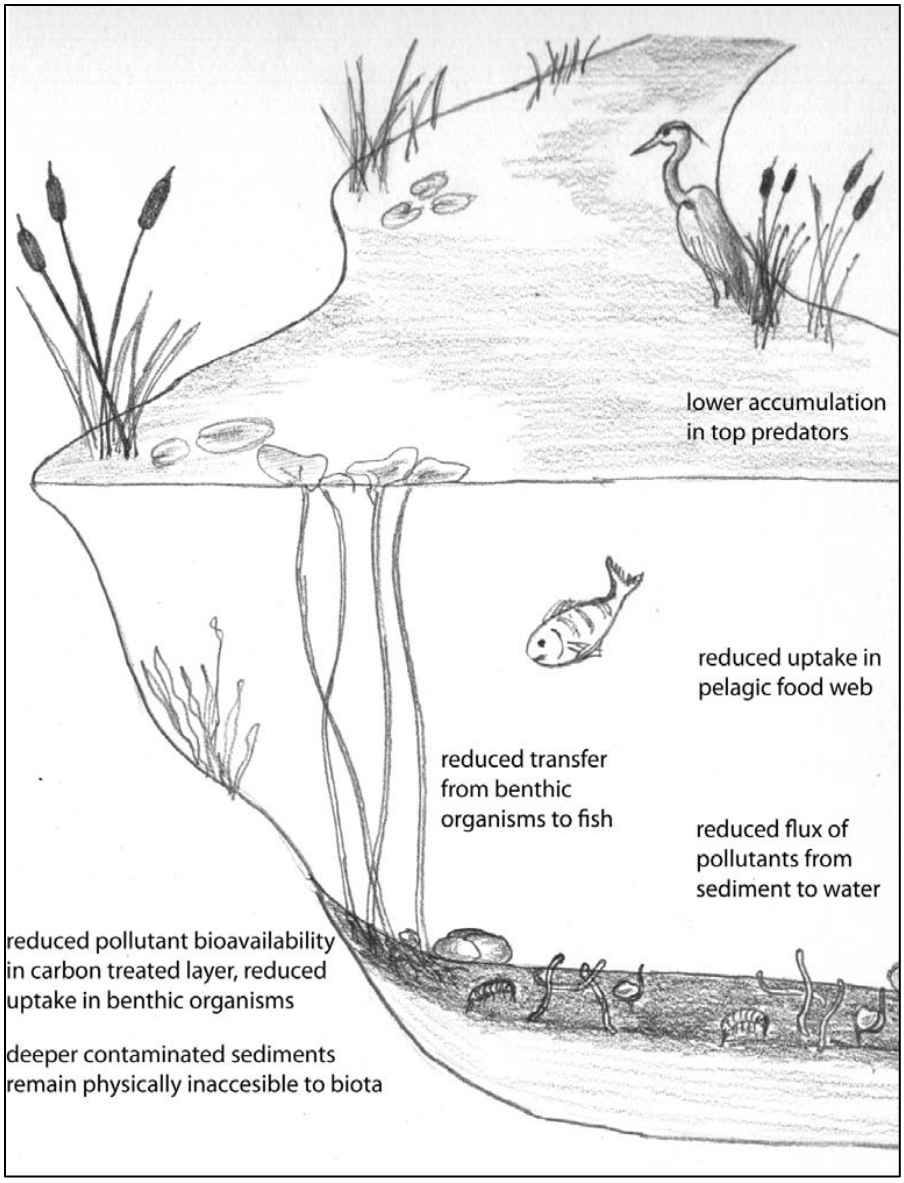

Figure 3. Conceptual illustration of the impacts on the food web from addition of activated carbon for the purposes of sequestering hydrophobic organic contaminants (Source: Beckingham & Ghosh, 2011)

Previous studies evaluating the effectiveness of activated carbon

Over the past decade, more than 25 pilot or full scale sediment treatment studies employing activated carbon were completed throughout the United States, Norway, and the Netherlands (Patmont et al., 2013). Both pilot scale experimental studies and full scale field applications at these various sites have shown activated carbon capable of reducing porewater concentration by 70 to 99 percent, depending on site conditions, dose of activated carbon applied, contaminant identity, and engineering parameters.

In addition to reducing porewater concentration and bioavailability, in situ treatment with activated carbon is less disruptive than traditional sediment remediation technologies such as dredging and capping. It is also less expensive than traditional remediation technologies, making it more economically justifiable and an increasingly preferable treatment for large scale cleanups. (Patmont et al., 2013)

Additional studies have been conducted to evaluate the impacts of contaminant sequestration in the food chain. In a study conducted by Kupryianchyk et al. (2013), various forms of activated carbon were found to significantly decrease the concentration of multiple hydrophobic organic chemicals in porewater, benthic invertebrates, zooplankton, macrophytes, and fish. During the six month laboratory study, PCB concentrations in a cohort of fish were reduced by a factor of 20. This study looked at both powdered and granular activated carbon application to sediment in a controlled freshwater environment. Invertebrates and Golden Orfe fish species were introduced into the system and monitored for approximately six months. PAH and PCB concentrations in fish invertebrates, porewater, and sediment were analyzed six times throughout the study period. This study by Kupryianchyk et al. (2013) helped to solidify the role of activated carbon as a viable remedial technology through direct risk reduction for both ecological and human health. (Kupryianchyk et al., 2013)

In 2006 a large scale pilot study was implemented by the U.S. EPA in the Lower Grasse River in Massena, New York, to asses various application methods for activated carbon placement and determine the success of activated carbon to reduce PCB flux from sediment. This demonstration provided one of the first comprehensive assessments of long term efficacy of activated carbon as a means of sequestering PCBs and PAHs in a riverine environment. Multiple placement methods were evaluated in this field scale study including application via a tiller mixing unit, direct injection with a tine sled, and surface application without mixing (Patmont et al., 2013). Monitoring for three years post placement showed PCB porewater concentrations decreased by more than 99 percent by the third year of monitoring. Bioaccumulation testing in the third year also showed greater than 90 percent reductions in PCB bioavailability. (Beckingham & Ghosh, 2011)

Hunters Point Naval Shipyard in San Francisco Bay, California, is another location where extensive pilot studies have been conducted to assess the ability of activated carbon to sequester PCBs. Prior to field deployment, laboratory studies conducted over a six month period using sediment collected from the site found a 92% reduction in PCB concentration when a 3.4% by weight dose of activated carbon was

applied to sediment from the site (Patmont et al., 2013). These laboratory results translated similarly in the field. Test plots were established in 2004 and 2006 using various mechanical methods to apply activated carbon to sediments in the intertidal mudflats of Hunters Point Naval Shipyard (Luthy, Choi, & Cho, 2013). The activated carbon was found to remain effective at sequestering PCBs at the five year monitoring period after initial treatment. Longer term success of the activated carbon after this five year monitoring period continues to be monitored. It was also found that during this study period PCB sorption partitioning may take more than five years to reach equilibrium. The Hunters Point Naval Shipyard site is the study area used extensively in work conducted by Luthy, Choi, and Cho and the basis for development and validation of the model used in this study.

Application of activated carbon at Puget Sound Naval Shipyard

In 2012 a small scale study was conducted by the U.S. Navy at Puget Sound Naval Shipyard in Sinclair Inlet near Bremerton, Washington, to evaluate physical, chemical, and biological endpoints to assess the effectiveness of activated carbon to reduce PCB concentrations in various media. As a part of this effort, a half acre plot adjacent to a pier at the shipyard was identified for treatment. The concentration of total PCBs in sediment averaged 241.1 ng/g dry weight with a standard deviation of 773.1 ng/g (Chadwick, Kirtay, Rosen, & Johnston, 2014).

The area was treated with a form of powdered activated carbon (PAC) known as AquaGate + PAC™. AquaGate + PAC™ is a proprietary blend made of small crushed stone cores coated with a bentonite-based clay used to adhere PAC to the stone cores. The formulation used for application at Puget Sound Naval Shipyard consisted of 2-5% (by weight) PAC, 5-10% bentonite clay and 85% aggregate (60 – 96 mm crushed stone). The aggregate and bentonite clay serves as a delivery mechanism for the PAC by increasing the overall effective density, allowing the product to easily sink to the sea floor. After placement, the PAC is designed to separate from the crushed stone core through dissolution of bentonite clay, allowing the PAC to incorporate into the native sediment (Figure 4) (Chadwick et al., 2014) .

Figure 4. Sediment profile images from Puget Sound Naval Shipyard showing PAC dissolved off the aggregate shortly after placement (Source: Chadwick et al., 2014)

Placement of the AquaGate + PAC™ occurred in October of 2012 over a two day period. The material was placed from a barge using a conveyor belt-type broadcast conveyor system. The activated carbon was placed through the water column and allowed to settle on the sediment surface without any additional form of mechanical mixing used as part of the placement technique. Use of the conveyor method achieved 90% coverage of the target area. Of that area, 70% received a target thickness of 5cm or greater with an average PAC concentration of 3.5% by mass in the amended layer. Monitoring results at ten months post construction showed bioaccumulation of total PCBs in invertebrates decreased by approximately 80% . Total PCBs in porewater decreased by approximately 90% at the ten month monitoring period as a result of the AC application, with total PCB porewater concentrations decreasing from 0.165 to 0.017 ng/L.
(Chadwick et al., 2014)

Model equations and theory

The PCB mass transfer model used for this study built upon previous efforts conducted by Werner and Gosh (2006). The model assumes intra-particle diffusion of contaminants associated with three different particle types (Figure 5).Intra-particle diffusion refers to the diffusion of contaminants within the pore space of a particle. Two different sediment particle types are incorporated into the model; sediment particles with slow intra-particle diffusion and slow desorption of contaminant and sediment particles with fast intra-particle diffusion and fast desorption of contaminant. The third particle type is activated carbon with the slowest diffusion and desorption kinetics because of strong sorption ability of organic contaminants. The model accounts for movement of contaminants by molecular diffusion in porewater, porewater dispersion, and advective flow.

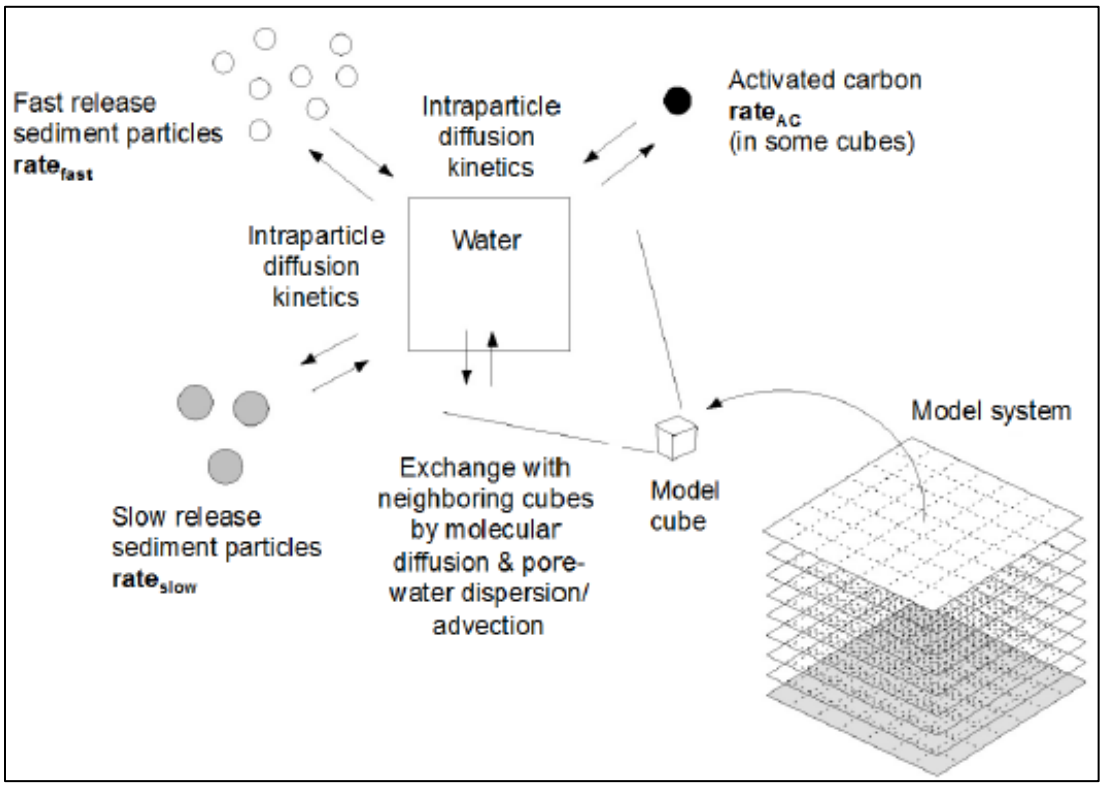

Figure 5. Conceptual illustration of contaminant movement between neighboring cubes via diffusion, dispersion, and advection. Three different compartments are depicted: slow releasing sediment particles, fast releasing sediment particles, and activated carbon (Luthy et al., 2013)

The model is able to simulate a series of different mixing regimes for activated carbon in both well mixed and quiescent systems. There are input parameter options for the model to indicate homogenously or well mixed distributed activated carbon with approximately 0.2 mm average porewater diffusion distance. The other input option is to assume poorly mixed activated carbon with approximately 1 mm average porewater diffusion distance.

The relevant formula that serves as the basis for the model is a basic mass transfer model from Hale and Werner that was modified to account for advective porewater flow:

$$\frac{dS_{aq}(x,y,z,t)}{dt} = D_{disp}\left[\frac{\partial^2 S_{aq}(x,y,z,t)}{\partial x^2}+\frac{\partial^2 S_{aq}(x,y,z,t)}{\partial y^2}+\frac{\partial^2 S_{aq}(x,y,z,t)}{\partial z^2}\right]$$ (dispersion)

S_{aq} = PCB water concentration

$$-\frac{V_{sed}(x,y,z)}{V_{aq}}\cdot\frac{d}{dt}\left[3\int_0^1 q^2 S_{sed\_fast}(x,y,z,q,t)dq+3\int_0^1 q^2 S_{sed\_slow}(x,y,z,q,t)dq\right]$$

(fast sed. desorption) (slow sed. desorption)

$$-\frac{V_{AC}(x,y,z)}{V_{aq}}\cdot\frac{d}{dt}\left[3\int_0^1 q^2 S_{AC}(x,y,z,q,t)dq\right]-u_z\frac{\partial S_{aq}(x,y,z,t)}{\partial z}$$

(AC desorption) (advection)

where V_j (cm^3) and S_j (g/cm^3) represent the total volume of each phase component in the cube and the volumetric PCB concentration in that phase respectively, and q (-) is the radial distance from the particle center divided by the particle radius. S_{sed_fast} (g/cm^3) is the amount of contaminant associated with $rate_{fast}$ per total volume of sediment and S_{sed_slow} (g/cm^3) is the amount of PCB associated with $rate_{slow}$ per total volume of sediment. The parameters, $rate_{fast}$ and $rate_{slow}$, refer to the PCB congener release rates for fast and slow release from sediment particles. D_{disp} (cm^2/s) denotes the dispersion coefficient, and u_z (cm/d) the porewater velocity in the z direction. The implementation of the intraparticle diffusion part of the model is based on the explicit numerical scheme described by Wu and Gschwend (1988).

PCB Congeners

The model is PCB congener specific. While the model can be run for any congener, PCB congeners 101, 153, and 180 were selected for model implementation by Luthy, Choi, and Cho because of their prevalence at Hunters Point Naval Shipyard, the study area of interest for model application and validation. Mass transfer parameters unique to each congener were identified through laboratory experiments for input into the model.

The structure for PCB congeners 101, 153, and 180 is presented in Figures 6a through 6c. These three congeners each represent different homolog groups and have high detection frequencies in the Lower Duwamish Waterway. Of the three congeners, PCB 180 has the highest relative toxicity, due to its di-ortho planar structure. PCB 180 has a Toxicity Equivalency Factor of 0.0001 relative to 2,3,7,8-TCDD (Eisler and Belisle, 1996).

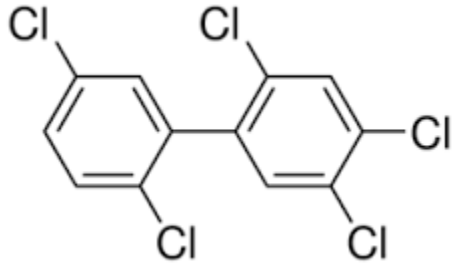

Figure 6a. Structure of PCB 101 (2,2',4,5,5'-Pentachlorobiphenyl)

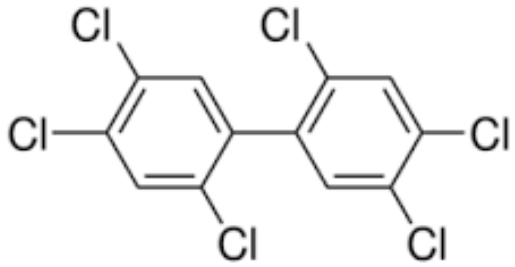

Figure 6b Structure of PCB 153 (2,2',4,4',5,5'-Hexachlorobiphenyl)

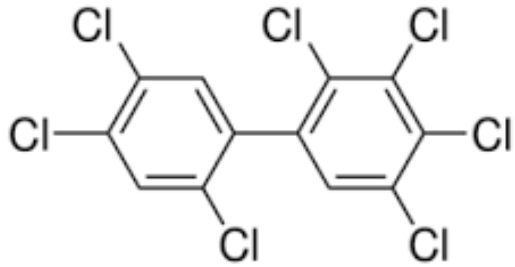

Figure 6c. Structure of PCB 180 (2,2',3,4,4',5,5'-Heptachlorobiphenyl)

Chapter 3. Methodology

This study relied upon a beta version of a PCB mass transfer model developed by Luthy, Choi, and Cho (2013) for use in MATLAB R2011b. The MATLAB script was integrated with Microsoft Excel to allow for data input and output directly through an Excel file.

The model allows customization of 22 different input parameters. Default or recommended values for the parameters are provided by Luthy, Choi, and Cho. A Subset of values was altered in order to represent site specific conditions for the Lower Duwamish Waterway and Puget Sound Naval Shipyard. Of note for parameters associated with AC properties, a particle size of 75-300 µm was used to represent granular AC, which is likely to be used at Lower Duwamish Waterway, and a particle size of 25-75 µm was used to represent powdered AC used at Puget Sound Naval Shipyard. (Zimmerman et al., 2005)

The sediment-water distribution coefficients derived by Luthy, Choi, and Cho were used for all three PCB congener model runs for Puget Sound Naval Shipyard. In addition, sediment-water distribution coefficients derived from experimental studies specific to the Lower Duwamish Waterway conducted by Gschwend et al. (2013) were also applied to the scenarios for Puget Sound Naval Shipyard. While the Lower Duwamish Waterway is an estuarine environment and Puget Sound Naval Shipyard is strictly marine, salinity values at Puget Sound Naval Shipyard were compared to those of the salt wedge that protrudes into the Lower Duwamish Waterway to ensure the Lower Duwamish Waterway specific distribution coefficients were applicable to Puget Sound Naval Shipyard. Salinity levels at the mouth of the Lower Duwamish Waterway average 25 parts per thousand (ppt) through the entire water column. The thickness of the freshwater layer increases throughout the Lower Duwamish Waterway as the river flow rate increases. However, the saltwater wedge interfaces with the sediment bottom for a large portion of the lower waterway. At Puget Sound Naval Shipyard, similar salinity concentrations are present, ranging from 28.3 to 30.3 ppt (Albertson, Newton, Eisner, Janzen, & Bell, 1993). Hunters Point Naval Shipyard, the site from which Luthy, Choi, and Cho derived the model's default distribution coefficient values, is also a marine environment with salinity levels averaging near 30 ppt (Geological Survey, 2007) and thus relevant to the Puget Sound Naval Shipyard site. Only sediment-water distribution coefficients derived by Gschwend for the Lower Duwamish Waterway were used for that specific site modeling. Salinity is an important consideration when applying sediment water partitioning

coefficients to different sites because increases in salinity will increase the expected sorption of sediment and carbon (Means, 1995)

To determine the influence of each individual parameter on model outcomes for the Lower Duwamish Waterway, select parameters were individually altered with minimum and maximum values while all others were held constant at a default or average value. Previously collected data from the Remedial Investigation and Feasibility Study for the Lower Duwamish Waterway Superfund Site (2010) were used to derive minimum, maximum, and default or average values for all site specific parameters. Parameters that were identified as having the minimum and maximum influence on model outcomes were combined to determine the overall range of potential concentration reduction in the Lower Duwamish Waterway. For this combination of values with minimum and maximum influence on PCB concentrations reductions, AC dose was held at a constant 4% with AC particle size representative of granular AC and the PCB congener concentrations were held at their average/default values. This was done to better elucidate the overall influence of site specific parameters and application methods. For parameters where no minimum or maximum value was identified, the average/default value was used when modeling the overall minimum and maximum influence on PCB concentration reductions.

For Puget Sound Naval Shipyard, the model was run using previously collected data and parameters that most accurately represented actual conditions at the site and the specific form (powdered) of activated carbon treatment. Existing monitoring data for Puget Sound Naval Shipyard collected at 10 month post construction was compared to predicted results to assess the accuracy of model to predict concentration reductions.

Tables 2a through 2d present the model parameters and default, minimum, and maximum values used for the Lower Duwamish Waterway as well as the default values used for Puget Sound Naval Shipyard.

Table 2a. Model input parameters for Lower Duwamish Waterway (LDW) and Puget Sound Naval Shipyard (PSNS) Common to all PCB Congeners

		Input Parameter Values for LDW and PSNS			
Parameter	**Units**	**LDW Default Value**	**LDW Minimum Value**	**LDW Maximum Value**	**PSNS Default Value**
AC Amendment Application					
Initial mechanical mixing with sediment and AC	minutes	0	NA	NA	0
AC-sediment contact in stagnant system	months	12	NA	36	12
Nominal mixing depth	cm	10	5	15	10
Nominal AC dose	g/g	0.04	0.02	1.0	0.035
Core-scale (5cm) AC distribution heterogeneity	unitless: 1 if homogeneous/ 2 if heterogeneous	2	1	2	2
MM-scale (2mm) AC distribution heterogeneity	unitless: 1 if homogeneous/ 2 if heterogeneous	2	1	2	2
Site Specific Properties					
Sediment Porosity	unitless	0.64	0.41	0.75	0.64
Sediment Particle Density	g/cm^3	2.3	NA	2.6	2.3
Porewater flow velocity	cm/d	0	NA	10	0
Mechanical dispersivity	cm	0.1	NA	NA	0.1
AC Properties					
AC Particle size(diameter) lower limit	µm	75	25	420	25
AC Particle size(diameter) Upper limit	µm	300	75	1700	75
AC Density	g/cm^3	1.96	NA	NA	1.96
AC Intraparticle porosity	unitless	0.55	NA	NA	0.55

Table 2b. Model input parameters for Lower Duwamish Waterway (LDW) and Puget Sound Naval Shipyard (PSNS) Specific to all PCB Congener 101 simulations.

		Input Parameter Values for LDW and PSNS			
Parameter	**Units**	**LDW Default Value**	**LDW Minimum Value**	**LDW Maximum Value**	**PSNS Default Value**
Mass Transfer Parameters					
Initial Sediment Concentration	ng/g	49	NA	5,600	40
Aqueous diffusivity	cm^2/s	$4.9x10^{-6}$	NA	NA	$4.9x10^{-6}$
Sediment-water distribution coefficient	cm^3/g	$6.4x10^4$	$4.1x10^4$	$9.6x10^4$	$6.4x10^4$ (Gschwend et al.); $7.0\ x10^4$ (Luthy et al.)
Fast release rate from sediment	1/s	$2.2x10^{-7}$	NA	NA	$2.2x10^{-7}$
Slow release rate from sediment	1/s	$9.7x10^{-10}$	NA	NA	$9.7x10^{-10}$
Mass fraction associated with slow rate	Unitless	0.66	NA	NA	0.66
Apparent AC-water partitioning coefficient	cm^3/g	$1.0x10^8$	NA	NA	$1.0x10^8$
Apparent diffusion coefficient for intraparticle diffusion with AC	1/s	$1.8x10^{-14}$	NA	NA	$1.8x10^{-14}$

Table 2c. Model input parameters for Lower Duwamish Waterway (LDW) and Puget Sound Naval Shipyard (PSNS) Specific to all PCB Congener 153 simulations.

		Input Parameter Values for LDW and PSNS			
Parameter	**Units**	**LDW Default Value**	**LDW Minimum Value**	**LDW Maximum Value**	**PSNS Default Value**
Mass Transfer Parameters					
Initial Sediment Concentration	ng/g	57	NA	9,090	25
Aqueous diffusivity	cm^2/s	$4.88x10^{-6}$	NA	NA	$4.88x10^{-6}$
Sediment-water distribution coefficient	cm^3/g	$1.8x10^5$	$7.5x10^4$	$2.4x10^6$	$1.8x10^5$(Gschwend et al.); $5.9x10^5$ (Luthy e .al.)
Fast release rate from sediment	1/s	1.9x10-7	NA	NA	$1.9x10^{-7}$
Slow release rate from sediment	1/s	3.2x10-10	NA	NA	$3.2x10^{-10}$
Mass fraction associated with slow rate	Unitless	0.66	NA	NA	0.66
Apparent AC-water partitioning coefficient	cm^3/g	$3.98x10^8$	NA	NA	$3.98x10^8$
Apparent diffusion coefficient for intraparticle diffusion with AC	1/s	$4.1x10^{-15}$	NA	NA	$4.1x10^{-15}$

Table 2d. Model input parameters for Lower Duwamish Waterway (LDW) and Puget Sound Naval Shipyard (PSNS) Specific to all PCB Congener 180 simulations.

		Input Parameter Values for LDW and PSNS			
Parameter	**Units**	**LDW Default Value**	**LDW Minimum Value**	**LDW Maximum Value**	**PSNS Default Value**
Mass Transfer Parameters					
Initial Sediment Concentration	ng/g	21	NA	1,600	8.5
Aqueous diffusivity	cm^2/s	$4.88x10^{-6}$	NA	NA	$4.88x10^{-6}$
Sediment-water distribution coefficient	cm^3/g	$1.69x10^5$	$6.8x10^4$	$8.6x10^5$	$1.69x10^5$ (Gschwend et.al.); $1.2x10^6$ (Luthy et.al.)
Fast release rate from sediment	1/s	$6.81x10^{-8}$	NA	NA	$6.81x10^{-8}$
Slow release rate from sediment	1/s	$1.14x10^{-9}$	NA	NA	$1.14x10^{-9}$
Mass fraction associated with slow rate	Unitless	0.76	NA	NA	0.76
Apparent AC-water partitioning coefficient	cm^3/g	$1.47x10^9$	NA	NA	$1.47x10^9$
Apparent diffusion coefficient for intraparticle diffusion with AC	1/s	$2.81x10^{-15}$	NA	NA	$2.81x10^{-15}$

Chapter 4. Results

Lower Duwamish Waterway

For the Lower Duwamish Waterway, predicted average porewater concentration reductions over a one year period after application of granular activated carbon to contaminated sediment are illustrated in Figure 7. Porewater concentration reductions were estimated at 81%, 68%, and 69% for PCB 101, 153 and 180, respectively. All simulations show a sharp initial decline immediately post GAC addition, followed by a declining rate of decrease.

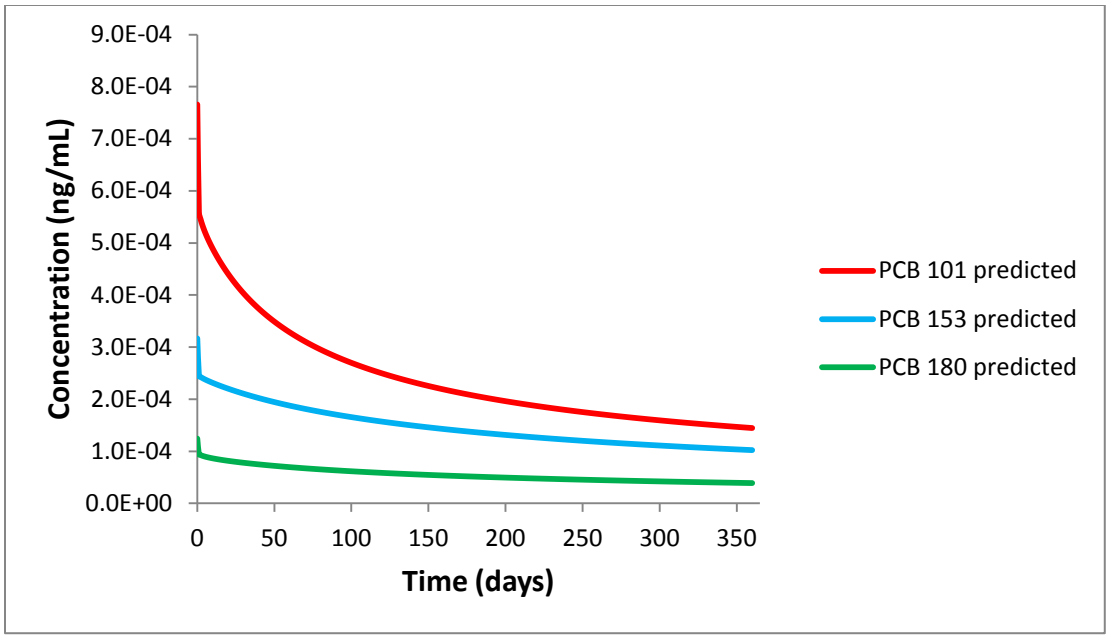

Figure 7. Lower Duwamish Waterway PCB porewater concentration reduction for PCB congeners 101, 153, and 180

Tables 3a through 3c provide the estimated concentration reductions as well as mass distribution for minimum and maximum parameter values individually modeled. For all congeners, the most influential parameters yielding the greatest porewater concentration reduction were the minimum activated carbon particle size and maximum sediment-water distribution coefficient. Percent reduction in porewater concentration under the scenario using the minimum activated carbon particle size ranged from 93% to 96% for the three PCB congeners. For the maximum sediment-water distribution coefficient, percent reductions in porewater concentration ranged 82% to 95% for the three PCB congeners. Minimum porewater concentration reduction was predicted at the maximum activated carbon particle size, with reductions ranging between 14% and 21% for the three PCB congeners.

Table 3a. Lower Duwamish Waterway PCB 101 minimum and maximum value results

		Concentration			Mass Distribution in the System (M_i/M_{total})			
		Porewater	Sediment	Activated	Sediment		Activated	Porewater
Parameter	**Days**	**Concentration (ng/mL)**	**Concentration (ng/g)**	**Carbon Concentration (ng/g)**	**Slow releasing**	**Fast releasing**	**Carbon**	
Pre- AC application	**0**	**$7.6x10^{-4}$**	**49***	**0**	**0.659**	**0.339**	**0**	**$1.2x10^{-5}$**
All Average/Default Parameters	**359**	**$1.4x10^{-4}$**	**24.3**	**539**	**0.424**	**0.0713**	**0. 504**	**$2.55x10^{-6}$**
AC Amendment Application								
36 Months AC-sediment contact in stagnant system	1079	7.78x10-5	13.8	768	0.244	0.038	0.717	1.3x10-6
MINIMUM Nominal mixing depth	359	$1.9x10^{-4}$	26.3	686	0.445	0.0911	0.463	$3.2x10^{-6}$
MAXIMUM Nominal mixing depth	359	$1.7x10^{-4}$	25.4	651	0.436	0.0827	0.481	$2.9x10^{-6}$
MINIMUM Nominal AC dose	359	$2.25x10^{-4}$	27.9	978	0.463	0.105	0.431	$3.7x10^{-6}$
MAXIMUM Nominal AC dose	359	$7.27x10^{-5}$	20.9	324	0.387	0.0389	0.573	$1.4x10^{-6}$
MINIMUM Core-scale (5cm) AC distribution heterogeneity	359	$1.07x10^{-4}$	22.5	646	0.406	0.0522	0.541	$1.8x10^{-6}$
MINIMUM MM-scale (2mm) AC distribution heterogeneity	359	$1.14x10^{-4}$	22.8	670	0.410	0.055	0.534	$1.9x10^{-7}$
MINIMUM Core-scale and MM-scale AC distribution heterogeneity	359	$8.1x10^{-4}$	21.2	695	0.394	0.039	0.566	$1.4x10^{-6}$
Site Specific Properties								
MINIMUM Sediment Porosity	359	$2.73x10^{-4}$	30.2	526	0.484	0.132	0.383	$1.8x10^{-6}$
MAXIMUM Sediment Porosity	359	$1.1x10^{-4}$	22.6	716	0.408	0.053	0.538	$3.2x10^{-6}$
MAXIMUM Sediment Particle Density	359	$1.44x10^{-4}$	24.3	543	0.424	0.072	0.503	$2.2x10^{-6}$
MAXIMUM Porewater flow velocity	359	$9.03x10^{-5}$	21.3	722	0.391	0.0434	0.563	$1.5x10^{-6}$
Activated Carbon Properties								
MINIMUM AC Particle size(diameter) lower/upper limit	359	$2.92x10^{-5}$	17.9	847	0.351	0.0138	0.635	$5.0x10^{-7}$
MAXIMUM AC Particle size(diameter) lower/upper limit	359	$6.06x10^{-4}$	45.5	806	0.628	0.299	0.0721	$1.0x10^{-5}$
Mass transfer Parameters								
MINIMUM Sediment-water distribution coefficient	360	$1.99x10^{-4}$	23.3	673	0.413	0.062	0.524	$3.4x10^{-6}$
MAXIMUM Sediment-water distribution coefficient	359	$1.37x10^{-4}$	27.2	536	0.454	0.100	0.445	$2.3x10^{-6}$
MAXIMUM Initial Sediment Concentration	359	1.83	285	$6.96x10^{4}$	0.431	0.078	0.490	2.7x10-6

*Sediment concentration is a measured mean value. The minimum detected value for PCB 101 is 0.41 ng/g and a maximum value of 5,600 ng/g.

Table 3b. Lower Duwamish Waterway PCB 153 minimum and maximum value results

		Concentration			Mass Distribution in the System (M_i/M_{total})			
		Porewater	Sediment	Activated	Sediment		Activated	Porewater
Parameter	**Days**	**Concentration (ng/mL)**	**Concentration (ng/g)**	**Carbon Concentration (ng/g)**	**Slow releasing**	**Fast releasing**	**Carbon**	
Pre- AC application	**0**	**$3.17x10^{-4}$**	**57***	**0**	**0.66**	**0.34**	**0**	**$4.7x10^{-6}$**
All Average/Default Parameters	**359**	**$1.02x10^{-4}$**	**38.1**	**460**	**0.547**	**0.121**	**0.330**	**$1.5x10^{-6}$**
AC Amendment Application								
36 Months AC-sediment contact in stagnant system	1080	$5.99x10^{-5}$	28.3	769	0.425	0.0700	0.504	$8.9x10^{-7}$
MINIMUM Nominal mixing depth	359	$1.08x10^{-4}$	38.7	467	0.550	0.1279	0.321	$1.6x10^{-6}$
MAXIMUM Nominal mixing depth	359	$9.48x10^{-5}$	37.4	481	0.543	0.112	0.344	$1.4x10^{-6}$
MINIMUM Nominal AC dose	359	$1.52x10^{-4}$	42.7	682	0.577	0.172	0.250	$2.1x10^{-6}$
MAXIMUM Nominal AC dose	359	$5.77x10^{-5}$	34.8	662	0.526	0.138	0.335	$4.4x10^{-6}$
MINIMUM Core-scale (5cm) AC distribution heterogeneity	359	$7.76x10^{-5}$	35.6	507	0.532	0.0922	0.375	$1.1x10^{-6}$
MINIMUM MM-scale (2mm) AC distribution heterogeneity	359	$8.93x10^{-5}$	36.8	517	0.540	0.1055	0.354	$1.3x10^{-6}$
MINIMUM Core-scale and MM-scale AC distribution heterogeneity	359	$7.18x10^{-5}$	35	550	0.529	0.0849	0.385	$1.07x10^{-6}$
Site Specific Properties								
MINIMUM Sediment Porosity	359	$1.61x10^{-4}$	43.9	363	0.582	0.188	0.229	$9.3x10^{-7}$
MAXIMUM Sediment Porosity	359	$9.58x10^{-5}$	37.4	604	0.544	0.111	0.343	$2.3x10^{-6}$
MAXIMUM Sediment Particle Density	359	$9.98x10^{-5}$	37.9	515	0.546	0.118	0.334	$1.3x10^{-6}$
MAXIMUM Porewater flow velocity	359	$5.77x10^{-5}$	33.2	650	0.515	0.0673	0.416	$8.5x10^{-7}$
Activated Carbon Properties								
MINIMUM AC Particle size(diameter) lower/upper limit	359	$1.56x10^{-5}$	28.1	717	0.474	0.0183	0.507	$2.3x10^{-7}$
MAXIMUM AC Particle size(diameter) lower/upper limit	359	$2.68x10^{-4}$	55.2	43.4	0.649	0.318	0.0314	$4.02x10^{-6}$
Mass transfer Parameters								
MINIMUM Sediment-water distribution coefficient	359	$1.44x10^{-4}$	33.5	689	0.517	0.0703	0.412	$2.1x10^{-6}$
MAXIMUM Sediment-water distribution coefficient	359	$1.71x10^{-5}$	50.7	151	0.621	0.267	0.110	$2.5x10^{-7}$
MAXIMUM Initial Sediment Concentration	359	$1.62x10^{-2}$	603	$7.7x10^{4}$	0.547	0.120	0.332	$1.5x10^{-6}$

*Sediment concentration is a measured mean value. The minimum detected value for PCB 153 is 0.25 ng/g and a maximum value of 9,090 ng/g.

Table 3c. Lower Duwamish Waterway PCB 180 minimum and maximum value results

		Concentration			Mass Distribution in the System (M_i/M_{total})			
		Porewater	Sediment	Activated	Sediment		Activated	Porewater
Parameter	**Days**	**Concentration (ng/mL)**	**Concentration (ng/g)**	**Carbon Concentration (ng/g)**	**Slow releasing**	**Fast releasing**	**Carbon**	
Pre- AC application	**0**	**$1.24x10^{-4}$**	**21**	**0**	**0.76**	**0.24**	**0**	**$5.05x10^{-6}$**
All Average/Default Parameters	**360**	**$3.9x10^{-5}$**	**12.9**	**199**	**0.528**	**0.084**	**0.387**	**$1.58x10^{-6}$**
AC Amendment Application								
36 Months AC-sediment contact in stagnant system	1079	$2.33x10^{-5}$	7.89	286	0.325	0.0507	0.624	$9.61x10^{-7}$
MINIMUM Nominal mixing depth	360	$4.43x10^{-5}$	13.4	190	0.544	0.095	0.360	$1.79x10^{-6}$
MAXIMUM Nominal mixing depth	360	$4.14x10^{-5}$	13.1	191	0.535	0.0897	0.375	$1.68x10^{-6}$
MINIMUM Nominal AC dose	360	$6.28x10^{-5}$	15.3	288	0.599	0.128	0.271	$2.43x10^{-6}$
MAXIMUM Nominal AC dose	360	$2.23x10^{-5}$	12.0	205	0.632	.0900	0.277	$1.81x10^{-6}$
MINIMUM Core-scale (5cm) AC distribution heterogeneity	360	$3.36x10^{-5}$	12.3	195	0.509	0.0734	0.416	$1.37x10^{-6}$
MINIMUM MM-scale (2mm) AC distribution heterogeneity	360	$3.66x10^{-5}$	12.6	215	0.520	0.0791	0.400	$1.48x10^{-6}$
MINIMUM Core-scale and MM-scale AC distribution heterogeneity	360	$3.01x10^{-5}$	11.9	228	0.500	0.065	0.434	$1.22x10^{-6}$
Site Specific Properties								
MINIMUM Sediment Porosity	359	$6.03x10^{-5}$	15.2	155	0.593	0.128	0.277	$9.5x10^{-7}$
MAXIMUM Sediment Porosity	360	$4.07x10^{-5}$	13	236	0.534	0.086	0.378	$2.7x10^{-6}$
MAXIMUM Sediment Particle Density	360	$3.86x10^{-5}$	12.9	203	0.527	0.0845	0.387	$1.4x10^{-6}$
MAXIMUM Porewater flow velocity	360	$2.64x10^{-5}$	11.3	280	0.480	0.056	0.462	$1.06x10^{-6}$
Activated Carbon Properties								
MINIMUM AC Particle size(diameter) lower/upper limit	359	9.19x10-6	8.84	297	0.401	0.0198	0.578	3.7x10-7
MAXIMUM AC Particle size(diameter) lower/upper limit	359	$1.06x10^{-4}$	20.3	17.4	0.741	0.226	0.0323	$4.3x10^{-6}$
Mass transfer Parameters								
MINIMUM Sediment-water distribution coefficient	359	$5.06x10^{-5}$	10.6	253	0.459	0.0444	0.496	$2.06x10^{-6}$
MAXIMUM Sediment-water distribution coefficient	359	$1.53x10^{-5}$	17.1	103	0.650	0.165	0.183	$6.2x10^{-7}$
MAXIMUM Initial Sediment Concentration	360	$2.95x10^{-3}$	979	$1.48x10^{4}$	0.527	0.0841	0.388	$1.5x10^{-6}$

*Sediment concentration is a measured mean value. The minimum detected value for PCB 180 is 0.15 ng/g and a maximum value of 1,600 ng/g.

Those parameter values that were determined to have the maximum and minimum influence on PCB porewater concentration reduction were combined to determine the gross minimum and maximum reductions possible in porewater (Figures 8 through 10).

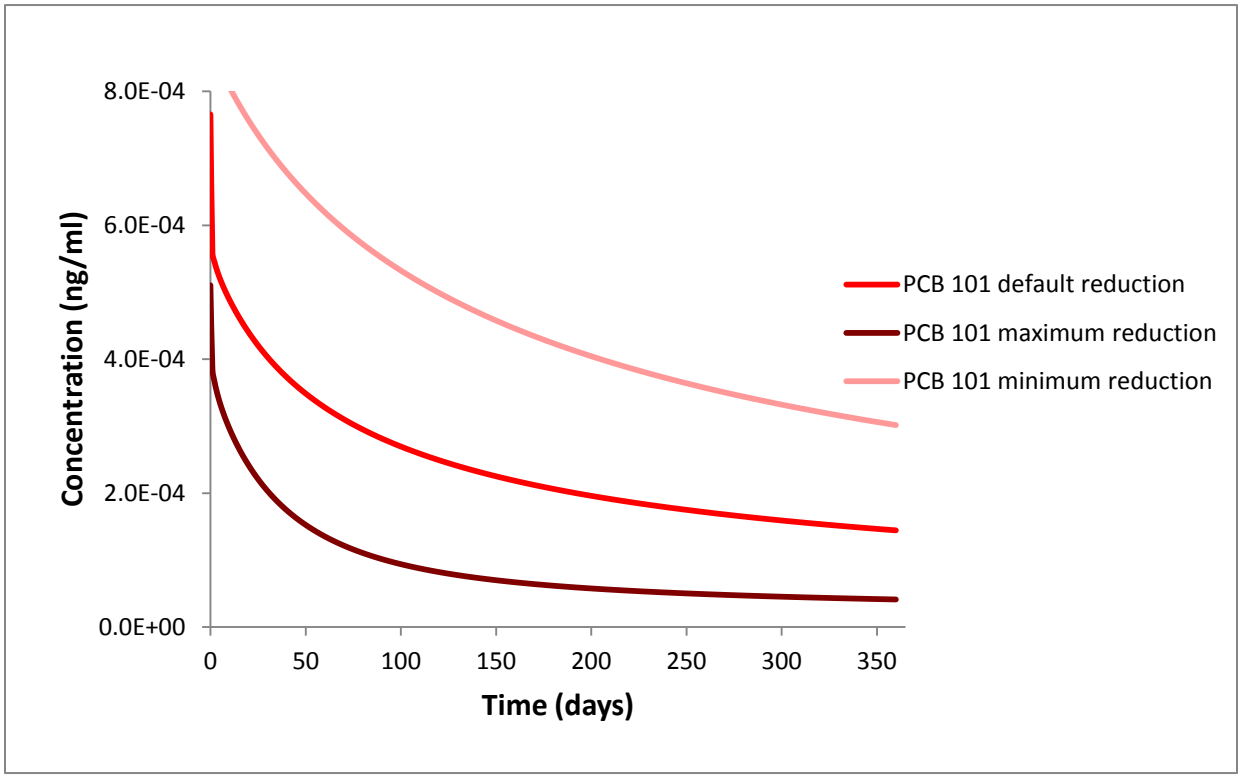

Figure 8. PCB 101 overall minimum, maximum, and default predicted concentration reductions in porewater for the Lower Duwamish Waterway

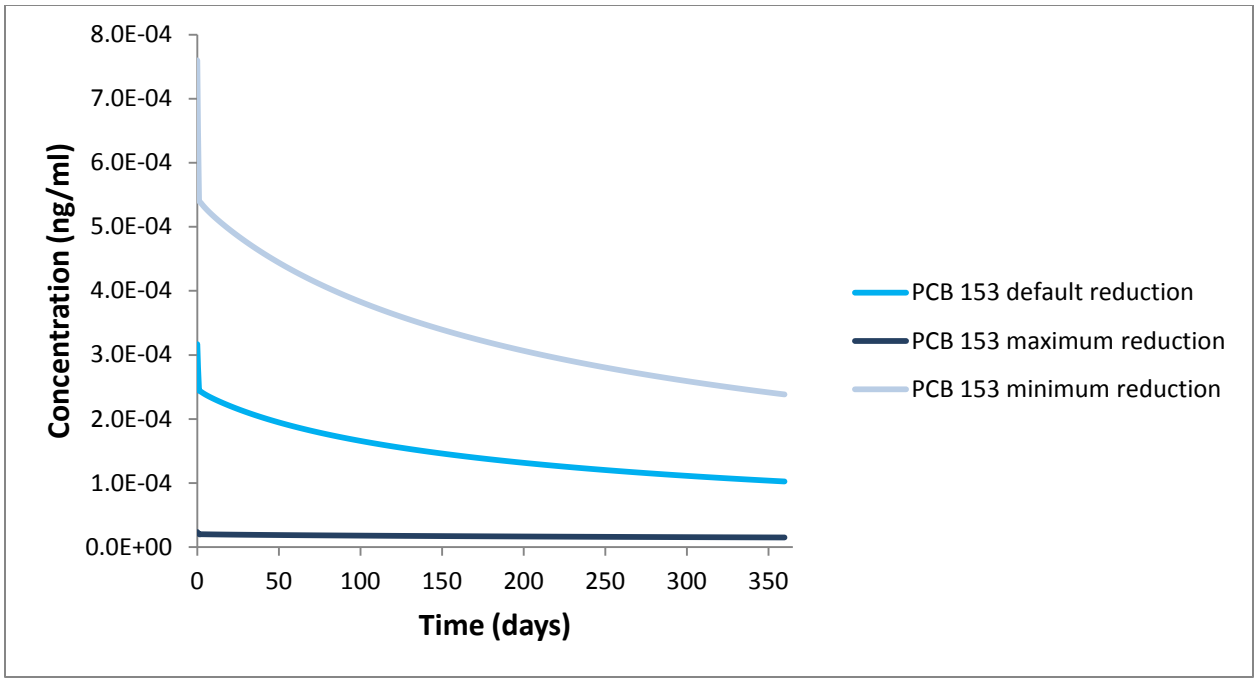

Figure 9. PCB 153 overall minimum, maximum, and default predicted concentration reductions in porewater for the Lower Duwamish Waterway

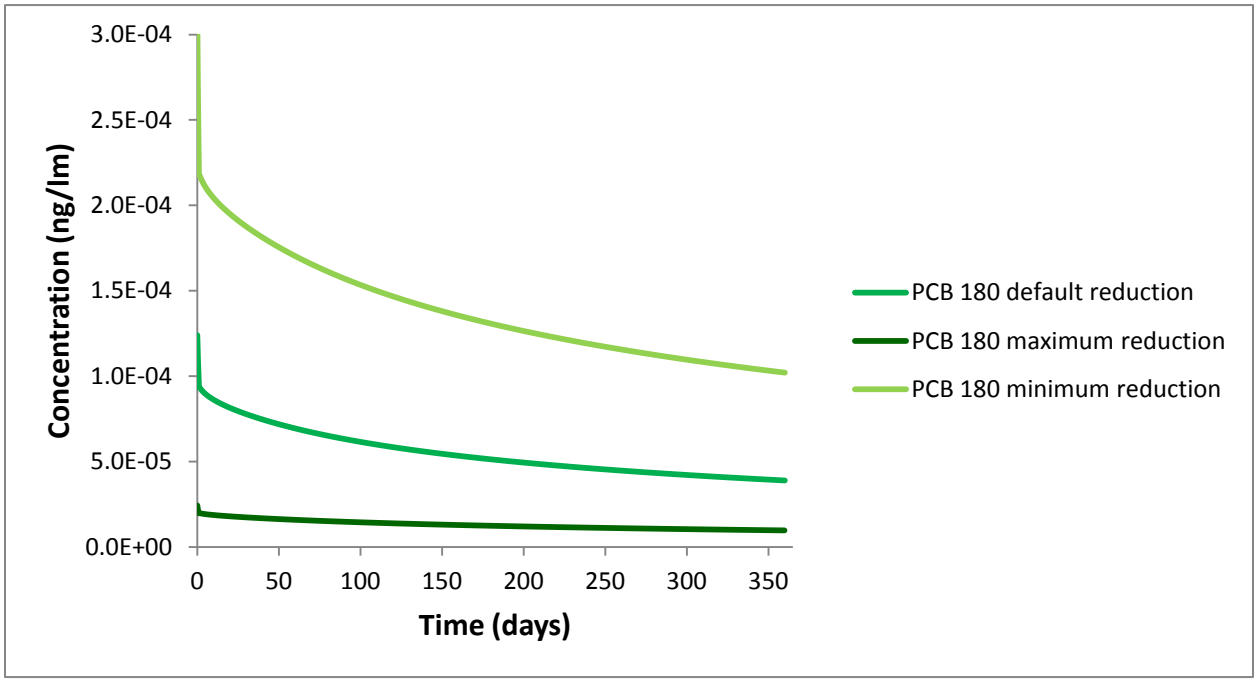

Figure 10. PCB 180 overall minimum, maximum, and default predicted concentration reductions in porewater for the Lower Duwamish Waterway

Puget Sound Naval Shipyard

For Puget Sound Naval Shipyard, the predicted sediment concentration reduction for PCB 180 was similar to the actual reduction measured in sediment at 10 months post activated carbon application. The model under predicted observed reductions for both PCB 101 and 153, but still fell within the 95% confidence interval on the measured mean at 10 months post construction. This was the case for both scenarios modeled with different sediment-water partitioning coefficients from Luthy et al. and Gschwend et al. (Figures 11 and 12). Percent reductions for predictions using the partitioning coefficient from Luthy et al. were 61, 42, and 40 percent for PCB 101, 153, and 180, respectively. Percent reductions for predictions using the partitioning coefficient from Geschwend et al. were 61, 49, and 58 percent for PCB 101, 153, and 180, respectively Sediment concentration reductions were assessed for Puget Sound Naval Shipyard because porewater concentrations measured at the site were not available for all congeners.

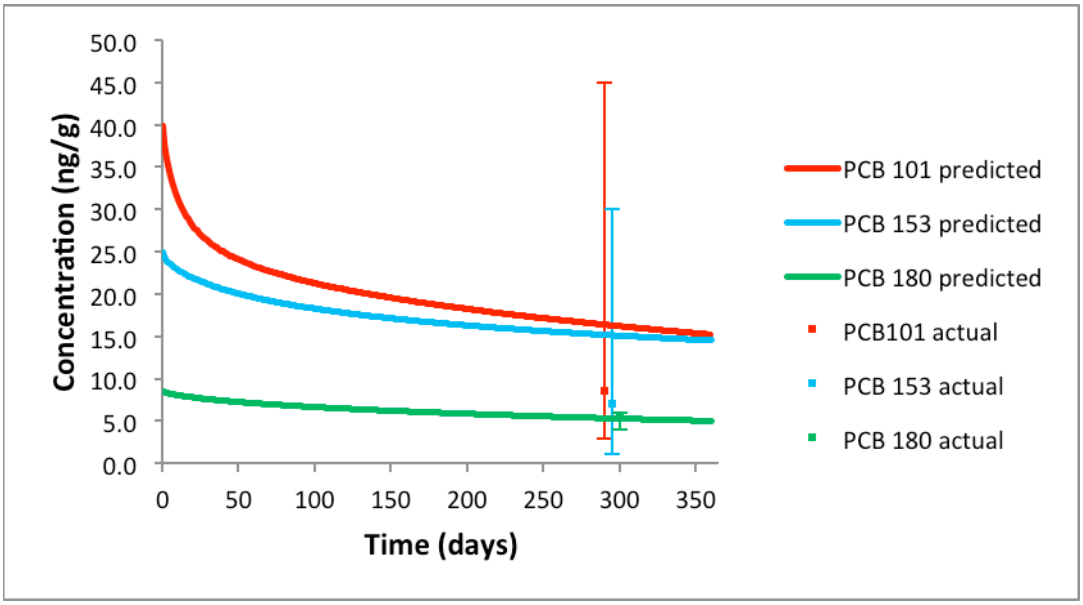

Figure 11. Predicted Puget Sound Naval Shipyard sediment concentration reduction for PCB Congeners 101, 153, and 160 using K_d from Luthy et al. (2013) and observed means (error bars are 95% CI).

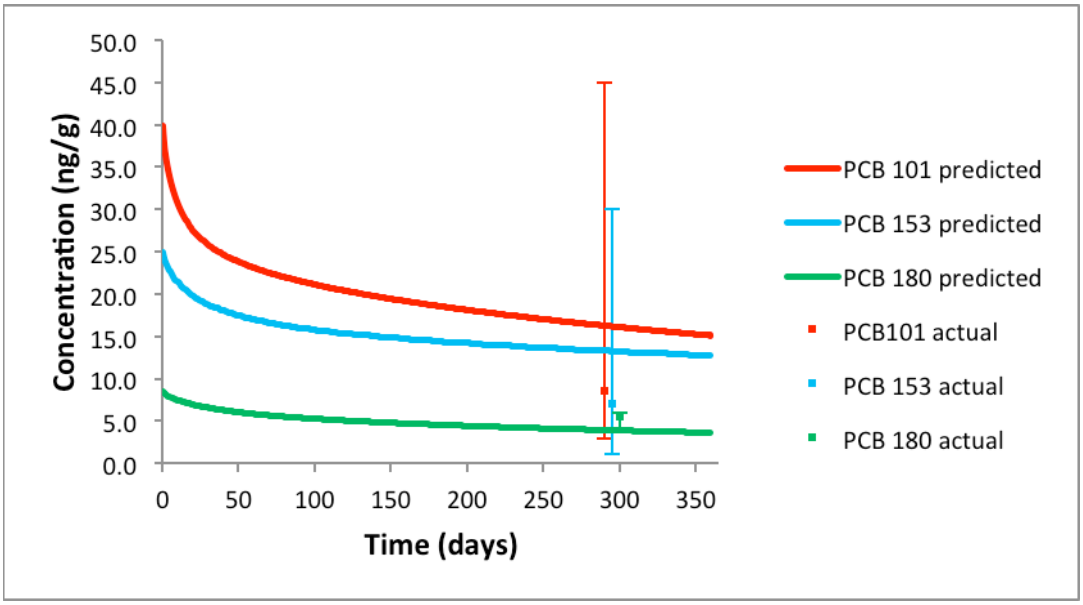

Figure 12. Predicted Puget Sound Naval Shipyard sediment concentration reduction for PCB Congeners 101, 153, and 160 using K_d from Gschwend et al. (2013) and observed means (error bars are 95% CI).

Chapter 5. Discussion

While activated carbon has been used in the treatment and purification of various media for several decades, its use in sediment remediation remains fairly novel. The various influences of site specific parameters, as well as the varying properties of differing forms of activated carbon, make predicting the true efficacy of activated carbon for this purpose uncertain. The mass transfer model used in this study provides a framework to elucidate the potential reductions that could be achieved through the application of activated carbon on PCB contaminated sediments.

There are several limitations to this study. First, the model only accounts for mechanical mixing and does not incorporate natural mixing processes that are likely to occur over time, specifically from bioturbation. Delivery method is also not accounted for in the model. The model assumes pure activated carbon product is placed directly on top of the native sediment layer and does not account for delivery with an aggregate or sand mixture; such is the case for both Puget Sound Naval Shipyard and the Lower Duwamish Waterway. Furthermore, the quality of the model output is dependent upon the quality of data availabe for input into the model. Because there are multiple parameters that can be customized with site specific data, it is important to evaluate the quality of that data prior to running the model. It may be necessary to run sensitivity analyses with the model if there is uncertainty in the parameters. This may be particularly important given the variability inherent to riverine environments and the heterogeneity exhibited by sediments. The model is also only able to account for the presence of one contaminant or congener. It is unclear how reductions may be affected by the presence of multiple hydrophobic organic contaminants and if competition for binding sites could reduce the efficacy of the activated carbon. Lastly, the quality of data used for Puget Sound Naval Shipyard was unknown for this study. A post construction monitoring report was the only available source of data for use in this study. Specifically, the report only provided sediment concentration reductions for all three PCB congeners, as opposed to porewater concentrations. It is unclear from the monitoring report how the sediment concentrations were analyzed. It is assumed that size fractionation of the sediment and activated carbon occurred in order to determine sediment concentrations and exclude concentrations associated with activated carbon. Collection and analytical methods could not be confirmed for the results. PCB concentrations and the measured reductions had to be graphically derived from the monitoring report. The results from the modeling effort had to be analyzed for sediment concentrations reductions as porewater concentration reductions were not available for all three PCB congeners of interest.

Despite these limitations, this mass transfer model serves as a potentially important tool when designing sediment remediation projects that incorporate activated carbon. The model predicted concentration reductions for Lower Duwamish Waterway at levels similar to previous field studies. While the model under predicted reductions for two congeners at Puget Sound Naval Shipyard, it provided an accurate prediction of PCB 180 reductions. The reason for this range in accuracy is likely due to the uncertainty associated with less chlorinated PCBs. Due to the physical properties of activated carbon, more hydrophobic organic compounds adsorb faster than less chlorinated compounds. The variability for lesser chlorinated PCBs to adsorb efficiently to activated carbon is also seen in the large 95% confidence intervals for PCB 153 and 101 relative to PCB 180, which has a much narrower 95% confidence interval from the Puget Sound Naval Shipyard data set. Keeping these limitations in mind,

this mass transfer model does serve as an important tool for future remediation work on the Lower Duwamish Waterway and the efforts currently underway to try and elucidate the potential efficacy of long term remediation under the Superfund cleanup. An inherent challenge to evaluating success of activated carbon is its relevance to cleanup values for contaminated sites. The main influence of activated carbon is on porewater concentrations. However, the Lower Duwamish Waterway, as well as other Superfund sites, do not set cleanup values for porewater. Therefore, the influence of activated carbon can only be evaluated in the long term through analysis of concentration reductions in fish tissue. Even then, there are other influences on fish tissue concentrations that may not allow for a direct evaluation of activated carbon success. This will continue to be a challenge for the Superfund program as activated carbon continues to be explored as a viable remedial technology for contaminated sediment sites.

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