Bioretention Capture Efficacy of PCBs from Stormwater – Stormwater Action Monitoring Effectiveness Study

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Bioretention Capture Efficacy of PCBs from Stormwater– Stormwater Action Monitoring Effectiveness Study

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Washington Stormwater Work Group

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1.0 INTRODUCTION

This project evaluates the degree that bioretention soil mix (BSM) removes polychlorinated biphenyls (PCBs) from an urban stormwater. While banned since the 1970s, PCBs are very common in urban stormwater. They are semi-volatile contaminants that off-gas from legacy and current incidental sources such as contaminated soils and sediments, caulking, paints, and dyes. The PCBs precipitate onto organic particulates, dust, and urban films because they are hydrophobic (water avoiding). This wet and dry deposition washes off in rain events and leads to contamination of urban stormwater and downstream waterbodies including Lake Washington and Puget Sound. Study goals were to determine if PCBs in stormwater are captured by BSM, and to estimate the efficacy of capture and retention of PCBs over a two-year period. The rates that PCBs are captured and retained by BSM in the Pacific Northwest are currently unknown.

The 2013–2018 Western Washington Phase I and Phase II Municipal Stormwater General Permits require the use of low impact development where feasible and bioretention is a commonly utilized low impact development best management practice (BMP) in Western Washington. Some jurisdictions also use the term "rain gardens," which are informally designed and built bioretention-like structures. Because rain gardens are not engineered structures under stormwater permits, their variable properties are not the focus of this project. Design specifications for bioretention facilities are described under BMP T7.30 in the Washington State Department of Ecology's (Ecology) Stormwater Management Manual for Western Washington (SMMWW) (Ecology 2014). The default design BSM is 60% sand, 40% compost, which was the focus of this study.

Project funding was provided through the pooled resources of the Regional Stormwater Monitoring Program, now called Stormwater Action Monitoring. This report is organized to provide a short summary of the study and its findings, with detailed methods and analyses included as appendices.

1.1 Study Questions

We evaluated PCB sequestration in mesocosms designed to represent bioretention BMPs. A mesocosm is larger than a bench-scale laboratory test environment, but smaller than a full-scale treatment facility and provided the best combination of real-world application with consistent and reproducible sampling units. Our objective was to develop a better understanding of how well BSM captures and retains PCBs across seasons over a two-year period. The overall questions addressed were:

1. When stormwater infiltrates through BSM, what percent of PCBs are removed?
2. Are PCBs retained differently by BSM in wet vs. dry conditions?
3. How rapidly do PCBs accumulate in BSM?

We address these, and related questions, in this report.

1.2   Study Design

We used soil column mesocosms to represent field conditions encountered by BSM as used in typical bioretention BMPs. The project team installed mesocosms in the field and they received highway runoff for 25 months. The following sections describe the mesocosms, their stormwater inputs, and how influents, effluents, and BSM were collected. For questions about removal efficacy, we used a before-after (treatment) statistical design. The other study questions were examined using repeated measures tests. We conducted both the "soil only" and the "with plants" treatments in triplicate, although even three samples per treatment may have limited the statistical power. There were six additional mesocosms on-site that received similar stormwater inputs; however, they were part of a separate study (Taylor et al. 2016) and not included in this analysis. They can be seen in some of the pictures below.

1.2.1   Study Site

We installed the mesocosms at a Washington State Department of Transportation (WSDOT) stormwater test site located underneath the Interstate-5 (I-5) Ship Canal Bridge in Seattle, Washington. I-5 is a multilane highway initially constructed in 1962 that currently serves approximately 270,000 vehicle trips per day. The site receives runoff from a 12.8 hectare (31.6 acres) drainage area including 9.2 hectares (22.7 acres) of pavement and 3.6 hectares (8.9 acres) of roadside landscaping. This runoff is gravity fed via two 30-inch concrete pipes to two stormwater vaults (Figure 1).
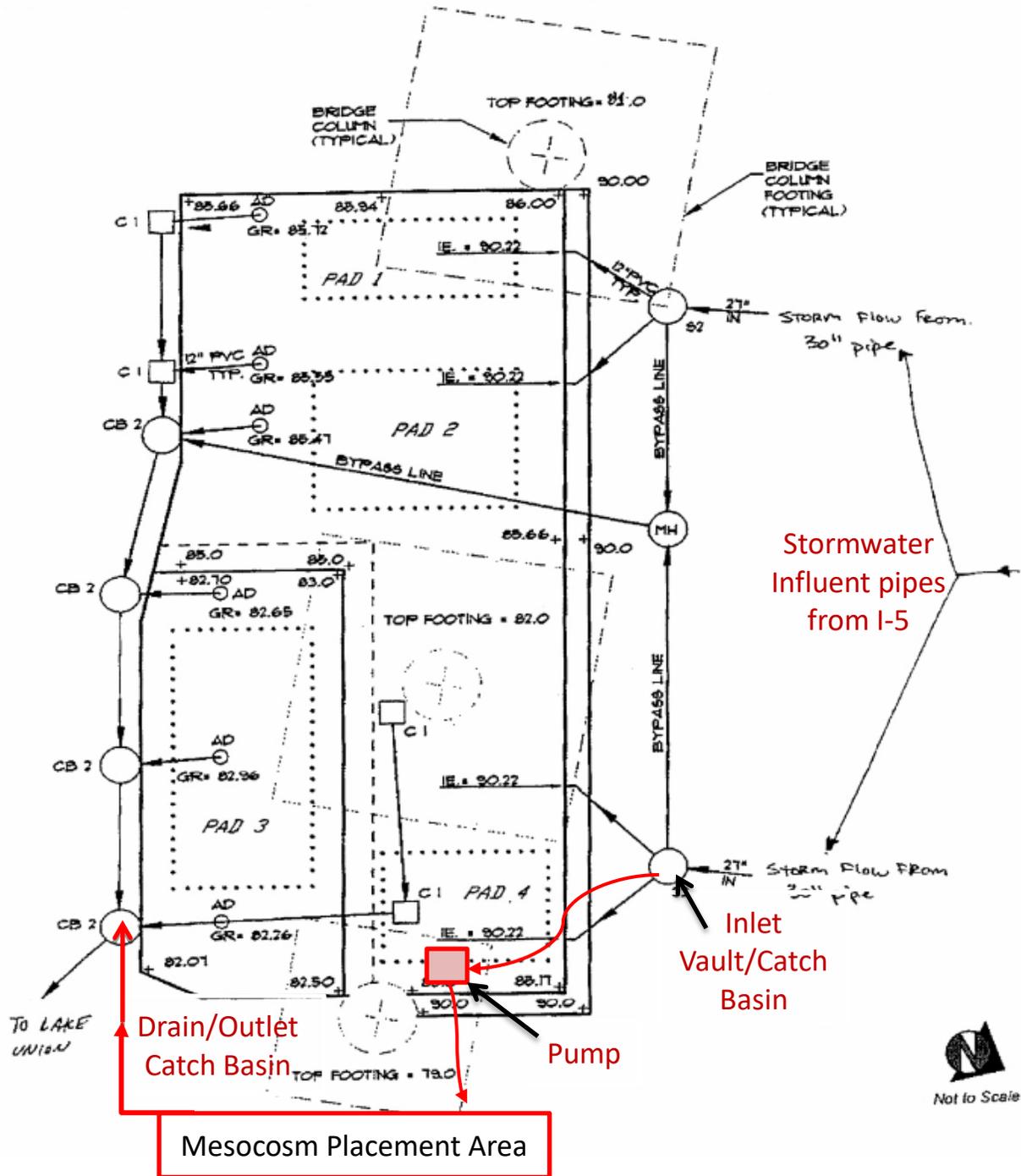
Figure 1. **Layout of WSDOT I-5 Ship Canal Stormwater Research Facility with vault inlet-drain lines shown. See Figure 2 for additional pump piping information.**

1.2.2　Mesocosm Design and Installation

Washington State University (WSU) staff built the bioretention mesocosms (Taylor et al. 2016). Briefly, they were stainless steel 55-gallon drums with BSM, a gravel underdrain, and a 2-inch slotted PVC outlet located at the bottom of the drum. We placed approximately 18-inches (145 ± 2.8 kgs) of BSM over an eight-inch gravel underdrain layer. All sands, composts, and gravels used in mesocosm construction, along with their compaction and permeability, conformed to SMMWW BMP T7.30 specifications. Compost was purchased commercially and derived from yard-waste without addition of biosolids or municipal solid wastes, per Ecology requirements. After construction, we covered the BSM with approximately four inches of wood chip mulch to improve moisture retention. Pacific ninebark (*Physocarpus capitatus*) were planted in 3 of the 6 mesocosms. The plants were bare root stock approximately 18 to 24 inches tall. They were selected to provide the same plant mass in each of the three planted mesocosms and planted immediately after the mulch was placed. Figure 4 illustrates the completed mesocosms immediately prior to initiation of stormwater dosing.

Figure 2.   Mesocosm installation immediately before stormwater dosing began in February 2016.

Out study originally planned to supply stormwater to the mesocosms from a bridge downspout via gravity, but no known, suitable, accessible, secure property was available for such an installation. We were required to pump the stormwater out of a vault and there was no established rainfall to flow rating (hydrograph) for the vault or its inputs. Thus, it was not possible to pump the stormwater out proportional to the rainfall on any given day. We instead used a float switch actuated pump with a constant flow rate.

The multichannel pump delivered a dose equivalent of a 6-month 24-hour storm event to each mesocosm whenever approximately two centimeters or more of water filled the vault

(Figure 1). On most rainy days, we estimate that the float switch would actuate with 0.1 inch (2.5mm) or more of rainfall. However, we also observed occasional dry periods between rain events when baseflow was present in the vault which complicates understanding the rainfall to dosing relationship. The baseflow water was also applied to the mesocosms; however, the source of the baseflow remains unknown.

Based on the surface area of each 55-gallon drum, the 6-month 24-hour design storm represented a flow rate of 120mL/min per mesocosm (Taylor et al. 2016). A float switch located inside the vault triggered the pumps (Figure 3) to turn on. A flow meter and totalizer on the pump inlet measured the rate and total volume of stormwater dosed to the mesocosms. We continuously monitored flow at the pump inlet throughout the deployment period, except for maintenance when the pumps were turned off (i.e. clogged tubing, power outages, and vandalism).

We verified the flow rate measurements with a graduated cylinder approximately monthly. Each mesocosm received between 0.0 and 2,121 L of stormwater depending on the month. Cumulatively, each mesocosm received a total of 13,207 L of stormwater over the 25-month study. April 2018 was the month with the greatest volume of stormwater applied with 2,121L dosed to each mesocosm. November 2018 through February 2019 had zero liters of stormwater applied due to vandalism of the pumps. Throughout the 25 month study, 32 weeks had stormwater doses from 100 L up to 944 L per mesocosm. Forty weeks had doses of 0.1 to 99 L, while the remaining 40 study weeks had no stormwater doses applied. Additionally, to irrigate the plantings during the summer months, we rerouted the pumps to draw clean tap water from a 250-gallon truck-mounted polyethylene tote.

To avoid PCB contamination from tubing, we used semi-rigid Teflon for the inlet and distribution tubing, while the peristaltic pump tubing was flexible platinum cured silicon (Figures 3 and 4). Distribution manifold blocks were made from high density polyethylene (HDPE), while connector fittings were nylon. Summer irrigation water was withdrawn from the polyethylene tote using (HDPE) tubing and distributed by the same pump using the stormwater distribution lines.
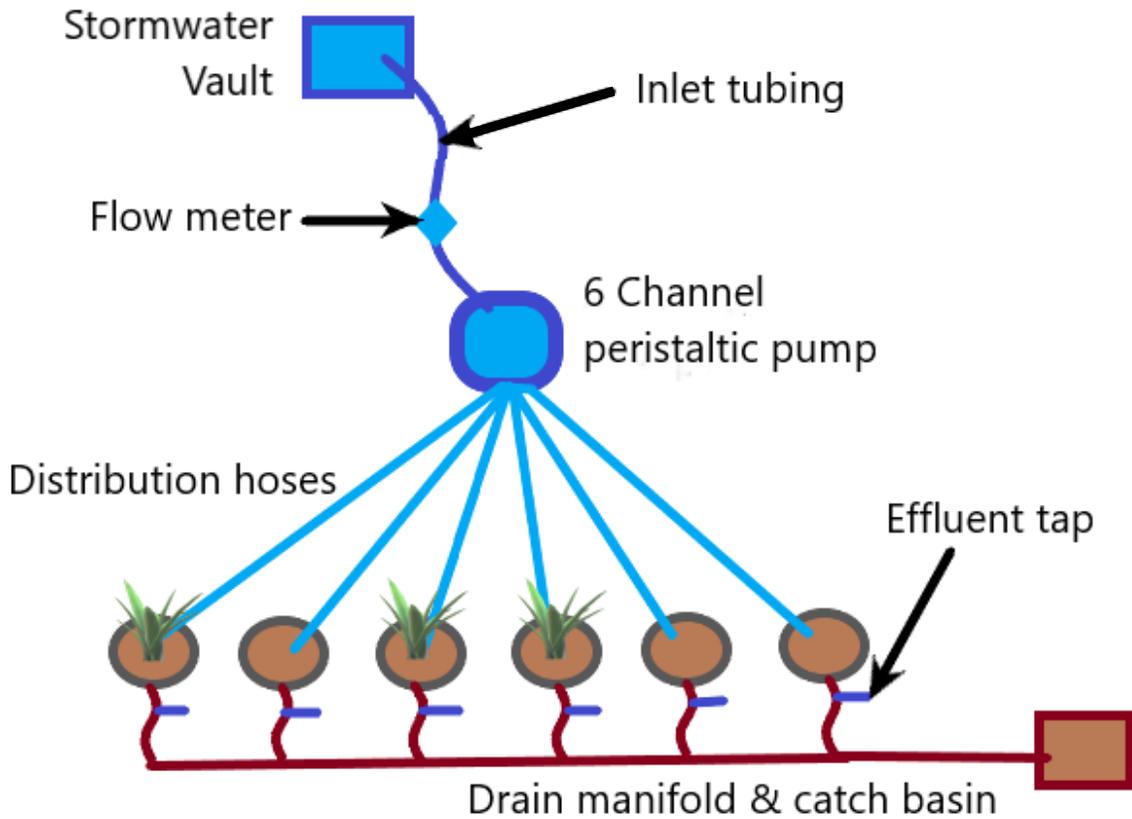
Figure 3. **Schematic of Mesocosm Placement Area with bare and planted mesocosms each sampled in triplicate.**

Figure 4.   Sampling pumps with distribution manifold and flow totalizer.

WSU investigators also used the mesocosms for other study questions evaluating reductions in stormwater effluent toxicity to fish. This other study also examined hydraulic conductivity of BSM over time. WSU used clean tap water to test hydraulic conductivity roughly quarterly. We are unable to rule out possible confounding effects of the hydraulic conductivity testing on PCB behavior, for instance the flushing of more soluble congeners from the BSM matrix. Although, we consider the impact *de minimus* and comparable to seasonal irrigation of a full scale bioretention BMP with clean city tap water sources to maintain plants. We sampled and analyzed stormwater influent, effluent, and mesocosm BSM as described below.

1.2.3   Analytical and Sampling Design

We evaluated the effectiveness of the BSM as part the treatment layer of this bioretention stormwater BMP to reduce PCBs at both the congener and homolog levels. There are 209 possible PCB congeners, each congener differs by the number (1 to 10) and location of the chlorine atoms attached to the biphenyl ring structure. A homolog is a group of PCB congeners based on the number of chlorine atoms they contain. Congeners with the same

number of chlorine atoms belong to the same homolog group and thus there are ten homolog groups.

After mesocosm construction was complete, we collected BSM samples to determine initial PCB concentrations. BSM samples were then collected on a roughly quarterly basis for the duration of this 25-month project. Stormwater influent and effluent samples were collected as close to quarterly as possible within weather and pump maintenance constraints. All BSM, influent and effluent samples were analyzed for PCBs by EPA method 1668 at Pacific Rim Laboratory in Sidney BC. WSU conducted a companion study to this project which analyzed split samples for total suspended solids (TSS), total organic carbon (TOC), and dissolved organic carbon (DOC). All raw data are available electronically in spreadsheets (Appendix D).

1.2.3.1 BSM Sampling Methods

We sampled BSM in the mesocosms using a one centimeter diameter stainless steel soil corer to collect a composite sample from across the entire 18-inch BSM portion of the mesocosm. The soil corer was used to collect three cores of BSM from each mesocosm per sampling event, which were then combined into a single composite sample. Each composite soil sample weighed about 3 to 15 grams depending on the water content. Seven composite samples were collected per BSM sampling event; three for each treatment along with one rotating field replicate. BSM samples were stored at 4° C before being shipped to Pacific Rim Laboratory in Sidney BC and analyzed for PCB congeners per EPA Method 1668. We skipped the fall/early winter BSM sampling event in 2018 because the pumps had been vandalized in November, 2018 and no stormwater had been dosed to the mesocosms between November 2018 and March 2019. Further details about these, and other deviations from the Quality Assurance Project Plan (QAPP) (King County 2016) are available in the project appendices.

1.2.3.2 Stormwater and Effluent Sampling Methods

Stormwater was sampled during rain events, typically when more than ¼ inch of rain was forecast to begin in the evening or early morning hours before a sampling day. While the stormwater vault occasionally had unpredictable baseflow, we did not sample baseflow water although on rainy days it may have been present and comingled with stormwater. Composite influent and effluent samples were collected in 7 L glass carboys. Influent was collected by rerouting the dosing tubing from all six mesocosms directly into their respective carboys (WSU's companion study used individual carboys of influent); our study's influent sample was roughly split from each of these influent carboys. Effluent was collected from a tap on the outlet of the slotted PVC underdrain pipe.

We collected both influent and effluent samples as time-weighted composites. For influent, approximately equal volumes of stormwater were collected for the first five minutes of every 25-minute period. Effluents were then collected for the remaining 20 minutes. This alternating composite scheme continued three to four times until sufficient sample volumes were collected over approximately 90–120 minutes; some storms with intermittent or delayed rainfall took up to four hours to collect sufficient volume. The

saturated hydraulic conductivities of the mesocosms were 45 ± 17 cm/hr (WSU unpublished data).

We collected composite influent samples in duplicate, splitting them each from multiple influent carboys. A single composite effluent sample was collected from each BSM treatment mesocosm (three replicates of each). A replicate composite effluent sample was collected from one mesocosm on a rotating basis. All samples were kept in the dark and on ice during collection. The composite samples were agitated and split into appropriate analytical containers in the field. Table 1 illustrates the dates samples were collected along with the cumulative stormwater dosing results, the sample numbers, and replicates.

Table 1. Dates, cumulative stormwater dose, and sample numbers for each sampling event.

Sampling Event date (D/M/Y)	Cumulative dose (L)	Influent	Influent replicate	Effluent	Effluent replicate	BSM	BSM replicate
2/16/2017	0					6	1
3/24/2017	1,002	1	1	6	1		
6/8/2017	1,947	1	1	6	1	6	1
9/28/2017	2,128					6	1
10/18/2017	2,376	1	1	6	1		
12/5/2017	3,823					6	1
12/19/2017	3,881	1	1	6	1		
2/28/2018	6,214					6	1
3/22/2018	6,509	1	1	6	1		
6/12/2018	11,873					6	1
10/25/2018	12,630	1	1	6	1		
1/23/2019	12,830	1	1	6	1		
3/12/2019	12,944	1	1	5[a]	1		
3/29/2019	13,207					6	1

[a] Effluent from unplanted mesocosm #10 was inadvertently not sampled during this event.

Further details about these, and other deviations from the Quality Assurance Project Plan (QAPP) (King County 2016) are provided in Appendix B.

1.2.3.3 Data Validation and Analysis

All PCB data were validated by Laboratory Data Consultants, a third party data validation company. EPA Region 10 PCB data validation guidelines (1995) were followed. One field blank was collected prior to initiation of sampling. We ran laboratory grade water through the Teflon and platinum cured silicon tubing, as well as the distribution manifold of the stormwater dosing system prior to use. PCBs in the blank sample were low (55 pg/L total) and we did not blank correct PCB results in environmental samples. Most PCB congener data had single pg/L sample detection limits. Consistent with EPA guidelines and past practices, total PCBs (and homolog totals) were summed using only detected congeners.

More detailed information is available in the appendices to this report; site photos (Appendix A), deviations from the QAPP (Appendix B), chain of custody forms for all samples collected (Appendix C), validated raw data (Appendix D), and statistical approaches and discussion (Appendix E).

2.0 KEY FINDINGS/RESULTS

We include here an overview of the key findings for each study objective and additional findings related to future performance. Detailed information about the study is available in the project QAPP (King County 2016) and appendices to this report. In general, data quality was acceptable to meet the project objectives with only an occasional result not meeting method or project objectives.

2.1 Where Did the PCBs in I-5 Stormwater Come From?

Regional air deposition data suggest that PCBs are widely deposited via wet and dry deposition and subsequently washed off in stormwater. This study measured an average total PCB concentration of 3,654 pg/L in I-5 runoff at Lake Union , whereas in a previous study (King County 2013) average total PCB concentrations in samples of I-90 Bridge runoff were 9,310 pg/L (N=4). The I-5 Bridge was built before the ban on PCBs in 1977, while the I-90 Bridge was built after the phase out of PCB production. There are no known PCB containing materials used in construction of either bridge, although PCBs have been found in some building materials in the past. In this case, the source of PCBs to roadways and highways like I-5 and I-90 is assumed to be "greasy" or urban grime films which accumulate on urban surfaces. These surface films tend to attract hydrophobic (water-repelling) chemicals such as PCBs (Wu et al. 2008a and 2008b). During rain events, these films and co-mingled PCBs then wash off into stormwater.

To more thoroughly examine whether the PCBs in I-5 stormwater reflect a local source, like roadway caulking which was found to be a key PCB source in East Tacoma, WA (Tacoma Public Works 2013), the PCB homolog pattern in mesocosm influents was compared to previous air deposition results from Beacon Hill. Beacon Hill is an Ecology maintained regional air quality sampling site in South Seattle which has also been used as a bulk deposition sampling location by King County (King County 2013). This air deposition site is located in Seattle's Jefferson Park, approximately 10 km (6 miles) south of the I-5 sampling location.

The top half of Figure 5 illustrates the distribution of PCB homologs in wet and dry air deposition across the ten PCB homolog groups. The PCB homolog pattern is remarkably similar to the distribution of homologs detected in the I-5 runoff collected as influent for this study (bottom half of Figure 5). Changes in the analytical laboratory and methods (see discussion of PCB co-elution issues in Appendix B) between the two studies limits our ability to conduct more sophisticated statistical analysis of these patterns.

Despite some roadways and highway related products like caulk (Tacoma Public Works 2013) and hydroseed (SRRTTF 2015) containing PCBs, the PCBs in I-5 runoff appear to be predominantly sourced from atmospheric deposition. There is no evidence of a PCB containing product as a predominant source to the stormwater used as part of this study.

Influent and effluent PCB concentrations measured by this study (Appendix D) are well within the range of PCBs found in urban stormwaters in the Lake Washington watershed (King County 2013). This suggests that bioretention BMPs receiving typical urban stormwater (i.e., not from fresh PCB sources like caulk, paint chips, or hydroseed) can be expected to perform similar to these mesocosms.
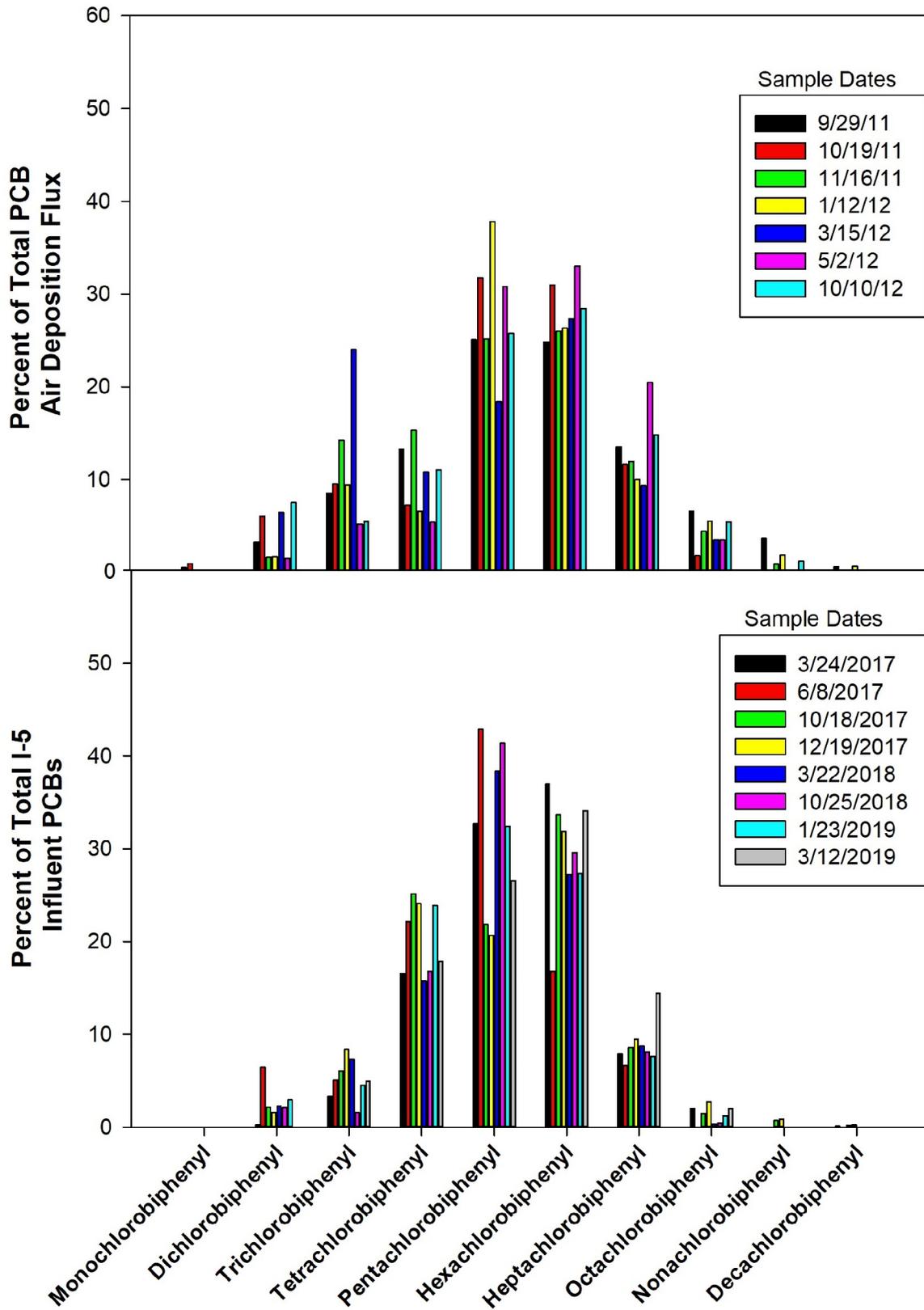
Figure 5. Beacon Hill Seattle bulk air deposition PCB homolog patterns (top, N=7) compared to I-5 influent patterns (bottom, N= 8) by PCB homolog group.

2.2   When Stormwater Infiltrates through BSM What Percent of PCBs Are Removed?

BSM, whether planted or bare, generally removes a high percentage of PCBs in stormwater and is considered an effective treatment BMP. Over the 25-month study duration and eight storm events sampled, the total PCB removal rate ranged from 63.74 to 99.75 percent (Table 2). While the study was conducted in triplicate, which is unusual for BMP effectiveness monitoring, there was no statistical difference (via a repeated measures ANOVA) in PCB removal between bare and planted mesocosms. We may not have seen differences due to weak statistical power, but also because the plants took over a year to develop beyond very small bare root seedlings.

Table 2.   **Mean percent total PCB removal from influent over the 25-month sampling period (± standard error).**

	Percent PCBs Removed by BSM ± SE	
Sampling Date	**Bare (n=3)**	**Planted (n=3)**
3/24/2017	80.7 ± 5.3	88.6 ± 3.5
6/8/2017	69.7 ± 5.7	68.2 ± 7.0
10/18/2017	94.5 ± 1.3	95.5 ± 0.5
12/19/2017	97.6 ± 0.9	98.3 ± 0.5
3/22/2018	98.9 ± 0.7	99.7 ± 0.1
10/25/2018	92.7 ± 3.6	96.6 ± 1.6
1/23/2019	89.4 ± 1.0	87.9 ± 1.8
3/12/2019	89.2 ± 1.4	89.8 ± 4.4*
Overall average	**89.1 ± 10.5**	**90.6 ± 10.8**

*Only two planted effluents were collected during this event

When we evaluated the results by PCB homolog group, mean removal performance was high for all homologs (Table 3) except decachlorobiphenyl (there is only one decachlorinated congener, PCB-209). PCB-209 in particular, was not present at high concentrations in influent (<0.02 to 22.5 pg/L, mean 4.8 pg/L), but occasionally present at low effluent concentrations (<11 pg/L). This resulted in a mean removal rate of 37.3% for decachlorobiphenyl. PCB congeners with between three and seven chlorine atoms dominated the homolog totals in influent with an average percent removal ranging from 86 to 96 percent.

Table 3. **Mean influent and effluent detected[a] PCB homolog concentrations with standard deviations, average percent removal, along with the standard deviation of the removal.**

PCB Homolog Group	Mean Influent pg/L (N=16)	Mean Effluent pg/L (N=55)	Mean % Removal via BSM
1	0.8	0.1	90.4 ± 19.2
2	67.2	13.5	79.5 ± 18.3
3	209.8	5.0	96.1 ± 6.8
4	743.5	47.5	90.6 ± 9.9
5	1097.6	126.6	86.1 ± 10.0
6	1144.1	95.8	88.8 ± 11.2
7	316.6	31.1	88.2 ± 21.2
8	57.2	5.8	72.2 ± 67.5
9	11.6	<0.0	99.9+ ± 0
10	4.8	1.4	37.3 ± 87.5
Sum all homologs	**3,653 ± 2422**	**290 ± 361**	**89.9 ± 10.5**

[a] Some homologs (e.g. mono- and deca-) were not consistently detected in influents or effluents which made calculation of standard deviations by homolog group reliant on substituted values. Thus standard deviations are only presented for the sum of detected PCBs.

2.3 Are PCBs Differentially Retained in BSM Seasonally?

This question was challenging to answer with the available data, principally because the annual PCB loads were small relative to the starting mass of PCBs in BSM (see Section 2.4 as well). When originally conceived, we intended this project to examine the possible vaporization or recycling of PCBs back into the urban atmosphere during warm dry summer weather. We had planned on addressing this question through a mass balance approach where:

$$starting\ soil\ PCB\ mass + influent\ PCB\ mass$$
$$=$$
$$ending\ PCB\ mass - effluent\ PCB\ mass - volatization\ PCB\ mass$$
$$- degraded\ PCB\ mass$$

PCBs are a semi-volatile contaminant and previous work in the Puget Sound region, Great Lakes, Asia, and northern Europe (Diamond 2000, King County 2013, Totten et al. 2006, Yeo et al. 2004) has shown they are present in urban air and condense onto hard surfaces and subsequently wash off when it rains. Because the influent PCB mass was quite small compared to the starting soil mass, we were not able to analytically measure increases in soil PCB concentrations. Thus, whether rain gardens and bioretention facilities, which retain PCBs during rain events, then allow the PCBs to off-gas/vaporize back into the atmosphere remains unknown.

This project was able to document the PCB load retained by BSM over the 25-month study duration. Despite these stormwater loads, a visual observation of the data suggest that PCB

concentrations in the BSM declined slightly (Figure 6) from the initial 6 and 15 µg/Kg background concentrations. However, statistical analysis indicated the trend was not statistically significant when tested by repeated measures ANOVA ($p = 0.054$). PCB concentrations in BSM after receiving stormwater for 25 months were statistically the same as concentrations at the beginning of the study.
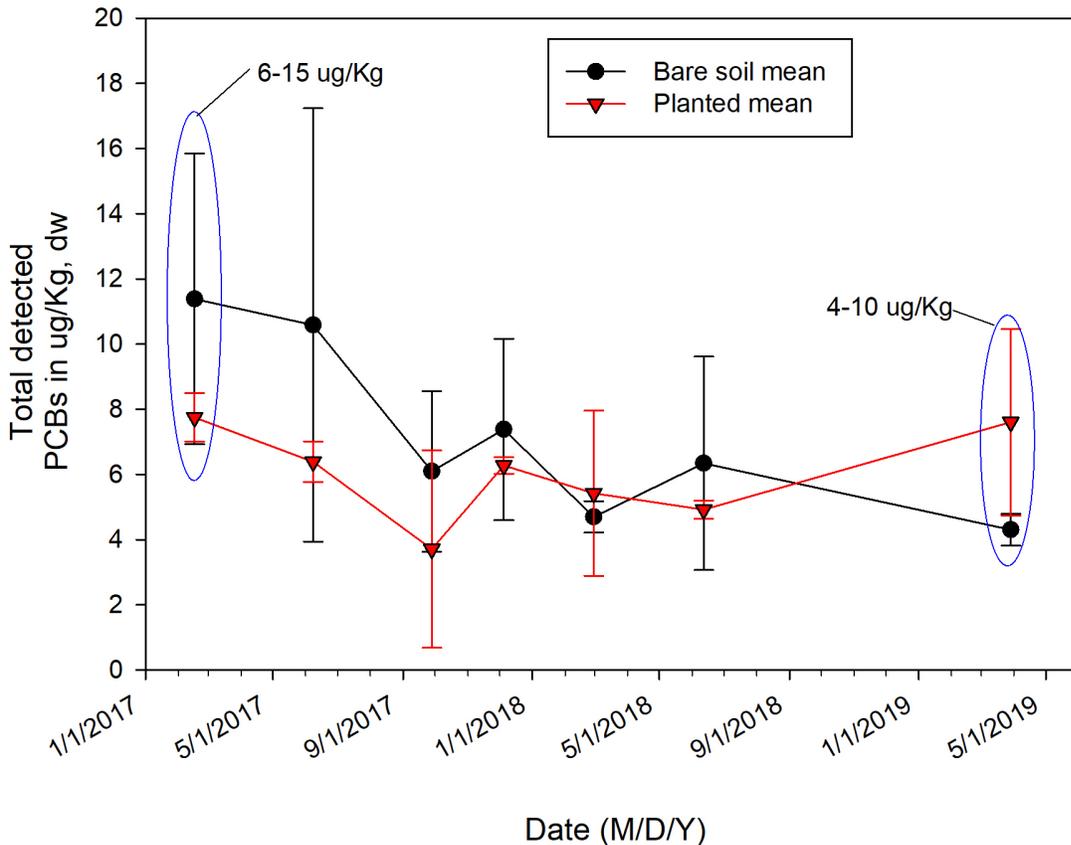
Figure 6. **Mean total detected PCB concentrations in BSM over time plus/minus one standard deviation.**

To examine if volatile PCB congeners were lost seasonally from BSM resulting in a shift in the congener pattern, we compared congener profiles for BSM samples to one another using an ordination analysis. Ordination is a statistical technique used to visually evaluate similarities and dissimilarities between samples with multiple variables. For this analysis, samples with similar PCB congener patterns plot close to each other and samples with dissimilar PCB congener patterns plot further from each other (Figure 7).

This analysis immediately revealed that two BSM samples appeared to be outliers due to very low concentrations (< detection limit of 0.003 µg/kg, dry weight [dw]) of PCB-183 and PCB-156 in one sample (L68722-2) and detection of the same congeners (0.003 to 0.006 µg/kg, dw) just above the sample detection limits in a second sample (L8722-5) (Figure 7). Results for all remaining BSM samples are tightly clustered.
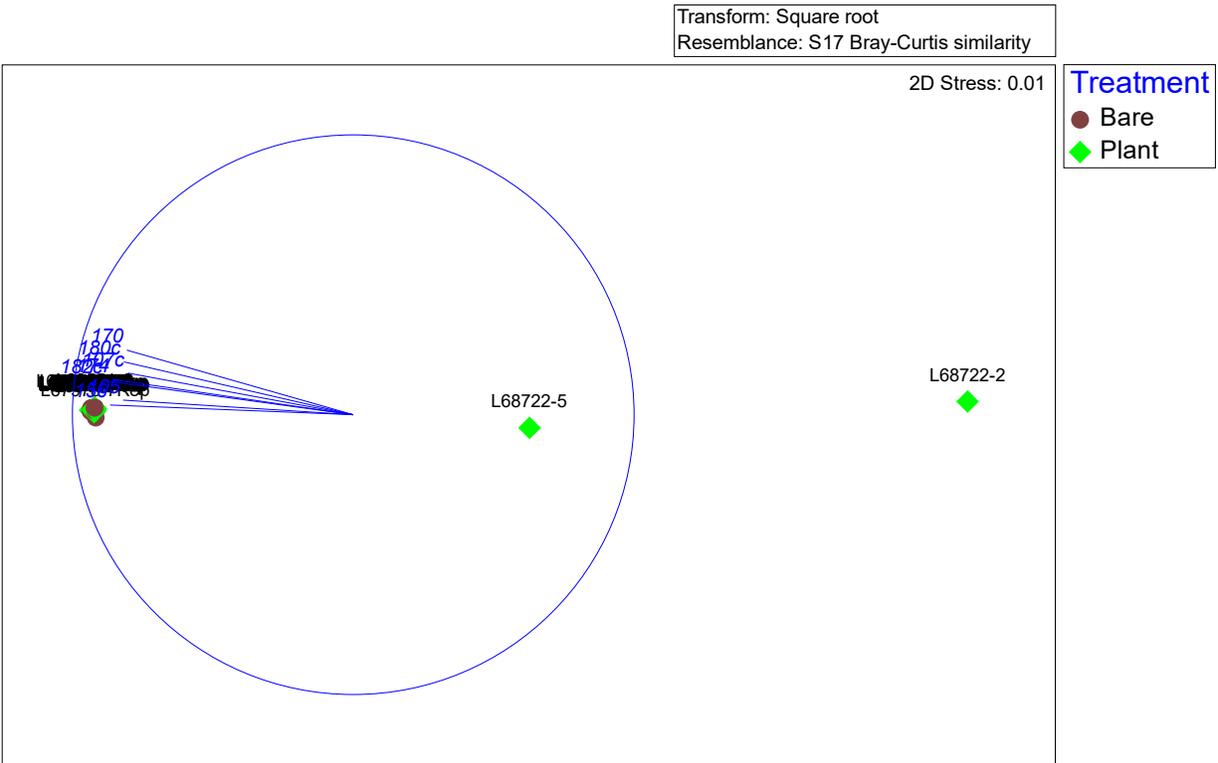
Figure 7.   Bray-Curtis ordination of all study BSM samples by bare BSM vs. planted BSM.

When the same analysis was conducted without the two outliers, there was no discernable difference in PCB congener patterns between planted and bare mesocosms. While our triplicate treatment mesocosms were more statistically rigorous than many unreplicated stormwater studies, the statistical power of triplicate samples is still comparatively weak. Only dramatic differences in PCB concentrations between bare and planted mesocosm performance would likely be statistically different. The small size of the Pacific Ninebark plants for the first ~15 months of the study also may have limited our ability to detect differences.

Based on the finding of no differences, the PCB BSM results for both bare and planted BSM were pooled and compared across seasons. While removal of the outliers resulted in the ability to distinguish samples that were otherwise tightly clustered in Figure 7, the results in Figure 8 do not illustrate a clear pattern or evidence of seasonal losses of more volatile congeners.
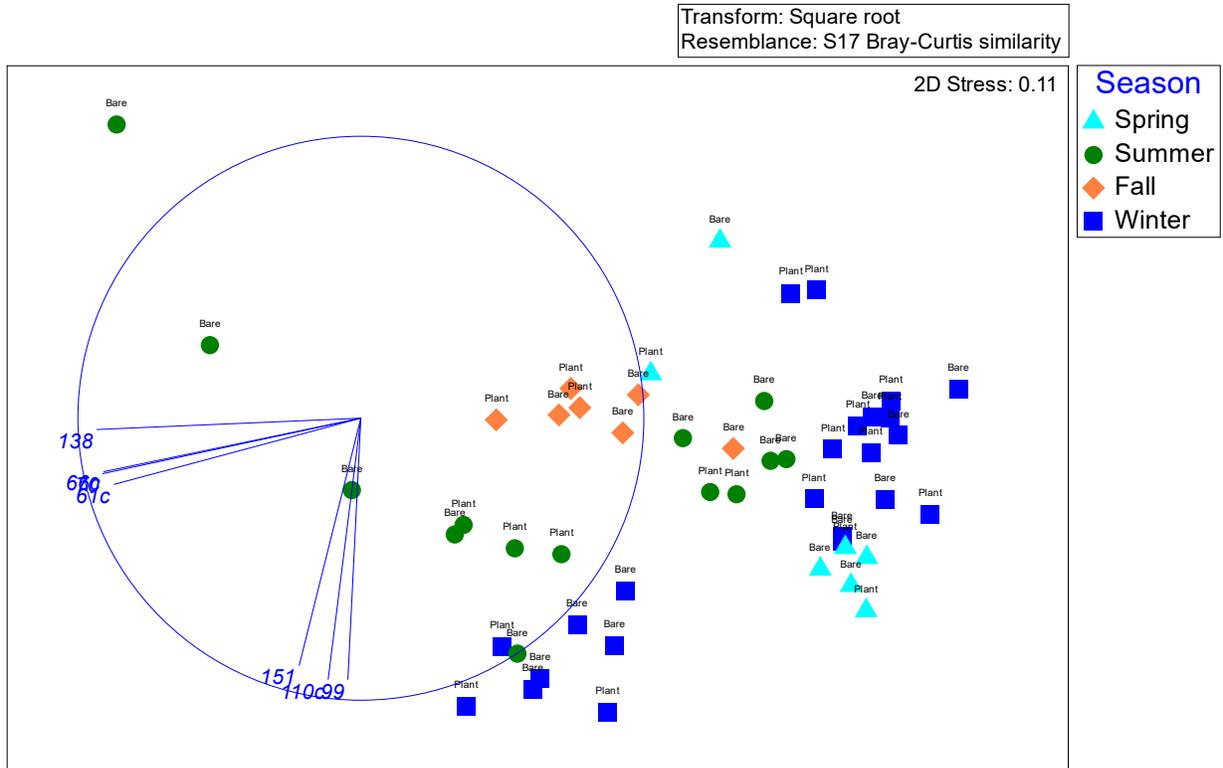
Figure 8.   Bare and planted Bray-Curtis ordination of study BSM samples across seasons (outliers removed).

The lack of evidence that volatile PCB congeners were off-gassing from BSM suggests that other mechanisms are responsible for the visualized slight downward trend in PCB concentrations over the 25-month study (Figure 6). This study was not specifically designed to assess possible off-gassing from BSM, but at a macro scale, no preferential off-gassing was apparent.

2.4   How Rapidly Do PCBs Accumulate in BSM?

PCBs are efficiently and effectively sequestered in BSM with average removal rates close to 90 percent (Table 2). These high rates of contaminant removal have sometimes raised questions about the longevity of bioretention facilities and disposal of BSM with potentially high concentrations of PCBs. In Washington State, the total PCB cleanup standard for soils at dangerous waste release sites is 1 mg/Kg dry weight (WAC 173-340, Table 740-1). PCB concentrations below this level are considered safe for any land use (e.g. residential, commercial, industrial). Due to this threshold, stormwater permittees and the public (Stiffler 2013) have expressed concern that bioretention facilities may accumulate PCBs above regulated concentrations over time.

For this study, stormwater was applied to the mesocosms typical of a moderately heavy 6-month design flow event (1.30 inches in 24 hours). Despite our pumps providing a constant flow that attenuated peak rainfall events, the overall annual stormwater volume received

by the mesocosms was actually slightly larger than would be expected for a comparable gravity-fed bioretention BMP.

During the 2017–2018 water year (October 2017 to September 2018), which was the only complete water year monitored, each mesocosm received 10,021 L of stormwater (the total 25-month study dosing was 13,207 L). The mesocosms were sized at 20:1 design ratio, i.e. twenty square meters of impervious surface would be treated by one square meter of BSM. The 10,021 L annual stormwater dose was equivalent to 196 centimeters of rainfall in Seattle, while the actual 2017-2018 water year rainfall was only 105 centimeters. Thus, during this portion of the study, the mesocosms were dosed with about 86 percent more stormwater than a gravity-fed bioretention facility built according to a 20:1 surface area ratio would have received. Because the mesocosms received more stormwater than a full-scale BMP, estimates of PCB accumulation rates in mesocosm BSM are considered conservative.

Despite 25 months of stormwater loading, including more stormwater than a comparable gravity-fed BMP would have received, mean total PCB concentrations in the BSM did not increase and visually appeared to decline over the study period (Figure 6). This hypothesis was tested with a repeated measures ANOVA which found that BSM PCB concentrations throughout the study were not significantly different (p=0.06). Figure 6, above, illustrates BSM PCB concentrations throughout the study.

There are several possible reasons why PCB concentrations in BSM did not change despite the 25 months of stormwater applied and the 90 percent PCB sequestration rate. These reasons are explored in the next section.

2.5 Where Do PCBs Applied To BSM Go?

As mentioned in Sections 2.2 and 2.4, despite receiving over 13,207 L of PCB contaminated stormwater during the 25-month study period and a 90 percent PCB removal rate, BSM PCB concentrations did not increase. Visually, there is a possible decline in bare soil concentrations, but we did not detect a statistically significant difference. This raises the question of what happened to the PCBs that were sequestered. We examine some possible explanations below.

2.5.1 Were PCBs Loadings Measurable in BSM?

Over the course of the 25-month study duration, the 13,207 L of stormwater applied to each mesocosm added a cumulative 51.7 µg load of PCBs to the BSM. About 3.4 µg of PCBs were cumulatively released from the BSM in effluent. Thus, 48.3 µg of PCBs were retained in the BSM in each mesocosm. Figure 9 illustrates the cumulative loads in and out of the mesocosms over the study duration.
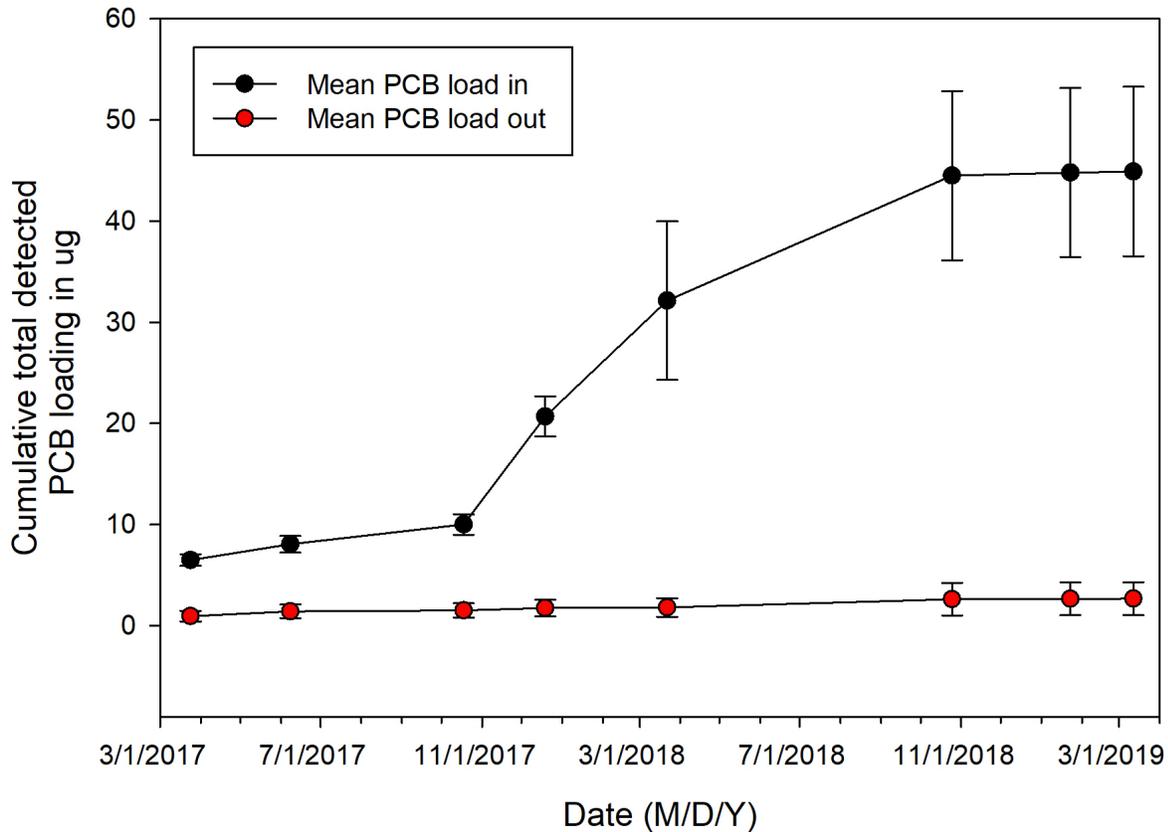
Figure 9.   Cumulative PCB loadings to mesocosm BSM with loses over time, plus/minus one cumulative standard deviation.

The 48.3 µg load of retained PCBs is substantive from a water quality perspective, and the starting PCB concentrations in BSM appear comparatively small at 6 to 13 µg/kg, dw. However, each mesocosm held 145 kg (±2.8 kg) of BSM. Thus, each mesocosm started the study with approximately 870 to 1,900 µg of PCBs sequestered in the BSM. Due to the initial starting mass of PCBs in the mesocosms, even 25 months of stormwater loadings only added an additional 2 to 5 percent more PCBs to the BSM. While the PCB congener analytical method (EPA 1668) is the most accurate and precise method available for PCBs, it cannot distinguish this relatively small difference between starting and ending concentrations—especially given the heterogeneity of the BSM PCB concentrations.

2.5.2   Did Mesocosm Plants or Soils Gain or Lose Mass and Change the PCB Concentrations?

The total mass of BSM used in the mesocosms was from a well-mixed covered pile with roughly equal water content. Each bucketful of BSM was weighed during installation to derive the 145 kgs (±2.8 kg) used in each mesocosm. The mesocosms evolved over the course of the twenty-five month study; the plants grew, the wood chip mulch appeared to decay, and other biological changes occurred within the BSM itself. Due to these multiple changes, as well as the potentially large effect moisture may have on weight, the soils were

not weighed at the end of the study. However, some estimates of the mass of soil gained or lost via influents and effluents can be derived from the TSS data collected by the WSU partner project also studying these mesocosms. The average influent TSS concentration was about 26 mg/L which resulted in a load of approximately 378 grams of suspended solids added to each mesocosm. On average, effluent TSS concentrations were about 7.5 mg/L, which equates to approximately 100 grams of TSS exported. Therefore, about 278 grams of TSS was retained in the BSM. These retained solids are less than a 0.2 percent increase in the mesocosm mass. Thus, the consistent concentrations of PCBs we measured in BSM throughout the 25-month study are not likely due to the PCB and BSM masses co-varying.

Similarly, the total mass of BSM plus plants, roots, and leaf litter was not measured at the conclusion of the study. Even though the Pacific Ninebark grew significantly over the 25 month study duration (e.g., compare Figure 2 to Figure 10), the final plant mass is unlikely to have represented more than one percent of the 145 kg starting mass of BSM. It does not appear that plants diluted or otherwise altered the PCB concentrations in BSM compared to the bare mesocosms (Figure 6), although the variability in both bare and planted mesocosms is intermittently high.

Figure 10.   Mesocosm plantings in July 2018 after 17 months of growth.

2.5.3   Did PCBs Off-Gas Into the Atmosphere or Degrade?

As discussed above (Section 2.2), our study was not ideally designed to measure PCB off-gassing from the mesocosms back into the urban atmosphere. It was also not designed to measure microbial degradation of PCBs. However, recent literature suggests that soils such as the sand/compost BSM used in this study may be well-suited to degrade PCBs. For instance, Macedo et al. (2007) found 41 different microbial species and strains of bacteria were capable of degrading PCBs in stream sediments not previously inoculated (spiked) or otherwise intentionally dosed with PCBs. This suggests that multiple bacteria capable of degrading PCBs were naturally present in that environment, although the degradation rates may be slow. Kjellerup et al. (2012) also found multiple species of PCB degrading bacteria in Baltimore Harbor, although degradation was probably inhibited by the 4 to 265

mg/Kg PCB concentrations, which are hundreds of times higher than levels in BSM. Both of these published studies found low (1-5%) but measureable PCB degradation rates in sediments.

Bacterial degradation at these slow rates is likely a function of the modest oxygen levels and lack of a robust fungal community in sediments. BSM, and particularly the compost used in BSM, has an abundant fungal community. The high hydraulic conductivity (45 ± 17 cm/hr) and intermittent saturation/desaturation of the BSM is expected to maintain aerobic conditions. While the fungal populations can vary by feedstock type (i.e., yard waste, hay, manure, hardwood etc.) and compost production method (i.e., windrow vs aerated static pile), compost supports rich and diverse fungal communities (Dehghani et al. 2012 and Neher et al. 2013). Certain fungal species can both remove chlorine from highly chlorinated congeners to make them easier to be further degraded by bacteria (Kjelerup et al. 2012), as well as fully mineralize PCBs. Mineralize means to completely convert to PCBs to inorganic forms of carbon like carbon dioxide.

Federici et al. (2012) found up to 33.6 percent PCB removal in 60 days by a strain of *Lentinus tigrinus*, a white-rot fungus common to forests. The soil PCB concentrations were thousands of times higher (~750 mg/Kg) than levels found in the BSM used in this study (6–13 µg/Kg), but wood decaying fungi like *L. tigrinus* are common and many different strains of fungi are often present in yard waste based composts. The most common factors limiting degradation of PCBs are anaerobic conditions, and very high, 100–1000+ mg/Kg PCB concentrations such as might be experienced at hazardous waste sites (Ruiz-Aguilar et al. 2002). Relative to conditions in the studies described above, our BSM mesocosm PCB levels were lower (4 to 15 µg/Kg range), the stormwater loadings were also relatively low (~25 µg/yr), and the BSM frequently fully drained, thus avoiding persistent anaerobic conditions. While fungal degradation of PCBs were not directly measured by this study, these conditions, combined with the yard waste compost based BSM and evidence of a robust fungal population as documented by WSU's companion study (unpublished data), indicate BSM is potentially a viable media supportive of the degradation of stormwater PCB loads.

2.6   Conclusions/Recommendations

The PCB concentrations, general chlorination levels and character of I-5 stormwater used for our mesocosm study was generally consistent with PCB concentrations and congener patterns measured from other highways and diffuse atmospheric sources such as wet and dry air deposition in the Seattle area. Removal effectiveness varied slightly depending on the PCB homolog group, but we observed an average of 90 percent removal. There was no apparent decline in effectiveness over the 25-month study duration.

Studies of bioretention facilities in the San Francisco area (David et al. 2014, Gilbreath et al. 2012, and Gilbreath et al. 2019) have also documented effective PCB removal and retention performance. Combined, both the published literature and results of our study, strongly supports that bioretention is generally highly effective for removing PCBs from most roadway and impervious surface runoff. When localized sources such as PCB containing

caulk, paint chips, or land with high soil concentrations of PCBs (e.g. >1 mg/Kg) due to spills are potentially present, BSM is expected to still be effective, but may saturate with PCBs or otherwise exceed regulated soil concentrations of 1 mg/Kg.

Despite these high removal rates, PCBs in effluent from BMPs containing BSM are likely to continue to exceed the currently applicable Washington State human health based water quality standard of 7 pg/L (EPA 2016). Effluent concentrations are close to the previous Washington State human health water quality standard of 170 pg/L (40 CFR 131.36). An 85 percent reduction in PCB loadings is close to what might be required for the Washington State Department of Health to remove the current fish consumption advisory on Lake Washington (King County 2014). Widespread application of bioretention with 85+ percent reductions in PCB concentrations is an effective tool to reduce PCBs in urban stormwater runoff, and help reduce fish tissue impairments.

Despite over two years of moderately high stormwater loads, BSM did not accumulate PCBs at levels greater than the initial starting concentrations which remained almost 3 orders of magnitude below regulated clean-up concentrations (e.g., 1 mg/Kg per WAC Table 740-1). BSM concentrations may have even declined despite the 25 months of stormwater loads applied, but this trend was not statistically significant. Other published work suggests that PCB loads such as these into BSM comprised of wood or yard waste based compost may create fungal communities especially well-suited to rapidly (weeks to month) degrade most PCBs. The extent which sand:compost based BSM degrades PCB from stormwater loadings warrants future studies at the laboratory or bench scale under controlled conditions with labelled PCBs to allow for tracking their behavior and/or degradation.

Overall, BSM was highly effective at removing PCBs from urban stormwater not associated with local hazardous waste sites. Based on the limited published literature available about the performance of bioretention and PCB treatment effectiveness (Gilbreath et al. 2019) our results are expected. The absence of atmospheric PCB losses via volatization could not be ruled out, but appears minimal. Widespread use of BMPs incorporating BSM could be an effective approach to significantly reduce PCB loading to impaired waterbodies with fish consumption advisories. We saw no evidence that PCBs are accumulating in BSM to regulated or dangerous concentrations over the two year timescale of the study. Less frequent, perhaps bi-annual, performance monitoring of full-scale bioretention facility PCB treatment effectiveness would be a valuable contribution towards understanding the long-term, installed, performance of bioretention in Western Washington. Full-scale performance monitoring should probably examine BMP maintenance issues such as clogging, replenishment of mulch, and plant watering/survival, concurrently.

3.0 REFERENCES

City of Tacoma. 2013. East Tacoma PCB Investigation.
https://cms.cityoftacoma.org/enviro/SurfaceWater/EastTacomaMeetingNov20.pdf

David, N., J.E. Leatherbarrow, D. Yee, L.J. McKee. 2014. Removal Efficiencies of a
Bioretention System for Trace Metals, PCBs, PAHs, and Dioxins in a Semiarid
Environment. J. Env. Eng. https://ascelibrary.org/doi/10.1061/(ASCE)EE.1943-
7870.0000921

Dehghani, R., M.A. Asadi, E. Charkhloo, G. Mostafaie, M. Saffari, G.A. Mousavi, and M.
Pourbabaei. 2012. Identification of Fungal Communities in Producing Compost by
Windrow Method. J. Env. Pro. 3:61-67.

Diamond, M.L., S.E. Gingrich, K. Fertuck, B.E. McCarry, G.A. Stern, B. Billeck, B. Grift, D.
Brooker, T.D. Yager. 2000. Evidence for Organic Film on an Impervious Urban
Surface: Characterization and Potential for Teratogenic Effects. Env. Sci. Tech.
34:2900-2908.

Ecology. 2014. 2012 Stormwater Management Manual for Western Washington, as
Amended in December 2014.
https://fortress.wa.gov/ecy/madcap/wq/2014SWMMWWinteractive/2014%20SW
MMWW.htm

EPA Region 10 SOP for the Validation of Method 1668 Toxic, Dioxin-like, PCB Data
(December 1995).

EPA. 2016. Letter to Maia Bellon, Director of Ecology from Danial Opalski, EPA Region 10.
https://www.epa.gov/sites/production/files/2017-10/documents/wawqs-letter-
11152016.pdf

Federici, E., M. Giubilei, G. Santi, G. Zanaroli, A. Negroni, F. Fava, M. Petruccioli,
A. D'Annibale. Bioaugmentation of a Historically Contaminated Soil by
Polychlorinated Biphenyls with *Lentinus tigrinus.* Microbial Cell Factories 11:35.

Gilbreath, A.N., S.P. Pearce, L.J. McKee. 2012. Monitoring and Results for El Cerrito Rain
Gardens. San Francisco Estuary Institute 4911 Central Ave. Richmond, CA 94804 .
Contribution Number 683.

Gilbreath, A., L. McKee, I. Shimabuku, D. Lin, L.M. Werbowski, X. Zhu, J. Grbic, and C.R.
Rochman. 2019. Multi-year Water Quality Performance and Mass Accumulation of

PCBs, Methyl-Mercury, Copper, and Microplastics in a Bioretention Rain Garden. San Francisco Estuary Institute and Aquatic Science Center, Richmond, CA.

King County. 2013. Estimating PCB and PBDE Loadings to the Lake Washington Watershed: Data Report. Prepared by Richard Jack and Jenée Colton, Water and Land Resources Division, Seattle, Washington, for US EPA Region 10. https://your.kingcounty.gov/dnrp/library/water-and-land/watersheds/cedar-river-lake-wa/lake-washington-pcb-pbde-loadings/epa-data-report-final-sept2013.pdf

King County. 2014. Modeling PCB Loading Reductions to the Lake Washington Watershed: Final Report. Prepared by Richard Jack, Jenée Colton, Curtis DeGasperi and Carly Greyell, Water and Land Resources Division. Seattle, Washington. https://your.kingcounty.gov/dnrp/library/water-and-land/watersheds/cedar-river-lake-wa/lake-washington-pcb-pbde-loadings/epa-lake-washington-final-report.pdf

King County. 2015. Lower Duwamish Waterway Source Control: Supplemental Bulk Atmospheric Deposition Study Final Data Report. Prepared by Jenée Colton, Martin Grassley, and Richard Jack. King County Department of Natural Resources and Parks, Water and Land Resources Division, Science and Technical Support Section. Seattle, Washington. https://your.kingcounty.gov/dnrp/library/wastewater/iw/SourceControl/Studies/Air/2015/LDW_SupBulkAirDepFinalDataReport_May2015.pdf

King County. 2016. Quality Assurance Project Plan: Bioretention Capture Efficacy of PCBs from Stormwater–RSMP Effectiveness Study. Prepared by Richard Jack, Water and Land Resources Division. Seattle, Washington.

Kjellerup, B.V., P. Paul, U. Ghosh, H.D. May, and K.R. Sowers. 2012. Spatial Distribution of PCB Dechlorinating Bacteria and Activities in Contaminated Soil. Appl. Env. Soil Sci. vol. 2012, Article ID 584970. https://doi.org/10.1155/2012/584970.

Leigh, M.B., P. Prouzová, M. Macková, M. Tomáš, D.P. Nagle, and J.S. Fletcher. 2006. Polychlorinated Biphenyl (PCB)-Degrading Bacteria Associated with Trees in a PCB-Contaminated Site. Appl. Env. Microbio. 72: 2331-2342.

Macedo, A.J., K.N. Timmis, and W-R. Abraham. 2007. Widespread Capacity to Metabolize Polychlorinated Biphenyls by Diverse Microbial Communities in Soils with No Significant Exposure to PCB Contamination. Env. Micro. 9(8): 1890-1897.

Neher, D.A., T.R. Weicht, S.T. Bates, J.W. Leff, and N. FIerer. 2013. Changes in Bacterial abd Fungal Communities across Compost Recipes, Preparation Methods, and Composting Times. PLOSone 8(11):e79512.

Ruiz-Aguilar, G.M.L., J.M. Fernández-Sánchez, Rodríguez-Vázquez, and H. Poggi-Varaldo. 2002. Degradation by White-Rot Fungi of High Concentrations of PCB Extracted from a Contaminated Soil. Adv. in Env. Res. 559-568.

SRRTTF. 2015. Hydroseed Pilot Project Summary Report. Spokane River Task Force, Spokane WA. http://srrttf.org/wp-content/uploads/2015/03/Hydroseed-Pilot-Project-Report-FINAL.pdf

Stiffler, L. 2013. Are Rain Gardens Mini Toxic Waste Sites? Sightline Institute, Seattle WA. https://www.sightline.org/2013/01/22/are-rain-gardens-mini-toxic-cleanup-sites/

Taylor, A., T. Knappenberger, and J. M McIntyre. 2016. Quality Assurance Project Plan. Field test of plants and fungi on bioretention performance over time. Washington State University, Puyallup, Wa.

Tigini, V., V. Prigione, S. Di Toro, F. Fava, and G. C Varese. 2009. Isolation and Characterisation of Polychlorinated Biphenyl (PCB) Degrading Fungi from a Historically Contaminated Soil. Microbial Cell Factories 8:5.

Totten, L.A., G. Stenchikov, C.L. Gigliotti, N. Lahoti, S. Eisenreich. 2006. Measurement and Modeling of Urban Atmospheric PCB Concentrations on a Small (8 km) Spatial Scale. Atmos. Env. 40:7940-7952.

Wu, R.W., T. Harner, M.L. Diamond. 2008. Partitioning Characteristics of PCB in Urban Surface Films. Atmos. Env. 42: 5696-5705.

Yeo, H.G., M. Choi, M.Y. Chun, T.W. Kim, K.C. Cho, and Y. Sunwoo. 2004. Concentrations Characteristics of Atmospheric PCBs for Urban and Rural Area, Korea. Sci. Tot. Env. 25(1-3):261-270.