



Bay Area Green Infrastructure Water Quality Synthesis

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Introduction

San Francisco Bay is impacted by the numerous urban pollutants that flow from the surrounding landscape during storm events. In San Francisco Bay, total maximum daily load (TMDL) clean-up plans are in place for polychlorinated biphenyls (PCBs) and mercury (Hg) (Davis et al., 2007; Davis et al., 2012). As municipalities strive to reach regulatory targets, green infrastructure (GI) presents a promising solution for managing stormwater pollutants while achieving additional environmental and social benefits. However, remaining data gaps including the best design layout, media composition, and vegetation and submerged zone effects on performance can prevent local managers from accurately assessing water quality benefits provided by green infrastructure as well as the maintenance needs to sustain adequate performance.

Increasingly, studies from around the world report good performance for pollutant reduction using a form of green infrastructure called bioretention rain gardens (Davis et al., 2003; Li and Davis, 2009; Diblasi et al., 2009; Hatt et al., 2009; Hunt et al., 2006). These studies have primarily measured nutrients, metals and, to a lesser degree, organic contaminants. Although a number of studies have indicated relatively good performance for copper ranging between 40-100% capture, with effluent concentrations generally <10 µg/L (Davis et al. 2003; Davis 2007; Hunt et al. 2008; Hatt et al. 2009; Li and Davis 2009, David et al. 2015), only one published study (David et al., 2015) reports the capture of PCBs and only two published studies report the capture of Hg (Li and Davis, 2009; David et al., 2015). The Li and Davis study showed influent and effluent PCB concentrations below laboratory detection limits.

Sources of PCBs in urban environments are mainly associated with residues from legacy uses in the older commercial and industrial areas of our cities that were developed or redeveloped prior to the PCB ban in 1979. PCB sources include electrical dielectric fluids, heat resistant plastics, hydraulic fluids and oils, and caulk (Erickson and Kaley, 2011; Klosterhaus et al., 2014). It is therefore expected that the greatest reductions of PCBs using green infrastructure would be likely to occur in the older urban and industrial areas. David et al. (2015) reported favorable performance for PCB reduction, but since the runoff came from a recently redeveloped parking lot, the influent concentrations were low (mean = 0.73 ng/L) relative to concentrations more commonly measured in flows emanating from catchment areas that include the older commercial and industrial land uses developed during the era of peak PCB usage prior to 1979 (e.g. mean = 14.5 ng/L: Gilbreath and McKee, 2015; mean = 13 ng/L: McKee et al., 2017). It is these older developed areas where managers are focusing green infrastructure and other best practice efforts to make greater progress towards meeting PCB TMDL targets.

Although there are legacy sources of Hg in our older urban areas from legacy uses in paint, batteries, thermostats, switches and many other uses, Hg is widely redistributed in the urban environment via atmospheric circulation and deposition (Davis et al 2012). It follows that wider distribution of green infrastructure may be a very useful tool for reducing Hg loads in addition to treatment in older urban areas. However, stormwater managers need more information about bioretention performance so that Hg load reduction estimates can be generated with enough confidence for TMDL compliance. In the one

study reporting on Hg performance, David et al. (2015) measured reduced concentrations after bioretention was implemented, but, complicating the performance results, the authors reported increased concentrations for total methylmercury (MeHg). The authors attributed the elevated MeHg to the anaerobic conditions caused by the incorrect installation of the subdrain which led to an environment conducive to microbial methylation. Given that MeHg is the bioavailable form of Hg and therefore of great concern in the region, the results from this single case study may contraindicate the use of bioretention. Additional case studies are necessary to understand the dynamics of Hg species capture in bioretention.

Green infrastructure implementation in the Bay Area is on the rise, and in parallel, tools, lessons and scientific data pertaining to improving that implementation and performance are being developed. The goal of this synthesis is to collate and synthesize all of the monitoring data collected in the Bay Area to-date, including data from 10 green infrastructure bioretention projects¹. Secondly, a literature review on available information for PCBs and Hg performance in GI is summarized, along with additional information on other pollutants and non-GI studies that may provide insights into how PCBs and Hg performance may be impacted by GI design. This data synthesis and literature review provides helpful insights into design improvements for the Bay Area to maximize performance, and highlight the many data gaps that remain.

Bay Area Green Infrastructure Water Quality Data Review

Project overview

The Bay Area green infrastructure water quality data utilized in this synthesis were gathered from three sources: The Bay Area Stormwater Management Agencies Association (BASMAA), California Department of Transportation (CalTrans), and the San Francisco Estuary Institute (SFEI). Each of these three organizations has monitored and collected stormwater pollutant data relevant to the goals of this synthesis.

BASMAA Green Infrastructure Studies

¹ Only bioretention projects were selected although the CW4CB project set included other green infrastructure and BMPs. Additionally, one site in the CW4CB (Richmond 1st and Cutting Cell 1) was omitted because only inlet concentrations were measured.

BASMAA completed the Clean Watersheds for a Clean Bay (CW4CB) project in 2017, funded by a US Environmental Protection Agency (USEPA) grant, that focused on urban runoff treatment retrofits. The MRP Provisions required permittees to install 10 pilot stormwater best management practices (BMPs) in locations across the Bay Area that had been identified as having elevated concentrations of pollutants, based upon current or historical land use or previous screening-level sediment sampling. The project monitored each location for BMP performance based on the removal of polychlorinated biphenyls (PCBs) and mercury (Hg). The objective was to evaluate various types of BMPs, document the knowledge gained, and evaluate the potential for achieving PCB and mercury load reductions through treatment control retrofit (BASMAA, 2017).

Of the 10 pilot projects, a subset were green infrastructure, either bioretention or bioretention plus other features. One additional project was a swale, but no water quality data were collected at that location so it is not reported here. The following provides a short summary for each of the projects reported on in this synthesis:

Bioretention:

- El Cerrito Green Streets: This bioretention project completed in 2010 created 19 individual rain garden cells along San Pablo Avenue in El Cerrito to capture stormwater runoff from the watershed comprising residential, commercial and transportation land uses. This monitoring occurred in water year (WY) 14 and WY15 (BASMAA, 2017). Other monitoring at this location was completed by SFEI (WY 12 and WY 17, described later).
- Bransten Road: This City of San Carlos bioretention project completed in 2013 created seven curb extension rain gardens in the Pulgas Creek Pump Station watershed, which has both industrial and commercial land uses. Due to on-site limitations, some cells have shallow soil media without an underdrain, while others have a thicker soil media and an underdrain. Pollutant monitoring was conducted in two of the cells for five storms during WYs 2014-2016 (BASMAA, 2017).
- PG&E Substation at 1st and Cutting Blvd: This City of Richmond bioretention project completed in 2014 created four cells for infiltration of stormwater. However, this project was unique in that they varied the composition of soil media, including one cell with standard media and no underdrain, one cell with standard media and an underdrain, and one cell with media augmented with Biochar and an underdrain. The bioretention collected water draining from a PG&E substation, although due to the small drainage basin area, some storms did not produce enough runoff to sample. Pollutant monitoring occurred during WYs 2015 and 2016 (BASMAA, 2017).
- West Oakland Industrial Area: This project installed six Filtera tree well filters in a highly industrial watershed in West Oakland. Each tree well was sized based upon the contributing watershed area. Pollutant monitoring occurred in two tree wells during four storms in WYs 2014 and 2015 (BASMAA, 2017).

Data were included from the CalTrans East Span Seismic Safety Project conducted at the San Francisco Oakland Bay Bridge (SFOBB). The San Francisco Bay Regional Water Quality Control Board requires stormwater dischargers, such as CalTrans, to quantify PCB and mercury discharges as part of the Waste Discharge Requirements of the San Francisco Bay TMDL for PCBs and mercury. As a result of construction on the SFOBB, the Water Board required mitigation due to the impacts of the project, and subsequent monitoring of the future mitigation sites. The mitigation focused upon installing pilot stormwater BMPs, including six bioretention basins to treat stormwater runoff from the Toll Plaza area, a bioswale, a biostrip, and two detention basins. The basins were constructed with experimental design features, so that the performance of these basins could be compared to control basins, with results informing future stormwater BMPs. In addition, CalTrans was required to monitor the treatment measures for five years post construction to characterize pollutant concentrations in the stormwater discharge. The monitoring aimed to evaluate the effectiveness of the bioretention basins for removing PCBs and mercury, along with other pollutants (CalTrans, 2014).

SFEI Green Infrastructure Studies

The San Francisco Estuary Institute (SFEI) has worked cooperatively with three cities across the Bay Area to conduct stormwater monitoring in four GI installations. The data included in this synthesis were collected in Daly City, El Cerrito, and Fremont

- At the Daly City Library, the EPA funded the City to install rain gardens in a small watershed that drains a parking lot and recreation center buildings. The project monitored pollutants during 3 storms in WY09 before construction began (the influent), and monitored pollutants exiting the gardens (effluent) during 7 storms in WY10. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report. A comparison of the results reported in the original David et al. (2015) report and those presented here is available in Appendix A
- The City of El Cerrito constructed a bioretention project along San Pablo Avenue in 2010, creating 19 individual rain garden cells that would capture runoff from the watershed that contains residential, commercial and transportation land uses. SFEI worked in collaboration with the San Francisco Estuary Partnership (SFEP) to conduct the monitoring with funding from the State Water Resources Control Board, through the Clean Water State Revolving Fund Project. After an initial year of visual observations in WY11, stormwater monitoring to capture samples for laboratory analysis of pollutants was conducted in WY12 by SFEI (Gilbreath et al., 2013). In addition, SFEI also conducted monitoring during WY17 with separate funding under a California Department of Water Resources grant also in collaboration with SFEP (Gilbreath et al., 2018).
- In 2011, the City of Fremont installed two tree well filters on a major street in a watershed with mixed commercial, light industrial and transportation land uses. One tree well was “traditional” with stormwater loading from the surface. The other tree well was designed so that stormwater entered via a perforated subsurface pipe. SFEI conducted pollutant monitoring in both tree wells during 5 storm events in WY 2013 and 2014 (Gilbreath et al., 2015). This pilot stormwater BMP project was in response to the 2009 Municipal Regional Stormwater NPDES Permit which

required municipalities to implement on-site stormwater management measures for large projects that created or replaced 10,000 square feet or more of impervious surface. The City installed the tree wells as part of the requirement that 10 pilot projects be installed across the Bay Area to help document the costs, performance, and water quality outcomes so that future projects could be better informed.

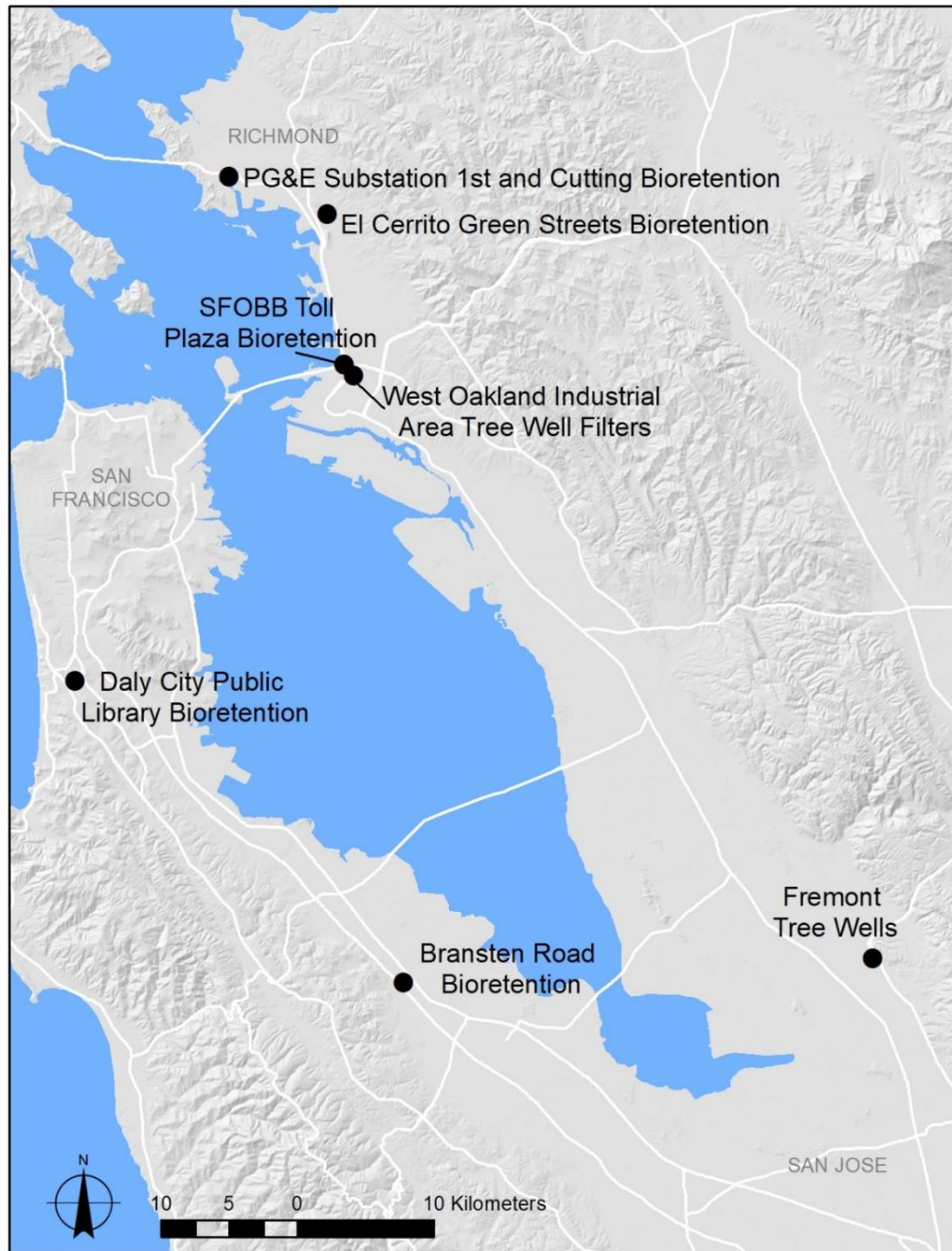


Figure 1. Map indicating the location of each Bay Area green infrastructure of BMP project described in this report.

Project Details and Construction Specifications

Table 1: Project details

Data Source	Site Name	Sponsor	Green Infrastructure Type	Date Site Construction Finalized	Watershed Area (km ²)	Watershed Area (acres)	Watershed Land Use
CW4CB	El Cerrito Green Streets	City of El Cerrito	Bioretention	Jul 2010	0.0069	1.7	Transportation, commercial, residential
CW4CB	Bransten Road	City of San Carlos	Bioretention	Nov 2014	0.0074	1.83	Industrial, commercial
CW4CB	PG&E Substation 1st and Cutting	City of Richmond	Bioretention	Sep 2014	0.0067	1.66	Industrial
CW4CB	West Oakland Industrial Area	City of Oakland	Media filter	Nov 2013	0.0032	0.8	Industrial, commercial
SFEI	Fremont Tree Wells	City of Fremont	Bioretention	2011	0.0014	0.34	Transportation, commercial, light industrial
SFEI	Daly City Library	Daly City	Bioretention	2009	0.0162	4.0	Parking lot, recreation center
Caltrans	SFOBB Toll Plaza	Caltrans	Bioretention	2008	0.58	143	Transportation

Table 2: Construction specifications

Site Name	Monitored portion	Total Green Infrastructure Surface Area (m ²)	Monitored Green Infrastructure Surface Area (m ²)	Soil Depth (cm)	Description of soil media	Drain Depth (cm)	Ponding Depth (cm)	Other description details
El Cerrito Green Streets	Northern cell at Eureka Ave	104	6.3	46	sandy loam	71	28	19 total cells. Not lined.
Bransten Road	-	295	-	-	-	-	-	7 total curb extensions. Partially lined. Cells 2, 4, 5, 6 without underdrain.
	Cell 7	-	28.3	46	bioretention soil mix	46	15	
PG&E Substation 1st and Cutting	-	178.6	-	-	-	-	-	All unlined.
	Cell 3	-	88.9 (cells 3 and 4)	46	Standard bioretention media (60% sand 40% compost soil mix)	46	15	
	Cell 4	-	88.9 (cells 3 and 4)	46	Standard bioretention media augmented with biochar (75% soil mix 25% biochar)	46	15	
Ettie Street Pump Station	-	706	-	76	1 bed is rhyolite sand; 1 bed is rhyolite sand, zeolite, granulated activated carbon mix	na	na	2 media filter beds with different media composition
West Oakland Industrial Area	-	10.5	-	-	-	-	-	6 total Filterra tree wells
	Tree Well 2	-	1.5	53	Filterra engineered media	107	-	
	Tree Well 6	-	1.5	53	Filterra engineered media	107	-	
Fremont Tree Wells	-	-	-	-	-	-	-	
	Subsurface loaded	54	27	76	Top 4-6" river cobble; 18" class II permeable layer (with influent pipe); 18" treatment soil (60% ASTM C-33 Sand, 40% compost); then 4" subdrain and 6" class II perm layer	102	0	
	Surface loaded	54	27	53	3" mulch; 18" treatment soil (60% ASTM C-33 Sand, 40% organics); then 4" subdrain and 6-12" class II perm layer	91	15	
Daly City Library	-	427	-	38	50mm of gravel mulch over 380mm of loamy sand filter soil material (84.2% sand, 7.5% silt, 8.2% clay, 5.3% organic content)	51	-	4 cells total. Pea gravel drainage gallery. Soil percolation rate of 198 mm/hr.
SFOBB Toll Plaza	Catchment 5	-	485 to 2,145	76	-	-	15	6 bioretention basins (treats 102 acres), 1 bioswale, 1 biostrip, 2 detention basins (treats 41 acres)

Table 3. Monitoring information

Site Name	Individual Monitored Portions	Pollutant Monitoring	Pollutant Monitoring Sample Years	Number of events, type of events	Inlet monitoring type	Sample n	Outlet monitoring type	Sample n	Flow Monitoring	Inflow monitoring method	Outflow monitoring method	Other monitoring	Data Output
El Cerrito Green Streets WY14-15	Northern cell at Eureka Ave	Y	WY 14, 15	2 events in WY14; WY 15 1 event. Rising and peak limbs targeted.	composite	3	composite	3	Y	gutter	pipe connected to underdrain	WY12	Loads
Bransten Road	-	Y	WY 14, 15, 16	5 events; Peak measured.	composite		composite		Y			Pre-construction 1 storm WY13	Loads
	Cell 7	Y				5		5	Y	gutter	vertical riser above underdrain		-
PG&E Substation 1st and Cutting	-	Y	WY 15, 16						Y			Cell 2 water level observation only	Loads
	Cell 3	Y		8 events	composite	8	composite	8	Y	gutter	pipe connected to underdrain		-
	Cell 4	Y		6 events	composite	6	composite	6	Y	gutter	pipe connected to underdrain		-
West Oakland Industrial Area	-	Y	WY 14, 15	4 events	composite		composite		Y	gutter	pipe connected to underdrain	6 Pre-construction street sediment samples WY13	Loads
	Tree well 2	Y				4		4	Y				-
	Tree well 6	Y				4		4	Y				-
El Cerrito Green Streets WY12	Northern cell at Eureka Ave	Y	WY12	4 events	composite (3) and discrete grab (4)	7	composite	4	N	ISCO, tubing in curb cut inlet	pipe connected to underdrain	WY11 wet season observations	Concentrations
El Cerrito Green Streets WY17	Northern cell at Eureka Ave	Y	WY17	4 events	composite	4	composite	4	N	ISCO, tubing in curb cut inlet	pipe connected to underdrain	WY12, 14, 15	Concentrations
Fremont Tree Wells	-	Y	WY 13, 14	5 events					N, observation only			WY12 visual monitoring (2 events)	Concentrations
	Subsurface loaded	Y			discrete grab (only WY13)	7	discrete grab	16 HgT, 11 PCB	N	subsurface pipe draining into garden	pipe connected to underdrain		-
	Surface loaded	Y			discrete grab	17 HgT, 11 PCB	discrete grab	17 HgT, 11 PCB	N	pipe draining into garden	pipe connected to underdrain		-
Daly City Library	-	Y	Influent WY09; Effluent WY10	3 WY09 preconstruction storms, 9 WY10 post construction storms; 50% peak, 50% receding.	grab	6	grab	12	Y	pre-construction subdrain pipe draining site	pipe from subdrain		Concentrations, FWMC, Loads
SFOBB Toll Plaza	Catchment 5 (Basins 1, 4, 5)	Y	WY 14	4 events	composite	5	composite	5	Y	weir and flume	flumes	WY14 flow monitoring in Catchment 2.	EMC

Limitations of Interpretation

Results and interpretations are presented in the following section. Several limitations are present concerning the interpretation of the data. First, there are many important differences between the sites in terms of **design, construction, and maintenance**. For example, soil depth, presence of an underdrain, depth of underdrain, soil compaction, media composition, vegetation species, density and health, irrigation practices, etc. can all impact the performance of a site so when multiple factors vary between sites, it is challenging to discern why one site performs better than another.

Many of the sites monitored were done so within a year or two of construction. This may still be within the window of time that these bioretention **systems are still settling** and so it can be difficult to understand how performance may be different once the initial period of maturation is completed.

The sampling completed was not a perfect **representation** of inlet and outlet concentrations. Sampling in these storms was intermittent, not always flow-weighted, and often did not capture the entire storm (e.g. sampling may have begun after substantial runoff had already occurred). The sampling is typically limited to <10 storms and does not represent the full range of storm types. Additionally, there is no perfect pairing between inlet and outlet samples. What flows in one storm may have residence time in the unit and flow out in a subsequent storm. You can get around this issue by sampling a large number of storms, but these projects were only pilot level.

When increased concentrations at the outlet are observed, causation is often unknown. It could be the result of too few storms sampled and that higher inlet concentrations were missed, or it could be that the pollutant is being sourced from the media. Ideally for Hg and Cu, pollutants in which we see mixed results, initial soil testing should be done to verify the concentrations at the beginning of an installation. Another reason could be that the initial part of the storm was not sampled well; the bulk of the pollutant mass (30-50%) for many pollutants is transported in the first 10-20% of the volume (Stenstrom and Kayhanian, 2005) so by missing samples in the initial onset of a storm, the influent concentrations may appear low. In contrast, it is relatively easy to capture the early portions of the effluent, and since effluent water quality is generally less variable, the sample result is more likely to have better representation of the effluent on the whole.

Although these challenges to interpretation are important to mention, such challenges should not preclude attempts to analyze and synthesize the data. It is important to understand the data limitations and then make inferences that can further the field of GI.

Results

The results for all 10 green infrastructure units are summarized here. Within the body of this report, we report and discuss data for SSC, PCBs, TOC, HgD, HgT, MeHg, CuD, CuT, and Pb. Information on other pollutants were collected in these studies but none with as many sites where the pollutants were collected and so just this subset is reported on in more detail. Study results for all the pollutants are provided in Appendix B. In summarizing and describing the results for each pollutant, the reader is referred to a summary statistics table in the section as well as Figures 2-4, 9 and 10. Prior to discussing the performance of the green infrastructure projects for each pollutant, the results of particle size measurements are summarized. Given that one of the most important mechanisms for pollutant removal using green infrastructure is the physical filtration of pollutants adsorbed to particles, the particle size data provides an important framework for assessing variable performance at each green infrastructure unit.

Suspended Sediment Concentration (SSC)

Average influent concentrations of suspended sediment to the 10 GI units ranged from 21.2 - 145 mg/L (Table 4, Figure 2). This represents a typical range for urban stormwater runoff (Clary et al., 2017; Gilbreath et al., 2018). Retention of suspended sediment is the primary mechanism for which most particle-associated pollutants are captured. Typically, green infrastructure is good at trapping suspended sediment (>80% capture), but common exceptions include when a unit is new and therefore the soil is still settling and compacting, or when inlet concentrations are so low that high performance (when evaluated as percent capture) is unlikely. Because sediment capture is so fundamental to pollutant capture, in this section, each unit (or group of units, where applicable) is described independently, and a summary synthesizing the SSC results follows.

Bransten Facility No. 7 Bioretention

Bransten Facility No. 7 is a partially lined bioretention cell monitored in the gutter of the inlet and in a vertical riser above the underdrain at the outlet. The unit is sized at 4% (ratio of the GI area to Drainage Management Area (DMA)), and had the standard bioretention media (60% sand and 40% compost soil mix).

In 5 storm events at the Bransten Facility No. 7 (Bransten), influent SSC ranged from 43 – 236 mg/L, with a mean of 145 and median nearly identical (Table 4). This was the highest mean and median influent relative to all sites measured. Reduction in the effluent was moderate at 59% of the mean influent. Each paired sample set of influent and effluent samples for the same storm event are graphed and compared to a 1:1 line that represents zero reduction of concentrations to get an overall sense of performance (Figure 3). Bransten effluent samples were typically lower than the influent samples; only in one case in which the influent sample was low (compared to all other influent samples) did the effluent exceed the influent in the same storm event. This suggests that in general the site receives greater SSC

concentrations than it discharges, though in times when SSC is very low at the inlet, effluent can exceed the influent and the unit can serve as a sediment source.

Performance, as calculated by the percent reduction in concentration, typically improves as influent concentrations increase (Kadlec and Knight, 1996). That is the case for many pollutants summarized here in this synthesis, and graphed for SSC in Figure 4. Graphs such as these highlight exceptions in which a site or two do not follow the typical pattern. In this case, it could be said that the Bransten performance as a percent reduction relative to influent concentration is slightly low compared to the other sites, especially SFOBB Toll Plaza 5/5 with very similar influent concentrations.

Particle size in the influent will affect capture by filtration, as well as potentially the removal of adsorbed pollutants. Particle size distribution in influent and effluent samples were averaged for each BMP. The concentrations of total solids within each classification, averaged for each BMP, are presented in Figure 5. The averaged distributions as a percentage of the total are presented in Figure 6 below. Finally, Figure 7 shows the percentage reduction by particle size for each unit.

As mentioned previously for total SSC, the samples measured for particle size distribution at Bransten Facility No. 7 decreased by almost 60% (Figure 5). The particle size distribution between inlet and outlet samples (as a percentage of the total) was similar for the size classes $1 < 25 \mu\text{m}$ and $63 < 500 \mu\text{m}$ (Figure 6), but changed for the other size classes, decreasing for the class $25 < 63 \mu\text{m}$ and increasing for the classes above $500 \mu\text{m}$. These data suggest that overall, there is moderate capture of the smaller size classes, but the unit is not retaining some of the larger size classes (although the grain size distribution of the media is unknown). Bransten Facility No. 7 was recently built when monitoring began, so leakage as the unit is settling is not uncommon. This kind of leakage sourced from within the unit should not necessarily lead to less pollutant capture if the media soils are free of the target pollutants.

Table 4. Summary statistics for suspended sediment concentration (SSC) (mg/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Bransten Facility No. 7	Influent	5	145		69	43.1	139	142	163	236
Bransten Facility No. 7	Effluent	5	59.7	59%	34.5	20	38.9	52	80.8	107
Daly City Public Library	Influent	3	21.2		12.8	8.45	14.7	21	27.5	34
Daly City Public Library	Effluent	7	20.9	1%	24.4	7.1	8.23	11.9	18.1	74.5
El Cerrito Bioretention Facility	Influent	11	104		121	14.6	34	43.4	132	395
El Cerrito Bioretention Facility	Effluent	11	5.5	95%	4.92	0.33	1.78	3.6	8.36	15.1
Fremont Tree Well Subsurface	Influent	5	87		68.9	15.3	23.2	83.4	151	162
Fremont Tree Well Subsurface	Effluent	4	33.9	61%	6.45	24.3	33.3	36.8	37.4	37.7
Fremont Tree Well Surface	Influent	5	87		68.9	15.3	23.2	83.4	151	162
Fremont Tree Well Surface	Effluent	5	27.8	68%	14.3	12.2	15.8	26.6	41	43.8
Richmond 1st & Cutting Cell 3	Influent	8	54.8		60.4	6.19	16.2	34.4	64.9	186
Richmond 1st & Cutting Cell 3	Effluent	8	51.1	7%	44.6	19.8	25.6	35.3	50.1	155
Richmond 1st & Cutting Cell 4	Influent	6	41.1		24.4	17.2	19.2	39.1	61.7	69.6
Richmond 1st & Cutting Cell 4	Effluent	6	53.5	-30%	96.6	4.27	7.25	17.8	25	250
SFOBB Toll Plaza - 5/5	Influent	3	144		198	20	29.4	38.8	206	373
SFOBB Toll Plaza - 5/5	Effluent	3	10.2	93%	4.79	6.34	7.56	8.78	12.2	15.6
West Oakland Tree Well 2	Influent	4	31.3		14.3	18.9	20.4	28.3	39.2	49.6
West Oakland Tree Well 2	Effluent	4	6.63	79%	3.99	2.02	4.11	6.77	9.3	11
West Oakland Tree Well 6	Influent	4	60.6		47.8	15.1	30.2	51.3	81.7	125
West Oakland Tree Well 6	Effluent	4	17	72%	9.45	6.8	10.7	16.5	22.7	28.1

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original reports. See comparison in Appendix A.

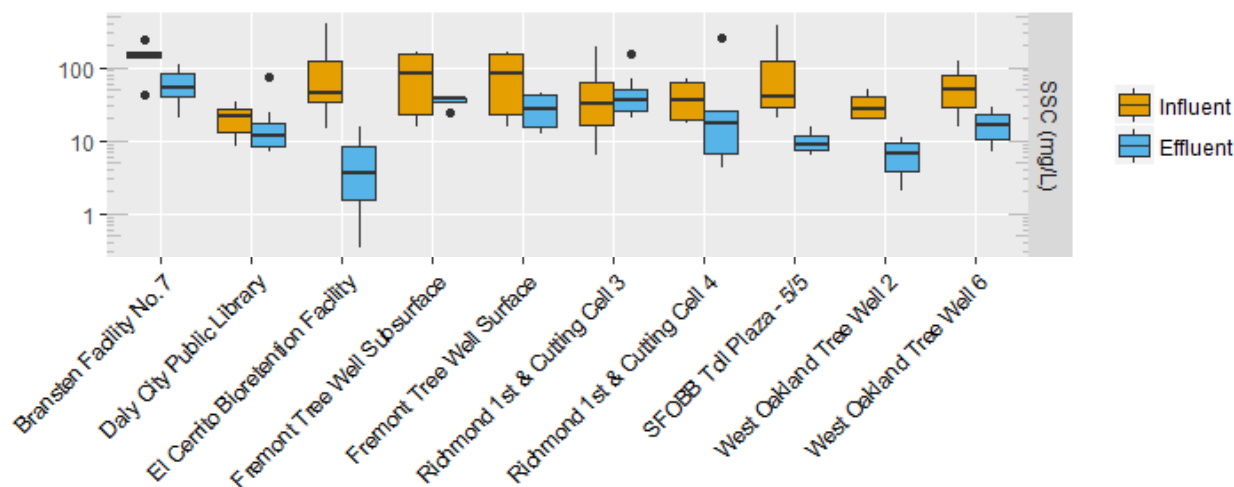


Figure 2. Boxplot of influent and effluent concentrations for SSC.

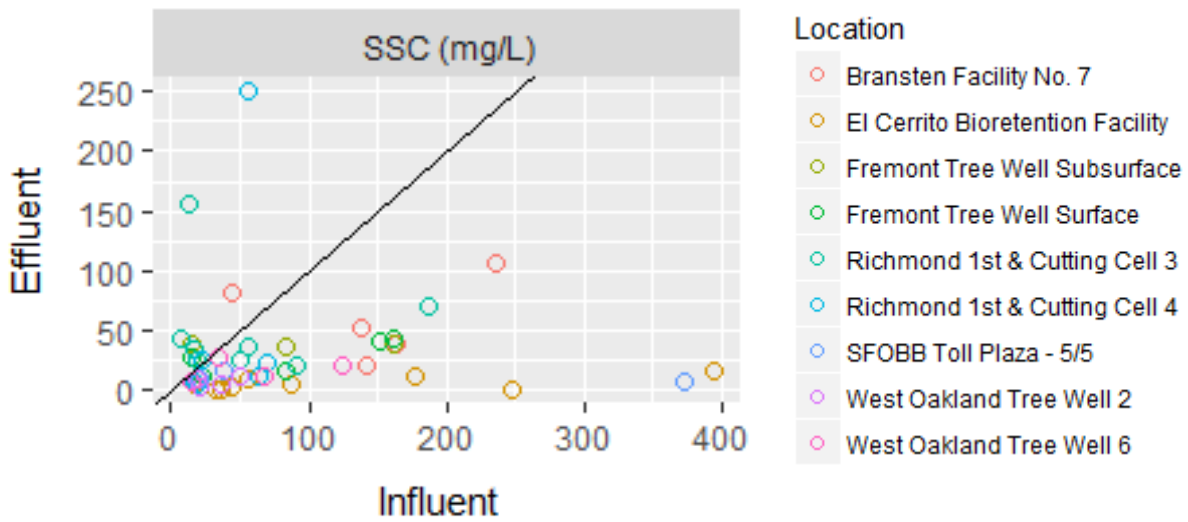


Figure 3. Scatterplot of influent and effluent paired samples. Sample points above the line indicate sample pairs in which the effluent concentration was higher than the influent.

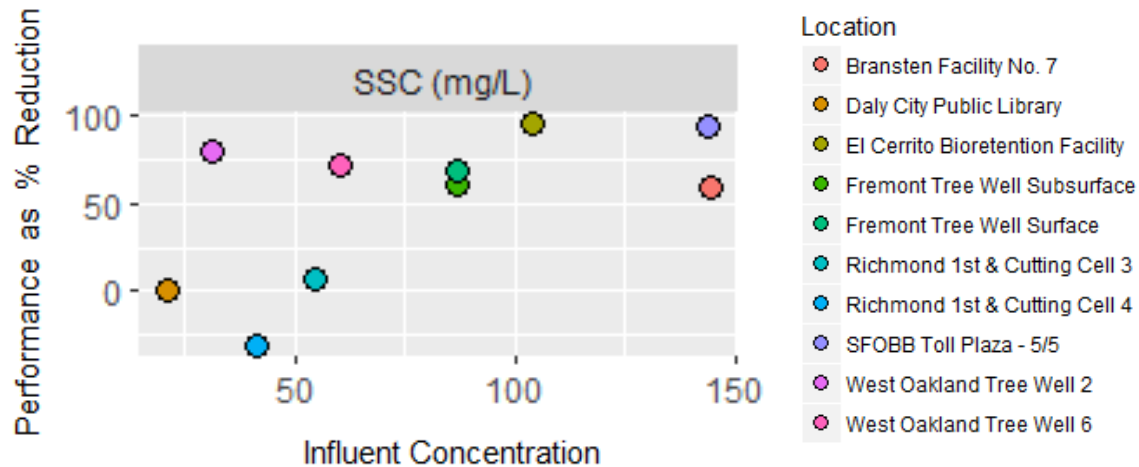


Figure 4. Performance as a function of influent concentrations.

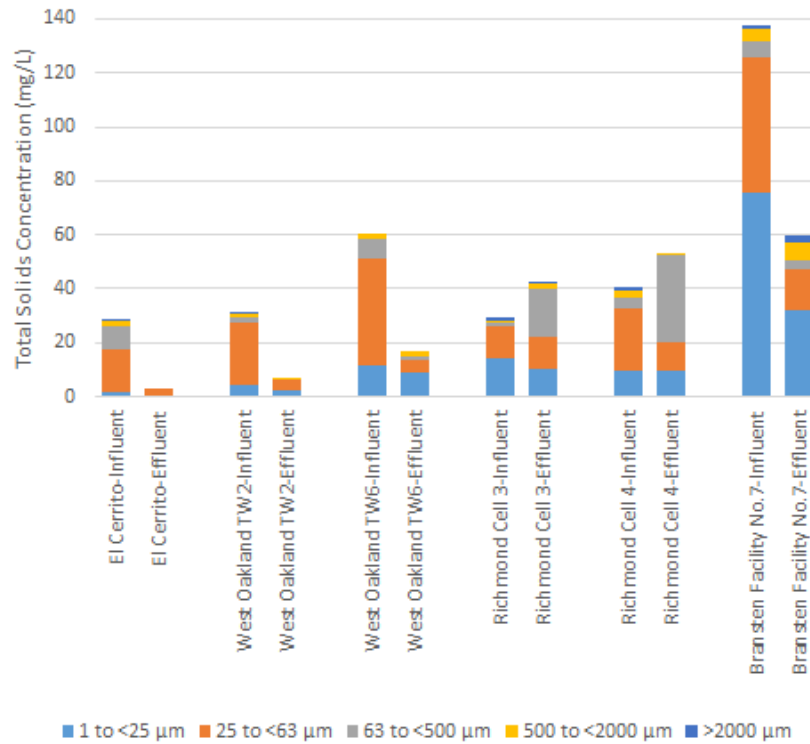


Figure 5. Particle Size Distribution of suspended sediment samples.

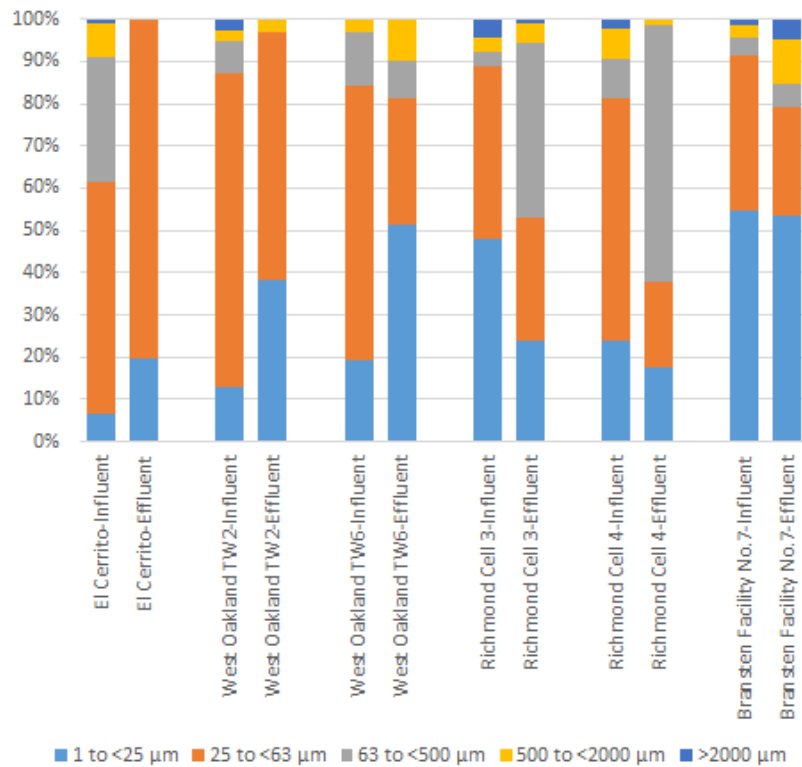


Figure 6. Particle Size Distribution of suspended sediment samples.

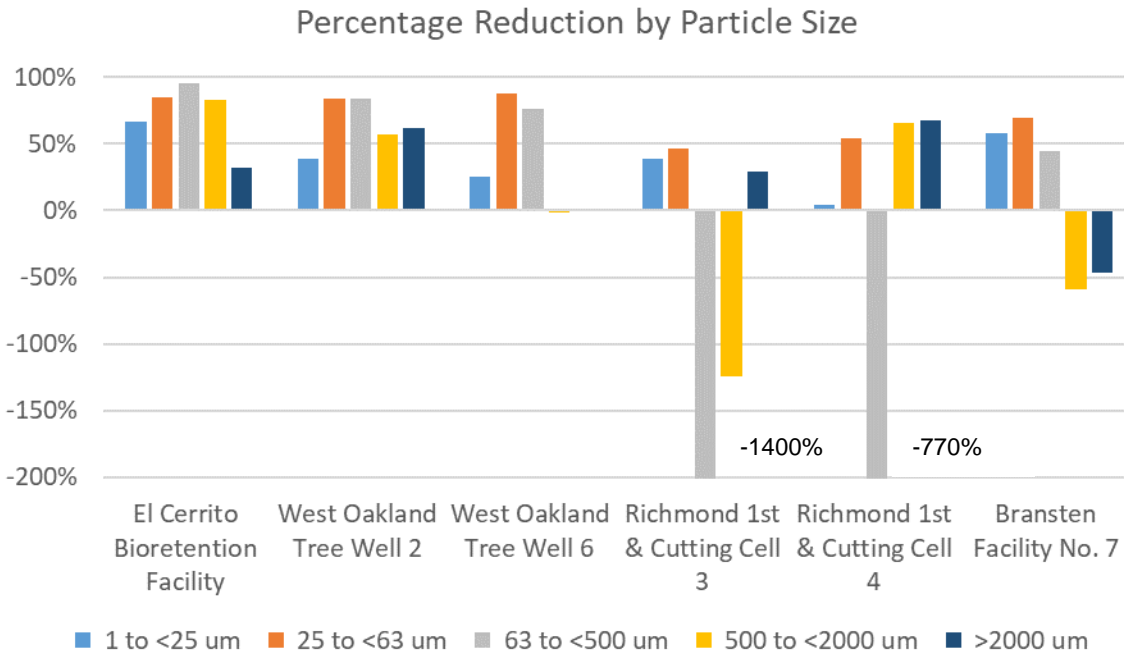


Figure 7. Percentage reduction by particle size of suspended sediment samples.

Daly City Public Library

Daly City Public Library was monitored pre- (3 storms) and post-construction (7 storms) from a subdrain draining the site. The unit is sized at 2.6% (GI:DMA) and has a pea gravel drainage gallery, with 50 mm of gravel mulch lying over 380 mm of loamy sand media (84% sand, 7.5% silt, 8.2% clay, 5.3% organic content).

At Daly City, the pre- and post-construction average SS concentrations were nearly equivalent although the median post-construction concentrations were lower (Table 4, Figure 2). Since this site was measured pre- and post-construction, rather than inlet and outlet during the same storm, this site is not graphed in the Figure 3 scatterplot of paired sample data. Daly City overall had low SSC, averaging just 21.2 mg/L pre-construction and 20.9 mg/L post-construction. Consequently, the data point representing Daly City in Figure 4 is far to the left, and has overall low total reduction. Despite this low reduction, the point does not appear to fall off the performance curve. In other words, the low performance may be due to low pre-construction concentrations. Another consideration for the lower performance is that the site was monitored immediately after construction and so it may have still been settling. Grain size was not measured at this site.

El Cerrito Bioretention Rain Gardens

El Cerrito Green Streets at San Pablo and Eureka Ave. is a series of 19 bioretention cells in a row. The monitored cell was the first in the row and measured just 0.2% of the DMA. The cells were not lined and

the bioretention media included 70% sandy loam, 10% clay, and 20% composited organic matter. Influent was measured at the gutter to the inlet and effluent was measured in a pipe connected to the underdrain.

The rain garden was very effective at capturing SSC, decreasing in mean concentrations at the inlet from 104 to 5.5 mg/L at the outlet (median inlet and outlet were 43.4 and 3.6 mg/L, respectively) (Table 4). SSC at the outlet was the lowest of any site in this synthesis (Figure 2). SSC capture was strong overall (95%), and strong even in the first year (79%), but performance did increase with time after construction (3 years monitored over 7 wet seasons).

In every storm the effluent concentration was less than the influent (Figure 3). In part, the high performance may be related to the relatively high influent concentrations (104 mg/L on average), whereas sites with lower influent concentrations did not perform as well (Figure 4). Particle size distribution was measured in WYs 2014 and 2015 (3 and 4 wet seasons post-construction, respectively). Nearly all of the largest size classes were removed, shifting the percent contribution of each size class to the finer fractions in the effluent.

Fremont Tree Wells – Subsurface and Surface

The two Fremont Tree Wells drain runoff from very similar drainage areas, however one drains stormwater onto its surface (a more traditional style) and the other drains stormwater into a subsurface drainage system that distributes the influent around the cell. Influent concentrations for both of these tree wells were similar and, subsequently, after initial sampling it was decided to discontinue sampling both inlets since they were not statistically different. Therefore, the inlet concentrations for one of the tree wells was considered to be representative of both.

Inlet SSC were moderate (average 87 mg/L) as were the reductions at the outlet (61 and 68% for the subsurface and surface-loaded tree wells, respectively) (Table 4). The median concentrations were very similar to the means. Effluent concentrations were much less variable than influent concentrations (Figure 2). In some instances, the effluent exceeded the influent (Figure 3), but mostly the samples fall below the 1:1 line. This is a good example of why it is important to sample multiple storms to get a good representation of a site. The moderate inlet concentrations and associated moderate capture appear to fall within the general trend on the performance curve (Figure 4). Grain size was not measured at this site.

Richmond 1st and Cutting Bioretention Cells 3 and 4

At 4.5% each, together the Richmond 1st and Cutting Bioretention Cells 3 and 4 outside of a PG&E substation had the largest surface area to drainage management area ratio of all the sites in the synthesis. Cell 3 was filled with what was termed “standard bioretention media”, consisting of 60% sand and 40% compost. Cell 4 media was 75% standard bioretention media mixed with 25% biochar. The cells were unlined, the drain depth was among the shallower in the group at just 46 cm, and the site was monitored in the gutter of the inlet and a pipe connected to the underdrain of the outlet.

Mean and median SSC influent and effluent were approximately equal at Cell 3, but Cell 4 was different in that the average effluent was greater than the average influent, but the median effluent was lower than the median influent. In general, effluent at Cell 3 was less variable than the influent, whereas the effluent from Cell 4 was more variable. While there is great uncertainty, it may be that the biochar mixed with the standard bioretention mix was causing more variable intermittent releases of suspended sediment.

A few samples, particularly those with very low influent SSC, were above the 1:1 line for their paired samples. Additionally, the Richmond 1st and Cutting sites have lower performance given their inlet concentrations, relative to sites with similar inlet concentrations like West Oakland Tree Well 2 and 6.

While total SSC decreased from influent to effluent in all of the other units, Richmond Cells 3 and 4 increased not just in the proportion of particles in size class 63 - <500 μm , but also in total mass in that size class. While at the same time concentrations of clay and silt at Richmond Cells 3 and 4 experienced a total decrease in particles <63 μm . This suggests that it is the bioretention media itself that is the source of the 63 - <500 μm particles in the effluent. It's possible that in time, the media in those cells will settle and compact, and export less suspended sediment (if it were to follow the time trajectory similar to the El Cerrito system). Nevertheless, it is promising that finer sediment (and presumably coarser as well) in the influent is being largely captured, and trapping along with it any particle-bound pollutants. This example highlights the weakness of the inlet versus outlet comparison which is based on the unreal assumption that what flows into the bioretention system is the same material as what flows out in a single storm; rather, in systems that are immature and leaking sediment, the inlet sediment may still be captured even if some soil media is leaking out the other side.

SFOBB 5/5 Bioretention

The SFOBB 5/5 bioretention basin treats the largest area (0.11 sq km) of any of the sites in this study, and has a moderate GI:DMA ratio at 1.3%. Additionally, the soil depth was amongst the deepest (76 cm) of any of the other units in this study. Average inlet concentrations were 144 mg/L whereas average effluent 10.2 mg/L and not very variable. This very high performing GI unit, installed at the SFOBB Toll Plaza, was monitored in WYs 2013 and 2014, five and six years after construction in 2008. This likely allowed the unit plenty of time to settle after initial construction.

At this site, there were no storms in which effluent SSC exceeded influent (Figure 3). Given the relatively high inlet SSC, the performance as a percentage reduction falls in line with the performance curve (Figure 4). Grain size was not measured at this site.

West Oakland Tree Well Filters 2 and 6

The West Oakland tree wells were monitored in the gutter of the inlet and a pipe connected to the underdrain at the outlet. Each tree well was just 0.7% GI:DMA, and had Filterra engineered media. We do not have the specifications of this soil mixture. The reductions in SSC were fairly good at these sites, reducing SSC by 72% and 79% for Tree Wells 2 and 6, respectively.

None of the influent SSC exceeded the effluent concentrations in the same storm event (Figure 3). Relative to performance at other sites given their influent concentrations, the tree wells may perform on the better side, especially Tree Well 2 which had the lowest effluent concentrations of any site (Figure 4). It might be the case that the Filterra media is better at retaining sediment in the earlier phases just after construction. This hypothesis would need further testing if SSC export in the initial phases of settling/compaction included excessive pollutant export.

The Tree Well influent was dominated by particles in the grain size class 25 – <63 μm (Figure 5). The Tree Wells did a good job removing particles in that size class. On average, like El Cerrito, the West Oakland Tree Well 2 projects removed all or nearly all sand and gravel (particles greater than or equal to 63 μm) (Figure 6 and 7). No substantial changes for the larger particles occurred in West Oakland Tree Well 6.

Summary

Suspended sediment reduction as the result of the bioretention or tree wells ranged from -30% (net export of SS) to 95%. With an overall large set of variables that could be contributing to differences (GI:DMA, media composition, time since construction, soil depth, etc.) relative to the number of sites, it is challenging to fully understand why some sites performed better than others, though we can make some hypotheses.

Most of the sites sampled with moderate or poor SSC performance were studied within 1-2 years of final construction. Jia et al. (2015) found that SSC actually increased at the outlet in the first few months after construction but in the second year of sampling, SSC was lower at the outlet relative to the inlet. Similarly, the El Cerrito bioretention rain gardens increased reductions in each successive study (3 studies over 7 years). The two sites with the highest performance (El Cerrito and SFOBB 5/5) were both measured multiple years after construction. Figure 8 is a modified version of Figure 4 and suggests different performance curves that may be related to different rain garden attributes. The yellow-orange dashed curve includes the El Cerrito and SFOBB 5/5 sites. This represents a hypothesized curve for sites with multiple years since construction.

In Figure 8, the dashed blue curve includes those sites measured in the wet season immediately after construction. The hypothesis is that in the year immediately following construction, reduction in SSC is only moderate, and in cases where influent SSC is low, net export is possible. We've drawn the line to exclude the Richmond 1st and Cutting Cell 4, hypothesizing that that cell exported more sediment because of the biochar addition to the media. It's possible with more studies that the line would be shifted slightly downward to include that data point. It is also presumed that with time those sites would shift higher in line with the yellow-orange line. And finally, the brown dashed curve is a hypothesized curve for sites with the Filterra engineered media in the wet season after construction.

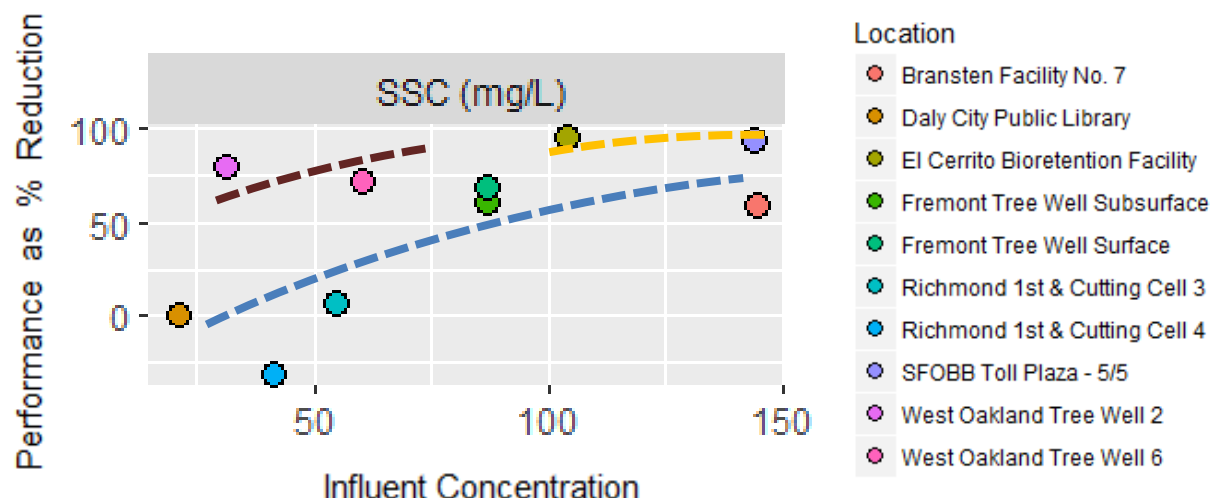


Figure 8. Performance as a function of influent concentrations (modified Figure 4).

Size fractions of sediment <63 μm were reduced at all locations in the project where grain size was measured. At half of the sites (including El Cerrito and the West Oakland Tree Wells), concentrations >63 μm were reduced whereas at the other three sites (including the Richmond 1st and Cutting Cells 3 and 4 and Bransten Facility No. 7), concentrations >63 μm increased. Just as with the performance curves, it may be that newly installed sites perform differently than those older locations or with the Filterra engineered media, and the specific difference is that the newly installed sites export coarser sediments likely sourced from the bioretention media itself.

Given the hypothesis that SSC export is sourced from the media itself, it may be that even the sites exporting sediment are performing well in capturing influent pollutants. Given the hypothesis that this SSC export will decrease over time (with site maturity), it follows that the ratio between total pollutant and SSC (sometimes referred to as a “particle ratio” or “estimated particle concentration”) should not be used as a means to compare across years for the same site, and should only be used with caution and full understanding when comparing between sites. In summary, although SSC capture is critical to pollutant capture and performance of bioretention, comparison between inlet and outlet concentrations – especially for recently installed sites which are still settling – can be a false indicator of particle-bound pollutant capture.

Total Organic Carbon (TOC)

Total organic carbon was measured at six locations. Median influent concentrations ranged from 1.63 to 14.8 mg/L, while median effluent concentrations ranged from 9.2 to 20.9 mg/L. At five of the six locations, effluent concentrations of TOC increased relative to the influent. Richmond 1st and Cutting Cells 3 and 4 had particularly large changes in TOC from inlet to outlet; at Cell 3 concentrations were almost 5 times greater at the outlet, and at Cell 4, concentrations were almost 7 times greater. This

corroborates the findings for SSC, in which these units performed most poorly of all the sites: if organic carbon is closely attached to soils in the units, it could be exported along with the suspended sediment.

TOC does follow a consistent pattern of better performance as influent concentrations increase (Figure 4). Only at Oakland Tree Well 6 was TOC somewhat reduced (14%), and this site happened to have one of the highest TOC influent concentrations. The media in Oakland Tree Wells 2 and 6 is a proprietary engineered media, unlike the rest of the sites in which a bioretention soil mix specified for the region was used. Organic compost is a common portion of the bioretention soil mix media (typically up to 40%) and can result in organic carbon leakage. Unlike for SSC, however, there is not a clear pattern related to soil mix or age of bioretention unit. Rather, regardless of the TOC concentrations in the influent, which varied 9-fold, effluent concentrations ranged from 9 to 20 mg/L, approximately a 2-fold difference. It may be that TOC export is muted by the bioretention units and affected by the influent concentrations such that the performance curve is strong.

The primary consequence of TOC release is that pollutants which attach to the TOC may be released as well. Dissolved organic carbon can flow right through the system, and particulate bound organic carbon on the finest fractions may also flow through without filtration. There is no strong correlation between TOC performance and HgT or PCB performance in this dataset, but as is discussed in the literature review (that follows), organic carbon does play an important role in pollutant capture and retention. It may be that the organic carbon export is primarily coupled with bioretention soil export due to initial settling of the system. This soil may not yet be polluted, which could explain why TOC does not correlate well with either Hg or PCBs (see details later). The pattern of TOC export does suggest that it is coupled with bioretention soil export. The pattern is similar to that seen for SSC. The El Cerrito bioretention rain gardens and the West Oakland Tree Wells all have TOC effluent average concentrations between 9.2 and 11.6 mg/L, whereas the newly installed sites with standard bioretention soil media have effluent concentrations nearly double, between 12 and 20.4 mg/L. Once the sites monitored directly after installation become settled and there is less sediment export, presumably there will also be less TOC export and the performance curve (Figure 10) will flatten somewhat with the data points in the lower left hand corner (the Richmond 1st and Cutting sites) rising in performance to some degree.

Dissolved organic carbon (not shown in the tables or graphs; refer to Appendix B) was only measured in the effluent at Daly City and both influent and effluent of El Cerrito Bioretention Facility in one of the monitoring years. In all cases, the total organic carbon was 90% or greater in the dissolved form, an observation consistent with our other Bay Area stormwater studies (McKee et al., 2005). The dissolved organic carbon is predominantly flowing right through the system, and in the case of El Cerrito for some storms, dissolved organic carbon increases in the effluent and explains the increase in TOC. Although there is no DOC data for the other sites, it may be the case that the increases in TOC are also the result of increasing DOC. To reiterate a previous statement, dissolution and export of organic carbon from a bioretention unit is problematic for pollutant capture and retention if it is organic carbon with pollutants adsorbed to it. It would be useful to measure DOC in future monitoring work to better understand the capture and release of TOC and DOC in bioretention.

Table 5. Summary statistics for total organic carbon (TOC (mg/L)) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Bransten Facility No. 7	Influent	5	16.4		6.59	10	13.9	14.8	15.7	27.5
Bransten Facility No. 7	Effluent	5	17.4	-6%	2.18	15.2	16.2	16.7	18.2	20.8
Daly City Public Library	Effluent	6	22.3		11.1	8.02	15.2	20.7	31.1	36.4
El Cerrito Bioretention Facility	Influent	7	8.53		3.86	6.88	6.95	7	7.33	17.3
El Cerrito Bioretention Facility	Effluent	7	9.22	-8%	2.74	5.4	7.56	9.2	10.5	13.8
Richmond 1st & Cutting Cell 3	Influent	8	5.43		4	1.38	2.24	4.6	7.05	12.5
Richmond 1st & Cutting Cell 3	Effluent	8	20.4	-276%	9.27	8.89	13.3	20.9	24.9	35.3
Richmond 1st & Cutting Cell 4	Influent	6	2.19		1.63	0.63	0.93	1.63	3.66	4.2
Richmond 1st & Cutting Cell 4	Effluent	6	12	-448%	6.13	5.6	6.9	11.5	16.7	19.6
West Oakland Tree Well 2	Influent	4	8.94		7.47	3.6	5.4	6.07	9.61	20
West Oakland Tree Well 2	Effluent	4	11.6	-30%	7.07	5.61	6.8	9.75	14.6	21.3
West Oakland Tree Well 6	Influent	4	12.4		9.19	4.4	6.34	10.2	16.3	25
West Oakland Tree Well 6	Effluent	4	10.8	13%	7.97	2.27	5.42	10.3	15.6	20.2

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

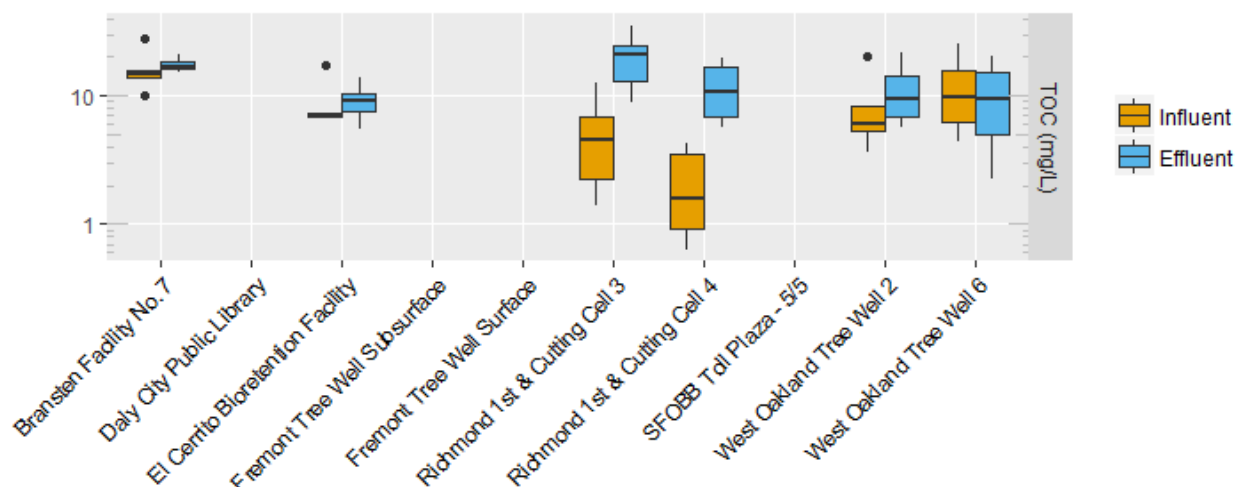


Figure 9. Boxplot of influent and effluent concentrations for TOC.

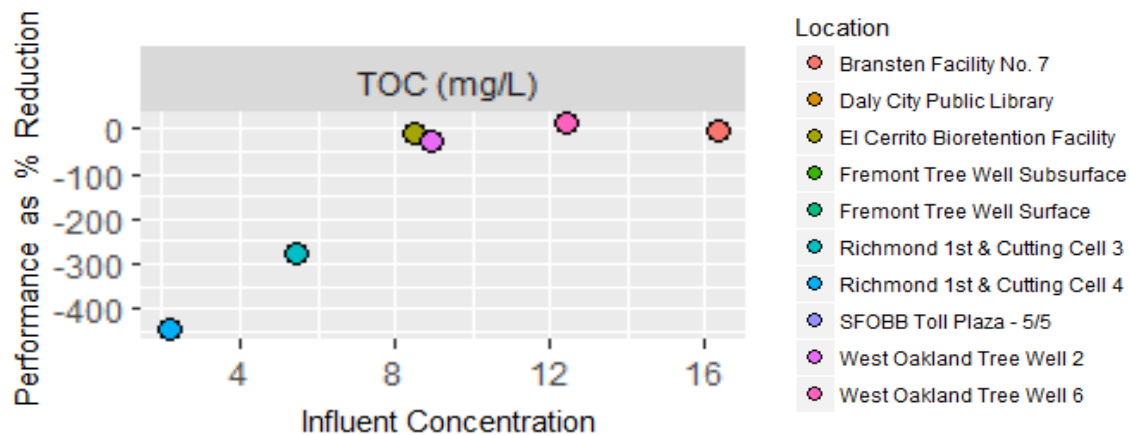


Figure 10. Performance as a function of influent concentrations.

Polychlorinated Biphenyls (PCBs)

Inlet PCB concentrations ranged from very low (mean at Daly City Public Library 0.73 ng/L) to very high (mean of 149 ng/L at Bransten Facility No. 7) (relative to regional stormwater data concentrations (Gilbreath et al., 2018)) (Table 6, Figure 11). PCBs across most of the sites were well-captured (>90% reduction). On a per sample basis, virtually all sample pairs are below the line indicating that influent concentrations were higher than effluent in each storm event (Figure 12); only at Bransten Road Facility No. 7 were effluent samples higher than influent samples. Again, with the exception of Bransten Road, there is a very strong relationship between influent concentration and performance. The cases in which performance was not as strong included those in which the influent concentration was very low to begin with (Daly City Public Library, both Fremont Tree Wells) (Figure 11, Figure 13), inhibiting high performance metrics as indicated by percent reduction (yet still the effluent concentration was low (<2 ng/L) at these sites (Table 6)). Alternatively, performance was inhibited in some cases in which the suspended sediment was not well-captured (also Daly City Public Library and Richmond 1st and Cutting Cell 3 (Table 6)). Bransten Facility No. 7 constitutes an important exception. The inlet concentration is very high at this site (mean 149 ng/L), but the effluent concentration is nearly double. At this location, although an underdrain was installed, only one side of the unit was lined with an impermeable liner. The area is known to have polluted soils, and the authors of the CW4CB project report concluded that water infiltrating into the polluted soils may have commingled with the sampled effluent, thereby elevating the effluent concentrations.

Unlike for SSC and TOC, there does not appear to be any relationship with the time since construction. The performance curve strongly suggests that performance is largely based on influent concentration. Also, the biochar amendment in the Richmond and Cutting Cell 4 may have had an impact on reducing PCB concentrations.

At El Cerrito, the one location with sampling over multiple years (3 years of sampling over 7 wet seasons), the average particle ratio (sum of PCBs divided by the SSC) in the effluent for each sampling year shows a consistent increase from 0.12 to 0.69 to 0.88 ng/mg. This finding is consistent with the media loss hypothesis discussed in the SSC section. In other words, per PCB mass in the effluent, there is more suspended sediment in the effluent during the period right after construction as compared with later monitoring. This is happening because the initial period of media loss does not have PCBs (PCBs are not in the soil media). As the bioretention unit matures, the PCBs in the effluent do not increase but rather the soil media loss decreases, leading to higher particle ratios.

Table 6. Summary statistics for PCBs (ng/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Bransten Facility No. 7	Influent	5	149		115	13.4	70.9	129	252	280
Bransten Facility No. 7	Effluent	5	297	-99%	207	48.3	207	255	374	603
Daly City Public Library	Influent	3	0.733		0.332	0.498	0.543	0.587	0.85	1.11
Daly City Public Library	Effluent	7	0.811	-11%	1.13	0.205	0.297	0.482	0.521	3.35
El Cerrito Bioretention Facility	Influent	11	29.7		65.7	3.02	5.63	7.6	14.1	226
El Cerrito Bioretention Facility	Effluent	11	1.13	96%	0.613	0.35	0.73	1	1.4	2.5
Fremont Tree Well Subsurface	Influent	4	4.88		5.82	0.926	1.28	2.59	6.18	13.4
Fremont Tree Well Subsurface	Effluent	3	1.99	59%	0.656	1.24	1.76	2.27	2.37	2.46
Fremont Tree Well Surface	Influent	4	4.88		5.82	0.926	1.28	2.59	6.18	13.4
Fremont Tree Well Surface	Effluent	4	1.9	61%	1.04	0.359	1.73	2.28	2.45	2.66
Richmond 1st & Cutting Cell 3	Influent	8	13.1		12.7	1.56	7.84	9.78	12.2	42.7
Richmond 1st & Cutting Cell 3	Effluent	8	5.13	61%	5.64	1.43	2.16	2.73	5.35	18.2
Richmond 1st & Cutting Cell 4	Influent	6	15.7		19.7	1.99	3.66	4.9	22.5	50.5
Richmond 1st & Cutting Cell 4	Effluent	6	0.676	96%	0.338	0.429	0.466	0.512	0.774	1.29
SFOBB Toll Plaza - 5/5	Influent	3	29.8		40.5	4.45	6.38	8.32	42.4	76.5
SFOBB Toll Plaza - 5/5	Effluent	3	2.24	92%	1.53	1.14	1.37	1.6	2.79	3.98
West Oakland Tree Well 2	Influent	4	24.3		13.6	6.29	19.8	25.9	30.4	39.1
West Oakland Tree Well 2	Effluent	4	1.92	92%	1.29	0.398	1.15	2	2.77	3.31
West Oakland Tree Well 6	Influent	4	135		109	28.8	83.7	112	163	286
West Oakland Tree Well 6	Effluent	4	7.97	94%	4.37	4.34	4.54	7.01	10.4	13.5

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

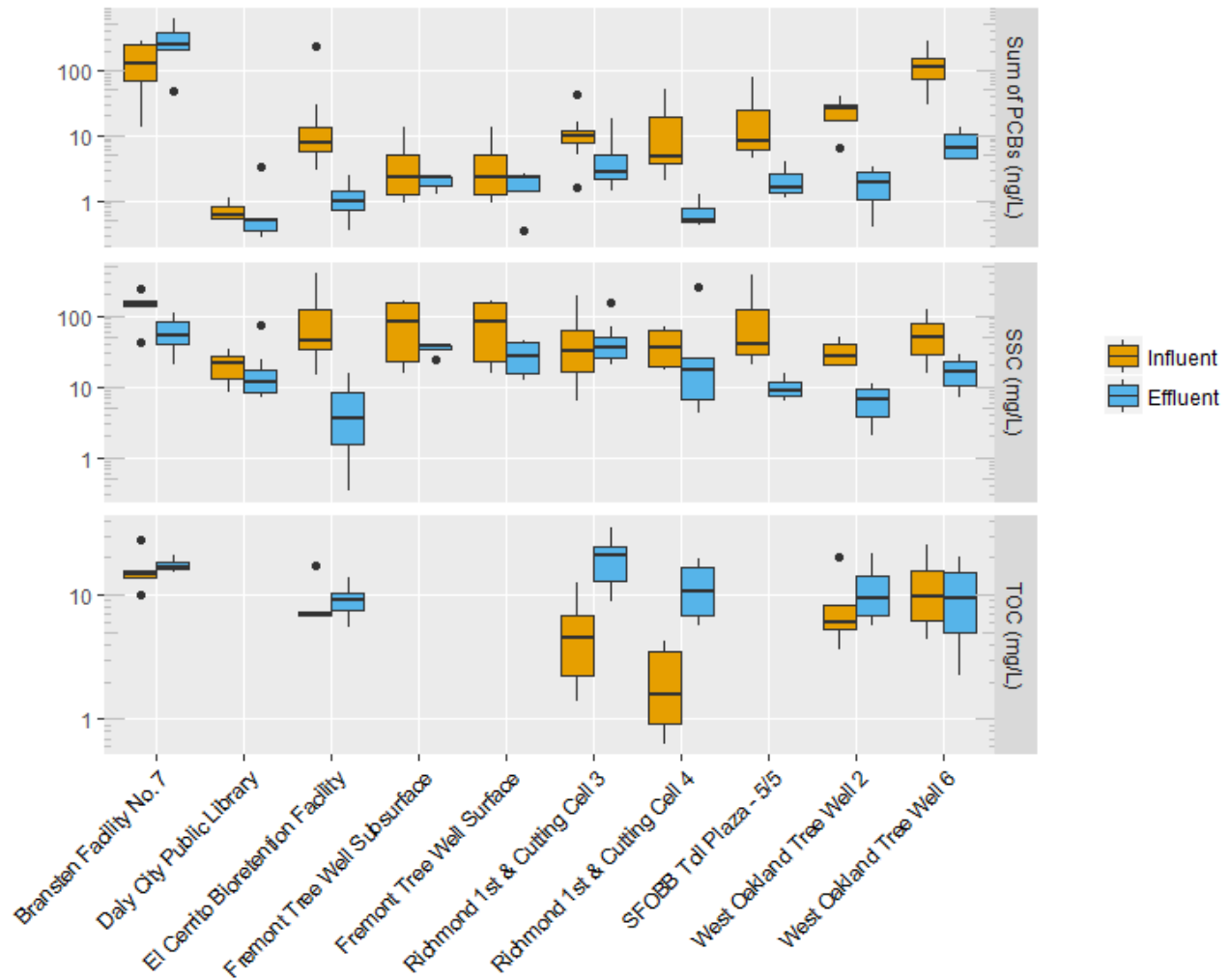


Figure 11. Boxplot of influent and effluent concentrations for PCBs, SSC and TOC.

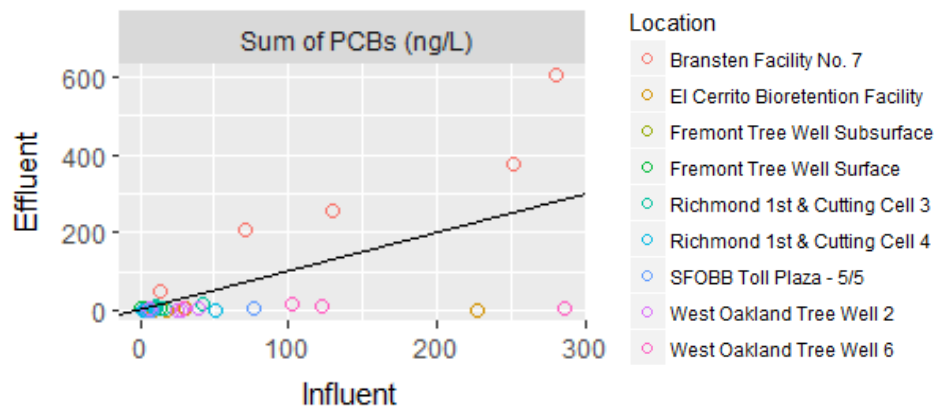


Figure 12. Scatterplot of influent and effluent paired samples. Sample points above the line indicate sample pairs in which the effluent concentration was higher than the influent, and vice versa for sample points below the line.

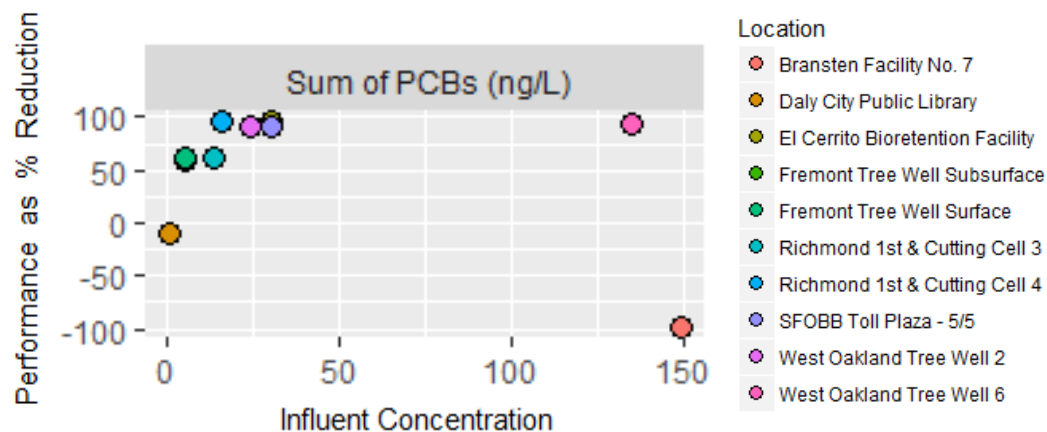


Figure 13. Performance as a function of influent concentrations.

Particle Size Distribution of PCBs

Nine influent and effluent sample pairs were measured for total PCBs and PCBs passing through a 10 μm sieve (the difference of these two numbers equating to the amount of PCBs in particles $>10 \mu\text{m}$). At one additional location, PCBs on particles smaller and larger than 10 μm were also measured in the influent only. At all sites, concentrations of PCBs were greater on particles that were larger than 10 μm (Figure 14). The BMPs captured between 55 percent and 98 percent (average 83 percent) of PCBs associated with particles $> 10 \mu\text{m}$.

These findings provide evidence that PCBs at these sites were strongly associated with larger particles, and that the larger particles were well-captured by the green infrastructure, likely through the process of physical filtration. This finding is consistent with the hypothesis presented by Yee and McKee (2010) that PCBs are associated with larger and heavier particles relative to Hg. That hypothesis was based on a settling experiment in which 30-70% of total PCBs easily settled out of suspension within 20 minutes, whereas only 10-30% of Hg settled out.

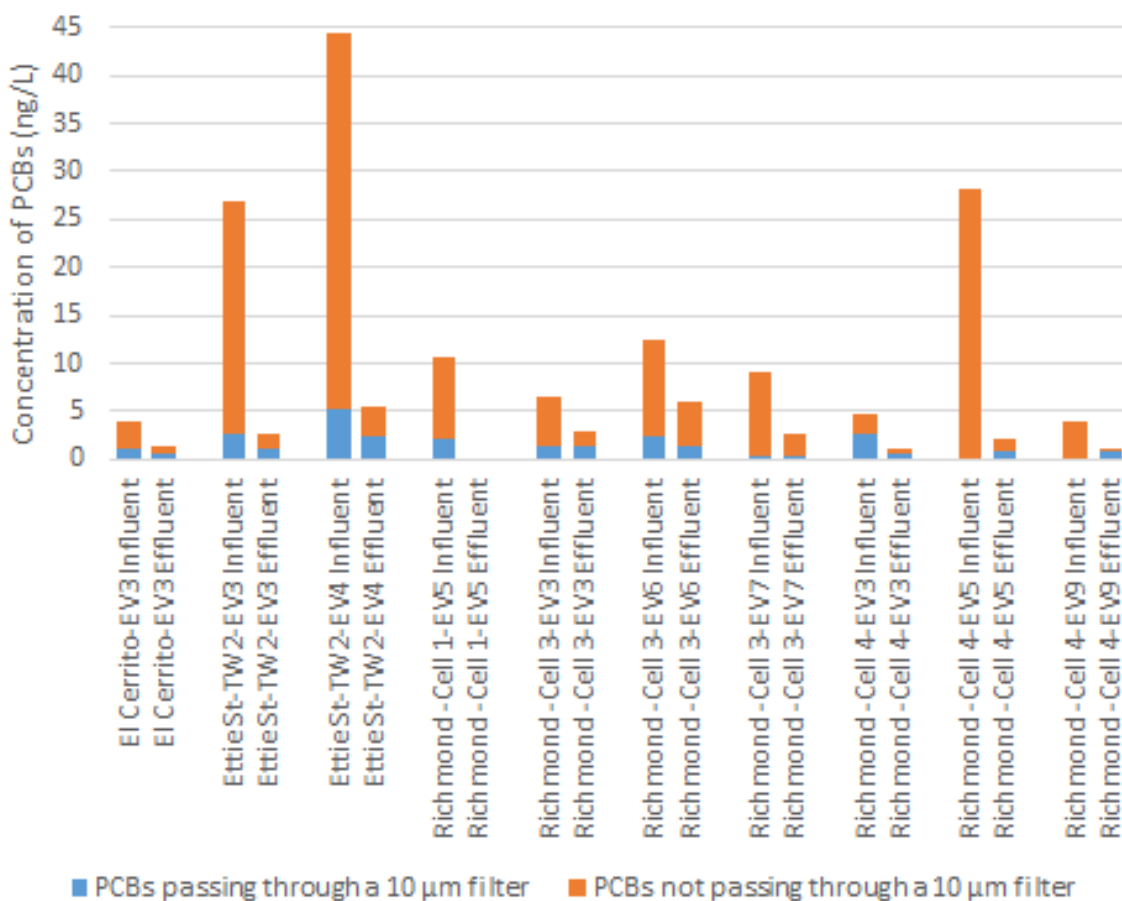


Figure 14: Concentrations of PCBs associated with smaller particles (<10 µm) and larger particles (≥10 µm) before and after treatment.

Mercury Species (HgT, HgD, and MeHg)

Total Hg was measured at 10 locations. Median influent concentrations at the ten locations ranged from 6.36 to 53.7 ng/L. Relative to 56 stormwater samples collected in urban Bay Area tributaries between WY 2015 and 2017, these concentrations range virtually the entire lower 3 quartiles (min = 5.6, median = 29.2, 75% = 49.1) (Gilbreath et al., 2018). Median effluent concentrations at the 10 GI locations ranged from 8.1 to 42.5 ng/L (Table 7, Figure 15). At six of the 10 locations, effluent concentrations of HgT increased relative to the influent. On a sample pair basis, about half of the storm samples had effluent less than the influent and about half were greater (Figure 16). The largest increases in HgT were measured at the Fremont Tree Wells and the Bransten Facility No. 7 where influent concentrations were particularly low; in contrast, the greatest reductions in HgT export were achieved at the Oakland Tree Wells where influent concentrations were higher.

The common pattern of performance increase given increasing influent concentrations is present for HgT, but not as strong as for PCBs or TOC (Figure 17). It may be the case that similar to SSC, there are two performance curves – one for recently installed sites (lower 6 points) versus another for more mature sites and those with the Filterra media (top 4 points).

Table 7. Summary statistics for total mercury (HgT) (ng/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Bransten Facility No. 7	Influent	5	6.53		5.33	0.22	4.26	6.36	7	14.8
Bransten Facility No. 7	Effluent	5	9.6	-47%	4.98	0.82	11	11	12.5	12.7
Daly City Public Library	Influent	3	21.9		21.2	5.16	10	14.8	30.3	45.8
Daly City Public Library	Effluent	7	20.2	8%	7.82	7.94	15	22.1	25.9	29.4
El Cerrito Bioretention Facility	Influent	11	21.3		21.6	8.57	10.1	14	22.1	83
El Cerrito Bioretention Facility	Effluent	11	11.9	44%	8.82	5.61	7.12	9.39	13.3	36.9
Fremont Tree Well Subsurface	Influent	5	11.2		6.29	4.45	7.93	8.12	16.3	19.4
Fremont Tree Well Subsurface	Effluent	4	15.1	-35%	1.54	14.2	14.3	14.4	15.2	17.4
Fremont Tree Well Surface	Influent	5	11.2		6.29	4.45	7.93	8.12	16.3	19.4
Fremont Tree Well Surface	Effluent	5	16.6	-48%	2.84	12.8	15.4	16.2	18.9	19.9
Richmond 1st & Cutting Cell 3	Influent	8	44.3		35.5	6.31	20	31.5	62.3	102
Richmond 1st & Cutting Cell 3	Effluent	8	49.1	-11%	18.3	28.8	38.6	42.5	60.7	82
Richmond 1st & Cutting Cell 4	Influent	6	27		24.5	6.3	8.56	17	42.3	65
Richmond 1st & Cutting Cell 4	Effluent	6	28.2	-4%	12.5	12.9	20	26.9	36	46
SFOBB Toll Plaza - 5/5	Influent	3	89.2		110	21.8	25.9	30	123	216
SFOBB Toll Plaza - 5/5	Effluent	3	55.6	38%	49.4	25.4	27.1	28.8	70.7	113
West Oakland Tree Well 2	Influent	4	24.6		5.12	17.2	23.6	26.1	27.1	29
West Oakland Tree Well 2	Effluent	4	9.55	61%	5.17	5.01	7.25	8.1	10.4	17
West Oakland Tree Well 6	Influent	4	78.2		67	30.5	34.7	53.7	97.2	175
West Oakland Tree Well 6	Effluent	4	25.9	67%	15.8	5.85	17.1	29	37.7	39.9

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

Dissolved Hg was only measured at five locations. Median influent concentrations at the five locations ranged from 2.35 - 8.00 ng/L, while median effluent concentrations ranged from 6.13 to 10.0 ng/L. Median effluent concentrations increased at all five locations relative to influent. The greatest increases were at the Fremont Tree Well Filters. In part, the extreme increase (>250%) may be because the influent was low to begin with. In the influent samples at all sites (with the exception of Bransten Facility No. 7 which had only one HgD sample), HgD comprised between 29 - 42% of the HgT, but the outlet comprised 36 - 91% in the dissolved phase. Similar to DOC, HgD poorly filters out of the system. Additionally, the data suggests HgD has net export from the system. In all cases, HgD increased at the outlet, except at El Cerrito where no significant change was measured. HgD export can increase as the result of dissolution if Hg attached to organic carbon dissolves. The source of this HgD could be that Hg in the media itself dissolves or from particulate Hg stored in the system from previous events. Unfortunately, there is too little HgD data and corresponding TOC or DOC data to develop hypotheses. Only a few sites measured/reported DOC and so we do not explore that analyte in this synthesis, but the data can be found in Appendix B.

Table 8. Summary statistics for dissolved mercury (HgD) (ng/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Bransten Facility No. 7	Influent	1	8		NA	8	8	8	8	8
Bransten Facility No. 7	Effluent	1	10	-25%	NA	10	10	10	10	10
Daly City Public Library	Influent	3	13.8		16.7	3.07	4.2	5.34	19.2	33
Daly City Public Library	Effluent	7	9.18	33%	4.56	3.11	7	7.99	10.8	17.5
El Cerrito Bioretention Facility	Influent	7	5.99		1.99	3.07	4.79	5.87	7.44	8.54
El Cerrito Bioretention Facility	Effluent	8	7.47	-25%	3.93	4.83	5.11	6.13	7.85	16.7
Fremont Tree Well Subsurface	Influent	5	2.51		0.976	1.41	2.06	2.35	2.68	4.04
Fremont Tree Well Subsurface	Effluent	4	6.56	-161%	0.785	5.79	5.95	6.52	7.13	7.41
Fremont Tree Well Surface	Influent	5	2.51		0.976	1.41	2.06	2.35	2.68	4.04
Fremont Tree Well Surface	Effluent	5	9.64	-284%	3.9	4.78	8.72	8.98	10.1	15.6

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

Total MeHg was measured in five units. Mean inlet concentrations ranged from 0.177 ng/L (in the Fremont tree well filters) and 0.63 ng/L at the Daly City Library. These concentrations are similar to the range of MeHgT concentrations measured in stormwater throughout the Bay Area (except watersheds in which HgT is also elevated such as the Guadalupe River) (McKee et al. 2012; McKee et al., 2015). Concentrations decreased at the outlet for most units between 23 and 69%, however, concentrations at the outlet increased at the Daly City Public Library where an underdrain was unintentionally left out of the construction. An underdrain was installed in all other units where MeHgT was measured.

Typically, low inlet concentrations make it difficult to achieve a large percentage reduction. However, the lowest inlet concentrations were measured at Fremont Tree Well Subsurface as well as the greatest percent reduction (Figure 17). One hypothesis for this occurrence is that because the surface of the unit is covered in rocks, perhaps there was a less pronounced wetting and drying cycles and therefore fewer occurrences of conditions favorable for methylation. Regardless, it is interesting that the performance curve shows decreasing performance relative to increasing inlet concentrations. This is opposite of all the other analytes. The Daly City point in the lower right hand corner is likely caused by the lack of an underdrain, and without this point, it may be that there is not an evident performance curve. More data is necessary for MeHg to better understand performance relative to influent, and what may be the cause of deviation from other analytes.

Table 9. Summary statistics for total methylmercury (MeHg) (ng/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Daly City Public Library	Influent	3	0.63		0.38	0.264	0.434	0.604	0.813	1.02
Daly City Public Library	Effluent	7	1.45	-130%	1.05	0.485	0.711	0.872	2.01	3.35
El Cerrito Bioretention Facility	Influent	8	0.255		0.0525	0.193	0.205	0.252	0.301	0.323
El Cerrito Bioretention Facility	Effluent	8	0.132	48%	0.0329	0.075	0.114	0.137	0.154	0.178
Fremont Tree Well Subsurface	Influent	4	0.177		0.0726	0.1	0.125	0.179	0.231	0.252
Fremont Tree Well Subsurface	Effluent	2	0.0549	69%	0.00124	0.054	0.0544	0.0549	0.0553	0.0558
Fremont Tree Well Surface	Influent	4	0.177		0.0726	0.1	0.125	0.179	0.231	0.252
Fremont Tree Well Surface	Effluent	4	0.102	42%	0.0417	0.0603	0.0743	0.0973	0.125	0.155
SFOBB Toll Plaza - 5/5	Influent	3	0.356		0.212	0.212	0.234	0.256	0.428	0.6
SFOBB Toll Plaza - 5/5	Effluent	3	0.275	23%	0.0913	0.188	0.227	0.266	0.318	0.37

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

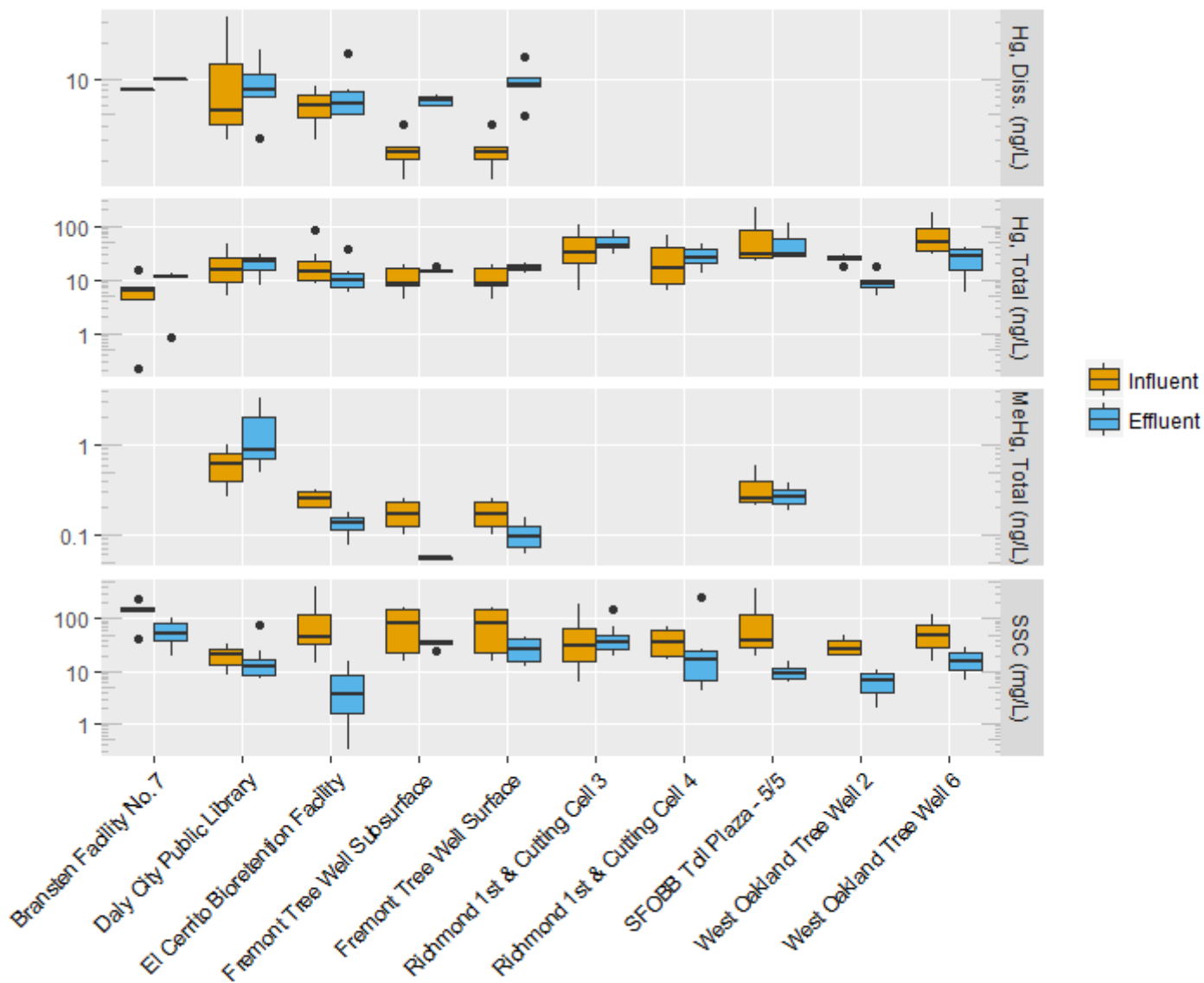


Figure 15. Boxplot of influent and effluent concentrations for Hg species and SSC.

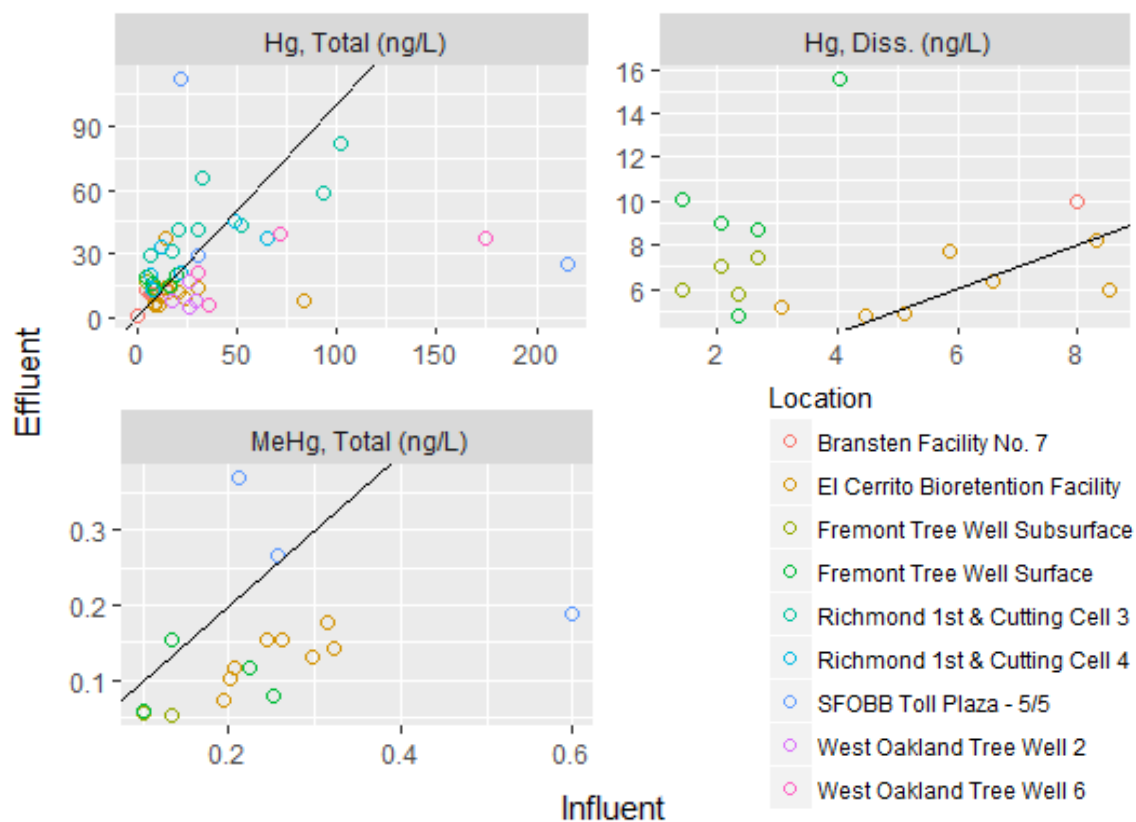


Figure 16. Scatterplot of influent and effluent paired samples. Sample points above the line indicate sample pairs in which the effluent concentration was higher than the influent, and vice versa for sample points below the line.

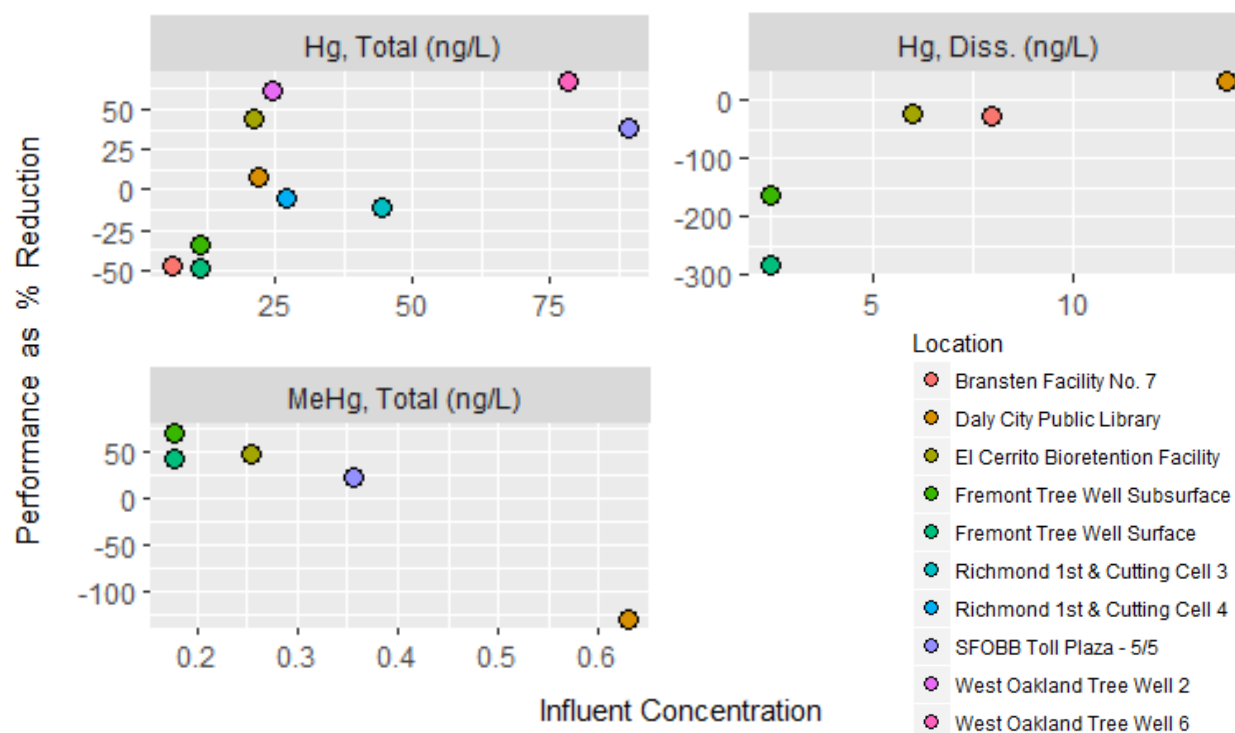


Figure 17. Performance as a function of influent concentrations.

Particle Size Distribution of HgT

Nine influent and effluent sample pairs were measured for HgT and Hg passing through a 10 μm sieve (the difference of these two numbers equating to the amount of HgT in particles $>10 \mu\text{m}$). At one additional location, HgT smaller and larger than 10 μm were also measured in just the influent. In contrast to PCBs, both the influent and effluent at most sites and storms were dominated by those particles that were *smaller* than 10 μm .

As written in the CW4CB report,

The mercury removed by the 10 μm filter was variable, ranging from none removed to an 89% reduction. The concentrations of mercury associated with larger particles did not consistently decrease from influent to effluent. At El Cerrito and the Ettie St. Tree Well Filter No. 2, the smallest size fraction remaining relatively constant between inlet and outlet but the larger particles were almost entirely captured. At Richmond 1st and Cutting Cells 3 and 4, particles $<10 \mu\text{m}$ were the primary size fraction to increase and cause increases at the outlet (though in 1/3rd of the cases, PCBs on particles $>10 \mu\text{m}$ also increased from inlet to outlet).

These findings provide evidence that HgT at these sites was strongly associated with smaller particles, and at most sites the larger particles were somewhat captured by the green infrastructure, though inconsistently across sites. This finding is consistent with the hypothesis presented by Yee and McKee

(2010) that Hg is associated with smaller particles than PCBs. That hypothesis was based on a settling experiment in which 30-70% of total PCBs easily settled out of suspension within 20 minutes, whereas only 10-30% of Hg settled out.

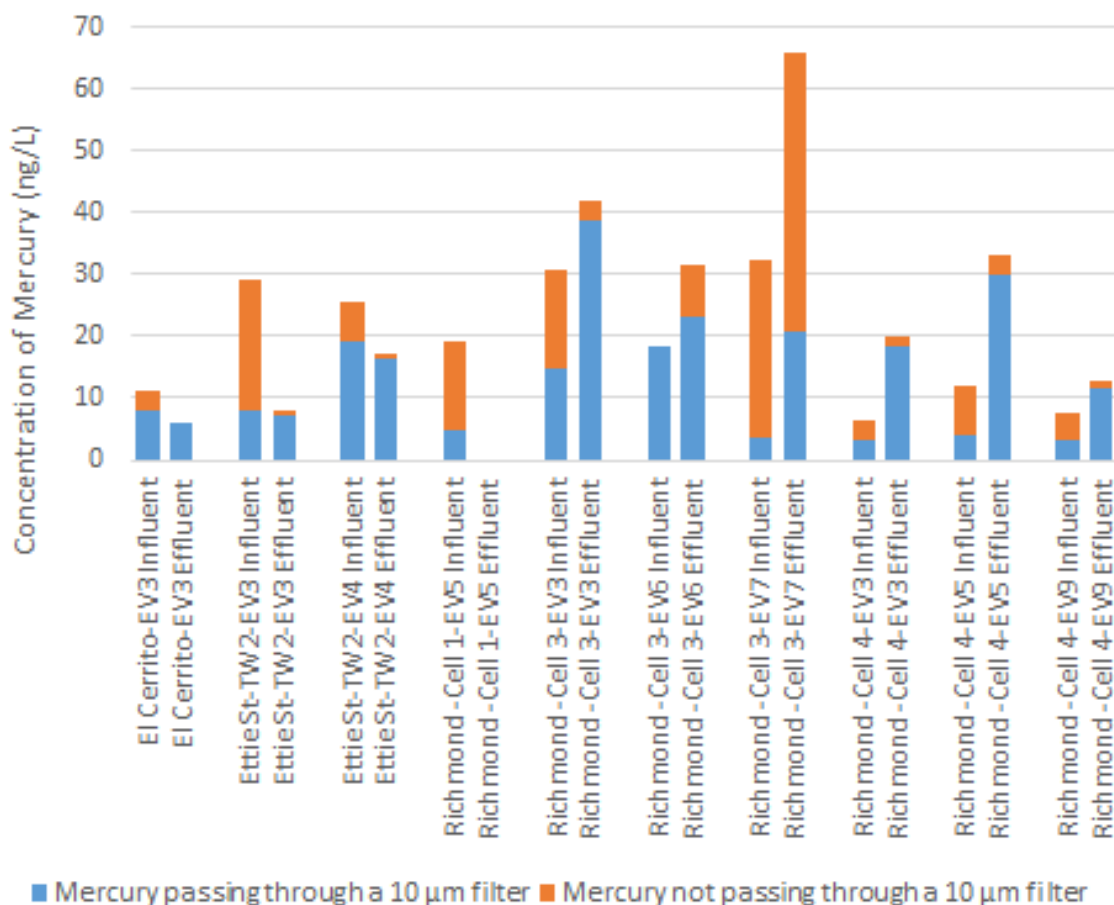


Figure 18: Concentrations of mercury on particles <10 µm and larger than ≥10 µm, both in the influent and effluent where measured.

Performance of Hg capture in bioretention is less clear than for some other analytes such as PCBs. The capture performance appears related to the influent concentrations, with the higher influent concentrations showing better performance and, as with SSC, it might be that soil media and years since construction also play a role, though more data is necessary to verify this. Overall, capture performance is not as strong as for other analytes; the best capture percentage is just 67%, which might be due to a larger percentage of the mass on finer particles or in the dissolved phase.

Total and Dissolved Copper (CuT and CuD)

Total Cu was measured at five locations. Median influent concentrations at the five locations ranged from 16.4 to 37.3 µg/L. These concentrations are similar to those sampled in other urban watersheds

around the Bay (means of six well-sampled watersheds ranged from 13.7 to 129 µg/L; Gilbreath et al., 2015; note: median in most cases is lower than the mean). Median effluent concentrations ranged from 7.03 to 27 µg/L. At four of the five locations, effluent concentrations of CuT were reduced. At SFOBB Toll Plaza 5/5, effluent concentrations increased. The increase in CuT at that site can largely be explained by an increase in CuD.

Dissolved Cu was measured at four locations (all of the same sites as CuT except Daly City Library). Median influent concentrations at the four locations ranged from 6 - 11.9 µg/L. These concentrations are also similar to those measured elsewhere in the Bay Area (means of six well-sampled watersheds ranged from 2.74 to 22.5 µg/L; Gilbreath et al., 2015; note: median in most cases would be lower than the mean). Median effluent concentrations ranged from 8.95 to 17 µg/L. Median effluent concentrations slightly decreased at all locations except the SFOBB Toll Plaza 5/5 location. The authors of that study hypothesized that during saline conditions present at the site, “competition for organic matter binding sites by other divalent cations present in salt, such as calcium and magnesium” prevented CuD from being captured. While this hypothesis may be true, it does not explain why CuD *increased* three-fold at the outlet.

With the exception of SFOBB 5/5, performance increase with increasing influent concentrations again held true for CuT and CuD. However, there are only a few samples for the curve.

Table 10. Summary statistics for total copper (CuT) (µg/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Daly City Public Library	Influent	3	46		38.9	12.2	24.7	37.3	62.9	88.6
Daly City Public Library	Effluent	7	9.9	78%	5.92	3.46	6.66	8.52	11.4	21.2
El Cerrito Bioretention Facility	Influent	8	25.3		12.5	14.5	17	20.3	28.4	48.2
El Cerrito Bioretention Facility	Effluent	8	8.12	68%	2.27	5.46	6.85	7.03	9.74	11.7
Fremont Tree Well Subsurface	Influent	4	19.8		16.3	5.9	7.36	16.4	28.9	40.6
Fremont Tree Well Subsurface	Effluent	3	11	44%	1.58	9.81	10.1	10.4	11.6	12.8
Fremont Tree Well Surface	Influent	4	19.8		16.3	5.9	7.36	16.4	28.9	40.6
Fremont Tree Well Surface	Effluent	4	12.2	38%	3.04	8.17	11.2	12.6	13.6	15.5
SFOBB Toll Plaza - 5/5	Influent	9	25.1		15.2	10	15	19	29	58
SFOBB Toll Plaza - 5/5	Effluent	9	39.9	-59%	31.6	13	18	27	56	91

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

Table 11. Summary statistics for dissolved copper (CuD) (µg/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
El Cerrito Bioretention Facility	Influent	3	15.8		12.6	7.51	8.54	9.57	19.9	30.2
El Cerrito Bioretention Facility	Effluent	4	8.6	46%	2.11	5.72	8.06	8.95	9.49	10.8
Fremont Tree Well Subsurface	Influent	5	10.5		6.84	2.29	5.15	11.9	14	19.3
Fremont Tree Well Subsurface	Effluent	4	9.38	11%	2	7.49	7.76	9.3	10.9	11.4
Fremont Tree Well Surface	Influent	5	10.5		6.84	2.29	5.15	11.9	14	19.3
Fremont Tree Well Surface	Effluent	5	10.5	0%	2.51	7.01	9.65	10.5	11.8	13.8
SFOBB Toll Plaza - 5/5	Influent	9	7.7		5.99	2.5	4.6	6	6.6	21
SFOBB Toll Plaza - 5/5	Effluent	9	30.9	-301%	27.6	7.6	14	17	45	84

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

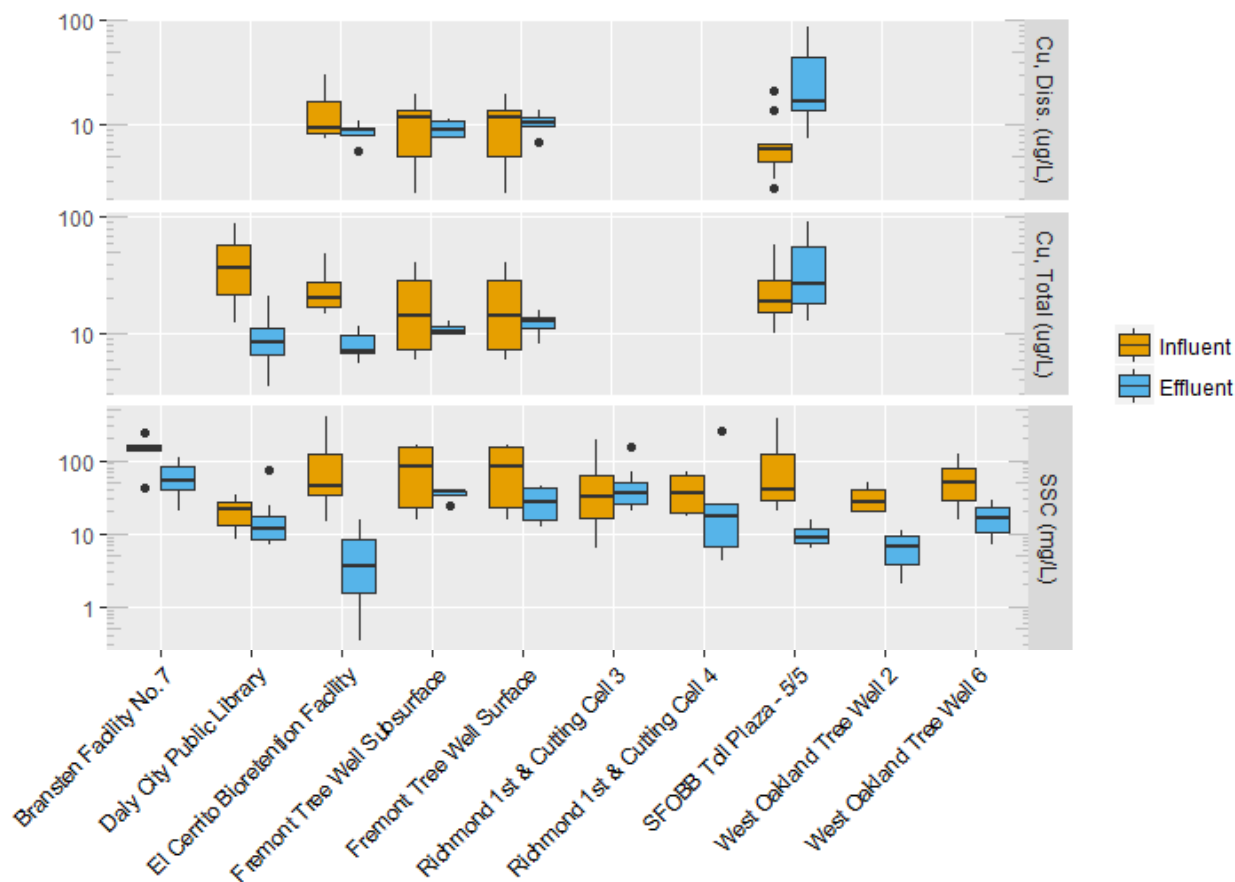


Figure 19. Boxplot of influent and effluent concentrations for copper and SSC.

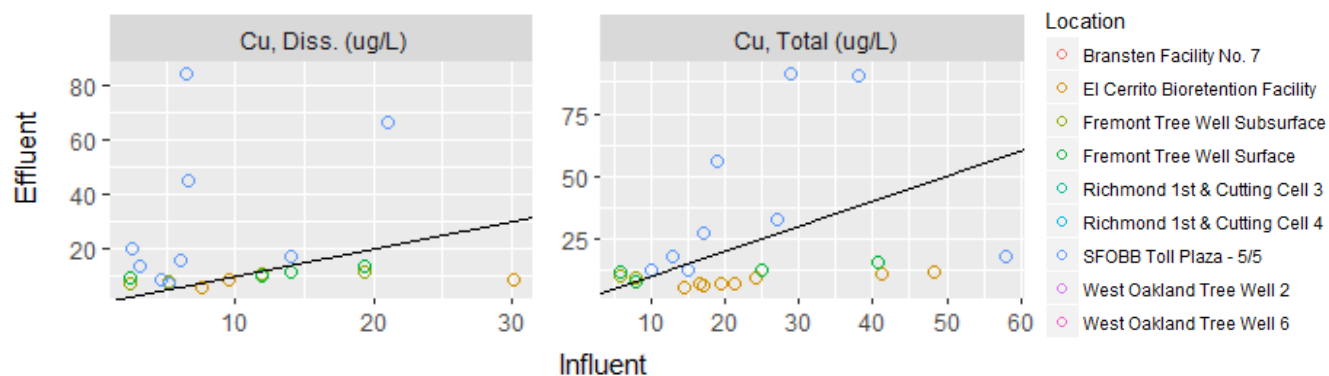


Figure 20. Scatterplot of influent and effluent paired samples. Sample points above the line indicate sample pairs in which the effluent concentration was higher than the influent, and vice versa for sample points below the line.

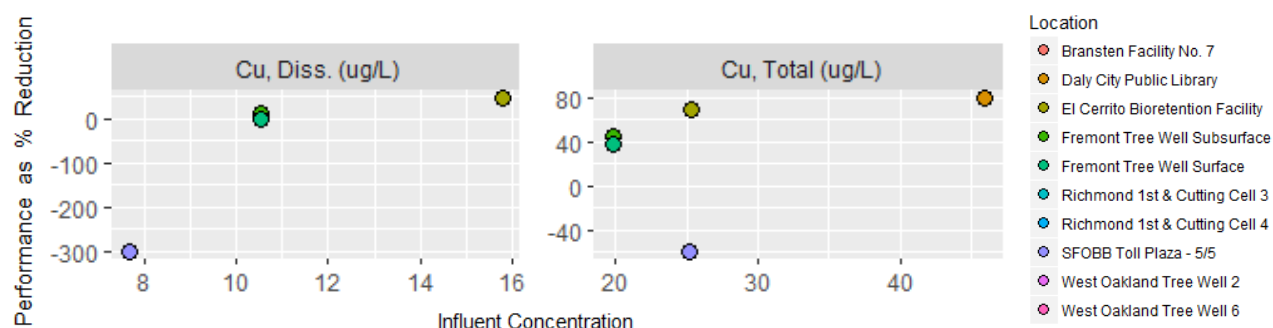


Figure 21. Performance as a function of influent concentrations.

At most sites, average total and dissolved copper decreased, with one major exception being the SFOBB 5/5 unit. Although it is not clear why concentrations at this site increased, the majority of the increase in copper was in the dissolved form. The outlet concentrations were higher than the influent at SFOBB 5/5 for almost all sample pairs. With the exception of SFOBB, the other sites follow a typical performance curve pattern in that the higher the influent, the greater the percentage reduction.

Lead (Pb)

Inlet Pb concentrations ranged from 3.55 (at Daly City Public Library) to 88.3 $\mu\text{g/L}$ (at West Oakland Tree Well No. 6) (Table 12, Figure 22). These concentrations are similar to those measured in other Bay Area urban watersheds (e.g. Zone 4 Line A: flow-weighted mean concentration 10 $\mu\text{g/L}$, range 0.18-40 $\mu\text{g/L}$; Guadalupe River: flow-weighted mean concentration 9.6 $\mu\text{g/L}$, range 0.2-81 $\mu\text{g/L}$) except that the West Oakland Tree Wells had median concentrations on the higher end (suggesting a local source). Lead decreased at every site between 31 and 88%. On a per sample basis, virtually all sample pairs are below the line indicating that influent concentrations were higher than effluent in each storm event (Figure 23); with the exception of a few samples at each SFOBB, Richmond 1st and Cutting Cells 3 and 4.

Lead somewhat follows the pattern of increasing performance with increasing influent concentrations though it is not as strong as for some other analytes (Figure 24). There may be a pattern of performance similar to that for SSC. The West Oakland Tree Wells, El Cerrito and SFOBB all have performance between 78-88%, while Bransten, Daly City and the two Richmond 1st and Cutting cells have lower performance between 31-55%. It could be that the two West Oakland Tree Wells have their own performance curve related to the proprietary media used, separate from the El Cerrito and SFOBB 5/5 which are the two locations with more years of maturation, and separate from the locations with only 1-2 years since construction (Bransten, Daly City and the Richmond 1st and Cutting cells). This is difficult to tease out, however, because these groupings also follow the same pattern of performance based on influent concentrations (the higher the influent concentration, the better the performance). More Pb data in bioretention may be able to better support or negate these hypotheses.

Table 12. Summary statistics for total lead (Pb) (µg/L) at each site.

Site	Influent/ Effluent	Event Count	Mean	% Reduction ^A	Std.Dev.	Minimum	25th Percentile	Median	75th Percentile	Maximum
Bransten Facility No. 7	Influent	5	10		5.46	2.86	7.39	9.75	12.6	17.4
Bransten Facility No. 7	Effluent	5	4.46	55%	2.15	1.89	3.31	4.33	5.14	7.63
Daly City Public Library	Influent	3	3.55		3.93	0.855	1.29	1.73	4.89	8.06
Daly City Public Library	Effluent	7	2.45	31%	2.07	0.966	1.12	1.42	2.91	6.7
El Cerrito Bioretention Facility	Influent	3	6.63		2.55	4.06	5.36	6.66	7.91	9.16
El Cerrito Bioretention Facility	Effluent	3	0.983	85%	0.189	0.804	0.884	0.964	1.07	1.18
Richmond 1st & Cutting Cell 3	Influent	8	9.85		7.62	2.24	5.23	7.46	11.9	25.9
Richmond 1st & Cutting Cell 3	Effluent	8	6.24	37%	3.24	2.3	3.17	6.36	8.54	11.1
Richmond 1st & Cutting Cell 4	Influent	6	8.42		8.25	1.57	3.4	5.72	9.59	24
Richmond 1st & Cutting Cell 4	Effluent	6	4.81	43%	4.63	1.63	2.18	3.55	4.17	14
SFOBB Toll Plaza - 5/5	Influent	9	14.9		15.7	3.2	4.6	9.2	19	53
SFOBB Toll Plaza - 5/5	Effluent	9	3.01	80%	1.76	0.9	2	2.5	4.1	5.9
West Oakland Tree Well 2	Influent	4	30		10.8	15.1	27.8	32.1	34.3	40.9
West Oakland Tree Well 2	Effluent	4	3.73	88%	1.34	2.27	2.77	3.83	4.79	5.01
West Oakland Tree Well 6	Influent	4	88.3		73	21.1	31.6	78.6	135	175
West Oakland Tree Well 6	Effluent	4	19	78%	8.55	10.4	14.4	17.5	22.1	30.6

A. Percent reduction is calculated as $1 - (\text{Effluent}/\text{Influent})$.

B. Sampling entailed grab sample collection and are reported on a grab sample basis in the original Daly City report (David et al., 2015). To provide the best comparison to other studies reported in this synthesis, we first created pseudo-composites by averaging the samples collected within the same storm. Consequently, results reported herein differ from those in the original report.

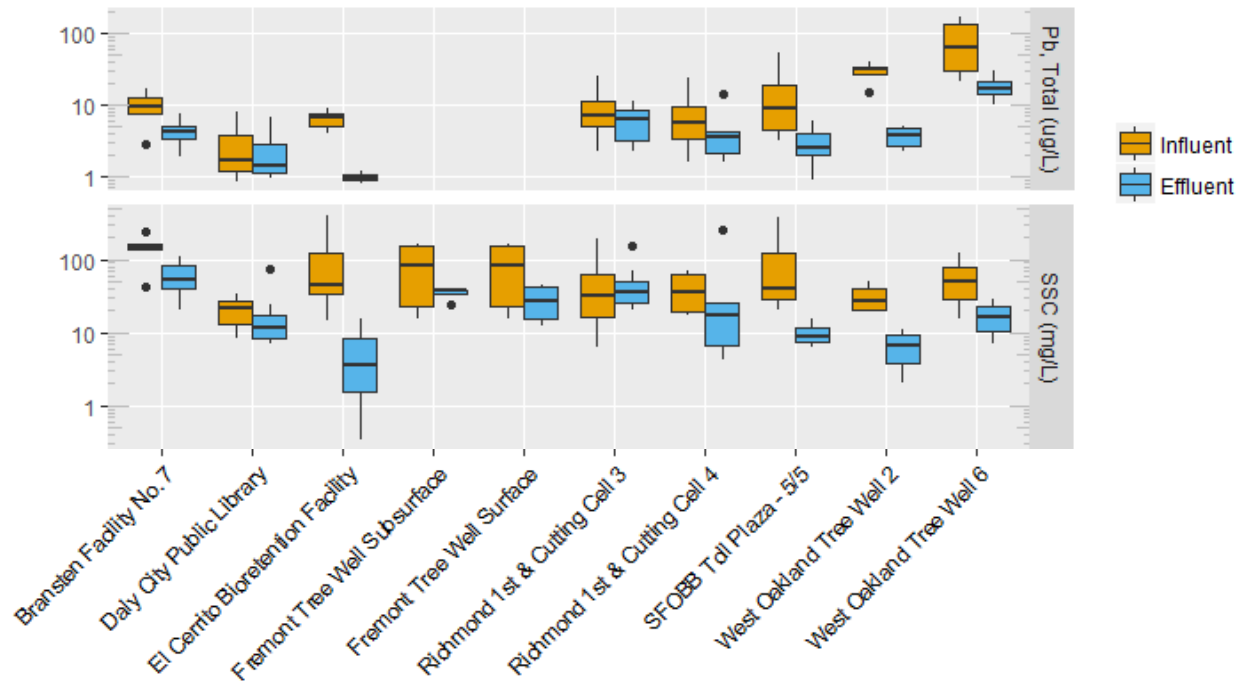


Figure 22. Boxplot of influent and effluent concentrations for Pb.

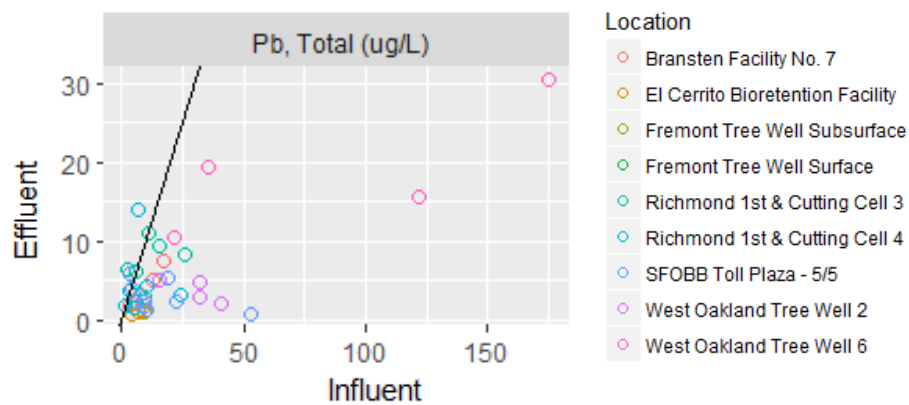


Figure 23. Scatterplot of influent and effluent paired samples. Sample points above the line indicate sample pairs in which the effluent concentration was higher than the influent, and vice versa for sample points below the line.

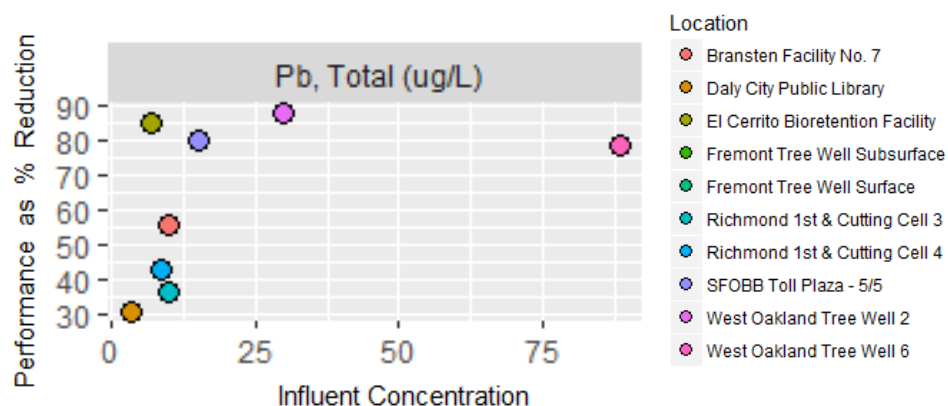


Figure 24. Performance as a function of influent concentrations.

In general, bioretention captures lead moderately well, and the capture performance appears related to the influent concentrations, with the higher influent concentrations showing better performance. It may be the case that soil media and years since construction also play a role, though more data is necessary to verify this. Overall, capture performance for Pb fits nicely into the conceptual model that bioretention is strong at capturing particle bound pollutants, and that performance can range up to 80-90%.

Water Quality Summary

The percentage concentration reduction is summarized for all sites and all analytes in Table 13 below. Several analytes in the synthesis appeared to have performance impacted by the age of the bioretention unit or the media composition (namely the West Oakland Tree Wells had Filterra engineered media). Therefore, Table 13 is organized with the two older sites at the top (El Cerrito and SFOBB), followed by the West Oakland Tree Wells and then the rest of the sites which were all monitored within 1-2 years of construction. The greater the positive reduction, the darker green the highlighting, and the more negative reduction (or greater increase at the outlet) the darker red the highlighting. Taken together, most sites had positive reductions in the effluent for SSC, PCBs and Pb. HgT, MeHg, CuD and CuT all had mixed results with some positive and some negative reductions. For the most part, TOC and HgD had net export.

Table 13. Summary of percentage reduction across all sites and all analytes. A positive reduction means the mean influent was greater than the mean effluent, and vice versa.

Site	SSC (mg/L)	PCBs (ng/L)	TOC (mg/L)	HgD (ng/L)	HgT (ng/L)	MeHg (ng/L)	CuD (ug/L)	CuT (ug/L)	Pb (ug/L)
El Cerrito Bioretention Facility	95%	96%	-8%	-25%	44%	48%	45%	68%	85%
SFOBB Toll Plaza - 5/5	93%	92%			38%	23%	-301%	-59%	80%
West Oakland Tree Well 2	79%	92%	-30%		61%				88%
West Oakland Tree Well 6	72%	94%	14%		67%				78%
Bransten Facility No. 7	59%	-100%	-6%	-25%	-47%				55%
Daly City Public Library	1%	-11%		33%	8%	-130%		78%	31%
Fremont Tree Well Subsurface	61%	59%		-161%	-34%	69%	11%	44%	
Fremont Tree Well Surface	68%	61%		-284%	-48%	42%	0%	38%	
Richmond 1st & Cutting Cell 3	7%	61%	-276%		-11%				37%
Richmond 1st & Cutting Cell 4	-30%	96%	-449%		-5%				43%

The best performing sites for SSC were those with more years since construction (El Cerrito and SFOBB 5/5), and secondarily using the Filterra engineered media as opposed to the standard bioretention mix. Net export of SSC and TOC suggests that the bioretention media itself can be a source, which appears to be the case especially for sites monitored in the wet season immediately following installation. This is likely because those sites are still settling and compacting and likely that export will lessen with site maturity. SSC and TOC export from the media did not necessarily influence effluent pollutant concentrations. Most sites had positive reductions for PCBs, CuT and Pb. Like SSC, the more mature sites and the sites with Filterra media were also the best performing for other heavy, particle bound pollutants (PCBs and Pb).

The performance based on percentage capture, however, does not tell the whole story of performance. The performance curves for most pollutants are in line with previous findings elsewhere that the higher the influent, typically the greater the performance when measured as a percent reduction. The performance curve for SSC is not strong, but possible explanations are previously discussed. The performance curve for HgT is also not strong. Total Hg requires further study to determine why some sites perform better than others, and what are the primary causes of net export.

In general, effluent concentrations were less variable than influent in most cases. Exceptions included those special cases of net export, e.g. SSC for Richmond 1st and Cutting Cell 4, MeHg for Daly City Public Library, and CuD and CuT for SFOBB 5/5.

The Richmond 1st and Cutting sites and the Bransten Rd. Facility No. 7 shared some of the worst performance reductions, despite having the largest GI:DMA. With this dataset, there appears to be no correlation between GI:DMA ratios and performance of treated effluent. However, it is important to note that this synthesis does not consider loads. At sites where bypass occurs, which is more likely at sites that are undersized, the net load export may be higher even if the volume actually treated has lower effluent concentrations.

Soil profile sampling results

At the El Cerrito Bioretention Facility, the soil profile was measured for some contaminants. Two composite soil core samples were collected in late spring 2017, at which time the cell had received stormwater runoff from seven wet seasons since installation. The composite sampling design aimed to represent two areas of the cell. The first composite consisted of homogenized samples from four cores collected in front of the two street inlets to the bioretention cell, thus representing the component of the cell that is “near-field”. A second composite consisted of homogenized samples from six “far-field” cores spaced throughout the remainder of the bioretention cell (hereafter referred to as the “body” of the bioretention cell). Cores were collected using a stainless-steel hand shovel which was cleaned prior to and between sample collection using an anionic free-rinsing detergent and deionized water rinse. The core composites were comprised of homogenized sub-samples collected at four depths: 0-50 mm, 50-100 mm, 100-150 mm, and 150-300 mm, all of which were located within the engineered bioretention soil mix. The soil segments at each depth were composited into a cleaned glass receptacle, mixed with a hand trowel for three minutes, subsampled into sterile glass jars and shipped frozen to the analytical laboratories.

The soil core results showed good (Hg and MeHg) to excellent (PCBs) performance for reducing concentrations of regulated pollutants in the San Francisco Bay. A small number of other field studies have reported that the pollutant capture is dominant in the top layers of the soil profile and decrease rapidly with increasing depth. For example, Komlos and Traver (2012) found that orthophosphate concentrations were highest on the surface layer, decreased with depth from 0-100 mm, and then were relatively constant from 100-300 mm deep. Dechesne et al. (2005) found that in four infiltration basins (ranging between 10 and 21 years old) heavy metal accumulation was greatest at the surface and decreased rapidly in the first 300-400 mm. Li and Davis (2008) collected cores down to a depth of 900 mm and analyzed for Cu, Pb and Zn 3.5 and 4.5 years after construction of a bioretention unit, and also found high surface accumulations in the top 200 mm. The soil profile results from this study show a similar pattern for PCBs, Hg and MeHg. Concentrations for each of the pollutants decreased with soil depth, with a few exceptions (Figures 25-27).

Horizontally within the unit, each of the pollutants measured are found in greater concentrations nearest the inlets (except at the 50-100 mm depth for PCBs, where the concentrations are equivalent). In particular, PCBs accumulated heavily in the top 50 mm layer near the inlets with concentrations more than 10 times greater than in the top layer of the rest of the unit (the body), as well as the deeper media layers. Mercury and MeHg had slightly higher concentrations near the inlets, but the difference was less pronounced. This suggests that Hg and MeHg are not settling out as quickly once entering the bioretention unit, and are therefore distributing more evenly across the surface.

Using the composite concentration data from this study and the soil mass in the unit, total pollutant mass in each depth interval of the soil profile was estimated (Figure 28). A greater proportion of the overall Hg and MeHg mass is present in the lower soil depths than the PCB mass. Consistent with the PCB and Hg fractionation data collected by Geosyntec Consultants (described previously in the Mercury

species section), these findings are all consistent with the conceptual model that PCBs in stormwater influent are attached to larger particles in greater proportions than are the Hg species, and therefore deposit more immediately in front of the inlets and are more likely to be filtered on the surface with less downward mobility than Hg and MeHg. The findings also suggest that filtration at the surface is likely one of the most important pollutant capture mechanisms for PCBs. Filtration also likely plays a role for Hg capture, but sorption in the lower layers may also be important.

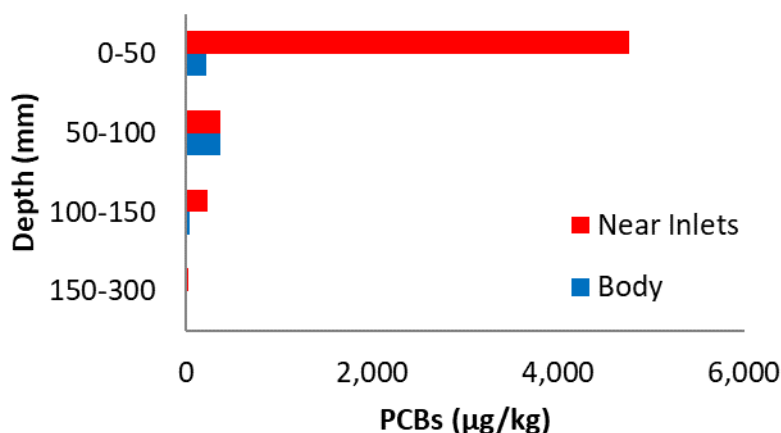


Figure 25. Soil PCB concentrations (ug/kg) at various depths (0-300 mm) in the bioretention unit.

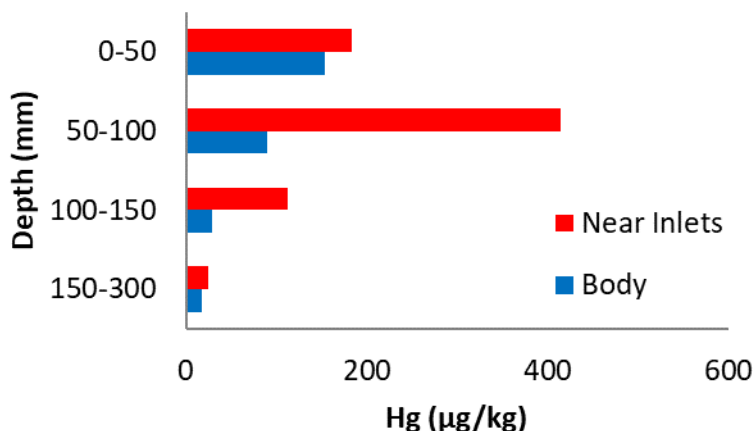


Figure 26. Soil Hg concentrations (ug/kg) at various depths (0-300 mm) in the bioretention unit.

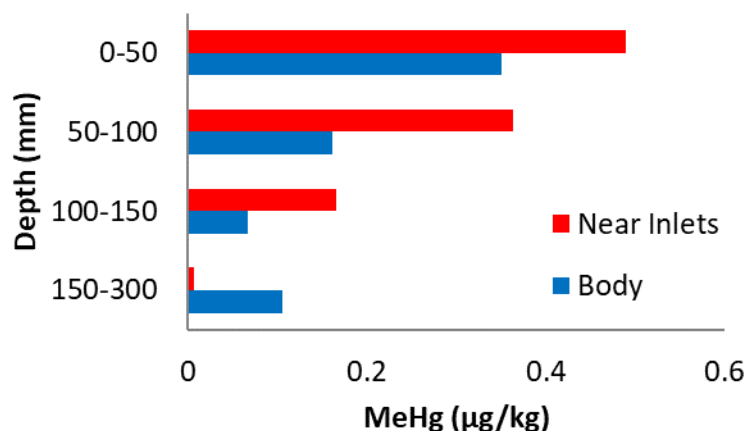


Figure 27. Soil MeHg concentrations (ug/kg) at various depths (0-12 inches) in the bioretention unit.

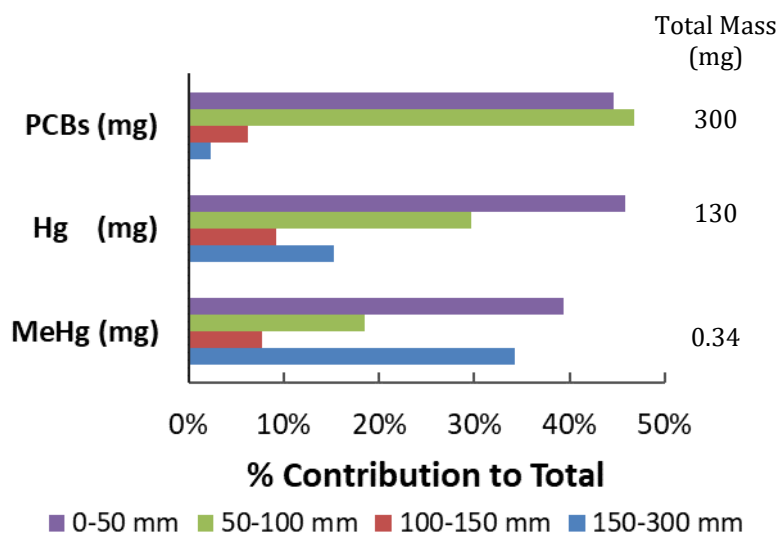


Figure 28. Estimation of mass (mg) of contaminants by depth throughout the entire rain garden (including both the inlets and the main bioretention unit by area).

Conclusions

The findings in this synthesis support the use of bioretention in the San Francisco Bay Area as one management option for meeting load reductions required by San Francisco Bay TMDLs. A performance curve can often explain the differences in performance between sites, typically with sites where influent concentrations are greater having the best performance. This finding suggests that to achieve the greatest pollutant reductions as the result of bioretention, it is important to place bioretention in areas

where pollutant concentrations are highest, and less benefit from a water quality perspective is achieved when units are placed in relatively cleaner areas.

In this synthesis, while the performance curves generally told the primary story for most pollutants, there was an underlying theme that the younger systems monitored within 1-2 years of construction were exporting suspended sediment and organic carbon from the media itself, and may be performing less well for PCBs, HgT and Pb. This is caused by the systems still settling and compacting after initial construction.

There has been a single soil profile study in the Bay Area to date. In that study and similar to other soil profile studies, PCBs, Hg and MeHg were all present at the highest concentrations in the top 100 mm in the surface media layers. PCBs deposited nearest the inlet whereas Hg was dispersed further from the inlet indicating a slower settling rate consistent with its presence on finer particles. These findings are important for managers to understand how frequently soil maintenance is required, especially since green infrastructure is intended for PCB capture and in this unit, the trigger for industrial soils had already been met for the surface layer near the inlet. This study highlights the importance of the surface layer for capturing PCBs and Hg species, and provides useful data for supporting decisions about media replacement and overall maintenance schedules.

This synthesis brings into focus numerous key data gaps:

- Mercury and Copper:
 - How do we design bioretention to trap finer particles?
 - How do we prevent dissolution of Hg and Cu?
- PCBs:
 - Is Filterra media better at trapping PCBs than standard bioretention soil mixes? Why?
 - After maturation, is biochar-enhanced soil media more effective at trapping PCBs?
- Maturation:
 - As sites mature, do sites with different soil media have difference in performance? And how does that change in performance differ for various pollutants?
 - Does performance decrease after some period of time i.e. when does breakthrough occur?
- Soil profile:
 - Is the distribution in the soil profile at all sites similar to that for El Cerrito?

These data gaps and others presented in the literature review section are important to address to continue to move the Bay Area forward towards the greatest efficiencies in bioretention use.

Hg and PCB literature review

Introduction

In addition to the synthesis of local data for PCBs, Hg, Cu, Pb and other ancillary data, this literature review is intended to outline findings from peer reviewed literature for the purpose of understanding how and for how long PCBs and Hg are removed by bioretention units. With this information as the starting point, we also make recommendations for improved bioretention unit design as well as highlight data gaps and make recommendations for additional studies.

The primary mechanisms for pollutant removal in bioretention include filtration, sorption, and vegetative uptake. These mechanisms, and their application to Hg and PCB capture in bioretention, are explored in turn in this literature review. In addition, some of the major mechanisms of PCB degradation are explored. In each appropriate subsection, design considerations are put forth, and in the section called “Overall Design Considerations”, all of the design considerations are put together for a proposal of an idealized bioretention unit for the enhanced capture of Hg and PCBs.

Mechanisms for pollutant reductions in the effluent

Sedimentation/filtration

Settling, surface straining and depth filtration all refer to the capture of particle-bound pollutants as they are physically restrained from further downward migration. This mechanism of pollutant capture is the most important mechanism for PCB and Hg removal in bioretention. Gilbreath et al. (2017) found that the mass of PCBs, Hg and MeHg captured in the top 100 mm in a 7-year old bioretention unit was 91%, 75% and 58%, respectively. This top heavy accumulation may in part be due to immediate capture through sorption of dissolved pollutants (Morgan et al., 2011), but more likely due to sedimentation and filtration near the surface.

Similar to the Gilbreath et al. (2017) study, numerous other studies have found that accumulation of pollutants in bioretention occur in a top-heavy manner, with the greatest mass of accumulation is in the top 150 mm of soil (Blecken et al., 2009; Li and Davis, 2008). Jones and Davis (2013) found that the greatest accumulations of Pb, Cu and Zn were found near the inlet and in the top 30-120 mm of the unit, with no evidence to suggest the metals had penetrated to lower depths.

Many factors influence pollutant removal by filtration, though primarily filtration is governed by the size of the polluted particles in the influent and the size of the pore spaces in the bioretention media; the inverse correlation of these two properties determine how easily a particle-bound pollutant can travel downward through the unit.

Particulate bound pollutants in the influent are candidates for removal by filtration. With regards to properties of the pollutants in the influent, “the particle size distribution, surface potential (measured as zeta potential), and morphological characteristics (area, diameter, perimeter, aspect ratio, and shape factor) of the fractionated sediment particles are expected to impact the effectiveness of particle removal” (Kayhanian et al. 2012). In comparing 27 samples of particle size distribution between influent and effluent of three different detention basins, Kayhanian et al. (2012) found that the effluent samples contained much higher proportions of the finest size fractions; the larger particles were disproportionately filtered out.

For stormwater managers, the bioretention media pore size is the controllable factor they can use to target pollutant capture through filtration. In a study by Morgan et al. (2011), the authors found that compost had a smaller effective diameter than sand, offering greater filtering ability than sand. Hatt et al. (2008) observed that because clay particles and organic matter swell when wet, these soil properties reduce porosity (a negative impact on hydraulic capacity) but enhance the capture of pollutants through filtration (a positive impact on reducing effluent concentrations). This trade-off between hydraulic capacity and filtration performance is a key design feature that stormwater engineers/managers must grapple with.

In this section we explore the properties of Hg and PCBs as they relate to the sedimentation/filtration mechanism of pollutant capture. The relevant properties include the typical particle size distribution for Hg and PCBs from land uses most likely to be treated by bioretention, the typical speciation of Hg and PCBs flowing into bioretention and the pore sizes of bioretention media filtering those particles. We review these topics in detail below.

Mercury

Predominantly, bioretention units are placed next to roadways and therefore much of the stormwater runoff that bioretention is treating is the roadway surface runoff. A large proportion of Hg in roadway surface runoff is atmospherically derived. Nearly 150 kg of Hg is estimated to blanket the Bay Area each year (Tsai and Hoenicke, 2001; McKee et al., 2003). Atmospherically derived Hg is commonly on very small particles that are deposited in rainfall, gaseous forms, or attached to windblown dust particles (McKee et al., 2003).

Particle size distribution in highway runoff has been reported in multiple studies, and possibly represents a decent surrogate to the particle distribution from urban roadways. Particles smaller than 50 μm in diameter account for >70% (by weight) of the TSS in runoff (Vignoles and Herremans, 1995; Roger et al., 1998; Andral et al., 1999; Kayhanian et al., 2008a) and one study reported that particles smaller than 20 μm account for more than 50% of the particulate mass in samples that have TSS concentrations below 100 mg/L. These very fine particles also have higher organic content (Kayhanian et al., 2008a, 2015; Lee et al., 2005) and the highest metal concentrations (Sansalone and Buchberger,

1997; Roger et al., 1998; Morquecho and Pitt, 2003; McKenzie et al., 2008; Kayhanian and Givens, 2011, Kayhanian et al., 2015). Further, studies have shown that metal concentrations increase with decreasing particle size (Lin et al., 2005; Hengren et al., 2006; Li et al., 2006; Tuccillo, 2006; Westerlund and Viklander, 2006; McKenzie et al., 2008).

These very small particles are the most likely to be entrained from a roadway into stormwater runoff, and early on during a storm. In a study of mass transport focused on the first flush in storms, Kayhanian and Stenstrom (2014) found that infiltration basins that can capture the first 20% of the storm volume and bypass the remaining volume can be twice as effective as a feature type that treats 20% of the storm volume throughout the entire period of runoff. But several studies have reported that particles <10 μm are not well captured in BMPs (Pettersson, 1998; Backstrom, 2002; Han et al., 2005; Li et al., 2006; Backstrom, 2002; Han et al., 2005). If captured within a bioretention unit, the smallest particles are then the most likely to be re-entrained, the least likely to settle, and therefore the most likely to flow out with any overflow from a unit.

Another key explanation as to why small particles are not filtered well is that they have high surface potential. This surface potential creates strong particle-particle repulsion, which prevents a particle from aggregating with other particles to form larger particles which are more effectively filtered. A common metric of surface potential is called the zeta potential. Particles are more likely to aggregate when in suspension if their zeta potential is closest to 0, or neutral. Higher positive or negative zeta potential leads to greater particle-particle repulsion. Kayhanian et al. measured the zeta potential of particles from highway runoff and vacuumed solids from a parking lot. The zeta potential of these particles ranged from -20 to -24 mV, indicating a strong particle-particle repulsion. Wastewater treatment systems often use a coagulant to neutralize these negative charges and improve the particle removal from settling and filtration processes. A goal for scientists could be to identify what media characteristics can promote the neutralization of these negatively charged particles.

A further challenge to filtration is due to the generation of macropores in the bioretention cell. Macropores are pathways in the soil media for water to pass through quickly with little filtration. Hatt et al. (2008) saw evidence of macropore creation in some of the media they were testing which they hypothesized was due to cracking during the dry periods. Similarly, Paus et al. (2014) hypothesized that the increased hydraulic capacity in bioretention units they studied was potentially in part a result of macropore generation due to root dieback of vegetation. The smaller the particle, such as the very fine particles to which Hg is most likely to be associated, the more likely it would be to flow through these macropores. Since wetting and drying is a characteristic of the semi-arid climate that encompasses the Bay Area region, vegetation and vegetation maintenance should be considered carefully in designing a system. Further, identifying the specific challenges and solutions associated with our specific climate pattern is a challenge we face in trying to apply findings from other regions.

PCBs

Filtration of particulate-phase PCBs is the primary mechanism for overall PCB removal from stormwater. PCBs have low water solubility, high molecular stability, and a tendency to adsorb to particles. Of the 209 PCB congeners, higher-chlorinated PCB congeners have increased stability and toxicity, decreased solubility and volatility (Passatore et al., 2014, LeFevre et al., 2014), and tend to partition to particulate matter, rather than air, which explains why PCB content in soils are generally dominated by higher-chlorinated homologs (Passatore et al., 2014). Indeed, stormwater measured in 13 watersheds distributed around the Bay had a particulate PCB portion ranging from 66% to 100% (Davis et al., 2017; Gilbreath & Wu et al., 2018, Gilbreath & McKee et al., 2018). The mean particulate portion was 87% and the median particulate portion was 90%.

PCB removal due to bioretention for most sites reported in this synthesis have excellent results (>90% reduction), particularly for those locations in which the influent concentrations are greater. Filtration works particularly well for PCBs likely because PCBs are adsorbed to particles large enough to be filtered out. Additionally, the assumption that PCBs are mainly associated with particulates, and, therefore, are removed primarily through filtration was further strengthened by analyses of PCBs in soil cores collected from the El Cerrito rain garden. After seven wet-weather seasons, in April 2017, two composite soil samples were collected to represent concentrations near the inlet versus the “body” of the rain garden. Both samples included subsamples from four depths within the engineered media: 0-50mm, 50-100mm, 100-150mm, and 150-300mm. The greatest particle concentrations of PCBs were found both in shallower depths and closer to the inlets (Figure 25).

The shallowness of PCBs and their proximity to the inlet are consistent with the hypothesis that PCBs in stormwater influent are attached to larger and heavier particles and, therefore, are more likely to be deposited near inlets and be filtered out on the surface of bioretention units with little downward mobility. This also suggests that filtration at the surface is the most important pollutant capture mechanisms for PCBs. Additional soil coring should be conducted to verify this distribution in other bioretention units.

Design Considerations

The implications of these findings is that physical filtration of particles should play a critical role in the design, selection and performance evaluation of BMPs. However, managers must grapple with the opposing needs for hydraulic capacity and fines filtration. Managers should also consider if PCBs, Hg, or both, are the pollutants targeted for capture; capture of HgT requires capture of finer particles, whereas if PCBs are the target, managers may choose to use coarser grained soils in order to increase infiltration rates and decrease the size of a BMP.

Key recommended design characteristics:

- The first flush should be treated most vigorously since this portion of the flow is most likely to include the highest proportion of metals (Kayhanian et al., 2012). This portion could be filtered through the finest media possible, or allowed to infiltrate with no underdrain. In the latter case, maintaining hydraulic capacity is prioritized over fine media filtration.
- The first flush captured in the bioretention unit should be prevented from overflowing/bypassing.
- Vegetation should be considered carefully, and studied further for improved design recommendations: vegetation can be used to counter the creation of macropores due to cracking during the dry periods (Hatt et al., 2009). This may be useful to prevent untreated stormwater passing quickly through the system. At the same time, vegetation may conversely encourage macropore generation, which may be useful to maintain hydraulic capacity because root growth and senescence counter compaction and clogging (Paus et al., 2014). These counter influences of vegetation and the specific impacts on Hg removal effectiveness should be studied further.
- Design could include multiple stages, each stage with increasing porosity to ensure everything is filtered to some degree while the initial first flush is filtered better through finer media.
- Design of pretreatment for sediment removal from storm water is considered important to reduce clogging and extend the lifetime of infiltration processes.
- Because PCBs have been shown to deposit in shallow (<10 cm) regions of bioinfiltration cells (Gilbreath & McKee et al., 2018), a shallower design could allow for cheaper and easier implementation of rain gardens with effectively equivalent levels of PCB removal. Various design depths should be studied to understand how performance increases with depth and at what depth performance plateaus.

Adsorption

Although the particulate bound fractions for both pollutants are more dominant, the dissolved fraction is particularly important because it is more bioavailable and therefore on an equal mass basis, generally has greater negative impacts to biota (Erickson et al., 2007; Kayhanian et al., 2012). In stormwater monitoring from the Bay Area, mercury and PCBs have been measured to include 10-38% (mean=22%; median=23%) and 0-34% (mean=10%; median=6%) dissolved fraction, respectively (Gilbreath et al., 2018). Pollutants in the dissolved phase will not be filtered out like much of the particulate bound fraction, but may adsorb to the bioretention media. Adsorption is the adhesion of ions, atoms or molecules to a surface (e.g. bioretention media, or plant roots). In this case, we are talking about the adsorption of a dissolved species (the sorbate) in a liquid form (stormwater) to a solid phase sorbent (bioretention media). If the sorbent has a higher affinity for the sorbate species, the sorbate is attracted to the sorbent and is bound there by different mechanisms. This process occurs until equilibrium is reached, after which time it is said that breakthrough occurs.

Mercury

Metal sorption, in part, depends on the characteristics of the metal (e.g., ionic radius, valance, and degree of hydration) (LeFevre et al., 2015). It also depends on the characteristics of the sorbent. For example, inorganic sorbents (e.g., clay minerals, iron, aluminum, and manganese hydroxides) may sorb dissolved metals but humic substances (e.g., fulvic and humic acids), which have a wide range of functional groups (e.g., carboxyl, hydroxyl, methoxy, quinone, and phenolic groups), are generally considered more chemically reactive with dissolved metals (Breeuwsma et al. 1986; Sparks 2003 in LeFevre et al., 2015). Studies have shown that organic matter plays an important role in sorption of dissolved metals. In a study including quantification of dissolved metal removal in bioretention, Davis et al. (2001b) attributed the dissolved metal sorption mainly to organic matter present in the bioretention media and the overlying mulch layer.

The type, proportion and size of organic matter affects the removal capacity of the filter media. Multiple authors have found that compost had a larger sorption capacity than sand (Morgan et al. 2011, Liao et al., 2009), and that time to breakthrough increased as compost fraction increased (Morgan et al., 2011), suggesting that sorption capacity is related to compost fraction. Similarly, Paus et al. (2014a) observed increasing capacity for removal of dissolved Cd and Zn in bioretention columns with increasing compost volume fraction of the media. Zhang et al. (2009) studied the Hg²⁺ adsorption capacity of humic acids versus fulvic acids. Humic acids had a higher adsorption capacity than fulvic acids, and also a lower desorption ratio. Referencing Ramamoorthy and Rust (1978), Liao et al. (2009) stated that Hg sorption was inversely correlated with particle size due to the larger surface area of smaller particles.

Metal sorption further depends on the solution chemistry (e.g., metal concentration, pH, ionic strength, competing cations). Typically, an equilibrium sorption model (e.g. Langmuir, Freundlich) is used to describe sorption relative to the dissolved metal concentration. In addition to the proportion of metal concentrations in the sorbate and sorbent, other variables that can alter the equilibrium include pH (Sauve et al., 2000), ionic strength, and presence of competing cations.

For example, pH has been shown to have important impacts on dissolved metal adsorption. Elevated pH can promote metals adsorption to the particulate species (Good et al. 2012), while low pH can encourage dissolution. There is evidence to suggest, however, that the bioretention media itself has a buffering capacity. Taylor and Cadno TEC Inc. (2013) argue that pH is “well buffered by exposure to hardness elements in bioretention fill media. Low pH rainfall water typically is seen to approach more neutral conditions, with a corresponding increase in hardness at the outlet (Chapman and Horner 2010, Dietz 2007).” Davis et al. (2003) experimented with varying influent pH between 6, 7 and 8 did not find this variation to have any impact. Nevertheless, organic materials can have acids, that lower the pH and promote dissolved species (organic-metal complexes) leaching from the system (LeFevre, 2015). A pH amendment is useful in rain gardens to provide adequate total metal removal and minimize any leaching of dissolved metal species.

Desorption

Once sorbed, Hg may stay sorbed and be removed permanently the next time the soil is replaced or desorb and be lost during a subsequent rain event. Liao et al (2009) tested mercury adsorption and desorption in three different media types and found that media with higher organic content bound Hg with high-energy sites that were very stable and led to very little desorption (<1% in many cases). However, Hg can desorb or be taken up by vegetation. Desorption is more likely for very small particles; a larger surface area to mass ratio leads to equilibrium more quickly than for larger particles. Additionally, if sorbed to organic matter, Hg could leach given any circumstance in which the media organic matter is leached. As an example, studies have shown a correlation between the release of dissolved organic carbon and copper (Amrhein et al. 1992, Li and Davis 2009; Blecken et al. 2011). Furthermore, Sauve et al. (2000) found that TOC concentrations often slightly increased from inlet to outlet, leading to increased dissolved metals mobility. That said, Li and Davis (2009) argued that since free metals have higher toxicity and bioavailability (Santore et al., 2001) as compared to complexed or particulate-bound metals; therefore, even if leached with organic matter, metals toxicity would be reduced. These statements warrant further investigation for Hg in bioretention specifically.

Climatic Influences

Both temperature and the wetting and drying regime of a given locale can influence the rate of adsorption and desorption. In terms of temperature, the rate of sorption decreases with decreasing temperature due to slower kinetics (LeFevre et al., 2015). Conversely, the equilibrium sorption capacity can be expected to increase with decreasing temperature due to weakening of the attractive forces between the sorbent and metal ions at high temperature, and therefore increased capacity at lower temperatures. Blecken et al. (2011) reported increased Cu removal with decreasing temperature (i.e., from 20 to 2°C), and explained this as the result of increased organic matter decomposition rates during the warmer months leading to increased release of dissolved organic matter and associated Cu. LeFevre et al. (2015) hypothesize that capacity (rather than slower kinetics), which occurs during cooler temperatures, is the more important variable in terms of bed lifetime. If this hypothesis is correct, it is positive for the Bay Area since stormwater runoff typically occurs in the cooler months (November-March).

Drying of bioretention units leads to oxidation and in turn, changes the chemical phase distribution of metals (Saeki et al., 1993). Drying and oxidation leads to more soluble/available metals (Caille et al., 2003; Stephens et al., 2001). When rewetting soils after a dry period, dissolved metal concentrations will be elevated. Additionally, extended dry periods “affect the soil structure (e.g. increased porosity, occurrence of fissures), and plant activity (decreased plant activity, possibly drought induced damage) in biofilters and thus the retention time and the plant effect on metals might change (Lefevre et al. 2015).

The Bay Area climate is characterized as predominantly dry between May and October, wetter during October through April, with this wet period having intermittent wet and dry periods with dry periods lasting up to 6 weeks in length. The alternating wet and dry periods can result in variable redox

conditions, degradation and dissolution of organic matter and, in turn, metal mobility (Minton 2005 in LeFevre et al., 2015). Laboratory experiments have shown wet and dry conditions up to 4 weeks in unvegetated columns had no significant impact on metal removal (Hatt et al. 2007b). In an experiment with vegetated columns, Blecken et al. (2009b) found that dry periods with duration longer than 3 weeks reduced metal removal performance, which they explained by the possible oxidation of previously accumulated metals, mobilization of fine sediments, development of preferential flow paths (or macropores), and reduced metal uptake in plants during dry periods.

Blecken et al. (2009) found that by introducing a submerged zone at the bottom of the biofilter, the negative effects of drying could be minimized and copper removal increased by 12%. LeFevre et al. conclude: Increased knowledge of the behaviour of biofilters under natural conditions (e.g. variable runoff volumes, extended periods of drying) is thus required.” These findings also suggest that incorporating irrigation into bioretention can be an important factor not only in maintaining the health of the vegetation but also in maintaining optimum Hg sorption. This is an area for further investigation.

PCBs

Adsorption of dissolved molecules increases as solubility decreases and degree of halogenation, i.e., chlorination, increases (LeFevre et al., 2014). In general, dissolved PCBs exhibit a high tendency to sorb to particulate matter. Sorption of organic compounds to particulate matter is an equilibrium process that can be linearly estimated using a compound's octanol-water partition coefficient or Log(Kow) value, where Kow is the ratio of particulate to dissolved, or aqueous, concentrations (Baker et al., 1986).

In a microcosm experiment, LeFevre et al. (2011) studied the fate of dissolved naphthalene (a polycyclic aromatic hydrocarbon) in three columns (two planted and one unplanted) over the span of five months. Comparable to 96% in the El Cerrito rain garden, 93% of naphthalene was removed in both vegetated columns with the following mechanistic fate: adsorption to soil was the dominant naphthalene removal mechanism (56–73%), although biodegradation (12–18%) and plant uptake (2–23%) were also important and volatilization was negligible (<0.04%). Photolysis was not considered. The Log(Kow) value for naphthalene is 3.3 whereas the Log(Kow) for PCBs ranges from 4.56 (isomers with one chlorine atom) to 9.6 (isomer with ten chlorine atoms) (LeFevre et al., 2014). Therefore, because adsorption is the quickest and most dominant mechanism for removal of dissolved naphthalene, it can be assumed that, depending on the media, an even greater proportion of dissolved PCBs are removed through adsorption during infiltration.

As the organic carbon and clay content increases, so does adsorption of PCBs and, thus, a decrease in bioavailability (Passatore et al., 2014).

Desorption

PCBs are extremely recalcitrant and difficult to remove from soil and sediment matrices. But, because of its irreversibility, sorption of PCBs to organic matter should be treated as a holding tank for other slower, important processes like biodegradation and plant uptake. To make matters more complicated, the isotherms for PCB adsorption and desorption display hysteresis, meaning that PCBs do not desorb at an equal but opposite rate to adsorption. However, Dominic et al. (1982) (Di Toro et al., 1982) found that PCB desorption isotherms can be approximated by a straight line. This linear estimation can only be applied for the first consecutive desorptions. Desorption kinetics depend on the sediment type and aqueous-phase chemistry. The adsorbent must be carefully selected for properties that allow for efficient extraction of PCBs while still allowing a rate of desorption that maximizes the rate of biodegradation. Additionally, certain root exudates have been shown to encourage desorption of organic pollutants (Ulrich et al., 2017).

Design Considerations

Multiple key factors should be considered for enhancing adsorption while decreasing desorption, including the bioretention media itself, bioretention cell structure and maintenance. The main considerations are listed below:

- **Organic and pH amendments:** Humic substances tend to be better at adsorption of metals than inorganic substances. The use of organic amendments such as mulch and/or leaf compost in bioretention media may result in a media with a higher metal sorption capacity (Jang et al. 2005; Sun and Davis 2007; Paus et al. 2014a, Passatore et al., 2014). Exhausted coffee grounds have also been identified as a strong Hg biosorbent (Macch et al., 1986). The trade-offs for increasing compost content, however, are decreased permeability of the media as well as the potential for increased nutrient release, and desorption with dissolution of organic carbon. To minimize dissolution, a pH amendment may be useful. As far as the authors know, activated carbon or biochar have not been studied for Hg capture in bioretention². However, activated carbon has been shown to be useful for removal of Hg from the coal-fired power plant flue gases, and that industry is working to find adsorbents that efficiently remove Hg with a lower carbon to Hg ratio, as well as a cheaper source of activated carbon than currently available (De et al., 2013).
- **Depth:** After bioretention media composition, a critical design parameter is the media depth. Greater media depth increases the number of sorption sites for removal of dissolved metals, and hence extends the time until metal breakthrough. Davis et al. (2003) reported that flow rate had a small effect on bioretention capture particularly for shallower designs, in which a slower flow rate allows the metals more contact time to adsorb. More importantly than depth,

² BASMAA currently has a study underway investigating biochar effectiveness for both PCBs and Hg. Results are expected in late 2018 or early 2019 (pers comm. Lisa Sabin, BASMAA representative).

however, the authors suggested that avoiding bypass is important to pollutant capture. Furthermore, Davis found shallow designs (61 cm deep) still removed 66%->99% (versus 78%->99% of deeper designs (91 cm)) of metal (Cu, Pb and Zn) concentrations; thus in terms of metal removal, it is important to keep in mind that a deeper design > shallow design >> no bioretention. Developing performance curves relative to bioretention depth could help managers better understand when bioretention is warranted despite the requirement for a shallower design in some applications.

- **Irrigation:** Since drying and oxidation can promote dissolution of metals in the next storm event, regular irrigation (and the literature suggests it could be as infrequent as every three weeks) is a key factor in maintaining sorption. Irrigation can also help maintain the health of the vegetation for optimum metals uptake (see below).
- **Submerged Zones:** Another design modification to decrease dissolution is the use of a submerged zone. The use of submerged zones can be very beneficial for removal of metals (Blecken et al., 2009) (as well as nitrogen), particularly for systems that will be subjected to long drying periods, possibly because the unit will not dry out as much. If variations in metal outflow concentrations - in particular, intermittent high output concentrations after long drying periods - are not acceptable, then using a submerged zone should be considered. Submerged zones, however, have not been tested with Hg relative to methylation of Hg. If tested and a submerged zone results in Hg methylation, submerged zones should be reconsidered and likely not used.
- **Multi-stage system:** Given the strong first flush signal for metals off roadways, enhancing the capture of fine and dissolved Hg in the initial volume could be an efficient design optimization. This may involve a multi-stage system in which the initial stage accepts the earliest runoff and is filtered through very small pore sized compost media, and/or is entirely infiltrated rather than utilizing an underdrain. Later stages in the system could have coarser particle media that filters more quickly and is underdrained. If underdrained, this initial stage could also benefit from extended contact time between the pollutants and retention media, which would encourage slower reactions through decreased flow rates (17q). Alternatively, Hsieh and Davis (2005) recommended a two media layer design. In such a design, the top layer would support vegetation growth and Hg adsorption using compost, and a lower sand-dominated layer to assist with Hg removal not otherwise captured via the compost. Further investigation into different configurations of multi-stage systems could help to identify optimum designs for Hg and PCB removal.

Vegetative Uptake

Mercury

Vegetative uptake, or phytoextraction, of mercury by plants is also a mechanism for capturing pollutant loads. “Plant roots accumulate metals through diffusion of metal ions to the root endodermis (passive uptake) and metabolic processes (active uptake)” (Alloway 1995). Metals accumulated in the roots will typically be translocated to the shoots over time. The primary benefit to phytoextraction would be that it restores the adsorption capacity of the soil. Differences in root surface area, root cation exchange capacity, root exudates, and the rate of evapotranspiration result in variations in metal uptake among plant species (Alloway 1995). Certain species, known as hyperaccumulators (e.g. *Thlaspi caerulescens*, *Salix viminalis*, *Helianthus annuus*), are capable of accumulating very high concentrations of metals (Salt et al. 1998) (LeFevre et al., 2015). After a certain amount of time and pollutant uptake, the plants are harvested and the pollutants are removed from the system permanently.

In studies using direct assay or mass balance calculations, plants have been shown to uptake between 0.2-10% of the total metal load capture in bioretention (Read et al. 2008, Dietz and Clausen 2006; Muthanna et al. 2007b; Sun and Davis 2007). These studies have looked at other metals, not Hg, and therefore study directly on Hg would be useful in bioretention. Further, as LeFevre et al. (2015) points out, the more limited metal phytoextraction that has been measured may be largely due to which plants are typically chosen for bioretention units; plants are typically natives selected for aesthetics and drought tolerance. These are important qualities, but GI can be co-located with other vegetation and trees that might be outside the GI unit but together with the GI create important habitat patches. Inside the GI unit, the benefits of hyperaccumulation may be large and should be considered when designing a bioretention system. There are over 400 species of metal hyperaccumulators. Identifying which of these may be ideal for Hg accumulation in bioretention in the Bay Area climate zone could help extend bioretention bed life and optimize the ongoing capacity of each unit.

A few of the over 400 species of metal hyperaccumulators are highlighted below. The Brassicaceae family, with 87 species identified for metal hyperaccumulation, is particularly promising (Prasad and Freitas, 2003), three of which are briefly described.

Mustard Plant (*Brassica juncea*): the mustard plant is the most promising of all the Brassicaceae family for phytoremediation of a wide variety of heavy metals (Prasad and Freitas, 2003; Nasar et al., 2012). Shiyab et al. (2009) found that in highly contaminated soils, Hg is phytotoxic for *Brassica juncea*, but pointed out that the high accumulation of Hg in the plant suggested it would be a good potential candidate for phytostabilization. Roots had 8 to 100 times the accumulation rate of Hg than other plants. Further study of *Brassica juncea* in bioretention should be investigated, and if determined to be useful in Bay Area bioretention conditions, it should be studied whether attempts to remove roots in addition to shoots is an important strategy.

Rapeseed (*Brassica napus*): is a bright-yellow flowering member of the family Brassicaceae (mustard or cabbage family), cultivated mainly for its oil-rich seed. It is the third-largest source of vegetable oil in the world. Rapeseed has been researched as a means of containing radionuclides that contaminated the soil after the Chernobyl disaster. Rapeseed was discovered to have a rate of uptake up to three times more than other grains.

Alpine Penny-cress (*Thlaspi caerulescens*): a flowering plant in the family Brassicaceae. Alpine pennycress has been cited in phytoremediation to have special phytoextractional properties and is known to absorb cadmium with very good results, and in certain instances is said to have absorbed zinc as well.

Basket Willow (*Salix viminalis*): a species of willow native to Europe, Western Asia, and the Himalayas. Increasingly the Basket Willow is being used for effluent treatment and wastewater gardens, and in cadmium phytoremediation for water purification (Perttu and Kowalik, 1997).

Common Sunflower (*Helianthus annuus*): can be used in phytoremediation to extract toxic substances from soil, such as metals and harmful bacteria from water. They were used to remove caesium-137 and strontium-90 from a nearby pond after the Chernobyl disaster, and a similar campaign was mounted in response to the Fukushima Daiichi nuclear disaster.

Chinese Brake Fern (*Pteris vittata* L.): Known to hyperaccumulate arsenic, chromium, copper, lead, mercury, nickel, and zinc (Duan et al., 2005).

Future studies should investigate which hyperaccumulators are best for Hg accumulation and in the Bay Area climatic zone, the impact on Hg capture via the other mechanisms (e.g. does vegetative uptake replenish the available sorption sites), and the related maintenance requirements.

PCBs

Dissolved contaminants can adsorb to plant roots and, depending on plant- and contaminant-specific properties, can enter plant tissue (Passatore et al., 2014). Once the compounds enter plant tissue, they may translocate to other areas of the plant and possibly volatilize, undergo mineralization, or become bound in plant tissues (Salt et al., 1998). These tissue-bound forms usually undergo some degree of transformation resulting in a decrease in toxicity and are usually unavailable to organisms which make this a desirable mechanism for PCB removal (LeFevre et al., 2011).

Factors used to predict whether a target chemical will be adsorbed to and taken up by plants are the lipophilicity and solubility of the contaminant in the water phase; the lipid, fiber, and carbohydrate content in plants; and the pH, pKa, organic content, water content, and texture of the soil (Salt et al., 1998, Collins et al., 2006, LeFevre et al., 2014). A wide range of contaminant-uptake capabilities are seen

across different plant species. Differences in plant partitioning and metabolism of organic contaminants should be considered during plant selection. Data to inform plant selections are lacking but some can be found through the U.S. Department of Agriculture at <http://www.nal.usda.gov/fnic/foodcomp/Data/SR16/reports/sr16page.htm>.

Though PCBs have been found at high levels on plant roots (Collins et al., 2006), only small amounts of PCBs are taken up by plants. Wild and Jones et al. estimated that organic chemicals with a Log(Kow) greater than 4 will be retained by plant roots whereas Salt et al. (1998) estimated that organic chemicals with a Log(Kow) ranging from 0.5 to 3.0 are more likely to be taken up by plants. The Log(Kow) for PCBs ranges from 4.56 to 9.6. Using the Log(Kow) value and plant physiology, Passatore estimated PCB fractions that were taken up by plants and compared her results to several field studies. She found that PCBs trapped by plant roots would usually not be taken up into plant tissue. However, she found that some weed species (*Vicia cracca*, *Polygonum persicaria*, etc.) and in zucchini (*Cucurbita pepo*) exhibited higher translocation rates which would increase plant uptake of PCBs.

Design Considerations

Since vegetative uptake and translocation to shoots is more feasible for Hg than PCBs, bioretention unit designers should emphasize the use of Hg hyperaccumulators. This would be particularly important in units where Hg accumulation in the upper 3-12 inches will eventually reach equilibrium and no longer be able to adsorb Hg, or Hg will accumulate so much that the soil must be replaced. Further investigation is required before recommending a particular species. This investigation should include identifying species of hyperaccumulators, considering the irrigation requirements, likelihood of survival and growth in our climate, and aesthetics.

PCB Degradation

Concentrations of PCBs in local bioretention media have been seen to exceed regulatory thresholds (Gilbreath et al., 2018). Several options exist for handling contaminated soils including removal and replacement, dilution, soil washing, etc. In situ degradation through phytoremediation and biodegradation are possibly desirable mechanisms to prevent dangerous levels of PCB-accumulation in bioretention-unit media. Due to the persistence of PCBs, the following are the largest obstacles for removal of PCBs through bioremediation: the low bioavailability of PCB molecules due to their sorption to particulate matter and the slow rate of biological degradation (Passatore et al., 2014).

Biodegradation

PCBs may be eliminated from bioretention units through complete mineralization to carbon dioxide, water, chloride, and biomass (LeFevre et al., 2011, Abramowicz et al., 1995). Complete degradation of

PCBs begins with anaerobic bacteria that perform reductive chlorination on the higher chlorinated congeners. Then, aerobic bacteria break down lesser chlorinated congeners through oxidative degradation resulting in chlorobenzoic acids, which are readily degraded by indigenous aerobic bacteria (Harkness et al., 1993, Abramowicz et al., 1995, Passatore et al., 2014).

Literature has revealed the following considerations regarding PCB biodegradation:

- Higher-chlorinated congeners are more recalcitrant, have a higher tendency to adsorb, and are, therefore, less bioavailable which results in slow degradation rates in bioretention units. (Abramowicz et al., 1995; Passatore et al., 2014).
- Anaerobic PCB-degrading bacteria are often less abundant in the environment. (Abramowicz et al., 1995).
- Rain gardens (when properly draining) maintain aerobic conditions (LeFevre et al., 2012).
- Temperature and pH play a large role in determining routes of microbial dechlorination (Passatore et al., 2014).
- Some metabolites produced during oxidation are toxic to PCB degrading microbial populations which could contribute to the slow kinetics of PCB mineralization (Passatore et al., 2014).
- After PCBs are introduced to a native microbial population, there is a lag period of around one to six months before activation of PCB-dioxygenase genes necessary for PCB degradation. This initial spike in degradation rate is usually followed by increasing rates of degradation due to further enrichment of PCB-degrading microbial populations (LeFevre et al., 2014, Passatore et al., 2014).
- A wide range of kinetic rates of PCB degradation have been found. A study conducted on cores in river sediment showed reduction of 62-72% of PCBs in 73 days (Harkness et al., 1993). Another study found reductive chlorination to be on the range of up to a 37-year half-life for decachlorobiphenyl, the highest chlorinated and most recalcitrant PCB congener (Passatore et al., 2014).
- Results from several studies showed that PCB degradation depends highly on plant species and indigenous microflora and that degradation of highly chlorinated PCBs occurs under methanogenic, sulfidogenic, iron (III) reducing and denitrifying conditions (Passatore et al., 2014).

Several studies showed that, when applied in the field, the inoculation of microbes (especially non-native groups) failed to induce increased metabolic degradation (Passatore et al., 2014, Harkness et al., 1993). Rather than introduce exogenous microorganisms, bioretention should be designed to encourage natural populations to degrade PCBs as studies have shown that native microbial populations capable of PCB metabolism are ubiquitous (Passatore et al., 2014).

In order to encourage complete mineralization of all PCB congeners, a combination of aerobic and anaerobic conditions are required and can occur naturally in the environment (Abramowicz et al., 1995). These conditions can also be enhanced through rhizostimulation (release of plant exudates that enhance fungal and bacterial degradation in the root zone or rhizosphere). However, to degrade the higher-

chlorinated PCBs bioretention-design would need to encourage more anaerobic conditions. Mineralization of PCBs can be induced through ensuring both aerobic and anaerobic conditions and the supply of the following catalyzing agents: nutrients, carbon sources, electron donors, electron acceptors, and mobilizing agents. Many of these can be further provided by plant roots (see section on rhizostimulation). In several PCB-polluted sites, the natural microflora, if adequately stimulated, was able to efficiently catalyze the degradation process.

Rhizostimulation

Several studies have seen increased removal of PCBs from vegetated soils compared with non-vegetated soils (LeFevre et al., 2014, Collins et al., 2006, Passatore et al., 2014, Salt et al., 1998). Phytoremediation is an inexpensive, promising, and environmentally friendly technology that effectively targets PCBs for removal (Salt et al., 1998).

Phytoremediation *ex planta*, or rhizostimulation, is the release of plant exudates that enhance fungal and bacterial degradation in the root zone or rhizosphere. Rhizodegradation is executed as a combination of the following four pathways: improving aerobic bacterial metabolism through diffusion of oxygen, supplying energy and electrons through organic carbon release from root turnover and root exudates, inducing PCB-catabolism enzymes through release of structural PCB analogs, and releasing biogenic surfactants in root exudates (Passatore et al., 2014; LeFevre et al., 2011; Leigh et al., 2006). Enhanced desorption in the presence of root exudates has also been observed (Ulrich et al., 2017). Root filaments can bring about both aerobic and anaerobic conditions in the same location that could possibly lead to all necessary steps for complete PCB mineralization. Furthermore, the mycorrhizal hyphae network increases the ability of roots to expand and function in smaller pores.

Rhizostimulation is periodic and depends greatly on the species of plant. Many plant species are able to survive in PCB-contaminated soils and can encourage growth of PCB-degrading microorganisms. Rhizostimulation can lead bacteria to degrade a wider range of congeners and to multiply two to four times in population size (Salt et al., 1998). Because indigenous plants and microbes are naturally contaminant-tolerant and do not risk ecosystem disequilibrium, they are the preferred choice in bioretention design. Generally, plants with deeper and denser roots lead to greater rhizostimulation (LeFevre et al., 2012).

Numerous studies have revealed an increase of microbial density, activity, and diversity due to rhizostimulation (Passatore et al., 2014, Chekol et al., 2004). A screening of PCB phytoremediation with seven different plant types determined that the presence of plants significantly increased PCB biodegradation and found varying effects between plant species (Chekol et al., 2004). Another study that tracked microbial activity in five species of matured trees in PCB-contaminated soil found variability between trees in rhizostimulation success. Leigh et al. (2006) also found that rhizostimulation is a promising strategy for PCB removal due to the enrichment of efficient PCB-degrading organisms (Leigh et al., 2006). These studies have identified different design aspects of rhizostimulation that have proven

effective for PCB removal. One highlight is Passatore's findings that both pine and willow trees facilitate impressive levels of biodegradation through their generation of plant secondary metabolites (Passatore et al., 2014). Passatore also found the willow-associated rhodococcus genus to be well adapted for PCB rhizoremediation and valuable because their resistance to dehydration makes them a low-maintenance choice for bioretention.

Volatilization

Volatilization is a measure of a compound's tendency to escape to the gaseous phase. LeFevre et al. (2015) found the percentage of dissolved naphthalene removed through volatilization to be negligible (<0.04%) during infiltration. Naphthalene's fairly low air-water partitioning coefficient ($\log K_{aw} = -1.74$; ref 40) combined with the tendency to sorb to soil organic matter ($\log K_{ow} = 3.33$; ref 40) explains the lack of volatilization. Because bioretention units are designed to allow for rapid infiltration, the fraction of PCBs removed through volatilization during infiltration is expected to be close to zero.

However, the long-term fate of PCBs in rain gardens is an important data gap. An increase in halogenation leads to a decrease in volatilization (LeFevre et al., 2014), so lower chlorinated congeners have more potential to volatilize from the particulate-bound phase. A few studies have found that compounds with a Henry's law constant (HLC) with units of $[\text{mol}/(\text{m}^3 \cdot \text{Pa})]$ greater than $2.5 \cdot 10^{-1}$ show an affinity for partitioning to the gas phase (Bromilow and Chamberlain (19) and Ryan et al. (18) from Collins et al., 2006). The HCL for PCBs range from $1.0 \cdot 10^{-2}$ to $9.6 \cdot 10^{-4} \text{ mol}/(\text{m}^3 \cdot \text{Pa})$. Estimates show that only 0.17% of environmentally accessible PCBs are in the atmosphere whereas 9.2% are in natural soils (LeFevre et al., 2014). This lack of PCBs in the atmosphere may be partially explained by photolysis (the decomposition of PCB molecules due to exposure to sunlight).

One study found the dimensionless HLC for 20 PCB congeners to increase from $1.22 \cdot 10^{-3}$ to $3.67 \cdot 10^{-2}$ with the degree of chlorination (Dunnivant and Elzeman, 1988). Based on these estimations, PCBs, especially lower-chlorinated congeners, are susceptible to volatilizing from particulate matter in the biofiltration units. Whether they can volatilize from these units depending on depth and other factors is an important data gap.

Design Considerations

- Use native plant species with deep and dense root systems to promote rhizostimulation.
- Manipulation of native rhizospheric bacteria is the most important tool for in situ elimination of PCBs. This could be accomplished by encouraging a co-existence of aerobic and anaerobic conditions with extra importance placed on anaerobic conditions (note: anaerobic conditions should be below surface such that mosquito propagation is prevented). One way to encourage anaerobic conditions is to include a submerged zone with an electron donor, such as shredded

newspaper, to stimulate anaerobic degradation of higher-chlorinated PCBs (LeFevre et al., 2014).

- Biodiversity in microbial populations should be encouraged.
- Use biosurfactants to encourage solubility of PCBs and subsequent biodegradation. (Salt et al., 1998).

A note about Mercury Methylation

Methylmercury, a generic term for compounds with the formula CH_3HgX , is a toxic contaminant that is found in many of our receiving waters. They arise by a process known as biomethylation. David et al. (2015) reported that post-installation concentrations of MeHg were higher than pre-installation conditions, as opposed to HgT and HgD which both decreased post-installation. The authors argued that because of miscommunication during the construction phase, a subdrain was left out, and the missing subdrain may have caused anaerobic conditions on the bottom of one cell. These conditions would favor MeHg production by bacteria. The authors suspected that anaerobic water from underneath the filter media could have possibly commingled with rainwater filtering through the system, causing the higher MeHg concentrations in the sampled effluent.

Design Considerations

No design suggestions are made at this time until further investigation is done.

Maintenance implications

Maintenance is critical to the long-term performance of bioretention units. Several studies have reported the challenge with surface clogging (Hatt et al., 2008) leading to the decline in infiltration rate and greater bypass, as well as concentration reductions (Lie et al., 2014). Hatt et al. (2008) recommended scraping off top 2-5 cm of filter media every 2 years. Lie et al. (2014) reported on a study in which the top 7.5 mm of media were scraped off the top of two sets of bioretention cells and found it to benefit the surface storage volume (increased it by 90%), and increased the infiltration rate by 10-fold. Additionally, overflows decreased from about 35% down to about 11%. And, the effluent post-surface soil removal was less polluted than the effluent pre-removal.

Areas to focus on for soil replacement include all parts of the treatment cell but with special attention, or greater replacement frequency, nearest the inlets. Gilbreath et al. (2018), as described in the soil profile section above, found that PCBs in particular were most heavily concentrated directly in front of the inlet. This spatial profile was not pronounced, however, for HgT. Jones and Davis (2013) also recommend mulch removal and/or replenishment, removal of significant particle deposits, and efforts

to maintain even distribution of inflow across the cell surface. Mulch replacement would be especially critical if the heavy carbon content of mulch is intended to be the cell's primary mechanism for adsorbing metals.

Soil washing may also provide some benefit to the long-term maintenance strategy for bioretention. Instead of complete replacement of the top level of soil, soil washing involves using water to physically separate the more contaminated soils, thereby concentrating the soils that actually need replacement from soil that can be reused on site. This may be an especially useful technique since, based on study findings reported herein, it is the finest soil fractions that are disproportionately associated with the greatest pollution. An added benefit of using such a technique is that by removing the most polluted, smallest soil fractions, greater hydraulic capacity would be regained. While Xu et al. (2014) acknowledged that soil washing is a "widely used" technique for reducing Hg contaminated soil needing further treatment, that study found that only 0.03-0.2% of the total Hg was removed by using wet sieving. Possibly important differences between the soil used by Xu et al. and likely characteristics of the most polluted soils in bioretention is that Xu et al. used coarser grained soils. Given the substantial benefits potentially gained, the effectiveness of using soil washing in bioretention to concentrate target pollutants, reduce the mass of polluted soils for further treatment or disposal, as well as restoring hydraulic capacity, should be investigated further and determined whether it is a cost-effective strategy.

Finally, maintaining the vegetation is a key component both for the sake of aesthetics, but also performance to reduce clogging and macropore development. Furthermore, if the use of hyperaccumulators becomes a more common practice, maintaining the vegetation would possibly offset some of the media replacement. At the same time, if hyperaccumulators are used, harvesting the vegetation occasionally may become a necessary part of the maintenance.

Overall Design Considerations

The data synthesis in the first part of this report showed that bioretention is generally very effective at capturing PCBs. Mercury is more challenging from a design standpoint. Because much of the load is found on very fine particles, mercury 1) is more easily entrained into surface water, 2) has a high surface potential that contributes to particle-particle repulsion and resistance to coagulation, 3) reaches equilibrium faster and therefore more likely to dissolve into solution, 4) will more easily pass through macropores, and 5) will overall settle out more slowly and thus will disproportionately be found in bypass/overflow. All other parameters being equal, the small size of particles that Hg tends to adsorb to make it more difficult to be filtered out than PCBs.

Due to the first flush effect for metals (since they tend to have greater concentrations on finer particles that are entrained relatively easily at the beginning of storms), it is good if the first flush can be filtered most vigorously and have a long settling time. On the contrary, PCBs don't have a clear first flush effect and therefore require treatment throughout the entire storm to ensure the greatest mass is captured;

furthermore, PCBs may be able to be filtered quickly through larger grain size media to get to capture the majority of the mass and with a primary goal to minimize bypass.

Primary Design Implication:

This dichotomy leads to two overarching suggestions. First, it is important for stormwater managers to define which pollutant(s) are the primary targets of the application of GI. Secondly, if a design must target both Hg and PCBs, a multi-stage system may be an efficient design optimization, with each stage having increasing porosity to ensure everything is filtered to some degree while the initial first flush is filtered better through finer media. The initial stage accepts the earliest runoff which is filtered through very small pore sized compost media, and/or is entirely infiltrated rather than utilizing an underdrain; or, if underdrained, this initial stage could also benefit from extended contact time between the pollutants and retention media, which would encourage slower reactions through decreased flow rates (17q). Later stages in the system could have coarser particle media that filters more quickly and is underdrained. By passing storm volume more quickly through coarser media, some filtration will be achieved for most or all of the storm volume, and minimize overall bypass. Alternative to multiple stages across the surface of a bioretention unit, Hsieh and Davis (2005) recommended a two-layer media design. In such a design, the top layer would support vegetation growth and Hg adsorption using compost, and a lower sand-dominated layer to assist with Hg removal not otherwise captured via the compost.

In addition to these overarching suggestions, below is a series of additional design considerations. Not all of these design considerations may be suitable for every GI unit. For many of these suggestions, cost-benefit analysis has not been conducted and may be unique to each situation, so managers must use discretion. For many of these suggestions, there has not been full scientific investigation but the suggestion is included due to the likelihood that it would have a beneficial impact on capturing pollutants. For many such cases, study suggestions are described in the section below.

- **Pre-treatment:** Design of pretreatment for sediment removal from storm water is considered important to reduce clogging and extend the lifetime of infiltration practices.
- **Preventing overflow:** Since the finest particles are least likely to settle and the first to be re-entrained (Kayhanian et al., 2012), the first flush captured in the bioretention unit should be prevented from overflowing.
- **Depth:** After bioretention media composition, a critical design parameter is the media depth.
 - Greater media depth increases the number of sorption sites for removal of dissolved metals, and hence extends the time until metal breakthrough. Davis et al. (2003) reported that flow rate had a small effect on bioretention capture particularly for shallower designs, in which a slower flow rate allows the metals more contact time to adsorb. More importantly than depth, however, the authors suggested that avoiding bypass was important to pollutant capture. Furthermore, Davis found shallow designs (61 cm deep) still removed 66%->99% (versus 78%->99% of deeper designs (91 cm)) of

metal (Cu, Pb and Zn) concentrations; thus in terms of metal removal, it is important to keep in mind that a deeper design > shallow design >> no bioretention.

- Because PCBs have been shown to deposit in shallow (<10 cm) regions of bioinfiltration cells (Gilbreath & McKee et al., 2018), a shallower design could allow for cheaper and easier implementation of rain gardens with effectively equivalent levels of PCB removal.
- **Irrigation:** Since drying and oxidation can promote dissolution of metals in the next storm event, regular irrigation (and the literature suggests it could be as infrequent as every three weeks) is a key factor in maintaining sorption. Irrigation can also help maintain the health of the vegetation for optimum metals uptake.
- **Submerged Zones:** At this time submerged zones may have contraindicating functions and we cannot recommend a submerged zone without further investigation.
- **Organic and pH amendments:** Humic substances tend to be better at adsorption of metals than inorganic substances. The use of organic amendments such as mulch and/or leaf compost in bioretention media may result in a media with a higher metal sorption capacity (Jang et al. 2005; Sun and Davis 2007; Paus et al. 2014a, Passatore et al., 2014). Exhausted coffee grounds have also been identified as a strong Hg biosorbent (Macch et al., 1986). The trade-offs for increasing compost content, however, are decreased permeability of the media as well as the potential for increased nutrient release, and desorption with dissolution of organic carbon. To minimize dissolution, a pH amendment may be useful.
- **Vegetation:** Use native plant species with deep and dense root systems to promote rhizostimulation.

Bay Area Scientific Data Gaps and Recommendations

This synthesis has identified numerous areas where data gaps exist. The following is a list of those data gaps along with recommended studies to answer those data gaps.

Layout

The primary design suggestion for targeting both Hg and PCB capture is a multi-stage system. Such a system should be tested, preferably alongside a more traditional single-stage system. Given that a multi-stage system is more complex, a cost-benefit analysis would also be useful.

Depth

After bioretention media composition, a critical design parameter is the media depth. Most of the pollutant mass captured was retained in the top 100 mm of soil, with filtration likely being the most important capture mechanism for PCBs and possibly also for Hg. Because PCBs have been shown to deposit in shallow (<10 cm) regions of bioinfiltration cells (Gilbreath & McKee et al., 2018), a shallower design could allow for cheaper and easier implementation of rain gardens with effectively equivalent levels of PCB removal. Various design depths should be studied to understand how performance

increases with depth and at what depth performance plateaus. Performance curves could be developed between performance and bioretention depth to help managers better understand when bioretention is warranted.

Media Composition

Studies have shown that the media composition can have significant impacts on the degree of capture and adsorption (LeFevre et al., 2015). The use of organic amendments such as mulch and/or leaf compost in bioretention media may result in a media with a high metal sorption capacity (Jang et al. 2005; Sun and Davis 2007; Paus et al. 2014a). The trade-offs for increasing compost content, however, are decreased permeability of the media (leading to a slower flow rate) as well as the potential for increased nutrient release, and desorption with dissolution of organic carbon. pH may be a major factor in organic carbon dissolution, yet pH amendments may help prevent such leaching. Leaching should be tested using various magnitudes of pH and also when utilizing pH amendments.

The zeta potential of particles in stormwater runoff is often very strong and leads to particle-particle repulsion. Further literature review and possible study should be conducted into what media characteristics can promote the neutralization of these negatively charged particles.

Vegetation

Vegetation has counter impacts on Hg removal effectiveness and should be studied further. Vegetation can be used to counter the creation of macropores due to cracking during the dry periods (Hatt et al., 2009). This may be useful to prevent untreated stormwater passing quickly through the system. At the same time, vegetation may conversely encourage macropore generation due to root growth and senescence (Paus et al., 2014). It would be useful to study vegetation impacts on mercury removal, both with and without irrigation.

Also, it would be useful to identify and test out the various potential plants for Hg hyperaccumulation in bioretention units. Future studies should investigate which hyperaccumulators are best for Hg accumulation and in the Bay Area climatic zone, the impact on Hg capture via the other mechanisms (e.g. does vegetative uptake replenish the available sorption sites), and the related maintenance requirements.

Submerged Zones

The use of submerged zones has been recommended for improving PCB degradation and preventing bioretention units from drying out. Manipulation of native rhizospheric bacteria is the most important tool for in situ elimination of PCBs. This could be accomplished by encouraging a co-existence of aerobic and anaerobic conditions with extra importance placed on anaerobic conditions. One way to encourage anaerobic conditions is to include a submerged zone with an electron donor, such as shredded newspaper, to stimulate anaerobic degradation of higher-chlorinated PCBs (LeFevre et al., 2014). A submerged zone at the bottom of a bioretention unit will also help maintain moisture, preventing drying out and macropore generation as well as decreasing oxidation which encourages dissolution (Blecken et al., 2009). Submerged zones, however, have not been tested with Hg relative to methylation of Hg. If

tested and a submerged zone results in Hg methylation, submerged zones should be reconsidered and likely not used.

Maintenance

Irrigation

Drying promotes oxidation and dissolution of metals. To prevent this from occurring, it may be useful to irrigate. It would be good to study different irrigation regimes and determine what works best to prevent dissolution.

Soil Profiles

Additional soil coring should be conducted to verify the vertical distribution of Hg and PCBs in other bioretention units (in addition to the study at the El Cerrito Bioretention Rain Garden).

Soil Washing

Soil washing is a water-based method for separating contaminants, which typically are sorbed onto clay, silt or organic soils, from coarser solids, and therefore reduces the total mass requiring further remediation or disposal. Given the substantial benefits potentially gained, the effectiveness of using soil washing in bioretention to concentrate target pollutants, reduce the mass of polluted soils for further treatment or disposal, as well as restoring hydraulic capacity, should be investigated further and determined whether it is a cost-effective strategy.

Soil Replacement

A cost-benefit analysis should be conducted on what to do when soil replacement is required.

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Appendix materials

Appendix A:

Table A1: Comparison between David et al. (2015) reported performance based on grabs versus performance reported in this synthesis based on pseudo-composites.

		Synthesis			David et al., 2015		
		Count	Mean	% Reduction	Count	Mean	% Reduction
SSC (mg/L)	Influent	3	21.2		6	21	
SSC (mg/L)	Effluent	7	20.9	1%	12	15	29%
TOC (mg/L)	Effluent	6	22.3		12	NR	
Sum of PCBs (ng/L)	Influent	3	0.733		6	0.73	
Sum of PCBs (ng/L)	Effluent	7	0.811	-11%	12	0.41	44%
Hg, Total (ng/L)	Influent	3	21.9		6	22	
Hg, Total (ng/L)	Effluent	7	20.2	8%	12	18	18%
Hg, Diss. (ng/L)	Influent	3	13.8		6	14	
Hg, Diss. (ng/L)	Effluent	7	9.18	33%	12	8.4	40%
MeHg, Total (ng/L)	Influent	3	0.63		6	0.63	
MeHg, Total (ng/L)	Effluent	7	1.45	-130%	12	1.6	-154%
Cu, Total (ug/L)	Influent	3	46		6	46	
Cu, Total (ug/L)	Effluent	7	9.9	78%	12	7.7	83%
Pb, Total (ug/L)	Influent	3	3.55		6	3.5	
Pb, Total (ug/L)	Effluent	7	2.45	31%	12	1.7	51%

Appendix B:

Water Quality Data – see excel spreadsheet named “San Pablo Spine Synthesis – Water Quality Data”