Fremont Tree Well Filters | LID Performance on a Redeveloped Urban Roadway

Technical Report

1. Introduction

This report complements the Fremont Tree Well Filter summary report by providing technical detail on the monitoring and analysis methods, data quality and results, as well as providing some suggested improvements for future GI monitoring. The intended audience includes stormwater managers, engineers and scientists, as well as city and environmental planners.

2. Background and Study Objectives

Over the past 100 years, urban drainage systems in the Bay Area have been designed to efficiently capture stormwater run-off from impervious surfaces and convey it to local rivers, creeks, or directly to San Francisco Bay thus protecting people, and urban infrastructure. Unfortunately, this design has led to the unintended consequences of poor water quality and a reduction in infiltration and subsequent base flows in urban creeks. In part due to urban runoff, San Francisco Bay is impaired by a number of pollutants including mercury, chlordane, dieldrin, DDT, dioxin compounds, furan compounds, PCBs and exotic species per the 2006 Clean Water Act 303d list of Water Quality Limited Segments. In addition, traditional urban landscapes are challenged by air quality and greenhouse gas emissions, elevated temperatures, accommodation of vehicular, bike, and pedestrian road uses, aesthetics, and habitat for local wildlife (e.g. butterflies, birds, and larger animals). Low impact development (LID) or Green Infrastructure (GI) (the processes of greening cityscapes) is a re-emerging approach that provides the opportunity to prevent (in new development) or reverse (in existing development and in re-development) these impacts by slowing, spreading, and infiltrating urban stormwater. LID is an innovative approach for managing stormwater runoff and provides a multitude of benefits including improved water quality, reduction of stormwater peak flow and volume, augmentation of groundwater basins, carbon sequestration, heat and greenhouse gas reduction, creating and connecting neighborhood green spaces and habitat, and traffic calming.

The 2009 version of the Municipal Regional Stormwater NPDES Permit required municipalities throughout the San Francisco Bay Area to implement on-site stormwater management measures for all projects that create or replace 10,000 square feet or more of impervious surface. However, there remained considerable uncertainty about the cost and magnitude of water quality improvements that could be achieved for each of the wide suite of pollutants of concern (POCs) impacting water quality in and around San Francisco Bay. In the public right-of-way, there are challenges with retrofitting onsite stormwater management measures within existing public space. Space for stormwater management measures competes with utilities, landscaping, sidewalks, and bike lanes. LID performance data do exist (flow, suspended sediment, some trace metals, PAHs, pathogens, and nutrients) for temperate systems with more consistent rainfall distribution. However, there remains limited to no performance data for semi-arid systems (IBMP Database, 2012). Additionally, in 2009, no performance data existed for the high priority pollutants (mercury species and trace organic contaminants) in the San Francisco Bay region and there also remains limited information regarding the proper operation and maintenance of these systems and the costs of this maintenance. The permit called for implementing 10 pilot LID retrofits. The permittees were asked to document the challenges, maintenance costs, lessons learned and water quality outcomes from these pilot projects to help inform decisions about effective and viable options for water quality improvement.

To meet these challenges, the City of Fremont developed a tree well filter system that integrates the requirements for full-size street trees and stormwater management into one device (Figure 1). One of the main drivers for the development of the tree well filter (TWF) was to create an open-bottom system to allow trees to root freely in native soil. The concrete-box proprietary systems available on the market at the time limited the type and size of tree that could be utilized in the system since roots are confined in the box. In addition, the City was concerned about the availability of the proprietary media in the long term, and therefore wanted to design a system that would use locally sourced soil.

The City designed TWF has a unique, subsurface-loaded design in which stormwater is introduced into the treatment measure via distribution pipes embedded in a Class II permeable layer, rather than on the surface of the TWF (Figure 2). The result of this innovation is that the TWF integrates well with the traditional suburban landscape which is an aesthetic that the City prefers. The TWFs are hydraulically-sized according to the Municipal Regional Stormwater NPDES Permit (MRP) Provision C.3.d. combination flow and volume design basis such that 80% of total runoff is managed over the life of the project. Soil used in the TWF meets the specifications included in Attachment L of the MRP; specifically, it is composed of 60% ASTM D 422 sand and 40% compost passing the Seal of Testing Assurance Standards with the intent of achieving a long-term infiltration rate of 5 inches per hour over the life of the facility. Stormwater initially enters the system through curb cuts which direct flow to a trash capture inlet. The trash capture inlet contains two compartments separated by a louver, behind which trash and large debris are captured prior to stormwater entering the second compartment. The raised inlet pipe in the second compartment allows stormwater to slow as the sump fills and coarse particles to settle out prior to stormwater entering the distribution pipes. The benefit of this design is that trash and road grime remain in the trash capture inlet and out of the distribution pipes, meeting the MRP Provision C.10 five mm trash capture requirement while also limiting clogging and extending the life of the treatment soil. In addition, the trash capture inlet facilitates maintenance by keeping most trash and debris in a centralized location for relative ease of maintenance via a vactor truck.

To test the effectiveness of pollutant removal and stormwater capture of the subsurface-loaded design, the City constructed an identically sized traditional surface-loaded TWF immediately adjacent to the subsurface-loaded TWF, ensuring that the storm hydrology and pollutant source areas were similar and thereby creating a paired sampling design. The surface-loaded TWF also included the same trash capture inlet as the subsurface loaded TWF; the only difference being that the stormwater inlet for the surface-loaded TWF discharges to the surface of the facility rather than discharging into distribution pipes. Both tree well filters were evaluated to determine the efficacy of pollutant removal and maintenance costs.

In this study, the Fremont TWFs were monitored over three years, first through qualitative observation and then through collection of stormwater samples for pollutant analysis during five storm events. The primary goals of this study were to: 1) qualitatively assess whether the TWFs were treating the permit-required volumes and flows (80% of the stormwater runoff volume or flow rates up to 0.2 inches/hr), and 2) measure the percent reduction in pollutant concentrations in each TWF. This study is helping fill important data gaps while testing LID performance for a unique set of climatic conditions and pollutants.

3. Methods

Site Description

This project retrofitted a moderate density urban feeder street with green stormwater infrastructure to help improve city aesthetics and treat urban runoff. The tree well filters (TWFs) were constructed on Osgood Road in Fremont, California (Figure 1A), where annual rainfall averages 14.3 inches (WRCC, 2014), 95% of which generally occurs during the months of October through April.

The total project watershed area occupies 0.34 acres in a primarily commercial and light industrial area. The catchment for each tree well filter is half the project area, or 0.17 acres. Near-field land uses include: the Assembly Hall of Jehovah's Witnesses, a large religious facility with a significant amount of parking area and landscaping, as well as a mixture of office buildings and light industrial/manufacturing building. The TWF drainage areas are composed of arterial roadway surfaces serving these adjacent land uses in addition to flow-through traffic. The specific location of the site or sampling area is shown in Figure 1. Osgood Road had average daily car trips ranging from approximately

10,000-15,000 prior to the improvement project. Originally, Osgood Road was a single lane road in both directions; the current configuration after the improvement project is two lanes in both directions.

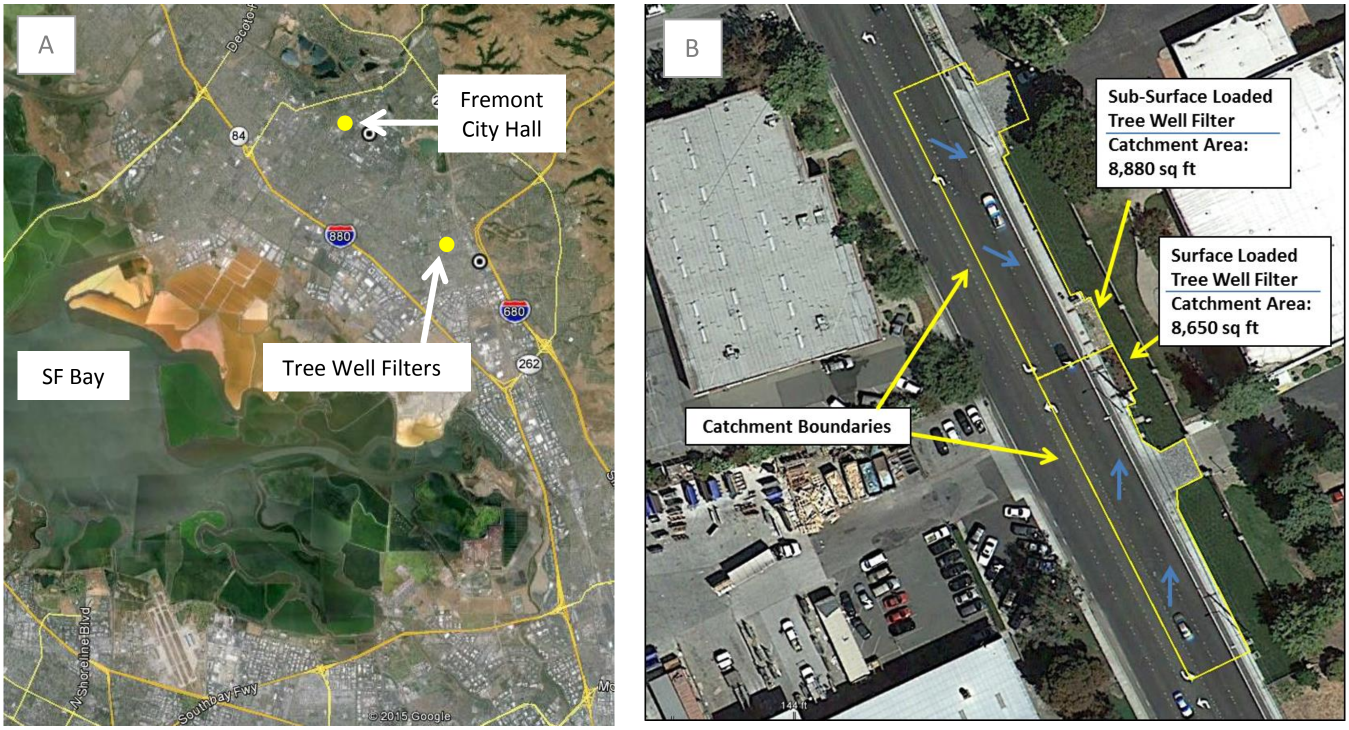


Figure 1. A) Location of the Fremont tree well filters relative to San Francisco Bay and the dense urban landscape of the southeast San Francisco Bay Area. B) The two tree well filters and their respective subcatchment boundaries.

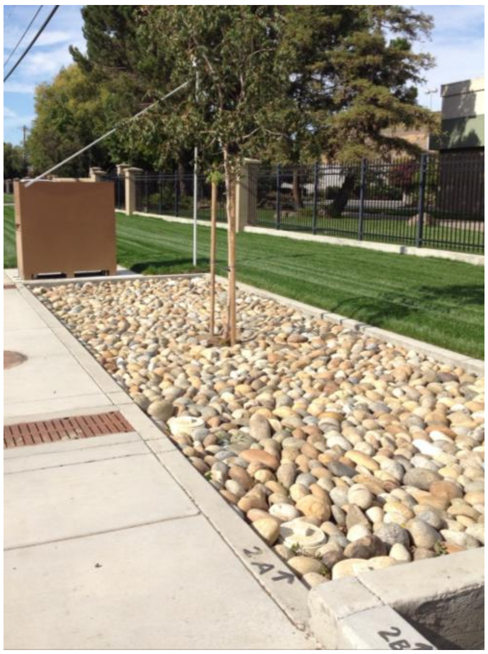
Two distinct TWF configurations were designed and built side-by-side so that they could be tested against one another for efficacy of pollutant removal and maintenance costs. The subcatchments were nearly identical in size and land use characteristics (Figure 1B). There were two primary differences between the two TWFs; the stormwater loading mechanism (loading from the surface or via a subsurface perforated distribution pipe running the length of most of the perimeter of the TWF) and the depth of the media. Within the subsurface loaded TWF, there is approximately 30 inches of a Class II Permeable layer and treatment soil between the perforated distribution pipe and the sub-drain. Within the surface loaded TWF, there is approximately 21 inches of media (overlying the sub-drain) along with 6 inches of surface ponding depth. More specifications are provided below in Figure 2.

Field Methods

During seven storm events, SFEI monitored the two TWFs. During the first two storm events (occurring in spring 2012) only qualitative observations were made about hydrology, trash, bypass and general functioning to support the final quantitative monitoring design. The remaining five storm events spread over Water Year 2013 and 2014 included sample collection for water quality analyses. Observations of flow characteristics were recorded and rainfall was measured on site using a Campbell Scientific TE525 Tipping Bucket rain gauge. Water quality sampling involved the collection of up to four discrete grab samples at the inlet and outlet of each TWF over the course of each storm. Clean hands sampling protocols were followed during sample collection. Either an ISCO 6712 pumping sampler or peristaltic Cole Parmer Masterflex E/S Portable Sampler was used to pump water into each discrete sampling container using cleaned (Teflon) or new and cleaned (silicon) tubing (Figure 3). Sample water for dissolved nutrients was filtered in the field by attaching a 0.45 µm capsule filter to a syringe. Sample water for dissolved metals was filtered in the analyzing laboratory. Turbidity was recorded periodically by onsite analysis of water samples using a portable Hach 2100P turbidimeter, or brought back to the laboratory for measurement. In most instances analysis was completed within or near to the EPA specified hold time of 48 hours, but generally, due to low turbidity (<100 NTU) and the use of vigorous agitation prior to measurement and no evidence of a bimodal population, there can be reasonable confidence in the data quality.

The sampling plan changed adaptively during the course of the project, first after the measured inlet PAH concentrations were below 1,800 ng/L, secondly because monitoring occurred during such dry years that an additional year of water quality monitoring was added to the project so that the allotted number of storms could be sampled, and lastly after water quality samples from the first two storms yielded no significant differences in concentrations at the inlets to the adjacent TWFs. Although sample sizes were very small, these observations were logical given the simplicity and homogeneity of the catchment area that was largely comprised of redeveloped road surfaces, and the absence of any known source areas. Based on these findings and this logic, decisions were made to discontinue sampling for PAHs altogether and inlet sampling at the subsurface-loaded TWF.

Subsurface Loaded tree well filter



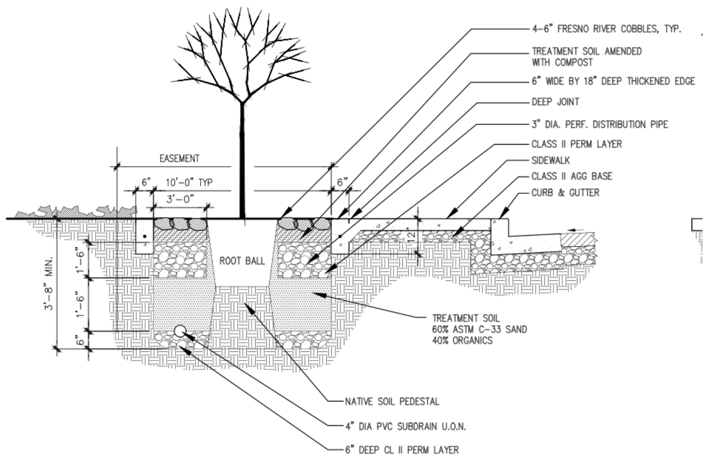
Trash and sediment capture area at the two in-line inlets.

Media layers:

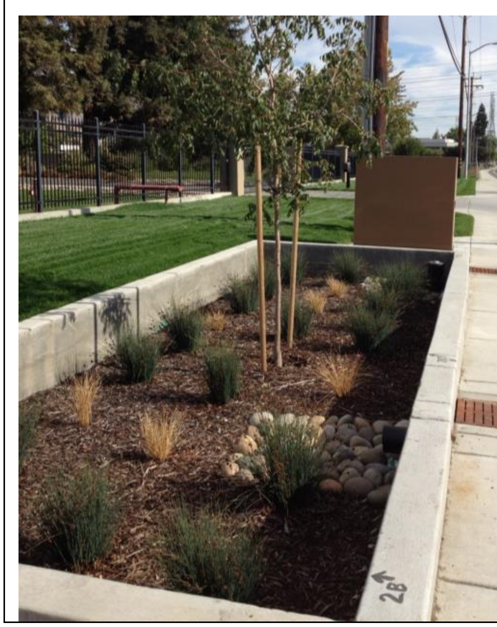
- 4-6" Fresno River Cobbles line the top

Treatment soil meeting the specifications in MRP Appendix L amended with compost

- 18" Class II perm layer
  - Within layer, 3" diameter perforated distribution pipe
- 18" treatment soil (60% ASTM C-33 Sand, 40% compost)
  - At bottom of layer, 4" diameter sub-drain
- 6" deep Class II perm layer



Surface Loaded tree well filter



Trash and sediment capture area at the two in-line inlets.

Media layers:

- 6" ponding depth (includes 3" mulch layer)
- 18" treatment soil meeting the specifications in MRP Appendix L (60% ASTM C-33 Sand, 40% organics)
  - At bottom of layer, 4" diameter sub-drain located approximately 3 ft below surface
- 6-12" deep Class II perm layer

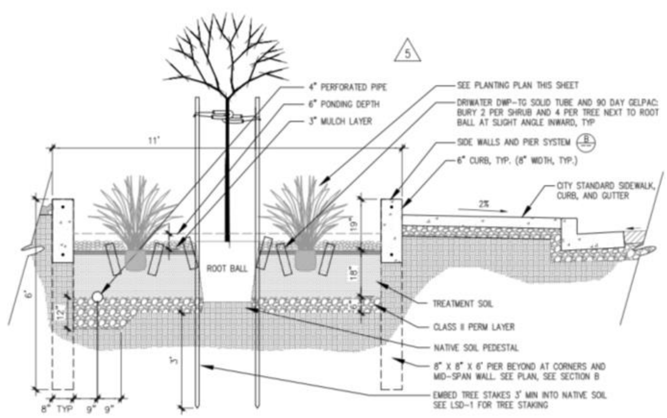


Figure 2. Photographs of the two Fremont TWFs and their respective sectional details.

Quality Assurance of the Chemical Analysis Data

Water quality samples were analyzed for polychlorinated biphenyls (PCBs: 40 congeners), polyaromatic hydrocrabons (PAHs: 25 analytes), total mercury (HgT), total dissolved mercury (HgD), total methyl mercury (MeHgT), total copper (CuT), total dissolved copper (CuD), suspended sediment concentration (SSC), ammonia (NH_3),nitrate plus nitrite (NO_3 + NO_2), total N (TN), total P (TP), and dissolved phosphate (PO_4). The analyzing laboratories and methods are recorded in Appendix A, along with a Quality Assurance narrative for each analyte. Quality assurance metrics for all analytes including sample count, percent non-detects, laboratory and field blank concentrations, method detection limits, recoveries from certified reference materials and matrix blank spikes, and relative standard deviations of field laboratory replicates are recorded in Appendix B Tables 1 and 2.

The quality of the chemical data was generally acceptable for all analytes. Nutrient data were generally acceptable. MDLs were sufficient with only dissolved NO_3 + NO_2 (13%) and dissolved NH_3 (16%) having non-detects (ND). Ammonia was found in one field blank at a concentration 2x the MDL (0.039 mg/L; MDL 0.015 mg/L; average MDL for lab blanks 0.026 mg/L), which was about 14% of the average concentration found in the field samples (0.28 mg/L). PCBs had some quality assurance issues mostly as the result of very low concentrations. About 12% of the congeners were not detected in the field samples and about 35% of the PCBs had some contamination in at least one of the method blanks. Five of 40 (13%) PCB field samples were censored due to having concentrations <3x the blank result (by batch). For Cu and Hg species, there were only one or two non-detects per analyte and matrix and otherwise all quality assurance metrics were good.

Figure 3. A) ISCO pumping sampler set up at the surface-loaded TWF inlet; SFEI staff member checking Cole Parmer peristaltic pumping sampler at subsurface-loaded tree well filter outlet. B) Stormwater runoff flowing into surface-loaded tree well filter during a monitored storm event.

Data Analysis

The Mann-Whitney rank sum test was used to evaluate statistical difference between the medians of the influent and effluent. This non-parametric statistical test was chosen because it operates on the entire dataset rather than data pairs[1]. Additionally, this test is in standard use within the International Stormwater BMP Database, data and information from which provide useful information in comparison to the Fremont TWF designs. For particulate associated pollutants, particle ratios (ratio of pollutant concentration to SSC) were calculated as one method for comparing the data but it is acknowledged that since particle ratios are a function of the pollutant and sediment concentrations, decreases in particle ratios are not always indicative of positive performance.

[1] "Pollutant layover" (described later in this report), or residence time, within the TWF in which pollutants entering the LID exit the LID in a later storm event confounds direct comparison of inlet and outlet samples from the same event.

4. Results

Monitored Storm Events and Turbidity Characterization

The TWFs were observed in WY 2012 during two short duration storm events in the spring with total rainfall depths of 0.23 and 0.46 inches. From these qualitative observations, it was noted that flow into the TWFs from each of the highly impervious catchments occurred rapidly in response to rainfall and quickly decreased after rainfall cessation. The surface-loaded TWF experienced outlet flows earlier than the subsurface-loaded TWF. Bypass occurred at the inlet of both units during the larger of the two storm events, though the proportion of volume that bypassed appeared to be much greater at the subsurface-loaded TWF. Conceptually these observations make sense relative to the volume of stormwater that could be infiltrated in a given amount of time at each TWF: the surface-loaded TWF could accept more runoff during this intense event because stormwater can pond above and then infiltrate over the entire surface area of that unit, which also resulted in the storage layer under the drain pipe filling more quickly and leading to earlier runoff from the tree well. Conversely, the subsurface-loaded TWF was limited to infiltrating the surface area of the openings in the perforated distribution pipe. This limitation led both to the storage area beneath the drain pipe taking longer to reach capacity and delaying stormwater from exiting the system out of the drain pipes, as well as the inlet being overwhelmed more quickly and resulting in a greater proportion of bypass. Water ponded at the top of the surface loaded TWF during both storm events. The larger storm event had water depths up to 12 inches at the TWF's primary inlet trench. Trash identified in the inlet trenches during these two observation events included Styrofoam pieces, candy wrappers, bottle caps, cigarette butts, small pieces of plastic, and leaf litter. Most trash was small in nature and confined to the first compartment in the trash capture inlet, and did not seem to obstruct water inflow from the trench into the TWF. These observations were used to refine and finalize the field sampling program planned for the following wet season.

Five storms of differing magnitude and duration were monitored for water quality, including two at the beginning of WY 2013 and three in WY 2014. These two years had below average rainfall (90% and 48% of normal for WYs 2013 and 2014, respectively). The five monitored storms ranged in duration from 4 to 24 hours and included total rainfall depths ranging between 0.15 and 2.32 inches. Storms with these characteristics are relatively common in Fremont: a 5-year, 24-hour storm is 2.42 inches; a 5-year, 3-hour storm is 1.04 inches; 1-year, 24-hour storm is 1.36 inches; a 1-year, 3-hour storm is 0.64 inches (NOAA Atlas 14, 2015).

Turbidity was measured throughout the storms during water quality sampling. The exceedance probability for the high frequency turbidity data (Figure 4) indicates a similar median for inlet and outlet turbidities, and the surface-loaded outlet was slightly higher than the subsurface-loaded outlet. The inlet turbidity varied over a broader range (3 – 376 NTU) compared with the outlet turbidities (which ranged between 9 and 204 NTU). This is a first indication of potentially low water quality performance from the TWFs since system losses sometimes exceed treatment benefits during multiple time points within storms. The plot shows that when turbidity was high, the TWFs appeared to reduce turbidity quite well. In contrast, performance was lower or negative at lower turbidities. Higher turbidities and suspended sediment concentrations in effluent may need to be addressed especially if effluent were to exceed water quality standards. These results are similar to findings from other local LID water quality studies (Gilbreath et al., 2012a) because the filtration process of the stormwater passing through the tree well filters modulates the incoming turbidity and exports a more uniform suspended sediment concentration (see Figure 6 in Water Quality Monitoring Results section). Individual measurements of turbidity throughout the five monitored storm events are plotted in Figure 5 along with rainfall for each storm.

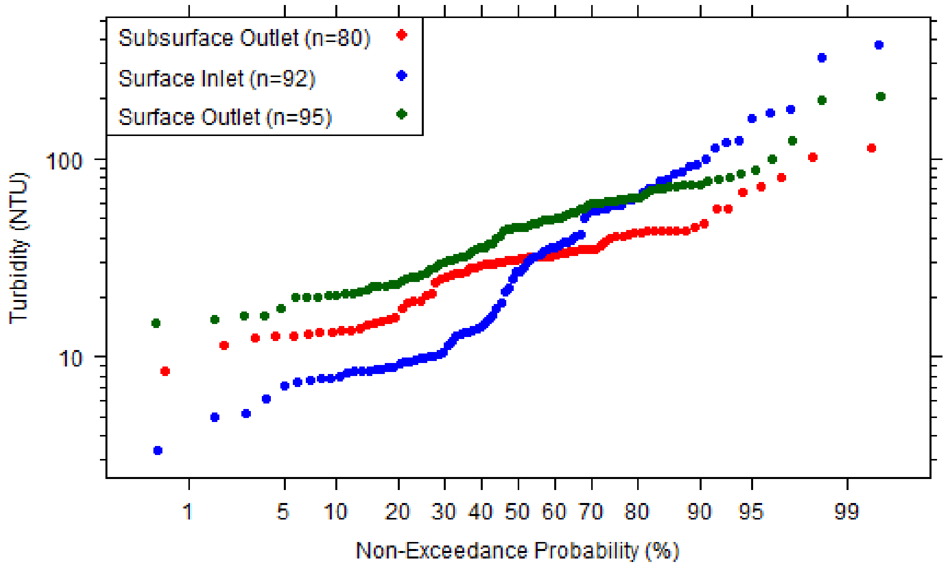


Figure 4. Probability plot for high frequency turbidity data.

Water Quality Monitoring Results

Based on the data from the first two storms events, differences in the pollutant concentrations at each of the two inlets were evaluated and determined to be insignificant (pairwise t-test, 95% confidence interval). This observation provided the opportunity to simplify the sampling design for this component and apply the saved resources to other aspects of the monitoring program. Therefore, after stakeholder consultation, it was decided to only sample the surface-loaded inlet in the subsequent storms. (Note: only inlet data for the surface loaded TWF was included and presented in the graphs and statistics in the body of this report.)

Median concentrations of inlet samples were lower than median concentrations of all outlet samples (both TWFs combined) for all pollutants except NH_3, SSC and MeHgT, which decreased at the outlet, and PCBs, CuT, CuD and TKN, which had no significant difference between inlet and outlet samples (Table 1). Similarly, median particle ratios between inlet and outlet samples all increased except for PCBs and MeHgT, which had no significant change.

In 35 samples, SSC ranged between 8.4 and 399 mg/L at the inlet, compared to 5.7-136 and 7.3-95 mg/L at the subsurface and surface-loaded outlets, respectively (n=33 at each outlet). The sum of PCBs was generally low at the inlet and outlets, with inlet maximum concentrations 11.4 ng/L and maximum outlet concentrations about half that, though median PCB concentrations at the inlet and outlets were approximately the same. Total and dissolved Hg were generally higher at the outlets than the inlet, and had a greater percentage in the dissolved phase at the outlets than the inlet (averaging approximately 50% in the dissolved phase at the outlets versus 31% at the inlet). Total MeHg was one of the few analytes to decrease at the outlets, with greater decreases at the subsurface-loaded TWF outlet than the surface-loaded outlet. Copper species did not clearly increase or decrease between the inlet and outlets, though the range of concentrations was more variable at the inlet and less so at the outlets. Similar to Hg, the percentage of Cu in the dissolved phase shifted from an average of 51% at the inlet to approximately 80% at the outlets.

Generally greater concentrations of nutrients appear to be exiting than entering the TWFs[2]. Total N, dissolved NO_3 + NO_2, TP and PO_4 all varied within a narrow range at the inlet and had significantly higher and more variable concentrations at the outlet. TKN was also generally higher at the outlet, but not significantly, whereas NH_3 was the only nutrient to decrease significantly between the inlet and the outlets of these systems. A typical dynamic for nitrogen species in bioretention is nitrification of NH_3 to NO_3 + NO_2 (Taylor and Cardno TEC, 2013), and therefore it is perhaps unsurprising to see decreased NH_3 concentrations along with increased NO_3 + NO_2. Multiple factors, or a

[2] It is also possible that the sod adjacent to the TWFs contributed nutrients. The sod is lush and likely to be fertilized. Runoff from this small area of sod may have flowed directly into the TWFs and not measured at the TWF inlets.

combination of factors, may explain the much higher effluent concentrations. Elevated nutrient concentrations may have entered the TWFs in previous storm events and exited during the storm events measured – the concept of pollutant layover described earlier. In this case, the TWFs are not the source of the nutrients. Alternatively, the TWFs may be the source of the nutrients from the compost media, the plant potting material, maintenance fertilizer or nutrient transformations via nitrification and denitrification and other potential transformations.

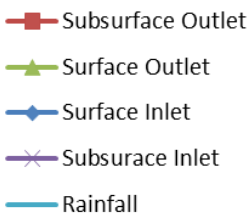
Differences between the TWF outlet concentrations:

Total methylmercury measured at the two TWF outlets was the only analyte with significantly different concentrations at the 95% confidence level. Additionally, the surface-loaded TWF had median concentrations approximately twice as high as the subsurface loaded TWF. We don't have enough data to understand why this difference exists, and there is no data in the published literature on MeHg processes within bioretention systems.

Other analytes that had significant differences (at the 90% confidence level) included HgD (higher at the surface-loaded outlet compared to the surface-loaded system), and the nutrients $NO_3 + NO_2$, TP and PO_4 (all higher at the subsurface-loaded outlet). It is most likely that the soil media properties in each of the TWFs were causing these differences in nutrient export. Both TWFs were designed to include 18 inches of treatment soil, consisting of 60% sand and 40% organics. The subsurface-loaded TWF also included a layer just under the cobble with an unmeasured depth that consisted of the same treatment soil and amended with compost. This additional compost-amended layer may be causing the export of more nutrients from the subsurface-loaded TWF. Additionally, the surface-loaded TWF has much more vegetation within it whereas the subsurface-loaded TWF only has a single small tree within it, potentially causing more uptake of nutrients in the surface-loaded TWF than the subsurface-loaded TWF.

Concentration variation between and within storms

For all analytes (except nutrients), the variation in inlet versus outlet samples across storms followed a similar trend to the turbidity, in which there was generally a broader range of variation, within and between storms, at the inlet than the outlet (Figure 7). Again, this pattern is similar to that observed in previous LID studies in the region (Gilbreath et al, 2012a). For nutrients, the converse was generally true. Also, the subsurface-loaded outlet is slightly less variable in export of the metals species than the surface-loaded outlet, but slightly more variable in the export of nutrients. Similar to turbidity, the TWFs temper the export concentrations for SSC, metals and PCBs.



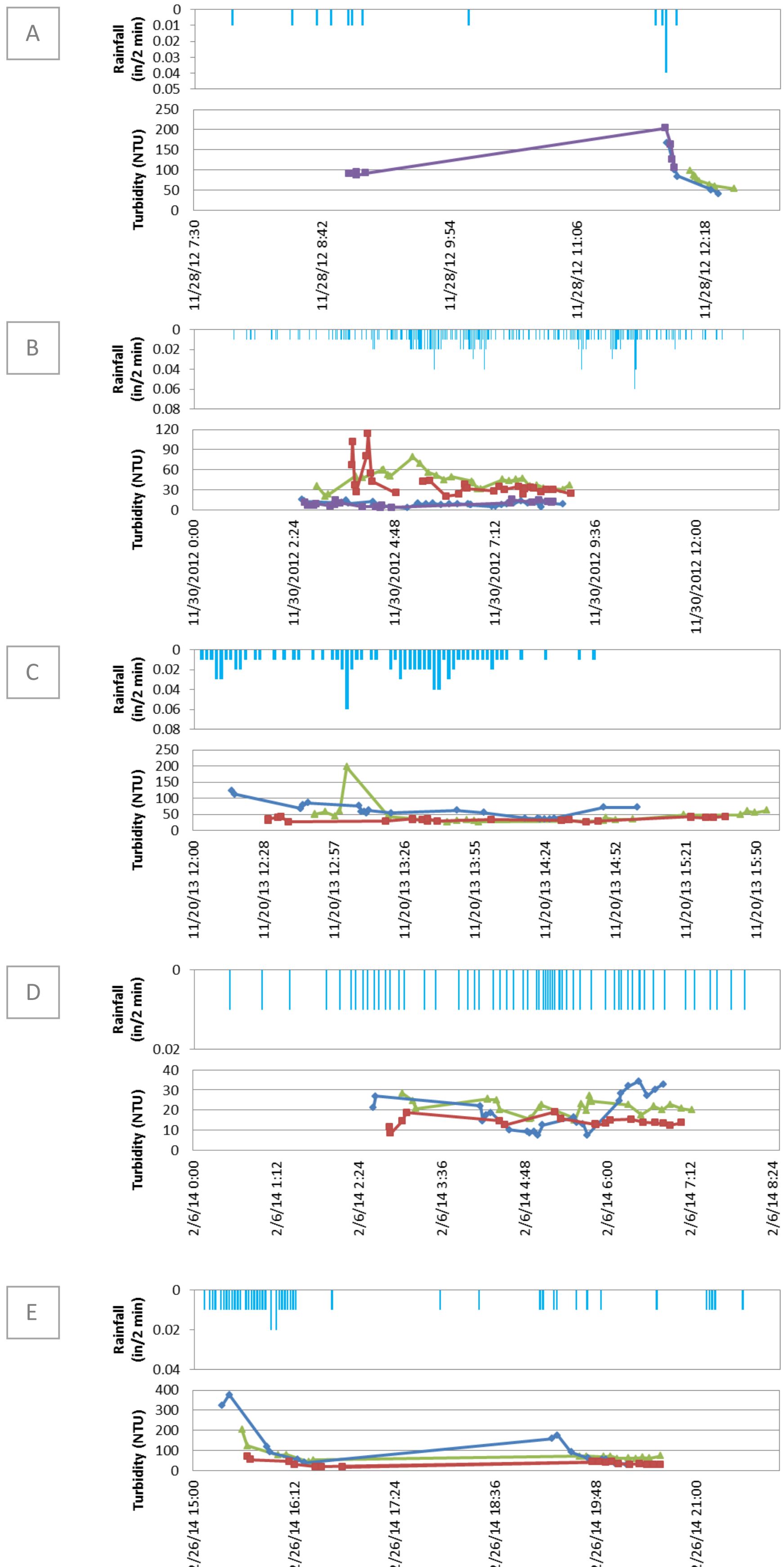


Figure 5. Inlet and outlet turbidity measured at each tree well filter during the five events monitored for water quality. Graphs are ordered chronologically from A-E.

Table 1. Median concentrations and particle ratios for all analytes studied. Non-parametric significance of differences evaluated using the Wilcoxon–Mann–Whitney two-sample rank-sum test. Note: in columns referring to median change from inlet to outlet, a positive number reflects an increase in concentrations from inlet to outlet and a negative (-) number reflects a decrease in concentrations from inlet to outlet. Highlights: Green = statistically significant reduction between influent and effluent concentration; Red = statistically significant increase between influent and effluent concentration; Yellow = reduction between influent and effluent concentration, but the difference was not statistically significant; Orange = increase between influent and effluent concentration, but the difference was not statistically significant.

Concentrations

	Inlet Median	Subsurface Outlet Median	Subsurface Median Change	Surface Outlet Median	Surface Median Change	Wilcoxon *p* value - Inlet vs Outlet	Significant? a=0.05	Significant? a=0.10	Wilcoxon *p* value - Subsurface vs Surface Outlet	Significant? a=0.05	Significant? a=0.10
Dissolved Ammonia (mg/L)	0.305	0.18	-41%	0.063	-79%	0.02	Yes	Yes	0.32	No	No
Dissolved Copper (ug/L)	7.39	9.26	25%	10.6	43%	0.23	No	No	0.25	No	No
Dissolved Mercury (ng/L)	1.94	6.28	223%	8.23	323%	0.00	Yes	Yes	0.09	No	Yes
Dissolved Nitrate + Nitrite (mg/L)	0.16	3.75	2240%	0.86	438%	0.00	Yes	Yes	0.06	No	Yes
Dissolved OrthoPhosphate (mg/L)	0.0735	1.4	1800%	0.76	934%	0.00	Yes	Yes	0.06	No	Yes
SSC (mg/L)	42	21	-50%	22	-48%	0.01	Yes	Yes	0.96	No	No
Sum of PCBs (ng/L)	1.87	1.62	-14%	1.72	-8%	0.60	No	No	0.62	No	No
Total Copper (ug/L)	7.96	11.1	40%	12	50%	0.60	No	No	0.71	No	No
Total Kjeldahl Nitrogen (mg/L)	0.58	1.9	228%	1.5	159%	0.11	No	No	0.20	No	No
Total Mercury (ng/L)	8.39	14.8	76%	14.8	76%	0.00	Yes	Yes	0.69	No	No
Total Methyl Mercury (ng/L)	0.112	0.055	-51%	0.0965	-14%	0.01	Yes	Yes	0.03	Yes	Yes
Total Nitrogen (mg/L)	0.792	6.7	745%	3.2	304%	0.00	Yes	Yes	0.11	No	No
Total Phosphorus (mg/L)	0.16	1.3	713%	0.93	481%	0.00	Yes	Yes	0.07	No	Yes

Particle Ratios

	Inlet Median	Subsurface Outlet Median	Subsurface Median Change	Surface Outlet Median	Surface Median Change	Wilcoxon *p* value - Inlet vs Outlet	Significant? a=0.05	Significant? a=0.10	Wilcoxon *p* value - Subsurface vs Surface Outlet	Significant? a=0.05	Significant? a=0.10
Sum of PCBs (ng/mg)	0.0578	0.0873	51%	0.0661	14%	0.79	No	No	0.53	No	No
Total Copper (ug/mg)	0.349	0.651	86%	0.689	97%	0.00	Yes	Yes	0.87	No	No
Total Kjeldahl Nitrogen (mg/mg)	0.0232	0.0656	183%	0.075	224%	0.00	Yes	Yes	1.00	No	No
Total Mercury (ng/mg)	0.195	0.609	212%	0.823	322%	0.00	Yes	Yes	0.51	No	No
Total Methyl Mercury (ng/mg)	0.00641	0.00208	-68%	0.00622	-3%	0.73	No	No	0.03	Yes	Yes
Total Nitrogen (mg/mg)	0.0323	0.248	668%	0.197	509%	0.00	Yes	Yes	0.54	No	No
Total Phosphorus (mg/mg)	0.00742	0.0612	724%	0.0583	686%	0.00	Yes	Yes	1.00	No	No

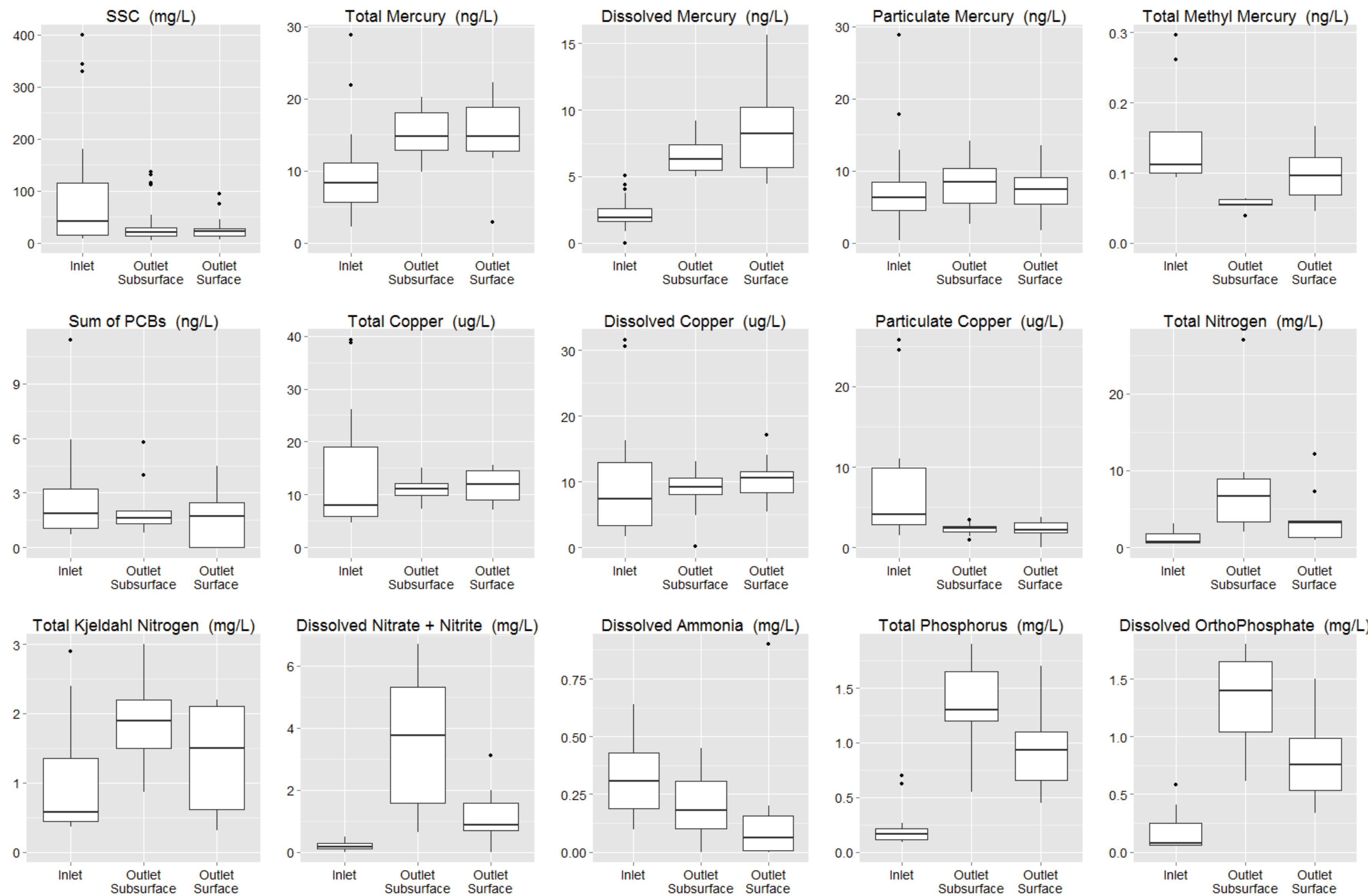


Figure 6. Distributions of concentrations measured throughout the study at the inlet (data from both tree well filters combined) and each tree well filter outlet.

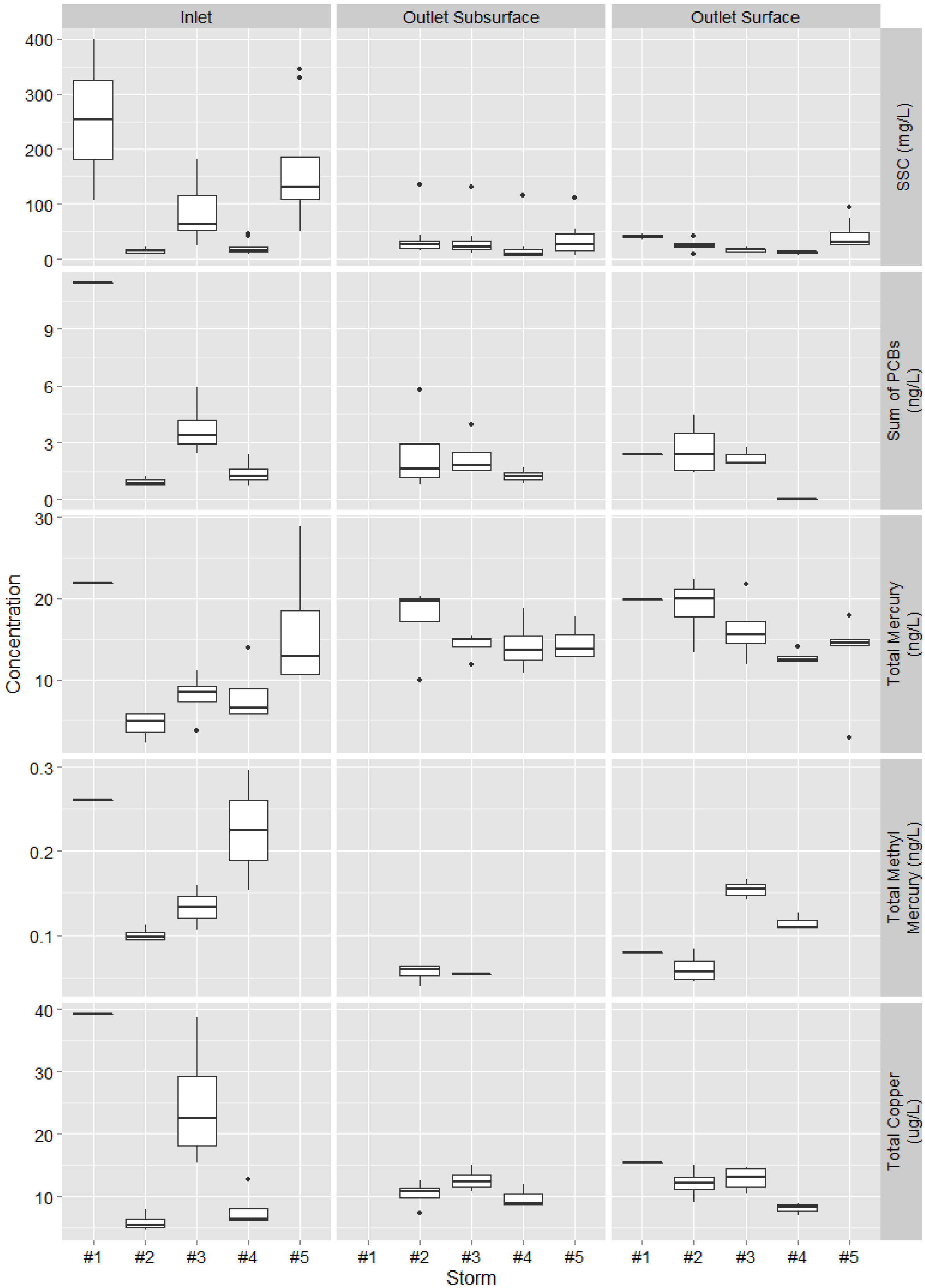


Figure 7. Box plots of analyte concentrations for each storm event. Note: some analytes only sampled in four storms.

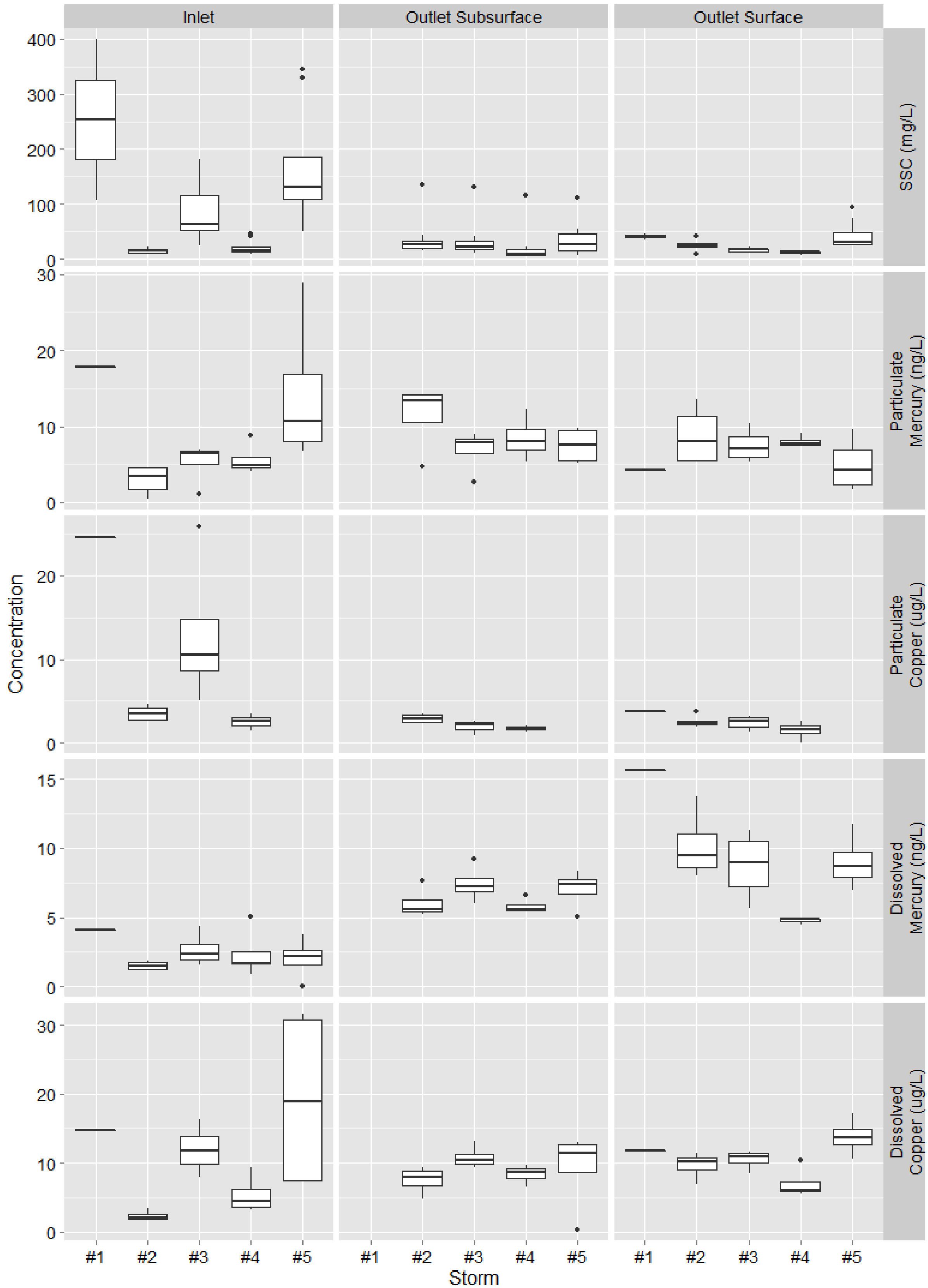


Figure 7 (cont). Box plots of analyte concentrations for each storm event. Note: some analytes only sampled in four storms.

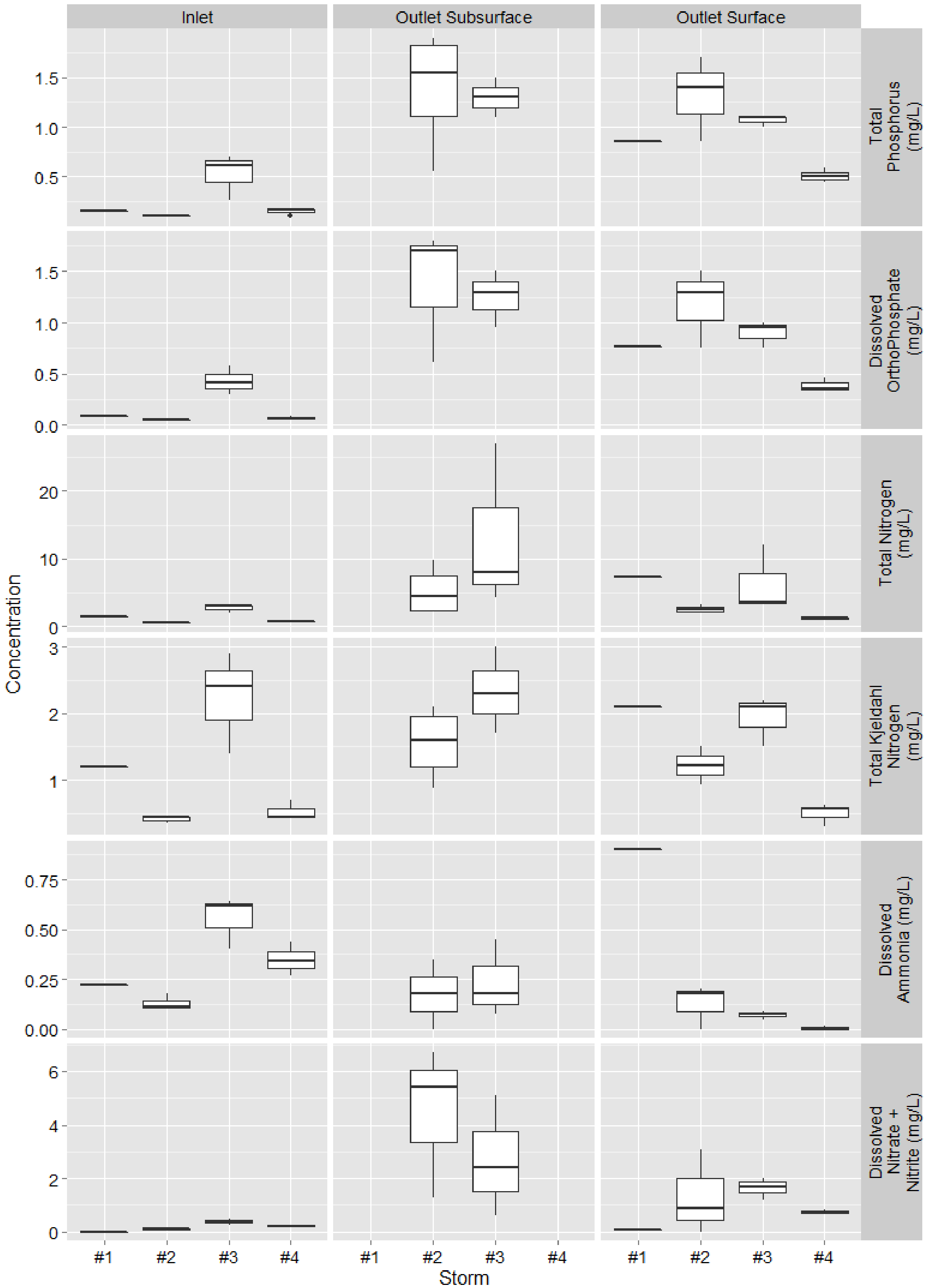


Figure 7 (cont). Box plots of analyte concentrations for each storm event. Note: some analytes only sampled in four storms.

4. Discussion

Do the TWFs meet the flow and volume-based permit requirements?

The Fremont TWFs were designed to meet the MRP C.3.d. permit hydraulic sizing requirements for the combination of flow and volume basis, and based on qualitative observations, it is likely they meet these sizing criteria. Treatment measures based on the combined flow and volume capacity requirements are designed to treat at least 80% of the total stormwater runoff, or minimally, flows with an influent rate of 0.2 in/hr. This study qualitatively assessed whether these hydraulic requirements were met through field observations made during six storm events of rainfall intensities varying between maximum rates of 0.21 in/hr and 0.72 in/hr (based on the maximum cumulative 20 minute rainfall for each observed storm) (Table 2). The TWFs captured 100% of the runoff during the two storm events with rainfall rates of 0.21 in/hr, whereas bypass was observed during three of the four events with rates greater than 0.32 in/hr (Figure 8 and Table 2). Based on these observations, it is likely the TWFs treat rainfall rates up to 0.2 in/hr.

Figure 8. Stormwater bypassing the TWF inlets and flowing directly into the storm drain untreated was observed during storm events with rainfall intensities of 0.33 in/hr and greater.

Table 2. Observations of inlet bypass during storms monitored, organized by maximum rainfall intensity.

Storm Date	Storm Duration (hrs)	Total Storm Event Rainfall (in)	Maximum Rainfall Intensity (in/hr)[a]	Observation of Bypass?
11/20/2013	4	0.89	0.72	Yes
4/12/2012	2	0.46	0.69	None at surface, but subsurface loaded TWF had substantial bypass
11/29 - 11/30/2012	24	2.32	0.57	Yes
2/26/2014	18	0.66	0.33	Yes, but shortlived
2/6/2014	11	0.61	0.24	Observations not recorded
3/27/2012	4	0.23	0.21	None
11/28/2012	4	0.15	0.21	None

[a] The maximum rainfall intensity is based on the maximum cumulative 20-minute rainfall for each storm, reported in inches per hour (the conversion requires multiplying the maximum 20-minute rainfall by 3).

Using the observational data coupled with assumptions about runoff and bypass using best professional judgment, it is estimated that the TWFs meet the annual runoff volume capture criteria in the MS4 Permit. A runoff coefficient (RC) was estimated for each storm event, based on the total rainfall for that event (larger storm events result in a greater proportion of the total rainfall running off) (Table 3). For all storm events with rainfall intensities >0.2 in/hr, the percentage of the runoff volume that bypassed the TWFs was estimated under two scenarios (moderate and high estimates) and the total bypass versus total runoff volume was calculated (Table 4). For all storm events with maximum rainfall intensity <0.2 in/hr, an assumption of no bypass was made. Under the moderate assignment of percentage bypass, 15% of the total volume would have bypassed, and under the high assignment of percentage bypass, 21% of the total volume would have bypassed (Table 4). To conclusively state whether the TWFs capture and treat 80% or more of the total stormwater runoff, flow monitoring of the inlets and overflow drain would be necessary. If TWF storm flow bypass is a concern, engineering modifications are possible (see recommendations section) that could improve the performance.

Table 3. Assignment of the estimated runoff coefficient based on total storm rainfall depth.

Storm Total Rainfall (in)	Runoff Coefficient Assignment
>1.2	95%
0.5 - 1.2	90%
0.25 - 0.5	80%
0.1 - 0.25	70%
0.05 - 0.1	50%
0.03 - 0.05	30%
0.03	10%
<0.03	0%

Table 4. Estimates of percentage total volume treated by tree well filters.

Bypass – Moderate Estimate

Storm Date(s)	Maximum 1 Hr Rainfall Depth (in)	Storm Duration (hrs)	Total Rainfall (in)	Maximum 10 Minute Rainfall Depth (in)	Precipitation Volume onto Catchment (ft^3)	Estimated Runoff Coefficient	Estimated Runoff Volume (ft^3)	Estimated Bypass %	Estimated Bypass Volume (ft^3)
12/23/2012	0.54	12	1.91	0.32	1,413	95%	1,343	30%	403
11/20/2013	0.52	4	0.89	0.14	659	90%	593	30%	178
12/1 - 12/2/2012	0.46	19	1.19	0.25	881	90%	793	30%	238
11/29 - 11/30/2012	0.42	24	2.32	0.13	1,717	95%	1,631	30%	489
11/17 - 11/18/2012	0.38	3	0.6	0.1	444	90%	400	20%	80
2/28 - 3/1/2014	0.36	28	0.93	0.16	688	90%	619	20%	124
2/26 - 2/27/2014	0.28	18	0.66	0.06	488	90%	440	10%	44
12/5/2012	0.26	3	0.33	0.09	244	80%	195	10%	20
12/22/2012	0.21	6	0.69	0.1	511	90%	460	10%	46
12/6 - 12/7/2013	0.21	2	0.32	0.08	237	80%	189	10%	19
Total estimated runoff volume in storms with maximum rainfall intensities <0.2 in/hr							4,225	0%	0
						Total	10,887	**15%**	1,640

Bypass – High Estimate

Storm Date(s)	Maximum 1 Hr Rainfall Depth (in)	Storm Duration (hrs)	Total Rainfall (in)	Maximum 10 Minute Rainfall Depth (in)	Precipitation Volume onto Catchment (ft^3)	Estimated Runoff Coefficient	Estimated Runoff Volume (ft^3)	Estimated Bypass %	Estimated Bypass Volume (ft^3)
12/23/2012	0.54	12	1.91	0.32	1,413	95%	1,343	40%	537
11/20/2013	0.52	4	0.89	0.14	659	90%	593	40%	237
12/1 - 12/2/2012	0.46	19	1.19	0.25	881	90%	793	40%	317
11/29 - 11/30/2012	0.42	24	2.32	0.13	1,717	95%	1,631	40%	652
11/17 - 11/18/2012	0.38	3	0.6	0.1	444	90%	400	30%	120
2/28 - 3/1/2014	0.36	28	0.93	0.16	688	90%	619	30%	186
2/26 - 2/27/2014	0.28	18	0.66	0.06	488	90%	440	20%	88
12/5/2012	0.26	3	0.33	0.09	244	80%	195	20%	39
12/22/2012	0.21	6	0.69	0.1	511	90%	460	20%	92
12/6 - 12/7/2013	0.21	2	0.32	0.08	237	80%	189	20%	38
Total estimated runoff volume in storms with maximum rainfall intensities <0.2 in/hr							4,225	0%	0
						Total	10,887	**21%**	2,306

Why weren't concentrations reduced, or reduced more? A look at concentration reductions from LID in other studies and the International Stormwater BMP Database

LID does not always result in water quality improvements for all pollutants. For example, in a meta-analysis of 44 peer-reviewed LID studies on phosphorous influent and effluent concentrations, phosphorous removal effectiveness ranged from -500% to 100%, with 18% of the studies having phosphorous release (a negative removal effectiveness) (Schechter et al., 2013). A brief review of stormwater quality and performance of local LID projects as well as the International Stormwater BMP Database (IBMP Database) illustrates that concentrations at the inlet (influent quality or effectively the magnitude of pollution in the catchment area), the specific pollutant and its source characteristics, and the type of LID all play a role in determining performance, in addition to other characteristics such as design specifications and maintenance challenges such as trash and leaf debris.

The LID type, pollutant and fraction matter

Different types of LID result in different degrees of water quality improvement which are dependent on the total volume control, mechanism(s) of pollutant removal and pollutants inherent within the LID itself. The IBMP Database compiles results from studies of all types of best management practices (BMPs; often used interchangeably with LID but including a broader variety of management practices) across the world (but mainly North American studies). Box and whisker plots of these results within the same pollutant category illustrate that different types of BMPs have different levels of performance. For example, Figure 9 illustrates that some BMPs are generally effective at removing phosphorous (i.e. composite, detention basin, manufactured device, media filter, porous pavement, retention pond and wetland basin all with statistically significant decreases) whereas other BMPs are on average net sources of phosphorous (i.e. grass strip, bioswale and green roof all with statistically significant increases)[3].

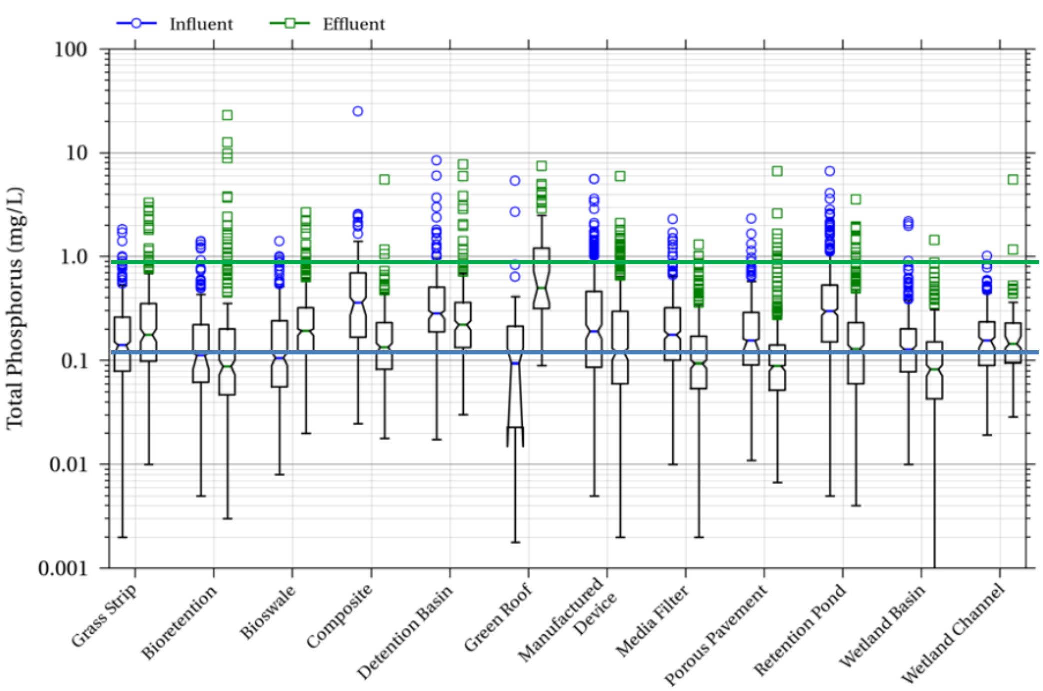


Figure 9. Total phosphorous concentrations at the inlet and outlet of various BMPs summarized in the International Best Management Practices Database. Note: Blue line across length of graph represents median inlet concentration measured at the Fremont tree well filters. The green line across the length of the graph represents the average of the median outlet concentrations at the two tree well filters. Relative to the range of results in the bioretention category, the Fremont TWF effluent is "outside the box", but within the range of results reported to the IBMP Database, whereas the influent is "inside the box".

[3] Excepting the TP, TSS, CuT and CuD graphs shown within this section, all other analytes for which the IBMP Database provides similar graphics are located in Appendix C.

The Fremont TWF designs installed on Osgood Road are most comparable to the bioretention category in the IBMP Database. The design aspects of a bioretention facility will have varying impacts on performance depending on the specific pollutant type and its fraction. For example, bioretention LIDs have been shown to have positive performance for particle-associated pollutants that readily settle or filter out (Hatt et al., 2009; Li and Davis, 2008). Bioretention has been less effective for dissolved pollutants (Trowsdale and Simcock, 2011), except to the degree that volume is reduced. Mixed results have been measured for nutrients (Hatt et al., 2009). These general findings are driven by the design specifics of bioretention and their expected mechanisms for pollutant removal.

Stormwater runoff diverted into bioretention LIDs work by filtering runoff through vegetation and soil media. Soil media can include mulch, compost, amended soil, and drain rock. Bioretention LIDs may or may not have subdrains underlying them, through which the filtered stormwater is exported out of the system to a storm drain system or receiving waters. The performance of a bioretention LID has much to do with how well the soil media filters out the pollutants of interest, and whether or not the soil media contains and leaches pollutants (e.g. the presence of a soil media enriched with nutrients or the application of nutrient-enriched fertilizers or copper fungicides can result in leaching of these pollutants). Additionally, internal processes may occur within the soil media of the bioretention itself that affect sorption and desorption of the pollutants, species transformations, and biological uptake. Bioretention performance on water quality is also largely impacted by volume control; because pollutant load reduction is a function of both pollutant concentrations and volume, bioretention that combines with significant volume reduction can lead to decreased loads of pollutants even when concentrations do not decrease.

Since sedimentation and filtration are the primary mechanisms by which bioretention removes pollutants, concentration reductions in bioretention tend to be greater for more particle-associated POCs than for pollutants in the dissolved fraction, and tend to be highly correlated with reductions in SSC or TSS. Additionally, the sources of the pollutants and the sediment characteristics of the catchment determine what size particle the pollutant attaches. For example, Hg and Cu from primarily aerial deposition and traffic-related activities and in low-sediment producing catchments tend to attach to extremely small particles (review by DeGroot and Weiss, 2008). It seems likely that the smaller the particle, the less likely it is to be filtered out as water passes through the compost-sand treatment media that is typical in many biofiltration designs.

The IBMP database box and whisker plots illustrate that some pollutants have mostly or exclusively positive performance results across all BMPs, whereas others have mixed performance or show no significant changes. For example, nutrients in effluent from bioretention tend to have mixed results given that the organic and compost media within a bioretention can leach nutrients (Figure 9, for example). Reduction in total suspended solids (TSS; for purposes of this report, comparable to SSC) appears to be very consistent across all BMP categories, including bioretention (Figure 10). Although CuT shows statistically significant reductions in each BMP category type, CuD shows few statistically significant differences (only the grass strip and retention pond categories) (Figures 11 and 12).

The Fremont TWF performance results for HgT and CuT (increases in median concentrations between 40 and 76%) are somewhat surprising given that SSC is reduced by approximately 50%. When the particulate fraction of these metals at the inlet is isolated by difference (total minus the dissolved fraction), there is a strong correlation between particulate Cu and SSC (R^2=0.97) and slightly less strong correlation between particulate Hg and SSC (R^2=0.8). The median particulate Cu reduction mimics the reduction in SSC (42 and 46% reduction between inlet each TWF outlet). For Cu, nearly all of the Cu that is retained is particulate and 80% of the Cu exiting the system is in the dissolved form. Similar results were found in another local LID study where Gilbreath et al. (2012a) measured poor performance for CuD reduction and approximately 90% of the effluent Cu was in the dissolved fraction. On the other hand, the TWFs do not appear to be very effective at filtering out Hg, even in the particulate form (particulate Hg increased 19 and 24% between the inlet and each of the TWF outlets). Similarly, although HgT reductions were seen in the Gilbreath et al. study, still approximately 50% of the effluent Hg was in the particulate form. As discussed by Gilbreath et al. (2012a), the conceptual working model is that coarser particles are more likely to be filtered out of the influent as it passes through the TWF whereas finer particles or those in the dissolved phase are more likely to pass through. It is most likely that the Hg and Cu sources in this watershed are primarily atmospheric deposition and from the vehicular traffic residues, both of which are likely to be in a very fine particulate or dissolved phase. Again, it is unclear why the TWFs seem to remove Cu particulate better than particulate Hg, but we propose that Hg in this watershed is likely associated with finer particles than Cu.

The data from these two studies suggest that if LID implementation is intended to target the reduction in Hg concentrations, more studies should be conducted to determine the particle size fractions most effectively filtered in bioretention and design specifications that may target sedimentation and filtration of smaller particle fractions, or improved sorption of metals (e.g. Davis et al., (2001) describe laboratory and pilot studies which implicate the surface mulch layer as being one of most important components in bioretention for metals removal). In the planning phases of bioretention projects, stormwater managers could then test the grain sizes prevalent in the catchment area.

It has previously been discussed that LID performance is known to vary in relation to site conditions and design constraints (Strecker et al., 2001; McNett et al., 2011, for example). In particular, LID projects in which the influent concentrations are particularly high tend to show greater reductions of pollutant concentrations in effluent than do LID in which influent concentrations are lower. Although this dataset is limited, comparing mean inlet concentrations for HgT, PCBs, and SSC against performance for the Fremont TWFs and two other regional LID studies (El Cerrito Rain Garden (Gilbreath et al., 2012a) and Daly City Library bioretention (David et al., proof completed)), the data supported the observation that LID with higher influent concentrations tend to result in greater reductions than LID with low influent concentrations (Figure 13). An important long-term goal is to monitor more LID in the semi-arid west for these target pollutants to better define these curves for differing LID designs (bioretention with and without subdrains, bioswales, pervious pavements, green roofs) and eventually be able to predict performance based on influent quality to support estimates of regional scale outcomes (perceived loads reductions towards TMDL goals).

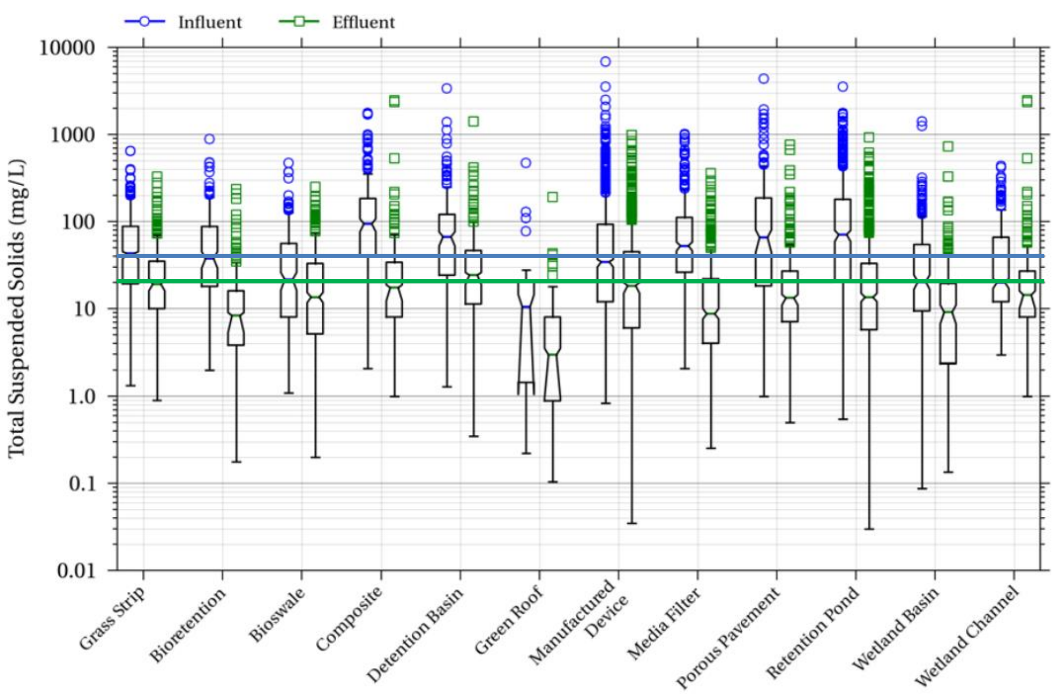


Figure 10. Total suspended solids concentrations at the inlet and outlet of various best management practices summarized in the International Best Management Practices Database. Note: Blue line across length of graph represents median inlet concentration of SSC measured at the Fremont tree well filters. The green line across the length of the graph represents the average of the median outlet concentrations of SSC at the two tree well filters.

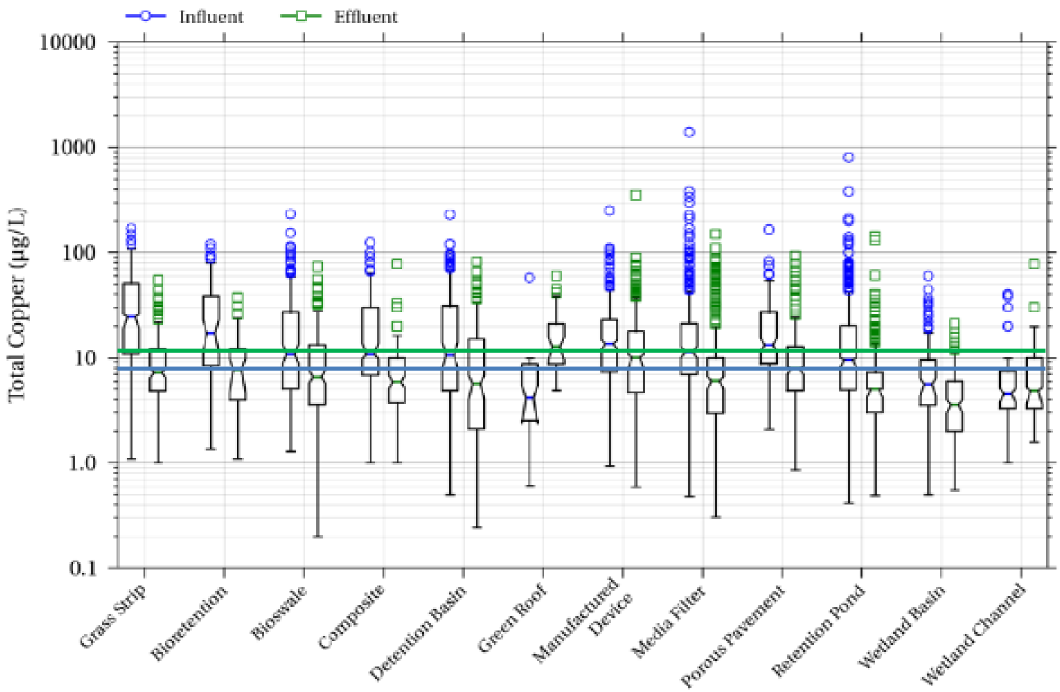


Figure 11. Total copper concentrations at the inlet and outlet of various best management practices summarized in the International Best Management Practices Database. Note: Blue line across length of graph represents median inlet concentration measured at the Fremont tree well filters. The green line across the length of the graph represents the average of the median outlet concentrations at the two tree well filters.

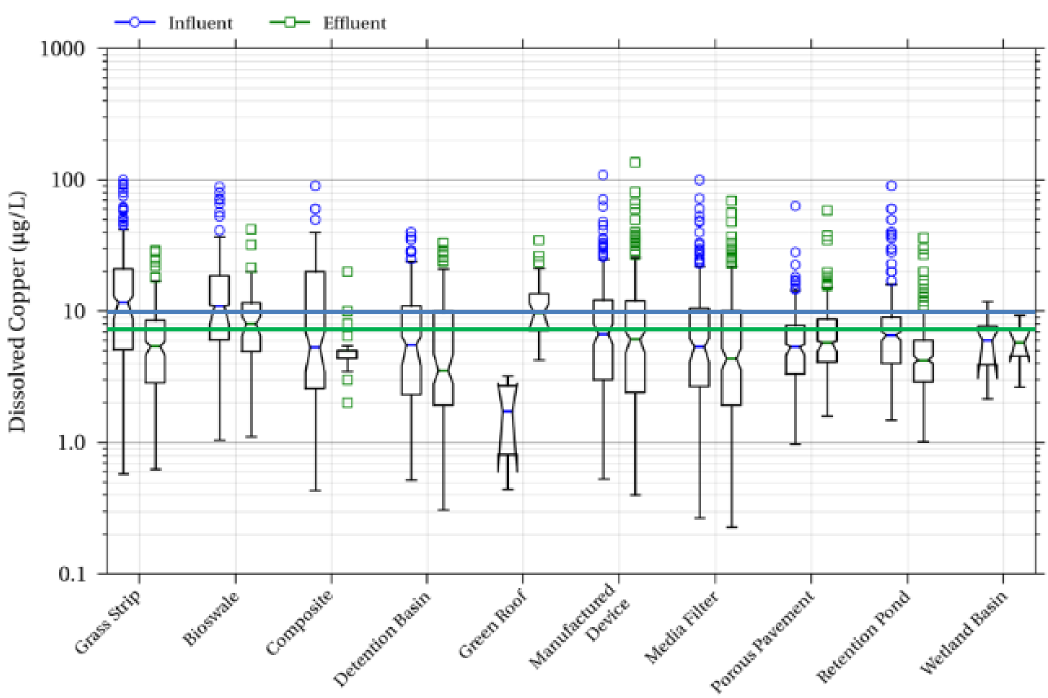


Figure 12. Dissolved copper concentrations at the inlet and outlet of various BMPs summarized in the IBMP Database. Note: Blue line across length of graph represents median inlet concentration measured at the Fremont tree well filters. The green line across the length of the graph represents the average of the median outlet concentrations at the two tree well filters.

The influent quality matters

Underlying the lower performance at sites with lower influent concentrations is the generally accepted concept that there are lower limits or irreducible concentrations, below which it is unlikely LID can *reliably* reduce pollutant levels. To put Fremont TWF influent and effluent concentrations in perspective, Table 5 reports median effluent concentrations for the two other regional LID studies (El Cerrito Rain Garden and Daly City Library bioretention), the median, 25th and 75th percentiles for bioretention studies in the IBMP Database, and median concentrations from untreated stormwater measured in predominantly urban watersheds across the Bay Area.

Influent concentrations to the Fremont TWFs are generally very low in comparison to Bay Area stormwater measured from larger, mixed-land use watersheds. Only CuD and NH_3 were exceptionally high relative to untreated stormwater measured in other Bay Area watersheds. PCBs, MeHgT and CuT concentrations measured at the Fremont inlet were in the lowest third of concentrations measured in other Bay Area watersheds, and all other analytes measured at the inlet had concentrations amongst the very lowest measured in the region. Consequently, the performance curves would suggest generally lower performance from the TWFs simply on account of low input concentrations, whereas they would be likely to perform better (based on this metric) if input concentrations were higher.

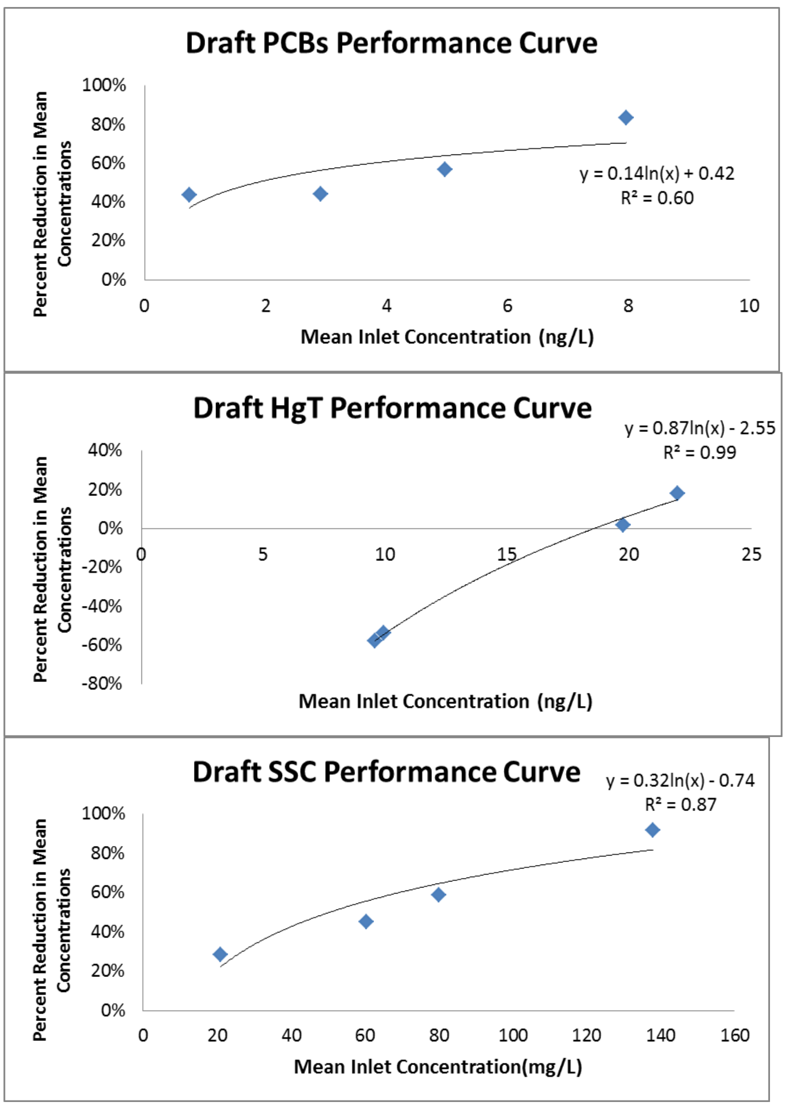


Figure 13. Draft performance curves for polychlorinated biphenyls, total mercury and suspended sediment based on findings from three Bay Area bioretention studies assuming their general design characteristics are generally part of the same archetype (0.2 inches per hour, 18 inches of compost media).

Table 5. Concentrations of influent and effluent at Fremont relative to effluent at other local low impact development bioretention design studies, bioretention studies in the International Best Management Practices Database, and untreated stormwater from urban Bay Area watersheds.

	Fremont TWFs (Medians)			Effluent from Regional/Local LID Studies (Medians)		IBMP Database Bioretention Studies[C]			Bay Area Untreated Stormwater[D]		
Analyte	Inlet	Subsurface Outlet	Surface Outlet	El Cerrito[A]	Daly City[B]	25%	Median	75%	Lowest Median	Highest Median	Count
SSC (mg/L)	42.0	21.0	22.0	10.9	9.9	5.0	10.0	23.8	37.0	1350	25
Sum of PCBs (ng/L)	1.87	1.62	1.72	1.33	0.415				0.286	159	23
Total Mercury (ng/L)	8.39	14.8	14.8	14.2	23.5				9.00	169	22
Dissolved Mercury (ng/L)	1.94	6.28	8.23	7.96	7.54				2.44	5.10	4
Total Methyl Mercury (ng/L)	0.112	0.055	0.097	0.154	1.340				0.00	1.77	21
Total Copper (ug/L)	7.96	11.1	12.0	9.11	8.52	4.50	9.80	17.9	1.82	35.0	8
Dissolved Copper (ug/L)	7.39	9.26	10.6	8.94		7.02	13.95	19.9	2.25	14.0	7
Total Nitrogen (mg/L)	0.792	6.70	3.20			0.290	0.380	0.580			
Total Kjeldahl Nitrogen (mg/L)	0.58	1.90	1.50			0.410	0.840	2.00	0.855	1.40	6
Dissolved Nitrate + Nitrite (mg/L)	0.160	3.75	0.860			0.110	0.240	0.510	0.140	0.950	7
Dissolved Ammonia (mg/L)	0.305	0.180	0.0630			0.0500	0.100	0.270	0.105	0.435	6
Total Phosphorus (mg/L)	0.160	1.30	0.930			0.050	0.110	0.320	0.230	0.390	6
Dissolved OrthoPhosphate (mg/L)	0.074	1.40	0.760			0.000	0.0100	0.0800	0.0770	0.200	7

[A] Source: Gilbreath et al., 2012a

[B] Source: David et al., 2015.

[C] Source: IBMP Database: data and summary reports available online at: www.bmpdatabase.org

[D] Sources: Gilbreath et al., 2012b; Gilbreath et al., Hunt et al., 2012; 2015; McKee et al., 2010; McKee et al., 2012; SFEI unpublished data

Although we may not have expected high performance, could we have reasonably expected better performance? The design of an LID facility is expected to influence irreducible concentrations, rather than there actually being an absolute irreducible concentration for a particular water quality constituent (Kadlec and Knight, 1996). With this acknowledged, we take the approach recommended by Smith and Job (2010), in which they use the 25% of effluent concentrations for a given parameter for a given facility type from the IBMP Database as a definition for the lower limit concentration (also often referred to as "irreducible concentration"). They propose that the 25% of the IBMP database is a reasonable marker below which LID cannot *reliably* be expected to further reduce pollutant concentrations. Based on this method of identifying the lower limit, or irreducible concentrations, NH_3 effluent concentrations at the Fremont surface-loaded outlet and CuD concentrations measured at both outlets may be considered irreducible (Table 5). Although dissolved copper in effluent from Fremont was higher than the influent, it was not significantly so and still between the 25% and median of concentrations reported in the IBMP[4]. This finding is not true, however, for the other analytes or NH_3 at the subsurface-loaded TWF.

In summary, LID performs better when the influent pollutant levels are higher. Relative to untreated stormwater measured in the Bay Area, concentrations of stormwater into the TWFs are generally low. That said, except for in the cases of CuD and NH_3, the poorer performance is probably not the result of the influent being at irreducible concentrations relative to the Fremont TWF design characteristics. Relative to other local LID studies, the Fremont TWF effluent concentrations of MeHg are low, other mercury species were similar across the studies, and although SSC, PCBs and CuT were higher, they were still in the lowest third of measurements of untreated stormwater in the Bay Area. With the exception of NH_3, nutrient export from the Fremont TWFs does appear to be higher than LID studies in the IBMP Database and are higher than untreated stormwater in the urban Bay Area watersheds measured.

Concentrations from previous storms likely matters

Given that bioretention has been shown to be effective at reducing metals concentrations (Davis et al., 2003; Davis, 2007; Hunt et al., 2008; Hatt et al., 2009; Li and Davis, 2009), the increases in median concentrations for HgT and CuT at Fremont were unexpected. Note that the increases in CuT were not significant, and Figures 6 and 7 illustrate the reason, that is, the range of the inlet concentration precluded significance. Inlet CuT concentrations were high in the first storm and low in the second. The outlet concentrations during the second storm were higher than the inlet. We might hypothesize that the CuT which entered the TWFs *during the first event or unmonitored* events (or unmonitored portions of events), subsequently exited the TWFs later *during monitored* events or portions of events. This phenomenon confounded the direct comparison of inlet and outlet concentrations during the same storm event.

A similar argument might be forwarded to HgT, though the increases for HgT were significant between inlet and outlet. The increases in HgT concentrations were relatively consistent for each storm event, and nearly the entire increase was attributed to significant and consistent increases in the dissolved fraction. These data suggest that a HgD source might exist within the soil media itself.

[4] Perhaps noteworthy in this table is that the fraction of CuD compared to CuT, and HgD compared to HgT, at Fremont inlets is quite different from the same fractions at Bay Area Untreated Stormwater when looking at the Highest Median. The ratio, however, it not unusual but rather in line with the dissolved:total ratios for numerous pollutants in stormwater that is low in suspended particles. In untreated stormwater, as suspended particulate matter increases, the dissolved proportion typically tends to decrease. Because Fremont has such low SSC at the inlets, the dissolved fraction of Cu and Hg is relatively high.

5. Conclusions

The purposes of this study were to: 1) qualitatively assess whether the TWFs were treating stormwater runoff at rainfall rates up to 0.2 in/hr, estimated to be equivalent to 80% of the total annual rainfall; 2) quantitatively assess whether the TWFs reduced pollutant concentrations in water entering the storm drain system; and 3) compare the effluent concentrations exiting the TWFs to findings from other studies of LID performance. Observations of flow and bypass occurred during six storms. The subsurface-loaded TWF appeared to accept less volume of stormwater into the TWF for treatment. Bypass did not occur at rainfall rates below 0.2 inches/hr), and did occur at rates >0.32 inches/hr. It was estimated that 80-85% of the total annual flow onto the catchment was treated by the TWFs.

The two Fremont TWFs had mixed performance for treatment of the stormwater pollutants measured in the study. SSC, MeHgT and NH_3 all showed significant decreases at the TWF outlets. The TWF media appears to be ineffective at capturing PCBs, copper species (particularly dissolved) and TKN, but does not appear to be a source of these pollutants (concentrations were not significantly different between the influent and effluent). The TWFs appear to leach HgT, HgD, TN, $NO_3 + NO_2$, TP and PO_4, which may be sourced from the TWF filtration media or, in the case of $NO_3 + NO_2$, through nitrification processes occurring in the TWF media. Some significant differences in performance between the two TWFs existed, namely, the subsurface-loaded TWF exported significantly lower HgD and MeHgT concentrations, while the surface-loaded TWF exported significantly lower $NO_3 + NO_2$, TP and PO_4 concentrations. Potential causes for these differences include differences in the influent, differences in the composition of the soil and compost within the TWF media

Although some contaminants were leached from the TWFs, compared with findings from bioretention studies in the IBMP Database, effluent concentrations from the Fremont TWFs were within the interquartile range of other data in the Database for SSC, CuT, CuD, TKN and NH3, but exceeded the interquartile range for TN, $NO_3 + NO_2$, TP and PO_4. Influent concentrations to the TWFs were generally low relative to concentrations measured in stormwater across the Bay Area, and clean influent generally leads to lower performance of an LID treatment facility. To improve explanation about the performance at the Fremont TWFs, more information about the grainsize of sediments within the catchment and pollutant concentrations present within the filter media are needed. The results of this study highlight that while bioretention placed in highly polluted watersheds may have high performance, if bioretention is placed in relatively "clean" watersheds, thoughtful consideration should be applied to the soil media (e.g. low-nutrient content media) and design specifications that promote sedimentation, filtration, binding of metals, and denitrification.

6. Recommendations

Recommendations specific to Fremont TWFs

Based on the observations and water quality assessment reported herein, we make the following recommendations to the TWF design to improve performance:

1) Alter the inlets to each TWF to allow more runoff to enter the TWFs and less volume to bypass untreated. Other considerations include drop away gutters, wider curb openings or slot drains, and/or slightly elevating the storm drain inlet while keeping it below the street level, which would reduce water flowing to the storm drain and preventing street flooding.
2) When major maintenance occurs including removal and replacement of the filtration media,
    a. The subdrains in each TWF could be elevated as high as permissible to increase storage. Indeed City of Fremont staff agree that the subdrain should be above the Class II perm layer (12" from native soil), and this has become standard for TWF installations in the City of Fremont. The deeper Class II perm layer allows for more storage prior to flow out the subdrain.
    b. The soil media used in the TWFs was specified by regional requirements that could not be changed at the time of installation. However, the results of this study suggest that the soil media may be a source of pollutants. At the front end of a project, the soil and compost media should both be investigated. Compost is a highly variable and often mixed product with usually no documentation on the source or

composition of the mix except for generalized statements about its source. Since compost often comes from former waste streams, mixing and contamination are not unusual. To achieve less nutrient export and/or improve adsorption of metals in future projects, refinements to the media used should be considered if regional requirements change. There may be trade-offs to performance, however. For example, several studies have investigated the appropriate makeup of compost media to help plants grow while also minimizing nutrient leaching (e.g. by using “low-P index” media). At the same time, however, it has also been discussed that organic matter provides binding sites for heavy metals and that organic matter has been found to improve a bioretention cell’s dissolved heavy metal removal lifespan (Morgan et al., 2011). Multiple layers of media targeting different pollutant classes (e.g. compost layers to bind metals and iron enhanced sands to remove phosphorous) may be required to treat the entire spectrum of pollutants. The science is rapidly expanding on this topic. Prior to soil media replacement perhaps in 5-10 years, the latest research available at that future time should be consulted.

Recommendations for future monitoring

Monitoring of green infrastructure is developing in the region: (this study), bioretention monitoring at the Daly City Library (David et al., 2012), the El Cerrito Rain Gardens (Gilbreath et al., 2012), flow monitoring of multiple green infrastructure sites in San Francisco (SFPUC and SFEI study in progress), management practice monitoring to support water quality objectives for the Fitzgerald Marine Reserve (San Mateo County and SFEI study in progress), monitoring of multiple green infrastructure sites along the San Pablo Spine (SFEP and SFEI study design in development), and those being completed by BASSMAA and its consultants (BASMAA, 2013).

Through these studies there is growing evidence for the following general concepts:

1. Bioretention systems capture particulate phase contaminants well,
2. For particulate pollutants that have atmospheric and road related sources (e.g. Hg and Cu), capture is moderate, consistent with the likelihood that a greater portion is in dissolved phase or on particles that are potentially fine enough to pass through the system,
3. Dissolved phase contaminants are poorly captured, consistent with the notion that the retention time in the system is too short to facilitate phase changes from dissolved to particulate.
4. Performance is a function of influent quality; the higher the pollutant concentrations in the source catchment, the greater the performance, whereas relatively clean influent can lead to negligible or even negative performance.

Remaining data gaps include:

Data Gap 1. With regards to nutrients, and organic carbon (BOD), concern remains about whether bioretention systems are a net source or net sink, and how this may change with each year of maturation after construction.

Data Gap 2. Little is known about the impacts of nitrification and denitrification on nutrient transformations within LIDs and the effect on effluent concentrations.

Data Gap 3. With regards to methylmercury, concern remains that bioretention systems, if built or maintained improperly, may lead to increased prevalence of low oxygen or anoxic conditions and might be a net source rather than a net sink; the presence and operation/configuration of a sub-drain needs further study. More generally, there is need for better understanding of how anaerobic conditions in these systems result in conversion of pollutant species.

Data Gap 4. Little data exist for how the maintenance of each system is challenged by source areas and design configuration, and how these factors influence system function in relation to water quality performance trash, leaf or other organic matter buildup at the inlets; in particular, how can LID design be modified to address multiple benefits (like trash capture) without loss of water quality performance?

Data Gap 5. Virtually no data exist locally or in the literature as to how these systems change in function over time with system maturation. Do they continue to trap pollutants during later years of maturation, when and how often will soil media need replacing, and how is this influenced by site and design characteristics?

Data Gap 6. No data exist locally or in the literature as to how performance of LID at capturing our target pollutants (Hg and PCBs) relates to media composition, or more generally, what is available and how to use advanced media for targeted pollutant removal (e.g., activated alumina for phosphorus removal).

Data Gap 7. Given that bioretention is prone to leaching nutrients, a regional assessment should be completed to understand the consequences of nutrient input from LID facilities and whether it is necessary and cost-effective to use specialized low-nutrient soils or add something to the treatment media standard design that captures and increases nutrient related treatment performance.

Data Gap 8. Clear standards and performance metrics for assessing the success of an LID project.

Monitoring LID in the region is generally carried out at a pilot level scale. In part, this is due to the monetary expense of analytical costs of the region’s target pollutant analyses (i.e. analysis of PCBs is approximately 30x the cost of nutrients analytes, and Hg is approximately 4x the cost). Given the draft performance curves presented above illustrate differing performance for SSC, PCBs and Hg, it is clear than no one surrogate (like turbidity or SSC) is suitable for describing and predicting performance. Pilot scale studies make it difficult to conclusively support the four general concepts presented and minimally begin to fill the remaining data gaps. Future monitoring designs should aim to address some of these data gaps but will need to do so by directly measuring the pollutants of concern that continue to impair water quality in San Francisco Bay and its watersheds.

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8. Appendices

Appendix A: Laboratory Methods and QA/QC

Table A1. Pollutants, analyzing laboratories and analytical methods.

Analysis	Laboratory	Method
SSC	Caltest Analytical Laboratory	ASTM D3977
Nutrients	Caltest Analytical Laboratory	SM 4500-NH3 B,C; SM 4500-N ORG C Nitrogen; SM 4500-P E Phosphorus; EPA 300.1
PCBs	AXYS Analytical Services Ltd	EPA 1668 (40 congeners)
PAHs	AXYS Analytical Services Ltd	MLA 021
Total & Dissolved Hg	Brooks Rand Laboratory	EPA 1631
Total Methyl Hg	Brooks Rand Laboratory	EPA 1630
Total & Disolved Cu	Brooks Rand Laboratory	EPA 1638M

Suspended Sediment Concentration: Suspended Sediment Concentration (SSC) was reported in 112 field samples. A field blank, lab blanks, laboratory control spike samples (LCSs), blind field replicates, and other client samples were also analyzed in 42 batches. The SSC data was generally acceptable. No samples were reported as non-detects. Laboratory replicates were not possible for SSC as the entire volume was consumed for each analysis. SSC precision was evaluated using the laboratory control spikes (LCSs). The average RSD (14.26%) was above the target (10%), but less than 2x target and so flagged but not censored. Blind field replicate RSDs were examined, but not used in the evaluation. Blind field replicate RSDs were variable as expected (average relative standard deviation (RSD) 40.05%) given typically rapid changes in sediment and flow between replicate samples collected in succession.

Nutrients: Data was reported for four analytes (Ammonia as N, Nitrate + Nitrite as N (dissolved fraction), OrthoPhosphate as P, and Phosphorus as P) measured in 30 water samples. Total Kjeldahl Nitrogen was reported for 29 water samples. Total Nitrogen values were calculated for 29 water samples. An equipment blank (for OrthoPhosphate as P), field blanks, lab blanks, laboratory control spike samples (LCSs), matrix spike/matrix spike replicates (MS/MSDs), blind field replicates, and other client samples were also analyzed in 42 batches.

Overall the nutrient data was generally acceptable. MDLs were sufficient with only dissolved Nitrate + Nitrite as N (12.9% NDs) and dissolved Ammonia as N (16.13% NDs) having non-detects. None of the nutrients were measured in the lab blanks or the equipment blank. No qualifiers were added. Ammonia as N was found in one field blank at a concentration 2x the MDL (0.039 mg/L; MDL 0.015 mg/L; average MDL for lab blanks 0.026 mg/L), which was about 14% of the average concentration found in the field samples (0.28 mg/L).

Precision and accuracy were assessed using the matrix spike/matrix spike replicate samples. Average RSDs were generally good, less than their target (10% for OrthoPhosphate as P, Phosphorus as P; 15% for the other analytes). Blind field replicate RSDs were examined and generally below the MQOs, but not used in the evaluation. Recovery for the nutrients was good, with average recovery errors less than their target (10% for OrthoPhosphate as P, Phosphorus as P; 15% for the other analytes), except for Total Kjeldhal Nitrogen which had an average recovery error of 16.64% and was flagged with a non-censoring qualifier. Total Nitrogen could not be evaluated as they were calculated values.

PCBs: Data were reported for 71 congeners in 40 water samples and 1 blind field replicate. Note: Only the 40 congeners previously identified as the most significant contributors to the San Francisco Bay were reported in this study (PCBs 8, 18, 28, 31, 33, 44, 49, 52, 56, 60, 66, 70, 74, 87, 95, 97, 99, 101, 105, 110, 118, 128, 132, 138, 141, 149, 151, 153, 156, 158, 170, 174, 177, 180, 183, 187, 194, 195, 201, and 203). A field blank, method lab blanks, and laboratory control spike sample (LCS) were also analyzed in five lab batches.

In WY 2013, 19 samples were collected. Overall the data were acceptable. MDLs were generally sufficient though 8 of the 71 PCB congeners (11%) were not detected in the field samples (ranging from 5 to 32% NDs). Data were not blank corrected. About 32% (23 out of 71) of the PCBs had some contamination in at least one of the two method blanks. PCB 8, 18, 33, 31, and 105 had respectively 47%, 32%, 21%, 5%, and 5% of sample results were censored due to having concentrations <3x the blank results (by batch). Precision was evaluated using LCS samples as they were the only replicates analyzed. Average RSDs for the 26 PCBs included in the LCS samples were well below the target MQO of 35% (all <7%). The laboratory control spike samples (LCSs) were also used to assess accuracy of PCBs as no CRMs or matrix spikes were reported. Recoveries were good, with recovery errors less than the target 35% for all reported 26 PCBs included in the LCS samples (all <21%).

In WY 2014, 21 samples were collected and one field blank. Overall the data were generally acceptable. Nine of the 71 PCB congeners in the field samples (13%) were not detected (ranging from 5 to 23% NDs). Data were not blank corrected. About 39% (28 out of 71) of the PCBs had some contamination in at least one of the three method blanks. PCB 28, 31, 33, 66, 70, 8, 18, 44, 49, 52, 56, 60, 87, 95, 99, 101, 105, 110, and 118 had respectively 64%, 64%, 64%, 32%, 32%, 18%, 18%, 18%, 18%, 18%, 18%, 18%, 18%, 18%, 18%, 18%, 18%, 18%, and 18% of sample results were censored due to having concentrations <3x the blank results (by batch). Blank contamination was found in the field blank for about 42% (30 out of 71) of the PCB congeners, but was not used for the evaluation. Average RSDs for the 26 PCBs included in the LCS samples were well below the target MQO of 35% (ranging from 2% to 8%). Recoveries in the LCS samples were good, with recovery errors less than the target 35% (ranging from 1% to 8%). The blind field replicate was not used for the evaluation, but RPDs ranged from 0 to 10%.

PAHs: Twenty five PAHs (acenaphthene, acenaphthylene, anthracene, benz[*a*]anthracene, benzo[*a*]pyrene, benzo[*b*]fluoranthene, benzo[*e*]pyrene, benzo[*g,h,i*]perylene, benzo[*k*]fluoranthene, biphenyl, chrysene, dibenz[*a,h*]anthracene, 2,6-dibenzothiophene, dimethylnaphthalene, fluoranthene, fluorene, indeno[1,2,3-*c,d*]pyrene, 1-methylnaphthalene, 2-methylnaphthalene, 1-methylphenanthrene, naphthalene, perylene, phenanthrene, pyrene, 2,3,5-trimethylnaphthalene) were analyzed during this study for 3 water samples. One lab blank, and one laboratory control spike sample (LCS) were also analyzed in one lab batch.

Overall the data were acceptable. MDLs were sufficient with nine of the 25 PAH analytes having non-detects (ranging from 33 to 100% NDs), with 66.6% (6 out of the 9) having >=50% NDs (acenaphthene, benz[*a*]anthracene, biphenyl, dibenz[*a,h*]anthracene, dibenzothiophene, and fluorene). Data were not blank corrected. About 50% (12 out of 25) of the PAHs had some contamination in the method blank. Biphenyl, fluorene, dibenzothiophene, and phenanthrene had respectively 100%, 100%, 66.6%, and 33.3% of sample results were censored due to having concentrations <3x the blank results (by batch).

Precision could not be evaluated as no replicates of any kind were analyzed. The laboratory control spike sample (LCS) was used to assess accuracy of PAHs as no CRMs or matrix spikes were reported. Recovery for the majority of PAH analytes was good, with recovery errors less than the target 35% for all reported analytes, except for 2,6-Dimethylnaphthalene (43.43% error), and 2,3,5-Trimethylnaphthalene (36.87% error), which were flagged but not censored.

Copper and Mercury: The dataset includes results for 32 grab water total phase samples for MeHg, and 56 to 60 for dissolved and total phases for Cu and Hg. Blind field duplicates, and replicates for non-project samples and matrix spikes were also reported. LCS, CRM, and MS samples were reported for Cu, CRM and MS for total Hg, and LCS and MS for MeHg.

Overall data were acceptable. Method sensitivity was sufficient, with only one or two NDs per analyte and matrix. Results were blank corrected, and blank standard deviations were <MDL. Precision was good, <12% average RSD for all analytes, well within the target 25% for Cu and 35% for Hg and MeHg. Recovery was good for CRMs, LCSs, and MS/MSDs, all well within 25 & 35% error targets (for Cu & MeHg/Hg respectively), with only total Hg anywhere near its 35% limit at around 28% average error for CRMs and MSs. Dissolved to total fraction ratios were good, with dissolved < total in all but one sample for copper, and even that was only 16% over a 1:1 ratio, within the range of measurement variation.

Hold time violations were applied to multiple total mercury samples collected during the November 28 and November 30, 2012 storm events. During the initial laboratory analysis of the samples (analysis initially performed within hold time), matrix interference in the samples resulted in very low recoveries on MS samples. The laboratory went through a series of re-analyses at small volumes to determine if the matrix interference could be eradicated. Acceptable matrix spike recoveries were obtained when samples were not shaken prior to sub sampling for analysis. The samples were reanalyzed with the new procedure but were out of analytical hold time and therefore qualified.

Appendix B: Results Summary Tables

Tables B1-B3 available in supplementary Excel File.
Table B1. Sample counts, percent non-detects, average method detection limit (MDL), field blank and laboratory blank concentrations for each analyte.
Table B2. Certified reference material, matrix spike and blank spike recoveries, field and lab replicate RSDs.
Table B3. Field sample results.

Table B4. Summary statistics for each analyte at each sampling station. The mean is presented, although the authors recommend use of the median statistic.

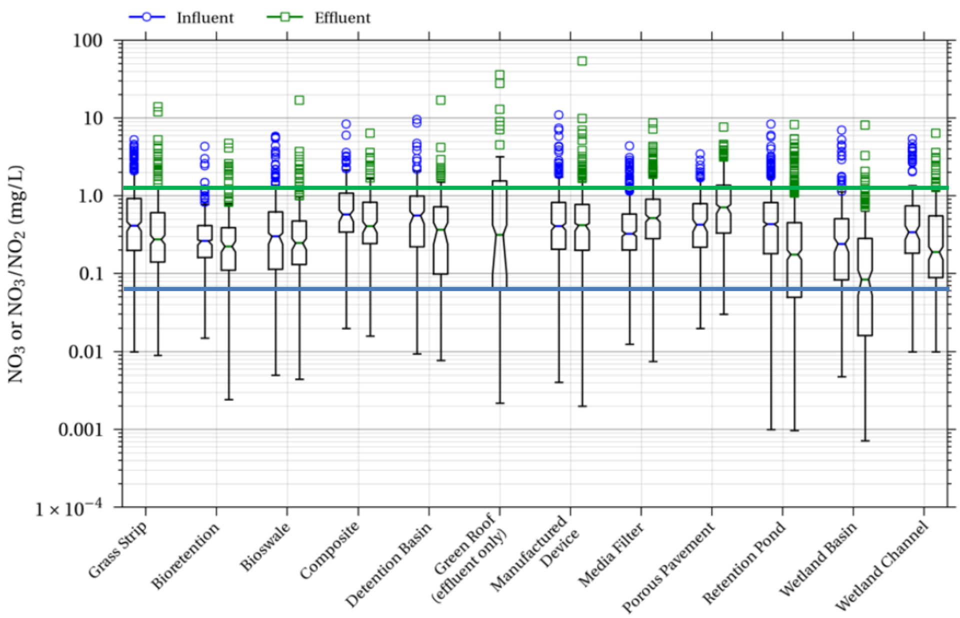
Location, Analyte (unit)	n	Mean	Std.Dev.	Minimum	25%	Median	75%	Maximum
Inlet Subsurface, Dissolved Ammonia (mg/L)	4	0.312	0.291	0.088	0.088	0.229	0.452	0.7
Inlet Surface, Dissolved Ammonia (mg/L)	10	0.332	0.194	0.099	0.19	0.305	0.43	0.64
Outlet Subsurface, Dissolved Ammonia (mg/L)	6	0.206	0.168	0	0.1	0.18	0.307	0.45
Outlet Surface, Dissolved Ammonia (mg/L)	10	0.151	0.273	0	0.0045	0.063	0.157	0.9
Inlet Subsurface, Dissolved Copper (ug/L)	6	6.76	6.65	1.62	2.46	4.97	7.14	19.5
Inlet Surface, Dissolved Copper (ug/L)	17	10	9.11	1.73	3.32	7.39	13	31.6
Outlet Subsurface, Dissolved Copper (ug/L)	17	8.95	3.16	0.227	8.11	9.26	10.6	13.1
Outlet Surface, Dissolved Copper (ug/L)	17	10.3	3.06	5.46	8.42	10.6	11.6	17.1
Inlet Subsurface, Dissolved Mercury (ng/L)	6	3.04	1.77	1.2	1.84	2.58	3.98	5.89
Inlet Surface, Dissolved Mercury (ng/L)	18	2.26	1.3	0	1.63	1.94	2.58	5.04
Outlet Subsurface, Dissolved Mercury (ng/L)	16	6.56	1.24	5.01	5.48	6.28	7.38	9.16
Outlet Surface, Dissolved Mercury (ng/L)	17	8.59	3.24	4.46	5.66	8.23	10.2	15.6
Inlet Subsurface, Dissolved Nitrate + Nitrite (mg/L)	4	0.038	0.0458	0	0	0.03	0.068	0.092
Inlet Surface, Dissolved Nitrate + Nitrite (mg/L)	8	0.195	0.155	0	0.102	0.16	0.272	0.5
Outlet Subsurface, Dissolved Nitrate + Nitrite (mg/L)	6	3.59	2.48	0.62	1.58	3.75	5.33	6.7
Outlet Surface, Dissolved Nitrate + Nitrite (mg/L)	10	1.12	0.937	0	0.682	0.86	1.58	3.1
Inlet Subsurface, Dissolved OrthoPhosphate (mg/L)	4	0.0648	0.0577	0.024	0.0337	0.0425	0.0735	0.15
Inlet Surface, Dissolved OrthoPhosphate (mg/L)	10	0.175	0.188	0.048	0.06	0.0735	0.248	0.58
Outlet Subsurface, Dissolved OrthoPhosphate (mg/L)	6	1.31	0.458	0.61	1.04	1.4	1.65	1.8
Outlet Surface, Dissolved OrthoPhosphate (mg/L)	10	0.818	0.384	0.34	0.532	0.76	0.988	1.5
Inlet Subsurface, SSC (mg/L)	11	60.4	86.3	3.8	12.5	15	68.5	284
Inlet Surface, SSC (mg/L)	35	80	99.1	8.4	15.5	42	115	399
Outlet Subsurface, SSC (mg/L)	33	33.4	36.2	5.7	14	21	30	136
Outlet Surface, SSC (mg/L)	33	25.4	18.5	7.3	14	22	28	95
Inlet Subsurface, Sum of HPAHs (ng/L)	3	757	685	129	391	653	1,070	1,490
Inlet Subsurface, Sum of LPAHs (ng/L)	3	152	136	15.7	83.6	151	220	288
Inlet Subsurface, Sum of PAHs (ng/L)	3	908	820	145	475	804	1,290	1,780
Inlet Subsurface, Sum of PCBs (ng/L)	6	4.96	8.98	0.247	0.666	1.06	3.07	23.1
Inlet Surface, Sum of PCBs (ng/L)	12	2.91	3.09	0.7	1.07	1.87	3.23	11.4
Outlet Subsurface, Sum of PCBs (ng/L)	10	2.14	1.55	0.804	1.33	1.62	2.03	5.77

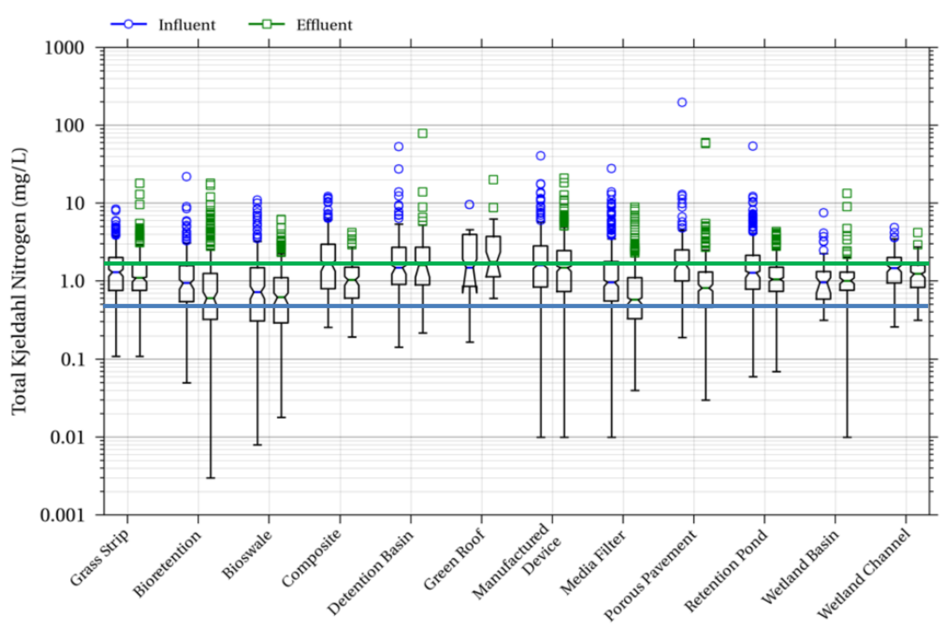
Location, Analyte (unit)	n	Mean	Std.Dev.	Minimum	25%	Median	75%	Maximum
Outlet Surface, Sum of PCBs (ng/L)	12	1.63	1.45	0	0	1.72	2.47	4.48
Inlet Subsurface, Total Copper (ug/L)	6	17.6	18.4	2.86	5.99	7.16	31.6	43.1
Inlet Surface, Total Copper (ug/L)	13	14.9	12.5	4.64	5.94	7.96	19	39.3
Outlet Subsurface, Total Copper (ug/L)	11	11.1	2.2	7.28	9.8	11.1	12.2	15
Outlet Surface, Total Copper (ug/L)	13	11.4	2.93	7.05	8.96	12	14.5	15.5
Inlet Subsurface, Total Kjeldahl Nitrogen (mg/L)	3	0.473	0.294	0.27	0.305	0.34	0.575	0.81
Inlet Surface, Total Kjeldahl Nitrogen (mg/L)	10	1.07	0.91	0.36	0.44	0.58	1.35	2.9
Outlet Subsurface, Total Kjeldahl Nitrogen (mg/L)	7	1.88	0.691	0.87	1.5	1.9	2.2	3
Outlet Surface, Total Kjeldahl Nitrogen (mg/L)	9	1.31	0.731	0.31	0.62	1.5	2.1	2.2
Inlet Subsurface, Total Mercury (ng/L)	6	9.57	6.74	3.2	5.2	6.58	14.9	18.6
Inlet Surface, Total Mercury (ng/L)	17	9.95	6.88	2.22	5.71	8.39	11.1	28.8
Outlet Subsurface, Total Mercury (ng/L)	16	15.1	3.29	9.92	12.8	14.8	18	20.2
Outlet Surface, Total Mercury (ng/L)	18	15.3	4.61	2.89	12.8	14.8	18.9	22.3
Inlet Subsurface, Total Methyl Mercury (ng/L)	6	0.138	0.0893	0.067	0.083	0.093	0.18	0.288
Inlet Surface, Total Methyl Mercury (ng/L)	9	0.153	0.0756	0.093	0.1	0.112	0.159	0.296
Outlet Subsurface, Total Methyl Mercury (ng/L)	6	0.0552	0.00917	0.039	0.054	0.055	0.062	0.064
Outlet Surface, Total Methyl Mercury (ng/L)	10	0.0976	0.0406	0.045	0.0685	0.0965	0.123	0.167
Inlet Subsurface, Total Nitrate + Nitrite (mg/L)	3	0.0847	0.0309	0.063	0.067	0.071	0.0955	0.12
Inlet Surface, Total Nitrate + Nitrite (mg/L)	10	0.254	0.166	0.1	0.16	0.195	0.254	0.6
Outlet Subsurface, Total Nitrate + Nitrite (mg/L)	7	6.73	8	1.1	1.85	4.8	6.75	24
Outlet Surface, Total Nitrate + Nitrite (mg/L)	9	2.58	3.13	0.64	0.75	1.2	2	10
Inlet Subsurface, Total Nitrogen (mg/L)	3	0.56	0.322	0.34	0.375	0.41	0.67	0.93
Inlet Surface, Total Nitrogen (mg/L)	10	1.33	1.02	0.49	0.625	0.792	1.76	3.15
Outlet Subsurface, Total Nitrogen (mg/L)	7	8.61	8.6	2.1	3.3	6.7	8.95	27
Outlet Surface, Total Nitrogen (mg/L)	9	3.88	3.64	0.95	1.37	3.2	3.5	12.1
Inlet Subsurface, Total Phosphorus (mg/L)	3	0.0897	0.0354	0.064	0.0695	0.075	0.103	0.13
Inlet Surface, Total Phosphorus (mg/L)	11	0.241	0.213	0.092	0.11	0.16	0.215	0.7
Outlet Subsurface, Total Phosphorus (mg/L)	7	1.35	0.454	0.55	1.2	1.3	1.65	1.9
Outlet Surface, Total Phosphorus (mg/L)	10	0.956	0.396	0.45	0.658	0.93	1.1	1.7

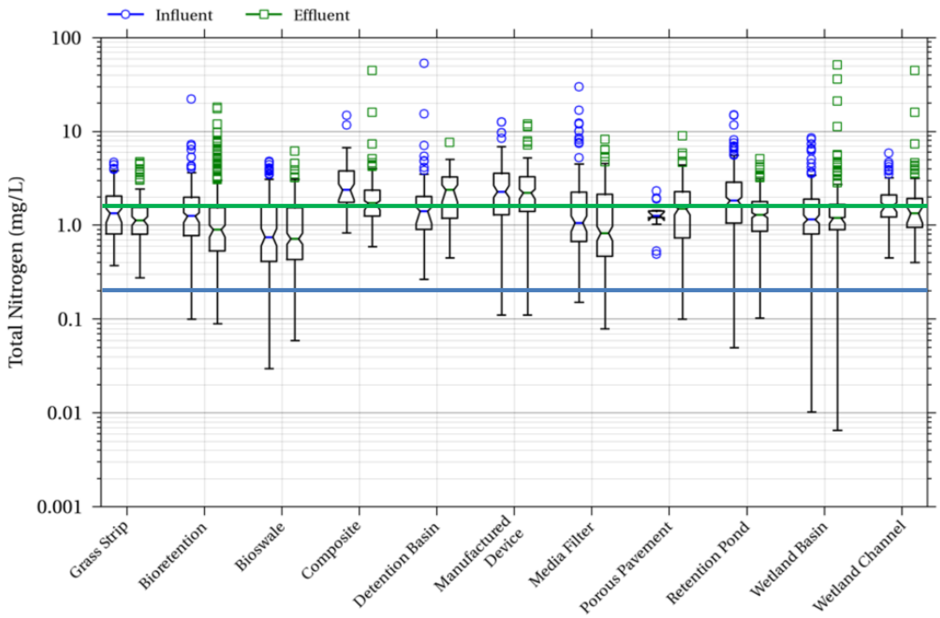
Appendix C: International Stormwater BMP Database Summary Comparison for Select Analytes

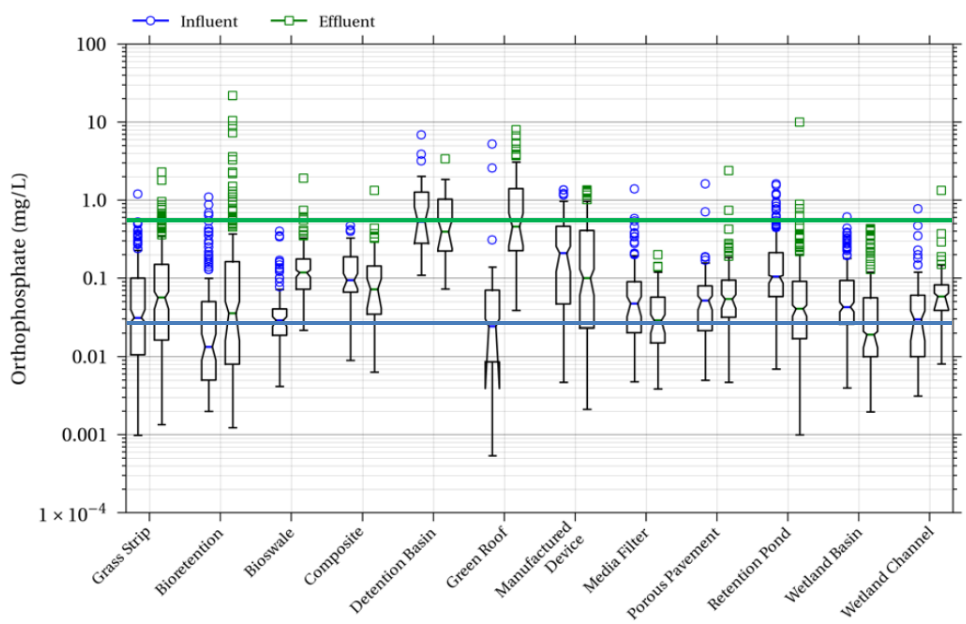
In the Discussion section of this report, boxplot summary graphs for select analytes are shown to compare and place in perspective the Fremont TWF data as well as bioretention performance relative to performance of other BMP (or LID) types. The analytes for which the IBMP Database has such summary graphs but which are not used in the Discussion section of this report are printed below. The IBMP Database does not have these summary graphics for ammonia, mercury species or PCBs because there is little to no data that has been measured for those analytes in LID applications.

Note: Blue line across length of graph represents median inlet concentration measured at the Fremont TWFs. The green line across the length of the graph represents the average of the median concentrations at the two TWFs.






Influent
Effluent
100
10
1.0
0.1
0.01
0.001
Total Nitrogen (mg/L)
Grass Strip
Bioretention
Bioswale
Composite
Detention Basin
Manufactured Device
Media Filter
Porous Pavement
Retention Pond
Wetland Basin
Wetland Channel


Influent
Effluent
100
10
1.0
0.1
0.01
0.001
1 × 10⁻⁴
Orthophosphate (mg/L)
Grass Strip
Bioretention
Bioswale
Composite
Detention Basin
Green Roof
Manufactured Device
Media Filter
Porous Pavement
Retention Pond
Wetland Basin
Wetland Channel