Effectiveness Monitoring of the South 356th Street Retrofit and Expansion Project, Federal Way, WA – SAM Effectiveness Study

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Executive summary

This study evaluated the effectiveness of stormwater treatment facilities built as part of an expansion and retrofit of a regional stormwater detention facility (RDF) in Federal Way, WA (South 356th Street Project). The study was funded by the Stormwater Action Monitoring Program to address data gaps identified by the Washington State Stormwater Work Group in 2014, and the work was conducted in 2015-2017.

The research question motivating this work was, "Do two new bioretention facilities and an expanded wetland complex improve water quality and reduce peak flows?" If so, this would add to the region's understanding of new stormwater treatment technologies and their effectiveness. The overall goal was to evaluate the effectiveness of two bioretention facilities (named east and west), a wetland complex, and the system as a whole. Four objectives, related to evaluating the performance of the individual facilities and the RDF as a whole, were completed to achieve this goal. Continuous flow monitoring was conducted at the inlets and outlets of the three facilities, and water samples were collected during 18 storms for chemical analysis. Each water sample was a flow-weighted composite of multiple aliquots (typically 36) collected over the course of a storm event. Each sample was intended to represent an integrated measure of chemical conditions at that location during the storm. In addition, water quality and macroinvertebrate community data collected before and after the retrofit were compared to determine whether overall performance of the RDF and conditions in the receiving waters had improved.

Stormwater treatment effectiveness, the ability of the facility to remove solids and pollutants from inflowing water, was estimated for each facility in two ways: change in concentration (e.g., amount of pollution per unit water) and change in mass of pollutant load between influent and effluent. Two challenges were encountered that made it difficult to compare the relative effectiveness of the three facilities. First, pollutant concentrations flowing into the bioretention facilities were much lower than those flowing into the wetland complex. In addition, due to challenges in the ability to reliably measure flow at all sampling locations, mass loading estimates could not be estimated for all locations and storms, and are less precise and likely less accurate than concentration estimates.

The first objective was to monitor the relative effectiveness of the three individual facilities. Overall, each facility reliably attenuated stormwater flow, but pollutant removal varied among the facilities. During storms, influent pollutant concentrations flowing into both bioretention facilities were low and similar. Effluent pollutant concentrations flowing out of the facilities were much more variable, suggesting the bioretention facilities were effective at reducing some pollutants while increasing others. Specifically, both bioretention facilities reduced levels of total and dissolved zinc, but in general, only the east bioretention facility reduced total lead concentrations. The bioretention facilities served as sources of all other metals analyzed (dissolved lead, total and dissolved copper, total and dissolved cadmium). The east facility, where water resides for a shorter period of time, was surprisingly more effective at reducing total suspended solids (TSS) than the

west facility. There is strong evidence that the west facility reduced concentrations of PAHs and PCBs. PAH and PCB concentrations were generally decreased in effluent from the east bioretention facility as well, but these reductions were not statistically significant. The most striking result was the large increase in nutrient concentrations from the bioretention facilities, notably in all measured forms of nitrogen and phosphorus.

The effectiveness of the wetland complex also varied by pollutant, but generally pollutant concentrations flowing into and out of the wetland complex were higher than levels flowing out of the bioretention facilities. The wetland complex reduced TSS, but not enough to meet the Washington Department of Ecology's (Ecology) goal of reducing effluent TSS to less than 20 milligrams per liter for all storms. Likewise, the wetland complex did not meet Ecology's goals for removal of dissolved copper or dissolved zinc. The wetland complex reduced turbidity, total nitrogen, and ammonia; however, similar to the bioretention facilities, it was also a source of orthophosphate. The wetland complex reduced concentrations of PAHs, PCBs, total zinc, total copper, total lead, and total cadmium. Overall, the percent reduction in pollutant concentrations was greatest in the wetland complex, but that is largely a function of the low influent concentrations flowing into the bioretention facilities which limited their potential for a more significant reduction.

The second objective was to evaluate performance of the entire RDF to reduce pollutants in stormwater. In general, comparison of the mass pollutant load between influent and effluent from the RDF indicated the RDF reduced the load for most, but not all pollutants of concern. Pollutant load reductions were observed for TSS, PAHs, and PCBs, as well as total lead, copper and zinc. However, the RDF was a source of the dissolved (and typically more toxic) form of these metals. By design, the bioretention facilities treated roughly 10% of the overall RDF flow, and therefore the relative difference in their performance was often insignificant when considering effectiveness of the entire RDF. Nutrients were one exception to this. For example, the study found the RDF exported significant amounts of phosphorus, and nearly 80% of the total phosphorus exported from the RDF was likely from the bioretention facilities.

A third objective was to determine whether RDF performance increased following the retrofit and expansion. The RDF attenuated peak flows and reduced loading of some pollutants. Based on pre- and post-retrofit turbidity data, it appears the retrofit increased the effectiveness of the RDF. Flow attenuation was surprisingly good given the increases in the amount of water observed flowing out of the RDF compared to the amount flowing in (typically ~40% increase during a storm). Despite the increased volume, peak flows were still reduced by the RDF.

The fourth objective was to determine if downstream water quality in the North Fork of West Hylebos Creek showed immediate improvements following the retrofit and expansion. The expanded RDF appears to have decreased turbidity, and stream temperature has remained stable despite an increase in temperature in the water flowing from the RDF. Macroinvertebrate data collection was limited to annual sampling for two years after the retrofit was completed, and it is not surprising that macroinvertebrate community health scores have not immediately improved. Continued monitoring will be needed to determine whether macroinvertebrate community health scores improve and if improvements can be attributed to the retrofit and expansion.

In conclusion, the evidence indicates that retrofitting stormwater facilities improved peak flow attenuation but yielded mixed benefits to water quality. However, given that the bioretention facilities increased nutrient concentrations in effluent discharged to receiving waters, similar types of bioretention facilities should not be built in basins with existing nutrient problems. Doing so could exacerbate water quality conditions, as considered in Ecology's guidance on siting bioretention facilities with underdrains.

It should be noted that the study results described here do not reflect current conditions at this site. Major road construction in April 2018, immediately following collection of the last set of samples, changed the influent pathway to the bioretention facilities. During this study, bioretention influent flowed through a series of grass-lined ditches before entering the facilities, and these ditches have been replaced with pipes. As a result, the bioretention facilities will likely receive an increased volume of stormwater, and influent pollutant concentrations will likely increase. Unfortunately, the road construction also permanently blocked access to several monitoring locations, so it will not be possible to monitor the effectiveness of these changes in the future without significant modifications.

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1.0 INTRODUCTION

This report presents an evaluation of the effectiveness of stormwater treatment facilities built as part of an expansion and retrofit of a regional stormwater detention facility (RDF) in Federal Way, WA, known as the "South 356th Street Project" (Figures 1 and 2). The retrofit, completed in 2014, included an expansion of a treatment wetland and the addition of two bioretention facilities. The expanded wetland complex included a new combined detention stormwater treatment wetland (CDSTW) that increased residence time of water draining from the original CDSTW (Figure 2). The new CDSTW added 3.8 acre-feet of active storage to the 21 acre-feet of active storage provided by the original CDSTW. Collectively, the two CDSTWs (the "wetland complex") treat runoff from approximately 189 acres of urban drainage (Figure 1, Appendix A). The bioretention facilities were added to treat previously untreated runoff from a smaller (22.6 acre) urban basin. This retrofit project site is at the headwaters of the North Fork of West Hylebos Creek which drains to the Hylebos Waterway and into Commencement Bay near Tacoma, WA. Additional details about the RDF and the North Fork of West Hylebos Creek can be found in the study's Quality Assurance Project Plan (King County 2015) and Appendix A.

The study was designed to address data gaps identified by the Washington State Stormwater Work Group regarding stormwater treatment technologies and especially their effectiveness when built as retrofits to reduce the impacts of stormwater on aquatic ecosystems in western Washington. Effectiveness monitoring is needed to evaluate whether new technologies are achieving the intended water quality and flow control goals. Note that the City of Federal Way incorporated stormwater best management practices and followed design guidelines to the extent possible. Due to the constraints at the site, however, some design criteria recommended at the time (Draft Low Impact Development Technical Guidance Manual for Puget Sound, WSU 2012) could not be incorporated into the retrofit. In addition, some non-standard design elements may have influenced the results of the study (e.g., bioretention soil depths greater than required). Thus, the facilities within the RDF (the two bioretention facilities and the two CDSTWs) do not necessarily represent other facilities with the same components.

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

1.1 Study goal and objectives

The overall goal was to evaluate two bioretention facilities, a wetland complex, and the system as a whole, for their ability to improve water quality of stormwater runoff and reduce peak flows (Figure 2; Appendix A). Studies like these are needed because they provide stormwater managers with critical information about how well new technologies (i.e., the bioretention facilities) perform in the field and how they can best be incorporated into retrofits or new stormwater facilities. This retrofit was selected for evaluation because: (1) the RDF was engineered to facilitate flow monitoring and sample collection before and after treatment at each of the bioretention facilities and the entire retrofitted and expanded detention facility; and (2) pre-retrofit monitoring data were available to assess effectiveness of the project on the local small stream. These qualities made it possible to address the following study objectives:

Individual Best Management Practices (BMPs)

- *Objective 1:* Evaluate the effectiveness of bioretention facilities and a retrofitted combined detention and stormwater treatment wetland complex to attenuate stormwater flows and reduce turbidity, nutrients, bacteria, metals, organic pollutants, and toxicity in stormwater runoff.

Systemwide

- *Objective 2:* Evaluate effectiveness of the entire, expanded RDF, to attenuate stormwater flows and improve water quality.
- *Objective 3:* Determine whether expansion and retrofit of the RDF has improved effectiveness of the original RDF, using pre- and post-retrofit turbidity and temperature data.
- *Objective 4:* Determine if there are improvements in the macroinvertebrate community and water temperature in the receiving waters that are correlated with the RDF retrofit and expansion.

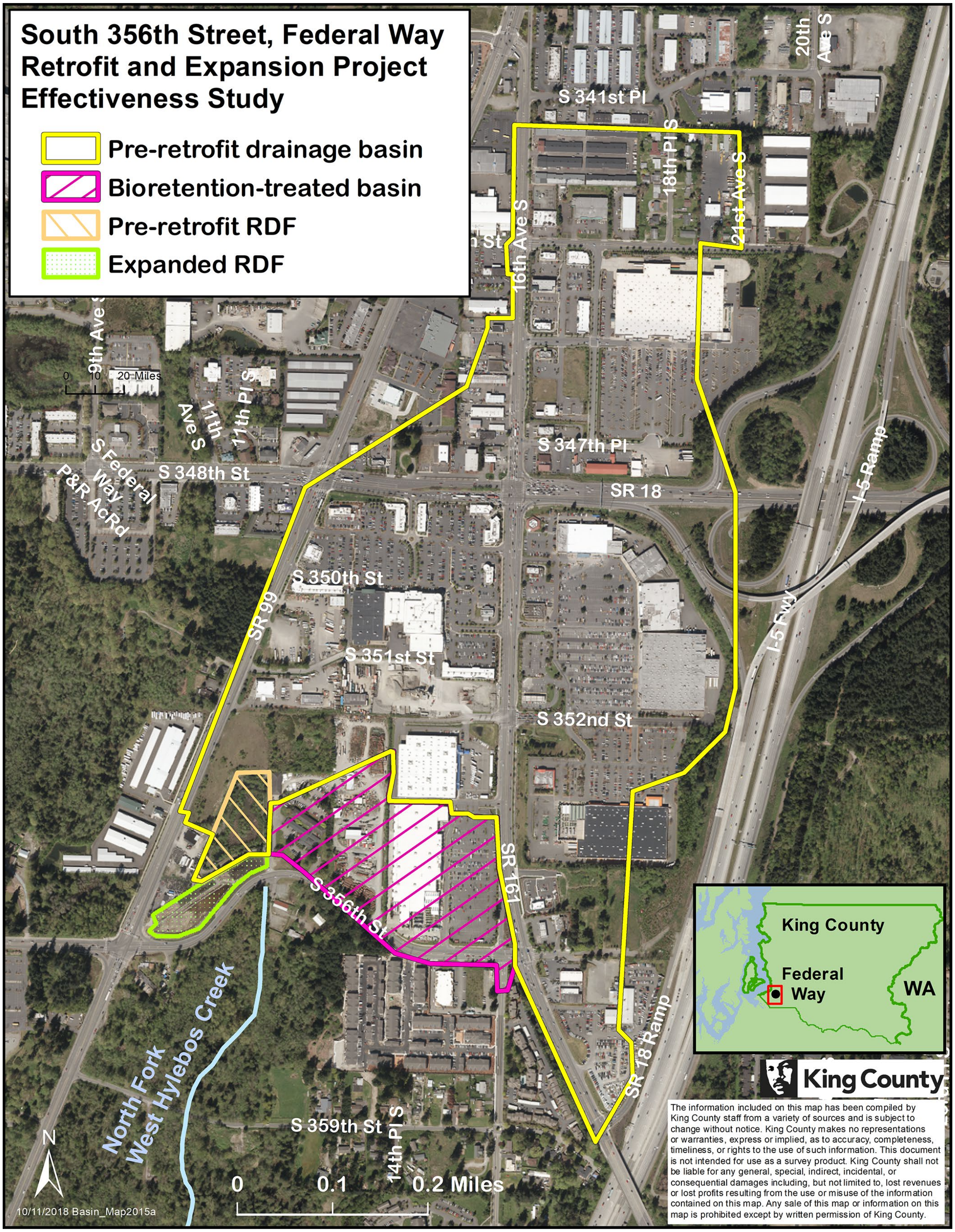

Figure 1. Drainage basins contributing flow to the South 356th Street RDF. Runoff from the pink basin had been untreated prior to the retrofit, but is now treated by the bioretention facilities in the expanded RDF.

1.2 Study design

The study was designed to monitor flow and water quality at six locations in the South 356th Street RDF and one site in the North Fork of West Hylebos Creek (Tables 1 and 2). Flow-weighted, composite samples collected at paired, inlet and outlet locations were used to assess effectiveness of the individual facilities and the entire RDF. Brief descriptions of the facilities and sampling locations are included in Table 1 and illustrated in Figure 2. Table 2 presents the study objectives and information collected at each sampling location that was used to address each objective.

Additional study design and project information, such as site history, basin characteristics, and retrofit design are available in the Quality Assurance Project Plan (QAPP; King County 2016) and Appendix A of this report. Additional appendices include chain of custody forms for each sample collected (Appendix B), notes regarding field sampling methods (Appendix C), laboratory methods (Appendix D), and data analysis methods and statistical results (Appendix E).

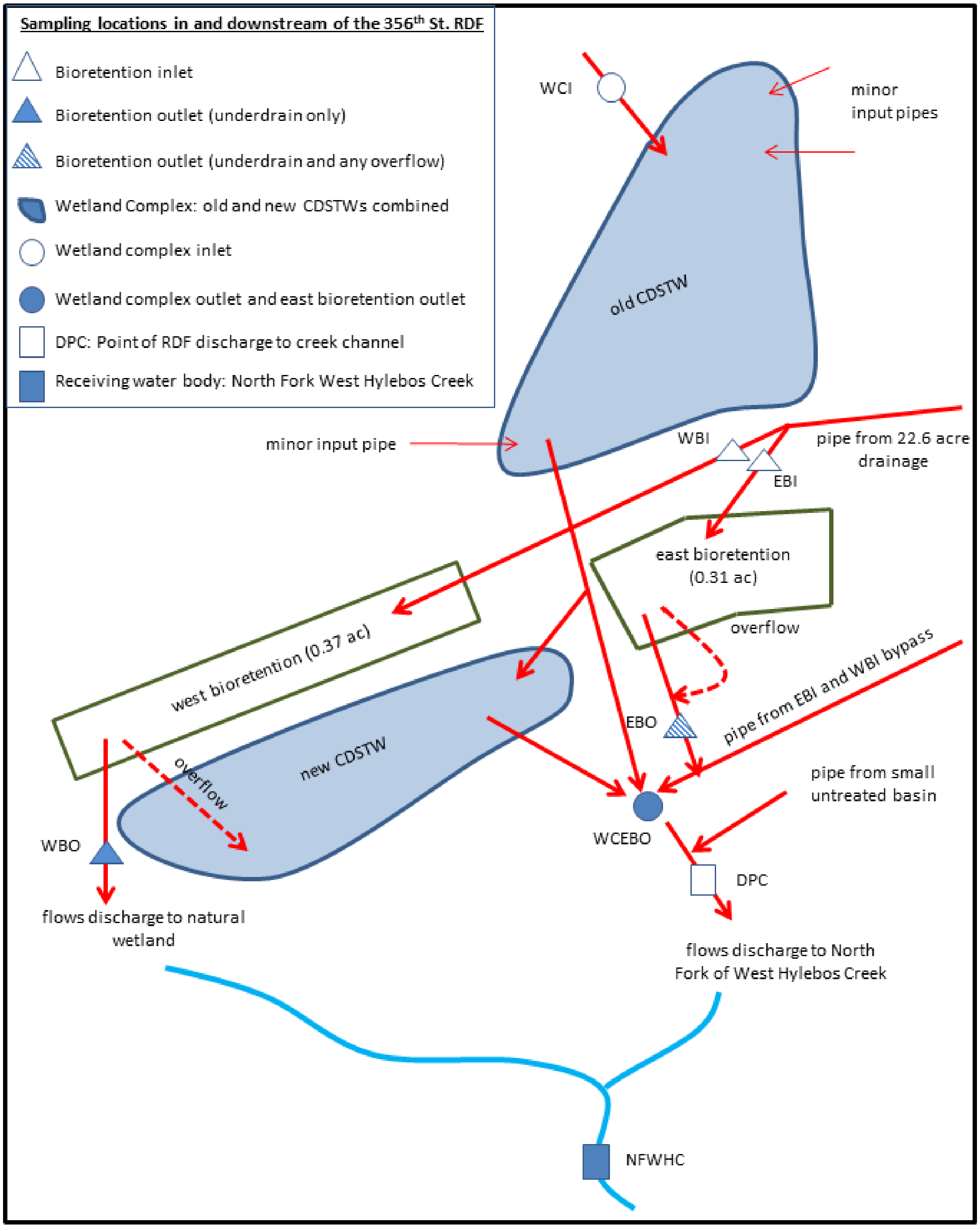

Figure 2. South 356th Street RDF flow paths (indicated by red arrows), project sampling locations and general facility information (not to scale). See Table 1 for a list of acronyms.

Table 1. Facility and sample location descriptions.

Stormwater Facility	Acronym	Brief Description of Facility	Sampling Locations
Regional Detention Facility	RDF	RDF refers to the entire facility, including the wetland complex and the bioretention facilities.	Inlet sample locations include WCI, EBI and WBI, and outlet locations include EBO, WBO and WCEBO. The discharge point from the RDF to North Fork of West Hylebos Creek (DPC) includes untreated runoff that combines with RDF outflow downstream of site WCEBO. Sites WCI and DPC were monitored pre- and post-retrofit to evaluate change in effectiveness of the entire RDF.
East Bioretention	EB	The EB is fully underdrained and has a 0.25 acre-feet (AF) storage capacity. Soil included 30 inches of bioretention soil media, topped with three inches of coarse compost.[1]	The inlet (EBI) receives runoff from a previously untreated basin. The outflow (and overflow) drain through the outlet (EBO) to a catch basin within the RDF.
West Bioretention	WB	The WB is partially underdrained and has a 0.28 AF storage capacity. In eastern half soil included 30 inches of bioretention soil media, topped with three inches of coarse compost[1]; In western half soil included 33 in of top soil Type A BSM, topped with native swale seed mix and soil amendment A BSA[2].	Like EB, the inlet (WBI) receives runoff from a previously untreated basin. The outflow (WBO) drains to a catch basin outside of the RDF and eventually to the creek via a natural wetland. Overflow drains to the New CDSTW and cannot be sampled directly.
Old Combined Detention and Stormwater Treatment Wetland	Old CDSTW	The Old CDSTW was built in 1997 and designed for detention, it is lined, and has 21 AF of active storage capacity. Over 90% of the water treated by the RDF enters through the inlet to this facility (WCI).	The inlet sampling location is WCI. The outflow is split, with some water flowing into the new CDSTW and some bypassing it, and therefore the outflow from the old CDSTW is not sampled directly.
New Combined Detention and Stormwater Treatment Wetland	New CDSTW	The New CDSTW was built in 2013-2014. It is unlined but built for detention. It is in-series with the Old CDSTW and was designed to increase residence time of water flowing from the Old CDSTW.	Inflow to the new CDSTW is from the old CDSTW and is not sampled. The outflow discharges to catch basin and is sampled at WCEBO.

Stormwater Facility	Acronym	Brief Description of Facility	Sampling Locations
Wetland Complex	WC	WC includes the Old and New CDSTWs. The WC outlet could not be sampled in isolation from EB outlet flows because they drain via multiple pipes to the same catch basin. However, flow at WCEBO is typically over 25 times more than flow at EBO, indicating the vast majority of water at WCEBO is from the WC. When describing pollutant concentrations, WC effectiveness was approximated by comparing concentrations at WCI and WCEBO. When describing pollutant loadings, WC effectiveness was estimated by comparing loadings at WCI to loadings at WCEBO after subtracting EBO loadings.	The inlet sample location is WCI, and outlet location is WCEBO. See description and Figure 2 for details.
North Fork of West Hylebos Creek	NFWHC	NFWHC is the receiving waters of the RDF. Flows at the sampling location are typically 1.3x higher than flows at WCEBO, indicating the majority of flow at this point is RDF outflows.	Creek sample location (NFWHC) is downstream of the RDF at S. 359th Street.

[1] All specifications in section 8-02.3(4)A for Bioretention Soil Media (BSM) quality and application, and all specifications in Section 9-14.4(8) Special Provisions for compost were met (WSDOT, 2010); however, this soil depth exceeds the 18 inch depth currently required (Ecology 2018).

[2] All specifications in Section 8-02.3(6) Special Provisions for BSA were met (WSDOT, 2010).

Table 2. A summary of the study objectives and data gathered to address those objectives.

Study Objective	Relevant Data	Sample Locations	Sampling Time Frame	Notes
1) Evaluate effectiveness of individual facilities	• Continuous flow • Water levels in EB and WB • Chemical analyses from flow-weighted composite samples • Pollutant loading estimates • Toxicity test results	Paired inlet and outlet locations for EB, WB, and WC (Table 1 describes how concentrations and loadings were calculated for WC)	18 storms, sampled from March 2016 through April 2017	Comparison of inlet and outlet data is complicated due to the piping system and overflow locations (Figure 2)
2) Evaluate effectiveness of entire RDF	• Continuous flow • Pollutant loadings estimates	Estimated loadings to and from RDF were calculated by summing inlet loadings (WCI, EBI, WBI) and subtracting outlet loadings (WBO, WCEBO)	5 storms, sampled from March 2016 through April 2017	Limited to 5 storms because flow data were only available from all locations for 5 storms
3) Evaluate if the retrofit and RDF expansion improved overall RDF effectiveness	• Continuous temperature • Continuous turbidity	Primary RDF inlet (WCI) and discharge point to creek (DPC)	Pre-retrofit: May 2011 – June 2014; Post-retrofit: March 2016 – April 2017	Range of daily average and max turbidity data limited to values less than the highest inlet value observed in the post-retrofit to limit range of inlet values to those comparable pre- and post-retrofit. Temperature data from 836 and 429 days, pre- and post-retrofit, respectively. See Appendix K.
4) Evaluate whether macroinvertebrate community and receiving water temperature improved with RDF retrofit and expansion	• BIBI and MMI scores from macroinvertebrate samples • Continuous temperature	Macroinvertebrate samples collected from NFWHC; pre- and post-retrofit water temperature data compared from WCI and NFWHC	Pre-retrofit macroinvertebrate data: 1999-2014; Post-retrofit macroinvertebrate data: 2016 and 2017; Pre-retrofit temp data: May 2011 – June 2014; Post-retrofit temp data: April 2016 – August 2017	Daily average and max temperature data from 836 and 429 days evaluated from wetland complex inlet and the creek, pre- and post-retrofit, respectively. See Appendix K.

2.0 KEY METHODS AND FINDINGS

This section includes a discussion of study methods and flow results, to provide context for the overall study findings, as well as a summary of key findings for each study onjective. Appendix F includes the validated, raw data generated for this study. Data quality was acceptable to meet the project objectives (Appendix G). Appendix H includes data summary tables and summary figures. Appendix I includes flow summary tables and figures for each location during each sampled storm event.

2.1 Flow monitoring and implications for interpreting pollutant concentrations and loadings

2.1.1 Flow monitoring: purpose and challenges

Continuous flow was measured at all sampling locations to assess the facilities' capacity to attenuate flow, as well as to trigger and pace the auto-samplers that collected water samples for chemical analysis. Flow measurements were used to calculate the total volume of stormwater runoff that passed by each sampling location and through each facility. The total volume of stormwater runoff and the pollutant concentration were multiplied to estimate pollutant loadings, or the mass of pollutants transported during each storm and at each location.

Stormwater pollution reduction effectiveness was calculated in two ways: simple concentration changes and mass loading changes between influent and effluent. For each facility, the relative effectiveness was assessed by comparing the change in pollutant concentrations in the influent and effluent and this is reported as the percent concentration reduction. The environmental significance of the change, in the pollutant mass retained or released, was assessed by comparing pollutant loading at the inlets and outlets. Both pollutant concentration and loading estimates were used to evaluate effectiveness of the facilities to remove pollutants, but there is greater certainty in the concentration estimates because of challenges in measuring flow volumes.

Water samples were collected at all seven locations during 18 storms (totaling 126 samples). Flow monitoring was successful during the most of the sampling events (90%), and personnel were able to collect representative flow-weighted samples that met sampling criteria (i.e., aliquots collected during a storm interval that included 1) the hydrograph peak, or 2) 50% of the total runoff volume within a 24-hour sampling interval). Sampling events were successful at two locations, the inlet and outlet of EB, during a storm on March 7, 2017 (Figures 3 and 4).

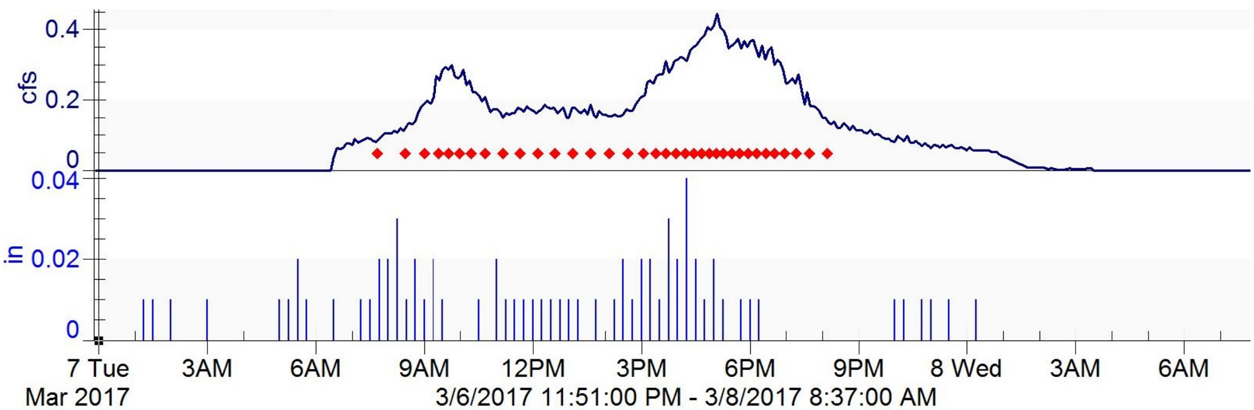

Figure 3. **Flow rate (cfs), rainfall (in) and sample aliquots collected (red diamonds) at the inlet of EB during Storm 10 on 3/7/2017.**

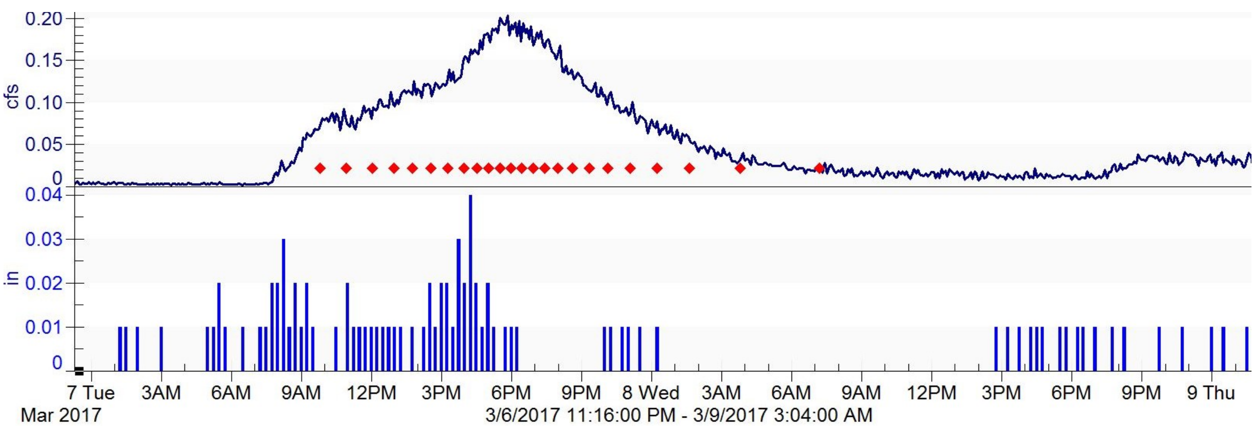

Figure 4. **Flow rate (cfs), rainfall (in) and sample aliquots collected (red diamonds) at the outlet of EB during Storm 10 on 3/7/2017.**

The flow meter malfunctioned, or the sampling criteria were not otherwise met during collection of 10% of the samples. During these situations, time-paced sampling was used to collect multiple aliquots or a large-volume single grab sample was collected. Based on an assessment of field conditions and a review of the hydrograph data from all locations, all of these samples were determined to be representative of storm event conditions and consequently included in analyses. As a result, pollutant concentration estimates exist for all locations and storm events for almost all parameters (Appendices H and I).

In contrast, volume estimates for at least one sampling location during most storms had significant uncertainty. The challenge was primarily in the west bioretention facility, where the long retention time made it impossible to determine a discrete start and stop time for individual storms. Alternatively, the facility overflowed and outflow volumes could not be measured accurately (Table 3). Reliable and usable flow data were obtained from west bioretention facility outlet (WBO) for seven of the 18 sampled storms (Table 3).

An additional uncertainty relates to the difference between inflows and outflows at each facility. The differences could reflect infiltration to groundwater (i.e., inflow>outflow) or groundwater intrusion (i.e., inflow<outflow). Alternatively, the differences could be due to measurement error (see Appendix G, section 4), or some combination of error and interactions with groundwater.

Minimal infiltration to or from the groundwater within the RDF was anticipated. The new facilities were unlined and the bioretention facilities were underdrained because of native soil impermeability. However, wetlands are ubiquitous in the area upstream and west of the RDF. Geologic tests prior to the retrofit indicated the water table near the RDF was high, and as a result a deep pond initially planned for the site was altered (Fei Tang, *personal communication*). Thus, complex sub-surface flows would be expected in this area and may explain some of the variation in flow volume estimates.

Flows in and out of the bioretention facilities indicated there was potentially infiltration during some storms and groundwater intrusion during others (Table 3), but the patterns are hard to interpret. On one hand, flow volume estimates suggest inflows exceeded outflows during some of the largest storm events (e.g., storms 4 and 9, Table 3), suggesting there was infiltration even when soils were likely saturated. In contrast, throughout the study, staff observed a small but steady discharge from each bioretention facility outlet, even after long dry periods with no measured inflow to the facilities. The continuous discharge suggests groundwater inflow likely contributed some input to the facilities, though it is unclear if and how this changed during storm events.

It is more likely that groundwater intrusion affected the wetland complex. The lowest elevation in the complex is more than three feet lower than that in the bioretention facilities, likely making it more susceptible to groundwater intrusion. Flow volumes measured at the wetland complex outlet typically exceeded the inlet flow by about 40%, suggesting some consistent yet unaccounted inflow. There were several minor inflow pipes that discharged to the old CDSTW (Figure 2), but it appeared unlikely that those small inputs could account for the large increase in volume.

As a result of the confounding factors affecting in flow volume estimates, loading estimates are only available for all locations for five storms. Loading estimates are available for the remaining storms, but not for all facilities. Although few in number, these loading estimates provide context for the concentration results. For instance, the wetland complex received and managed 90% of the incoming flows, while the bioretention facilities were typically about 10% of the total flow to the RDF (Figure 5). Thus, moderate reductions (or increases) in pollutant concentrations within the bioretention facilities were insignificant in the context of loadings and the entire RDF.

Table 3. Inflow and outflow volume estimates for the east and west bioretention facilities for sampled storms. Relative percent difference (RPD) between inlet and outlet flow was calculated when data were available for both locations.

Storm Number	East Bioretention Facility				West Bioretention Facility			
	Total Storm Volume In (cubic feet)	Total Storm Volume Out (cubic feet)	RPD (%)	Summary	Total Storm Volume In (cubic feet)	Total Storm Volume Out (cubic feet)	RPD (%)	Summary
1	10503	19133	58	Out > In	18587	ND	NA	NA
2	886	3948	127	Out > In	276	ND	NA	NA
3	ND	17624	NA	NA	16083	9593	51	In > Out
4	32254	25584	23	In > Out	17017	10154	51	In > Out
5	4236	11105	90	Out > In	2442	3332	31	Out > In
6	3587	6606	59	Out > In	2267	ND	NA	NA
7	ND	27124	NA	NA	21386	14100*	41	In > Out*
8	47779	ND	NA	NA	21404	17791*	18	In > Out*
9	62077	32689	62	In > Out	29678	ND	NA	NA
10	12197	8278	38	In > Out	6492	ND	NA	NA
11	19162	13010	38	In > Out	9017	5388	50	In > Out
12	ND	12065	NA	NA	8319	4347	63	In > Out
13	28602	18874	41	In > Out	12918	9097*	35	In > Out*
14	3465	3562	3	Out > In	2315	ND	NA	NA
15	14190	10380	31	In > Out	6398	ND	NA	NA
16	5238	5799	10	Out > In	4034	ND	NA	NA
17	7160	7896	10	Out > In	4242	6450	41	Out > In
18	4365	5047	14	Out > In	2834	4756	51	Out > In
Average			43				43	

* Facility overflowed; measured outflow volume is likely an underestimate of total outflow.

ND - no data or unreliable data.

NA - insufficient data to make comparison.

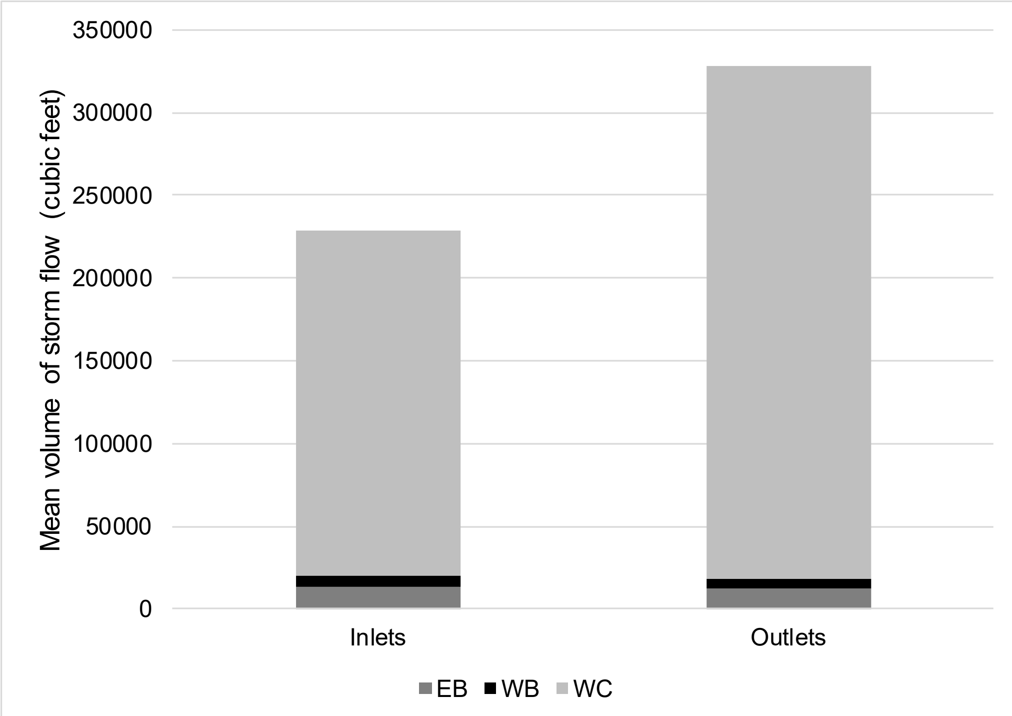

Figure 5. Mean storm runoff volume passing through each sampling location per storm (n=5 storms). The difference between inlet and outlet volume is likely explained by the inflow of groundwater to the wetland complex, as well as measurement error.

2.1.2 Implications of flow monitoring results

The important distinction between concentration and loading in this study, and the implications for evaluating effectiveness, are best illustrated with two examples. One challenge in this study is assessing how concentration reductions at each facility scale up to affect overall changes in pollutant loads. An additional complication relates to the possibility that groundwater inflows to WC could "dilute" the treatment. If the excess volumes in WC outflows were due to intruding pollutant-free groundwater (Figure 5), the apparent treatment by the WC could actually be dilution rather than treatment.

Concentrations of dissolved zinc (DZn) and loads were reduced by the bioretention facilities but not by the wetland complex (Figures 6 and 7). Effluent concentrations in the bioretention facilities during all storms were less than the influent concentrations (Figure 6). Likewise, for all storms for which reliable volume estimates were available, DZn loads were reduced by the bioretention facilities (Figure 7). In contrast, DZn concentrations in the wetland complex effluent were typically higher (Figure 6) and loads increased (Figure 7). Overall, when considering all inlet and outlet loads, the RDF was a net source of DZn (Figure 7). The bioretention facilities were individually effective in that they contributed only about 1% of the total RDF load of dissolved zinc, but because they treat a small fraction of the RDF runoff, their effect was negligible when considering the RDF overall.

The conclusion that the wetland complex is a source of DZn is consistent regardless of assumptions about groundwater intrusion. On average, there was a 20% increase in DZn concentration in the wetland complex (Figure 6) and typically a 1.4-factor increase in flow volume. If that additional volume were clean groundwater, the increase in DZn due to "treatment" may have been closer to 79% on average, instead of 20%. For pollutants, like DZn, that increase in concentration in the wetland complex, clean groundwater inflows may obscure our understanding of the relative effectiveness of the WC compared to other facilities.

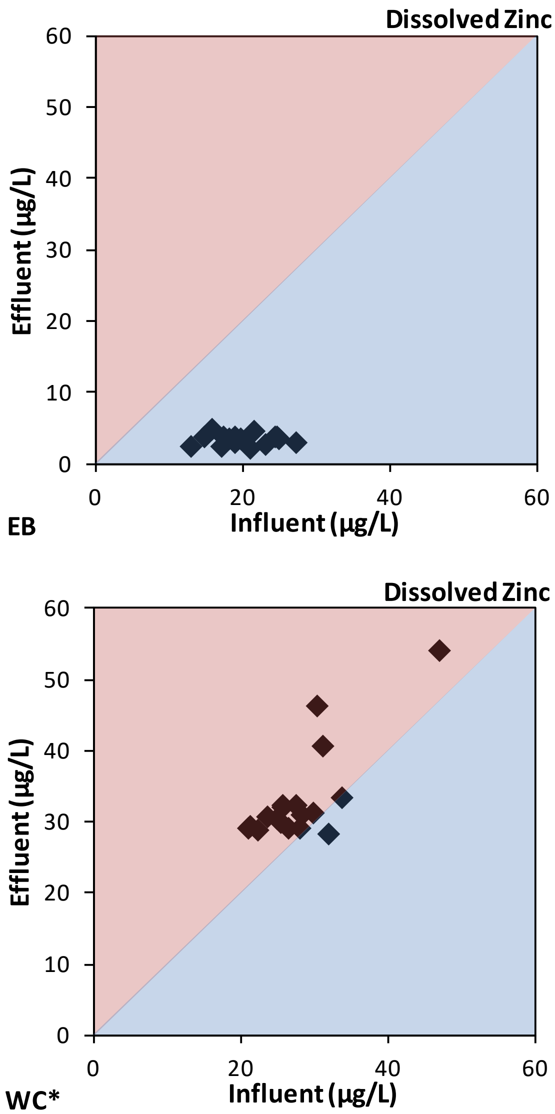

Figure 6. DZn concentrations in influent and effluent at EB andWB facilities, and WC during individual storms (diamonds). * WC influent = WCI; WC effluent = WCEBO. Points above the 1:1 line (In the red) illustrate the facility was a source of DZn; points below the 1:1 line (blue) illustrate the facility was a sink.

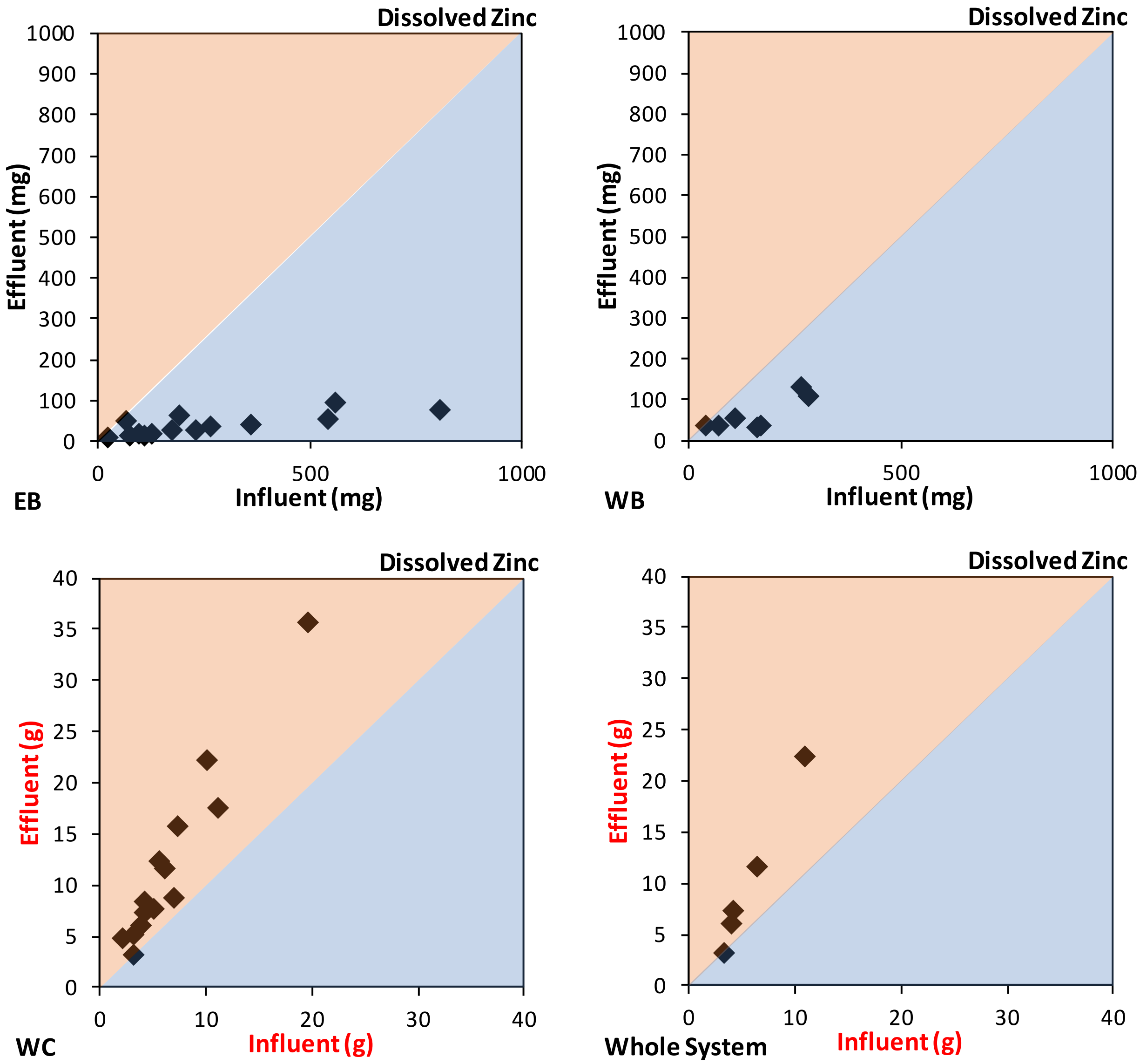

Figure 7. Dissolved zinc (DZn) load in influent and effluent at the bioretention facilities (EB and WB), wetland complex (WC), and whole RDF system during individual storms (diamonds). Red axis labels highlight a change in units. Points above the 1:1 line illustrate the facility was a source of DZn; points below the 1:1 line illustrate the facility was a sink. See Appendix A for how loads at WC and the whole system are calculated.

TP concentrations and loads illustrate a different pattern. TP concentrations in EB and WB influent were low (average in both 0.03 mg/L); however, but effluent concentrations were often orders of magnitude higher (up to 3.83 mg/L in WB) (Figure 8). In contrast, TP concentrations in WC influent were slightly higher than in EB and WB (average 0.06 mg/L), but effluent concentrations were generally unchanged (Figure 8). The relative percent increase between WC influent and effluent was typically 1%, whereas the increase was 2232% and 7670% in EB and WB, respectively. For the wetland complex, the result is somewhat worse if the excess flow volume was actually clean groundwater (51% increase), but it is still less than the increase observed in the bioretention effluent. The effect of high concentrations in the bioretention effluent are obvious in the load estimates (Figure 9). Although the bioretention facilities treat less than 10% of the RDF influent, they contributed on average 79% of the TP load from the whole RDF (Figure 9).

Thus, in the case of DZn, the bioretention facilities effectively reduced concentrations, but had a negligible effect on RDF effectiveness, overall. In contrast, the bioretention facilities significantly increased TP instead of removing it. Results from other parameters are included in the following sections and in Appendix H.

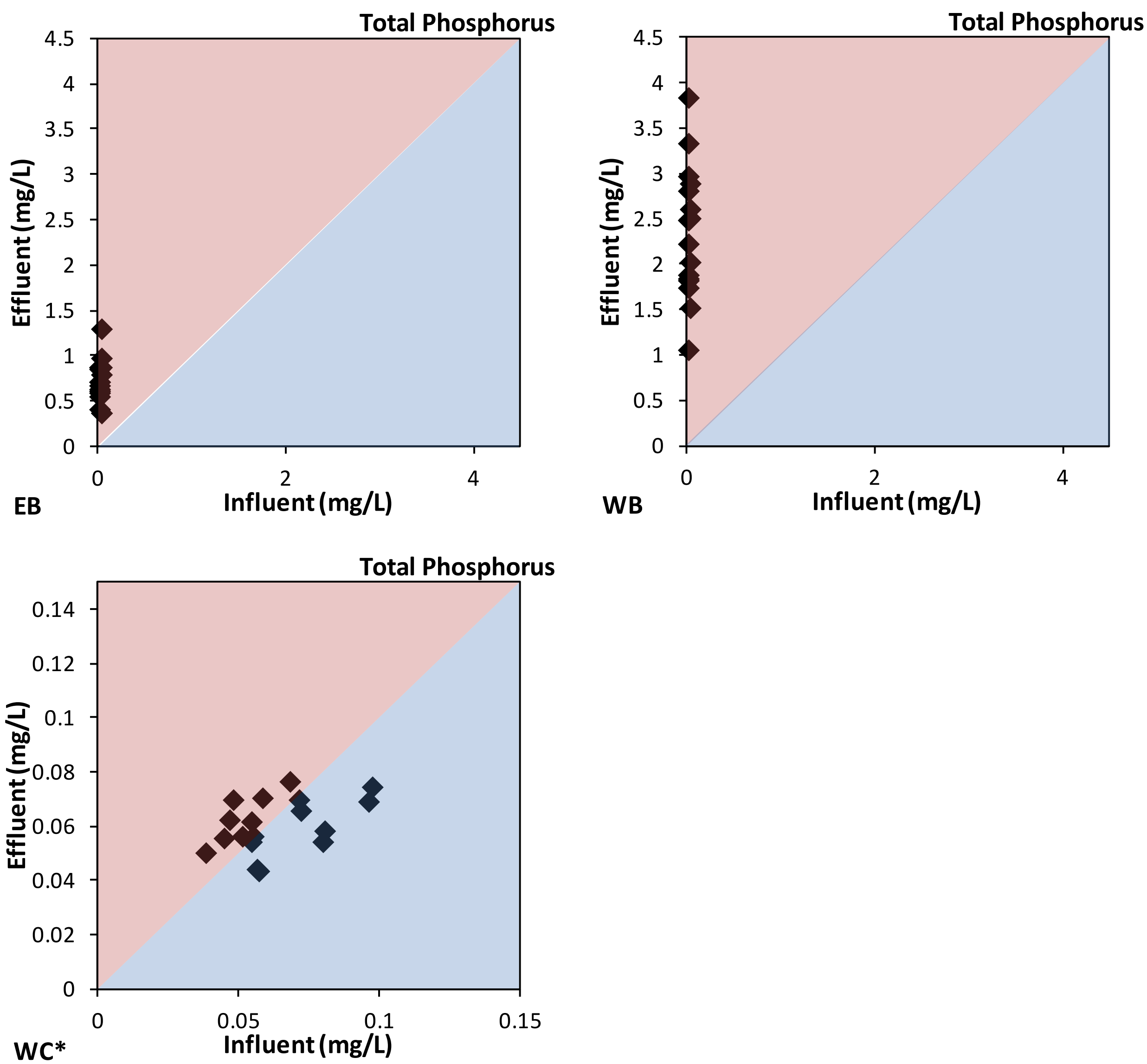

Figure 8. TP concentrations in influent and effluent at EB and WB facilities, and WC during individual storms (diamonds). * WC influent = WCI; WC effluent = WCEBO.

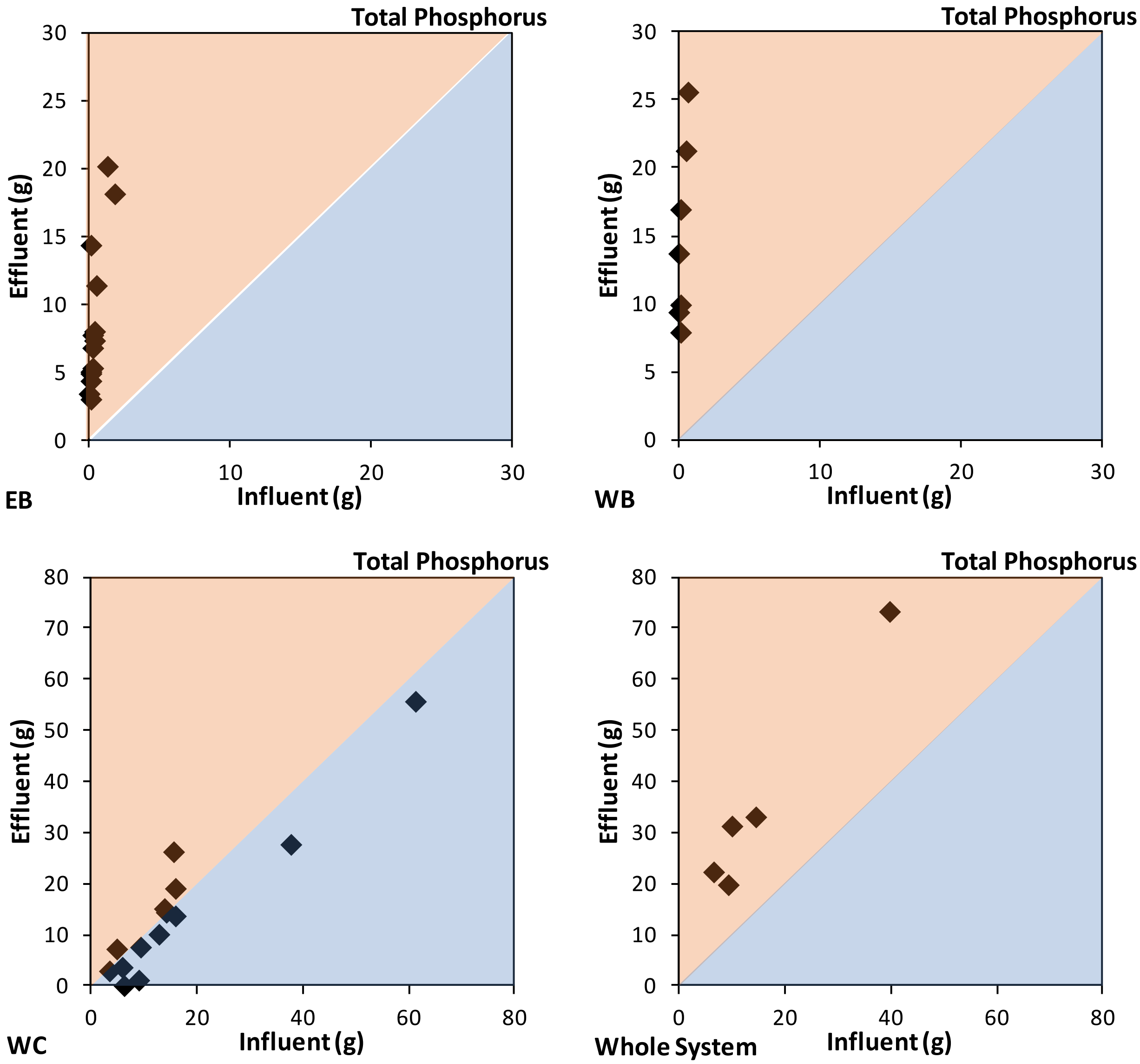

Figure 9. TP loads in influent and effluent at EB and WB facilities, WC, and the whole RDF system during individual storms (diamonds). Points above the 1:1 line illustrate the facility was a source of TP; points below the 1:1 line illustrate the facility was a sink.

2.2 Effectiveness of individual BMPs

Objective 1: **Evaluate the relative effectiveness of individual bioretention facilities and a retrofitted wetland complex to attenuate stormwater flows and reduce turbidity, nutrients, bacteria, metals, select organic pollutants, and toxicity in stormwater runoff.**

2.2.1 Flow attenuation

Peak flows were attenuated throughout the RDF, as measured by the delay in peak flow timing and reduction in peak flow rate through each facility and the RDF as a whole during storm events (Table 4). This attenuation was observed despite the increase in outflows from the RDF (typically 1.4x higher than inflow volumes; Figure 5), and no consistent evidence of infiltration (or loss of volume) in the bioretention facilities (Table 3).

Table 4. Reduction in peak flow rate and delay in peak flow timing at each facility and RDF overall.

Location	Number of storms included in calculation	Median percent reduction in peak flow rate	Median delay in timing of peak flows between inlet and outlet (hours:min)
East bioretention facility (EBO-EBI)	15	-45%	1:58
West bioretention facility (WBO-WBI)	11	-83%	6:25
Wetland Complex (WCEBO-WCI)	17	-48%	7:00
RDF to stream (NFWHC-WCI)	17	-37%	2:42

2.2.2 Stormwater treatment

The following section summarizes performance of each stormwater treatment facility for each group of parameters assessed during 18 sampled storms. The tables report concentration data for each parameter measured at each location, including the percent concentration reduction for each facility. The percent concentration reduction is calculated as the percent difference between the median influent and effluent concentrations. The significance of the difference between inlet and outlet concentrations for each facility was evaluated with an Asymptotic Two-sample Fisher-Pitman Permutation test, described in Appendix E.

Influent pollutant concentrations were comparable between the EB and WB, but were generally more than two times higher at the inlet of the WC. This difference makes comparison of performance among facilities problematic. For example, based on percent reduction, the WC generally appears more effective than the bioretention facilities at reducing some pollutants. However, concentration data indicate effluent concentrations discharged from the bioretention facilities were often lower than levels in the WC effluent. Accordingly, comparisons among facilities should be avoided as they are potentially misleading.

It is not clear why influent pollutant concentrations to the bioretention cells (EB and WB) were typically lower than influent concentrations to the WC. Possible reasons may be differences in the basin size or that the 'ditch' immediately prior to the bioretention facilities provided some pre-treatment. Stormwater draining to EB and WB is sourced from a smaller (22.6 acres), but more densely developed basin (Figure 1), whereas the influent stormwater for the WC drains 189 acres. Also, at the time of the study, stormwater runoff to EB and WB flowed through grassy roadside ditches before reaching the facilities (Appendix A). Suspended particulates may have settled in the ditches. This theory is supported by the consistently lower influent pollutant concentrations detected at these sites compared to levels in the WC, particularly those associated with particulates (e.g., TSS, total organic carbon, particulate metals fraction, and PAHs; Tables 8 -13). The ditches no longer exist as the final road construction near the site piped this water directly to the bioretention facilities.

2.2.2.1 Pollutants with Technology Assessment Protocol – Ecology (TAPE) Performance Goals

Performance goals based on pollutant concentrations specified by the Technology Assessment Protocol – Ecology (TAPE) (Ecology 2018), and are listed in Table 5. These were used in part to evaluate performance of the individual facilities. The TAPE program specifies goals for a subset of pollutants measured in the study (Table 6). Some values are estimated; data validation flags and additional details are included in Appendix H.

Table 5. TAPE performance goals (adapted from Ecology 2018).

Performance Goal	Influent Range	Criteria
Basic Treatment	20-100 mg/L total suspended solids (TSS)	Effluent goal < 20 mg/L TSS
	100-200 mg/L TSS	≥ 80% TSS removal
Dissolved Metals Treatment	Dissolved copper 0.005 - 0.02 mg/ L	Must meet basic treatment goal and exhibit ≥ 30% dissolved copper removal
	Dissolved zinc 0.02 - 0.3 mg/L	Must meet basic treatment goal and exhibit ≥ 60% dissolved zinc removal
Phosphorus Treatment	Total phosphorus (TP) 0.1 - 0.5 mg/L	Must meet basic treatment goal and exhibit ≥ 50% TP removal

In addition to but separate from the TAPE goals, statistical tests were used to determine if differences in influent and effluent concentrations were significant (See Appendix E for methods). The results of those tests are indicated by asterisks.

The comparison of each facility's performance to the TAPE goals illustrates some research challenges. The WC often performed better than the EB and WB, when considering percent pollutant reduction; however, effluent concentrations from the WC often did not meet the TAPE goals. For example, the WC had the greatest percent reduction in TSS concentrations, but TSS concentrations in the EB and WB effluent were generally lower than those in WC effluent. The TAPE goals for TSS did not apply to the EB and WB because the influent concentrations were very low (<20 mg/L), and the WC failed to meet the TSS goal because effluent concentrations were not reduced enough in two of the 16 storms when influent concentrations > 20 mg/L. The percent reduction of various pollutants achieved by the WC was often statistically significant, but the effluent concentrations were not sufficiently reduced to meet the TAPE goals.

Table 6. Summary of TSS, dissolved copper, dissolved zinc and total phosphorus concentrations at each location and percent concentration reduction at each facility. Color shading indicates if facility met TAPE performance goals: grey indicates goals not applicable due to low influent concentrations; red indicates facility did not meet goals for all storms; blue indicates the facility met goals for each qualifying storm event.

Parameter		Inlets			Outlets			Stream	Percent Concentration Reduction[1]		
		Bioretention facilities		Wetland complex (WCI)	Bioretention facilities		Wetland complex (WCEBO)	NFWHC	Bioretention facilities		Wetland complex
		East (EBI)	West (WBI)		East (EBO)	West (WBO)			East	West	
TSS (mg/L)	Median	4.74	4.43	37.2	1.95	2.72	8.12	12.1	59% **	39%	78% ***
	Min	1.22	1.68	9.79	0.84	0.74	2.8	3.33			
	Max	14.5	14.2	61.2	6.24	14.8	22.4	27.3			
	25th %	3.1	3.6	26.5	1.8	1.4	5.9	7.6	Influent and effluent <20 mg/L	Influent and effluent <20 mg/L	For influent 20-100 mg/L (n=16), effluent >20mg/L in 2 samples
	75th %	5.7	6.7	47.0	2.5	7.9	13.2	19.2			
	FOD	17/17	18/18	18/18	18/18	17/18	18/18	18/18			
Dissolved Copper (µg/L)	Median	2.26	2.23	3.2	3.81	5.31	3.27	2.46	-69% **	-138% **	-2%
	Min	0.94	0.99	2.05	1.6	2.08	2.62	1.7			
	Max	4.27	4.8	5.36	7.09	14.1	5.94	5.52			
	25th %	1.83	1.83	2.72	2.69	3.72	2.94	2.34	Influent <5 µg/L	Influent <5 µg/L	For influent 5-20 µg/L (n=1), <30% reduction (influent for other storms <5 µg/L)
	75th %	3.29	3.40	3.75	4.35	6.16	3.37	2.79			
	FOD	18/18	18/18	18/18	18/18	18/18	18/18	18/18			
Dissolved Zinc (µg/L)	Median	18.9	19	27	3.51	7.43	30.8	14.8	81% ***	61% ***	-14% ***
	Min	13	12.4	21	2.2	4.96	28.2	12.3			
	Max	27.2	27.1	47	4.86	13.9	54	25.3			
	25th %	17.5	17.9	25.1	3.1	6.4	29.3	13.8	For influent 20-300 µg/L, >60% reduction	For influent 20-300 µg/L, >60% reduction	For influent 20-300 µg/L (n=18), median increase of 14%
	75th %	22.7	23.8	30.3	3.8	8.3	32.4	15.6			
	FOD	18/18	18/18	18/18	18/18	18/18	18/18	18/18			
Total Phosphorus (mg/L)	Median	0.0294	0.0329	0.0569	0.691	2.48	0.0596	0.0528	-2250% ***	-7438% ***	-5%
	Min	0.0212	0.0222	0.0382	0.369	1.05	0.0433	0.0364			
	Max	0.0483	0.0444	0.0977	1.3	3.83	0.0767	0.107			
	25th %	0.026	0.026	0.052	0.601	1.843	0.055	0.043	Influent <0.1 mg/L, but large increases	Influent <0.1 mg/L, but large increases	Influent <0.1 mg/L, but minimal increases
	75th %	0.035	0.036	0.072	0.865	2.860	0.069	0.061			
	FOD	17/17	17/17	18/18	18/18	18/18	18/18	18/18			

[1] Significance assessed using Asymptotic Two-sample Fisher-Pitman Permutation tests (Appendix E); two-way p-values reported as * = p<0.05, ** = p<0.01, *** = p<0.001

Summary statistics include median, minimum, maximum, 25th and 75th percentile, and frequency of detects (FOD).

2.2.2.2 Pollutants without TAPE Performance Goals

Most of the pollutants monitored for the project do not have established TAPE performance goals. Thus, the color scheme in the following tables is intended to indicate whether pollutant concentrations were typically reduced or increased in each facility, and whether the difference between the effluent and influent concentrations was statistically significant. The color key is presented in Table 7.

Table 7. Color coding used to describe performance of each facility and significance of change in pollutant concentration in effluent vs. influent.

Color	Performance	Effluent: Influent	Significant change?
	Good	<	Significantly reduced
	Good	<	Somewhat reduced, but not significant
	Poor	>	Somewhat increased, but not significant
	Poor	>	Significantly increased

Concentration results are included in tables and discussed briefly. Note some values are estimates. Italicized values represent the method detection limits for samples in which the pollutant was not detected. Data validation flags and additional details are included in Appendix H. Loading results are discussed in the next section (Objective 2).

Conventional parameters: turbidity and conductivity

Turbidity was significantly reduced by the WC and moderately reduced by the EB and WB (Table 8). However, the significance of this reduction at the WC is somewhat misleading because influent concentrations were so much higher. Conductivity tended to increase at all sites, with significant increases at the WB. (Note these data are from flow-weighted composite samples from 18 events; continuous turbidity data are discussed in section 2.3.)

Table 8. Summary of turbidity and conductivity data from each location and the percent concentration reduction observed at each facility.

Parameter		Inlets: Bioretention facilities East (EBI)	Inlets: Bioretention facilities West (WBI)	Inlets: Wetland complex (WCI)	Outlets: Bioretention facilities East (EBO)	Outlets: Bioretention facilities West (WBO)	Outlets: Wetland complex (WCEBO)	Stream: NFWHC	Percent Concentration Reduction[1]: Bioretention facilities East	Percent Concentration Reduction[1]: Bioretention facilities West	Percent Concentration Reduction[1]: Wetland complex
Turbidity (NTU)	Median	6.12	5.9	27.9	4.4	4.69	12.5	14	28%	21%	55% **
	Min	2.38	2.85	10.5	2.2	2.55	4.55	4.72			
	Max	12.9	12.5	56.8	9.23	17.9	41.1	35.7			
	25th %	4.61	4.32	21.48	3.66	3.37	8.78	9.16			
	75th %	7.53	7.42	34.78	5.50	7.42	21.40	20.83			
	FOD	17/17	17/17	18/18	18/18	18/18	18/18	18/18			
Conductivity (µmhos/cm)	Median	27.1	26.7	40.1	69.4	119	68.8	125	-156%	-346% **	-72%
	Min	19.1	19.5	27.2	37.7	71.7	37.5	87.1			
	Max	223	211	140	246	376	267	272			
	25th %	20.9	21.8	34.1	56.6	112.5	50.4	98.0			
	75th %	28.3	33.8	48.8	88.5	148.8	84.1	151.0			
	FOD	17/17	17/17	18/18	18/18	18/18	18/18	18/18			

[1] Significance assessed using Asymptotic Two-sample Fisher-Pitman Permutation tests (Appendix E); two-way p-values reported as * = p<0.05, ** = p<0.01, *** = p<0.001

Nutrients

The treatment facilities performed poorly for most nutrient parameters (Table 9). However, the WC performed better than the bioretention sites, particularly for total nitrogen and ammonia nitrogen, for which significant decreases in concentration were observed. In contrast, on average, orthophosphate (OP) concentrations increased by more than a factor of three at the WC. See Table 6 for total phosphorus summary.

Table 9. Summary of nutrient data from each location and percent concentration reduction observed at each facility.

Parameter		Inlets			Outlets			Stream	Percent Concentration Reduction[1]		
		Bioretention facilities		Wetland complex (WCI)	Bioretention facilities		Wetland complex (WCEBO)	NFWHC	Bioretention facilities		Wetland complex
		East (EBI)	West (WBI)		East (EBO)	West (WBO)			East	West	
Orthophosphate P (µg/L)	Median	0.0102	0.00987	0.00508	0.603	2.02	0.0221	0.0167	-5812%	-20366%	-335%
	Min	0.00429	0.00445	0.00286	0.284	0.93	0.0134	0.0117	***	***	***
	Max	0.0211	0.0207	0.0131	1.01	3.13	0.0343	0.0263			
	25th %	0.0077	0.0082	0.0039	0.5258	1.72	0.0205	0.0147			
	75th %	0.0128	0.0126	0.0098	0.7408	2.218	0.0256	0.0188			
	FOD	17/17	18/18	18/18	18/18	18/18	18/18	18/18			
Total Nitrogen (mg/L)	Median	0.296	0.255	0.567	1.15	2.89	0.434	0.616	-289%	-1033%	23%
	Min	0.161	0.18	0.382	0.445	1.48	0.273	0.561	***	***	***
	Max	0.459	0.476	0.774	2.38	6.52	0.517	1			
	25th %	0.219	0.244	0.452	0.913	2.283	0.374	0.607			
	75th %	0.396	0.381	0.675	1.323	3.928	0.484	0.683			
	FOD	17/17	17/17	18/18	18/18	18/18	18/18	18/18			
Nitrate + Nitrite N (mg/L)	Median	0.0962	0.0879	0.152	0.379	0.851	0.147	0.294	-294%	-868%	3%
	Min	0.0526	0.0539	0.0909	0.123	0.0899	0.04	0.212	***	***	
	Max	0.166	0.171	0.26	0.834	4.25	0.204	0.403			
	25th %	0.070	0.073	0.122	0.266	0.591	0.094	0.255			
	75th %	0.132	0.134	0.171	0.533	1.253	0.166	0.320			
	FOD	17/17	18/18	18/18	18/18	18/18	18/18	18/18			
Ammonia N (mg/L)	Median	0.0387	0.0388	0.0962	0.0556	0.254	0.0351	0.0147	-44%	-555%	64%
	Min	*0.002*	*0.002*	0.0489	0.0333	0.147	0.0112	0.0028	*	***	***
	Max	0.0928	0.0901	0.164	0.22	0.687	0.129	0.0778			
	25th %	0.0229	0.0225	0.0677	0.0445	0.2068	0.0186	0.0056			
	75th %	0.0748	0.0595	0.1245	0.1053	0.4240	0.0615	0.0309			
	FOD	16/17	17/18	18/18	18/18	18/18	18/18	18/18			

[1] Significance assessed using Asymptotic Two-sample Fisher-Pitman Permutation tests (Appendix E); two-way p-values reported as * = p<0.05, ** = p<0.01, *** = p<0.001

All effluent nutrient concentrations were significantly higher than influent concentrations at both bioretention sites, with the WB exhibiting the poorest performance for all nutrient parameters. Median total nitrogen concentrations increased by a factor of 4 at the EB, and a factor of 11 at the WB. Median total phosphorus concentrations increased by a factor of 24 at the EB and a factor of 75 at the WB (Table 6). OP concentrations increased more than any other parameter at the bioretention sites; median concentrations increased by a factor of 59 at the EB and a factor of 205 at the WB.

As with other bioretention systems with 60% sand/40% compost mix, the source of the excess nutrients was likely compost in the soil mix as well as the coarse compost added on top. As mentioned above, the depth of soil (30 inches) in the bioretention facilities was greater than what is currently required (18 inches) and also likely contributed to the high nutrient concentrations in the effluent. Although the observed nutrient concentrations in the bioretention effluent were high, they are well within the range and often lower than concentrations found in other studies (Chahal et al. 2016; Herrera 2016). Over the storm sampling interval (3/2016 – 4/2017), there was no consistent change in effluent concentrations for any of the measured nutrients.

The higher concentrations in the WB effluent may be due to the WB's slower infiltration rate. Additional potential nutrients sources include groundwater flowing into the facilities and wildlife urine or excrement (e.g., Canada geese and other water fowl) inhabiting the RDF (Appendix A).

Bacteria

Effluent fecal coliform concentrations were generally lower at the bioretention sites than the WC (Table 10). Even so, there was no evidence that any of the facilities effectively reduced fecal coliform concentrations; differences were not statistically significant at any site.

Table 10. Summary of bacteria data from each location and percent concentration reduction observed at each facility.

Parameter		Inlets			Outlets			Stream	Percent Concentration Reduction[1]		
		Bioretention facilities		Wetland complex (WCI)	Bioretention facilities		Wetland complex (WCEBO)	NFWHC	Bioretention facilities		Wetland complex
		East (EBI)	West (WBI)		East (EBO)	West (WBO)			East	West	
Fecal Coliform (CFU/100mL)	Median	102	100	515	45	7	94	53	56%	93%	82%
	Min	9	9	80	23	1	10	4			
	Max	1,900	1,500	1,100	200	410	900	410			
	25th %	52	28	328	29	2	48	34			
	75th %	218	135	615	57	48	170	138			
	FOD	10/10	10/10	10/10	10/10	10/10	10/10	10/10			

Metals

The bioretention facilities and the WC were not equally effective in reducing total and dissolved metals, nor was the effectiveness of each consistent across metals (Tables 6 and 11). Based on percent reduction calculations, the WC was more effective than the EB and WB in reducing all total and dissolved metals in the effluent, except zinc (Tables 6 and 11). The WC reduced concentrations of all total metals, but increased concentrations of dissolved zinc (Tables 6 and 11). But as with other pollutants, this apparent effectiveness is explained in part by the higher influent metals concentrations at WCI compared to EBI or WBI (Table 11). For total copper, effluent concentrations were typically similar among the outlets, but for total lead, the WC effluent concentrations were typically higher than the EB and WB effluent.

Table 11. Summary of metals data from each location and percent concentration reduction observed at each facility.

Parameter		Inlets			Outlets			Stream	Percent Concentration Reduction[1]		
		Bioretention facilities		Wetland complex (WCI)	Bioretention facilities		Wetland complex (WCEBO)	NFWHC	Bioretention facilities		Wetland complex
		East (EBI)	West (WBI)		East (EBO)	West (WBO)			East	West	
Total Zinc (µg/L)	Median	26.2	26.1	63.8	4.78	8.28	40.5	26	82%	68%	37%
	Min	17.1	18.9	41.9	3.62	6.08	34.3	16.7	***	***	***
	Max	38.4	35.1	97.3	6.34	16.2	67.7	44.8			
	25th %	23.3	22.9	53.1	4.4	8.0	37.1	20.4			
	75th %	30.5	31.0	77.1	5.6	10.7	45.3	30.8			
	FOD	18/18	18/18	18/18	18/18	18/18	18/18	18/18			
Total Copper (µg/L)	Median	3.54	3.52	10.6	4.07	5.67	5.21	3.86	-15%	-61%	51%
	Min	1.9	2.03	5.77	1.8	2.6	3.76	2.45		*	***
	Max	5.95	6.55	15.3	8.3	17	8.11	6.38			
	25th %	3.04	2.99	7.97	3.13	4.09	4.33	3.11			
	75th %	4.48	4.63	11.48	4.73	6.68	6.40	4.66			
	FOD	18/18	18/18	18/18	18/18	18/18	18/18	18/18			
Total Lead (µg/L)	Median	0.624	0.607	3.58	0.43	0.858	1.29	1.52	31%	-41%	64%
	Min	0.21	0.25	1.27	0.2	0.3	0.44	0.557	*		***
	Max	1.52	1.46	6.23	0.823	2.08	2.3	3.88			
	25th %	0.48	0.45	2.86	0.33	0.72	0.62	0.93			
	75th %	0.79	0.75	4.38	0.54	1.18	1.75	2.18			
	FOD	18/18	18/18	18/18	18/18	18/18	18/18	18/18			
Dissolved Lead (µg/L)	Median	*0.1*	NC	0.12	0.23	0.663	0.16	0.21	-130%	NC[2]	-33%
	Min	*0.1*	*0.1*	*0.1*	*0.1*	0.12	*0.1*	0.13	***		
	Max	0.11	0.11	0.37	0.56	1.14	0.683	0.34			
	25th %	0.1	0.1	0.11	0.16	0.48	0.15	0.17			
	75th %	0.1	0.1	0.19	0.29	0.79	0.18	0.24			
	FOD	3/18	2/18	14/18	16/18	18/18	17/18	18/18			
Total Cadmium (µg/L)	Median	NC	NC	0.063	*0.05*	0.053	*0.05*	*0.05*	NC	NC	21%
	Min	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*			*
	Max	0.072	0.11	0.1	0.12	0.19	0.093	0.072			
	25th %	0.05	0.05	0.05	0.05	0.05	0.05	0.05			
	75th %	0.05	0.05	0.08	0.05	0.07	0.05	0.05			
	FOD	1/18	1/18	13/18	4/18	9/18	3/18	4/18			
Dissolved Cadmium (µg/L)	Median	NC	NC	NC	NC	*0.05*	NC	NC	NC	NC	NC
	Min	NC	*0.05*	NC	NC	*0.05*	*0.05*	NC			
	Max	*0.05*	0.07	*0.05*	*0.05*	0.15	0.064	*0.05*			
	25th %	NC	NC	NC	NC	0.05	NC	NC			
	75th %	NC	NC	NC	NC	0.052	NC	NC			
	FOD	0/18	1/18	0/18	0/18	5/18	2/18	0/18			

[1] Significance assessed using Asymptotic Two-sample Fisher-Pitman Permutation tests (Appendix E); two-way p-values reported as * = p<0.05, ** = p<0.01, *** = p<0.001

[2] NC indicates not calculated because of low number of detects

While influent metals concentrations were similar between the two bioretention sites, effluent concentrations were frequently higher at the WB compared to the EB. Performance of the EB and WB to reduce total and dissolved metals was poor to moderate, with the exception of zinc, which was significantly reduced at both sites. Total cadmium was rarely detected in the EB and WB influent, but frequently detected in effluent. However, effluent concentrations were generally within a factor of two of the method detection limit. Despite an increase in some total lead concentrations, on average, effluent levels decreased in the EB. Concentrations of dissolved copper increased in both the EB and WB (Table 6) and dissolved lead significantly increased in the EB (Table 11).

The bioretention soil mix may be the source of the metals from the bioretention facilities, but effluent concentrations were relatively low compared to concentrations found in other studies with similar soil mixes (Chahal et al. 2016; Herrera 2016). As with nutrients, the higher concentrations in the WB effluent may be due to facility's slower infiltration rate.

Select organic pollutants

Concentrations of PAHs and PCBs were significantly reduced by both the WB and the WC (Table 12). As with some other parameters, a comparison of the concentrations among facilities would be misleading because the WC influent PAH concentrations were greater than influent concentrations to the EB and WB. The WB had the lowest effluent concentrations of both PAHs and PCBs, closely followed by the EB. The WC significantly reduced total PAH concentrations, but on average, the WC effluent concentrations were higher than EB and WB influent concentrations.

Table 12. Summary of PAH and PCB data from each location and percent concentration reduction observed at each facility.

Parameter		Inlets			Outlets			Stream	Percent Concentration Reduction[1]		
		Bioretention facilities		Wetland complex (WCI)	Bioretention facilities		Wetland complex (WCEBO)	NFWHC	Bioretention facilities		Wetland complex
		East (EBI)	West (WBI)		East (EBO)	West (WBO)			East	West	
Total PAHs (µg/L)	Median	0.0158	0.0146	0.287	*0.0094*	*0.0094*	0.03	0.018	41%	36% *	90% ***
	Min	0.0078	*0.0094*	0.046	0.007	0.0056	*0.0094*	*0.0094*			
	Max	0.0967	0.113	0.641	0.0451	*0.024*	0.238	0.078			
	25th %	0.0104	0.011	0.1905	*0.0094*	*0.0094*	0.024	0.011			
	75th %	0.024	0.024	0.3847	0.0204	*0.0094*	0.0785	0.024			
	FOD	11/17	11/17	18/18	5/18	4/18	13/18	12/18			
Total PCBs (pg/L)	Median	551	529	1,290	111	112	406	541	80%	79% *	69% **
	Min	203	199	27	7.89	1.73	70.4	224			
	Max	6,200	2,440	3,910	1,230	665	1,890	3,220			
	25th %	352	402	1000	90	29	165	458			
	75th %	772	960	1790	208	196	681	1325			
	FOD	15/15	13/13	15/15	15/15	13/13	15/15	15/15			

[1] Significance assessed using Asymptotic Two-sample Fisher-Pitman Permutation tests (Appendix E); two-way p-values reported as * = p<0.05, ** = p<0.01, *** = p<0.001

Other conventional parameters

Total organic carbon (TOC), dissolved organic carbon (DOC), and hardness levels are not necessarily indicative of poor water quality; furthermore, increases in organic carbon and hardness can help reduce the toxicity of some pollutants (e.g., dissolved metals). Accordingly, color shading was not included in Table 13.

Concentrations of TOC, DOC and hardness were significantly increased in the EB and WB effluent. The WC significantly decreased effluent TOC concentrations, but generally increased DOC concentrations. This suggests that the WC was more effective at reducing particulate organic carbon than DOC. Hardness increased in all facilities. Changes in pH differed by facility, but effluent samples were all within a relatively neutral pH range (i.e., 6.3 to 7.4 pH units).

Table 13. Summary of organic carbon, pH and hardness data from each location and percent concentration reduction observed at each facility.

Parameter		Inlets			Outlets			Stream	Percent Concentration Reduction[1]		
		Bioretention facilities		Wetland complex (WCI)	Bioretention facilities		Wetland complex (WCEBO)	NFWHC	Bioretention facilities		Wetland complex
		East (EBI)	West (WBI)		East (EBO)	West (WBO)			East	West	
TOC (mg/L)	Median	1.62	1.65	5.04	5.95	14.2	3.23	5.85	-267%	-761%	36%
	Min	1.1	1.24	1.59	2.67	6.49	2.29	3.94	***	***	***
	Max	3.01	3.16	7.4	13.9	33.8	4.44	10.30			
	25th %	1.35	1.49	3.73	4.97	12.23	2.58	5.35			
	75th %	1.99	2.24	5.57	7.90	19.5	3.88	6.34			
	FOD	17/17	18/18	18/18	18/18	18/18	18/18	18/18			
DOC (mg/L)	Median	1.54	1.75	2.57	5.84	14.1	2.97	4.92	-279%	-706%	-16%
	Min	0.71	0.86	1.14	1.18	6.41	1.66	3.59	***	***	
	Max	2.81	3.1	4.05	13.5	28.1	4.45	8.69			
	25th %	1.05	1.36	1.95	4.76	11.63	2.51	4.75			
	75th %	1.76	2.1	3.12	8.16	17.95	3.60	5.33			
	FOD	17/17	18/18	18/18	18/18	18/18	18/18	18/18			
pH (pH units)	Median	6.98	6.97	7.05	6.82	6.74	7.09	7.49	2%	3%	-1%
	Min	6.5	6.48	6.58	6.45	6.37	6.53	7.06		*	
	Max	7.33	7.13	7.21	7.1	7.16	7.35	7.71			
	25th %	6.92	6.92	6.95	6.73	6.59	6.91	7.27			
	75th %	7.03	7	7.11	6.938	6.858	7.18	7.65			
	FOD	17/17	17/17	18/18	18/18	18/18	18/18	18/18			
Hardness (mg $CaCO_3$/L)	Median	7.44	7.74	14.5	18	33.9	19.9	46.5	-142%	-338%	-37%
	Min	4.71	4.89	10.4	7.85	14.4	12.6	30.2	***	***	**
	Max	12.7	12.3	28.5	44.8	82	36	70.1			
	25th %	5.83	5.69	12.78	11.58	28.33	15.53	38.5			
	75th %	8.48	8.47	16.33	22.03	43.65	24.08	59.1			
	FOD	18/18	18/18	18/18	18/18	18/18	18/18	18/18			

[1] Significance assessed using Asymptotic Two-sample Fisher-Pitman Permutation tests (Appendix E); two-way p-values reported as * = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$

Toxicity

Toxicity tests were conducted on samples from each location for six storm events using two daphnia (water flea) species, *Daphnia pulex* (acute test) and *Ceriodaphnia dubia* (chronic test). No chronic toxicity was observed from any influent or effluent stormwater sample taken at the RDF. Downstream creek samples were not toxic to *C. dubia*. Acute toxicity was found in two of six storms for the influent samples from EBI but not from WBI. No effluent samples were found to be acutely toxic to *D. pulex*. The limited test results indicate toxicity may be due to low hardness (low survival was observed in low-hardness controls), or a combination of low hardness, PAHs, and possibly dissolved copper, lead and/or zinc. Effluent samples at EBO and WBO consistently had lower total PAH and dissolved zinc concentrations than influent samples at EBI and WBI. While dissolved copper and lead concentrations were commonly higher in the bioretention effluent samples, hardness and DOC concentrations were also much higher in the effluent samples, which would help mitigate metals toxicity (See Appendix F3 and H3 for details and QC information).

2.3 System-wide effectiveness

***Objective 2:* Evaluate the effectiveness of the entire, expanded RDF, to attenuate stormwater flows and improve water quality.**

Flow attenuation

The entire RDF attenuated stormwater flows by delaying the timing of peak flow and reducing peak flow rates of stormwater flowing into receiving waters. The median delay in peak flow timing at the RDF outlet compared to the inlet was 7 hours. In contrast, flow rate typically peaked much faster in the stream (median delay in peak flow rate at the stream compared to the RDF inlet was only 2 hours and 42 minutes). Likewise, during the 18 sampled storms, the RDF typically reduced peak flow rates by 48% between the main inlet and outlet, but only reduced peak flows by 37% between the main RDF inlet and the stream. These flow measures corroborate observations that the stream reach between South 356th St. and South 359th St. gains flow from shallow groundwater. The observation of groundwater intrusion into the wetland complex, however, did not impact the success of the RDF retrofit design in providing stormwater flow controls.

Water quality

In general, overall performance of the RDF is dominated by the performance of the WC. This is because the vast majority (>90%) of the flow is routed via the WC with only 10% of the flow routed through the EB and WB. The entire RDF improved several water quality measures, as demonstrated by comparing loadings in inlets and outlets of the entire RDF for five storms. On average, the RDF reduced loads of TSS, ammonia, PCBs, PAHs, total copper, total lead and total zinc.

The RDF increased loads of dissolved copper, dissolved lead, and dissolved zinc. The RDF was also a significant source of total nitrogen, total phosphorus, and orthophosphorus. The nutrient increases were coming from the EB and WB, not the WC. The WC reduced OP loads by 264% on average, but overall OP loads from the entire RDF increased by 1555% (Appendix H). Extremely high OP concentrations in the bioretention effluent likely overwhelmed the treatment provided by the WC.

The RDF increased loads for other parameters, but these results do not necessarily indicate an undesirable result. The RDF was a source of TOC and DOC, and hardness levels increased within the RDF to concentrations more typical of natural streams.

***Objective 3:* Determine if the expansion and retrofit of the RDF have improved the effectiveness of the RDF, using pre- and post-retrofit turbidity and temperature data.**

Turbidity

Analysis of continuous turbidity monitoring data from the stream approximately 0.25 miles downstream of the RDF indicate the RDF was more effective at reducing turbidity after the retrofit and expansion. Statistical analyses comparing pre- and post-retrofit turbidity data from the RDF inlet and outlet indicate that while the RDF significantly reduced daily average and daily maximum concentrations both before and after the retrofit, the relative treatment increased post-retrofit. (e.g., Figure 10; Appendix K). After the retrofit, daily maximum inlet turbidity levels outlet values were typically lower and in a similar range (Figures 10 and 11).

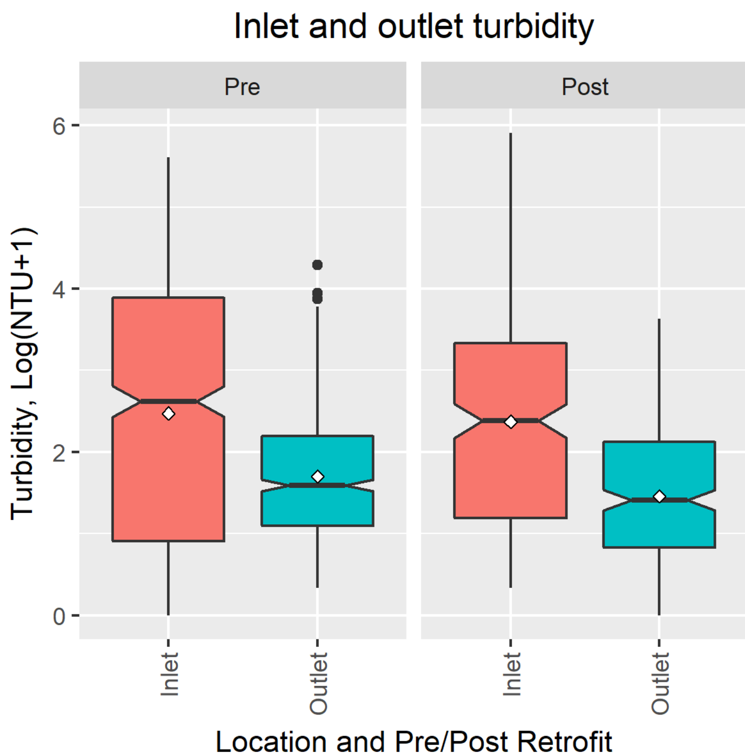

Figure 10. Box plots of log-transformed daily maximum turbidity concentrations at the RDF inlet and outlet, pre- and post-retrofit.

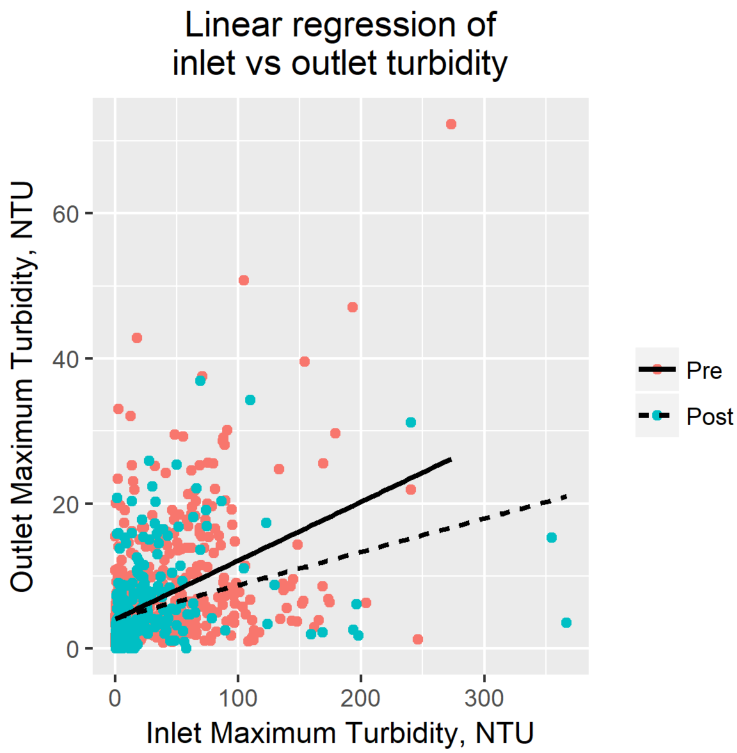

Figure 11. Plot of daily maximum turbidity at the RDF inlet and outlet, pre- and post- retrofit.

Temperature

Prior to the RDF retrofit and expansion, water temperature remained relatively constant between the RDF inlet and outlet. However, following the RDF expansion daily average and daily maximum water temperature significantly increased approximately 0.9 at the inlet and 1.1°C at the outlet due to treatment (Figure 12; Appendix K). Temperature increases both between the inlet and outlet, and between pre- and post-retrofit, were significant; however, this is likely due to differences in ambient air temperature during the sampling intervals (i.e., post-retrofit years happened to be warmer than pre-retrofit years). Although the continuous pre-and post-retrofit data records were similar in the distribution of data across months, there were some gaps in both intervals during summer months when the hottest temperatures would be expected. Additional monitoring is needed, especially during summer months, to assess long-term trends in warming within the RDF.

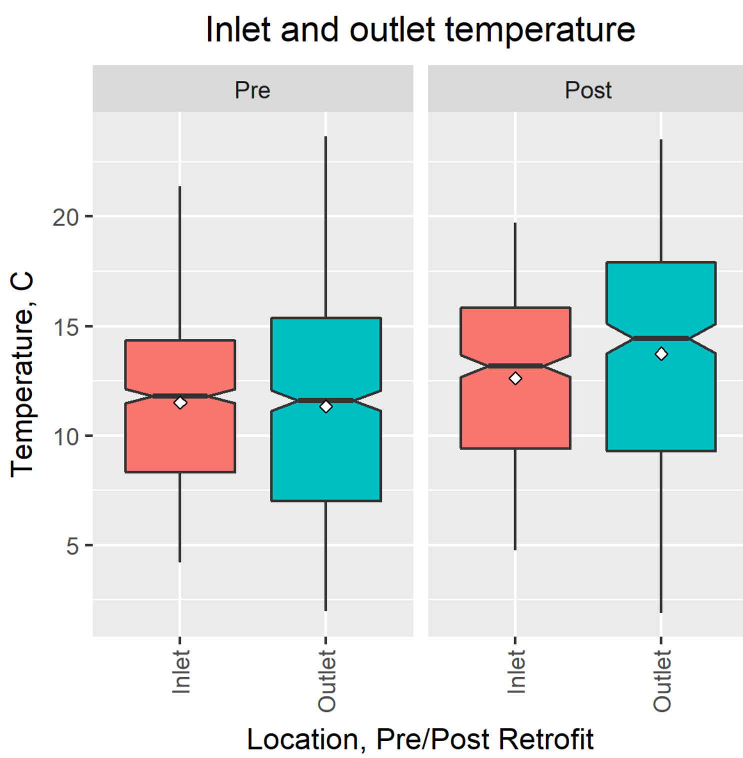

Figure 12. Box plots of daily maximum temperatures in the RDF inlet and outlet, pre- and post-retrofit.

Objective 4: Determine if there are improvements in the macroinvertebrate community and water temperatures in receiving waters that are correlated with the RDF retrofit and expansion.

Macroinvertebrate trends

Post retrofit monitoring of the macroinvertebrate community in the receiving waters 0.25 miles downstream of the RDF suggests there were no improvements in stream health, as indicated by biotic integrity indices, during the two years of post-retrofit monitoring (Figure 13). However, it would be unreasonable to expect a significant improvement over such a short time. Two multi-metric indices, the Puget Lowlands Benthic Index of Biotic Integrity (BIBI) and WA Department of Ecology's (Ecology) Multi-Metric Index for Western Washington (MMI), were used to characterize the macroinvertebrate community in the stream pre- and post-retrofit. The scores indicate that the community may have gradually improved since it was first monitored in 1999, but there is no improvement in scores that can be correlated with the RDF retrofit and expansion (Figure 13). The average (n=3) score for samples collected post-retrofit indicate the stream is in fair or good condition (BIBI and MMI scores, respectively). These scores provide a post-retrofit baseline to evaluate future changes. All data are available on the Puget Sound Stream Benthos website (www.pugetsoundstreambenthos.org).

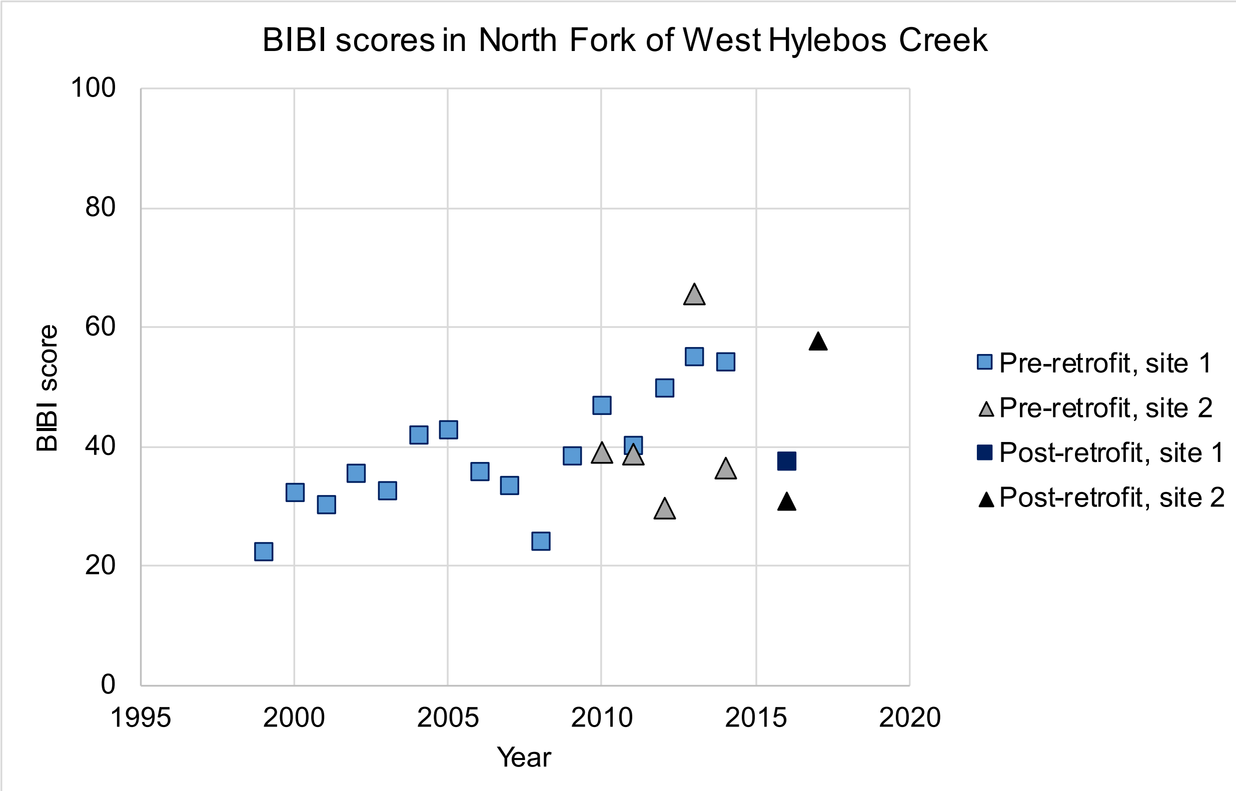

Figure 13. BIBI scores from two sites downstream of the RDF, before and after the retrofit and expansion. Site 1 is immediately upstream of S. 359th Street, and site 2 is immediately downstream of S. 359th Street.

Stream temperature

Stream temperature, monitored at South 359th Street, does not appear to be affected by the RDF retrofit and expansion. Daily maximum temperature is typically approximately 1°C cooler than the RDF outlet temperature (Figure 7; Appendix K), due to groundwater inflow and riparian shading (Smith 2006). Cooling was consistent pre- and post-retrofit. Stream temperature was warmer after the retrofit than before, but this increase was correlated with higher inlet temperature, and not a change in the stream's cooling capacity post-retrofit.

As inlet and ambient temperatures increase, stream temperature would be expected to increase, but it appears groundwater infiltration in the reach between South 356th and South 359th Streets remains important in cooling the stream.

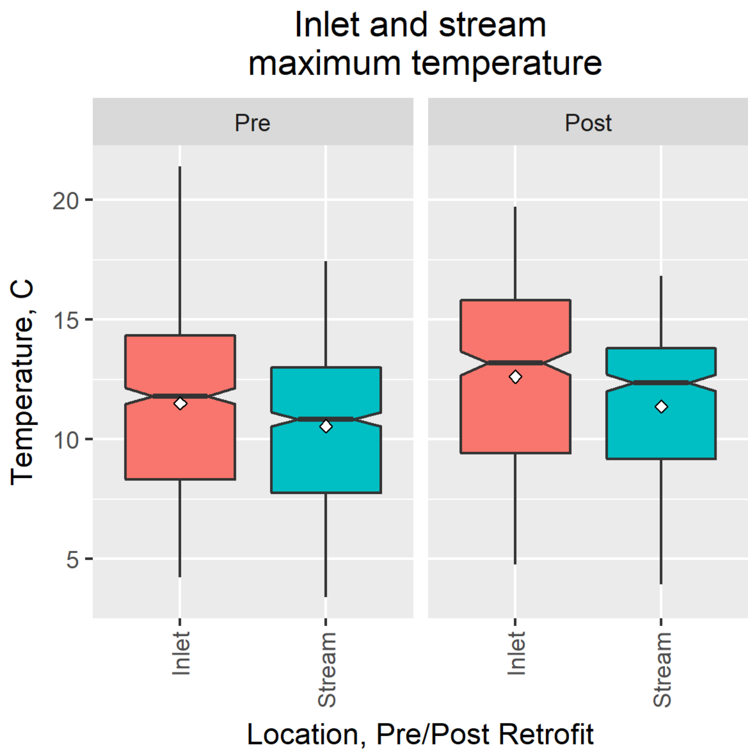

Figure 14. Box plots of daily maximum temperature at the RDF inlet and in the North Fork of West Hylebos Creek at 359th St., pre- and post-retrofit.

3.0 LESSONS LEARNED AND RECOMMENDATIONS

This section highlights things that worked well and contributed to the study's success, as well as challenges that limited the study's success. The abbreviated lessons learned and recommendations for future studies or projects are listed in bold.

Monitoring the effectiveness of the South 356th Street RDF was made successful by having the ability to monitor flow at multiple relevant locations and the existence of several years of pre-retrofit data. The project was also a success because of several lessons learned in the process, which are outlined here as recommendations for future studies.

- **Determine flow patterns at each sampling location early in the project.** The rainfall versus flow relationships developed over 8 months by staff early in the project significantly improved the ease of collecting storm samples (Appendix I). Developing the rainfall/flow relationships required extensive flow monitoring, and delayed the start of sample collection, but the effort led to greater success in meeting storm and sampling criteria.
- **Be clear and reasonable when defining storm and sampling criteria, and then be diligent in monitoring the forecast for suitable storms.** Field technicians, lab technicians, project managers, and Ecology staff discussed and agreed upon storm and sample criteria. Once sampling began, field staff were opportunistic and prepared to sample eligible storms. This included checking forecasts on weekends and using modems to program and initiate samplers after hours. This effort resulted in a complete set of representative flow-weighted samples for 18 storms.
- **Work with partners to ensure project goes smoothly.** Coordinating with City of Federal Way staff went smoothly, which resulted in a clear and easy exchange of information.
- **Be prepared for vandalism.** King County and City of Federal Way staff anticipated equipment may be vandalized and actions were taken to secure equipment to the degree possible. Several vandalism incidents did interrupt sampling, but diligent checking and quick replacement of gear insured data gaps were minimal.
- **Scaling for efficient monitoring on standard parameters at a larger scale.** It was relatively cheap to monitor continuous temperature and turbidity with YSI sondes. Although sondes cannot assess the complex suite of pollutants that may be of interest, their cost and ease-of-use may improve our ability to track some parameters at more stations.

There were also many challenges that affected the study and ultimately limited its success.

- **Anticipate delays when monitoring new facilities**. This project was delayed because it was necessary to replace the underdrain in the east bioretention facility. Sampling was also stalled due to a delay in the establishment of plantings in the new

CDSTW. These delays caused concern that storm targets would be missed, and anticipating those delays would have been helpful in the planning process.

- **Expect that continuous flow monitoring will be challenging.** Installing flow instruments in pipes for continuous flow monitoring was much more difficult than anticipated. Several sampling locations were accessible but very difficult to sample reliably due to the limited confined spaces, pipe angles, and the catch basin design that limited the type of equipment that could be used. Equipment that was initially expected to function properly at a given sites ultimately needed to be changed or amended, and this added time and frustration. As a result the uncertainty in flows and loadings was increased, reducing the statistical power to detect real changes.
- **Assess groundwater flows before defining project scope and investing time in surface water monitoring.** Groundwater flow volumes, primarily into the wetland complex, appeared to be much greater than anticipated. The unanticipated groundwater intrusion made it difficult to assess if pipe inflow and outflow estimates were reasonable. It also introduced uncertainty regarding effectiveness of the facilities, because the quality and volume of the groundwater was unknown.
- **Anticipate when it may not be possible to validate field measurements and acknowledge how that affects data quality.** Validating flow measurements (i.e., with a bucket test) was only realistically possible at three of seven locations, and only at during low flow conditions. The volume estimates are less accurate and less precise because of this, as well as the groundwater infiltration and intrusion.
- **Be clear about the kind of storms and conditions the project is characterizing.** Sample collection during a number of storms was not initiated due to the antecedent dry period criterion. Less intense storms were not sampled because they did not generate enough runoff to the bioretention system. Therefore, interpretation of the effectiveness is limited to moderate storms conditions (rainfall events of >0.25 inches and <2.4 inches).
- **Anticipate and ask about potential conflicts and timelines.** The sampling ended abruptly in April 2017, before all 20 planned storms could be sampled, because of road construction on South 356th Street. There had been a miscommunication between City of Federal Way departments about the timing of construction, and unfortunately this resulted in ending the sampling earlier than planned.

4.0 REFERENCES

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Additional references are cited in appendices.