FINAL REPORT

CITY OF REDMOND SIX SWALES BIORETENTION MONITORING

Prepared for
City of Redmond Public Works
Natural Resources Division

Prepared by
Herrera Environmental Consultants, Inc.

Note:
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Prepared for
City of Redmond Public Works
Natural Resources Division
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PREFACE

This study would not have been possible without grant funding from the Washington State Department of Ecology (Ecology). The City of Redmond Department of Public Works Natural Resources Division would like to thank the project team members for their support through this effort. The Construction and Transportation Division was cooperative throughout the planning and construction process and this study would not have been feasible without their cooperation. Kindred Hydro, Inc. conducted preliminary infiltration testing and permeability analysis of the media. In addition, we would like to thank Brown and Caldwell, Inc. and Perteet, Inc. for the bioretention design, Cedar Grove, Inc. for support with the study of the bioretention soil mix, and Herrera Environmental Consultants, Inc. for support with study design, monitoring support, and reporting. Last, the City of Redmond would like to thank the interagency group that is focused on improving the performance of bioretention in Washington State.

EXECUTIVE SUMMARY

The City of Redmond (the City) obtains nearly 40 percent of its drinking water supply from shallow wells within its urban core. With increased regional emphasis on the use of low impact development (LID) systems that rely on infiltration for treating stormwater runoff, the City wished to investigate potential impacts to groundwater quality that might occur if these systems are widely constructed. Recent research in the region has indicated that bioretention built with the 60/40 Sand/Compost specification (60/40 mix) leaches pollutants that may impact sensitive downstream receiving waters (Herrera 2015b). In 2013, the City of Redmond completed a study (2013 185th Avenue Northeast study) that showed significant pollutant export from a bioretention cell (referred to as bioretention swales in Redmond) that was constructed with the 60/40 mix (Herrera 2014a). The follow up study presented herein was subsequently funded by Ecology with the goal of confirming pollutant export/flushing after construction and developing alternative, higher performing, media blends.

To implement this study, Herrera Environmental Consultants (Herrera) conducted hydrologic and water quality monitoring at six new bioretention swales. Four of the swales were constructed in connection with improvements to the City's Maintenance and Operations Center Decant Facility (MOC). The remaining two were constructed on 185th Avenue Northeast, south of the intersection with Northeast 76th Street. One of the six bioretention swales was constructed with the same bioretention soil mix (BSM) (i.e., 60/40 mix) that was used for the 2013 185th Avenue Northeast study. The five other bioretention swales were constructed with alternative BSMs as described below.

Study Systems

The swales were designed to infiltrate 91 percent of the annual runoff volume that drained to them through an 18-inch deep BSM, as predicted using WWHM3. The City procured the bioretention media mixes directly to ensure a higher degree of quality control. Four of the swales are located at the City's Maintenance and Operations Center (MOC) on Northeast 76th Street in Redmond, Washington. These four swales (referred to as D1-60/40, D2-RBSM, D3-LSMV, and D4-LSW) are co-located in a block design with a shared inlet. The two remaining bioretention swales are located on 185th Avenue Southeast, 200 feet north of the intersection with Northeast 68th Street. One swale is located on the west side of the road (referred to as 185-RBSMs), and the other is located immediately across the street on the east side of the road (referred to as 185-Coir). Table ES-1 provides information on the BSMs used in each swale.

Table ES-1. Bioretention Soil Mixes for MOC and 185th Bioretention Swales.	
Bioretention Swale Name	**Bioretention Soil Mix**
D1-60/40	60% sand, 40% compost
D2-RBSM	60% sand, 15% compost, 15% biochar; 10% shredded bark
D3-LSMV	50% sand, 50% Loamy Sand (source 1)
D4-LSW	50% sand, 50% Loamy Sand (source 2)
185-RBSMs	60% sand, 15% compost, 15% biochar; 10% shredded bark
185-Coir	80% sand, 20% coconut coir

Sampling Procedures

Monitoring was implemented using a Washington DOE approved quality assurance project plan (QAPP) that met Technology Assessment Protocol – Ecology (TAPE) standards for study design. A combination of automated sampling and grab sampling was used to characterize influent and effluent water qualities and evaluate the performance of the study systems. Automated monitoring equipment was installed to continuously measure influent, effluent, and bypass flows. The automated equipment collected flow-weighted composite samples of the system's influent and effluent during between 17 and 20 events depending on the swale. Water quality monitoring was initiated immediately after the bioretention swales were installed and continued for 13 months from the collection of the first sample. The collected flow-weighted composite samples were analyzed for the following water quality parameters:

- pH
- Total suspended solids
- Particle size distribution (influent only)
- Copper, total and dissolved
- Lead, total and dissolved
- Zinc, total and dissolved
- Total phosphorus
- Orthophosphate
- Total Kjeldahl nitrogen
- Nitrite-nitrate nitrogen
- Hardness
- Dissolved organic carbon
- Major cations: Ca (calcium), Mg (magnesium), Na (sodium), and K (potassium)
- Major anions: SO_4 S(sulfate), Cl (chloride)
- Alkalinity
- Sulfide

In addition, field personnel collected grab samples during between 13 and 16 storm events per swale. Grab samples were collected for the following water quality parameters:

- Fecal coliform
- Total petroleum hydrocarbons (TPH)

During the course of the study, these grab samples were collected for events with and without corresponding flow-weighted composite samples.

Data obtained through this monitoring were subsequently analyzed in the following ways:

- Computation of pollutant removal efficiencies with bootstrap confidence intervals
- Statistical comparisons of influent and effluent concentrations
- Flushing analysis of all six swales
- Comparison of effluent concentrations to applicable standards

Hydrologic Performance

During the monitoring period, 117 individual events were identified at the MOC and there was zero bypass recorded. At 185-Coir 103 individual events were identified and two of those produced bypass flow. At 185-RBSMs 111 individual events were identified and 10 of those produced bypass flow. Bypass volumes were not recorded but the bypass frequency analysis above indicates that the MOC was likely much larger than needed to treat 91 percent of the annual runoff volume (visual observations using time-lapse photography indicated that ponding depth never exceeded 1–inch). The bioretention swales on 185th Avenue Northeast were also likely oversized as the infiltration rate was assumed to be 2 inch/hour when in fact it was much higher.

Controlled infiltration testing was conducted on May 20 through May 23, 2014, at the MOC. Infiltration testing was not conducted at 185th Avenue Northeast at the time because the BSM installed was identical to the BSM installed in D2-RBSM at the MOC. On May 26, 2014, new sand and coconut coir media were installed at 185-Coir, this new BSM was infiltration tested 1 year later on May 29, 2015. The Sand and Coir mix had the highest infiltration rate (61 inches per hour [in/hr]) when compared with the other BSMs, the 60/40 Sand/Compost mix had the second highest infiltration rate at 11.8 in/hr. Reducing the compost content and adding biochar and shredded bark to the mix (i.e., creating the RBSM mix) apparently reduced the infiltration rate by about 50 percent: infiltration rates at D2-RBSM were 6.0 in/hr. The Loamy Sand swales had the lowest infiltration rates of between 1.3 and 5.1 in/hr based on lab permeability testing.

Water Quality Performance

For the majority of parameters, the 185-Coir swale flushed its pollutants more quickly (by 20 percent of the water year [20%WY]) than the other swales and stabilized at effluent concentrations which were well below those of the other swales. Nutrient export was greatest from the swales containing compost, with the loamy-sand swales exporting equivalent nitrate+nitrite, but less total phosphorus. Again, after an initial flush, the 185-Coir swale effluent had the lowest nutrient content of all the swales. Copper export was greatest from the swales containing compost. The Loamy Sand swales exported copper at a slightly lower level, while the 185-Coir swale reduced copper concentrations (though not significantly) despite the fact that concentrations were very low at the influent (mean = 4.1 micrograms per liter [ug/L]). All six swales performed very well at reducing concentrations of total and dissolved zinc, TPH-Oil, and fecal coliform.

When the water quality results measured at each swale were compared to the Technology Assessment Protocol—Ecology (TAPE) criteria (Ecology 2011), it was apparent that after a brief flushing period of 10%WY all of the swales would meet the basic treatment criteria of ≥ 80 percent reduction in total suspended solids (TSS). Similarly, after 10%WY the 185-Coir swale was able to meet the total phosphorus criteria of ≥ 50 percent reduction. However, none of the other swales met this criteria, even after the flushing period was complete. Among the swales there were few qualifying samples available for comparison to the TAPE enhanced treatment (zinc and copper) criteria. However, the trend indicated that 185-Coir was the only swale which would meet the enhanced treatment goals for zinc and copper (≥ 60 and ≥ 30 percent, respectively), this despite having the highest infiltration rate (and thus lowest contact time with the media) of all the swales.

SPLP extractions indicated that the compost fraction was the largest contributor to copper and nutrient export. The biochar also seemed to be a source of nutrients. These SPLP results were reflected in the field data as the systems which contained compost exported the highest levels of copper among the six swales, while the systems with compost and biochar exported the highest levels of nutrients.

One of the primary objectives of this study was to determine if export from the study systems would result in exceedances of groundwater quality criteria. No groundwater quality criteria were exceeded in any of the effluent samples. However, surface water criteria were frequently exceeded at all the swales except 185-Coir, due to elevated export of dissolved copper.

Findings

The results from this study corroborate other recent studies in the region (Herrera 2015b) indicating that bioretention systems which utilize a BSM which meets the Ecology 60/40 specification will act as a pollutant generating source of nutrients and copper. These findings indicate that the previous assumptions regarding metals and nutrient reductions in bioretention, as summarized in two recent local literature reviews (Geosyntec 2013; Taylor Aquatic Science and Policy and Cardno TEC 2013), are not accurate for the 60/40 mix installed to the *2012 Stormwater Management Manual for Western Washington* specifications.

For systems installed with underdrains which discharge to sensitive receiving waters there is a potential for increasing downstream nutrient and copper loading. For such applications, future bioretention projects should use sand with low metal and nutrient concentrations and find organic alternatives to compost, such as coconut coir. Follow up studies at both the bench scale and field scale are currently being conducted with the goal of formulating a BSM that does not export pollutants, while still reducing influent pollutant concentrations.

INTRODUCTION

The City of Redmond (the City) obtains approximately 40 percent of its drinking water supply from shallow wells within its urban core. With increased regional emphasis on the use of low impact development (LID) systems that rely on infiltration for treating stormwater runoff, the City has been investigating potential impacts to groundwater quality that might occur if LID systems are widely constructed. The specific concern is that groundwater quality in shallow unconfined aquifers may deteriorate if stormwater runoff from surrounding land uses receives inadequate treatment prior to infiltration.

In 2013, the City of Redmond (City) completed a study (2013 185th Avenue Northeast study) that showed significant pollutant export from a bioretention cell (referred to as bioretention swales in Redmond) that was constructed with 60 percent sand and 40 percent compost (60/40 mix) for the 185th Avenue Extension Project (Herrera 2014a). Specifically, measured effluent concentrations from the system were typically higher than influent concentrations for all of the following parameters: total suspended solids, total phosphorus, soluble reactive phosphorus, total copper, dissolved copper, total lead, dissolved lead, total Kjeldahl nitrogen, and nitrate + nitrite nitrogen. For many of these parameters this export appeared to exhibit a "flushing" pattern such that effluent concentrations tended to decrease over time relative to maximum values that were measured immediately following construction of the system. The only parameters that were not exported from the system were dissolved zinc, total zinc, motor oil, and fecal coliform. Consequently, instead of acting as a pollutant sink, the system was acting as a source for a majority of the pollutants measured. Follow-up testing indicated the specific source of the pollutants was the compost and sand used to construct the bioretention soil mix (BSM) for the bioretention swale.

To confirm these results and investigate alternative BSMs that do not exhibit similar pollutant export, the City implemented a follow-up monitoring project to evaluate the treatment performance of six new bioretention swales. Four of these bioretention swales were constructed in connection with improvements to the City's Maintenance and Operations Center Decant Facility (MOC). The remaining two were constructed in connection with a later phase of the 185th Street Extension Project. One of the bioretention swales was constructed with the same BSM specification (i.e., 60/40 mix) that was used for the 2013 185th Avenue Northeast study. The five other bioretention swales were constructed with alternative BSMs as described below. The locations of the six new bioretention swales are shown on Figure 1.

This document represents the final project report covering the complete monitoring period from April 19, 2014, to April 31, 2015. Monitoring of each swale began within 1 week of the system going online so that the flushing dynamics were fully characterized. A full project schedule is provided in Table 1. The specific goals of this report are as follows:

- Document hydrologic and water quality treatment performance of the study systems in order to determine if alternate media perform better than the standard 60/40 mix.

- Present an analysis of whether pollutant concentrations in effluent from the study system could contribute to groundwater contamination.
- Summarize results from analyses that were performed to identify specific materials used in the construction of the study system that are contributing to the pollutant export problem.
- Make recommendations for future research as necessary.

Table 1. Project Schedule.

Project Element	2013 Q1	2013 Q2	2013 Q3	2013 Q4	2014 Q1	2014 Q2	2014 Q3	2014 Q4	2015 Q1	2015 Q2
Design	■	■								
Ecology Grant			■	■	■	■	■	■	■	■
Construction				■	■					
Bioretention Operational						■	■	■	■	■
Monitoring						■	■	■	■	■
Infiltration Test 1						■				
Infiltration Test 2										
Mid Project Report									■	
Final Report										■

This document is organized into the following sections:

- Technology Description
- Methods
- Results
- Discussion
- Conclusions

Legend

- Project location
- Highway
- Stream

Figure 1.
Vicinity Map for the Six Bioretention Systems Study in Redmond, Washington.

N

0 500 1,000 2,000 Feet

HERRERA

Aerial: USDA, 2009

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TECHNOLOGY DESCRIPTION

Bioretention provides runoff treatment of flows through a variety of physical and chemical unit processes. This section describes the test systems that were constructed for this study and their associated treatment processes, sizing methods, expected treatment capabilities, expected design life, and maintenance procedures.

Physical Description

This section describes the physical configuration of the study systems. The MOC swales and the 185th swales were designed by Brown and Caldwell, Inc. and Perteet, Inc., respectively. First the MOC swales are described, followed by the 185th swales.

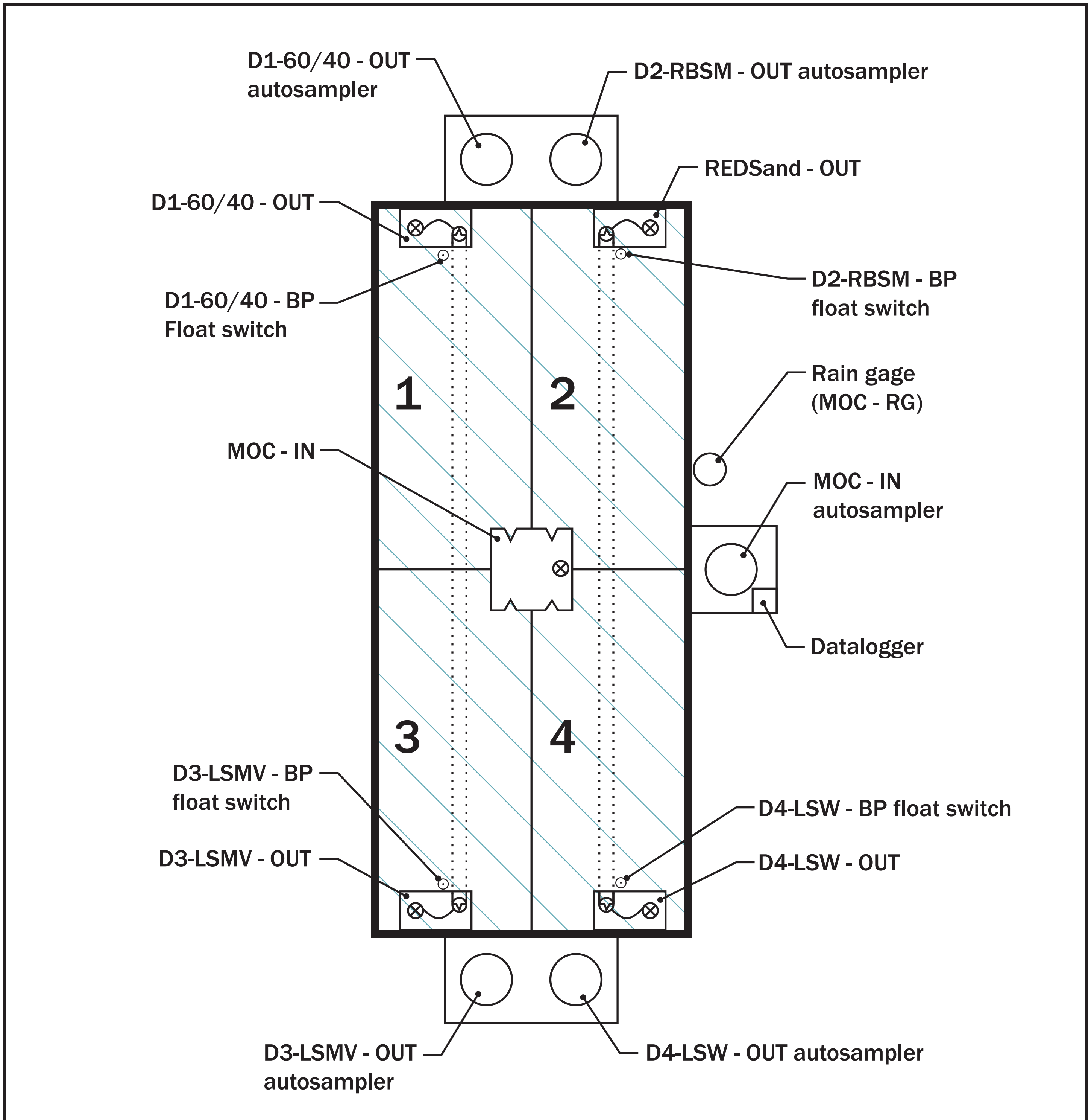
MOC

Four swales are located at the City's Maintenance and Operations Center (MOC) on Northeast 76th Street in Redmond, Washington (Figure 1). These four swales (referred to as D1-60/40, D2-RBSM, D3-LSMV, and D4-LSW) are co-located in a block design with a shared inlet (Figure 2). Approximately 3.7 acres of the MOC drain to an existing detention vault. Water from the vault is pumped to the swales with a two-stage pump through a force main.

Each of the swales at the MOC is 10 feet wide and 57 feet long and is constructed with concrete walls and a 40-mil high-density polyethylene (HDPE) liner along the base and walls. An 8-inch slotted underdrain pipe is located in the center of each swale and backfilled with Type 26 aggregate (following the City of Seattle specification) to provide drainage for stormwater that has infiltrated through an 18-inch BSM layer above (the BSM composition varies depending upon the swale). No geotextiles were used in the construction of each swale.

The bypass structures at the terminus of each swale were designed to maintain a 12-inch maximum ponding depth in the bioretention swales. Based on WWHM3 modelling, the water quality design flow rate for the MOC swales is 0.43 cubic feet per second (cfs), or 0.11 cfs (49 gallons per minute) per swale. In the event of a high-flow bypass, the overflow structures were designed so that sampling effluent could still occur without commingling of treated and untreated runoff. The overflow structures were also equipped with an optional orifice control and riser to provide more control over infiltration rates and depth of saturation within the swales. Design drawings of the swales located at the MOC are provided in Appendix A. Throughout the remainder of this document, these swales are collectively identified as the MOC bioretention swales.

Table 2 identifies the BSMs that were used to construct each bioretention swale.



Legend

- Pressure transducer
- Weir
- Underdrain
- Equipment enclosure
- Bioretention cell

Figure 2.
Monitoring Components for the MOC Bioretention Systems.

N

Not to scale

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Table 2. Bioretention Soil Mixes for MOC and 185th Bioretention Swales.	
Bioretention Swale Name	**Bioretention Soil Mix**
D1-60/40	60% sand, 40% compost
D2-RBSM	60% sand, 15% compost, 15% biochar; 10% shredded bark
D3-LSMV	50% sand, 50% Loamy Sand (source 1)
D4-LSW	50% sand, 50% Loamy Sand (source 2)
185-RBSMs	60% sand, 15% compost, 15% biochar; 10% shredded bark
185-Coir	80% sand, 20% coconut coir

185th Swales

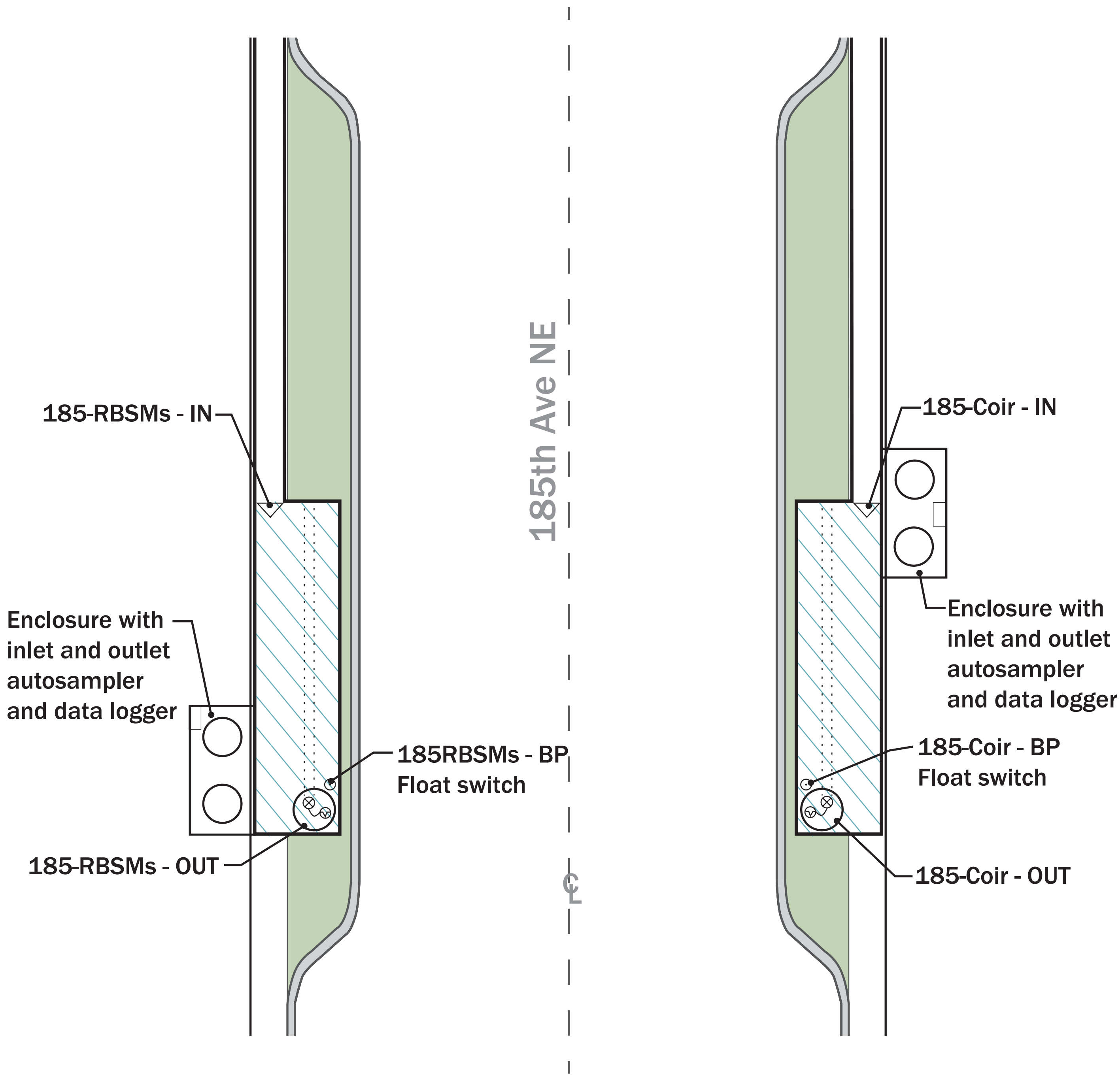
The two remaining bioretention swales are located on 185th Avenue Northeast, 200 feet north of the intersection with Northeast 68th Street (Figure 1). One swale is located on the west side of the road (referred to as 185-RBSMs), and the other is located immediately across the street on the east side of the road (referred to as 185-Coir). These two swales are each 180 square feet, and each have a contributing drainage area of 10,630 square feet.

The swales on 185th Avenue Northeast were constructed using concrete vaults with sealed openings along the bottom. Steel pans and epoxy were used to seal the openings. If infiltration is desired in the future, the City will perforate or remove the pans. Each swale is outfitted with a slotted 6-inch underdrain pipe embedded in an 18-inch-thick Type 26 aggregate bed (following the City of Seattle specification) that is overlain by 18 inches of BSM. The underdrain pipes enter a control structure that also serves as the overflow structure during large storm events. The design flow rate for each swale is estimated to be 0.02 cfs or 9 gallons per minute. Runoff enters both swales from the roadway through a grated rectangular trench on the curb line (Figure 3). Water leaving each swale enters an infiltration gallery installed underneath the adjacent sidewalk on the west side of the road. Design drawings of the swales on 185th Avenue Southeast are provided in Appendix A. Throughout the remainder of this document, these swales are collectively identified as the 185th bioretention swales.

Table 2 identifies the BSMs that were used to construct each bioretention swale. Photographs of the all of the bioretention swales are also provided in Figure 4.

Bioretention Soil Mix

The BSM components were analyzed for multiple parameters to ensure that the mixes met local specifications. Numerous applicable specifications exist in the region, including the Stormwater Management Manual for Western Washington (Ecology 2012), the Low Impact Development Technical Guidance Manual for Puget Sound (Hinman and Wulkan 2012), the WSDOT compost specification (WSDOT 2012), and WAC 173-350-220. Tables 3, 4, and 5 compare the materials used in the BSMs to the applicable specifications for the aggregate, compost, and bioretention soil mix fractions, respectively.



Legend

- Pressure transducer
- Weir
- Underdrain
- Flume
- Equipment enclosure
- Bioretention cell

Figure 3.

Monitoring Components for the 185th Bioretention Systems.

N

Not to scale

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185-Coir

185-RBSMs

MOC D-1 (top left); MOC D-2 (top right); MOC-D3 (bottom left); MOC-D4 (bottom right)

Figure 4. Photographs of the MOC and 185th Bioretention Swales.

Table 3 indicates that the sand used for all six of the swales met all the gradation criteria except that it had about 1 percent less fines (percent passing the 200 sieve) than required. Because of this, the coefficient of curve requirement was also not met. Table 4 is specific to the compost which was used in D1-60/40, D2-RBSM, and 185-RBSMs. The results are based on quarterly testing conducted by Cedar Grove, Inc.; the results reflect testing that was conducted during the third quarter of 2013 when construction of the swales began. As is apparent from data in Table 4, the compost met all the local specifications which were measured. Metals were not measured, but it is highly unlikely that the metals criteria were exceeded because the specification limits are about an order of magnitude higher than typical concentrations found in Cedar Grove compost.

Table 3. Aggregate Specifications Compared with the Aggregate Used in the Six Swales Study.

Item	Bioretention System Aggregate	LID Manual/SMMWW Aggregate Specification	Within Specification? Yes/No
% passing 3/8″	100	100	Yes
% passing 4 sieve	98.6	95 to 100	Yes
% passing 10 sieve	78.7	75 to 90	Yes
% passing 40 sieve	35	25 to 40	Yes
% passing 100 sieve	5.1	4 to 10	Yes
% passing 200 sieve	1.3	2 to 5	No
Coefficient of Uniformity (D60/D10)	4.3	≥ 4	Yes
Coefficient of Curve ((D30)^2/D60*D10)	0.78	1 to 3	No

LID Manual = Low Impact Development Technical Guidance Manual for Puget Sound (Hinman and Wulkan 2012).
SMMWW = Stormwater Management Manual for Western Washington (Ecology 2012).

Table 4. Compost Specifications Compared with the Compost Used in the Six Swales Study.

Item	Bioretention System Compost	LID Manual/SMMWW Aggregate Specification	Within Specification? Yes/No
Copper (mg/kg)	NA	< 750	Yes
Zinc (mg/kg)	NA	< 1,400	Yes
Carbon:Nitrogen	17.8	< 35:1	Yes
Type 1 Feedstock (% yard waste)	85	> 65	Yes
Type 2 Feedstock (% manure)	0	0	Yes
Type 3 Feedstock (% meat and food waste)	15	≤ 35	Yes
Type 4 Feedstock (% municipal solid waste)	0	0	Yes
%Moisture	No Visible	No visible	Yes
pH	8.06	6.0 to 8.5	Yes
Manufactured inert materials (%)	< 0.5	< 1	Yes
Organic Matter (%)	53.1	≥ 40	Yes
Soluble Salt (mmhos/cm)	3.1	< 4.0	Yes
Compost Maturity (%)	88	> 80	Yes
Compost Stability (mg CO_2–C/g OM/day)	3.2	≤ 7	Yes

LID Manual = Low Impact Development Technical Guidance Manual for Puget Sound (Hinman and Wulkan 2012).
mg/kg: milligrams per kilogram.
mmhos/cm = _millimhos per centimeter.
mg CO2-C/g OM/day = _milligrams CO2 per gram of organic matter per day.
SMMWW = Stormwater Management Manual for Western Washington (Ecology 2012).

Table 5. Bioretention Soil Mix Specifications Compared with the Bioretention Soil Mix Used in the Six Swales Study.

Item	60/40	Red Mix	MV Loamy Sand	Woodinville Loamy Sand	Sand and Coir	LID Manual/ SMMWW BSM Specification
% aggregate	60	60	50	50	80	60 to 65
% compost	40	15	0	0	0	35 to 40
CEC (meq/100 g)	7.38	4.75	6.49	5.83	1.42	≥ 5
Total phosphorus (mg/kg)	589	540	533	760	468	< 0.25[a]
pH	NA	NA	NA	NA	NA	5.5 to 7.0
Organic Matter (%)	5.1	4.0	3.7	2.4	1.3	4 to 8
Lab Permeability (in/hr)	15	5.2	1.3	5.1	66	2 to 12

[a] This criterion is a ratio of oxalate phosphorus and oxalate iron and aluminum using SSSA Mono.9 6-2.3 and is not applicable to the phosphorus analysis conducted in this study following EPA 365.2.

CEC = cation exchange capacity.

in/hr = inches per hour.

LID Manual = Low Impact Development Technical Guidance Manual for Puget Sound (Hinman and Wulkan 2012).

meq/100 g = milli-equivalents per 100 grams.

mg/kg = milligrams per kilogram.

NA = not available.

Table 5 is applicable to all of the BSMs used in this study. The analyses were conducted on the mixed media and indicate the following:

- The 60/40 mix met the cation exchange capacity (CEC) and percent organic matter criteria. However, the initial infiltration rate was greater than 12 in/hr. This was likely due to the fact that the sand had fewer fines than required. pH was not measured so that criterion could not be assessed. Total phosphorus exceeded 0.25 UNITS, but the method used (EPA 365.2) was different from the recommended method in the 2012 LID manual, so the comparison is not valid.

- The Redmond Mix (D2-RBSM and 185-RBSMs) met the infiltration rate criterion, but did not meet the CEC or organic matter criteria. pH was not measured so that criterion could not be assessed. Total phosphorus exceeded 0.25, but the method used (EPA 365.2) was different from the recommended method in the 2012 LID manual, so the comparison is not valid.

- The MV Loamy Sand (D3-LSMV) met the CEC criterion, but did not meet the infiltration rate or organic matter criteria. pH was not measured so that criterion could not be assessed. Total phosphorus exceeded 0.25, but the method used (EPA 365.2) was different from the recommended method in the 2012 LID manual, so the comparison is not valid.

- The Woodinville Loamy Sand (D4-LSW) met the CEC and the infiltration rate criteria, but did not meet the organic matter criterion. The differences between the Loamy Sand seen in Table 5 highlights the fact that the characteristics of soils specified as Loamy Sands can vary widely. pH was not measured so that criterion could not be assessed. Total phosphorus exceeded 0.25, but the method used (EPA 365.2) was different from the recommended method in the 2012 LID manual, so the comparison is not valid.

- The Sand and Coir mix (185-Coir) did not meet the CEC, organic matter, or infiltration rate criteria. pH was not measured so that criterion could not be assessed. Total phosphorus exceeded 0.25, but the method used (EPA 365.2) was different from the recommended method in the 2012 LID manual, so the comparison is not valid. The fact that the 185-Coir mix did not meet any of the criteria but still performed very well at pollutant removal is an issue which is addressed below in the *Results* section.

Treatment Processes

Bioretention provides water quality treatment of captured flows through physical and chemical unit processes. Runoff treatment is achieved through sedimentation, filtration, and adsorption.

Sedimentation

Bioretention is designed to reduce flow velocities in the ponded water and in the filter media. This promotes gravity settling of entrained particles. The amount of sedimentation is a function of particle density, size, water density, turbulence, and residence time.

Filtration

Particulates are physically removed from suspension as they come into contact with the filter media. The filter retains those particles that are unable to follow the tortuous channels of connected void space within the BSM. Pollutant removal rates achieved through filtration are a function of the stormwater composition and media properties including permeability, grain size, and hydraulic conductivity.

Adsorption

Unlike filtration, where physical processes control removal of sediment from suspension, adsorption relies on opposing surface charges of the media and dissolved constituents to remove pollutants from stormwater. The media contains material with a high surface area so that the binding sites are numerous and not easily exhausted. In addition, the filter media has a high CEC, which promotes the removal of positively charged dissolved pollutants (including metal ions) from solution.

Pollutant Export from Bioretention Soil Mix

Although the bioretention soil mix is effective at removing pollutants through sedimentation, filtration, and adsorption, the media itself can act as a pollutant source, creating situations where effluent from the swale has higher concentrations of pollutants than the stormwater entering the swales for treatment. Fine sands and associated bound pollutants will export during a flushing period of variable duration. In addition, labile nutrients and other bound pollutants will leach from the compost fraction for an undetermined amount of time. The documented export of pollutants from study systems is described in the *Results* section of this report.

Sizing Methodology

The MOC swales were sized using the Western Washington Hydrology Model, Version 3 (WWHM3). Within WWHM3, the system was modeled as one continuous gravel infiltration trench with an assumed infiltration rate of 1.5 inches per hour and a drainage area of 2.79 acres (0.37 acre lawn, 2.42 acres impervious). The stormwater influent to the swale is pumped, so a WWHM3 SSD table was used to model the two stage flow rate. The facility was sized to treat 91.23 percent of the total annual volume.

The 185th swales were modeled independently using MGS Flood version 4.29. Within MGS Flood, each bioretention facility was modeled as a basic wet pond with an assumed infiltration rate of 2 inches per hour and a drainage area of 0.24 acres, all impervious. The 15-minute time step simulation concluded that 93.78 percent of the annual flow volume was treated. The simulation also confirmed that the swales met the LID Performance Standard (8 percent 2-year through 50 percent 2-year).

Expected Treatment Capabilities

Bioretention systems are approved in the State of Washington to remove suspended solids, gross solids, and heavy metals. Compared with other stormwater treatment best management practices (BMPs), bioretention has not been well studied. However, in recent years there has been a growing body of literature characterizing bioretention performance. Table 6 presents results from a recent literature review of field and laboratory tests of bioretention systems (Geosyntec 2013). These literature removal rates are presented again in the *Discussion* section and compared with the results from this study.

Table 6. Bioretention Performance Data.

Item	Number of Studies	Median % Removal	Median Influent	Median Effluent	Units
Total Suspended Solids (TSS)	30	83	39	8	mg/L
Fecal Coliform	6	77	4,172	290	#/100 mL
Oil and Grease	16	99	1.35	0.28	mg/L
Total Copper (Cu)	11	46	13	6	µg/L
Dissolved Cu	4	61	10.7	11.1	µg/L
Total Lead (Pb)	18	81	9.9	3.2	µg/L
Dissolved Pb	3	70	0.5	1.3	µg/L
Total Zinc (Zn)	20	76	100	18	µg/L
Dissolved Zn	5	64	49	25	µg/L
Total Phosphorus (P)	28	57	0.12	0.10	mg/L
Total Nitrogen (N)	17	44	1.3	1.1	mg/L
Nitrate	27	8	0.36	0.22	mg/L
Ammonia	13	49	0.20	0.04	mg/L

Expected Design Life

The expected design life of bioretention facilities will vary depending upon system sizing and influent pollutant loading. In general, it is expected that the swales in this study will last 25 years before the media will need to be replaced.

Maintenance Procedures

In 2013, the Washington State Department of Ecology (Ecology) issued a Low Impact Development Operation and Maintenance Manual (Herrera 2013). The manual recommends the following maintenance procedures on an annual basis:

- Check side slopes for erosion, compaction, and rodent activity, and remediate as needed
- Check any concrete sidewalls for cracks and repair as needed
- Check stability of rockery sidewalls
- Remove excess sediment from the bottom area of the facility and replace vegetation and mulch as necessary
- Check for erosion around check dams and repair as needed
- Make sure inlets are functioning as designed
- Check vegetation health and replace plants as needed

In addition, the following should be conducted on a twice per year and after major storm events:

- Remediate excessive trash and leaf accumulation in facility
- Check for excessive overflow or ponded water more than 48 hours after an event

Finally, irrigation may be required during the first two dry seasons for plant establishment.

METHODS

This section begins with a general overview of the monitoring design and describes the specific procedures that were implemented to meet the goals of the project. It then describes in more detail the site location, test systems, monitoring schedule, and specific methods used to obtain the hydrologic and water quality data. Analytical methods, quality assurance and control measures, data management procedures, and data analysis procedures are also discussed.

Monitoring Design

This project entailed the collection of hydrologic, water quality, and sediment monitoring data from the study system to evaluate its treatment performance consistent with the overall objectives of this study. Separate sections below describe the sampling process design that was used in conjunction with each of the monitoring elements. Figures 2 and 3 show the physical monitoring elements that comprise the sampling process design.

Hydrologic Monitoring

Study system influent and effluent flows were monitored continuously over the following periods:

- MOC: 4/18/14 to 5/4/15
- 185-RBSMs: 3/26/14 to 5/4/15
- 185-Coir: 5/27/14 to 5/4/15

The month delay in beginning the monitoring at 185-Coir was due to leaks in the system which were discovered after it originally went online on March 26, 2014. The original BSM (the Redmond Mix) was removed on May 19, 2014, and replaced with a mix consisting of 80 percent sand and 20 percent coconut coir. This coir mix was not indicated in the QAPP, but based on initial performance of the Redmond Mix observed at the MOC and on the west side of 185th Street, it was determined that the project would benefit from testing an alternate mix which did not contain compost.

System bypass duration and frequency were monitored continuously. In addition, precipitation depths at the MOC were monitored continuously over the same period. Controlled infiltration testing and flow testing of the hydrologic monitoring equipment also occurred during the study period. The specific procedures that were used in conjunction with these activities are described in detail below.

Monitoring Stations

Influent flows entering the MOC bioretention swales were monitored with four adjustable 110 degree v-notch weirs set to the same elevation (Figure 2). A stilling well equipped with a Campbell Scientific CS451-L pressure transducer was installed in the central vault that will hold the influent flow prior to entry into each swale. This pressure transducer was used to facilitate the accurate measurement of water levels above each of the weir crests at an influent flow-monitoring station designated MOC-IN.

Effluent flows from the MOC swales were monitored at the terminus of each of the four underdrains at stations designated D1-60/40-OUT, D2-RBSM-OUT, D3-LSMV-OUT, and D4-LSW-OUT (Figure 2). In order to quantify flows, each of the four outlet stations were equipped with a Campbell Scientific CS451-L pressure transducer and an 8-inch Thel-Mar weir.

The pressure transducers at each monitoring station for the MOC bioretention swales were interfaced with a Campbell Scientific CR1000 data logger that was programmed to cache measurements every 10 seconds and record average water levels behind the weirs on a 5-minute time step. The data logger then converted these water level readings to estimates of discharge based on standard hydraulic equations (Walkowiak 2006). The data logger was interfaced with a Raven XTV digital cellular modem. This communication system was configured to automatically download data and send text message alarms to field technicians and project managers.

A Gem Sensors LS-750 float switch was installed immediately adjacent to the bypass structure in each of the four MOC bioretention swales (Figure 2); these monitoring stations were designated D1-60/40-BP, D2-RBSM-BP, D3-LSMV-BP, and D4-LSW-BP (Figure 2). The float switches were interfaced with the same Campbell Scientific CR1000 data logger described above in connection with the inlet and outlet stations. The data logger was programmed to scan every 10 seconds and record the presence/absence of bypass conditions in addition to the duration of bypass.

To facilitate continuous monitoring of precipitation depths, a hydrologic monitoring station designated MOC-RG was installed adjacent to the equipment enclosure for the Campbell Scientific CR1000 data logger described above (Figure 2). Precipitation depths were monitored by a Texas Electronics TE-525WS rain gauge. The rain gauge was installed on an 8-foot steel pole and interfaced with the data logger. The gauge was located near the center of a parking lot so there were no issues with overhanging trees, power lines, or structures.

As mentioned above, the data logger was also equipped with an Airlink Raven XTV digital cellular modem to allow communication with the system via remote access. A 120-volt dual-power receptacle was installed by the City to provide power for all of the monitoring equipment. The data logger and digital cellular modem were housed in a utility box equipment enclosure. Conduit was installed to convey pressure transducer cabling and automated sampler suction lines from the base of the enclosure to each station.

All discharge data and rainfall data stored on the data logger were remotely downloaded every 5 minutes via cellular telemetry. These data were then processed and validated in accordance with procedures described in the project QAPP (Herrera 2014c).

Influent flows entering the 185-RBSMs and 185-Coir bioretention swales were monitored in concrete channels located along the curb lines on either side of the street (Figure 3); these stations were designated 185-RBSMs-IN and 185-Coir-IN. At each station, stilling wells equipped with INW PS-9805 pressure transducers were installed in association with 6-inch H-flumes to facilitate accurate measurement of influent flows to each swale.

Effluent flows were monitored in the 8-inch slotted underdrain located at the southern terminus of the bioretention swales (Figure 3); these stations were designated 185-RBSMs-OUT and 185-Coir-OUT. To facilitate accurate measurement of effluent flows, stations 185-RBSMs-OUT and 185-Coir-OUT were each equipped with an INW PS-9805 pressure transducer and an 8-inch Thel-Mar weir.

Separate Campbell Scientific CR1000 data loggers were also installed in association with the 185-RBSMs and 185-Coir bioretention swales and programmed to cache measurements every 10 seconds and record data on a 5-minute time step. The data loggers then converted all water level readings to estimates of discharge based on standard hydraulic equations (Walkowiak 2006). The data loggers were interfaced with Raven XTV digital cellular modems. This communication system was configured to automatically download data and send text message alarms to field technicians and project managers.

A Gem Sensors LS-750 float switch was installed immediately adjacent to the bypass structure located at the southern terminus of the 185-RBSMs and 185-Coir bioretention swales; these monitoring stations were designated 185-RBSMs-BP and 185-Coir-BP (Figure 3). The float switches were interfaced with their respective Campbell Scientific CR1000 data loggers installed at each bioretention swale. The data logger was programmed to scan every 10 seconds and record the presence/absence of bypass conditions in addition to the duration of bypass.

Precipitation depth were not monitored at the 185-RBSMs or 185-Coir bioretention swales. Instead, precipitation data for these swales were collected at the MOC-RG gauge described above. This gauge is only located 1/3 of a mile away so rainfall patterns were assumed to be similar between the monitoring locations.

As mentioned above, the data loggers at the 185-RBSMs or 185-Coir bioretention swales were also equipped with an Airlink Raven XTV digital cellular modem to allow communication with the systems via remote access. Because power was not available at either of the 185-RBSMs or 185-Coir bioretention swales, each station was equipped with 60-watt solar panels, charge controllers, and 180-amp-hr deep-cycle marine batteries. The batteries and electronics were housed in separate utility enclosures for each station. Conduit was installed to convey pressure transducer cabling and automated sampler suction lines from the base of the enclosures to monitoring points.

All discharge data and rainfall data stored on the data loggers were remotely downloaded on a daily basis via cellular telemetry. These data were then processed and validated in accordance with procedures described in the project QAPP (Herrera 2014c).

Controlled Infiltration Testing

After the bioretention swales were constructed, controlled infiltration testing was performed to evaluate infiltration rates on the surface of the swales. Surface infiltration rates were measured using procedures adopted from Ecology's (2012) pilot infiltration test. Water from a hydrant was discharged into a 3-foot by 6-foot frame that was sunk 12 inches into the BSM layer of each swale. After the flow rate remained stable (constant) for a period of 120 minutes at a ponding depth of 12 inches, the water was turned off and the rate of infiltration recorded (in inches/hour) until all the water has infiltrated to the surface of the BSM. This method has been shown to provide the most accurate estimates of infiltration rates for large-scale infiltration facilities (Seattle University 2004).

Detailed methods for the infiltration testing can be found in the memorandum drafted after the testing was completed (Herrera 2014b).

Flow Testing

All of the project weirs and flumes, with the exception of the MOC outlets, were flow tested to ensure the equipment was working properly. The MOC outlets could not be tested due to issues with access to the pipe upstream of the weir. Care was taken to test flow rates across the full range of flows that were expected at each monitoring location. The specific field procedures that were implemented in connection with the flow testing are as follows:

1. Water from a nearby fire hydrant was routed to the site using approximately 100 feet of a 2-inch-diameter fire hose. A rotometer was attached to the fire hose to measure the discharge rate of the water.

2. The flows from the rotometer were checked by timing flow into a graduated 30-gallon plastic container. This was repeated for four different flow rates.

3. The flow from the hydrant was set to 10 percent of the capacity of the target weir or flume, and water was discharged upstream of the influent monitoring stations. Once flows stabilized, the flow rate was recorded on the data logger and compared with the flow rate on the rotometer.

4. This process was repeated for flow rates at 25, 50, and 90 percent capacity of the associated weir.

Water Quality Monitoring

Water quality monitoring for this project was performed with the goal of obtaining 20 paired influent and effluent water samples from each of the bioretention systems. A combination of automated sampling (for collecting flow-weighted composite samples) and grab sampling was used to characterize influent and effluent water qualities. The procedures used to collect these samples are described below.

Automated Sampling

To facilitate the collection of flow-weighted composite samples, ISCO 6712 automated samplers were installed in association with the influent and effluent monitoring stations for the bioretention swale on 185th Avenue. At the MOC-IN station a Sigma 900 Max refrigerated automated sampler was deployed and Hach SD900 samplers were deployed at the MOC outlets (Figure 2).

Each automated sampler was housed in the same secure enclosures that were described above in connection with the hydrologic monitoring. Polytetrafluoroethylene (PTFE) lined sample tubing was routed via 1.5-inch buried conduit from the automated samplers in the enclosure to the sample collection locations (Figures 2 and 3). A sample intake strainer was installed at each sample collection location.

The five automated samplers for MOC bioretention swales were powered by a 120-volt dual-power receptacle that was housed in their enclosures. The four automated samplers for the 185th bioretention swales were powered by deep-cycle marine batteries that were charged with solar panels (see description above).

Guidelines from the Technology Assessment Protocol—Ecology (TAPE) were used for delineating and qualifying valid events (Ecology 2011). The following conditions served as guidelines in defining the acceptability of specific storm events for sampling:

- **Target storm depth**: A minimum of 0.15 inch of precipitation over a 24-hour period.
- **Antecedent conditions**: A period of at least 6 hours preceding the event with less than 0.04 inch of precipitation.
- **End of storm**: A continuous period of at least 6 hours after the event with less than 0.04 inch of precipitation.

Antecedent conditions and storm predictions were monitored via the Internet, and a determination was made as to whether to target an approaching storm. Once a storm was targeted, field staff visited each station to verify that the equipment was operational and to start the sampling program. A clean 20-liter high density polyethylene (HDPE) bottle and crushed ice were also placed in the sampling equipment at that time. The speed and intensity of incoming storm events were tracked using Internet-accessible, Doppler radar images. Actual rainfall totals during sampled storm events were quantified on the basis of data from the rain gauge installed at the site.

During the storm event sampling, the datalogger was programmed to enable the sampling routine in response to a predefined increase in water level (stage) each station independently. The automated samplers were then programmed to collect 220-milliliter (mL) sample aliquots at preset flow increments. The particular flow increments varied based on the expected storm magnitude. Based on the expected size of the storm, the flow increment was adjusted to ensure that the following criteria for acceptable composite samples were met at each station:

- A minimum of 10 aliquots.
- Sampling was targeted to capture at least 75 percent of the hydrograph.
- Due to sample holding time considerations, the maximum duration of automated sample collection was 36 hours.

After each targeted storm event, field personnel returned to each station, made visual and operational checks of the sampling equipment, and determined the total number of aliquots composited. Pursuant to the sampling criteria identified above, the minimum number of composite aliquots that constituted an acceptable sample was ten. If the sample was determined to be acceptable, the carboy was immediately capped, removed from the automated sampler, and kept below 6 degrees Celsius (°C) using ice during transport to the laboratory. All samples were delivered to the laboratory with appropriate chain-of-custody documentation. Collected flow-weighted composite samples were analyzed for the following parameters.

Flow-weighted composite samples from each storm event were analyzed for the following suite of parameters:

- pH
- Total suspended solids
- Particle size distribution (influent only)
- Copper, total and dissolved
- Lead, total and dissolved
- Zinc, total and dissolved
- Total phosphorus
- Orthophosphate
- Total Kjeldahl nitrogen
- Nitrite-nitrate nitrogen
- Hardness
- Dissolved organic carbon
- Major cations: Ca (calcium), Mg (magnesium), Na (sodium), and K (potassium)
- Major anions: SO4 (sulfate), Cl (chloride)
- Alkalinity
- Sulfide

Sampling occurred with the goal of collecting 20 paired flow-weighted composite samples over the duration of the project. However, by the end of the project this goal was only reached at four of the six swales (those located at the MOC). In total, 17 paired composite samples were collected at 185-Coir and 18 paired composite samples at 185-RBSMs.

Grab Sampling

When the first aliquot was collected during an event targeted for automated sampling, the data loggers described in the section above sent an alarm via text message to alert field personnel that stormwater is now flowing into the bioretention swales. Field personnel then mobilized to collect grab samples for:

- Fecal coliform
- Total petroleum hydrocarbons

Over the course of the study, grab samples were collected for events with and without corresponding flow-weighted composite samples with the goal of 20 paired influent and effluent grab samples are collected for each bioretention swale. However, this goal was not reach at any of the bioretention swales. Instead 18 paired grab samples were collected at the MOC bioretention swales and 14 were collected at both the bioretention swales on 185th Avenue.

Bioretention Soil Mix Monitoring

In addition to water sampling, three soil samples were collected from the bioretention soil mix stockpile when the bioretention systems were being constructed. One sample was collected from: the sand component, the compost component, and the BSMs. Each sample consisted of three composite samples. Field technicians collected each subsample with a stainless steel scoop and composited the subsample in a stainless steel bowl before placing the samples in glass jars for transport, on ice, to the laboratory. The samples were analyzed to assess the soil chemistry prior to installing the soil mix in the study system. The soil samples were analyzed for the parameters listed below. Table 7 presents additional information regarding the analytes measured in each sample.

- Cation exchange capacity (CEC)
- Particle size distribution
- Loss on ignition
- Total copper
- Total zinc
- Total phosphorus

Synthetic Precipitation Leaching Protocol (SPLP) Extractions

To identify specific materials used in the construction of the study system that might be contributing to the pollutant export problem, Synthetic Precipitation Leaching Protocol (SPLP) extractions were performed on the following individual components of the system:

- Sand fraction of bioretention soil mix
- Compost fraction of bioretention soil mix
- Maple Valley Loamy Sand
- Woodinville Loamy Sand

Table 7. Sediment Quality Analysis Methods and Detection Limits.

Parameter	Analytical Method	Method Number[a]	Field Sample Container	Total Holding Time[b]	Field Preservation	Laboratory Preservation	Actual Reporting Limit/ Resolution	Target Reporting Limit/ Resolution	Units
CEC	Sodium replacement	S-10.10[c]	4-oz glass or poly	2 days	Cool ≤ 4°C	Cool ≤ 4°C	0.1	NA	meq/100 g
Grain size	Sieve/ Hydrometer	ASTM D422		6 months			0.1	NA	%
Total carbon	Infrared detection	EPA 9060 mod		14 days; 6 months if frozen			0.01	0.1	%
Total phosphorus	Colorimetric	EPA 365.2		2 days			0.01	NA	mg/kg

[a] EPA method numbers are from US EPA (1986), and ASTM method number is from ASTM (2003).

[b] Holding time specified in the referenced methods.

[c] From Gavlak et al. (2003)

°C = degrees Celsius

CEC = cation exchange capacity

meq/100 g = milliequivalent per 100 gram

mg/kg = milligrams per kilogram

NA = not applicable

- MOC Type 26 Drainage Material
- 185th Type 26 Drainage Material
- Biochar
- Shredded Bark
- Coconut Coir
- Mulch that was applied to the surface of each system

The leachate from these extractions were analyzed for the following pollutants of concern for export from the study system:

- Copper, dissolved
- Zinc, dissolved
- Lead, dissolved
- Total phosphorus
- Nitrite-nitrate nitrogen
- Total Kjeldahl nitrogen

Analytical Methods

Analytical methods for this project are summarized in Tables 7 and 8. Aquatic Research, Inc. in Seattle, Washington, was the primary laboratory used for this project. The soil samples were analyzed at Analytical Resources, Inc. in Tukwila, Washington. All laboratories are certified by Ecology and participate in audits and inter-laboratory studies by Ecology and the US Environmental Protection Agency (US EPA). Those performance and system audits have verified the adequacy of the laboratories' standard operating procedures, which include preventive maintenance and data reduction procedures. Both laboratories provided sample and quality control data in standardized reports suitable for evaluating project data. The laboratory reports also included case narratives summarizing any problems encountered in the analyses.

Quality Assurance and Control Measures

Field, laboratory, and data management quality control procedures used in this project are discussed in this section. Memorandums summarizing results from quality assurance reviews that were performed on hydrologic and water quality data can be found in Appendices B and C, respectively.

Field Quality Assurance/Quality Control

Field personnel implemented a number of quality assurance/quality control procedures to evaluate sample contamination and sampling precision. Those procedures are described below.

Rinsate Blanks

Automated samplers were cleaned using the rinse and purge-pump-purge cycle between each aliquot. In addition, before each event, field personnel back-flushed the sample line with reagent-grade water. Rinsate blanks were collected prior to sampling the first storm event on April 18, 2014, and again on October 10, 2014. Field staff collected each field blank by pumping reagent-grade water through the intake tubing into a pre-cleaned sample container. The volume of reagent grade water pumped through the sampler for the equipment blank was similar to the volume of water collected during a typical storm event.

Field Duplicate Samples

Field duplicates were collected for composite and grab samples on every sample round. To collect the composite sample duplicate, the sample was split from the composite bottle using a churn splitter. The duplicate samples were submitted to the laboratory and labeled as separate (blind) samples. The resultant data from these samples were used to assess variation in the analytical results that is attributable to environmental (natural), sub-sampling, and analytical variability.

Flow Measurements

The precision and bias of the automated flow measurement equipment were tested prior to monitoring on February 7, 2014, and at the end of the project on May 5, 2015. The methods used for these tests and associated results are presented in the hydrologic data quality assurance memorandum in Appendix B. In addition, the levels sensors were routinely calibrated during the course of the project. Level calibration data can also be found in the hydrologic data quality assurance memorandum in Appendix B.

Laboratory Quality Control

Accuracy of the laboratory analyses was verified through the use of blank analyses, duplicate analyses, laboratory control spikes, and matrix spikes in accordance with the US EPA methods employed. Aquatic Research, Inc. and Analytical Resources, Inc., (both Ecology-certified) were responsible for conducting internal quality control and quality assurance measures in accordance with their own quality assurance plans.

Water quality results were first reviewed at the laboratories for errors or omissions and to verify compliance with acceptance criteria. The laboratories also validated the results by examining the completeness of the data package to determine whether method procedures and laboratory quality assurance procedures were followed. The laboratories documented their review, verification, and validation in case narratives that accompanied the analytical results.

Table 8. Water Quality Analysis Methods and Detection Limits.

Parameter	Analytical Method	Method Number[a]	Minimum Volume of Water Required for Analysis	Field Sample Container[b]	Pre-Filtration Holding Time	Total Holding Time[c]	Field Preservation	Laboratory Preservation	Reporting Limit	Units
pH	Probe	EPA 150.2	50 mL	20-L HDPE bottle	NA	24 hours	Cool ≤ 6°C	NA	0.1	Std. units
Total suspended solids	Gravimetric[d]	SM 2540D	500 mL		NA	7 days		Cool ≤ 6°C	1.0	mg/L
Total phosphorus	Automated ascorbic acid	EPA 365.3	125 mL		NA	28 days		Cool ≤ 6°C, H_2SO_4 to pH < 2	0.002	mg/L
Orthophosphate	Automated ascorbic acid	EPA 365.1			12 hours[e]	48 hours[e]		Filter, Cool ≤ 6°C	0.001	mg/L
Total Kjeldahl nitrogen	Automated Cadmium Reduction	EPA 351.2			NA	28 days		Cool ≤ 6°C, H_2SO_4 to pH < 2	0.200	mg/L
Nitrate+nitrite	Titration	EPA 353.2			24 hours				0.01	mg/L
Hardness as $CaCO_3$	Titration	SM 2340C	100 mL		NA	28 days		Cool ≤ 6°C	1.0	mg/L
Copper, dissolved	ICP-MS	EPA 200.8	250 mL		12 hours[e]	6 months		Filter, Cool ≤ 6°C, HNO_3 to pH < 2	0.0001	mg/L
Copper, total					NA			Cool ≤ 6°C, HNO_3 to pH < 2	0.0001	mg/L
Lead, dissolved					12 hours[e]			Filter, Cool ≤ 6°C, HNO_3 to pH < 2	0.001	mg/L
Lead, total					NA			Cool ≤ 6°C, HNO_3 to pH < 2	0.001	mg/L
Zinc, dissolved					12 hours[e]			Filter, Cool ≤ 6°C, HNO_3 to pH < 2	0.001	mg/L
Zinc, total					NA			Cool ≤ 6°C, HNO_3 to pH < 2	0.005	mg/L
Fecal coliform bacteria	Membrane filter	SM 9222D	100 mL	250 mL glass bottle	24 hours	24 hours	Cool ≤ 10°C	Cool ≤ 10°C	2	mg/L
TPH	GC/FID	NWTPH-Dx[f]	1 L	(2) 500 mL amber glass	7 days to extraction	40 days to analysis	Cool ≤ 6°C	Cool ≤ 6°C	0.05 to 0.1	mg/L
Particle size distribution	Sieve	ASTM 3977 mod	1 L	20-L HDPE bottle	NA	NA		Cool ≤ 6°C	0.1	mg/L
Dissolved organic carbon	High temperature furnace	EPA415.1	60 mL		24 hours	28 days		Filter, Cool ≤ 6°C, H_2SO_4 to pH < 2	0.250	mg/L
Total calcium	ICP	EPA 200.7	250 mL		NA	6 months		Cool ≤ 6°C, HNO_3 to pH < 2	0.100	mg/L
Total magnesium									0.100	mg/L
Total sodium									0.500	mg/L
Total potassium									0.500	mg/L
Chloride	Colorimetric	SM 4500-CL-E	100 mL			28 days		Cool ≤ 6°C	0.50	mg/L
Sulfate		SM 4500-SO4-F							1.00	mg/L
Sulfide		SM 4500 S2-D				7 days		Cool ≤ 6°C, Zn acetate + NaOH to pH > 9.0	0.05	mg/L
Alkalinity	Titration	SM 2320 B	100 mL			14 days		Cool ≤ 6°C	1.00	mg$CaCO_3$/L

[a] SM method numbers are from APHA et al. (1998); EPA method numbers are from US EPA (1983; 1984). The 18th edition of *Standard Methods for the Examination of Water and Wastewater* (APHA et al. 1992) is the current legally adopted version in the *Code of Federal Regulations*.

[b] Samples will be split from the 20-L HDPE bottle using a 22-liter churn splitter.

[c] Holding time specified in US EPA guidance (US EPA 1983, 1984) or referenced in APHA et al. (1992) for equivalent method.

[d] A G4 glass fiber filter will be used for the total suspended solids filtration.

[e] US EPA requires filtering for dissolved metals and orthophosphate within 15 minutes of the collection of the last aliquot. This goal is exceedingly difficult to meet when conducting flow-weighted sampling. A more practical proxy goal for this study is 12 hours. Both goals will be reported with the data. A 0.45-micron polycarbonate filter will be used for metals and orthophosphate filtration.

[f] Washington State Department of Ecology methods (Ecology 1997) includes silica gel extract cleanup step.

C = Celsius.
ICP = inductively coupled plasma / atomic emission spectroscopy.
ICP-MS = inductively coupled plasma / mass spectrometry.
GC/FID = gas chromatography / flame ionization detection.
GC/PID = gas chromatography / photo ionization detection.
mg/L = milligrams per liter.
HDPE = High-Density Polyethylene.
NA = not applicable.

Data were reviewed and validated within 7 days of receiving results from a laboratory. The review was performed to ensure that all data were consistent, correct, and complete, and that all required quality control information was provided. Specific quality control elements for the data were also examined to determine if the Method Quality Objectives (MQOs) specified in the QAPP for the project (Herrera 2014c) were met. Results from the data validation reviews were summarized in quality assurance worksheets that were prepared for each sample batch (Appendix B). Values associated with minor quality control problems were considered estimates and assigned *J* qualifiers. Values associated with major quality control problems were rejected and qualified with an *R*. Estimated values were used for evaluation purposes, while rejected values were not used.

Data Management Procedures

All project laboratories reported analytical results within 30 days of receipt of the samples. The laboratories provided sample and quality control data in standardized reports that were suitable for evaluating the project data. The reports included all raw data, including raw quality assurance data, and all quality control results associated with the data. The reports also included case narratives summarizing any problems encountered in the analyses, corrective actions taken, changes to the referenced method, and an explanation of data qualifiers. Laboratory analytical and quality control results were delivered from the laboratory in both electronic and hardcopy form.

Data from the dataloggers were remotely transferred on a 10-minute basis. The hydrologic data from each monitoring station were imported directly into an Aquarius (version 3.1) SQL based database for subsequent analysis and archiving purposes. Any data anomalies, including gaps, spikes, drift, and other irregularities, were identified and corrected within the Aquarius environment. A log of all the data corrections, including date of correction, type of correction, data corrected, and user identification is provided in Appendix C.

After the data were checked for errors and corrected, a custom program written in visual basic was applied to the flow, rain, and sample collection time data. The program uses algorithm to segregate storms based on TAPE (Ecology 2011) criteria identified above in the *Water Quality Monitoring Procedures* section. Once the events were delineated, the algorithm calculated the following storm statistics:

- **Precipitation**:
    - Start time
    - Stop time
    - Duration (hours)
    - Antecedent dry period (hours)
    - Depth (inches)
    - Peak intensity (inches/5 minutes)

- Peak intensity (inches/hour)
- Average intensity (inches/hour)

- **Flow**:
  - Start time
  - Stop time
  - Duration (hours)
  - Peak Flow (cubic feet per second)
  - Average Flow (cubic feet per second)
  - Storm Volume (cubic feet)
- **Sampling**:
  - Start time
  - Stop time
  - Duration (hours)
  - Number of aliquots
  - Volume represented by sampling (cf)
  - Percent of storm sampled by volume

The storm statistics were stored in conjunction with associated water quality data in the SQL database. The laboratory reports, field notes, and event hydrograph were also stored in the database with each event. Once compiled, these data were checked for data entry errors. If errors were found, they were corrected and the date and time of the correction was logged in the database. After these checks were performed, one-page individual storm reports for each sampled event were automatically generated from the database (Appendix D). Once the data were verified and validated, they were exported to StatSoft's Statistica (version 11) software for analysis.

Data Analysis Procedures

Data analysis was be performed to meet the following objectives of the monitoring project:

- Document hydrologic and water quality treatment performance of the study system, as demonstrated by field testing performed in accordance with the project QAPP
- Compare pollutant flushing dynamics among bioretention swales constructed with different BSMs.

Separate subsections, below, describe the specific data analysis procedures that were applied to meet these objectives.

Evaluation of Bioretention Treatment Performance

To evaluate the treatment performance of the bioretention swale, the following data compilations and analyses were generated from the monitoring results:

- Statistical comparisons of influent and effluent concentrations were performed.
- Pollutant removal efficiency was calculated for each parameter during each storm event.

Each of these activities is described in more detail below.

Statistical Comparisons of Influent and Effluent Pollutant Concentrations

Statistical analyses were performed to determine whether there were significant differences in pollutant concentrations between the influent and effluent of each bioretention system. The specific null hypothesis (H_o) and alternative hypothesis (H_a) for these analyses are as follows:

H_o: Influent and effluent pollutant concentrations are equal

H_a: Influent and effluent pollutant concentrations are not equal

To evaluate these hypotheses, a two-tailed Wilcoxon signed-rank test (Helsel and Hirsch 2002) was used to compare the influent and effluent performance data. (The Wilcoxon signed-rank test is a nonparametric analogue to the paired t-test.) Statistical significance was assessed based on an alpha (α) level of 0.05.

Pollutant Removal Efficiency Calculations

The removal efficiencies for each monitoring parameter during each storm event was calculated using the following formula:

$$\text{Percent Removal} = \frac{100[A-B]}{A}$$

where: A = Storm 1 influent concentration

B = Storm 1 effluent concentration

When pollutant removal efficiencies were compared with TAPE standards the influent concentrations were screen and a bootstrap analysis of percent removals was conducted per the 2011 TAPE protocol.

Statistical Evaluation of Performance Goals

Statistical analyses were performed to determine whether the collected data demonstrated the bioretention swales met applicable performance goals specified in the TAPE guidelines

(Ecology 2011) for basic, enhanced, phosphorus, and oil treatment. Pursuant to the TAPE guidelines (Ecology 2011), the statistical analysis will involve the computation of bootstrapped confidence intervals around the mean effluent concentration or pollutant removal efficiency.

Comparison to Applicable Water Quality Standards

To provide a frame of reference for evaluating the treatment performance of the bioretention swales, influent and effluent concentrations from each swale were compared to applicable drinking and groundwater water quality standards for Washington State as defined in WAC 173-201A. Additionally, the effluent data were compared with NPDES Industrial Benchmarks (Ecology 2009). Finally, the toxicity of the treated effluent for aquatic organism was evaluated using the Biotic Ligand Model (BLM). The BLM is a bioavailability model that uses receiving water body characteristics and monitoring data to develop site-specific water quality criteria for metals. Input data for the BLM in this analysis include:

- pH
- Dissolved organic carbon
- Major cations: Ca, Mg, Na, and K
- Major anions: SO_4, Cl
- Alkalinity
- Sulfide

RESULTS

The results described in this section are from monitoring that occurred from April 19, 2014, to April 31, 2015. Separate subsections present results from leaching, hydrologic, and water quality monitoring. Additional information related to project data can also be found in the following appendices:

- **Appendix D** Individual Storm Reports
- **Appendix E** Standardized Field Forms
- **Appendix F** Water Quality and Flow Metrics Database
- **Appendix G** Groundwater Quality Criteria
- **Appendix H** Laboratory Reports
- **Appendix I** Infiltration Testing Memorandum
- **Appendix J** Water Quality Data Boxplots

Leaching Analysis

Previous studies have indicated that nutrient and metals leaching from the swales may be an issue. Consequently, SPLP analyses were conducted to try and determine which BSM components would contribute most to the flushing at full scale. Table 9 indicates that the compost leaches the most Total Kjeldahl nitrogen, total phosphorus, copper, lead, and zinc. The biochar leached the most nitrate+nitrite and the second most total phosphorus, but leached the least amount of metals (all non-detect). The Type-26 drainage gravel used in the swales on 185th Avenue Northeast exhibited the lowest total phosphorus, while the coconut coir had the lowest nitrate+nitrite values.

Table 9. Results from Synthetic Precipitation Leaching of BSM Components.

Component	Date	Nitrate+ Nitrite (mg/L)	Total Kjeldahl Nitrogen (mg/L)	Total Phosphorus (mg/L)	Copper (ug/L)	Lead (ug/L)	Zinc (ug/L)
Biochar	4/25/2014	0.968	**1**	3.35	**0.5**	**0.1**	**4**
Shredded Bark	4/25/2014	0.062	3.2	2.05	5.1	0.5	20
Maple Valley Sandy Loam	4/25/2014	0.028	**1**	0.149	5	1.9	6
MOC Type 26	4/25/2014	0.028	**1**	0.112	5.6	0.7	5
Woodinville Loamy Sand	4/25/2014	0.161	**1**	0.16	8.6	3.6	11
Mulch	4/25/2014	0.02	2.7	0.135	6.4	1	11
Cedar Grove Compost	4/25/2014	0.115	70	10.3	44.7	18.1	95
IKON Sand	4/25/2014	0.029	**1**	0.109	7.3	1.2	5
185th Type 26	4/25/2014	0.025	**1**	0.093	9.2	1.2	8
Coco Coir	12/17/2014	**0.1**	1.7	0.309	3.7	0.3	8

Bold indicates value at the reporting limit.

Hydrologic Data

To provide some context for interpreting the monitoring results, this section compares rainfall totals measured during the monitoring period relative to historical data. Separate sections then evaluate the bypass results and the infiltration testing results. Finally, the flow results are reported for both the inlet and outlet stations. Appendix B summarizes results from the quality assurance review that was performed on the hydrologic data prior to their analysis.

Historical Rainfall Data Comparison

To provide some context for interpreting the hydrologic performance of the study system, an analysis was performed on rainfall data collected at the Western Regional Climate Center (WRCC) rain gauge at Sea-Tac airport to determine if rainfall totals from the monitoring period (i.e., April 2014 through April 2015) were anomalous. The WRCC gauge is located approximately 18 miles southwest of the project site. The analysis specifically involved a comparison of rainfall totals measured at the WRCC rain gauge over the monitoring period to averaged totals for the same gauge from the 63-year historical record.

Results from this analysis showed the average annual rainfall total at the Sea-Tac rain gauge from 1949 through 2014 was 38.4 inches (<http://green2.kingcounty.gov/hydrology/PrecipitationGraphs.aspx>). In comparison, the rainfall total at the Sea-Tac rain gauge over the 2014 water year was 39.1 inches, indicating that the study period occurred during a neither abnormally dry nor wet water year.

To check the accuracy of the MOC-RG gauge, the associated results were compared to results from other calibrated rain gauges in the region for the period of April 2014 through April 2015. Specifically, the total MOC-RG precipitation from April 19, 2014, through April 30, 2015, was compared to the record from the King County gauge operated at Marymoore Park (<http://green2.kingcounty.gov/hydrology/GaugeMetaData.aspx>), which is 1.3 miles from the project location. During this period, the gage at the MOC recorded 40.5 inches of rain while the gauge at Marymoore recorded 48.2 inches. The reason for this 17.4 percent discrepancy is unclear as the MOC-RG rain gauge was calibrated both before and after the monitoring period and was within 2 percent accuracy.

Bypass Analysis

During the monitoring period, 117 individual events were identified at the MOC and there was zero bypass recorded. At 185-Coir, 103 individual events were identified and two of those produced bypass flow. At 185-RBSMs, 111 individual events were identified and 10 of those produced bypass flow. Bypass volumes were not recorded but the bypass frequency analysis above indicates that the MOC was likely oversized (visual observations using time-lapse photography indicated that ponding depth never exceeded 1 inch). The bioretention swales on 185th Avenue Northeast were also likely oversized as the infiltration rate was assumed to be 2 inch/hour when in fact it was much higher (see *Controlled Infiltration Testing* section below).

Controlled Infiltration Testing

Controlled infiltration testing was conducted on May 20 through 23, 2014, at the MOC. Infiltration testing was not conducted at 185th Avenue Northeast at the time because the BSM installed was identical to the BSM installed in D2-RBSM at the MOC. On May 26, 2014, new sand and coconut coir media were installed at 185-Coir; this new BSM was infiltration tested 1 year later on May 29, 2015. The results of all the infiltration testing are presented in Table 10. The results for the Loamy Sands were biased high due to short circuiting down the cell wall during test flooding; consequently, lab permeability test results were used in place of field results for these BSMs. A memorandum describing the infiltration testing conducted at the MOC is provided in Appendix I.

Table 10. Results from Infiltration Testing

Swale	Bioretention Soil Mix	Infiltration Rate (in/hr)
D1-60/40	ECY-60/40	11.8[a]
D2-RBSM	Redmond Mix	6.0[a]
D3-LSMV	Maple Valley Loamy Sand	1.3[b]
D4-LSW	Woodinville Loamy Sand	5.1[b]
185-Coir	Sand and Coconut Coir	61[c]

[a] Determined using 6- x 3-foot infiltration frame.

[b] Determined by lab permeability testing (ASTM D2434). Field testing results biased high by water short circuiting down the walls of the cell when it was completely flooded.

[c] Determined using 6- x 3-foot infiltration frame 1 year after media installation.

As can be seen in Table 10, the Sand and Coir mix had the highest infiltration rate (61 in/hr) when compared with the other BSMs, and the 60/40 Sand/Compost mix had the second highest infiltration rate at 11.8 in/hr. Reducing the compost content and adding biochar and shredded bark to the mix (i.e., creating the RBSM mix) apparently reduced the infiltration rate by about 50 percent: infiltration rates at D2-RBSM were 6.0 in/hr. The Loamy Sands had the lowest infiltration rates of between 1.3 and 5.1 in/hr, based on lab permeability testing.

Water Quality Data

This section summarizes water quality data collected during the April 2014 through April 2015 monitoring period. It begins with an evaluation of data representativeness based on criteria that were previously identified in the project QAPP (Herrera 2014c). It then presents results under separate subsections for the following groups of parameters: Solids, Nutrients, Metals, and Other. Each subsection provides a comparison of influent and effluent concentrations, followed by a temporal analysis of the observed pollutant export; where applicable, the effluent results are also compared with groundwater standards to determine if infiltration through bioretention systems may pose a risk to groundwater in Redmond. In addition, results from the BLM analysis are presented.

A total of 24 parameters were analyzed in this study, to improve readability this section focuses on those parameters which have been deemed more important in terms of water quality treatment and the potential for export from the swales. Below is a detailed description of total suspended solids (TSS), total phosphorus (TP), nitrate+nitrite, dissolved copper, and dissolved zinc results. Appendix J provides boxplots and statistical comparisons among stations for all 24 measured parameters. A summary table of mean concentration and percent removals for all 24 parameters is also provided in the subsequent section.

Water Quality Data Representativeness

During the 20-month monitoring period, 26 storm events were successfully sampled by either grab or composite sample, or both. Tables 11, 12, and 13 present the results of the storm event and sampling criteria for each event and provide a comparison to the goals identified in the project QAPP (Herrera 2014c) and in the *Methods* section, above.

As is apparent from Table 11, the majority of the sampled storm events at the MOC met the storm and sampling criteria. There were three events where either the sample count, storm depth, or antecedent dry period criteria were not met; however, because the criteria were nearly met and because other criteria for those same events were met, the associated samples were deemed representative. The February 5, 2015, event did not meet the sample coverage goal; however, a commonly used criterion in the region for sample coverage is that the coverage calculation should only apply to the first 24 hours of the event. For the first 24 hours the coverage was close to 100 percent, so the associated sample was deemed representative.

As is apparent from Table 12, the majority of the sampled storm events at 185-Coir met the storm and sampling criteria. There were four events where either the sample count, sample coverage, or antecedent dry period criteria were not met; however, because the criteria were nearly met and because other criteria for those same events were met, the associated samples were deemed representative. The first storm to discharge to the 185-Coir bioretention swale after commissioning was on June 13, 2014; during the storm, only four aliquots were collected at the outlet. Due to the desire to collect the first flush, this sample was submitted and analyzed even though the sample count criterion was not met.

As is apparent from Table 13, the majority of the sampled storm events at 185-RBSMs met the storm and sampling criteria. There were three events where either the sample count or sample coverage criteria were not met; however, because the criteria were nearly met and because other criteria for those same events were met, the associated samples were deemed representative.

Solids Results

Unlike with dissolved pollutants, the export or reduction of TSS as it passes through a bioretention cell can be influenced by factors such as underdrain slot size, drainage layer grain size relative to underdrain slots, compaction, and other physical factors. It can be assumed that after an initial establishment period where physical settling and flushing of fines will result in TSS export, effluent concentrations subsequently will stabilize and then vary slightly as a function of influent concentrations. This is, indeed, the pattern observed among the six swales (Figure 5).

Table 11. Storm and Sampling Criteria for the Sampled Storm Events at the MOC.

Event Start Date/Time	Total Precip. (in)	Antecedent Dry Period (hr)	MOC-IN	D1-OUT	D2-OUT	D3-OUT	D4-OUT	MOC-IN	D1-OUT	D2-OUT	D3-OUT	D4-OUT	MOC-IN	D1-OUT	D2-OUT	D3-OUT	D4-OUT
			Sample Count	Sample Count	Sample Count	Sample Count	Sample Count	Sample Duration (hr)	Sample Duration (hr)	Sample Duration (hr)	Sample Duration (hr)	Sample Duration (hr)	Sample Coverage %	Sample Coverage %	Sample Coverage %	Sample Coverage %	Sample Coverage %
4/19/2014 11:45	0.24	22	66	41	47	71	63	2.8	7.0	4.4	4.1	4.3	97.0	97.9	97.8	97.8	96.9
4/21/2014 21:05	0.46	55	39	41	39	37	36	9.0	10.3	10.3	9.5	9.5	97.9	98.7	98.7	96.8	98.0
4/23/2014 14:00	0.41	15	23	24	23	20	21	9.6	10.3	10.8	9.8	10.2	88.5	90.0	90.6	87.7	90.0
6/13/2014 1:40	0.33	435	20	17	16	14	16	2.1	2.1	2.5	2.1	2.5	97.0	93.5	97.7	93.8	98.2
7/23/2014 1:45	1.35	646	35	36	36	35	33	13.7	14.1	14.0	14.0	13.9	96.7	99.3	98.1	97.2	97.9
8/12/2014 21:25	0.80	254	58	56	51	55	51	8.3	8.4	8.2	8.3	8.3	97.5	98.7	96.1	98.1	97.7
9/23/2014 14:10	1.09	350	42	46	43	37	36	15.5	16.6	16.1	15.9	15.2	96.2	100.0	97.3	99.5	95.6
9/29/2014 15:20	0.28	79	22	18	17	15	16	2.5	2.5	2.6	3.2	2.5	92.7	94.6	98.2	92.2	94.5
10/13/2014 19:25	0.80	50	78	67	62	69	67	9.1	8.9	9.2	9.8	10.5	98.3	97.5	98.6	99.4	99.7
10/17/2014 12:10	0.48	47	51	41	37	37	38	22.0	21.8	22.0	21.9	22.1	98.3	95.0	96.2	94.6	96.1
10/22/2014 3:05	1.45	14	42	46	39	33	30	23.3	23.5	23.5	23.0	22.8	98.1	97.7	96.9	96.1	95.1
10/25/2014 8:30	0.28	10	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only
10/28/2014 0:05	0.39	34	26	21	23	20	19	6.6	7.0	6.8	6.8	7.3	97.7	99.4	96.3	96.4	97.8
11/21/2014 10:55	0.40	32	44	44	34	27	26	6.6	7.0	12.4	6.6	6.8	99.3	99.4	96.7	96.7	97.4
12/6/2014 0:55	0.18	14	12	13	10	**8**	**7**	2.1	2.4	3.0	3.0	2.8	92.9	93.8	91.4	95.2	91.5
12/10/2014 13:50	0.20	11	20	22	17	13	12	4.8	5.0	7.6	5.6	5.8	94.7	94.8	97.8	95.3	95.3
12/19/2014 23:50	0.37	20	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only
1/4/2015 23:45	0.33	14	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only
1/15/2015 9:45	0.20	124	15	18	13	10	10	2.6	3.3	3.0	5.8	3.0	94.2	98.4	93.1	99.9	92.8
1/23/2015 6:55	**0.14**	20	13	14	10	**8**	**8**	1.8	2.3	12.4	3.8	3.3	93.6	97.5	97.8	98.7	93.0
2/4/2015 11:15	0.26	21	29	36	39	23	23	3.8	5.1	6.6	7.5	4.8	97.7	99.7	98.1	99.6	95.3
2/5/2015 18:20	1.22	**4**	99	100	100	100	100	18.6	18.1	18.3	21.9	20.2	**55.9**	**52.5**	**46.1**	**62.7**	**63.7**
3/15/2015 2:40	2.16	697	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only
3/31/2015 2:15	0.24	131	31	24	23	25	26	3.1	3.0	3.5	4.2	4.0	97.6	95.6	94.9	98.7	95.9
4/10/2015 17:45	0.37	213	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only
4/13/2015 14:15	0.47	46	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only	grab only
QAPP Criteria	**≥ 0.15**	**≥ 6**	**≥ 10**	**≥ 10**	**≥ 10**	**≥ 10**	**≥ 10**	**≤ 36**	**≤ 36**	**≤ 36**	**≤ 36**	**≤ 36**	**≥ 75**	**≥ 75**	**≥ 75**	**≥ 75**	**≥ 75**

Greyed cells indicate criteria which did not meet the QAPP thresholds.

Table 12. Storm and Sampling Criteria for the Sampled Storm Events at 185-Coir.

Event Start Date	Total Precip. (in)	Antecedent Dry Period (hr)	185-Coir-IN Sample Count	185-Coir-OUT Sample Count	185-Coir-IN Sample Duration (hr)	185-Coir-OUT Sample Duration (hr)	185-Coir-IN Sample Coverage %	185-Coir-OUT Sample Coverage %
6/13/2014 1:40	0.37	435	11	**4**	8.3	1.3	92.1	79.1
6/15/2014 14:35	0.58	12	16	91	12.8	5.3	75.5	**71.1**
7/23/2014 1:45	1.35	646	21	34	9.6	10.0	93.8	96.5
8/12/2014 21:25	0.80	254	38	69	6.1	4.7	98.3	97.7
9/23/2014 14:10	1.09	350	19	28	17.1	14.9	98.8	96.8
9/29/2014 15:20	0.28	79	15	**9**	3.4	0.8	92.4	82.6
10/15/2014 1:25	0.45	22	10	35	10.5	10.8	89.5	92.9
10/17/2014 12:10	0.48	47	43	26	21.4	9.0	99.0	97.4
10/22/2014 3:05	1.45	14	grab only	grab only	grab only	grab only	grab only	grab only
10/25/2014 8:30	0.28	10	10	**8**	6.5	2.3	94.4	76.7
10/28/2014 0:05	0.39	34	32	29	6.0	3.9	95.2	96.0
11/21/2014 10:55	0.40	32	13	13	4.5	2.8	91.2	90.4
12/10/2014 13:50	0.20	11	41	12	6.5	2.2	98.2	83.4
12/19/2014 23:50	0.37	20	grab only	grab only	grab only	grab only	grab only	grab only
1/4/2015 23:45	0.33	14	grab only	grab only	grab only	grab only	grab only	grab only
2/4/2015 11:15	0.26	21	11	36	5.0	2.0	90.8	95.8
2/5/2015 13:55	1.27	**5**	101	100	21.2	18.2	91.5	77.0
2/8/2015 21:05	0.16	23	28	17	1.3	0.8	89.5	89.1
3/14/2015 0:35	0.64	53	26	77	8.4	6.3	93.9	97.7
3/15/2015 2:40	2.16	17	grab only	grab only	grab only	grab only	grab only	grab only
3/31/2015 2:15	0.62	131	23	59	15.3	12.7	95.4	99.4
4/13/2015 14:15	0.47	46	grab only	grab only	grab only	grab only	grab only	grab only
QAPP Criteria	**≥ 0.15**	**≥ 6**	**≥ 10**	**≥ 10**	**≤ 36**	**≤ 36**	**≥ 75**	**≥ 75**

Grey-shaded cells indicate criteria which did not meet the QAPP thresholds.

Table 13. Storm and Sampling Criteria for the Sampled Storm Events at 185-RBSMs.								
			185-RBSMs-IN	185-RBSMs-OUT	185-RBSMs-IN	185-RBSMs-OUT	185-RBSMs-IN	185-RBSMs-OUT
Event Start Date	**Total Precip. (in)**	**Antecedent Dry Period (hr)**	**Sample Count**	**Sample Count**	**Sample Duration (hr)**	**Sample Duration (hr)**	**Sample Coverage %**	**Sample Coverage %**
4/19/2014 11:45	0.24	22	51	16	5.2	0.8	97.5	84.0
5/8/2014 12:55	0.53	54	24	48	7.8	8.2	95.8	97.6
7/23/2014 1:45	1.35	646	21	23	9.8	9.9	97.7	93.7
8/12/2014 21:25	0.80	254	39	100	6.4	3.2	99.2	77.4
9/23/2014 14:10	1.09	350	24	15	16.8	14.5	96.4	95.8
9/29/2014 15:20	0.28	79	17	**7**	3.7	0.6	96.5	77.8
10/13/2014 19:25	0.80	50	56	50	7.4	4.3	98.8	98.4
10/17/2014 12:10	0.48	47	28	10	21.0	6.1	97.1	95.6
10/22/2014 3:05	1.45	14	19	12	26.9	20.2	98.3	94.4
10/25/2014 8:30	0.28	10	**8**	**8**	6.1	0.9	87.4	79.3
10/28/2014 0:05	0.39	34	33	30	6.2	3.5	97.0	95.8
11/21/2014 10:55	0.40	32	13	11	4.7	3.0	90.8	93.6
11/25/2014 1:15	0.46	11	12	17	5.7	5.5	91.4	97.5
12/10/2014 13:50	0.20	11	**8**	**8**	4.7	1.9	87.4	75.8
12/19/2014 23:50	0.37	20	grab only	grab only	grab only	grab only	grab only	grab only
1/4/2015 23:45	0.33	14	grab only	grab only	grab only	grab only	grab only	grab only
2/5/2015 13:55	1.27	5	84	100	25.9	17.6	99.2	**69.5**
3/14/2015 0:35	0.64	53	17	97	8.7	6.6	95.3	96.8
3/15/2015 2:40	2.16	17	grab only	grab only	grab only	grab only	grab only	grab only
3/31/2015 2:15	0.62	131	21	16	15.1	14.4	93.8	99.1
4/13/2015 14:15	0.47	46	32	30	3.8	3.6	94.6	96.0
QAPP Criteria	**≥ 0.15**	**≥ 6**	**≥ 10**	**≥ 10**	**≤ 36**	**≤ 36**	**≥ 75**	**≥ 75**

Grey-shaded cells indicate criteria which did not meet the QAPP thresholds.

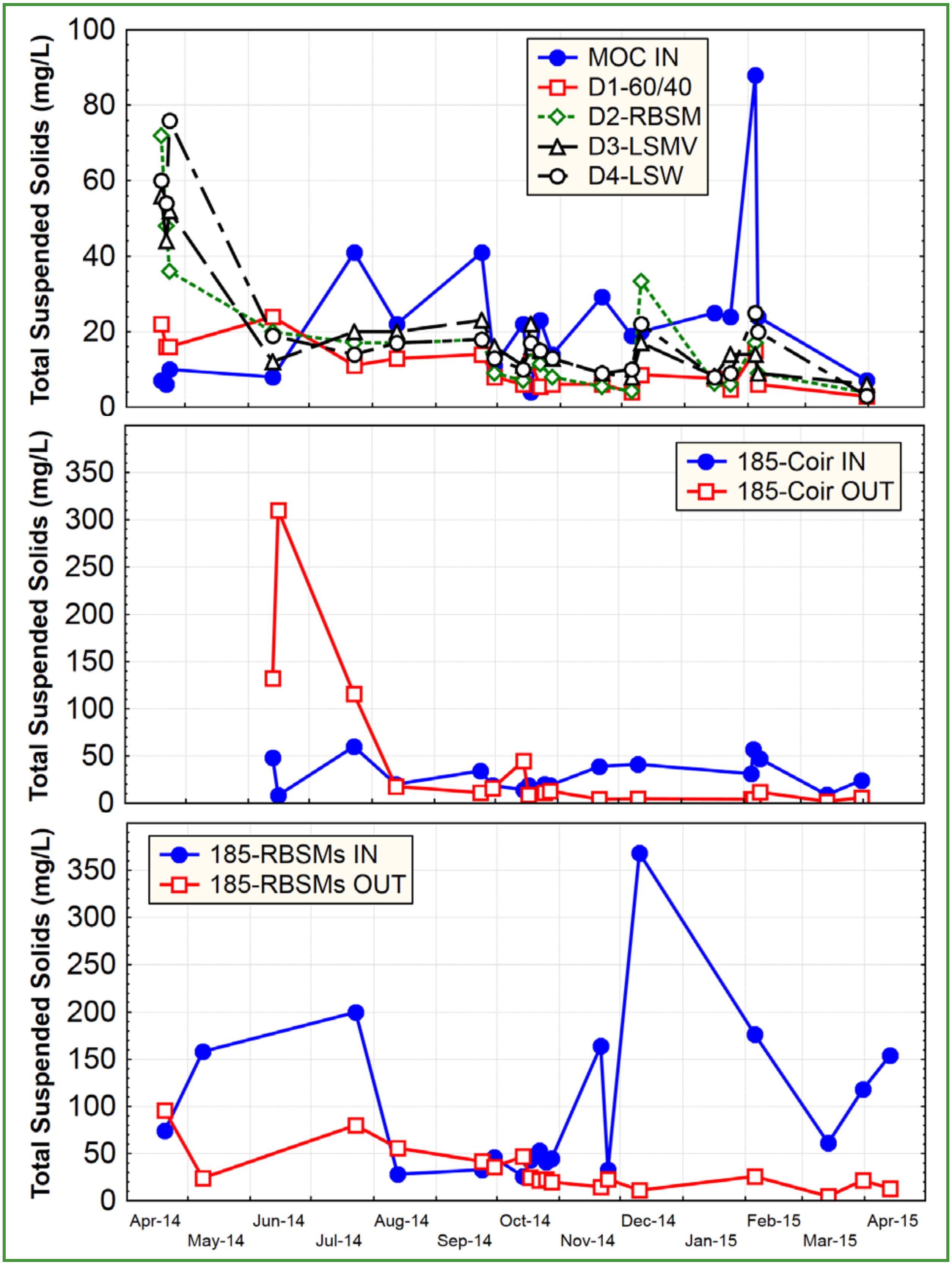


Figure 5. Total Suspended Solids Influent and Effluent Pollutographs.

After approximately 50 percent of a typical water years' worth of flow (50%WY) entered the systems, TSS values were roughly equivalent among the six swales (Figure 6). The one exception was that 185-RBSMs was still elevated at 50%WY and did not stabilize until 80%WY. The 185-RBSMs swale had the highest influent concentrations (mean of 101 mg/L) among the swales and this was likely a factor in the effluent response (Table 14).

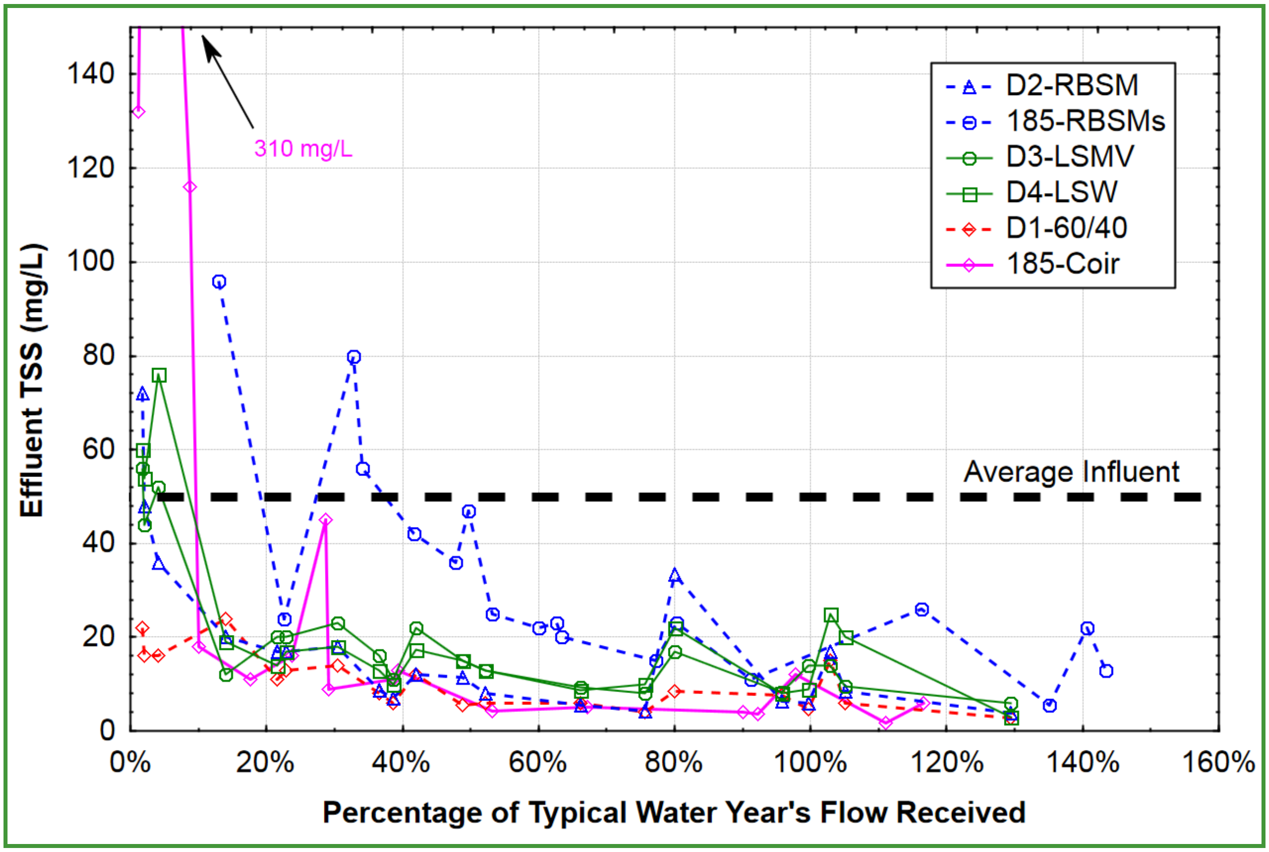


Figure 6. Total Suspended Solids Effluent Pollutographs as a Function of Rainfall Received.

Overall, the swale with the lowest effluent TSS concentrations was D1-60/40, the swale with the standard 60 percent sand, 40 percent compost mix. However, Figure 6 indicates that after the 50%WY flush, both D1-60/40 and 185-Coir performed very similarly and better than the other swales. The swale with the highest average percent reduction (39 percent) was 185-RBSMs, which was likely due to the fact that the swale also had the highest influent concentrations. The Loamy Sand swales D3-LSMV and D4-LSW had the lowest infiltration rates but, surprisingly, not the highest TSS removals. This may have been due to the export of fines from these swales as they had more silt and clay in the BSM than the other swales.

The 2012 Stormwater Management Manual for Western Washington (Ecology 2012) and the TAPE (Ecology 2011) dictate that "Basic Treatment" BMPs will remove greater than or equal to 80 percent TSS for influent concentrations greater than 100 mg/L, and have effluent concentrations no higher than 20 mg/L when influent concentrations are between 20 and 100 mg/L. Table 15 indicates that every system met the TSS removal criterion except 185-Coir and 185-RBSMs. As indicated above, 185-RBSMs exhibited continued high TSS effluent concentrations through 80%WY; this resulted in the swale not meeting the basic criterion for influent concentrations between 20 and 100 mg/L.

Table 14. Chemistry Summary Table.

Parameter	Units	MOC-IN	D1-60/40-OUT				D2-RBSM-OUT				D3-LSMV-OUT				D4-LSW-OUT				185-Coir-IN	185-Coir-OUT				185-RBSMs-IN	185-RBSMs-OUT			
		Mean In	Mean Out	Mean % Reduction	L95	U95	Mean Out	Mean % Reduction	L95	U95	Mean Out	Mean % Reduction	L95	U95	Mean Out	Mean % Reduction	L95	U95	Mean In	Mean Out	Mean % Reduction	L95	U95	Mean In	Mean Out	Mean % Reduction	L95	U95
Alkalinity	mgCaCO3/L	15.9	39.9	-163%	-267%	-73%	37.4	-154%	-203%	-111%	23.0	-53%	-70%	-38%	21.6	-43%	-57%	-31%	6.4	14.6	-128%	-156%	-100%	9.3	46.2	-415%	-484%	-346%
Chloride	mg/L	3.4	3.6	-9%	-14%	-5%	3.7	-17%	-25%	-10%	3.6	-12%	-19%	-6%	3.5	-13%	-20%	-6%	0.9	1.1	-50%	-93%	-12%	1.1	2.6	-170%	-231%	-111%
Dissolved Copper	mg/L	0.0056	0.0086	-74%	-100%	-49%	0.0067	-33%	-46%	-19%	0.0054	-6%	-17%	5%	0.0064	-16%	-28%	-6%	0.0041	0.0028	-9%	-54%	29%	0.0041	0.0078	-111%	-151%	-75%
Dissolved Lead	mg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Dissolved Organic Carbon	mg/L	7.28	8.52	-19%	-35%	-5%	7.84	-15%	-26%	-3%	6.46	6%	-4%	16%	7.05	-2%	-12%	7%	3.25	3.24	-15%	-35%	2%	3.08	7.41	-174%	-235%	-122%
Dissolved Zinc	mg/L	0.0426	0.0058	86%	84%	88%	0.00425	89%	88%	91%	NC	NC	NC	NC	0.004925	88%	85%	90%	0.0148	NC	NC	NC	NC	0.0175	0.0039	76%	71%	80%
Hardness	mgCaCO3/L	15.3	30.3	-117%	-184%	-59%	32.4	-137%	-187%	-94%	22.6	-65%	-93%	-38%	22.2	-61%	-85%	-38%	7.5	16.4	-138%	-203%	-85%	13.8	43.1	-316%	-408%	-228%
Nitrate + Nitrite	mg/L	0.138	0.501	-546%	-934%	-277%	0.545	-1,028%	-2,257%	-321%	0.446	-343%	-574%	-188%	0.383	-257%	-380%	-160%	0.112	0.145	-61%	-100%	-25%	0.117	0.865	-765%	-1,032%	-543%
Ortho-phosphorus	mg/L	0.294	0.275	-105%	-137%	-72%	0.362	-262%	-362%	-172%	0.073	53%	45%	61%	0.086	48%	40%	56%	0.020	0.040941	-968%	-1,524%	-497%	0.009	0.321	-7,296%	-9,276%	-5,391%
pH	pH units	6.9	6.9	0%	-2%	1%	7.1	-3%	-5%	-1%	7.0	-1%	-2%	0%	6.9	0%	-1%	1%	6.8	7.0	-4%	-5%	-2%	6.8	7.3	-7%	-10%	-5%
Total Phosphorus	mg/L	0.485	0.459	-52%	-82%	-24%	0.539	-98%	-140%	-57%	0.204	26%	3%	45%	0.220	24%	3%	44%	0.106	0.219353	-347%	-942%	8%	0.219	0.533	-285%	-382%	-191%
SSL-Coarse > 75um	mg/L	3.2	2.1	-51%	-134%	18%	2.8	-51%	-138%	21%	2.9	-60%	-158%	13%	3.1	-55%	-160%	25%	17.4	2.2	58%	8%	90%	74.3	1.4	94%	88%	98%
SSL-Fine < 75um	mg/L	16.0	8.8	-5%	-45%	32%	18.6	-258%	-550%	-23%	18.2	-210%	-413%	-43%	20.2	-238%	-466%	-50%	13.3	37.8	-660%	-1641%	-41%	48.8	34.5	-117%	-207%	-31%
Sulfate	mg/L	1.18	1.15	-14%	-32%	1%	1.44	-31%	-53%	-11%	1.50	-50%	-74%	-26%	1.22	-33%	-65%	-6%	1.32	1.33	-25%	-70%	15%	1.55	1.44	-6%	-29%	17%
Sulfide	mg/L	0.17	0.13	-1%	-23%	17%	0.19	-74%	-135%	-22%	0.15	-2%	-18%	12%	0.15	-9%	-40%	14%	0.15	0.14	-7%	-43%	20%	0.16	0.17	-43%	-119%	2%
Total Calcium	mg/L	5.00	8.99	-93%	-145%	-47%	7.88	-70%	-96%	-48%	5.16	-10%	-23%	1%	5.12	-9%	-20%	1%	2.62	3.69	-46%	-69%	-25%	4.39	11.57	-206%	-258%	-158%
Total Copper	mg/L	0.0095	0.0115	-45%	-70%	-21%	0.0110	-44%	-86%	-9%	0.0100	-28%	-55%	-4%	0.0113	-36%	-65%	-11%	0.0101	0.0127	-64%	-175%	29%	0.0188	0.0151	-12%	-43%	18%
Total Kjeldahl Nitrogen	mg/L	1.63	1.20	-15%	-45%	11%	0.98	5%	-12%	22%	0.69	26%	4%	44%	0.70	24%	-6%	47%	0.90	1.08	-18%	-99%	49%	1.56	1.07	10%	-8%	29%
Total Lead	mg/L	0.0016	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	0.0036	NC	NC	NC	NC	0.0044	0.0013	32%	8%	56%
Total Magnesium	mg/L	0.70	1.90	-311%	-499%	-150%	3.10	-673%	-1,052%	-379%	2.37	-550%	-959%	-262%	2.28	-508%	-859%	-258%	0.25	1.75	-1,231%	-1,693%	-812%	0.82	3.46	-1,983%	-3,026%	-1,050%
Total Potassium	mg/L	2.12	7.83	-330%	-546%	-141%	6.59	-242%	-339%	-153%	2.44	-18%	-25%	-10%	2.75	-35%	-47%	-23%	0.60	1.86	-333%	-481%	-218%	0.92	8.00	-1,253%	-1,711%	-815%
Total Sodium	mg/L	3.29	3.76	-23%	-33%	-13%	4.70	-57%	-78%	-37%	4.55	-53%	-68%	-37%	4.24	-41%	-54%	-29%	1.04	2.33	-116%	-171%	-66%	1.89	2.53	-47%	-72%	-24%

Table 14 (continued). Chemistry Summary Table.

Parameter	Units	MOC-IN	D1-60/40-OUT				D2-RBSM-OUT				D3-LSMV-OUT				D4-LSW-OUT				185-Coir-IN	185-Coir-OUT				185-RBSMs-IN	185-RBSMs-OUT			
		Mean In	Mean Out	Mean % Reduction	L95	U95	Mean Out	Mean % Reduction	L95	U95	Mean Out	Mean % Reduction	L95	U95	Mean Out	Mean % Reduction	L95	U95	Mean In	Mean Out	Mean % Reduction	L95	U95	Mean In	Mean Out	Mean % Reduction	L95	U95
TSS	mg/L	22.3	10.4	8%	-34%	45%	18.0	-75%	-179%	15%	19.5	-85%	-178%	0%	21.6	-104%	-212%	-9%	29.9	42.3	-203%	-645%	46%	101.2	32.6	39%	15%	60%
Total Zinc	mg/L	0.0678	0.0141	78%	72%	84%	0.0109	84%	81%	86%	0.0121	81%	78%	84%	0.0142	79%	76%	82%	0.0391	0.0158	45%	5%	77%	0.0957	0.0149	77%	72%	83%
Fecal Coliform	CFU/100mL	10,721	6,641	-9%	-55%	31%	5,603	-46%	-161%	35%	5,626	-1%	-91%	58%	6,008	-14%	-89%	46%	929	430	31%	-2%	58%	4,162	1,591	-27%	-132%	48%
TPH – Diesel	mg/L	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
TPH – Motor Oil	mg/L	0.24	0.12	39%	27%	50%	0.12	41%	28%	53%	0.16	17%	-25%	47%	0.13	37%	26%	49%	0.45	NC	NC	NC	NC	0.67	0.14	64%	50%	77%

CFU/100mL = colony forming units per 100 milliliters.

LCL95 = lower 95 percent confidence limit on the mean (calculated with a bootstrap approach).

UCL95 = upper 95 percent confidence limit on the mean (calculated with a bootstrap approach).

NC = not calculable because more than 50 percent of the data were at or below the reporting limit.

TPH = total petroleum hydrocarbons.

TSS = total suspended solids.

Bold values in red indicate a significant increase between inlet and outlet; *italicized* values in blue indicate a significant decrease; values in black indicate no significant difference between inlet and the outlet (Wilcoxon Signed Rank test α = 0.05).

Table 15. Swale Performance Versus TAPE Effluent and Removal Performance Criteria.

		Goal	D1-60/40	D2-RBSM	D3-LSMV	D4-LSW	185-Coir	185-RBSMs
Basic Treatment	**Total Suspended Solids 20 to 100 mg/L**	Mean Effluent < 20 mg/L	10.7 (11)	17.6 (11)	16.9 (11)	17.9 (11)	51.9[a] (11)	48.5 (11)
	Total Suspended Solids 100 to 200 mg/L	Mean Removal ≥ 80%	NC	NC	NC	NC	NC	**87% (5)**
	Total Suspended Solids > 200 mg/L	Mean Removal > 80%	NC	NC	NC	NC	NC	**79% (2)**
Dissolved Metals Treatment	**Dissolved Copper**	Mean Removal ≥ 30%	**-24% (7)**	**-17% (7)**	**12%(7)**	**-20% (7)**	**54% (3)**	**-58% (6)**
	Dissolved Zinc	Mean Removal ≥ 60%	84% (18)	89% (18)	90% (17)	86% (18)	**90% (4)**	**79% (5)**
Phosphorus Treatment	**Total Phosphorus**	Mean Removal ≥ 50%	-108% (16)	-174% (16)	-11% (16)	-12% (16)	**28%[b] (7)**	-304% (14)

Red = does not meet TAPE effluent or removal criteria.

Blue = does meet TAPE effluent or removal criteria.

Bold values are mean values because sample count was less than 8. Non-bold values are bootstrapped 95 percent confidence intervals about the mean (LCL for percent removal, UCL for effluent TSS).

NC = not calculable. No influent values in these ranges.

Values in parentheses are the number of paired samples included in the analysis.

[a] After 10%WY flush the UCL95 mean effluent value was 10.9 mg/L, which meets the performance goal.

[b] After the 10%WY flush the mean percent removal was 71.2 percent (n=4) which meets the performance goal.

However, for influent concentrations between 100 and 200 mg/L, 185-RBSMs met the standard. 185-Coir did not meet the standard due to the large TSS flush during 10%WY. If those three samples are excluded the mean effluent drops to 10.9 mg/L and the system meets the TSS removal criterion. These results indicate that, after a brief flushing period, bioretention swales with varying BSMs will all meet the TSS removal criterion.

Nutrient Results

The Department of Ecology has restrictions on the use of bioretention within 1/4 of a mile from phosphorus sensitive waters (Ecology 2012) because numerous studies have indicated that bioretention can export phosphorus. The findings from this study corroborated the results from the literature for the majority of the swales tested. TP export was the norm through the duration of the study for all the systems containing compost (Figure 7). The Loamy Sand swales (D3-LSMV and D4-LSW) exhibited the best TP removal performance, removing 26 and 24 percent of the TP, respectively (Table 14). 185-Coir exhibited a large TP flush during the first 10%WY (associated with the large TSS flush), but then effluent concentration were lower than all the other swales combined (Figure 8), even approaching irreducible concentrations.

Generally, all the swales flushed TP by 20%WY and then stabilized (Figure 8). Once stabilized, it is clear how the systems' performance relates. The systems with compost perform similarly, with stabilized effluent concentrations around 0.4 mg/L, the Loamy Sands stabilize at around 0.2 mg/L, while the swale with coconut coir stabilizes at around 0.05 mg/L (Figure 8).

The TAPE criterion for TP performance is 50 percent TP removal for influent concentrations between 0.1 and 0.5 mg/L. None of the swales met this criterion. The one exception was that if the 10%WY flush is excluded at 185-Coir, the subsequent percent TP reduction is 71.2 percent, exceeding the criterion of 50 percent removal (Table 15). Thus, it would appear that after an initial flushing period the 185-Coir mix could be considered a phosphorus treatment BMP.

Each of the six monitored swales tended to export nitrate+nitrite through the duration of the study (Figure 9). Nitrate flushing dynamics were complex. By 50%WY it appeared as if the nitrate+nitrite had flushed out of the systems (Figure 10), but then effluent concentrations increased again. This was not due to an increase in influent concentrations (Figure 9), but instead perhaps to mineralization of nitrogen from the organic to dissolved form within the BSM during variable environmental conditions (e.g., temperature, pH, plant establishment, etc.). As can be seen in Figure 9 and Table 14, 185-Coir exported the least nitrate+nitrite (mean effluent = 0.145 mg/L) while 185-RBSMs exported the most (mean effluent = 0.865 mg/L). All four swales performed similarly at the MOC, exporting nitrate+nitrite through the duration of the study (Figure 9). It should be noted that Ecology does not have a removal requirement for nitrate+nitrite as they do for total phosphorus, but these results are still informative for the more widespread (beyond municipal applications) use of bioretention.

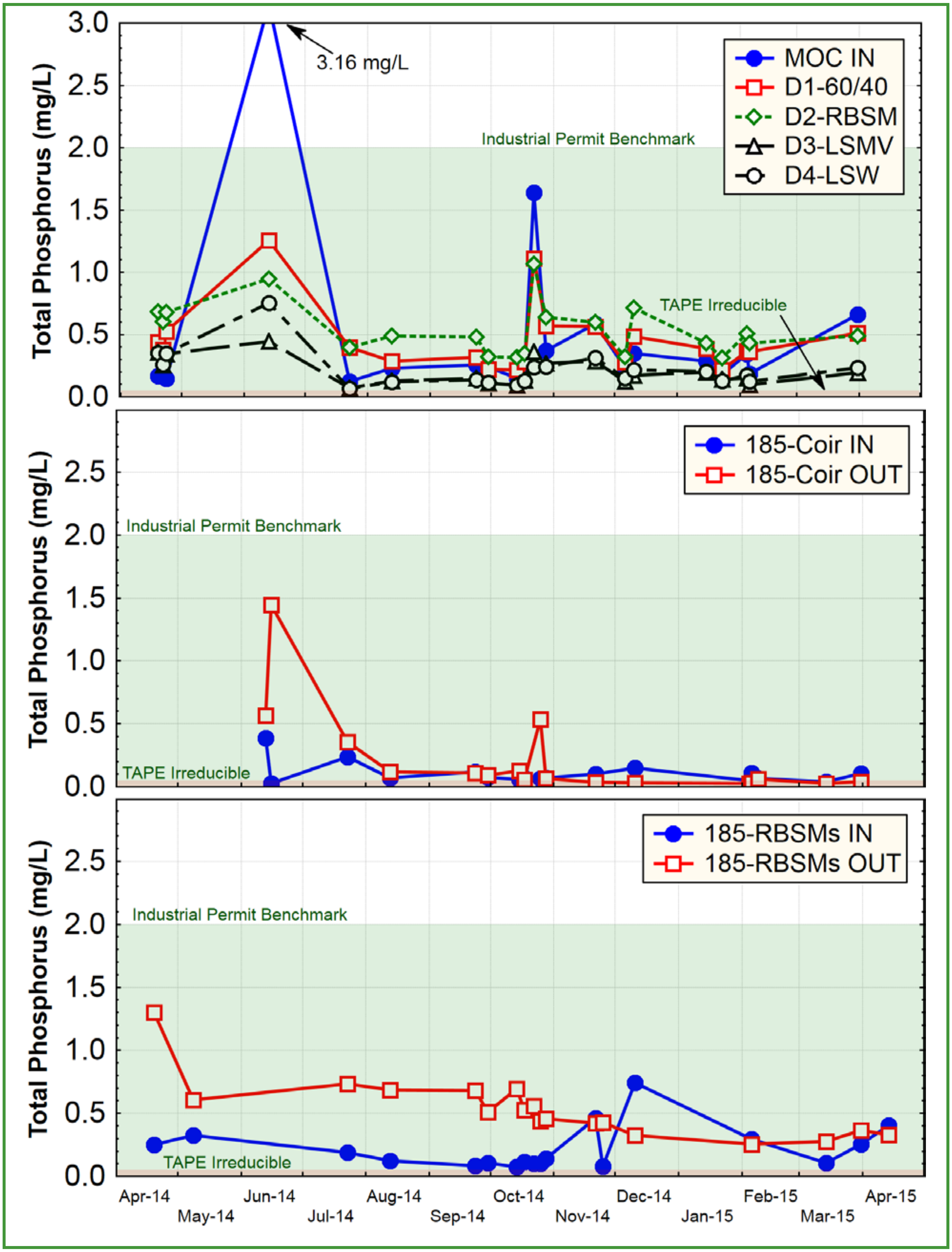
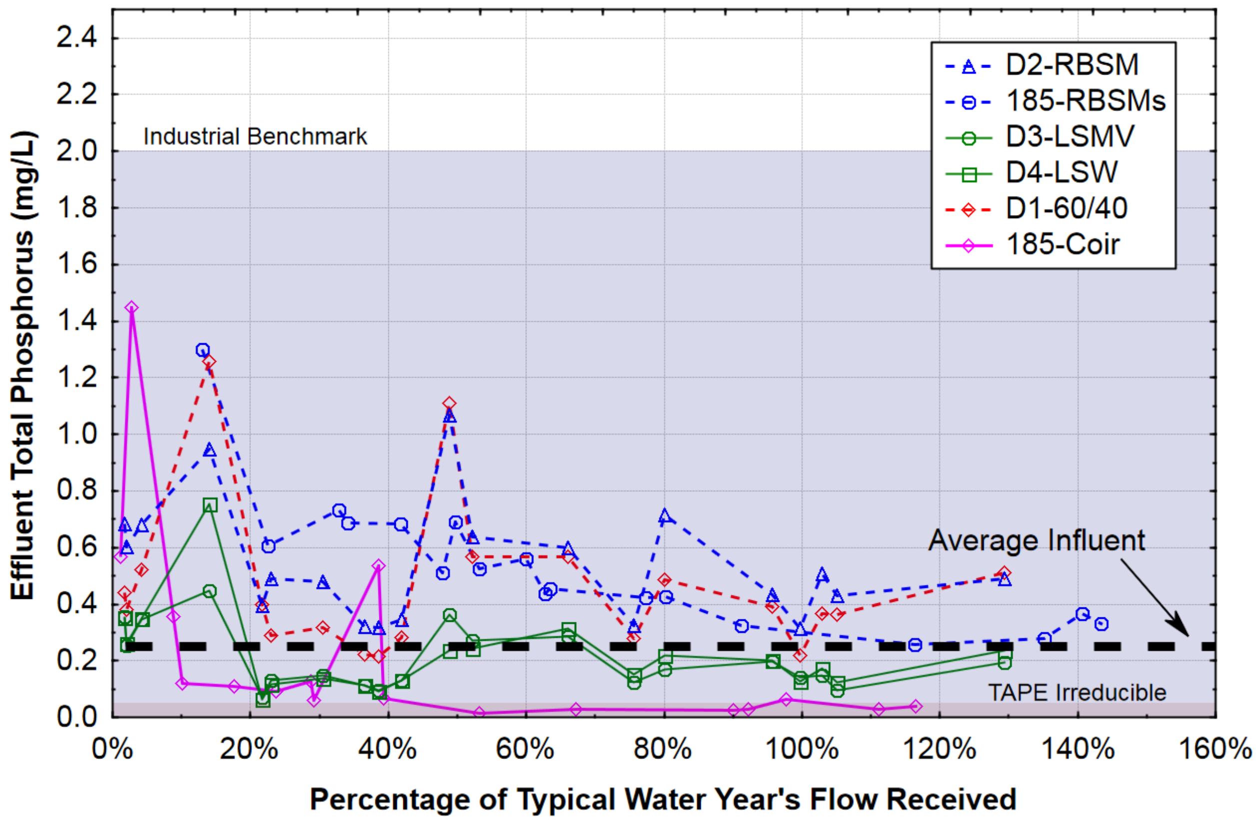


Figure 7. Total Phosphorus Influent and Effluent Pollutographs.



TAPE Irreducible: minimum allowable TAPE influent (0.1 mg/L) reduced by 50 percent. Equivalent to level achievable by phosphorus treatment BMP.

Average Influent: average concentration of all influent data in study.

Figure 8. Total Phosphorus Effluent Pollutographs as a Function of Rainfall Received.

The groundwater criterion for nitrate+nitrite of 10 mg/L is more than five times the highest effluent concentration; therefore, nitrate+nitrite groundwater contamination does not seem to be of concern in this study as it was in the 2013 185th Avenue Northeast study (Herrera 2014a). However, the industrial permit benchmark was exceeded on numerous occasions in the effluent of all the swales except 185-Coir (Figures 9 and 10). Further research on nitrate+nitrite removal in Sand and Coir mixes has been conducted by Kitsap County (Herrera 2015a); findings from that other study have corroborated these results, indicating that Sand and Coir is a far superior nitrate+nitrite filter than sand and compost.

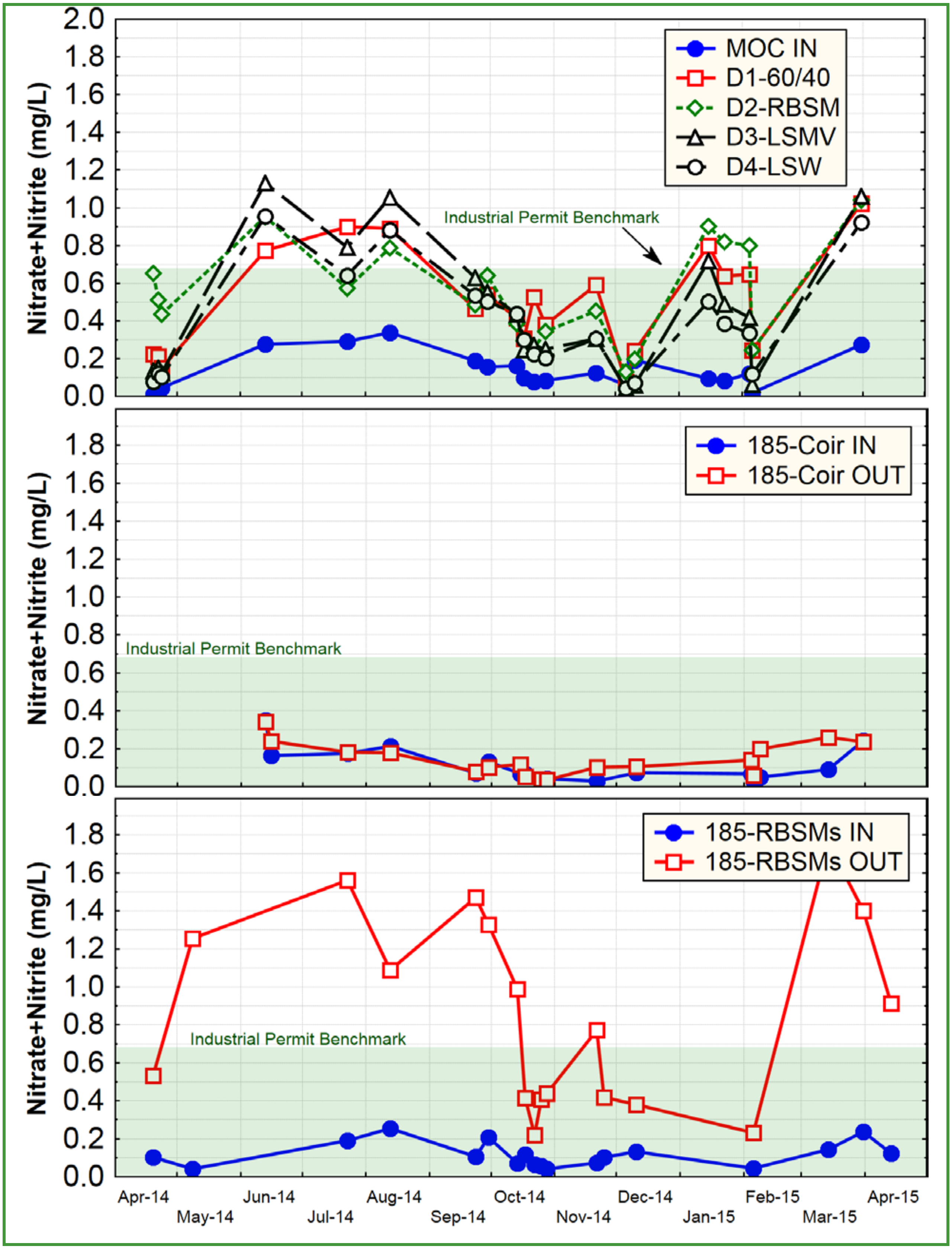
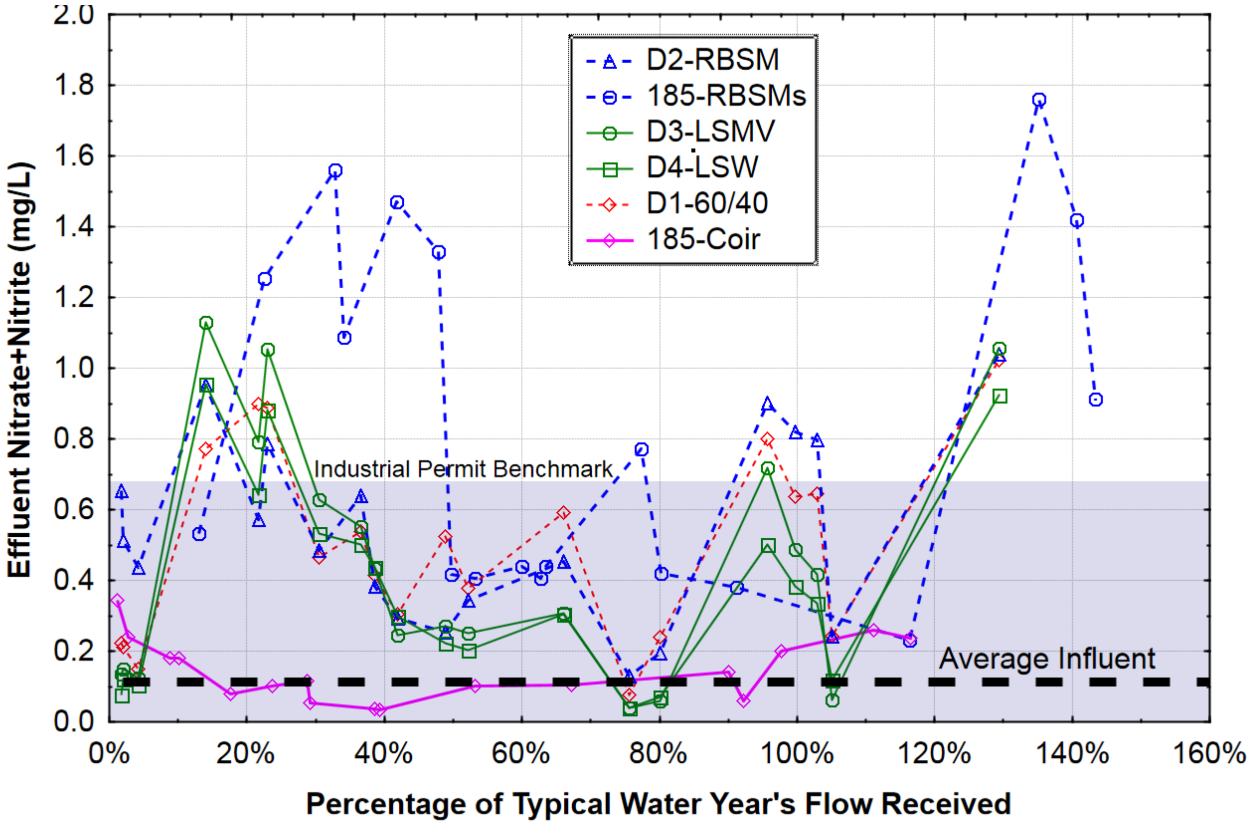


Figure 9. Nitrate+Nitrite Influent and Effluent Pollutographs.



Average Influent: average concentration of all influent data in study.

Figure 10. Nitrate+Nitrite Effluent Pollutographs as a Function of Rainfall Received.

Metals Results

Results from previous studies at the Washington State University LID Research Facility and the 2013 185th Avenue Northeast study (Herrera 2014a) indicate that during the first year after installation bioretention systems built with the Ecology 60/40 mix will export copper. To verify this, dissolved copper influent and effluent concentrations were monitored at each swale. 185-Coir flushed the most rapidly out of all the swales; within 10%WY, concentrations were near 2 ug/L, below the irreducible threshold as determined by TAPE (Figure 11). This swale also had the lowest overall dissolved copper effluent concentrations with a mean value of 2.8 ug/L (Table 14). Flushing at the remainder of the swales was not very pronounced and took about 1 water year until effluent concentration converged between 3 and 4 ug/L (Figure 11).

The systems with compost exhibited the highest dissolved copper effluent concentrations (Figure 12 and Table 14), while the Loamy Sand swales exported slightly less. The highest average effluent concentration was observed at D1-60/40 (8.6 ug/L). Adding biochar to target copper only marginally helped as the RBSM swales exported an average of 7.25 ug/L dissolved copper.

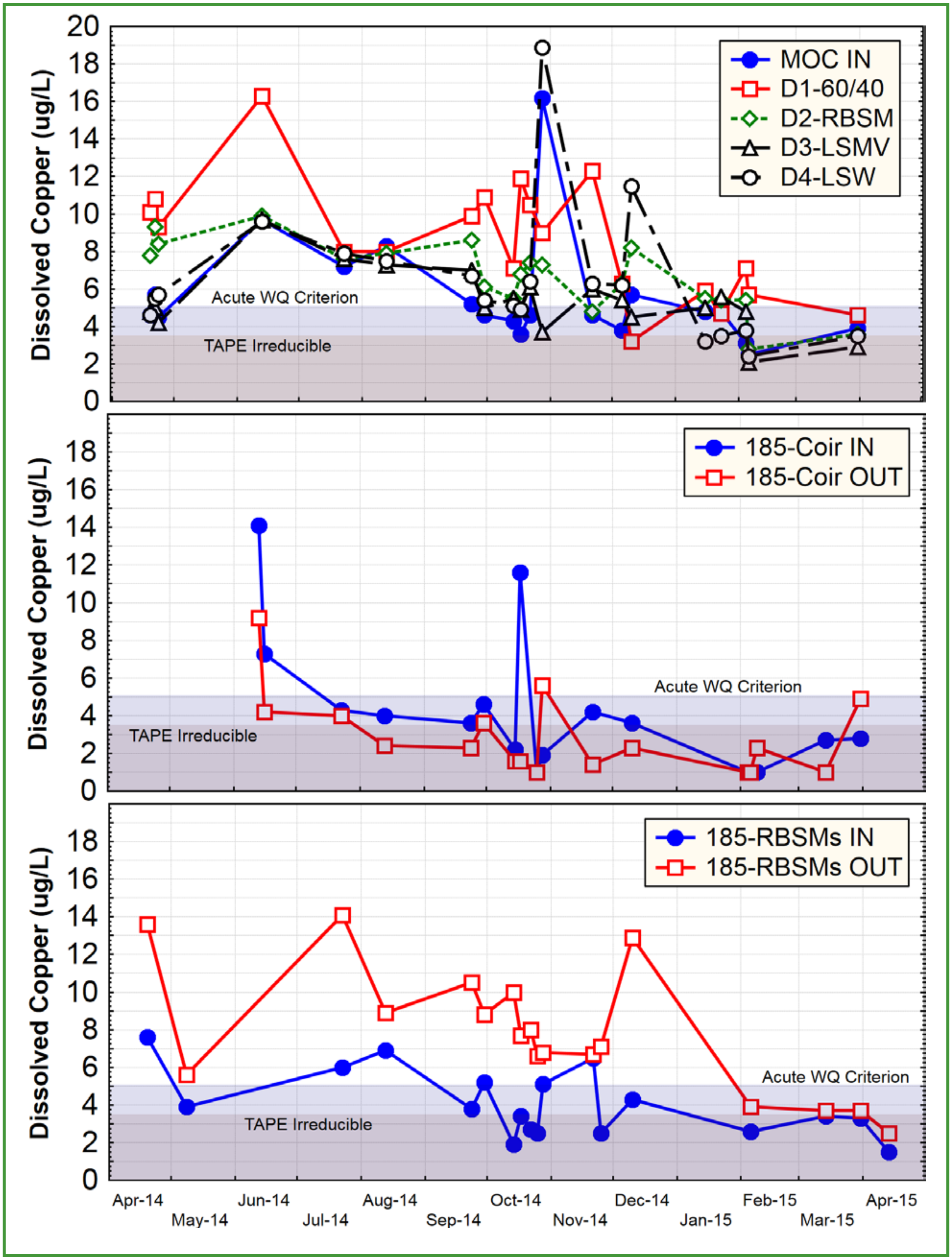
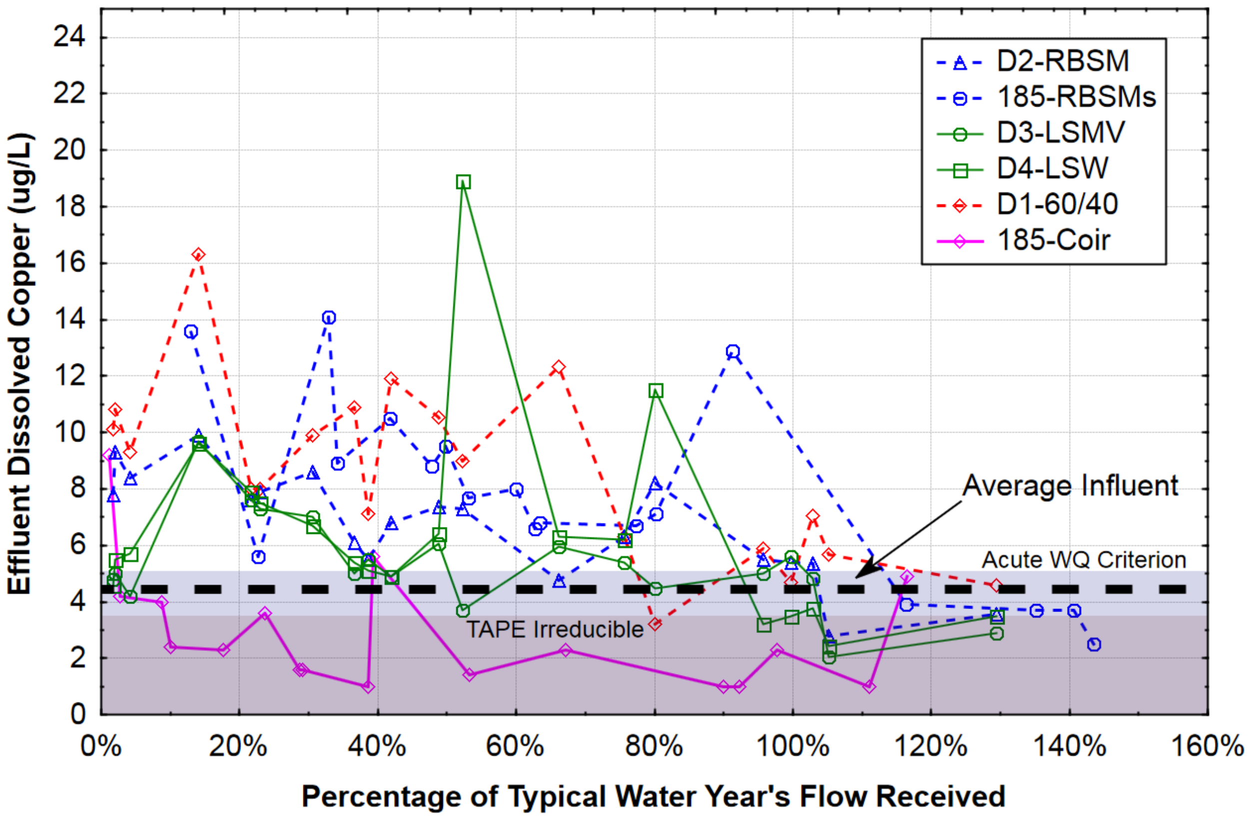


Figure 11. **Dissolved Copper Influent and Effluent Pollutographs.**



Notes: Acute WQ criterion based on average hardness of all effluents (27.8 $mgCaCO_3$/L).
TAPE Irreducible: minimum allowable TAPE influent (5 ug/L) reduced by 30 percent. Equivalent to level achievable by enhanced treatment BMP.
Average Influent: average concentration of all influent data in study.

Figure 12. Dissolved Copper Effluent Pollutographs as a Function of Rainfall Received.

As expected, all of the swales performed well when it came to the removal of dissolved zinc. Table 14 indicates that percent removals were 88, 91, 90, and 80 percent for D1-60/40, D2-RBSM, D4-LSW, and 185-RBSMs. Both D3-LSMV and 185-Coir had average effluent concentrations that were at or below the reporting limit, so percent removals could not be calculated (Table 14). However, if ½ the RL is assumed for the effluent the percent removals would be 88 and 66 percent for D3-LSMV and 185-Coir, respectively. Temporal figures for zinc were not generated because there was not a clear flushing pattern, and zinc removals were high for all of the swales.

Table 15 indicates that when the TAPE criteria are used to assess if the swales would be considered enhanced BMPs (those capable of treating metals), they all pass the zinc threshold of > 60 percent dissolved zinc removal. However, the dissolved copper removal criterion of > 30 percent was only achieved at the 185-Coir. It should be noted that in a TAPE assessment the minimum n-value must be 12 before the percent reduction goals can be assessed using a bootstrap assessment of confidence intervals about the mean. Table 15 indicates n-values and only calculates bootstrapped assessments of the mean when the n-value was greater than 7. For a true TAPE assessment to be conducted, the number of qualifying samples would have to be increased. Regardless, the data trend indicates that the swale closest to meeting the TAPE criteria for Basic, Enhanced, and Phosphorus treatment is 185-Coir.

There are no groundwater criteria for copper or zinc. The acute freshwater water quality dissolved copper criterion was exceeded in the effluent of all the swales until 100%WY (Figure 12). The one exception was that the 185-Coir swale dropped below the acute water quality criterion after the first storm and remained below this threshold for the remainder of the study (except for the October 28, 2014 event) (Figure 12). Research by Linbo et al. (2009) has indicated the copper acute water quality criterion is not an accurate assessment of potential toxicity for fish because numerous other constituents bind with copper and inhibit uptake by organisms. To address this, the BLM (HydroQual 2007) was used to provide more rigorous assessment of copper toxicity in this study. The BLM incorporates metal speciation and the protective effects of competing cations into a more accurate assessment of potential toxicity from bioavailable metals. The inputs to the model are as follows:

- Temperature
- pH
- Dissolved Organic carbon
- Major Cations (Ca, Mg, Na, K)
- Major anions (SO_4 and Cl)
- Alkalinity
- Sulfide

The results from the model runs are presented in Table 16 along with the average DOC:Cu ratio. This ratio has been used as a more simple assessment of copper bioavailability in comparison to the BLM. The BLM was run on each collected sample. 185-Coir-IN had the highest percentage of influent samples that were determined to be toxic (59 percent). Of the effluent stations, D1-60/40 had the highest percentage of samples that were determined to be toxic (40 percent), which was surprising considering that the influent (MOC-IN) had no toxic samples (Table 16). The BLM also returned a value for Toxicity Units (TU): if TU is above 1.0, the sample is considered toxic; if it is below 1.0, it is considered non-toxic. The average TU values and average percent TU reduction for each swale are presented in Table 16. As is apparent, 185-Coir and 185-RBSMs performed the best in terms of TU reduction. MOC-60/40 increased TU by 33 percent. The lowest overall TU values at the effluent stations were 0.5 at 185-RBSMs, D2-RBSM, and D3-LSMV.

An alternative approach to assessing copper bioavailability is by using a DOC:Cu ratio. Table 16 indicates that, on average, all the stations had DOC:Cu ratios which exceeded the 0.1 bioavailability threshold. The highest ratio was at MOC-IN followed by 185-Coir-OUT, the lowest ratios (still protective) were measured at 185-Coir-IN and 185-RBSMs-IN. Taken together these results indicate that the D1-60/40 was one of the worst performing swales when toxicity was assessed with the BLM. The swales with biochar added (185-RBSMs and D2-RBSM) performed the best. Given that the 185-Coir swale had the most toxic influent of all the swales (Table 16), it also performed very well.

Table 16. Results from the Biotic Ligand Model Copper Toxicity Testing.					
Name	Station	% Samples Toxic	Average Acute TU	Average % TU Reduction	Average DOC:Cu[a]
185-Coir	IN	59%	**1.5**		0.87
185-Coir	OUT	29%	0.9	40	1.24
185-RBSMs	IN	50%	**1.1**		0.80
185-RBSMs	OUT	11%	0.5	54	1.07
MOC	IN	0%	0.6		1.47
D1-60/40	OUT	40%	0.8	-33	1.04
D2-RBSM	OUT	5%	0.5	17	1.20
D3-LSMV	OUT	5%	0.5	17	1.23
D4-LSW	OUT	0%	0.7	13	1.27

TU = Toxic Units. If value exceed 1 the water is considered toxic per the BLM and the values are set **bold**.

[a] DOC:Cu ratio of greater than 0.1 is considered protective for fish per Jenifer McIntyre (McIntyre et al. 2008).

Results for Other Parameters

Hardness, alkalinity, and chloride were increased between influent and effluent at each swale (Table 14; Appendix J). There is no groundwater standard for hardness. The groundwater standard for chloride is 250 mg/L. The highest chloride value observed in the study was measured at the D1-60/40 outlet, but it was well below the groundwater standard at only 16 mg/L (Appendix F; Appendix J.

Dissolved organic carbon (DOC) was elevated to around 7 mg/L on average at all the effluent stations except at 185-Coir where the mean DOC effluent concentration was 3.24 mg/L (Table 14; Appendix J).

Total petroleum hydrocarbons – oil range (TPH-Oil) was reduced by all of the swales (Table 14; Appendix J). 185-Coir was the most effective at TPH removal with 12 of the 13 effluent samples at or below the TPH-Oil reporting limit.

Fecal coliform bacteria were also reduced at nearly every swale. For example, the MOC-IN influent concentration averaged 10,721 CFU/100mL while the effluent concentrations averaged 6641, 5603, 5626, and 6008 CFU/100mL for D1-60/40, D2-RBSM, D3-LSMV, and D4-LSW, respectively (Table 14; Appendix J). However, due to a high degree of variability in the data, the percent removal values did not reflect this reduction.

DISCUSSION

One objective of this study was to determine if the export observed in the 2013 185th Avenue Northeast study was an anomaly or typical of bioretention built to the Ecology default BSM specification. The one swale built to this specification, D1-60/40, exported more dissolved copper than any of the other systems (mean effluent = 8.6 mg/L, mean removal = -74 percent). In addition, high levels of nutrients were also exported from D1-60/40(e.g., mean effluent TP = 0.539 mg/L, mean effluent nitrate+nitrite = 0.501 mg/L). This level of export was only to be exceeded at 185-RBSMs and D2-RBSM (the apparent effect of reducing compost and adding shredded bark and biochar to the mix was to trap more metals, but release more nutrients). This study reinforced the finding that nutrient and copper export from BSMs containing compost is an issue of concern. The very high initial flushing levels of nutrients (e.g., TP ~ 5 mg/L, nitrate+nitrite ~ 100 mg/L) observed in the 2013 185th Avenue Northeast study were not replicated in this study; however, there was export nevertheless.

Based on the results of this study, the 2013 185th Avenue Northeast study (Herrera 2014a), the research at WSU (WSU 2014), and the unpublished results from numerous other studies in the region, it can safely be said that the previous assumptions regarding metals and nutrient retention in bioretention, as summarized in two recent local literature reviews (Geosyntec 2013; Taylor Aquatic Science and Policy and Cardno TEC 2013), is not accurate for the 60/40 default mix installed to Ecology specifications. Table 6 reports results from a literature review conducted for the City of Seattle (Geosyntec 2013) with the goal of determining a range of applicable pollutant removal rates and achievable effluent concentrations for bioretention swales that will be constructed within the City. In Table 6, expected dissolved copper, nitrate+nitrite, and total phosphorus reductions were 61, 8, and 57 percent, respectively. In this study, reductions of -74, -546, and -52 percent were observed, respectively. Due to discrepancies of this magnitude, it is advised to use the knowledge gained from local studies over those garnered from national literature reviews, which are apparently not representative of performance of bioretention systems built to Washington State Department of Ecology default BSM specifications.

Much of this document has focused on the dynamics of pollutant flushing from bioretention systems. However, it is also important to note the pollutants do not flush from these systems and are actually retained. Specifically, all of the six swales performed well for total and dissolved zinc removal as well as the removal of TPH-Oil (Table 14; Appendix J). The systems also generally did well at the removal of fecal coliform bacteria; however, due to high variability at the inlet and outlet, the percent removals suffered (Table 14). Finally, after an initial flush, the majority of the swales met the TAPE criteria for TSS removal (Table 15).

McIntyre et al. (2008) indicate that elevated dissolved organic carbon levels in water will help ameliorate copper neurotoxicity. Because bioretention systems with compost tend to export high levels of DOC (see Table 14; Appendix J), it may be assumed that the high dissolved copper export observed in this study may not be an issue. In lieu of conducting toxicity tests that were outside the scope of this study, the BLM was used to obtain a better understanding of effluent toxicity from the various swales. This analysis indicated that of all the swales, D1-60/40 had the highest percentage of samples that were determined to be toxic. These results would indicate that, despite the high DOC export from the 60/40 swale, copper toxicity may still be an issue. Follow up toxicity studies of effluent from the six swales in this study would need to be conducted to address this question more thoroughly.

CONCLUSIONS

This study was conducted as a follow up to the 2013 185th Avenue Northeast bioretention study (Herrera 2014a) which indicated that significant pollutant export was observed from a BSM consisting of the Ecology specified 60 percent sand, 40 percent compost mix. The objective of the study was to try and replicate the export observed in the 2013 study, to identify alternative BSMs that do not exhibit the same pollutant export patterns, to determine if groundwater quality would be threatened given measured pollutant effluent concentrations from the BSMs, and to compare the treatment performance of the BSMs to performance criteria from TAPE.

Infiltration testing indicated that D1-60/40 infiltrated at a rate of 11.8 inches per hour, which is typical of mixes which meet the Ecology specification. The 60/40 mix also met the majority of the specification criteria for the aggregate and compost components, so it can be assumed that the performance of the D1-60/40 swale was typical of most bioretention cells built to the Ecology manual specification. Infiltration testing of the Loamy Sand indicated that the hydraulic conductivity of these BSMs was low and variable (D3-LSMV = 1.3 in/hr, D4-LSW = 5.1 in/hr). It appeared as if adding biochar and shredded bark to the 60/40 mix and reducing the compost to create the RBSM mix resulted in a reduction of infiltration rates. The measured infiltration rate at D2-RBSM was 6.0 in/hr, half that of the 60/40 mix. Finally, the highest observed infiltration rate was measured at 185-Coir. The 61 in/hr rate was five times higher than the 60/40 mix. Despite these very high infiltration rates, the 185-Coir swale had the best runoff treatment performance.

In general, the 185-Coir swale flushed its pollutants more quickly (by 20%WY) than the other swales and stabilized at effluent concentrations which were well below those of the other swales. Nutrient export was greatest from the swales containing compost, with the loamy-sand swales exporting equivalent nitrate+nitrite, but less total phosphorus. Again, after an initial flush, the 185-Coir swale effluent had the lowest nutrient concentrations of all the swales. Copper export was greatest from the swales containing compost. The Loamy Sand swales exported copper at a slightly lower level, while the 185-Coir swale reduced copper concentrations (though not significantly) despite the fact that concentrations were very low at the influent (mean = 4.1 ug/L). All six swales performed very well at reducing concentrations of total and dissolved zinc, TPH-Oil, and fecal coliform.

When the water quality results measured at each swale were compared to TAPE performance criteria, it was apparent that after a brief flushing period of 10%WY all of the swales would meet the basic treatment criteria of ≥ 80 percent TSS reduction. Similarly, after 10%WY the 185-Coir swale was able to meet the total phosphorus criteria of ≥ 50 percent reduction. However, none of the other swales met this criteria even after the flushing period was complete. Among the swales there were few qualifying samples available for comparison to the TAPE performance criteria for metals. However, the trend indicated that 185-Coir was the only swale which would meet the enhanced treatment goals for zinc and copper (≥ 60 and ≥ 30 percent, respectively), this despite having the highest infiltration rate of all the swales.

SPLP extractions indicated that the compost fraction was the largest contributor to copper and nutrient export. The biochar also seemed to be a source of nutrients. These SPLP results were reflected in the field data as the systems which contained compost exported the highest levels of nutrients and copper among the six swales.

One of the primary objectives of this study was to determine if export from the study system would result in exceedances of groundwater quality criteria. No groundwater quality criteria were exceeded in any of the effluent samples. However, surface water criteria were frequently exceeded at all the swales, except 185-Coir, due to elevated export of dissolved copper.

Based on the results of this study, the 2013 185th Avenue Northeast study (Herrera 2014a), and the results from WSU (WSU 2014), it is apparent that the Ecology mix of 60 percent sand and 40 percent compost is an inferior blend for pollutant treatment. It is recommended that future research focus on blends which do not include compost, as not only does it export pollutants for an extended flushing period, but does not seem to retain pollutants as well as alternative blends, particularly blends containing sand and coconut coir.

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APPENDIX A

Design Drawings

APPENDIX B

Hydrologic Data Quality Assurance Memorandum

APPENDIX C

Water Quality Data Quality Assurance Memorandum

APPENDIX D

Individual Storm Reports

APPENDIX E

Standardized Field Forms

APPENDIX F

Water Quality and Flow Statistic Database

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APPENDIX G

Groundwater Quality Criteria

APPENDIX H

Laboratory Reports

APPENDIX I

Infiltration Testing Memorandum

APPENDIX J

Water Quality Data Boxplots