Swale on Yale: Innovative Regional Green Stormwater Infrastructure in an Urban Neighborhood

Presented at StormCon, Bellevue, WA August 27 – 31, 2017

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Introduction

From October 2015 through July 2016, Seattle Public Utilities (SPU) conducted a performance evaluation of Swale 2 of the Capitol Hill Water Quality Project (CHWQP). The project is a unique, regional-scale stormwater treatment facility consisting of four biofiltration swales, a pre-treatment device, and related piping located in urban neighborhood of Seattle, Washington. Since CHWQP is a voluntary, retrofit project, it was not required to treat a set amount of impervious surface. The design approach optimized cost-effectiveness by maximizing utilization of site physical constraints relative to reduction in stormwater pollutant loading to Lake Union. The final design resulted in estimated pollutant loads to the project that are approximately four (need to double check) times greater compared to a code-based biofiltration facility.

This performance evaluation was performed to determine the as-built stormwater treatment performance of one (referred to as “Swale 2” or “Swale”) of the four project swales (two swales are online, and two are currently under construction).

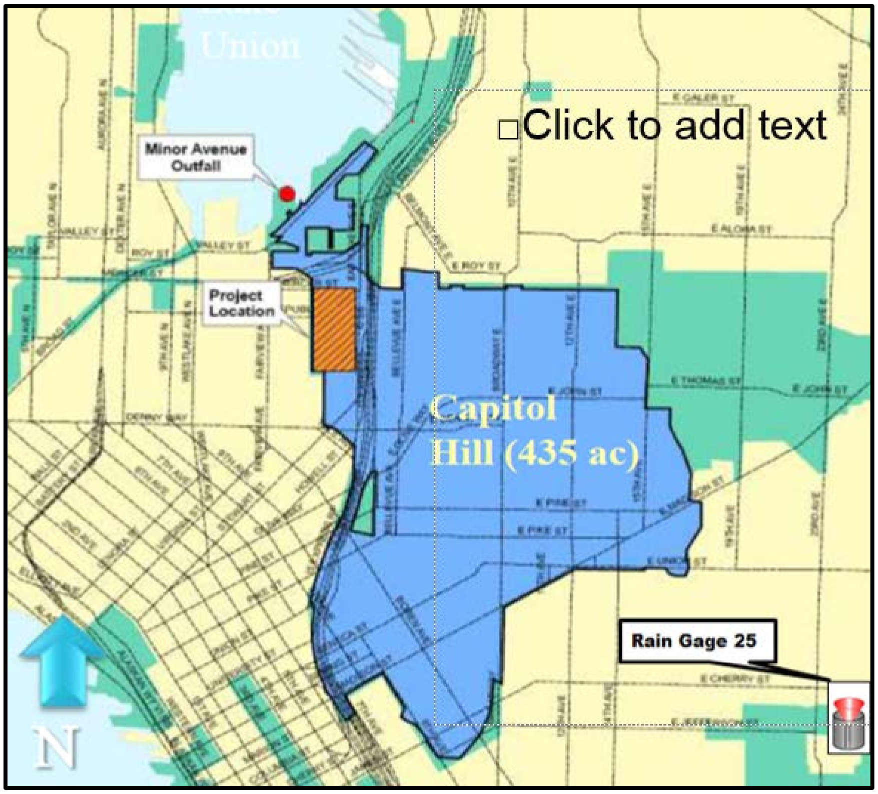
This report summarizes findings from the first year of monitoring, this evaluation is based on analyses of water quality, rainfall, and flow data. A total of nine stormwater events were sampled at Swale 2 between October 2015 and July 2016 with water quality samples collected at the swale’s inlet, underdrain outlet, and surface flow outlet.

The monitoring work was performed in accordance with the “Capitol Hill Water Quality Project Swale 2 Post-Construction Monitoring Quality Assurance Project Plan (QAPP),” dated June 24, 2015.

Design Approach

The CHWQP was designed to treat a portion of the stormwater flows from the 435-acre partially-separated Minor Avenue sub-basin of Capitol Hill which drains to South Lake Union via the Minor Avenue Storm Outfall. Of the total 435-acre basin, it is estimated that 74 percent drains to a dedicated public storm drain and the remaining 26 percent drains to a combined sewer system. Figure 1 below shows the basin area draining to the project.

Figure 1. CHWQP drainage area



Since CHWQP is a voluntary, retrofit project, it is not required to treat a set amount of impervious surface. The design approach optimized cost-effectiveness by maximizing utilization of site physical constraints relative to reduction in pollutant loading to Lake Union. Vulcan provided technical and professional services and funded approximately $1.3 million of the design and construction costs, and provided an easement to the city along the front of their development. The easement, along with a reduction in the adjacent City roadway width, provided sufficient space to construct the project swales and still have adequate pedestrian walkways.

The project consists of four wet biofiltration swales with an underdrain system that provides some bioretention operating in an off-line capacity.

The design team considered two key parameters to optimize the pollutant load reduction benefits:

1. **Water Quality Design Flow Rate** – rather than using the code-required design flow rate that estimates treatment for 91 percent of the average annual runoff volume, the team optimized the design flow rate to maximize the swale treatment capacity. This reduced the off-line flow rate to less than half required by code with a resulting reduction in the volume treated by only a quarter (the final design is estimated to treated 73 percent of the code-based volume treated).
2. **Swale Removal Performance** – rather than sizing the swales using empirical results with a code required k factor, the team optimized the swale design parameters using Ideal Settling Basin Theory (ISBT), which is a simple unit process-based model for predicting swale performance based on hydraulic residence time and particle size distribution. The

> ISBT predicts a removal efficiency for the volume treated at a specified depth; provides for sensitivity analysis for parameters such as influent concentration, particle size, velocity, age, vegetation cover, and grass height; and a means to estimate the volume that may be infiltrated.

Table 1 summarizes the project design assumptions and performance compared to assumptions and performance for equivalent swales designed using code requirements. To treat the complete project basin to code performance standards, 28 blocks of swales would be required. By following a cost-effectiveness approach, the project was designed to remove approximately 57 percent of the code target load in four blocks of swales. The four blocks of swales were designed to reduce the pollutant load almost *four times*[1] more compared to a code-based approach.

Table 1. Project Design Approach Compared to Code-Equivalent Targets

	Project Design	**Code Target**	**Percent of Code Target**
Average annual volume treated (acre-feet)	470	640	73%
Off-line water quality flow (cfs)	7.2	15	48%
Swale design flow (cfs)	7.2	48.6	15%
Removal Efficiency (%)	62	80	78%
Load removed (kg TSS/year)[2]	22,500	39,400	57%
Load removed by biofiltration	16,900	39,400	---
Load removed by bioretention	5,600	0	---
Swale length (ft)	1,041	7,030	15%
Swale blocks	4	28	14%
SPU unit cost (PV $/kg TSS removed per year)	~20 to 28	~62 to 64	---

Project Description

The CHWQP operates by diverting a portion of flows (modeling estimates are approximately 60 percent of total basin flow) from an existing 72-in Public Storm Drain (PSD) to an offline facility consisting of pretreatment by a Vortechs 16000 swirl concentrator (Vortechs) followed by treatment in one of four biofiltration swales (swales) (Figure 2). The project was designed to be highly flexible, with weirs controlling the diversion rate to the pretreatment structure and flow splitters controlling flows to each of the four independent swales.

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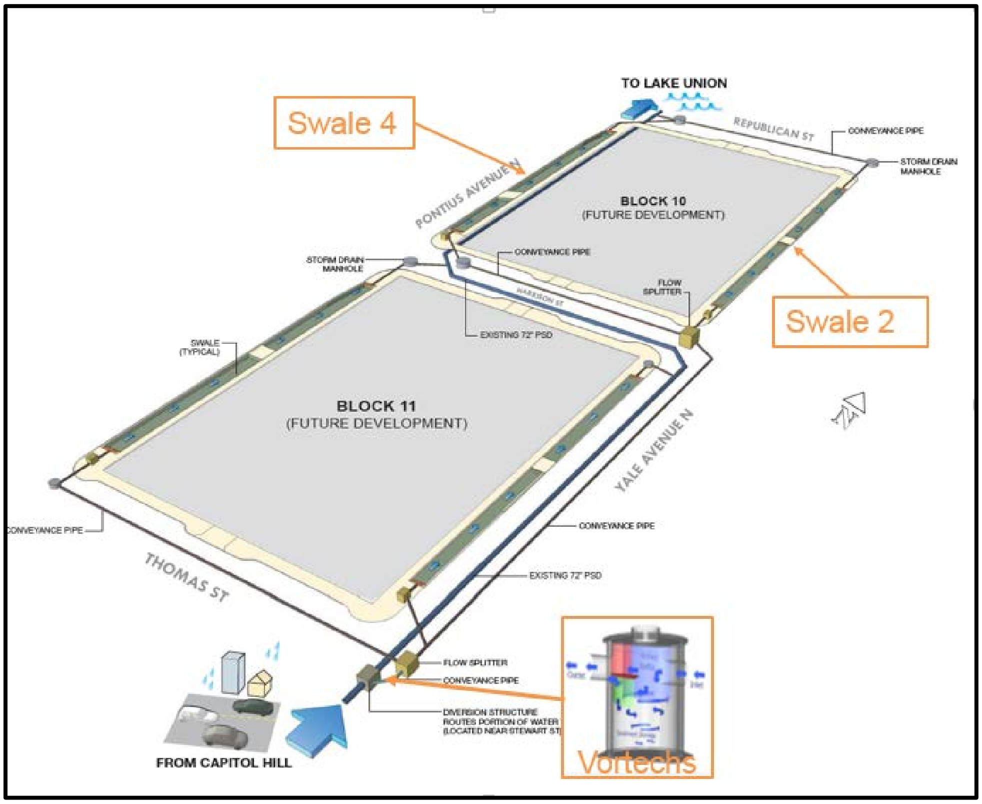
[1] The code approach is estimated remove ~5 to 6 kg TSS/linear foot of swale. The cost-effective approach is estimated to remove~20 to 23 kg TSS/linear foot of swale.

[2] Assumed runoff concentration of 62 mg/L TSS based on land-use.

Figure 2. CHWQP schematic view



The Vortechs was installed during the summer 2012, and Swale 2 (on Yale Street) and Swale 4 (on Pontius Street) went online in October 2015. The final two project swales (Swales 1 and 3) are not yet constructed but planned to be completed by summer 2018. Swale 2 was preselected for monitoring and was constructed with numerous underground vaults and related piping to facilitate monitoring.

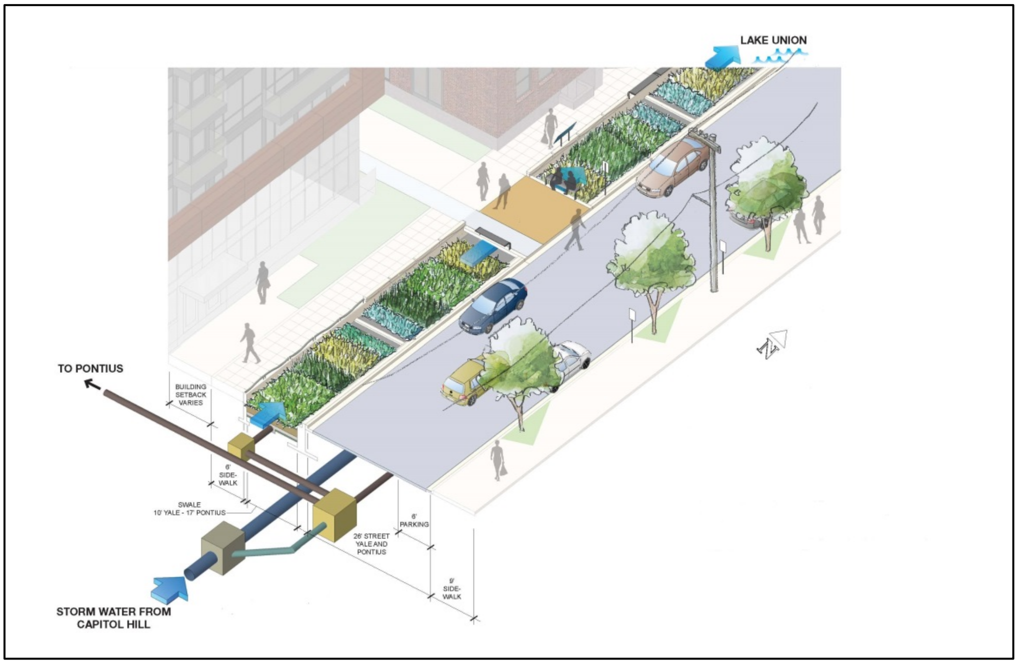
Swale 2 Description

Swale 2 is a one-block long swale located on the west side of Yale Avenue N between Harrison and Republican Streets (Figure 3). Swale 2 is located adjacent to properties with the street addresses from 403 to 423 Yale Avenue North.

Figure 3. Photograph of Swale 2 (looking north).

A flow splitter located just upstream from the Swale 2 diverts the first stormwater flow in the storm drain up to the design flow rate 1.26 cubic feet second (cfs) into Swale 2. Flows exceeding 1.26 cfs are diverted to other project swales or back into the existing 72-inch PSD. Figure 4 presents the Swale 2 pipe view.

Figure 4. Swale 2 Pipe View



At the inlet end of Swale 2, hydraulic head forces inlet flow in a 12-inch diameter ductile iron pipe (DIP) to upwell out of a trench drain across the width of the vertically-walled swale and begin a laminar path down the swale. Approximately every 50 feet down the length of the swale, a broad-crested concrete weir re-disperses the flow across the width of the swale (referred to as “flow-spreaders”). Densely planted (10-inch centered) species of Carex and Juncus within the swale provides contact surfaces and roughness to lower flow velocity and allowing suspended solids to settle. The swale is lined with a clay/geotextile liner to prevent infiltration and a 6-inch diameter, slotted, polyvinyl chloride (PVC) underdrain is located in gravel bedding above the liner to convey water that passes through the bioretention soil media back to the storm drain. The bioretention soil media is, per the City of Seattle 2011 standard specification, composed of approximately 60 percent aggregate and 40 percent compost and is produced by Cedar Grove. Swale 2 design parameters are presented in Table 2.

Table 2. Swale 2 design parameters.

Slope	Total Length	Water Quality Length[1]	Bottom Width	Design Flow Depth	Design Flow Rate	Residence Time
0.011 feet/foot	293 feet	264 feet	10.5 feet	4.0 inches	1.26 cubic feet/second	12.21 minutes

1 – Water quality length is defined as the length of the swale minus weirs and pedestrian crossings.

At the downstream end of Swale 2, a trench drain collects the treated surface flow and conveys it via a 12-inch DIP outlet pipe into a concrete vault. The 6-inch diameter underdrain outlet also flows directly into this same vault. These two flows are comingled in this vault before flowing back to the existing 72-inch storm drain.

Monitoring Approach

The monitoring approach is outlined in the project QAPP. Flow data from each station was stored on a 5-minute time step using a combination of velocity meters and weirs with pressure transducers. Automated samplers were programmed to collect flow-weighted composite samples from each of the three monitoring stations. Telemetry was used to control the equipment and download the data on a 5-minute interval. Samples were analyzed for the parameters listed in Table 3.

Table 3. Stormwater Analytes, Methods, and Reporting Limits (RL)

Analyte Group	Analyte	RL	Units	Lab Method
Conventionals	Hardness	1.0	mg/L CaCO3	*SM2540-D*
	Dissolved Organic Carbon	1.0	mg/L	SM5310-B
	Total Suspended Solids (TSS)	1.0	mg/L	SM2540-D
Metals	Copper - Dissolved	0.5	ug/L	EPA200.8
	Copper - Total	5.0	ug/L	EPA200.8
	Zinc - Dissolved	4.0	ug/L	EPA200.8
	Zinc - Total	4.0	ug/L	EPA200.8
	Lead – Total	1.0	ug/L	EPA200.8
	Lead – Dissolved	0.01	ug/L	EPA200.8
Nutrients	Ortho-Phosphate	0.004	mg-P/L	SM4500-PE
	Phosphorus, Total	0.016	mg-P/L	SM4500-P
	Nitrate-Nitrite (N03-N02)	0.01	mg-P/L	EPA 353.2
Petroleum Hydrocarbons	Semivolatiles (NWTPH-Dx)	0.01	mg/L	NWTPH-Dx
Bacteria	Fecal Coliform	1	cfu/100mL	SM9222-D

Results

This section presents the results from the hydrologic and water quality monitoring of Swale 2 at CHWQP. Monitoring was conducted at 3 monitoring stations, the inlet to Swale 2, the surface swale outlet, and the underdrain outlet. The first section below presents the hydrologic results, followed by the water quality results.

Hydrologic Monitoring Results

Flow rate was monitored at each of the three stations from October 2016 to July 2017. During that period 108 individual storm events were quantified based on the storm criteria identified in the project QAPP. The design inflow rate of Swale 2 was 1.26 cubic feet per second (cfs) and the actual measured average inflow rate was 0.77 cfs. Table 4 presents the average Swale 2 measured flow rates at the three monitoring locations.

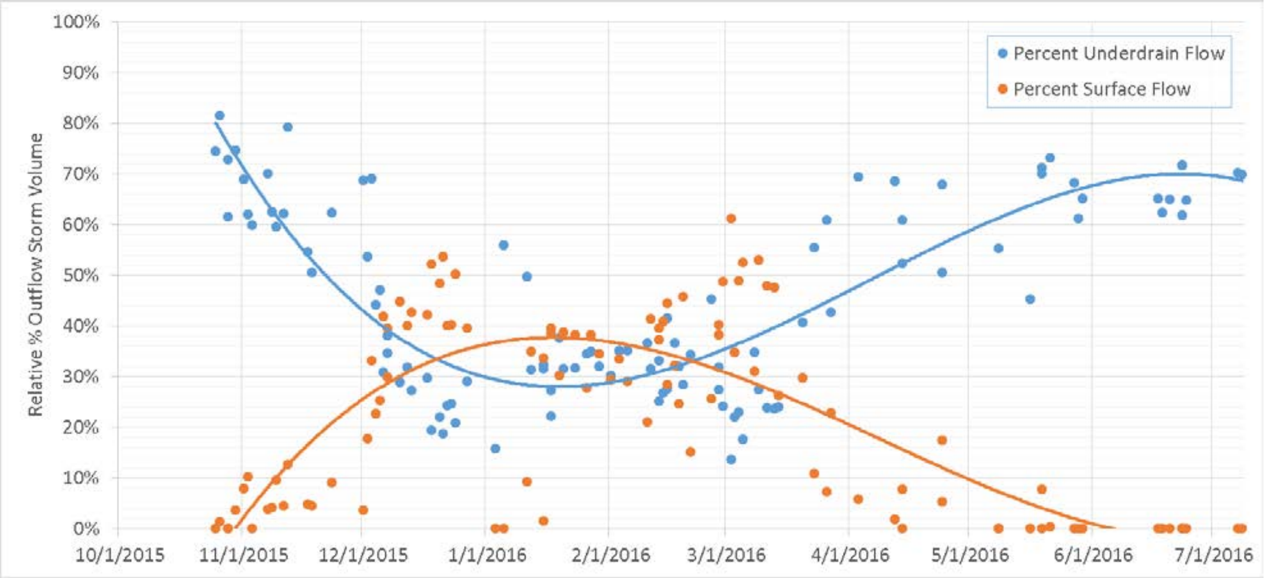
Table 4. Swale 2 Hydrologic Results

Monitoring Location	Average Peak Flow Rate (cfs)	Average Peak Flow Rate (gpm)	Percent Volume Relative to Inflow [1]
Inflow	**0.71**	**318**	**100**
Surface Outflow	0.25	110	28
Underdrain Outflow	0.27	121	45

[1] a 28 percent volume loss was identified during monitoring. Loss occurred through evapotranspiration, leaking through the clay liner, and/or instrument error.

The average peak storm flow was measured at approximately 39 percent less than design rate which is attributed to the flow splitter upstream from the two online swales (the monitored Swale 2, and the unmonitored Swale 4) being configured incorrectly to send a higher portion of the flow to Swale 4 and thereby reducing the flow sent to Swale 2. This lower Swale 2 inflow rate resulted in more flow infiltrating through the bioretention media and exiting through the underdrain versus staying on the surface down the length of the swale. During many fall and spring storms when the bioretention media was drier and the storm event runoff quantities were lower, no flow made it all the way down the surface of the swale without infiltrating into the media. This seasonal pattern in surface flow versus underdrain flow can be clearly seen in Figure 5. As is apparent, during the warmer drier months the majority of the flow exits through the underdrain, while during the coldest wettest months of the winter the outflow from the underdrain and surface drain are about equal.

Figure 5. Relative Percent of Underdrain and Surface Flow over Time at CH2.



There was no observable trend in surface flow increasing relative to underdrain flow over time, in other words, during the 8 month monitoring period there was no sign that the infiltration rates were decreasing as sediment was deposited on the surface of the swale. Based on this, and the fact that and the water quality results below indicate good pollutant removal performance for most parameters, it is recommended that the flow to Swale 2 be increased.

During the monitoring period rainfall totaled 43.4 inches. This resulted in a total Swale 2 inflow volume of 9.4 million gallons. Of the inflow volume 2.6 million gallons was treated by the swale surface and 4.1 million gallons were treated by passing through the media, the remaining 2.7 million gallons (or 28 percent of the total inflow volume) was lost to evapotranspiration, or leaked through the clay liner. In addition instrument error could account for a portion of the lost volume.

Water Quality Monitoring Results

The water quality treatment performance of Swale 2 was evaluated using two methods. For evaluating the overall performance of Swale 2, the inlet mass load was compared to the sum of the two outlet mass loads. For evaluating the relative performance of each outlet pathway, the inlet concentration was compared to each of the two outlet concentrations. In addition a flow-weighted average effluent concentration was calculated for the outlets to derive an estimate of average effluent concentration for comparison with the inlet.

Table 5 presents median concentrations for each of the 13 water quality parameters measured in the study. As is apparent, the surface pathway had lower effluent concentration that the underdrain pathway for all of the measured nutrients: total phosphorus, ortho-phosphate, and nitrate+nitrite. This is likely due to the fact that the compost in the media was adding nutrients to the stormwater as it infiltrated. Conversely, the underdrain pathway exhibited lower concentrations than the surface pathway for total suspended solids, total and dissolved copper, zinc, and lead, fecal coliform, diesel, and motor oil.

Results from a Kruskal-Wallis rank sum test are presented in Table 5 along with the median concentrations. If a median value is significantly lower at an effluent station versus the influent it is bolded in the table, if it is significantly higher than the influent it is italicized. As is apparent the reductions along the surface pathway were only significant for total suspended solids, total phosphorus, total copper, and total lead. The underdrain exhibited significant reductions for total suspended solids, total and dissolved copper, total and dissolved lead, fecal coliform, motor oil and diesel, consequently, it was the more effective treatment pathway. However, despite significant reductions for the parameters listed above, the underdrain pathway was a significant source for ortho-phosphate. Again, likely due to nutrient leaching from the compost in the bioretention media.

Table 6 presents the mean percent reduction data for, 1. the total mass load in versus the total mass load out, 2. the inlet concentration versus the outlet concentration for each pathway, and 3. the inlet concentration versus the flow-weighted outlet concentration. The concentration comparison for each pathway again indicates that the underdrain pathway was less effective for nutrient removal when compared with the surface pathway and indeed increased nutrient concentrations versus the inlet. Nutrients aside, the underdrain pathway was very effective at reducing influent concentrations. It should be noted that there were three high outlier results for zinc in the underdrain, the source of this zinc is still unknown. In Table 6, the outliers were removed prior to calculating the percent reduction.

The flow-weighted concentration comparison between the inlet and outlets provides an estimate of overall system performance. The results indicate an average total suspended solids removal of 92.3 percent, this is well above the 65 percent design goal and even exceeds the code goal of 80 percent. In addition the metals removal results are very high and qualify the system as an “enhanced treatment” BMP per the Washington State Department of Ecology guidelines (>30 percent dissolved copper removal and >60 percent dissolved zinc removal). The system was also characterized by superior bacteria and hydrocarbon removals with 74.6, 74.7, and 77.4 percent reductions for fecal coliform, diesel range hydrocarbons, and motor oil range hydrocarbons, respectively.

Load reductions where superior to concentration reductions due to the loss of 28.7 percent of the influent volume in the system. For example, the load based total suspended solids reductions were 95.2 percent. Despite the nutrient export from the underdrain the system still exhibited a 28.5 and an 18.4 percent reduction for total phosphorus and nitrate+nitrite, respectively, when calculated on a load basis.

In general, the water quality performance of Swale 2 is considered excellent relative to other stormwater facilities, both proprietary and in the public domain that SPU has monitored. Total phosphorus, copper, fecal coliform, and hydrocarbon removal generally exceeded other stormwater management facilities monitored previously by SPU. This performance is even more impressive because this was a retrofit project so SPU designed the swales to receive much greater pollutant loading compared to a similar code-based biofiltration swales.

The only parameters which was exported from the system on a load basis was ortho-phosphate, the soluble form of phosphorus that is most bio-available and can stimulate excess algae growth and depletion of dissolved oxygen. In order to prevent the export of this nutrient the yet to be constructed Swales 1 and 3 will be configured with a polishing layer of advanced media designed to retain nutrients. This polishing layer will be placed between the underdrain and the bioretention media. Future monitoring of Swales 1 and 3 will quantify the effect of the polishing layer on nutrient dynamics.

Table 5. Median Concentrations and Statistical Results

Parameter	Swale 2 Median Influent Concentration	Swale 2 Median Surface Outflow Concentration	Swale 2 Median Underdrain Outflow Concentration	Kruskal-Wallis P-Value
Total Suspended Solids (mg/L)	37.9	**11.8**	**1.2**	<0.001
Total Phosphorus (mg/L)	0.288	**0.152**	0.290	0.015
Ortho-Phosphate (mg/L)	0.11	0.086	*0.284*	0.010
Nitrate + Nitrite (mg/L)	0.577	0.393	0.700	0.117
Total Copper (ug/L)	30.9	**19.2**	**4.5**	<0.001
Dissolved Copper (ug/L)	12.2	12	**4.5**	<0.001

Parameter	Swale 2 Median Influent Concentration	Swale 2 Median Surface Outflow Concentration	Swale 2 Median Underdrain Outflow Concentration	Kruskal-Wallis P-Value
Total Zinc (ug/L)	106	68	39	0.359
Dissolved Zinc (ug/L)	47	44	30	0.379
Total Lead (ug/L)	8.4	**3.9**	**0.4**	<0.001
Dissolved Lead (ug/L)	0.6	0.7	**0.2**	0.002
Fecal Coliform (CFU/ 100mL)	9150	8900	**1200**	0.001
Diesel Range Hydrocarbons (mg/L)	0.38	0.18	**0.1**	0.001
Motor Oil Range Hydrocarbons (mg/L)	1.1	0.37	**0.2**	<0.001

Bold values indicate that the outlet is significantly lower than the inlet, *italicized* values indicate that the outlet is significantly higher than the inlet.

Table 6. Water Quality Percent Reduction Results

	Load-Based Removal Sum of Both Outlets Compared to Inlet	Concentration-Based Removal Each Outlet Compared to Inlet		Concentration-Based Removal Both Outlets Compared to inlet
Parameter	Swale 2 Total Load Removal (mean percent)	Surface Outflow (mean percent)	Underdrain (mean percent)	Swale 2 Total Concentration Reduction (flow-weighted average)
Total Suspended Solids	95.2	68.0	94.7	92.3
Total Phosphorus	28.5	42.7	-10.0	2.3
Ortho-Phosphate	-60.7	18.1	-237.2	-160.9
Nitrate + Nitrite	18.4	17.7	-43.2	-30.9
Total Copper	83.7	34.8	84.2	78.9
Dissolved Copper	70.1	-12.1	63.5	59.9
Total Zinc	79.6*	29.2*	91.7*	70.8*
Dissolved Zinc	67.9*	-5.0*	85.9*	53.9*
Total Lead	91.8	58.7	95.2	89.5
Dissolved Lead	72.0	2.5	63.4	60
Fecal Coliform	82.2	2.1	77.8	74.6
Diesel Range Hydrocarbons	77.9	22.0	74.2	74.7
Motor Oil Range Hydrocarbons	82.3	30.8	84.0	77.4

** Outliers were removed prior to calculation*

Conclusions

Influent and effluent chemistry and flow for Swale 2 of the CHWQP in Seattle, Washington was monitored from October 2015 through July 2016. Because it was a retrofit, the system did not have to be built to current code for water quality treatment. Instead the design was optimized for performance given the site constraints and desire to maximize the treated volume. The project was able to remove suspended solids for $20 – 28 per pound, while the code target would have resulted in $60 – 64 per pound. Consequently, the system is very cost effective and an ideal design for an urban retrofit situation.

There were two primary treatment pathways through the BMP, the surface drain (swale treatment) and underdrain (bioretention treatment). The majority of the water (45 percent) passed through the underdrain, while 28 percent of the water exited the surface drain and 28 percent was either infiltrated or lost to evapotranspiration. There was a seasonality to the flow pathways with nearly the entire flow exiting the underdrain during the dry months and relatively equal apportionment between the surface and underdrain pathways during the wet months.

Swale 2 performed well at removing total suspended solids, metals, bacteria, and hydrocarbons. In fact, the performance was better than the majority of the BMPs employed by SPU, including bioretention. Despite this, the nutrient removal performance was insufficient, and in the case of ortho-phosphate, the system actually exported. Future designs will include a layer of sorbent media beneath the bioretention media to absorb the nutrients being exported from the system.

Presenter Bios

Mr. Hutchinson is an environmental monitoring and stormwater management specialist with over 25 years of experience working in the private and public sectors. He is a regional expert on water quality monitoring, specializing in monitoring to evaluate stormwater treatment best management practices (BMPs). He created and has managed the stormwater monitoring program for Seattle Public Utilities since 2008. He previously managed the in-house environmental monitoring section for the Portland Bureau of Environmental Services where he worked from 1996 to 2008. He began his career as a geologist and project manager working on environmental and geotechnical engineering projects. He was the Principal Investigator for this study.

Dr. Ahearn is an associate environmental scientist with 15 years of experience studying the environmental ramifications of human alteration to aquatic systems. He has designed studies, collected data, and conducted detailed pollutant loading assessments for over 100 stormwater treatment structures (e.g., wet ponds, swales, filter strips, green roofs, pervious pavement, and proprietary systems) in the Puget Sound area. He has extensive hands-on knowledge of green infrastructure and, having designed and implemented the monitoring network at the Washington State University Low Impact Development Research Center, is involved in cutting edge stormwater treatment research.