Project Report

VUSP – PADEP: Best Management Practice National Monitoring Site

Year 14 – 2017

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Nonpoint Source
National Monitoring Program
Clean Water Act Section 319

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PROJECT OVERVIEW

Starting in the late 1990s, there was a sea change towards minor drainage systems with an emphasis on more sustainable and distributed stormwater management practices beyond just flood protection. In the following two decades, there has continued to be an evolution in the way we understand, design, and assess stormwater control measures (termed Best Management Practices, BMPs). These BMPs treat various forms of water pollution, including runoff volume and peak flows and constituents from urban stormwater. As research and practice has progressed and become more systematic and scientific, the stormwater community began using the terms Stormwater Control Measures (SCM; National Research Council 2009, ASCE/WEF Manual of Practice 2012) and Green Infrastructure (GI). The Water and Environment Federation publication "Rainfall to Results: The Future of Stormwater" (2015) explores the continuing need to advance the stormwater profession, and the importance of resilience in GI. The Villanova Urban Stormwater Partnership has been a leader in research and supported policy development over the past two decades.

Recognizing the need for research and public education, Villanova University, in collaboration with the Pennsylvania Department of Environmental Protection (PADEP), formed the Villanova Urban Stormwater Partnership (VUSP) in 2002 and created the Stormwater Control Measure Research and Demonstration Park on its campus near Philadelphia, PA. This project was accepted into the U.S. EPA National Nonpoint Source Monitoring Program in 2003.

The goals of the Villanova University Stormwater SCM Research and Demonstration Park are:

- To improve our understanding of nonpoint source pollution;
- To scientifically evaluate the effectiveness of watershed technologies designed to control nonpoint source pollution; and
- To export our results and lessons learned to the stormwater community.

Since 1999, the VUSP has constructed and monitored multiple innovative SCM devices to include a constructed stormwater wetland, bioinfiltration and bioretention rain gardens, pervious pavements (concrete / asphalt / pavers), an infiltration trench, a green roof, and a treatment train. Additionally, experimental setups have been built to target specific research and design questions related to SCMs, such as rain garden lysimeters. Information on the design and construction of applicable SCMs, as well as the design of monitoring efforts, was presented in two 319 program publications (Traver 2004, 2010). Building on the success of the VUSP and expanding the scope of work and expertise of the research team, the VUSP is transitioning to a broader organization – the Villanova Center for Resilient Water Systems (VCRWS). This has been a natural progression to "engage with society to create resilient engineered solutions for global water challenges." The VCRWS combines stormwater research with work under a changing climate, rapid urbanization, and aging infrastructure to ensure stormwater management infrastructure is resilient over time. The core mission of VCRWS remains to apply scientific knowledge "to advance the evolving field of sustainable stormwater management and to foster the development of public and private partnerships through research." Continuous monitoring of wet weather flows and pollution entering and exiting each SCM enables the effectiveness of these technologies to be measured and evaluated. The longevity of this study increases our knowledge of how these devices work and how to ensure their long-term performance. The data generated from this research work is one of the longest and most extensive data sets that currently exists and has enabled much advancement of knowledge and application. What is unique to this study is that as a specific research goal for an SCM is reached, the focus shifts to either another aspect. For example, the focus on the Bioinfiltration Rain Garden has shifted from basic surface water hydrology to vadose zone soil hydrology and ultimate fate of pollutants. It also is enabling future research on longevity and aging. This process is supported by feedback from the VUSP partners, which includes PADEP representation. Each site is instrumented to facilitate study of runoff volume, peak flow, and quality.

While this report is focused on the results from the 319 NPS program, this program indirectly aids and is enhanced by the synergy of several VCRWS projects. For example, financial support for the construction and monitoring of the SCMs has come from a variety of sources. Construction has been funded through the USEPA Section 319 Nonpoint Source program, the Pennsylvania Growing Greener program, and Villanova University. Monitoring has been supported by the EPA Section 319 NPS program, in collaboration with research projects funded through Pennsylvania Growing Greener, the VUSP corporate partners, the NOAA Coastal Zone Program, EPA Region III

104B3, and several targeted EPA grants. A project comparing bioretention sites across multiple universities, including Villanova University, was completed in 2010, funded by the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET).

While we are careful to keep the projects distinct, synergies with other research projects in the area both aid in the depth of the research, and in advancing the knowledge base of the profession. Funding from the National Science Foundation has focused on implementing real time control at three sites on campus, including the Constructed Stormwater Wetland. Off campus projects research on the Delaware Watershed Initiative supported by the William Penn Foundation, applied research with the Philadelphia Water Department, I-95 Bioswales with PennDot, and a USEPA Star Grant.

Educational signage is installed at each 319 SCM site to enhance the learning experience and the VCRWS website facilitates technology transfer. The experiences gained through the construction, operation, monitoring, and evaluation of these sites form the basis for the outreach and education component of the Research and Demonstration Park. The research teams regularly presents at local, regional, national, and international conferences and highlights the findings derived from this project's research.

This project report focuses on data of the active sites for 2017 and activities of the partnership through Summer 2018. For 2017, the Bioinfiltration Rain Garden and the Constructed Stormwater Wetland monitoring and analysis was supported by the 319 NPS program.

PROJECT BACKGROUND

Villanova has been studying the two highlighted sites (Bioinfiltration Rain Garden and Constructed Stormwater Wetland) since their construction in some capacity, and the direction of research has lead the field. Websites for each stormwater project can be viewed through the following link: http://www.villanova.edu/vusp.

Figure 1. A.) Photograph of VU Bioinfiltration Rain Garden BMP (2007). B) Photograph of VU Bioinfiltration Rain Garden BMP (July 2017). The site has matured over time with volunteer plant species inhabiting the site along with planned plantings.

Bioinfiltration Rain Garden (BRG) (PA Growing Greener Grant, constructed summer 2001). This bioinfiltration SCM (previously termed Bioinfiltration Traffic Island) was created by retrofitting an existing traffic island on Villanova's campus (Figure 1). The facility intercepts runoff from a highly impervious (50%) student parking and roadway area (0.26 ha) that previously was collected by inlets and delivered through culverts to a dry detention basin. The SCM is designed to control runoff from smaller storms (1 – 3 cm) through capture and infiltration of the first flush. Water quality and quantity studies are ongoing. Capture of small storms (less than 1 in) treats more than 97% of the annual rainfall (Lord, 2013), thus improving water quality, reducing erosive storm peaks, and contributing to the water table.

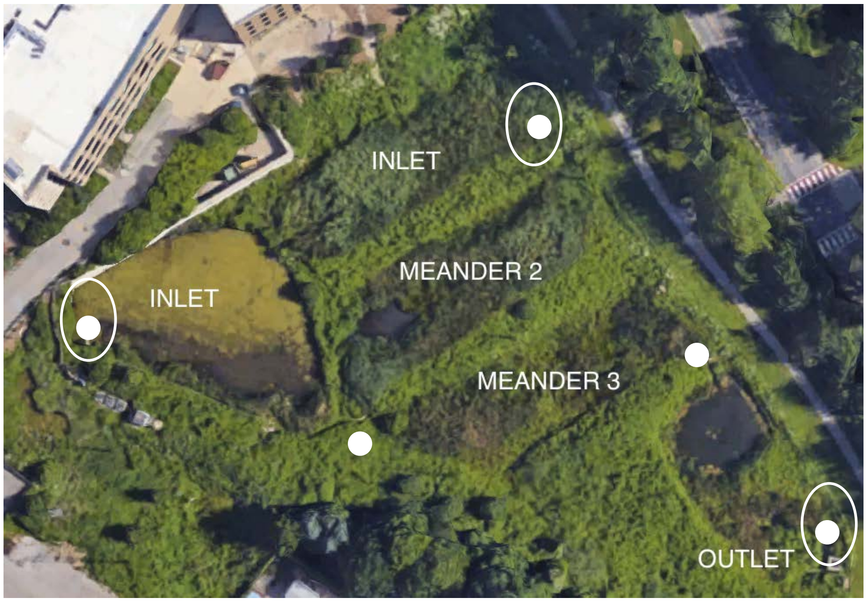

Figure 2. Photograph of VU Constructed Stormwater Wetland from Google Earth (2016). This photograph is from the summer when algae can grow in the inlet, although the system is self-cleansing and the algae is dissipates over time. Vegetation in and around the meanders continues to mature, creating an ecosystem. Open white circles are where there is continuous flow monitoring and the closed white dots are where water quality samples are taken.

Constructed Stormwater Wetlands (319 Grant – constructed in 1998, reconstructed in 2010). An existing stormwater detention basin on Villanova University's property was converted into an extended detention wetland SCM, and was reconfigured in 2010 (Figure 2); this site was reintroduced as a 319 NPS project in May 2011. Currently, the site has established vegetation growth and fauna have moved into the ecosystem. The constructed stormwater wetland treats runoff from 19.6 ha, including 10.3 ha of impervious surface. The watershed includes student's residence halls, classroom buildings, parking, roads, and a railroad. Baseflow and wet weather flow quality and quantity studies are ongoing, along with more specific studies measuring retention times, flow alteration, and nutrient cycling. Water quality and quantity improvements have been measured from influent to effluent. The project has been published as an EPA 319 Success Stories Part III.

Water Resources of Concern All sites are built to mitigate the effects of urban stormwater runoff on receiving streams and groundwater. This includes water quality, baseflow recharge, and stream bank protection. The Bioinfiltration Rain Garden is at the headwaters of the Darby Creek Watershed, which discharges to the Delaware River, and the Constructed Stormwater Wetlands is at the headwaters of Mill Creek, which is a tributary to the Schuylkill River. Both Darby and Mill Creeks are rated as degraded and listed on the 303d list, with urban runoff listed as the cause. The WEF report (2015) notes that 2015 marks the 25th anniversary of the USEPA stormwater permitting program, yet "Despite these efforts, stormwater is the only growing source of water pollution in many watersheds throughout North America."

As stated earlier, all projects are developed to mitigate the effects of urban runoff. The Bioinfiltration Rain Garden is designed to remove the first portion of a storm event from reaching the receiving system, reduce erosive peak flows, and enable biological and chemical treatment for water quality parameters. The constructed stormwater wetland is designed for water quality treatment, extending contact with the vegetation, and slowing down and reducing peak flows.

Project Time Frame A key goal to this project is to monitor all sites for as long as we are learning about them, creating a unique and robust dataset. Lessons range from best practices for monitoring and analysis to a deeper understanding of physical and hydrological processes within the systems. Initial monitoring for water quality and quantity for the Bioinfiltration Rain Garden commenced October 1, 2003. During this first year of monitoring, it was discovered that sampling from the traffic island bowl did not adequately represent the inflow conditions so first flush samplers were installed. It was also discovered that unexpected extremely large levels of chloride reduced the minimum detection level of the laboratory instruments for dissolved nutrients. These issues were addressed through development of new laboratory techniques and purchase of new equipment. Three wells were added to the

Bioinfiltration Rain Garden site in 2007 to facilitate groundwater monitoring. In 2008 a composite sampler was added to replace grab sampling from the bowl. Over the past few years, substantial partner funds have been used to update the site instrumentation as the focus on the site changes to enumerating both groundwater and surface water perspectives. Four more wells were constructed in March 2012 to further define the influence of the traffic island on groundwater mounding. The initial monitoring period for the Constructed Stormwater Wetlands site was in 2011. Like the Bioinfiltration Rain Garden, site monitoring is continually evaluated and modified to provide high quality data at the Constructed Stormwater Wetlands. Flow meters and sensors have been upgraded, new control features have been added (e.g., real time controlled gates), and protocols for assessment techniques have been developed (e.g., tracer studies). Data from monitoring in 2017 is included in this report.

PROJECT DESIGN

Nonpoint Source Control Strategy The control strategy is to assess flow volumes and rates and pollutant loads for wet weather flows entering and exiting the SCMs. The inflow and outflow of individual SCMs are examined.

Project Schedule

Site	Status	Initial Monitoring Phase	Notes
Bioinfiltration Rain Garden	Monitoring Underway 10/01/04-Present	10/01/03-09/30/04	Improvements: Added first flush samplers + bowl lysimeter in 2003/04. GW Well added 2006 Additional GW Wells added 2007 Composite Bowl Sampler added in 2008. Additional GW Wells added 2012 Soil Moisture Meters added 2012/13 Concrete inflow flume added in 2013 Outflow Level instrumentation and V-notch Weir updated 2013/14
Constructed Stormwater Wetland	Baseflow and Wet Weather Monitoring Underway 05/11-Present	05/11 – 12/11	Water quality autosamplers added in 2014 Flow monitoring equipment updated in 2014/15 Temperature sensors added in 2014 Control gate at meander 1 added in 2016, at outlet in 2017

Monitoring Design

Bioinfiltration Rain Garden (Figures 1, 3 and 4) This SCM has a custom-designed monitoring system to evaluate the surface water quality and quantity, as well as groundwater (vadose zone) quality. The site has rain gages, water sampling devices, flow / level recorders, and soil moisture meters. Water quality samples are collected using automated samplers, first flush samplers, grab samples, and lysimeters. Flow leaving the site is split into infiltration and overflow for large storm events.

Stormwater quantity: Runoff enters the system via a concrete inlet channel (replacing the previous inlet system that consisted of two curb cuts) and from a culvert that intercepts runoff from upstream conveyance pipes. Water quantity parameters are continuously monitored at a 5-minute time step.

- Rainfall is measured with a tipping bucket rain gage. Overflow is estimated through a model calibrated to a combination V-notch weir / pressure transducer. The outflow V-notch weir was replaced in 2014 and the pressure transducer updated to a more accurate model, taking advantage of industry advances.
- Depth within the bowl is measured directly. This measurement was updated in 2013 to a highly accurate bubble sensor. Past methods included using an ultrasonic level recorder and pressure transducer.
- Inflow is determined from a calibrated hydrologic model using precipitation.
- Multiple pressure transducers are installed in surrounding wells. There are periods where monitoring was inactive due to equipment repairs.

Stormwater quality: Surface runoff and sub-surface vadose zone samples are collected for approximately 10-15 storms/year.

- A first-flush sampler catches the first 5 L of direct runoff from the impervious surface and the grass area adjacent to the basin. When the inlet channel was reconstructed in Fall 2013, the first-flush sampler was permanently embedded into the concrete approach channel to ensure a representative sample is taken.
- An autosampler is used to take a composite sample of storm events from the bowl. Two grab samples are collected if the autosampler malfunctions (one surface water sample during the storm event and one at the conclusion of rainfall if ponded water remains).
- A composite grab sample is taken from the outflow weir (for overflow events).
- Lysimeters are located at depths of 0, 1.2, and 2.4 m beneath the surface. The sample is extracted from the soil through the use of a pressure-vacuum soil water sampler.
    - Collected water samples are treated as a composite sample.
    - Only dissolved fractions are collected from the vadose zone samples and the sample volume is limited, occasionally limiting the number of parameter tests performed.
- Grab samples of the groundwater from surrounding wells have been taken in the past. These samples were part of a SCM project that was completed.

Figure 3 shows a schematic plan drawing of the sampling locations for surface water samples at the Bioinfiltration Rain Garden and Figure 4 shows the profile position of sensors and sampling locations.

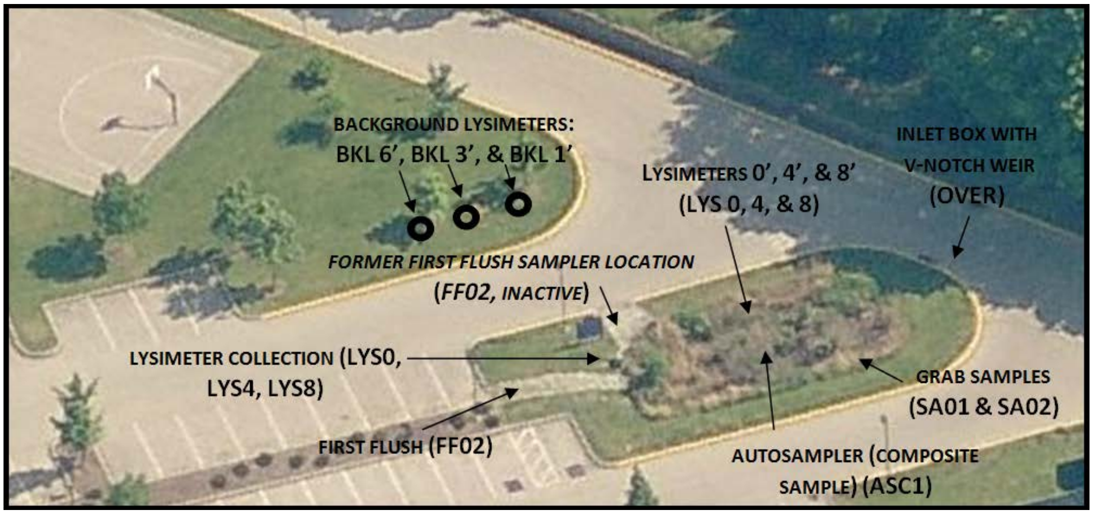

Figure 3. Schematic of BRG surface sampling locations (Lord 2013, modified)

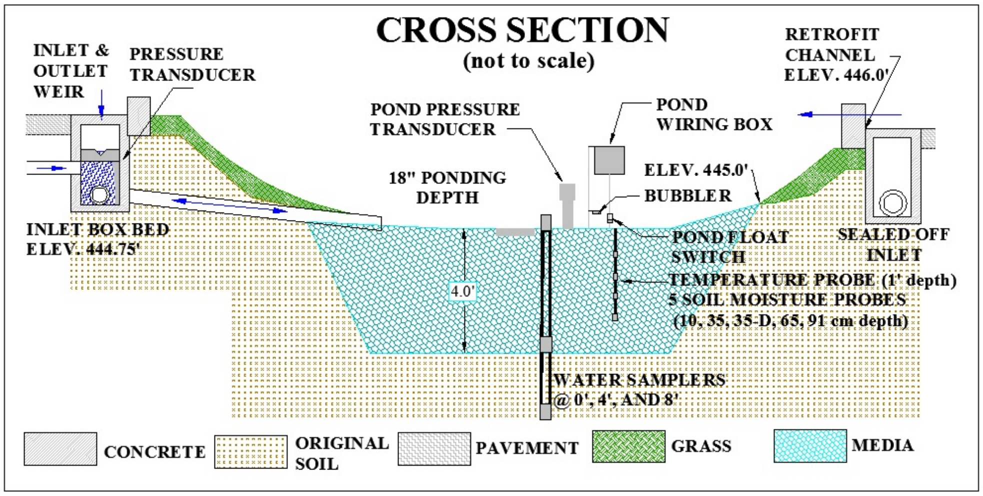

Figure 4. Diagram of BRG subsurface sampling locations

Constructed Stormwater Wetland (Figure 2) This SCM has a custom-designed monitoring system to evaluate the surface water quality and quantity. The site has a rain gage, water sampling devices, and flow / level recorders. Water quality samples are collected using automated samplers and grab samples. Flow is split into baseflow, storm flow, and interflow (i.e., the flow as it transitions from storm flow to baseflow).

Stormwater quantity: Runoff enters the system predominantly through two large pipes with 17% of the inflow from overland flow and other minor points of entry. Flow exits through one outlet structure. Water quantity parameters are continuously monitored at a 5-minute time step.

- Rainfall is measured with a heated tipping bucket rain gage (which enables snow precipitation measurements).
- There are area-velocimeters in each of the two major inlet pipes and the outlet pipe.
- There is a redundant weir/pressure transducer system measuring flow at the outlet.
- There is a small portion of flow into the CSW (6.6 acres, 90% impervious) not accounted for with the existing monitoring plan. A Stormwater Management Model (EPA-SWMM) was developed and calibrated to CSW flows and it was determined that there was 17% (±7%) unmeasured inflow. This model is used to supplement the unmeasured inflow rates.

Stormwater quality: Surface runoff samples and baseflow samples are collected for approximately 12 events/year each.

- Baseflow samples are taken as grab samples (two replicates at each location, 600 L grab sample) are collected at the following locations: Inlet, End Meander 1, End Meander 2, End Meander 3, and the Outlet (Figure 2).
- Grab samples were taken for storms prior to 2014 when autosamplers were implemented for storm sampling (two grab samples were collected at the Inlet, End Meander 1, End Meander 2, End Meander 3, and the Outlet).
- Autosamplers have been used since 2014 to take storm samples (each composite bottle holds three samples that were collected at a specific rainfall volume at the Inlet and after a time delay at End Meander 1 and Outlet).
- There were four dissolved oxygen sensors in the system that we decommissioned in 2016.
- There are temperature sensors within the system.
- Spot samples have been taken in connection with targeted research questions as needed.

Sampling Methods According to the EPA (2002) manual Urban Stormwater BMP Performance Monitoring, "Proper sampling methods are essential in conducting a BMP monitoring program in order to ensure resulting data are meaningful and representative of the water and other media being processed by the BMP." Water quality sampling is conducted using automated samplers, first flush samplers, grab samples and lysimeters as per the VUSP QAAP revised / approved 2015.

The Sigma 900/950 automated sampler is a stand-alone unit capable of taking up to 24 discrete water samples per storm event. Each sample is collected in a special plastic bottle made especially to fit in the automated sampler. To get a consistent sampling routine, each sampling location is wired to the data logger and can be triggered through rainfall or depth of water in the SCM. A sampling protocol is set for each site.

First flush samples are collected using the GKY First Flush Sampler, a passive stormwater sampler that can hold up to 5 L of water (Figure 5). The lid of each sampler is constructed with five sampling ports, each of which can be plugged to control the rate collected runoff enters the sampler. Plastic flaps on the underside of each port function as closing mechanisms, preventing additional water from entering the sampler once it has reached its capacity. Each sampler is fitted with a 5 L removable plastic container and lid to permit sample transport.

Figure 5. Photograph of GKY First Flush sampler

Grab samples are taken with a 1 L bottle from the pond in the BRG. The grab samples are collected from the top 3 inches of the ponding accumulated within the BRG carefully, to ensure that no sediments or additional substances are collected along with the water sample.

Lysimeters are a porous container installed in the soil profile and can be connected to a vacuum. Lysimeters work by overcoming soil water tension or negative pressure created by capillary forces. By creating a vacuum or negative pressure greater than the soil suction holding the water within the capillary spaces, a hydraulic gradient is established for the water to flow through the porous ceramic cup into the lysimeter’s chamber for collection.

Laboratory Analysis The water quality samples are analyzed in Villanova University’s Resilient Water Analytical Laboratory. All analyses are typically completed within 24 hours of sample collection. Any samples not analyzed within 24 hours are preserved according to appropriate protocols established for each analysis.

Variables measured include:

- pH
- Conductivity
- Total Suspended Solids (surface samples)
- Chlorides
- Nutrients - N, P (Dissolved - Various Species)
- Metals - Various (Dissolved - Various Forms; BRG Only)

This list is adjusted based upon what is found at the site and the direction of the research governing board. Some of these tests are only applicable to the surface or groundwater samples. Currently, analyses are performed using spectrophotometry, ion chromatography, and atomic adsorption equipment. An approved Quality Assurance Project Plan (QAPP) is in place. Unexpected extreme values of chlorides from road salt interfered with the nitrate, nitrite, and orthophosphate HPLC analysis for the first several years. This was corrected through the purchase of new laboratory equipment in 2008. Upgrades to the nutrient measuring laboratory testing equipment occurred in 2015 and were funded by the VUSP Partners.

Data

Bioinfiltration Rain Garden

The surface water results of pollutants and flows entering and exiting the BRG from a surface water perspective are presented in Tables 1 and 2. Table 1 is a record of all storm events sampled for the past decade (2008-2017) and Table 2 presents results only from 2017 to allow comparison of the removal percentages for that individual year to that of a longer record.

Table 1. Bioinfiltration Rain Garden - Surface Flow Performance 2008 – 2017

Traffic Island Surface Water Analysis				
Lifetime Totals (2008-2017)				
	# of Storms	Inflow	Overflow	Removal Efficiency
Water Quantity (Events with R > 0.25")	376	6,669,625 L	2,249,528 L	66.3%
Water Quantity (Events 0.05" <= R <=1.6")	482	5,509,284 L	599,744 L	89.1%
Water Quantity (Events with Water Quality Measured)	155	8,352,968 L	4,561,339 L	45.4%
Total Suspended Solids (TSS)	135	1873 kg	139 kg	92.6%
Total Dissolved Solids (TDS)	128	1022 kg	89 kg	91.3%
Total Nitrogen (TN) as N	12	134 g	17 g	87.3%
Total Kjeldahl Nitrogen (TKN) as N	90	6399 g	2033 g	68.2%
NO2 as N	108	176 g	39 g	77.6%
NO3 as N	113	1402 g	410 g	70.7%
Total Phosphorus (TP) as P	42	4617 g	1233 g	73.3%
Total Kjeldahl Phosphorus (TKP) as P	68	120 g	40 g	66.7%
Phosphate (PO4) as P	106	2446 g	496 g	79.7%
Chloride (CHL)	121	262 kg	132 kg	49.6%
Total Cadmium	91	2872 mg	276 mg	90.4%
Total Chromium	97	95866 mg	4782 mg	95.0%
Total Copper	104	81328 mg	3043 mg	96.3%
Total Zinc	87	242916 mg	23108 mg	90.5%
Total Lead	95	18520 mg	940 mg	94.9%

*Assumes Curve Number flow of 98 from impervious surface

**The TDS values obtained for the period of 2003 to 2015 is from testing, and TDS data from 2016 and onwards were obtained from conductivity. (See page 12)

*** Total N or P from both the HACH and current EAZYCHEM analysis

****The values represented in the table above were obtained from a combination of the data reported in the previous reports and the data available in the database.

Table 2. Bioinfiltration Rain Garden - Surface Flow Performance 2017

Traffic Island Surface Water Analysis				
2017				
	# of Storms	Inflow	Overflow	Removal Efficiency
Water Quantity (Events with R > 0.25")	41	1,133,143 L	210,247 L	81.4%
Water Quantity (Events 0.05" <= R <=1.6")	76	936,514 L	77,561 L	91.7%
Water Quantity (Events with Water Quality Measured)	10	322,904 L	43,145 L	86.6%
Total Suspended Solids (TSS)	8	7 kg	1 kg	84.3%
Total Dissolved Solids (TDS)	8	11 kg	1 kg	90.5%
Total Kjeldahl Nitrogen (TKN) as N	4	88 g	0 g	100.0%
NO2 as N	7	4 g	0 g	87.6%
NO3 as N	6	32 g	5 g	84.0%
Total Kjeldahl Phosphorus (TKP) as P	4	9 g	0 g	100.0%
Phosphate (PO4) as P	6	9 g	0 g	100.0%
Chloride (CHL)	8	5 kg	1 kg	83.9%
Total Cadmium*	9	142 mg	20 mg	85.9%
Total Chromium*	9	2441 mg	326 mg	86.6%
Total Copper*	9	2654 mg	299 mg	88.8%
Total Zinc*	9	23959 mg	7477 mg	68.8%
Total Lead*	9	1132 mg	206 mg	81.8%

*Assumes Curve Number flow of 98 from impervious surface

**The TDS values obtained for the period of 2003 to 2015 is from testing, and TDS data for 2016 and onwards were obtained from conductivity. (See page 12)

*** Insufficient outflow samples were measured to obtain a representative removal efficiency

****The values represented in the table above were obtained from a combination of the data reported in the previous reports and the data available in the database.

Note: Overflow generally only occurs when the rainfall depth exceeds 1 in (2.5 cm). Of the ten storms analyzed for water quality, only one resulted in overflow. Without having sufficient overflow events tested, the values stated in the table do not give a robust representation of the overflow characteristics. The values do represent performance for these storm events.

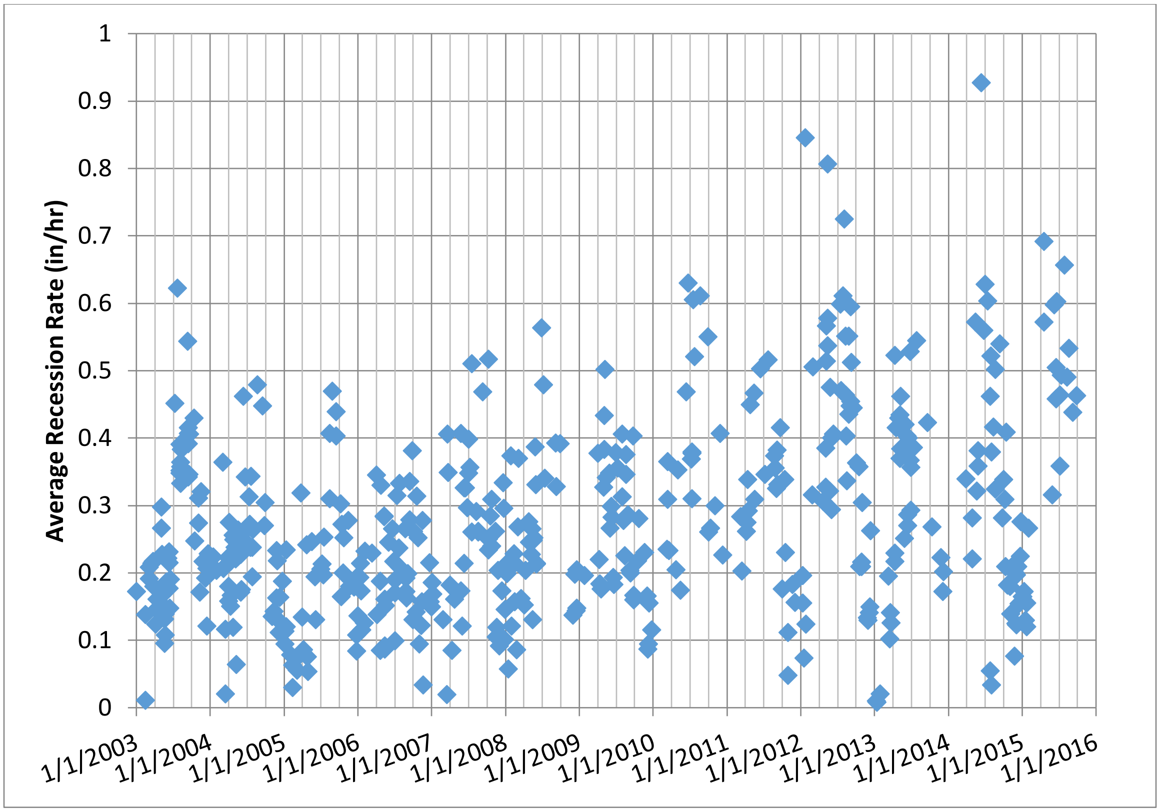

Figure 6. Historical Record of Ponding Recession Rates at BRG

Figure 6 presents a historical record of the measured ponding recession rates. As described in past reports, the variation of performance is partially due to temperature and soil moisture. No reduction in recession rates is evident, though the spread seems to be increasing. Figure 7 presents the monthly hydrologic performance.

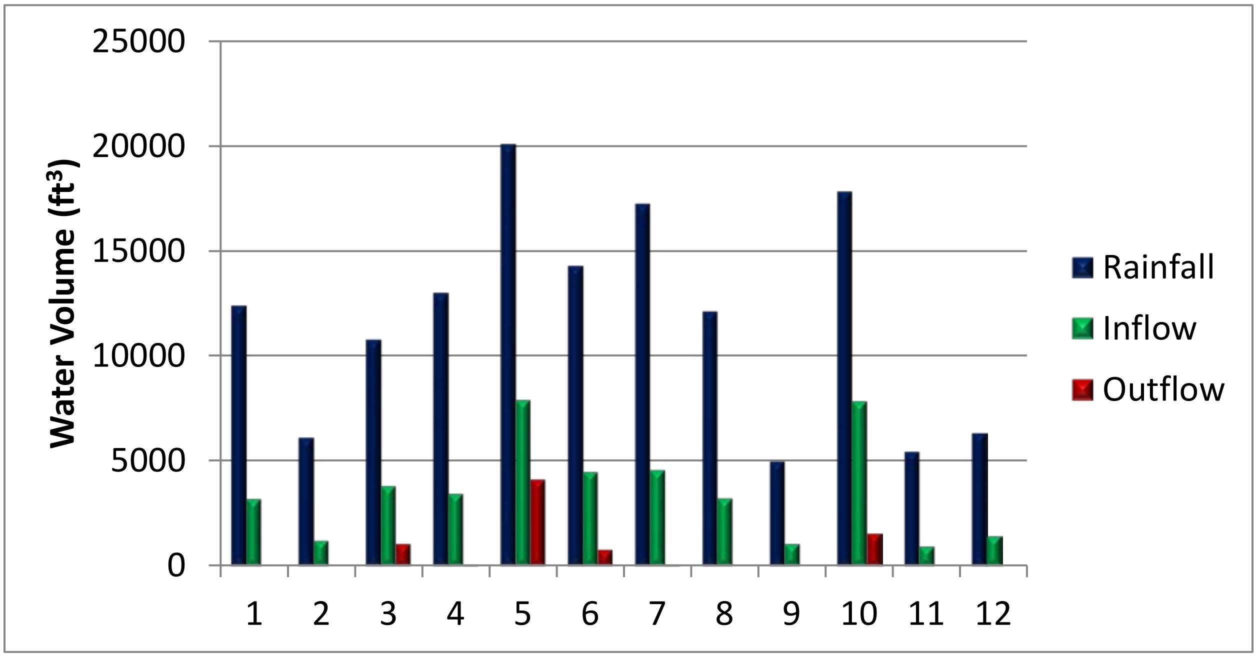

Figure 7. Monthly Hydrologic Balance of 2017 at BRG

BRG Subsurface: The subsurface results (Table 3) are presented as concentrations (mg/L) of each pollutant as measured at the 0, 1.2, and 2.4 m level. As it is not yet known how much of the captured volumes are infiltrated versus evapotranspired, we are unable to estimate mass loadings. Concentrations at 0, 25, 50, 75, and 100% levels refer to quartiles from cumulative frequency distribution of observed values. This table shows the quality changes due to water movement through the media and surrounding soil.

Table 3. Bioinfiltration Rain Garden Vadose Zone Sampling 2008-2017

3a - Bioinfiltration Rain Garden Vadose Zone Analysis - Surface Concentrations							
Life of Bioinfiltration Rain Garden							
Water Quantity	Detection Limit	Num. of Storms	Concentration				
			0% (Min)	25%	50%	75%	100% (Max)
TDS (mg/l)	-	76	6	40	73	178	1445
pH	-	98	4.18	6.72	7.04	7.31	8.01
Conductivity (µS/cm)	-	98	45	75	101	151	1014
TN (mg/l) as N	0.1-1.7 mg/l	29	0.10	0.85	1.30	2.10	5.00
TKN (mg/l) as N	0.05-0.1 mg/l	63	0.050	0.36	0.68	1.03	3.92
NO2 (mg/l) as N	0.005-0.2 mg/l	98	0.00	0.01	0.03	0.11	4.22
NO3 (mg/l) as N	0.01-0.2 mg/l	68	0.00	0.15	0.31	0.71	3.45
NOx (mg/l) as N	0.05-0.1 mg/l	68	0.01	0.18	0.36	1.00	3.55
TP (mg/l) as P	0.01-0.06mg/l	69	0.03	0.26	0.54	0.92	2.58
TKP (mg/l) as P	0.01-0.06mg/l	54	0.03	0.09	0.17	0.26	0.56
PO4 (mg/l) as P	0.01-0.2 mg/l	88	0.01	0.03	0.11	0.21	0.94
CHL (mg/l)	0.2-1.0 mg/l	98	0.3	7.1	18.1	47.4	789.9
Dissolved Cadmium (µg/l)	0.01-5.0 µg/l	84	0.19	0.40	0.40	0.40	4.51
Dissolved Chromium (µg/l)	0.5-5.0 µg/l	85	0.32	2.50	2.50	3.25	25.47
Dissolved Copper (µg/l)	0.5-5.0 µg/l	79	0.86	3.47	7.98	15.71	44.56
Dissolved Lead (µg/l)	0.5-5.0 µg/l	80	0.25	2.50	2.50	2.50	2.50
Dissolved Zinc (µg/l)	4.8-10.0 µg/l	80	0.01	0.03	0.03	0.05	0.74

*Non-detects are reported as half of the detection limit

3b - Bioinfiltration Rain Garden Vadose Zone Analysis - Concentrations at 4 feet

Life of Bioinfiltration Rain Garden

Water Quantity	Detection Limit	Num. of Storms	Concentration				
			0% (Min)	25%	50%	75%	100% (Max)
TDS (mg/l)	-	88	6	174	257	581	10134
pH	-	110	5.69	6.66	6.91	7.26	9.19
Conductivity (µS/cm)	-	109	6	316	425	774	11220
TN (mg/l) as N	0.1-1.7 mg/l	42	0.10	0.85	0.85	1.22	4.10
TKN (mg/l) as N	0.05-0.1 mg/l	71	0.05	0.10	0.19	0.39	3.16
NO2 (mg/l) as N	0.005-0.2 mg/l	102	0.00	0.00	0.00	0.02	1.29
NO3 (mg/l) as N	0.01-0.2 mg/l	83	0.01	0.12	0.26	0.43	1.47
NOx (mg/l) as N	0.05-0.1 mg/l	83	0.01	0.12	0.26	0.45	1.48
TP (mg/l) as P	0.01-0.06mg/l	99	0.03	0.17	0.31	0.58	4.81
TKP (mg/l) as P	0.01-0.06mg/l	58	0.01	0.03	0.03	0.05	0.12
PO4 (mg/l) as P	0.01-0.2 mg/l	88	0.00	0.01	0.03	0.05	1.03
CHL (mg/l)	0.2-1.0 mg/l	104	1.0	18.9	61.3	227.8	3902.0
Dissolved Cadmium (µg/l)	0.01-5.0 µg/l	94	0.05	0.40	0.40	0.40	6.37
Dissolved Chromium (µg/l)	0.5-5.0 µg/l	97	0.25	2.50	2.50	2.50	100.69
Dissolved Copper (µg/l)	0.5-5.0 µg/l	96	0.85	2.50	2.52	7.92	60.84
Dissolved Lead (µg/l)	0.5-5.0 µg/l	97	0.25	2.45	2.50	2.50	9.93
Dissolved Zinc (µg/l)	4.8-10.0 µg/l	91	0.00	0.03	0.03	0.04	2.50

*Non-detects are reported as half of the detection limit

3c - Bioinfiltration Rain Garden Vadose Zone Analysis - Concentrations at 8 feet							
Life of Bioinfiltration Rain Garden							
Water Quantity	Detection Limits (Vary over life)	Num. of Storms	Concentration				
			0% (Min)	25%	50%	75%	100% (Max)
TDS (mg/l)	-	93	6	185	262	398	8659
pH	-	109	4.37	6.70	6.91	7.11	9.15
Conductivity (µS/cm)	-	108	35	279	387	506	9930
TN (mg/l) as N	0.1-1.7 mg/l	39	0.10	0.85	0.85	1.42	3.95
TKN (mg/l) as N	0.05-0.1 mg/l	72	0.05	0.12	0.24	0.49	7.60
NO2 (mg/l) as N	0.005-0.2 mg/l	103	0.00	0.00	0.00	0.02	2.59
NO3 (mg/l) as N	0.01-0.2 mg/l	82	0.00	0.18	0.32	0.64	3.09
NOx (mg/l) as N	0.05-0.1 mg/l	82	0.03	0.19	0.32	0.65	3.10
TP (mg/l) as P	0.01-0.06mg/l	98	0.01	0.14	0.31	0.54	4.17
TKP (mg/l) as P	0.01-0.06mg/l	58	0.01	0.03	0.03	0.06	0.55
PO4 (mg/l) as P	0.01-0.2 mg/l	89	0.00	0.01	0.03	0.04	3.29
CHL (mg/l)	0.2-1.0 mg/l	105	1.0	7.4	26.2	143.9	1739.8
Dissolved Cadmium (µg/l)	0.01-5.0 µg/l	93	0.05	0.40	0.40	0.40	2.19
Dissolved Chromium (µg/l)	0.5-5.0 µg/l	98	0.25	2.50	2.50	2.50	32.42
Dissolved Copper (µg/l)	0.5-5.0 µg/l	99	0.85	2.50	5.70	8.92	32.67
Dissolved Lead (µg/l)	0.5-5.0 µg/l	95	0.25	2.45	2.50	2.50	2.50
Dissolved Zinc (µg/l)	4.8-10.0 µg/l	90	0.00	0.03	0.03	0.05	2.50

*Non-detects are reported as half of the detection limit

Table 3d was developed to highlight the changes in the vadose zone environmental constituents as it travels through the soil media. You can see the change in average concentration as the water moves from the surface, and then through the media, and then through four feet of the parent soil.

3d - Bioinfiltration Rain Garden Vadose Zone Analysis						
Life of Bioinfiltration Rain Garden						
Water Quantity	Surface		4ft		8ft	
	# Storms	50%	# Storms	50%	# Storms	50%
TDS (mg/l)	76	73	88	257	93	262
pH	98	7.04	110	6.91	109	6.91
Conductivity (µS/cm)	98	101	109	425	108	387
TN (mg/l) as N	29	1.30	42	0.85	39	0.85
TKN (mg/l) as N	63	0.68	71	0.19	72	0.24
NO2 (mg/l) as N	98	0.03	102	0.00	103	0.00
NO3 (mg/l) as N	68	0.31	83	0.26	82	0.32
NOx (mg/l) as N	68	0.36	83	0.26	82	0.32
TP (mg/l) as P	69	0.54	99	0.31	98	0.31
TKP (mg/l) as P	54	0.17	58	0.03	58	0.03
PO4 (mg/l) as P	88	0.11	88	0.03	89	0.03
CHL (mg/l)	98	18.1	104	61.3	105	26.2
Dissolved Cadmium (µg/l)	84	0.40	94	0.40	93	0.40
Dissolved Chromium (µg/l)	85	2.50	97	2.50	98	2.50
Dissolved Copper (µg/l)	79	7.98	96	2.52	99	5.70
Dissolved Lead (µg/l)	80	2.50	97	2.50	95	2.50
Dissolved Zinc (µg/l)	80	0.03	91	0.03	90	0.03

*Non-detects are reported as half of the detection limit

Figures 8 through 11 show this same water quality data from Table 3 with a probability perspective, which aids in our understanding of the environmental unit processes. These figures suggest TDS and Chloride increase as they enter the soil media, but then the risk of exceedance drops as it exits the media and enters the surrounding soil. This may be in part due to chloride remaining in the soil due to evapotranspiration and are washed through the system.

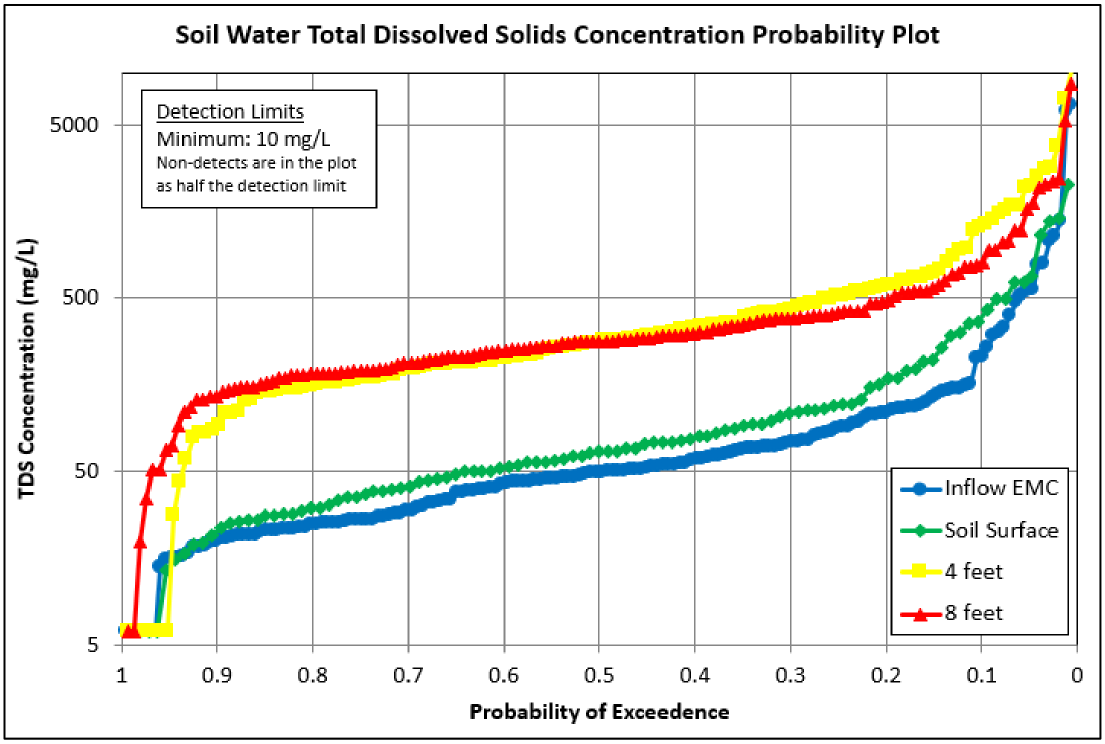

Figure 8. TDS Concentration Probability Plot

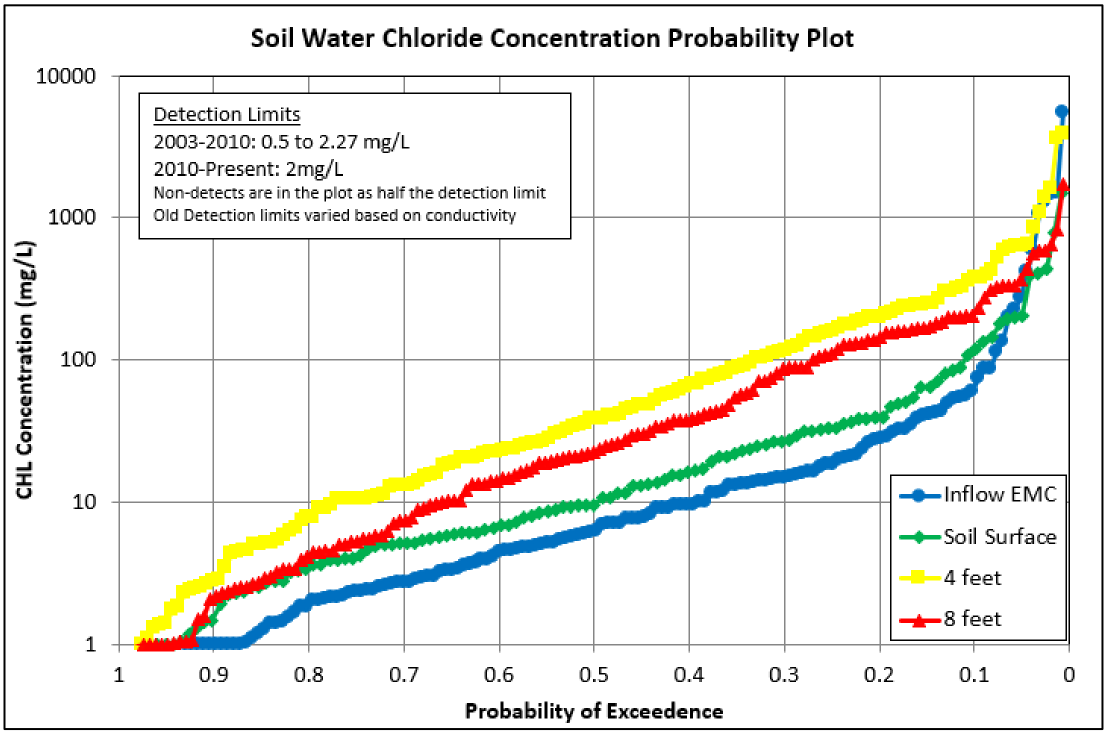

Figure 9. Chloride Concentration Probability Plot

The opposite is true with TKN, TP, and Orthophosphate (Figures 10 and 11). There is a large reduction as the water moves from the surface to the 4 ft mark, and then there is a relative lack of change as water moves into the native soil. The increased investment in laboratory analysis has greatly aided our understanding.

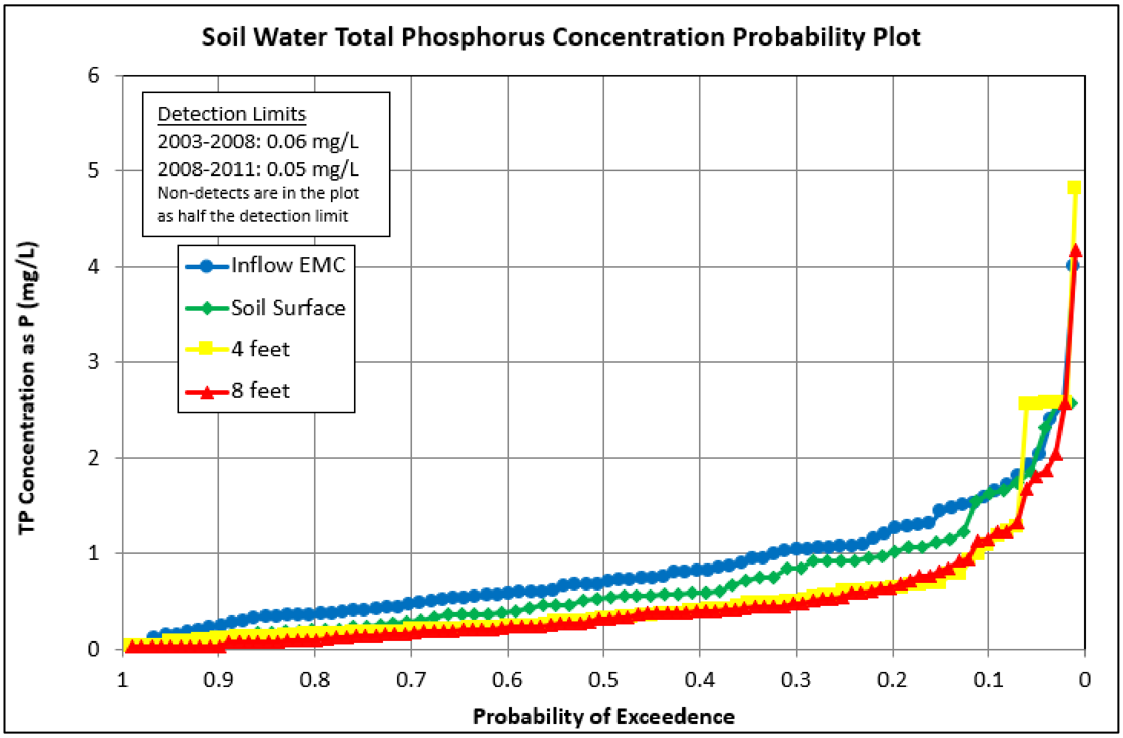

Figure 10. TP probability plot

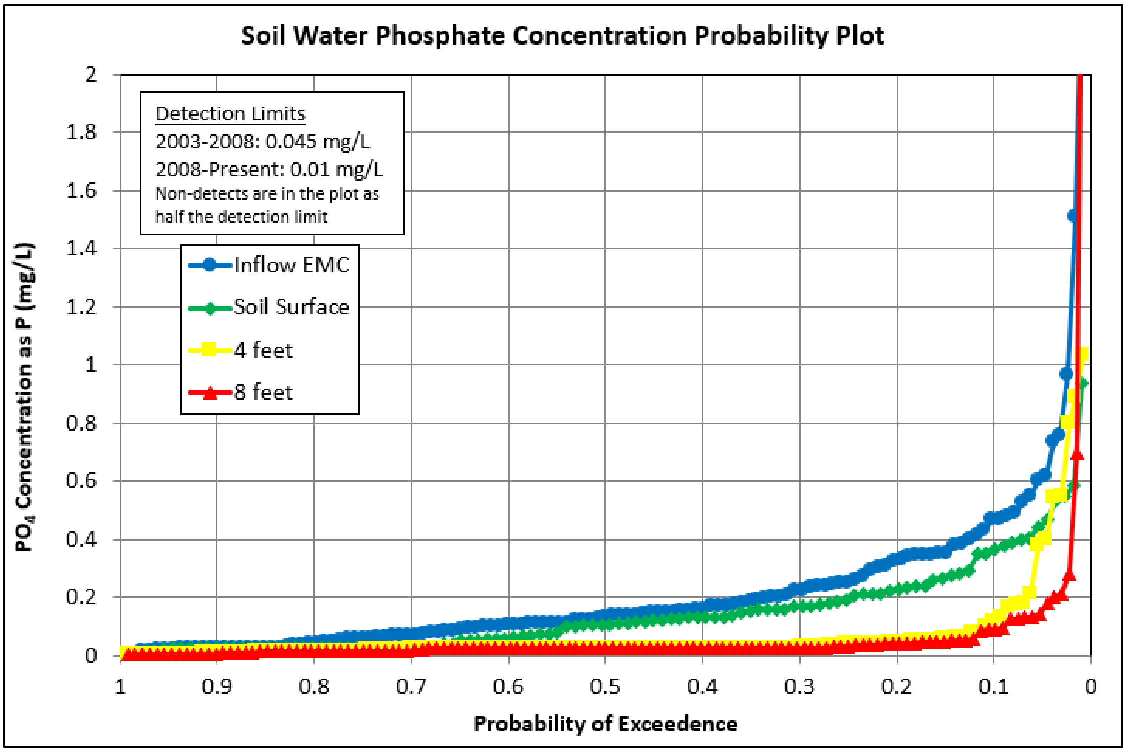

Figure 11. Orthophosphate probability plot

BRG Observations: Overall, while rainfall patterns change from year to year, the BRG is able to maintain its overall performance, as seen when comparing 2017 data to the past decade. calendar year 2016 was very different from 2015. Over time, there is a linkage of individual storm patterns to the performance. A key factor is whether overflow was generated. For only one water quality sampling event observed outflow. There were more outflow occurrences, but still a relatively low volume overall (Figure 7). Based on these results, and for the need to support SCM water quality design crediting, the VUSP is currently (in 2018) evaluating BRG performance in connection with specific storm volumes and patterns volume. The results from the Bioinfiltration Rain Garden continue to educate the profession, and we are learning from the ability to monitor sites in depth over time. The current work that is aiding our understanding of the ET / infiltration balance will add a new dimension to these results.

Constructed Stormwater Wetlands

The Constructed Stormwater Wetlands (CSW) Project was returned to the 319 NPS project in 2010. 2010 - 2011 was the Initial Monitoring Phase, and since the site has been under the current monitoring design. Site instrumentation was updated and installed and the revision of the monitoring design to match the changes to the site and project goals was done. It was determined that the focus of this study is on both flow and nutrients.

The CSW has three separate flow monitoring locations: the main campus inlet, the west campus inlet, and the outlet. Each parameter monitored is recorded in 5 minute intervals. The flow monitoring program was providing high quality data by the beginning of the 2012. Table 4 presents average flow data for storm and base flow conditions from 2012 to 2017, which shows that there is average flow rate reduction, generally, from inlet to outlet under both base and storm flow periods.

Table 4. Average storm and base flows (with standard deviations) from 2012 – 2017 with n as the number of inlet observations (with k SWMM supplemented events for missing data) and m as the number of outlet observations.

			Avg of Avg Flow In (CFS)	Avg of Avg Flow Out (CFS)	In vs Out - Statistically different? (t-test)
2012	Storm	n = 66, m = 38, k = 44	1.22 (0.90)	1.37 (1.67)	No (0.59)
	BF	n = 115, m = 70, k = 83	0.32 (0.42)	0.84 (0.35)	No (0.55)
2013	Storm	n = 69, m = 64, k = 38	1.29 (0.95)	0.67 (0.40)	Yes (<0.0001)
	BF	n = 126, m = 115, k = 81	0.19 (0.14)	0.16 (0.15)	Yes (0.0478)
2014	Storm	n = 73, m = 73, k = 40	1.48 (1.07)	0.88 (0.41)	Yes (<0.0001)
	BF	n = 129, m = 129, k = 83	0.33 (0.30)	0.25 (0.19)	Yes (0.009)
2015	Storm	n = 52, m = 52, k = 46	1.89 (1.12)	0.85 (0.34)	Yes (<0.0001)
	BF	n = 95, m = 95, k = 90	0.45 (0.80)	0.20 (0.12)	Yes (0.0026)
2016	Storm	n = 64, m = 40, k = 55	2.23 (1.21)	0.69 (0.29)	Yes (<0.0001)
	BF	n = 115, m = 73, k = 87	0.51 (0.42)	0.20 (0.18)	Yes (<0.0001)
2017	Storm	n = 70, m = 65, k = 38	1.14 (1.09)	0.78 (0.31)	Yes (<0.0001)
	BF	n = 127, m = 119, k = 73	0.45 (0.67)	0.24 (0.13)	Yes (<0.0001)

Table 5 presents peak flow reductions for storm events. There was an average peak flow reduction from inlet to outlet of 55% in 2012, 91% in 2013, 85% in 2014, 94% in 2015, 94% in 2016, and 91% in 2017. This peak flow reduction was matched with an average volume reduction of 32% in 2012, 49% in 2013, 46% in 2014, 55% in 2015, 66% in 2016, and 32% in 2017 during storm events. Additionally, there was an average volume reduction of 72% in

2012, 51% in 2013, 43% in 2014, 72% in 2015, 68% in 2016, and 52% in 2017 through the CSW for baseflow conditions, which may be attributed to evapotranspiration and groundwater recharge.

Table 5. Peak flow analysis for storms

			Average Storm Size (in)	**Avg. Peak Flow Reduction (CFS)**	**Avg. Peak % Reduction**
2012	Storm	n = 66, m = 38, k = 44	0.64 (0.74)	21.60	55%
2013	Storm	n = 69, m = 64, k = 38	0.76 (0.82)	39.83	91%
2014	Storm	n = 73, m = 73, k = 40	0.65 (0.83)	24.92	85%
2015	Storm	n = 52, m = 52, k = 46	0.74 (0.55)	61.24	94%
2016	Storm	n = 64, m = 40, k = 55	0.57 (0.50)	63.91	94%
2017	Storm	n = 70, m = 65, k = 38	0.49 (0.44)	35.24	91%

During this study, water quality sampling was conducted during baseflow conditions and storm events. Table 6 presents baseflow water quality parameters from 2011 - 2017, with reductions for all constituents except chlorides and total dissolved solids on average, which are expected results. Table 7 presents storm grab sample water quality parameters from 2011 – 2017, with a reduction of all constituents while Table 8 presents the storm autosampler water quality parameter for 2014 – 2017. It is important to note that the number of observations analyzed per event varies and said ranges are shown in the number of observations column. Additionally, more data must be acquired before any comparisons can be made between the grab sample observations and the autosampler observations.

Table 6. CSW 2.0 Baseflow 2011 - 2017 Average Water Quality Performance

Quality Parameter	n	Conc In (mg/L)	SD In	Conc Out (mg/L)	SD Out	% Removed	Non-Detect min & max (mg/L)
TN	36	3.11	1.38	1.21	0.80	61%	-
TKN	43	0.98	1.03	0.86	0.87	13%	0.01, 20.0
NO_2	70	0.092	0.16	0.055	0.27	40%	0.01, 10.0
NO_3	59	2.13	1.08	0.48	0.50	78%	0.01, 10.0
TP/TKP	58	0.20	0.16	0.14	0.23	30%	0.01, 20.0
PO_4	56	0.095	0.09	0.035	0.04	63%	0.01, 5.0
CHL	67	335	283	434	502	-30%	0.01, 200.0
TSS	71	25	100	16	29	34%	-
TDS	72	673	326	788	664	-17%	-

Table 7. CSW 2.0 Storm Events 2011 - 2017 Average Water Quality Performance

Quality Parameter	n	Conc In (mg/L)	SD In	Conc Out (mg/L)	SD Out	% Removed	Non-Detect min & max (mg/L)
TN	20	2.90	2.67	1.78	1.49	39%	-
TKN	27	1.09	1.01	1.00	1.19	9%	0.01, 20.0
NO_2	36	0.049	0.03	0.040	0.03	18%	0.01, 10.0
NO_3	26	1.55	2.25	0.64	0.50	59%	0.01, 10.0
TP/TKP	36	0.27	0.22	0.20	0.18	25%	0.01, 20.0
PO_4	29	0.065	0.06	0.050	0.04	22%	0.01, 5.0
CHL	36	340	473	210	325	38%	0.01, 200.0
TSS	39	16	19	12	11	23%	-
TDS	39	556	547	380	451	32%	-

Table 8. CSW 2.0 Storm Events 2014 - 2017 Average Water Quality Performance (Autosamplers)

Quality Parameter	n	Conc In (mg/L)	SD In	Conc Out (mg/L)	SD Out	% Removed	Non-Detect min & max (mg/L)
TN	3 to 16	2.16	1.04	1.38	0.63	36%	-
TKN	4 to 18	1.04	0.92	0.68	0.49	35%	0.01, 20.0
NO2	8 to 30	0.09	0.14	0.04	0.03	60%	0.01, 10.0
NO3	5 to 26	0.91	0.61	0.58	0.34	36%	0.01, 10.0
TP/TKP	8 to 326	0.20	0.16	0.17	0.15	14%	0.01, 20.0
PO4	5 to 25	0.06	0.03	0.08	0.05	-37%	0.01, 5.0
CHL	8 to 33	102.97	176.64	132.06	192.31	-28%	0.01, 200.0
TSS	8 to 33	30.38	45.20	14.43	25.29	53%	-
TDS	8 to 34	275.53	359.37	313.40	334.60	-14%	-

Focusing on two nutrients of concern, nitrogen and phosphorus (TKP includes all forms of phosphorus that have been converted to orthophosphate), it is seen that almost all the storm and baseflow observations reduced total nitrogen from Inlet to Outlet and were below water quality standards for PA (Figure 12) while the results from the storm samples taken by the Autosampler (2014-2017) fall below the PA standard for total nitrogen (Figure 13). Total phosphorus almost always had a reduction, although about 51% of effluent observations had concentrations greater than in-stream water quality standards for PA during a storm event and only around 21% of effluent observations had concentrations above the water quality standards during baseflow events (Figure 14). The effluent results from the storm samples taken by the Autosamplers have approximately 46% events fall below the PA standard for total phosphorus (Figure 15). In both cases, reductions tended to be seen from the inlet to the outlet.

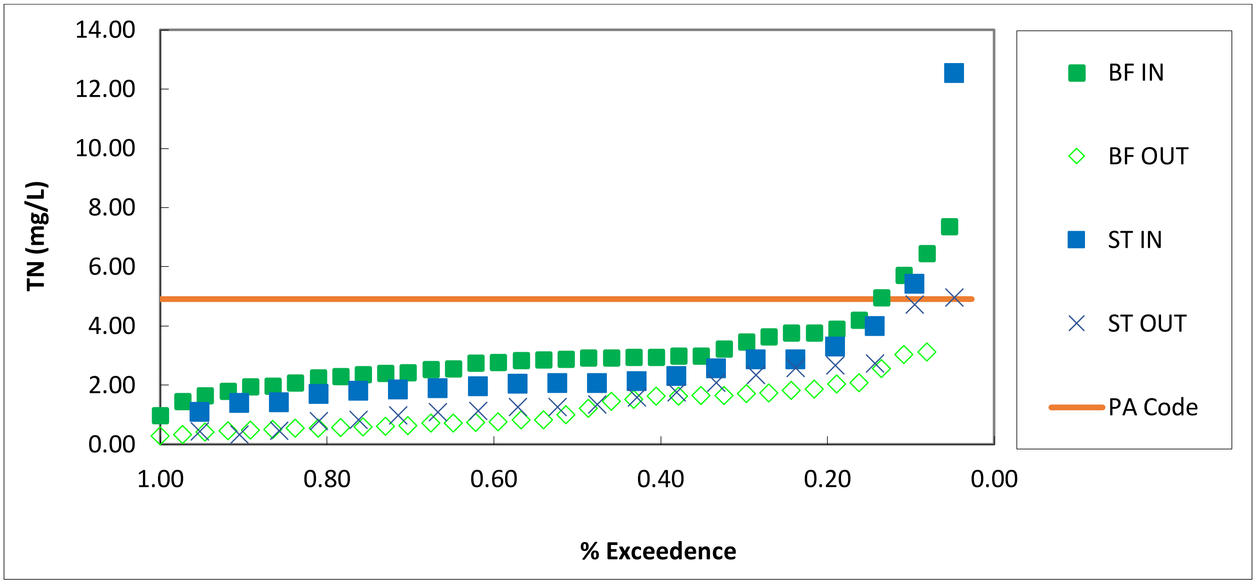

Figure 12. Percent Exceedance Concentration for Total Nitrogen 2011 – 2017 where BF is baseflow and ST is storm.

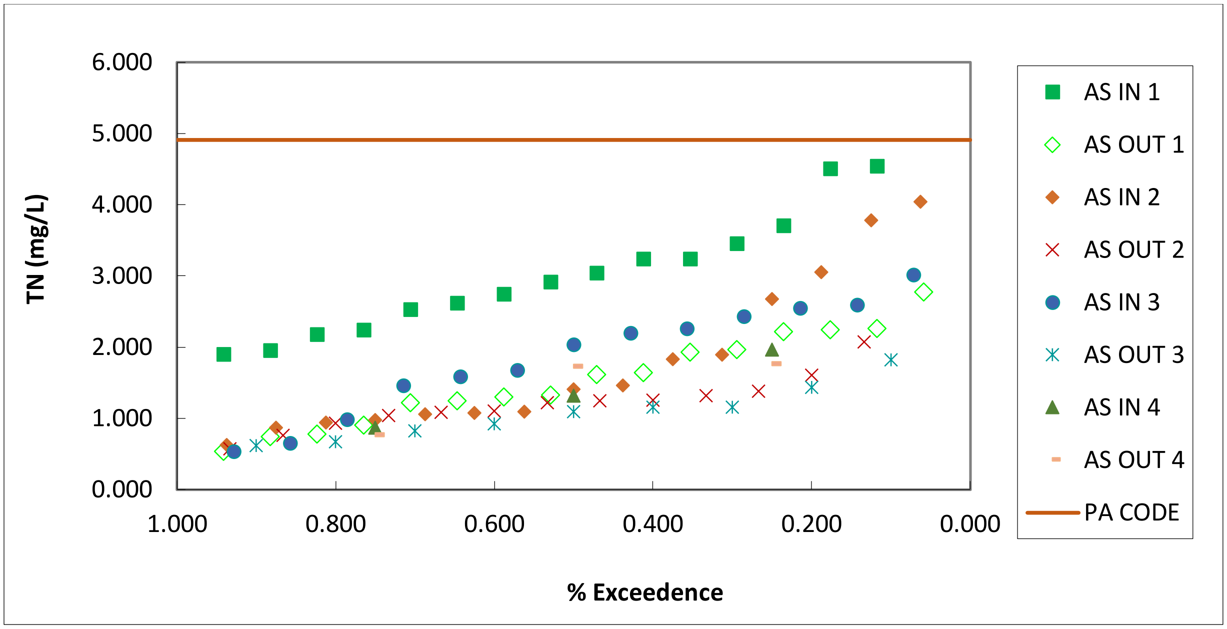

Figure 13. Percent Exceedance Concentration for Total Nitrogen 2014 -2017 Autosamplers (AS) where 4 storm samples were taken at both the Inlet and the Outlet.

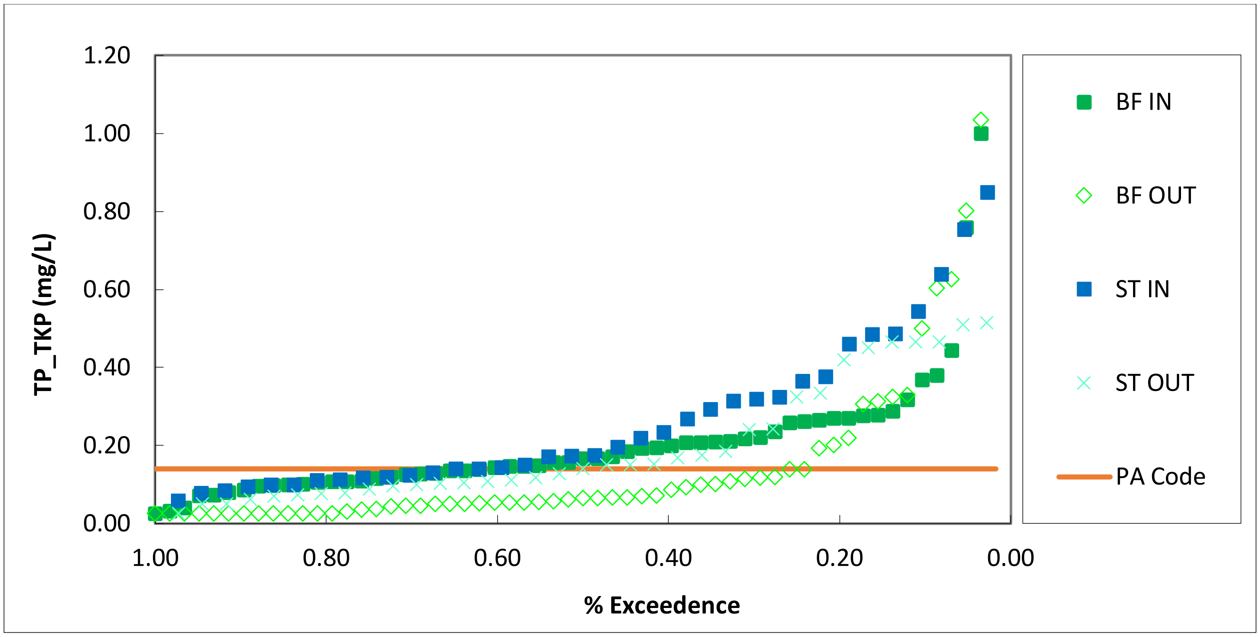

Figure 14. Percent Exceedance Concentration for Total Phosphorus 2011 – 2017 where BF is baseflow and ST is storm.

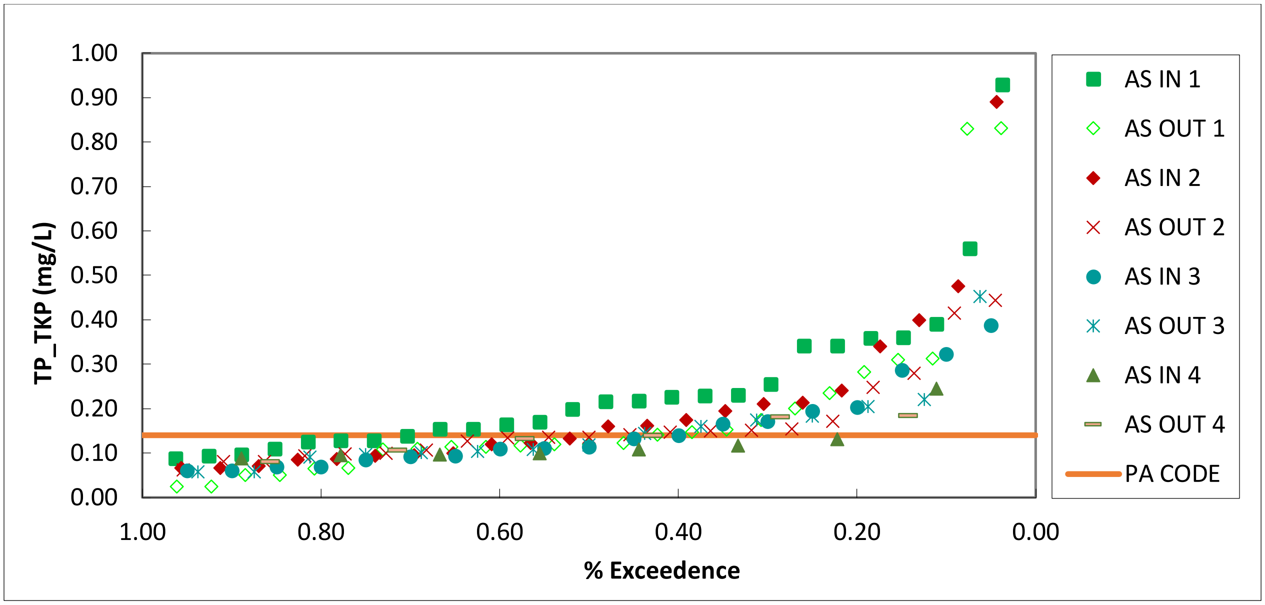

Figure 15. Percent Exceedance Concentration for Total Phosphorus 2014 -2017 Autosamplers (AS) where 4 storm samples were taken at both the Inlet and the Outlet.

Additionally, there were a minimal number of storm and baseflow observations from 2011 - 2017 where the effluent Total Suspended Solids (TSS) was greater than in-stream water quality standards for s. Figure 16 presents TSS data from 2011 - 2017 comparing the influent to effluent.

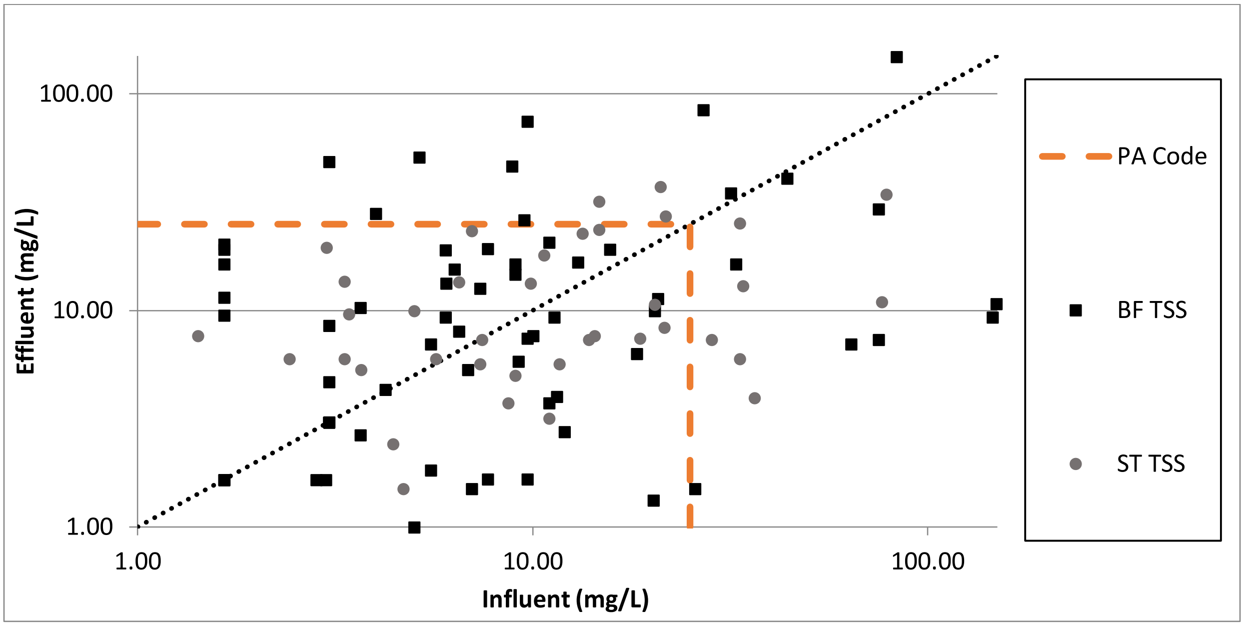

Figure 16. Total Suspended Solids Concentration Effluent vs. Influent Plot 2011 – 2017 where BF is baseflow and ST is storm.

Another area of study is the mass load reduction throughout the system. Table 9 below presents the mass load reductions for baseflow conditions during 2017 showing a percent removal of over 21% for all constituents. Table 10 below presents the mass load reductions for storm events during 2017 showing a percent removal of over 26% for all constituents Additionally, the percent removal of constituents during 2017 is on par with the percent removal shown in previous years, except for chloride, TSS, and TDS, as seen in Figure 17 and Figure 18 for baseflow conditions and storm events, respectively. There was much construction activity in the watershed that may have contributed to elevated solids loading.

Table 9. 2017 Baseflow Mass Loads

Quality Parameter	Sample Size	Mass In (kg)	SD In	Mass Out (kg)	SD Out	Mass removed (kg)	% Removed
TN	5	315.27	67.44	72.79	65.23	242.48	77%
TKN	6	64.95	24.20	35.61	59.14	29.34	45%
NO_2	11	10.91	13.28	0.48	0.56	10.44	96%
NO_3	9	253.47	66.26	35.42	50.98	218.05	86%
TP/TKP	11	21.54	17.18	6.58	21.30	14.96	69%
PO_4	9	9.36	8.61	1.54	1.08	7.82	84%
CHL	11	28534	29923	18757	14960	9778	34%
TSS	12	941	2905	740	2219	200	21%
TDS	12	71809	40789	42144	18211	29665	41%

Table 10. 2017 Storm Mass Loads

Quality Parameter	Sample Size	Mass In (kg)	SD In	Mass Out (kg)	SD Out	Mass removed (kg)	% Removed
TN	5	206.65	98.89	84.18	31.57	122.47	59%
TKN	6	114.46	78.54	49.93	25.53	64.54	56%
NO2	8	5.31	3.29	1.94	1.61	3.37	63%
NO3	7	71.77	45.72	31.60	10.49	40.18	56%
TP/TKP	5	21.20	19.79	6.98	3.34	14.22	67%
PO4	6	5.16	2.61	3.83	2.23	1.33	26%
CHL	9	7537	4693	5372	2267	2165	29%
TSS	9	4342	5837	1682	1873	2660	61%
TDS	9	20092	12820	13138	5527	6954	35%

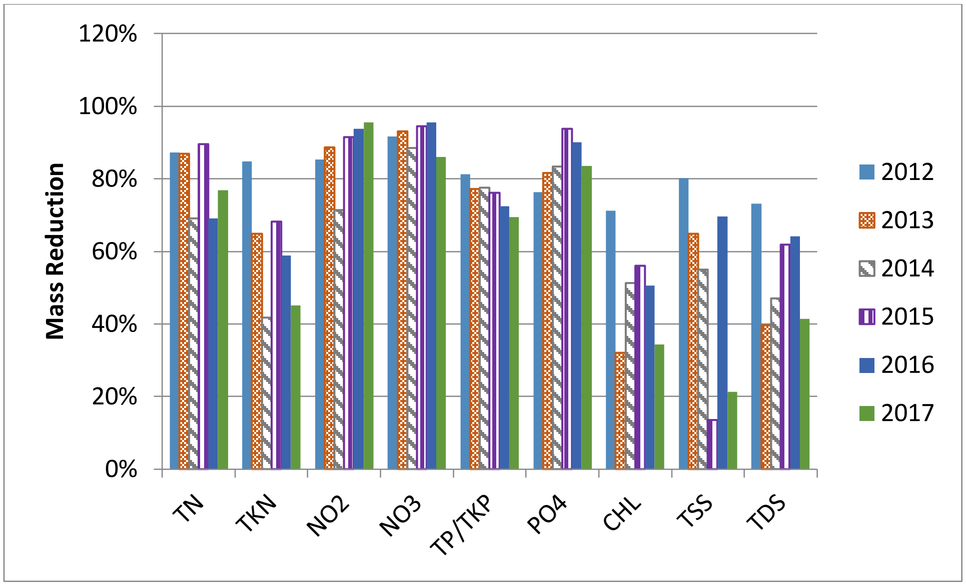

Figure 17. Baseflow 2012 - 2016 Mass Load Reduction

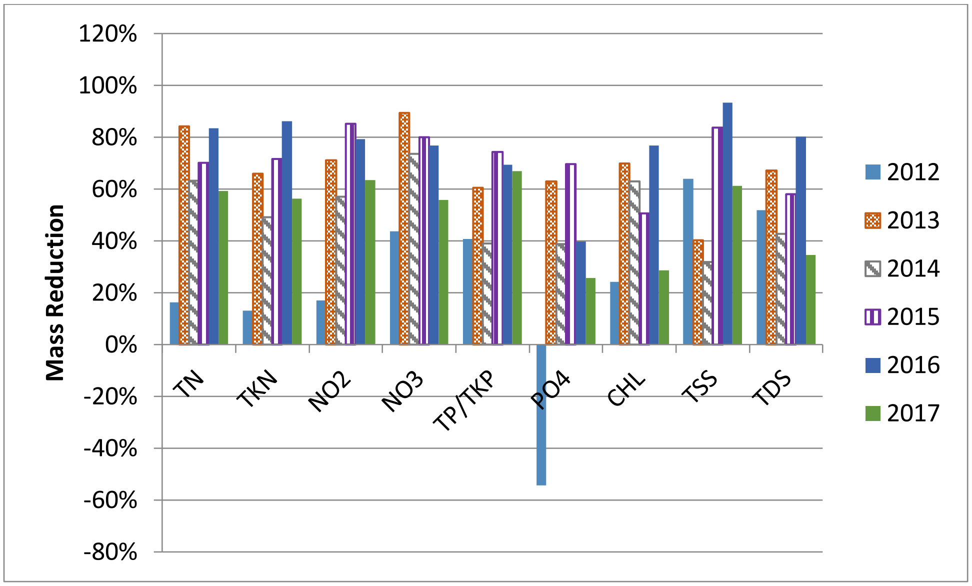

Figure 18. Storm 2012 - 2016 Mass Load Reduction

In addition to analyzing the performance of the CSW in terms of water quality, the retention time within the wetlands was also studied. For this study two Rhodamine WT probes were deployed during either baseflow conditions or storm events at different locations within the CSW (Figure 2) and a known volume of Rhodamine WT Dye was released at the Inlet. Preliminary data show tests that were run in 2017 with the probes located at the beginning of the first meander, the beginning of the third meander, the end of the third meander, and at the outlet structure. Figure 20 below shows the results of a tracer test from the start of the first meander to the outlet, while Figure 21 and Figure 22 show the results of the tracer tests from the beginning of the third meander to the end of the third meander during baseflow conditions. From these figures, a mean residence time of 41.9 hours from the start of the first meander to the outlet was determined (Figure 19) as well as a mean residence time of 3.6 hours and 5.6 hours from the start of the third meander to the end of the third meander (Figures 20 and 21, respectively).

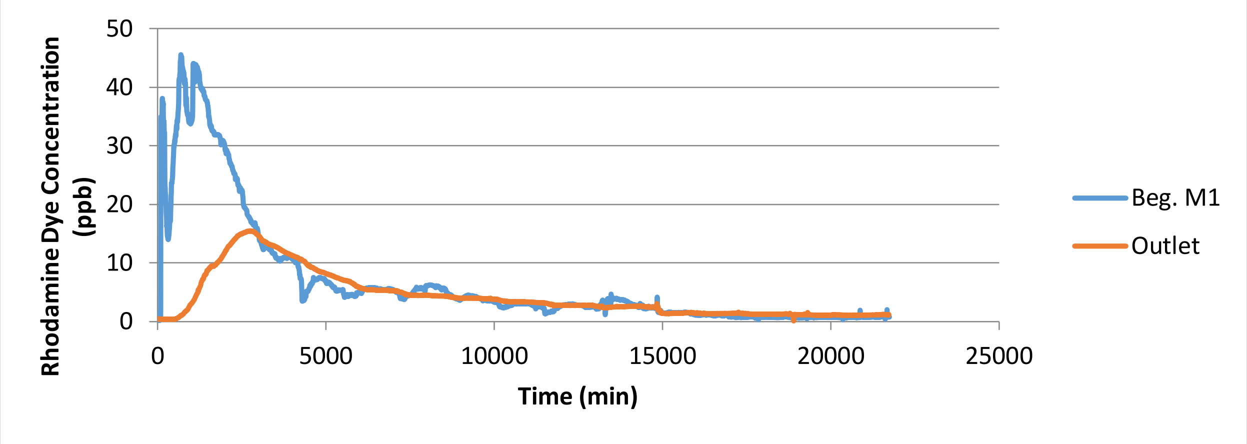

Figure 19. Baseflow Rhodamine Dye Tracer Test Results from the Beginning of the First Meander to the Outlet, conducted on 2/15/2017.

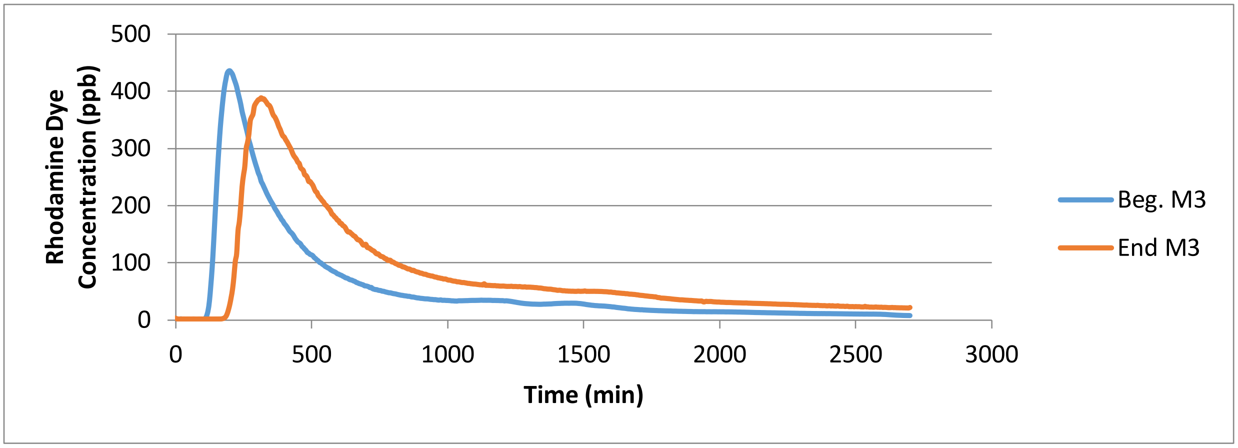

Figure 20. Baseflow Rhodamine Dye Tracer Test Results from the Beginning of the Third Meander to the End of the Third Meander, conducted on 9/27/2017.

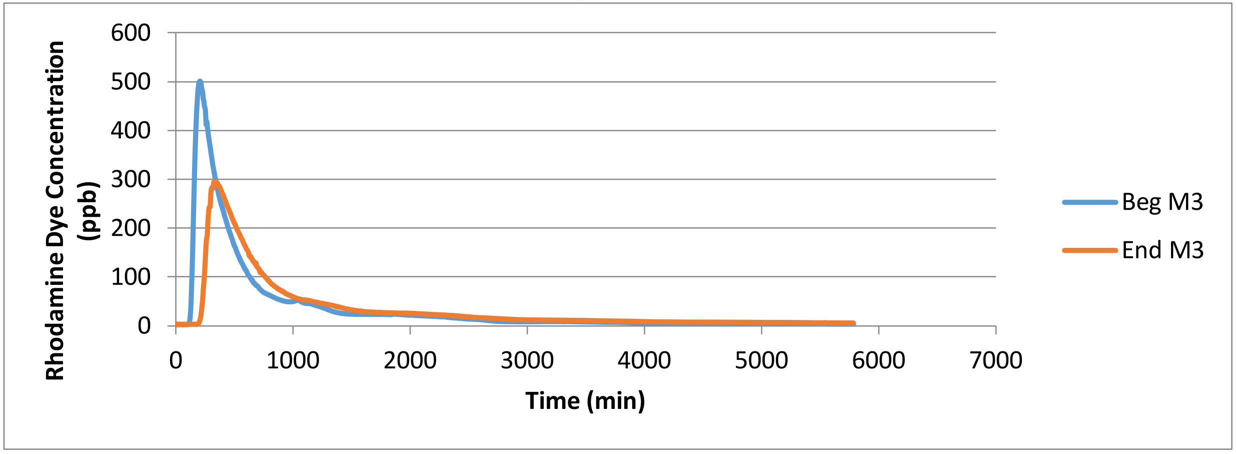

Figure 21. Baseflow Rhodamine Dye Tracer Test Results from the Beginning of the First Meander to the Outlet, conducted on 10/2/2017.

Figure 22 shows the results of a tracer test from the start of the first meander to the outlet during a storm event, while Figure 23 and Figure 24 show the results of tracer tests from the beginning of the first meander to the end of the first meander, both during storm events. From these figures, an average mean residence time of 51.6 hours from the start of the first meander to the outlet was determined (Figure 23), as well as a mean residence time of 2.94 hours and 14.5 hours from the beginning of the first meander to the end of the first meander (Figures 23 and 24, respectively). The average storm size for these tests was 0.43 inches with a standard deviation of 0.34 inches.

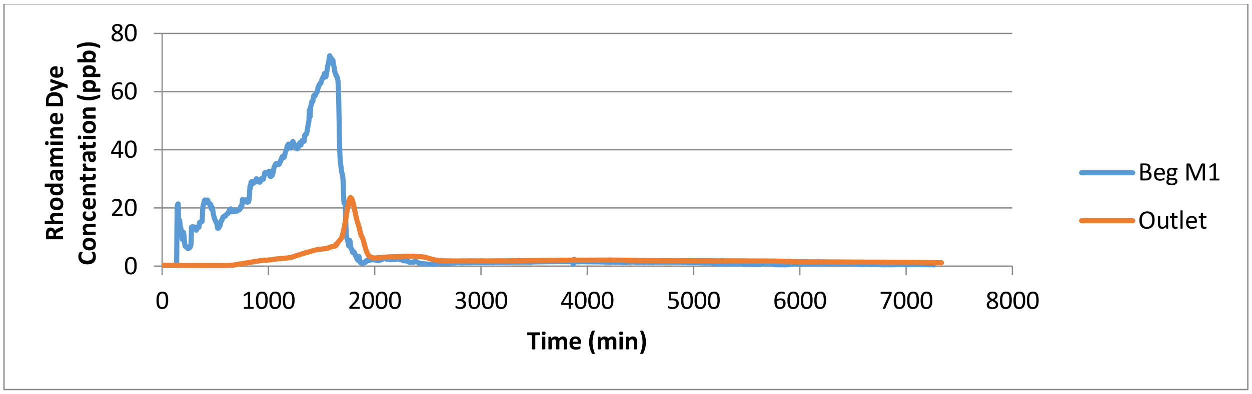

Figure 22. Storm (0.8 in., 57 hrs) Rhodamine Dye Tracer Test Results from the Beginning of the First Meander to the Outlet, conducted on 1/22/2017.

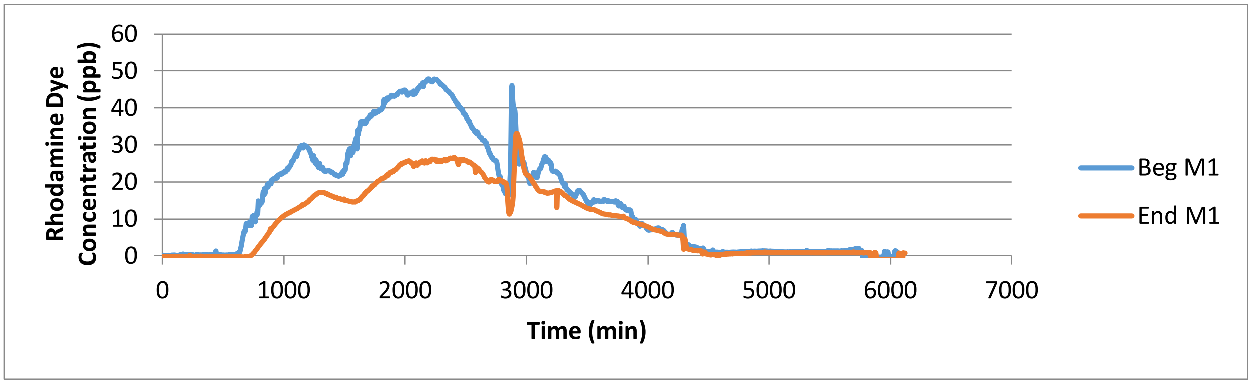

Figure 23. Storm (0.12 in., 4 hrs) Rhodamine Dye Tracer Test Results from the Beginning of the First Meander to the Outlet, conducted on 3/25/2017.

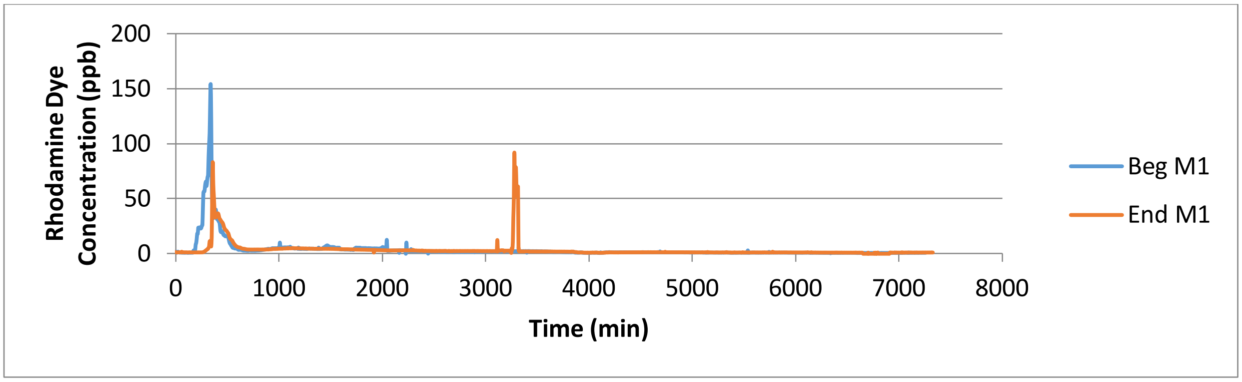

Figure 24. Storm (0.38 in., 19 hrs) Rhodamine Dye Tracer Test Results from the Beginning of the First Meander to the Outlet, conducted on 4/3/2017.

FINDINGS & RECOMMENDATIONS – Year 1-14

The advantage of conducting long-term investigation into multiple SCMs has been the ability to track performance changes over time and to contrast performance of different BMP types. Further, additional research grants from CICEET, the William Penn Foundation, and the Pennsylvania Growing Greener program among others has allowed us to perform expanded analysis beyond that funded by the EPA 319 National Nonpoint Source Monitoring Program. This research work coupled with our day to day experiences have led to the following findings and recommendations.

Findings

Proof of Concept: Results from constructing, operating, and monitoring green infrastructure infiltration BMPs have proven that these devices are robust, and are effective in removing pollutants and runoff volume from the surface stream. As observed in both the BRG and CSW, while there are annual and seasonal variations, the overall performance is consistent. When designed and built correctly, to include pretreatment for high producing TSS drainage areas, they should be expected to operate with minimal maintenance for long periods of time. *There should not be any expectations of failure or performance reductions for maintained sites.*

Effectiveness of Small Storm Capture: The efficiency of designing for small storms has been proven. Results from all sites have shown that because the majority of the region's rainfall is produced by smaller storms, SCMs designed for smaller storms are extremely effective in reducing runoff volume and capturing surface pollutants in regions with similar climates. For the Bioinfiltration Rain Garden, while only having a surface volume capture equaling ½ in of runoff from impervious surfaces, 100% of the runoff from the first ½ in of rain is removed, 97% of from the next ½ in and 50% from larger storms. In 2017, 92% of all inflow volume was retained within the BRG.

Variability of Infiltration Rate: Results from all sites have shown that the rate of infiltration during a specific storm is extremely variable, and dependent on season, temperature, soil moisture, and rainfall pattern. On a yearly basis, this variation has not interfered with performance, but must be considered when conducting municipal inspection / monitoring programs.

Robustness: Continuing performance of the Villanova University SCMs with minimal maintenance demonstrates the robustness of green infrastructure practices, as long as the systems are sited, designed, and constructed appropriately. After fourteen years, no major maintenance has been required of the bioinfiltration sites. At the constructed stormwater wetland, as vegetation has become more established since 2011, the system continues to minimize outflow rates, despite variable inflow.

Longevity and Annual/Seasonal Variations: A study based on the results of this project has shown that there is no statistical reduction in performance (Emerson and Traver 2008), which continues to be true. Longevity is achieved through proper design, construction, and siting (characteristics of the drainage area). Runoff from different contributing areas has been found to vary considerably in quality. Pretreatment devices would extend the life of infiltration SCMs in high pollutant loading areas.

Importance of Considering Rainfall Patterns / Volumes: Clearly the storm sizes influence the water quality picture. Having more small events can greatly increase the volume reduction performance, compared to years with droughts and extreme events. An annual approach would be more representative then individual storm events.

Vegetated Systems

Evapotranspiration is significant: Results from the 319 and companion Growing Greener studies have verified the significance of infiltration in removing soil water and recovering void space. There should be no concern in this region over back to back events as evidenced by the data. The chief reason for reduced ET was the lack of soil moisture. We can now recommend ET focused vegetated systems for areas with high water tables, polluted soils, or other areas where infiltration is not desirable.

Balance[BW2] *of Deep Infiltration versus Evapotranspiration*: Still a work in progress, but analysis of the groundwater mounding is making us believe that the volumes evapotranspired are substantial, which means the volume that reaches the groundwater is much smaller then commonly assumed. This also means that the volumes of potential contaminants passing through the soil media are also much less than expected.

Static Design – Analysis from the BRG sites and other VCRWS studies shows repeatability of performance of volume reduction, which is often greater than the designed volume removal performance because of dynamic hydrologic processes.

Dynamic Design – We are regularly seeing volume reduction for storms larger than the design volume. Current and future research is moving toward how to credit and design to address these larger rain event volumes.

BioInfiltration Soil Media – Phosphorus. The site has been shown to be effective in reducing phosphorus with a slow infiltrating media mix. The volume of phosphorus reduction is related to that caught in the soil layer. A refereed journal article on this subject (Komlos et al. 2012) found that the top 10 cm of soils would last at least 20 years before all the receptors were full, not including the great remainder of the soil media below that. Needless to say there is no reason to expect reduced performance in the foreseeable future. Similar to metals the removal mechanism is in the top portion of the soil profile.

BioInfiltration Soil Media – Depth. We are still unclear as whether we would see the same performance with three feet as we are to four feet of depth for both volume and pollutant removals. Current studies will aid in our understanding.

Permeable Pavements

Thermal Benefit - Analysis of data has clearly demonstrated the effectiveness of temperature reduction for the PAPC site.

Water Quality - Analysis of data has clearly demonstrated the effectiveness of pollutant abatement for this site.

Stormwater Wetlands

Importance of Vegetation: As the wetland matures in the context of vegetation establishment, performance in the areas of water quality and quantity have improved. The CSW increased in treatment performance on both peak flow and volume reduction levels during storm events. In 2012 the average peak flow reduction during a storm was 55% and in 2017 it was 91%. In regards to water quality, nearly all the parameters measured for baseflow and storm events have increased with respect to concentration percentage removed from inlet to outlet since the system was first built (2011) and operates within a range of performance annually due to variations in climate and land use. When considering the mass removed of each constituent, the treatment capability is emphasized as it is the combined effort of concentration and volume reduction. The treatment capacity of the CSW comes from natural processes, specifically the slowing of flows through dense vegetation, that are allowed to happen through the long retention times. Further research will be conducted to account for the various contributions to nitrogen and phosphorus removal in the wetland. Additionally, it is necessary to maintain wetland systems to have a diverse and abundant plant mix that will enable natural biodiversity.

Natural Biodiversity: Not only does the stormwater wetland provide treatment performance on both a water quality and quantity level, it also provides a habitat to many plant and animal species. Biodiversity is an important aspect of an ecosystem because of its role in boosting productivity. By productivity this includes but is not limited to providing an array of healthy species, playing an important part in ecological services, and even letting an ecosystem recover or adjust to extreme events or disturbances. Apart from the biological benefits of biodiversity, a well-balanced ecosystem provides educational value along with community involvement.

Volume Reduction – We are seeing substantial volume reduction for both storm and base flow systems, indicating contributions to the groundwater table and to evapotranspiration. These results are under further study.

Sustainability

Life Cycle analysis – A life cycle approach is needed for SCM evaluation of ancillary benefits. For example, the embodied energy and pollutants produced when quarrying sand (energy, carbon, etc.) and producing mulch for the Bioinfiltration Rain Garden negated the environments benefits for the first two years of its life. Quantified life cycle benefits (or avoided impacts) during the operation phase of the system suggest that continued environmental performance of rain gardens and other green infrastructure offer services that not only offset adverse life cycle impacts but provide net benefits. A Master's study predicts that rain garden vegetation mitigates the carbon emission impact equivalent to one car per year (Flynn and Traver 2011).

Recommendations

Dynamic Green Infrastructure Design. It is recommended that a dynamic approach to GI design be incorporated that includes the regional weather patterns, and infiltration during the event using a continuous model approach be considered during the revision of the Pennsylvania Stormwater BMP manual. Increase of the infiltration foot print area should be encouraged.

Bioinfiltration Rain Garden – ET – Current literature and experience from a companion Growing Greener ET grant has increased our understanding of the role of ET. Much of the water captured is evapotranspirated depending on the design. This couples with the minimal risk of occurrence of back to back rainfall events should allow longer ponding durations then presently allowed. It is recommended that a rain garden design for areas where infiltration is not easily utilized be developed that holds water with in the root zone of the soil to utilize ET as the primary removal mechanism. It is also recommended to include ET in volume capture and treatment.

Bioinfiltration Rain Garden – Bowl Depth **-** The longevity of the site with minimal maintenance leads us to recommend that depths of the bowl can be increased to a minimum of 18" from a hydrologic perspective. It is recognized that in some areas this would not be desirable from a convenience or safety factor. This would reduce the footprint and expand the use of this type of control measure.

Media – High flow rate sand media may not be our best alternative, and in fact native on site soil may be superior (from both site performance and life cycle impact perspectives). The life cycle footprint of mulch (significant production impacts) also suggest that the use of mulch should be limited to helping establish initial vegetation and only be applied as needed thereafter. These recommendations are still being researched.

Performance Crediting – To properly credit pollutant removals requires a linkage of volumes and quality rates. An annual approach provides a more accurate depiction then extreme events.

Sustainable Design – Treatment Train – Our experiences with multiple designs lead us to recommend that a sustainable treatment train design concept be recommended in future Pennsylvania BMP Manuals. First flush / frequent storms should be targeted with filtration / volume reduction designs that are robust and can be maintained. This would include rain gardens or swales, sheet flow, or other easily accessible processes. Further volume reduction or rate SCMs (Infiltration Trenches etc) can then be employed for larger storms. Note that pervious pavements also follow this concept with the surface acting as a filter.

Constructed Stormwater Wetland – The wetland system, like other systems, are passive systems in that stormwater moves in and out as storms occur. Unlike other systems, the wetland supports aquatic life and is often used to target several, often conflicting goals, such as water quantity reduction, nutrient retention, temperature moderation, and adequate dissolved oxygen levels. To be able to accommodate these complex goals simultaneously, it may be beneficial to add real-time controls to the system via a system of gates that can direct the flow in response to existing and forecast conditions. Additionally, it could be beneficial to isolate physical processes to increase treatment of specific pollutants of concern.

Indirect Benefits

Introduction to the Profession: These sites have introduced the concept of using infiltration BMP's to both the Profession and the Public across Pennsylvania and the United States if not the world. Lessons Learned as to design, maintenance, expected performance are disseminated through tours, internet sites, and through presentations.

National International Perspective. The results of this work have led to requests for presentations to Congress, EPA Office of water and many others. Villanova cohosted the 2011 Low Impact Development conference with over 700 attendees. Dr. Traver was a panel member for the National Research Council report commissioned by EPA entitled *Urban Stormwater Management in the United States (2009).* Note that the research from this project is heavily referenced in this report. In 2015 Dr. Traver was an invited guest to a meeting of experts convened by WEF in developing their stormwater strategy, and is now a member of the WEF Stormwater Institute steering committee. More recently, VUSP personnel have presented at stormwater events in China, Ireland, and Panama.

Regional Perspective. The results of this work have led to many tours and requests for presentations across the area and the state. This is evidenced by the 311 attendees of the 2015 PA Stormwater Symposium.

Catalyst for Advanced Studies: Through the continuing data stream, more advanced studies are using this data. Reminder that no faculty time is included in the 319 NPS grant. Funded Projects by William Penn with Temple University, and the USEPA, NSF and PWD extend the value of this work.

Catalyst for Studies by others: The data submitted to the ASCE – EPA BMP National Database is supporting other studies nationwide on BMP Performance. Dr. Traver was on an expert panel reviewing a rewrite to include LID in the database. Unfortunately, inclusion of data is sporadic depending on funding for the BMP Manual data team.

Education: The graduate students who are supported on this grant enter the workforce as engineers with advanced understanding of stormwater design to mitigate nonpoint source pollution. In addition, these results are used in undergraduate and graduate engineering classes at Villanova, supporting the advancement of the profession, and aiding in the protection of the water resources of the Commonwealth.

Green Infrastructure: Villanova now routinely builds pervious pavements and rain gardens as part of new building projects. Including ARRA projects, Villanova now has 15+ rain gardens, and five pervious pavement sites. The Stormwater wetland is visited and used by other departments and is an admired feature on campus. A future retrofit project is expected to remove the first 2 inches +/- of runoff from a large paved site.

PROGRAM OUTREACH

Project information is disseminated to the environmental, land development, scientific, and regulatory communities through a number of networks. First, the results are presented in peer reviewed journals as well as at industry conferences at both the national and local levels. Second, Villanova hosts a biannual statewide stormwater symposium that is used to support outreach. The Pennsylvania Stormwater Symposium is broadcasted and archived live at no charge over the internet. Our Outreach activities on a continuous basis include our graduate student seminars, campus tours to community members including high school students from nearby schools, invited lectures and workshops by our faculty members at different occasions.

All project reports and theses are available on the web (www.villanova.edu/VUSP). Additionally, to increase VUSP interaction with public and private partners, the VUSP has recently introduced a Twitter account (https://twitter.com/vuspteam) and blog (http://vusp.wordpress.com/) to disseminate pertinent findings and provide updates.

It should be noted that the work is also incorporated in the graduate and undergraduate classes at Villanova, and that graduate students working on the project gain a wealth of experience.

Some other highlights of our outreach are as follows:

- VCRWS faculty and students volunteered for the St. Thomas of Villanova Day of Service. Since 2014, we yearly partner with PWD and community members to plant and maintain rain gardens.
- VCRWS hosted its ninth Pennsylvania Stormwater Management Symposium in October 2017 and there were over 300 representatives from academia, industry and the public sector in attendance.
- VCRWS organizes and participates in STEM programs.

Future Directions and Recommendations

Similar to last year’s statement, the Villanova Stormwater Research and Demonstration Park remains a viable and valuable research tool. The proximity of the on-campus SCMs to the students and laboratory allow a depth of exploration and visibility not realistic elsewhere. These findings confirm the need to continue studying the operation of green infrastructure infiltration SCMs, to further understand the unit processes as they age. Progress continues on understanding the relationships between site characteristics, load and volume to SCM design, but more research is needed. As understanding advances, the VUSP expects that the design methods used for these SCMs will change to more accurately represent the hydrologic, chemical and biological processes involved, and that these changes will lead to more resilient systems. Given the long-term nature of the affiliated datasets, upcoming research is going to do a comprehensive analysis of rainfall characteristics to connect to systems performances to determine how reliable and predictable the systems’ performance is. Simply stated, these changes will advance our ability to protect our waters. Currently, funding is in place through 2019, and it is the expectation of the researchers to continue this work on both current and future BMPs at the Villanova campus.

Bioinfiltration Rain Garden - Emphasis will continue on understanding the water balance, and extreme event performance.

July 2016
- Start

2016 – 2017
- Publication on Dynamic Design -
- Meeting of Partners to discuss research needs
    - Note: Research direction will be informed through these discussions.
    - Research direction is expected to examine longevity and role of media, bowl and vegetation.

2017-2018
- Publications relating linkage of water quantity to quality.
- Hydrologic Water Cycle Performance – Roles of ET and infiltration.
- Site to be a focus for the 2017 Pennsylvania Stormwater Symposium.

2018-2019
- Update to BMP database as appropriate.
- Publication based on 2017 research direction.
    - Expected to examine longevity and role of media, bowl and vegetation.

June 2019 Contract End

Stormwater Wetland - Monitoring for this project was restarted in 2011. More data is required to build an understanding of the ultimate fate of pollutants as well as retention times within the system. A series of invasive plants are currently taking over the ecosystem and a plan is underway to re-introduce native species. One of the berms that has eroded over the past years has been rehabilitated during summer 2016 and will be monitored to ensure its integrity. In connection with a National Science Foundation grant, two automated gates will be added at Meander 1 and Outlet to have active control over flow through the system to ideally better manipulate flow through the system to meet stormwater goals.

Pre Contract
- Begin invasive species eradication and native species implementation, including use of goats to control plant growth.

July 2016
- Start

2016 – 2017
- Update to BMP database as appropriate.
- Publication on wetland travel times and temperature.
- Meeting of Partners to discuss research needs
    - Note: Research direction will be informed through these discussions.
    - Research direction is expected to examine longevity and role of media, bowl and vegetation.
- Continue native species implementation

2017-2018
- Publications on nutrient cycling through the wetland.
- Site to be a focus for the 2017 Pennsylvania Stormwater Symposium.

2018-2019
- Update to BMP database as appropriate.
- Publication based on 2017 research direction.
- Expected to integrate findings relating this work to the National Science Foundation project adding smart controls.

June 2019 Contract End

Published Major Works

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3. Zaremba, G., Molina, S., Wadzuk, B., Traver, R., "Retrofitting a Constructed Stormwater Wetland with Real Time Control." Proceedings of the 2017 EWRI World Environmental and Water Resources Congress, Sacramento, CA, May 21-25.
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OTHER PERTINENT INFORMATION[BW5]

VUSP Mission Statement:

The mission of the Villanova Urban Stormwater Partnership is to advance the evolving field of sustainable stormwater management and to foster the development of public and private partnerships through research.

* VUSP Media & Outreach include:

VUSP Website: http://www.villanova.edu/VUSP
VUSP Twitter (@vuspteam): https://twitter.com/vuspteam

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