Project Report

VUSP ~ PaDEP - Best Management Practice National Monitoring Site

Year 9

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Nonpoint Source
National Monitoring Program
Clean Water Act Section 319

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VUSP
VILLANOVA URBAN STORMWATER PARTNERSHIP

http://www.villanova.edu/VUSP

PROJECT OVERVIEW

Since the early 1990's the field of stormwater management has undergone a dramatic shift from a myopic- flood prevention approach to a more sustainable view that embraces both water quality and quantity. A new suite of control measures termed Best Management Practices (BMPs) was developed to treat various forms of water pollution including runoff volume and peak flows from urban stormwater. As these practices evolve, many in the stormwater community are using the term Stormwater Control Measures (SCM) to reflect the growing science basis of these designs as acknowledged by the Joint ASCE/WEF Manual of Practice titles "Design of Urban Stormwater Controls," and the National Academies report entitled Urban Stormwater Management in the United States (National Research Council 2008).

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 a 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 (NMP) in 2003.

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

1) To improve our understanding of nonpoint source pollution;

2) To scientifically evaluate the effectiveness of watershed technologies designed to control nonpoint source pollution; and

3) To export our results and lessons learned to the stormwater community.

Since 1999, VUSP has constructed and monitored multiple innovative SCM devices to include a stormwater wetland, bioinfiltration and bioretention rain gardens, pervious concrete / porous asphalt installations, an infiltration trench, green roof and a treatment train. Other practices on campus include both wet and dry ponds, rain barrels, a bioswale and a seepage pit estimated to have been built in the 1890s. Information on the design and construction of some of these SCMs, as well as the design of monitoring efforts, was presented in two 319 program publications (Traver 2004, 2010).

By monitoring wet weather flows and pollution entering and exiting each BMP, the effectiveness of these technologies can be measured and evaluated. The longevity of the study increases our knowledge of how these devices work, and how to ensure their performance over long periods of time. What is unique to this study is that as the SCMs research goals are reached, the focus has shifted to either a another aspect or a different SCM. This process is supported by feedback from the VUSP partners to include 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, it does indirectly aid, and is enhanced by the synergy of several projects on campus. For example financial support for the construction and monitoring of the BMPs has come from a variety of sources. Construction has been funded through the Pennsylvania Section 319 Nonpoint Source program, the Pennsylvania Growing Greener I and II programs, and Villanova University Facilities Department. Monitoring has been supported by EPA Section 319

NMP, in collaboration with research projects funded through the William Penn Foundation, 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).

Educational signage has been installed at each SCM site as appropriate to enhance the learning experience and a website has been created to facilitate 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.

This project report focuses on data of the active sites for 2012, and activities of the partnership through 1 November 2013. For 2012, The Bioinfiltration Rain Garden, and the Constructed Stormwater Wetland were monitored supported by the 319 NPS program.

PROJECT BACKGROUND

Even before the term was developed, “Green Infrastructure” infiltration SCMs have been the focus of much research at Villanova. Each of the sites described below has been under study since construction. Websites for each stormwater BMP project can be viewed through the following link: http://www.villanova.edu/vusp.

Figure 1. Photograph of VU Bioinfiltration Rain Garden BMP (2007).

Bioinfiltration Rain Garden (BRG). (PA Growing Greener Grant, constructed summer 2001). This bioinfiltration BMP (previously termed Bioinifiltration Traffic Island) was created by retrofitting an existing traffic island on Villanova’s campus as shown in Figure 1. The facility intercepts runoff from a highly impervious (50%) student parking area and road (0.53 ha) that previously would be collected by inlets and delivered through culverts to a dry detention basin. The BMP is designed to control runoff from smaller storms (1 – 3 cm) through capture and infiltration of the first flush. Capture of these small storms treats more than 80% of the annual rainfall, thus improving water quality, reducing downstream bank erosion and maintaining baseflow.

Figure 2 Photograph of VU Constructed Stormwater Wetland from Google Earth (2013).

Stormwater Wetland – (319 Grant – 1998, 2010 - concluded) An existing stormwater detention basin on Villanova University property was converted into an extended detention wetland BMP, and was rebuilt during 2010. Currently the site has established vegetation growth over the past year and fauna have moved into the ecosystem. The constructed stormwater wetland treats runoff from a 43 acre site that includes 27 acres of impervious surface. The watershed includes student's residence halls, classroom buildings, parking, roads and a railroad. The contributing watershed forms the headwaters of a watershed listed as medium priority on the degraded watershed list, and treats flows that impacts a high priority stream segment on the 303(d) list. Educational signage has been installed to enhance the learning experience, and a website has been created to facilitate technology transfer. The project has been published as an EPA 319 Success Stories Part III. This site was reintroduced as a 319 NPS project in May 2011. Baseflow and wet weather flow quality and quantity studies are ongoing, along with, more specific studies measuring dissolved oxygen levels and algal production. Water quality and quantity improvements have been measured from influent to effluent.

Supporting SCM Project sites: Several additional SCM sites that were reported previously are currently not under study. These include the Infiltration Trench, Porous Concrete, and Porous Concrete / Pervious Asphalt SCMs. Note that the porous concrete site is now made up of porous pavers, and is the subject of proposals for future study. Details of these sites are available in Student Thesis / Dissertations, Journal articles, in the NWQEP Notes from 2004 and 2010, Past NMP reports and the VUSP website.

Water Resources of Concern

All sites are built to mitigate the effects of urban stormwater runoff on area 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, while Constructed Stormwater Wetlands is at the headwaters of Mill Creek, which is a tributary to the Schuylkill River.

Water Uses and Impairments

Both Darby and Mill Creeks are rated as degraded and listed on the 303d list, with urban runoff listed as the cause. Note that urban runoff is rated as the Nation's third highest leading source of water pollution (EPA, 1998 and 2002b). The EPA Region III website lists stormwater as the second highest cause of stream impairment as measured by river miles.

Pollutant Sources

Unlike many types of polluted water, stormwater typically is characterized by rapidly changing and widely fluctuating flows; in some instances high flow periods are accompanied by high concentrations of pollutants, leading to exceptionally elevated short-term loads to receiving waters. In addition to suspended solids, nitrogen and phosphorus, stormwater runoff may contain elevated concentrations of lead and zinc, which also have the potential to affect receiving waters adversely.

Pre-Project Water Quality

For this project, inflow to the stormwater BMP sites is treated as the pre-project water quality.

Water Quality Objectives

As stated earlier, all projects are developed to mitigate the effects of urban runoff. The infiltration projects are designed to remove the volume of the first portion of the storm event from the surface stream thus recharging baseflow and treating the first flush. The constructed stormwater wetland is designed for treatment, extending contact with the vegetation, and slowing down and reducing peak flows.

Project Time Frame

The project time frame is to monitor all sites for six to ten years. 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 and the porous concrete rock bed did not adequately represent the inflow conditions so first flush samplers were installed for both these practices. 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 have been addressed through development of new laboratory techniques and purchase of new equipment. Multiple 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 this past year, 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.

The Constructed Stormwater Wetlands site was in the Initial Monitoring Period for 2011. Data from monitoring in 2012 is included below.

PROJECT DESIGN

Nonpoint Source Control Strategy

The control strategy is to assess flow volumes, rates and pollutant loads for wet weather flows entering and exiting the BMPs. The inflow and outflow of individual BMPs are examined.

Project Schedule

Site	Status	Initial Monitoring Phase	Notes
Bio-Infiltration Rain Garden	Monitoring Underway 10/01/04-Current	10/01/03-09/30/04	IMP - added first flush samplers + bowl lysimeter. GW Well added 2006 Additional GW Wells added 2007 Composite Bowl Sampler added in 2008. Additional GW Wells added 2012 Outflow Level instrumentation updated 2013 Soil Moisture Meters added 2012/13 Concrete inflow flume added in 2013
Stormwater Wetland	Baseflow and Wet Weather Monitoring Underway 05/11 - Current	05/11 – 12/11	Added new flow monitoring equipment, Weir assemblies, and DO and Temperature probes

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 as well as soil moisture meters. Water quality samples were 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. As sampling is conducted from the vadose zone, soil lysimeters are used to collect water samples under the beds (treated as a composite sample). Note that only dissolved fractions are collected from the vadose zone samples and that the sample volume is limited, occasionally limiting the number of tests performed.

Stormwater quantity: The Bioinfiltration Rain Garden has been equipped to accept runoff entering the system via two inlets (north and south), and from a culvert that intercepts runoff from an adjacent culvert.

- Rainfall is measured in 5-minute intervals with a tipping bucket rain gage. Overflow is estimated through a model calibrated to a combination V notch weir / pressure transducer. The overflow pressure transducer was updated to a more accurate model in 2013, taking advantage of industry advances.
- Depth within the bowl is measured directly. This was updated to 2013 to a highly accurate bubble meter. Past methods included using an ultrasonic level recorder and pressure transducer.
- Inflow is determined from a calibrated hydrologic model using all data mentioned previously.
- Multiple pressure transducers are installed in surrounding wells. This was inactive over this period, but is again being monitored in 2013.

Stormwater quality: Surface runoff and sub-surface vadose zone samples are collected for approximately 12-18 storms/year.

- Two first-flush samplers catch the first two L of direct runoff from the impervious surface and the grass area adjacent to the basin.
- Initially, a grab sample was collected of surface water during the storm event, with a second sample collected at the conclusion of rainfall, if ponding had occurred. This has been replaced by an automated composite sampler.
- A composite grab sample is taken from the outflow weir.
- 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.
- Grab samples have been taken in the past of the groundwater from surrounding wells. These samples were part of a SCM project that was completed.
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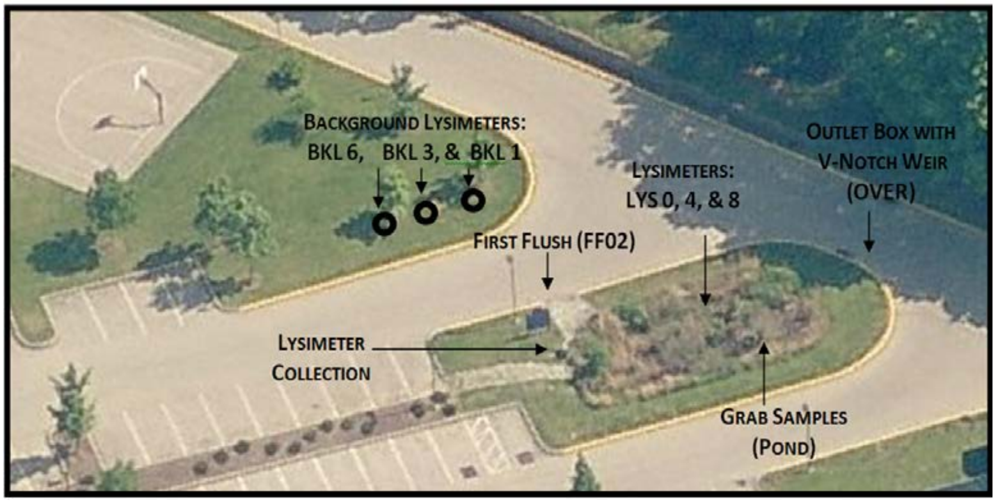
Figure 3 shows a schematic drawing of the sampling locations for surface water samples at the Bioinfiltration Rain Garden, and Figure 4 shows the horizontal position of the groundwater lysimeters.



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

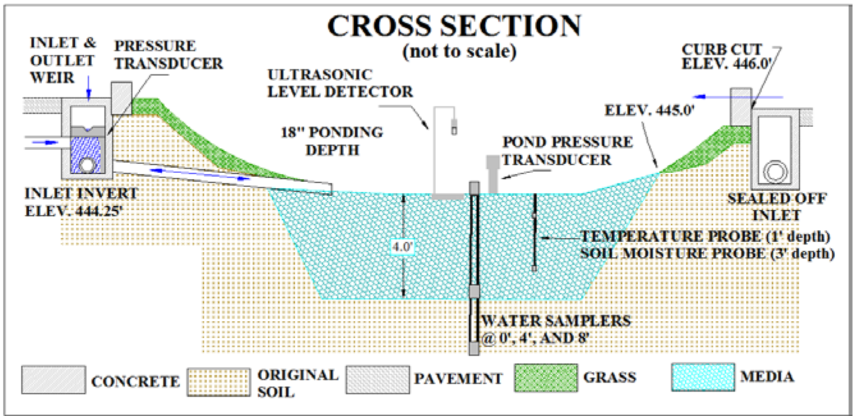


Figure 4. Diagram of BRG subsurface sampling locations

Constructed Stormwater Wetland (Figure 2) – The Constructed Stormwater Wetland has a custom-designed monitoring system to evaluate the surface water quality and quantity. The site has a rain gage and other climate data and flow / level recorders. Water quality samples were collected using grab samples. There are four dissolved oxygen and temperature sensors within the system. The water quantity sampling is currently at the inlet and outlet. There is a velocimeter at the two main inlet pipes that records flow data at 5 min intervals continuously. There is a velocimeter and a redundant weir/pressure transducer system measuring flow at 5 min intervals at the outlet. The water quality sampling includes sampling during storm flow and baseflow times at the inlet, outlet and each meander. The samples collected for both base and stormflow are analyzed for the general and nutrient constituents.

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 2013.

Automated Samplers –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 350 ml glass bottle made especially to fit in the automated sampler. To get a consistent sampling routine, the automated samplers need to communicate and be able to be triggered through the data logger. Each sampling location is wired to the data logger – and can be triggered through rainfall or depth of water in the BMP. A sampling protocol is set for each site.

First flush samples were 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 5 sampling ports, each of which can be plugged to control the rate at which 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

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 chamber for collection.

Laboratory Analysis

The samples are analyzed in Villanova University's Civil and Environmental Engineering Water Resources 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)
- Dissolved Solids (depending on volume collected)
- Chlorides
- Nutrients - N, P (Dissolved - Various Forms)

- Metals - Various (Dissolved - Various Forms)

This list is adjusted based upon what is found at the site and the direction of the research governing board. Note that some of these tests are only applicable to the surface or ground water 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.

Monitoring Results - Each of the green infrastructure SCMs is monitored for both quality and flow. Research results are used to further our understanding of how each SCM performs from both a surface and subsurface water perspective.

Bioinfiltration Rain Garden (Previously known as the Bioinfiltration Traffic Island)

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, while Table 2 presents results from 2012 to allow comparison of the removal percentages for that individual year to that of the complete record.

Table 1. Bioinfiltration Rain Garden - Surface Flow Performance 2003 – 2012

Traffic Island Surface Water Analysis

Lifetime Totals

	# of Storms	Inflow	Outflow	Removal Efficiency
Water Quantity (All Events > 0.25")	474	-	-	-
Water Quantity (Events with Hydrology Measured)	144	27,187,583 L	13,279,661 L	51.2%
Water Quantity (Events with Quality and Hydrology Measured)*	144	10,187,070 L	6,161,828 L	39.5%
Water Quantitiy (Events <=1.6")	717	11,314,241 L	1,367,729 L	87.9%
Total Suspended Solids (TSS)	130	2253 kg	134 kg	94.0%
Total Dissolved Solids (TDS)	131	1584 kg	220 kg	86.1%
Total Nitrogen (TN) as N	44	4520 g	832 g	81.6%
Total Kjeldahl Nitrogen (TKN) as N	41	5405 g	1976 g	63.4%
NO2 as N	97	723 g	301 g	58.3%
NO3 as N	100	16288 g	7975 g	51.0%
Total Phosphorus (TP) as P	98	8163 g	4259 g	47.8%
Total Kjeldahl Phosphorus (TKP) as P				
Phosphate (PO4) as P	94	3381 g	1371 g	59.4%
Chloride (CHL)	105	464 kg	132 kg	71.6%
Total Cadmium	70	40711 mg	12092 mg	70.3%
Total Chromium	84	244726 mg	117396 mg	52.0%
Total Copper	84	452918 mg	296808 mg	34.5%
Total Lead	87	193546 mg	26989 mg	86.1%

*Number of events here could be less than number of sampled events for any particular pollutant because these events are only > 0.25" of rainfall

**Assumes Curve Number flow of 98 from impervious surface

Table 2. Bioinfiltration Rain Garden - Surface Flow Performance 2012.

Traffic Island Surface Water Analysis

2012

	# of Storms	Inflow	Outflow	Removal Efficiency
Water Quantity (Events with R > 0.25")	37	2,000,384 L	968,661 L	51.6%
Water Quantity (Events 0.05" <= R <=1.6")	71	923,359 L	142,652 L	84.6%
Water Quantity (Events with Water Quality Measured)	15	1,076,666 L	629,463 L	41.5%
Total Suspended Solids (TSS)	15	271 kg	49 kg	82.0%
Total Dissolved Solids (TDS)*	15	98 kg	49 kg	50.1%
Total Nitrogen (TN) as N	0	0 g	0 g	-
Total Kjeldahl Nitrogen (TKN) as N*	9	931 g	476 g	48.9%
NO2 as N	12	25 g	9 g	61.7%
NO3 as N	11	371 g	74 g	80.1%
Total Phosphorus (TP) as P	0	0 g	0 g	-
Total Kjeldahl Phosphorus (TKP) as P	11	0.07 g	0.00 g	96.9%
Phosphate (PO4) as P	9	140 g	77 g	45.1%
Chloride (CHL)	11	31 kg	8 kg	73.9%
Total Cadmium	12	7443 mg	2040 mg	72.6%
Total Chromium	12	21051 mg	9542 mg	54.7%
Total Copper	12	52088 mg	15765 mg	69.7%
Total Lead	12	37283 mg	5883 mg	84.2%

* 10-29-12 storm event (Hurricane Sandy) was an outlier and skewed the overall removal efficiency (esp. TDS and TKN)

Note the significant reduction of surface water pollutants achieved through bioinfiltration. It is interesting to see the effect of Superstorm Sandy, whose high volume increased the yearly capture , and skewed the overall removal . The comparison of 2012 to the long term record is used to further our understanding of the volume and pollutant removal of the site as it ages.

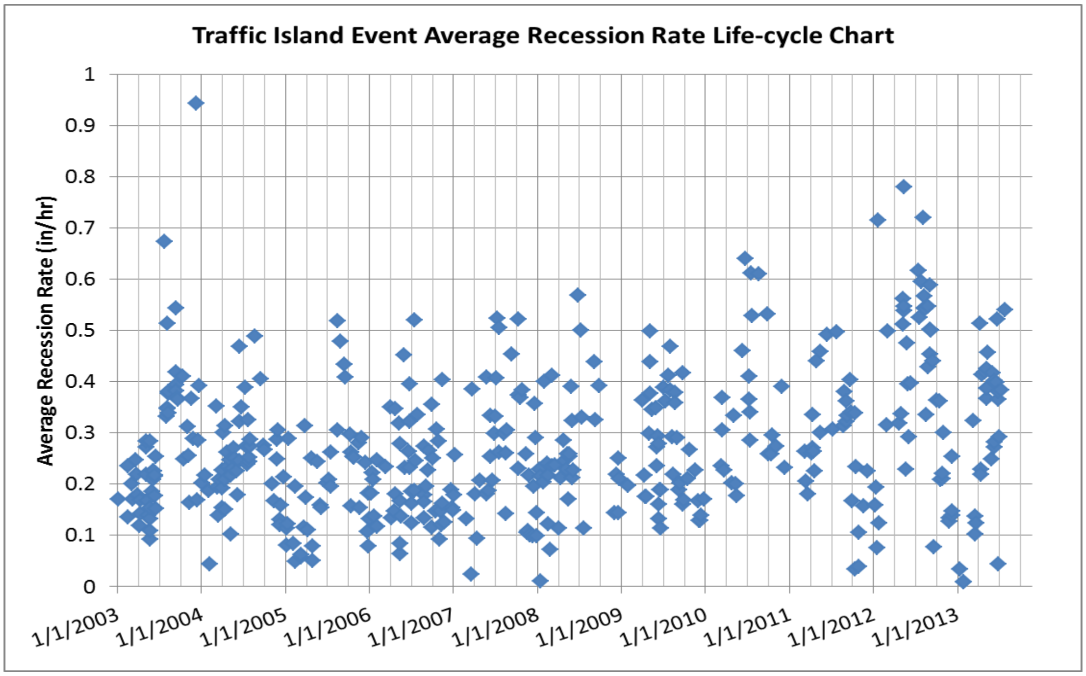


Figure 6. Historical Record of Infiltration Rates

Figure 6 presents a historical record of the measured infiltration rates. As described in past reports, the variation of performance is partially due to temperature and soil moisture. (note data for late Dec – January is not included). Note the continued unaffected performance with time and possible recession rate increase.

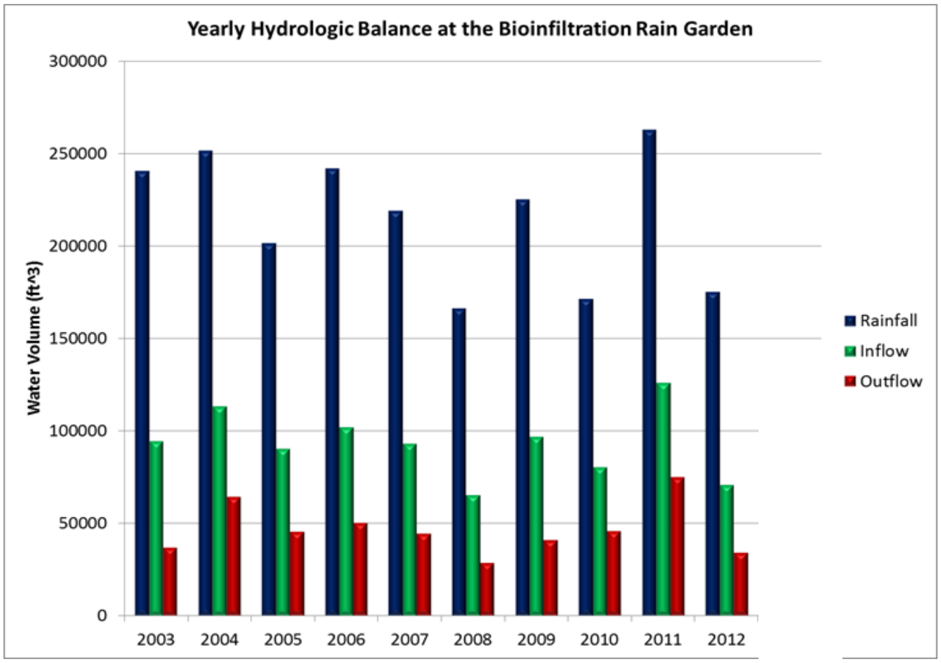


Figure 7. Historical Yearly Hydrologic Balance

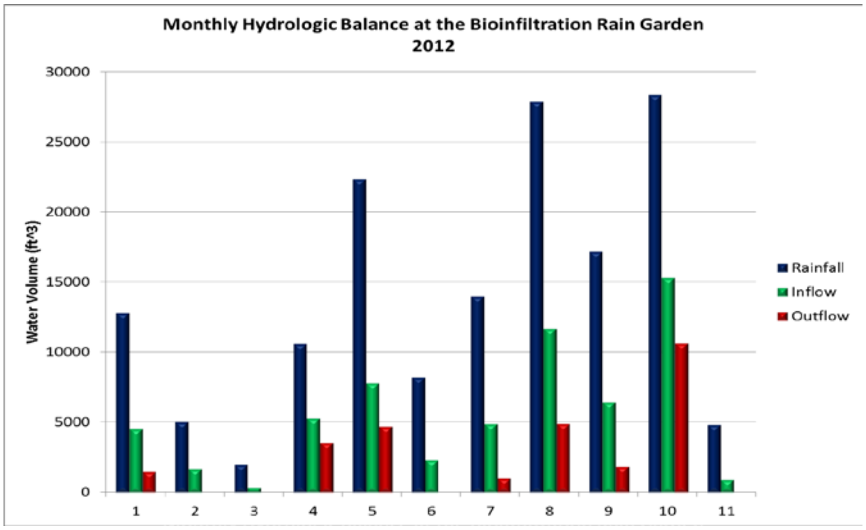


Figure 8. 2012 Monthly Hydrologic Balance

Figure 7 and Figure 8 presents the yearly and monthly hydrologic performance. It is interesting to note the high rainfall versus the inflow. This shows the effect of the vegetated areas that consist of 50% of the watershed. For 2012, the effect of Sandy in October is clearly shown, but overall the rainfall was more evenly distributed over this year than in 2011.

A Thesis completed in May 2013 by Ms. Laura Lord on Nitrogen included an analysis on the volume reduction performance and ponding. The results are presented in Tables 3a and 3b below.

Table 3a – Surface Volume Reduction

Storm Size	Sample Size	Average Volume Reduction
Small (<1.27 cm)	115	100%
Medium (1.27 – 2.54 cm)	127	87%
Large (>2.54 cm)	122	50%

Table 3b – Surface Ponding Durations

Storm Size	Sample Size	Average Ponding Duration
Small (<1.27 cm)	115	14 hrs +/- 17 hrs
Medium (1.27 – 2.54 cm)	127	29 hrs +/- 24 hrs
Large (>2.54 cm)	122	52 hrs +/- 33 hrs
	364	32 hrs +/- 30 hrs

Note that the removal for 2.54cms (1 inch storm) is close to 100% even with a bowl storage that is approximately half that size over the impervious surface, and a ponding duration an much longer then perceived standards. Note that ponding is measured from the beginning of the rainfall. This further emphasizes the remarkable performance of these control measures.

The subsurface results (Table 4) 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.

Table 4. Bioinfiltration Raingarden Vadose Zone Sampling 2003-2012. Concentrations at 0, 25, 50, 75, and 100 percent levels refer to quartiles from cumulative frequency distribution of observed values.

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)	-	62	13	35	74	147	2283
pH	-	76	4.18	6.40	6.70	7.08	8.01
Conductivity (µS/cm)	-	78	32	58	83	149	4080
TN (mg/l) as N	0.1-1.7 mg/l	29	0.10	0.50	1.30	2.10	5.00
TKN (mg/l) as N	0.05-0.1 mg/l	28	0.007	0.48	0.70	1.46	3.92
NO2 (mg/l) as N	0.005-0.2 mg/l	68	0.00	0.05	0.10	0.50	4.22
NO3 (mg/l) as N	0.01-0.2 mg/l	70	0.01	0.18	0.44	0.52	7.30
NOx (mg/l) as N	0.05-0.1 mg/l	27	0.03	0.42	0.70	1.25	5.42
TP (mg/l) as P	0.01-0.06mg/l	69	0.03	0.30	0.54	0.92	2.58
TKP (mg/l) as P	0.01-0.06mg/l	6	0.00	0.01	0.03	0.20	0.56
PO4 (mg/l) as P	0.01-0.2 mg/l	70	0.01	0.11	0.21	0.50	5.84
CHL (mg/l)	0.2-1.0 mg/l	70	0.8	4.1	11.2	31.1	1507.9
Dissolved Cadmium (µg/l)	0.01-5.0 µg/l	37	0.05	0.25	0.40	2.12	5.02
Dissolved Chromium (µg/l)	0.5-5.0 µg/l	45	0.25	1.10	2.50	2.90	46.34
Dissolved Copper (µg/l)	0.5-5.0 µg/l	44	1.40	4.30	7.16	15.41	62.83
Dissolved Lead (µg/l)	0.5-5.0 µg/l	48	0.25	2.40	2.40	2.50	27.71
Dissolved Zinc (µg/l)	4.8-10.0 µg/l	29	0.41	25.00	55.28	71.50	1438.00

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

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)	-	107	0	206	288	518	38007
pH	-	121	5.69	6.65	6.87	7.21	9.19
Conductivity (µS/cm)	-	121	3	347	473	635	11220
TN (mg/l) as N	0.1-1.7 mg/l	42	0.10	0.50	0.50	1.22	4.10
TKN (mg/l) as N	0.05-0.1 mg/l	38	0.01	0.10	0.34	0.65	3.16
NO2 (mg/l) as N	0.005-0.2 mg/l	100	0.00	0.01	0.17	0.57	2.78
NO3 (mg/l) as N	0.01-0.2 mg/l	100	0.01	0.15	0.30	0.50	8.60
NOx (mg/l) as N	0.05-0.1 mg/l	42	0.03	0.19	0.33	0.58	1.51
TP (mg/l) as P	0.01-0.06mg/l	99	0.03	0.18	0.31	0.58	4.81
TKP (mg/l) as P	0.01-0.06mg/l	11	0.00	0.00	0.03	0.05	0.13
PO4 (mg/l) as P	0.01-0.2 mg/l	90	0.00	0.03	0.19	0.50	11.82
CHL (mg/l)	0.2-1.0 mg/l	108	0.5	8.8	30.6	114.5	1619.5
Dissolved Cadmium (µg/l)	0.01-5.0 µg/l	57	0.01	0.25	0.40	2.50	5.10
Dissolved Chromium (µg/l)	0.5-5.0 µg/l	66	0.25	1.10	2.50	3.82	55.80
Dissolved Copper (µg/l)	0.5-5.0 µg/l	66	0.20	2.43	5.28	11.15	111.49
Dissolved Lead (µg/l)	0.5-5.0 µg/l	74	0.07	1.32	2.40	2.50	26.70
Dissolved Zinc (µg/l)	4.8-10.0 µg/l	49	2.40	25.00	45.32	62.00	165.30

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

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)	-	114	20	228	301	423	50191
pH	-	120	4.33	6.63	6.84	7.02	9.15
Conductivity (µS/cm)	-	120	3	363	442	562	9930
TN (mg/l) as N	0.1-1.7 mg/l	39	0.10	0.50	0.50	1.42	3.95
TKN (mg/l) as N	0.05-0.1 mg/l	41	0.02	0.08	0.28	0.62	7.60
NO2 (mg/l) as N	0.005-0.2 mg/l	103	0.00	0.01	0.20	0.72	3.48
NO3 (mg/l) as N	0.01-0.2 mg/l	102	0.00	0.11	0.45	0.55	10.40
NOx (mg/l) as N	0.05-0.1 mg/l	42	0.00	0.11	0.31	0.90	22.57
TP (mg/l) as P	0.01-0.06mg/l	98	0.01	0.16	0.35	0.54	4.17
TKP (mg/l) as P	0.01-0.06mg/l	12	0.00	0.00	0.02	0.03	0.24
PO4 (mg/l) as P	0.01-0.2 mg/l	94	0.00	0.03	0.14	0.50	4.88
CHL (mg/l)	0.2-1.0 mg/l	103	0.1	6.5	22.0	120.6	821.3
Dissolved Cadmium (µg/l)	0.01-5.0 µg/l	59	0.04	0.25	0.40	1.54	4.99
Dissolved Chromium (µg/l)	0.5-5.0 µg/l	69	0.19	1.10	2.50	2.50	86.70
Dissolved Copper (µg/l)	0.5-5.0 µg/l	67	0.12	2.47	5.98	13.13	31.22
Dissolved Lead (µg/l)	0.5-5.0 µg/l	75	0.20	1.01	2.40	2.50	8.90
Dissolved Zinc (µg/l)	4.8-10.0 µg/l	50	1.59	25.00	46.70	64.69	129.00

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

The following figure is an alternative method to evaluate the performance from a probability of exceedance perspective. They include all data from the project inception.

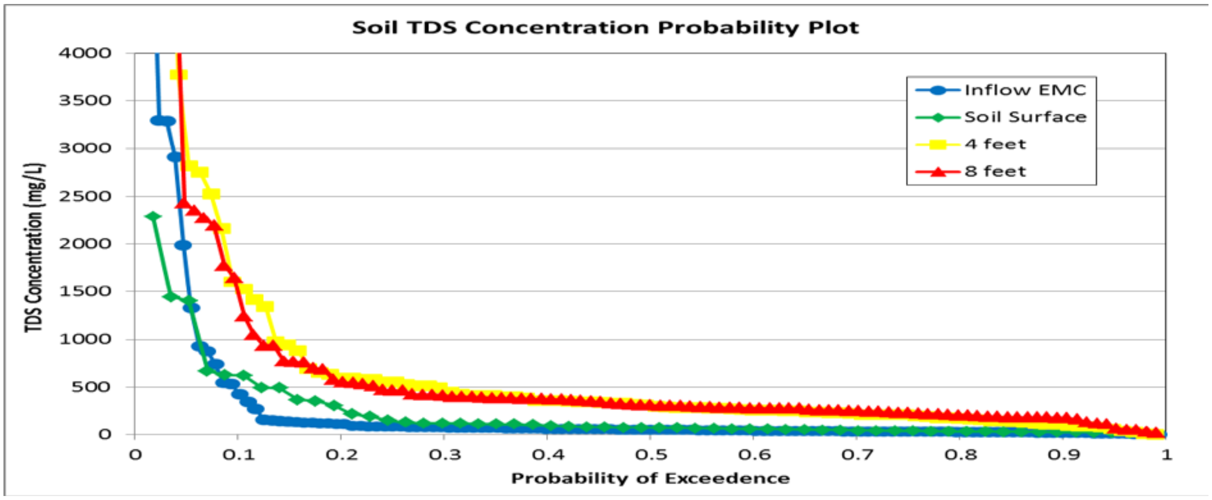


Figure 9. TDS Exceedence Probability

Note that as expected, TDS slightly increases and then is constant as it moves through the soil mantle, though there appears to be little change after the four foot depth mark.

Research Results Nutrients

Over this grant period, two substantial projects focused on nutrients. The following results are from projects by Dr. John Komlos and Laura Lord funded by this grant. Dr. John Komlos performed a study to examine the orthophosphate removals by the raingarden. He was able to match the removals to the increase within the soil mantle, and track how far down the removals occurred, and then estimate the longevity of the system. The following plot and table are from the ASCE publication:

Komlos, J. and Traver, R. (2012). "Long-Term Orthophosphate Removal in a Field-Scale Storm-Water Bioinfiltration Rain Garden."*J. Environ. Eng.*, 138(10), 991–998.

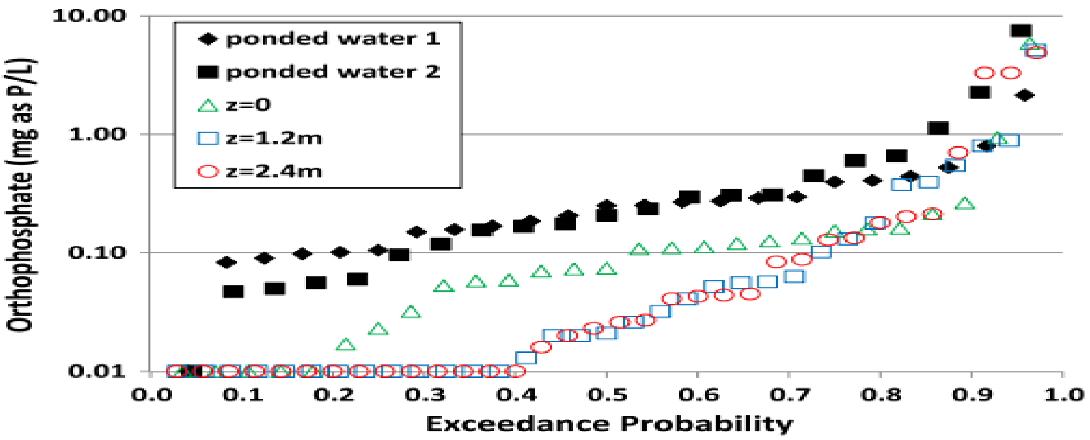


Figure 10. Orthophosphate (PO_4^{3-}–P) concentrations versus probability of exceedance for ponded water samples taken at the beginning of the storm event (ponded water 1), ponded water samples taken at the end of the storm event (ponded water 2), and pore water samples collected at the surface water/infiltration bed interface (z ¼ 0 m), and 1.2 and 2.4 m below the surface water/infiltration bed interface; data ranges from February 2008 [when the analytical procedure was changed, resulting in a lower detection limit (0.01 mg/L)] to November 2010

Table 5 Estimation of the Time until Orthophosphate Saturation for Each Depth

Depth (cm)	$(x/m)^a$	Average amount of PO_4^3–P currently sorbed on soil in sections 2–5[b]	Additional PO_4^3–P that can be sorbed onto soil in sections 2–5[c]	Additional PO_4^3–P that can be sorbed onto soil in sections 2–5[d] (kg)	Number of years until saturation for each layer[e] (years)
0–5	0.081	0.099	saturated	saturated	—
5–10	0.050	0.055	saturated	saturated	—
10–15	0.074	0.055	0.019	0.18	8
15–20	0.091	0.054	0.037	0.34	15
20–25	0.091	0.044	0.047	0.43	25
25–30	0.091	0.051	0.040	0.37	19

[a] x/m is the maximum amount of PO_4^3–P that can be sorbed to the soil (mg $PO_4{}^3 - P/g$ dry soil) when the soil is in equilibrium with the storm water infiltrating through the infiltration bed (see text for more description). The x/m values were calculated to be 0.11 mg $PO_4^3 - P/g$ dry soil, 0.05 mg $PO_4^3 - P/g$ dry soil, and 0.09 mg $PO_4^3 - P/g$ dry soil for soil from depths of 0, 7.6, and 30.5 cm, respectively. Values presented in column 2 are a weighted average of the 3 x/m values. It was assumed that the 0 cm x/m value was representative of the first 3 cm of soil. This assumption was based on visual observation showing the top 3 cm of soil to be consistently black in color throughout the site, while below 3 cm was brown in color. The 7.6-cm x/m value was assumed to be representative for depths of 3–12 cm. The 30.5-cm x/m value was assumed to be representative for depths of 12–30 cm.

[b] Adapted from Fig. 7. Units are mg $PO_4^3 - P/g$ dry soil.

[c] (column 2–column 3).

[d] (column 4) * mass of soil in each section. Mass of soil in each section was estimated to be 9.16×10^3 kg (see Table 1).

[e] (column 5/mass of PO_4^3–P sorbed in each section per year). See Table 2 for mass of PO_4^3–P sorbed in each section per year.

Note that as presented in Table 5, there is 19 years before the 30 cm (foot) of the system loses it's capacity to reduce Orthophosphate, leaving the following 3 feet of media to take over the task. Any activity that would remove / replace surface media adds removal capacity

Another project completed during this period was the thesis prepared by Ms. Laura Lord. She studied the nitrogen cycle, which has much different removal mechanisms. She found clear evidence of reduction of NOx, higher then found in literature, that we suspect can be related to the extended duration of saturation, due to the more normal infiltration patterns of the Villanova Bioinfiltration Raingarden (as compared to high percentage sand / underdrained systems). The figures below summarize her work.
Lord, L. E. (2013). Evaluation of nitrogen removal and fate within a bioinfiltration stormwater control measure. Villanova University

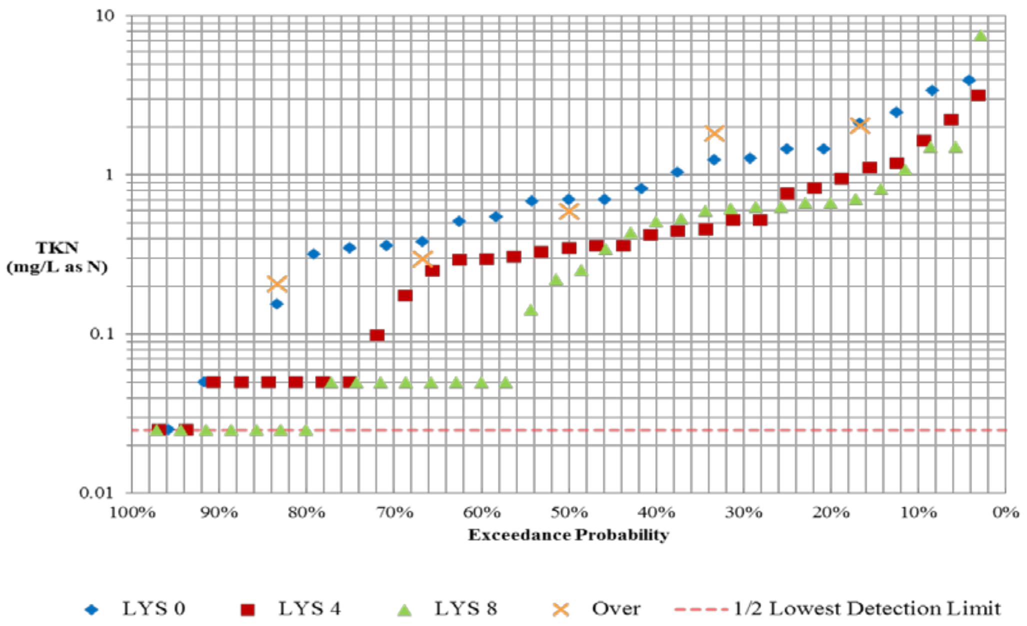


Figure 11 – TKN

Note on this figure, that the reduction in TKN as it moves through the soil column from the surface (Lysimeter 0 to the bottom of the media (Lysimter 4) and further through the soil to Lysimeter 8. Over flow once within the bowl is not treated, though reduced greatly when volume is incorporated.

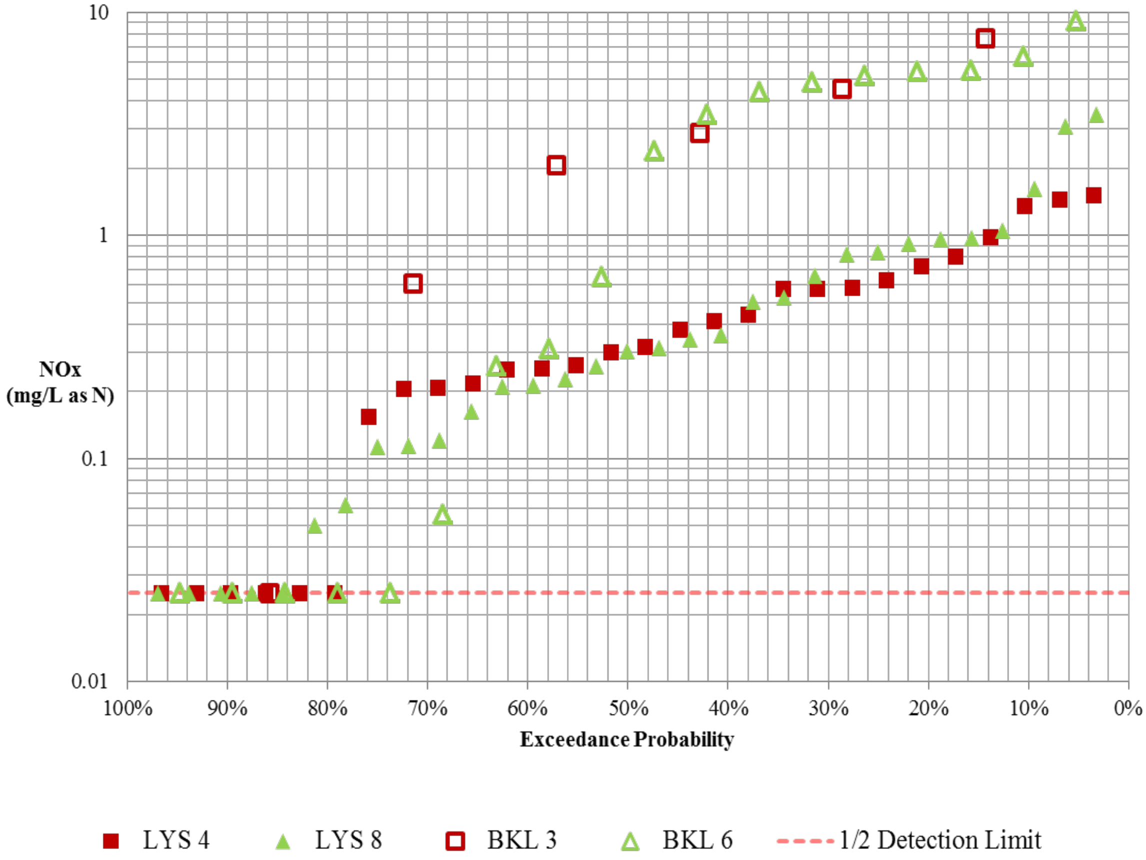


Figure 12 – NO-X - N

This figure is similar to the last, except it looks like there is no further reduction after it leaves the media supporting the hypothesis that the extended wetting of ths oil is the mechanism. What is important to note is the comparison of lysimeter 4 with that of the two back ground lysimeters (3 ft and 6 ft deep). These two show that the NOx-N level is an order of magnitude HIGHER under the grass nearby then what is leaving the media.

Table 6 – Surface Pollutant Load Reductions

	Nutrient	TKN	NO$_x$-N
	n	18	18
Median Sample Load (g)	Mass In	33.3	20.9
	Mass Over	0	0
	% Reduction	100%	100%

A further conclusion of the importance of incorporating the flow is evident when examine the median water quality event of the data. For the value 100% of both the TKN and NOx-N are removed. For larger storm there is pollutant export, but it is reduced as a function of the volume.

Constructed Stormwater Wetlands

At the request of PaDEP, the Constructed Stormwater Wetlands (CSW) Project was returned to the 319 NPS project. For 2011, it was considered to be in the Initial Monitoring Phase, which has concluded. First the site instrumentation was reinstalled and updated through 2011, and the monitoring design was revised to match the changes to the site and project goals, yielding an approved QAPP in 2012. The focus is on both flow and nutrients for this site.

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 five minute intervals. However, there is a small portion of flow into the CSW (6.6 acres, 90% impervious) are not accounted for with the existing monitoring plan. A Stormwater Management Model (EPA-SWMM) was developed to simulate all flow that drains to the CSW. The model was calibrated against collected data and is applied to all monitored storm flows to adjust for this additional flow or to fill in data if flow measurement equipment was offline. Observed inflows and simulated, "adjusted," inflows were compared and there was an average 17% (±7%) flow rate difference between the observed and simulated flow; this model error was considered acceptable. The monitoring from 2011 exemplified issues with flow monitoring equipment (either faulty sensors or inappropriate sensor location). The flow monitoring program was providing high quality data by the beginning of the 2012. Table 7 presents average flow data for storm and base flow conditions.

Table 7. Average storm and base flows (with standard deviations) for 2012. n is the number of inlet observations (with k SWMM supplemented events for missing data) and m is the number of outlet observations.

	Storm	**Baseflow**
	(n=20, m= 20, k=7)	**(n=19, m=19, k=2)**
Avg Flow In with (CFS)	1.37 (1.00)	0.17 (0.09)
Avg Flow Out with (CFS)	1.28 (0.96)	0.09 (0.06)
In vs Out - Statistically different? (t-test)	*No (0.5046)*	*Yes (0.0006)*

Table 8 presents peak flow reductions for storm events. There was an average peak flow reduction from inlet to outlet of 59%. This peak flow reduction was matched with a 25% volume reduction during storm events. Additionally, there was a 41% volume reduction through the CSW for baseflow conditions, which may be attributed to evapotranspiration and groundwater recharge.

Table 8. Peak flow analysis for storms

	Storm
	(n=15, m=16, k=4)
In vs Out - Statistically different? (t-test)	*Yes (0.0129)*
Average Storm Size (inches)	*1.05*
Avg Peak Flow Reduction (CFS)	7.45
Avg Peak % Reduction	**59%**
Avg Peak Lag (hr)	1.56

For this application, water quality sampling is conducted using grab samples (two replicates at each location, 350 L grab sample). Each location (Inlet, Meander 1, Meander 2, Meander 3, and Outlet) has access for grab samples. The current storm sampling routine involves collecting 2 grab samples the Inlet, Meander 1, Meander 2, Meander 3, and the Outlet for a total of 10-12 storm samples per year and 10-12 base flow samples per year. Table 9 presents baseflow water quality parameters over the study period, with reductions for all constituents except chlorides, total dissolved solids and total suspended solids on average. These results are expected for chlorides and dissolved solids. There were a few events where it is believed there was some erosion that contribute to an overall average addition of suspended solids exiting the CSW.

Table 9. Baseflow water quality.

Baseflow: 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	8	2.93	1.20	1.59	0.83	46%	-
TKN	10	1.33	1.01	0.96	0.70	28%	0.01, 20.0
NO2	15	0.08	0.05	0.04	0.03	49%	0.01, 10.0
NO3	13	1.65	0.81	0.51	0.42	69%	0.01, 10.0
TP/TKP	10	0.26	0.27	0.18	0.31	30%	0.01, 20.0
PO4	11	0.08	0.09	0.05	0.06	33%	0.01, 5.0
PO4F	4	0.04	0.04	0.01	0.00	69%	0.01, 5.0
CHL	12	495	435	579	548	-17%	0.01, 200
TSS	16	19	21	20	21	-3%	-
TDS	17	601	267	683	463	-14%	-

Water quality for storm events removed all constituents except for soluble reactive phosphorus (SRP, filtered phosphate, PO_4) (Table 9).

Table 10. Storm event water quality

Storm: Average Water Quality Performance						
Quality Parameter	**n**	**Conc In (mg/L)**	**SD In**	**Conc Out (mg/L)**	**SD Out**	**% Removed**
TN	11	2.23	0.91	1.86	1.53	17%
TKN	15	1.44	0.88	1.35	1.30	6%
NO2	16	0.05	0.03	0.05	0.02	4%
NO3	15	1.14	1.02	0.70	0.39	39%
TP/TKP	20	0.31	0.24	0.25	0.16	21%
PO4	16	0.07	0.05	0.06	0.04	8%
PO4F	5	0.03	0.03	0.07	0.11	-120%
CHL	16	206	332	192	392	7%
TSS	22	22	21	15	11	31%
TDS	22	439	518	324	514	26%

Focusing on nutrients of concern, nitrogen and phosphorus, it is seen that almost all the observations reduced total nitrogen from inlet to outlet and were below water quality standards (Figure 13). Total phosphorus almost always had reduction, although about 60% of effluent observations had concentrations greater than in-stream water quality standards for PA (Figure 14). In both cases, reductions tended to be seen from inlet to outlet when observing concentrations at each meander. Figure 17 presents total suspended solids data comparing the influent to effluent. There were only three storm observations where the effluent TSS was greater than in-stream water quality standards. There were several base and storm observations where solids were added to the effluent. As the system continues to mature and vegetation is established, this is expected to reduce. Mass loads are presented in Tables 11 and 12. Mass load reduction was observed for all flow conditions and for all constituents, except for SRP during storm events.

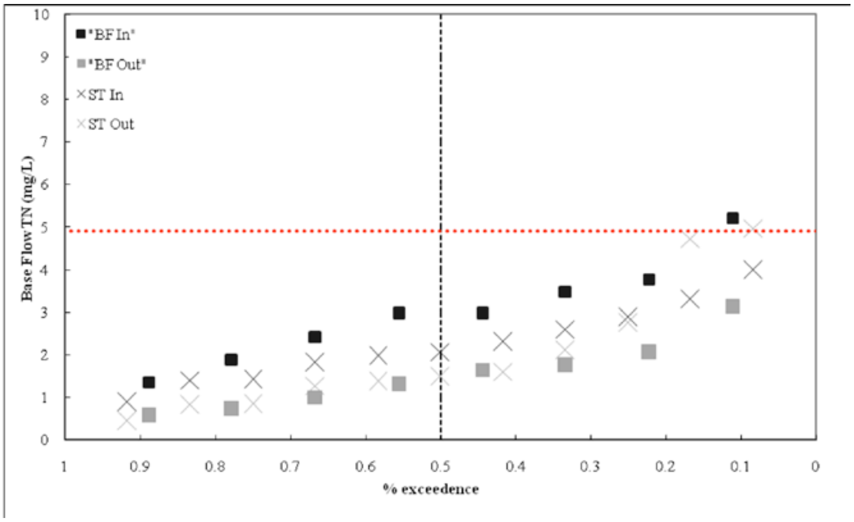


Figure 13. Percent Exceedance Concentration for Total Nitrogen

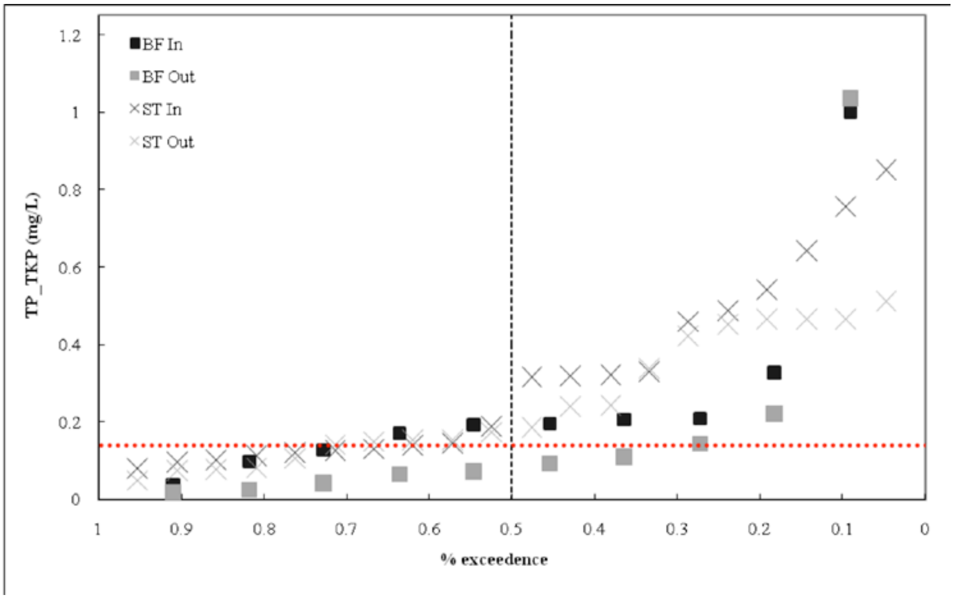


Figure 14. Percent Exceedance Concentration for Total Phosphorus

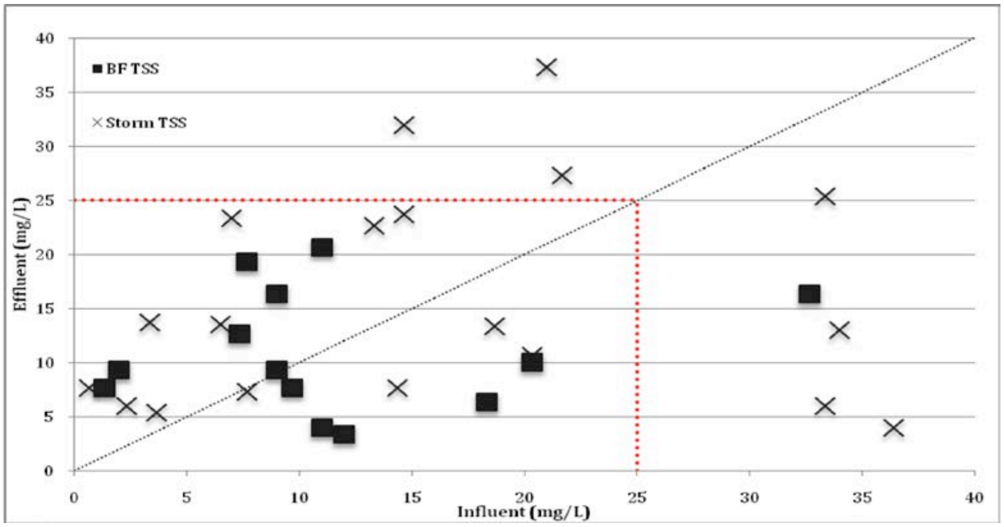


Figure 15. Total Suspended Solids Concentration Effluent vs. Influent Plot

Table 11. Baseflow mass loads

Baseflow: Average Quality Performance							
Quality Parameter	**Sample Size**	**Mass In (kg)**	**SD In**	**Mass Out (kg)**	**SD Out**	**Mass removed (kg)**	**% Removed**
TN	8	445	96.2	128	44.3	318	71%
TKN	10	202	81.2	77.2	37.4	125	62%
NO2	15	12.1	4.01	3.28	1.68	9	73%
NO3	13	251	65.0	40.9	22.3	210	84%
TP/TKP	10	39.7	21.9	14.7	16.2	25	63%
PO4	11	12.3	7.28	4.33	3.37	8	65%
PO4F	4	6.67	3.17	1.09	0.26	6	84%
CHL	12	75207	34974	46574	29397	28634	38%
TSS	16	2893	1682	1583	1137	1310	45%
TDS	17	91277	21508	54950	24831	36328	40%

Table 12. Storm mass loads

Storms: Average Quality Performance							
Quality Parameter	**Sample Size**	**Mass In (kg)**	**SD In**	**Mass Out (kg)**	**SD Out**	**Mass removed (kg)**	**% Removed**
TN	11	514	143	324	161	190	37%
TKN	15	331	139	235	137	96.5	29%
NO2	16	11.9	4.44	8.80	2.22	3.07	26%
NO3	15	262	161	123	41	140	53%
TP/TKP	20	71.9	37.4	43.0	16.7	28.8	40%
PO4	16	15.0	7.55	10.5	3.76	4.51	30%
PO4F	5	7.56	4.88	12.6	11.13	-5.02	-66%
CHL	16	47544	52401	33554	41121	13989	29%
TSS	22	4978	3353	2593	1129	2385	48%
TDS	22	101189	81775	56543	53941	44646	44%

To further understand the relationship between Dissolved Oxygen and Nitrogen, we have built a floating platform with hanging DO probes at variable depths (Figure 16). This was constructed over the winter 2011/2012, collected data will be further discussed in the 2013 report. Integrating DO data with the baseflow sampling is anticipated to provide deeper understanding of the nitrogen cycle. Additionally, temperature through the CSW will be monitored to understand how inflow is cooled or heated as it moves through the system to determine its impact on thermal warming or mitigation for effluent reaching the downstream receiving body. There is an observed diurnal difference in DO and levels that are anoxic indicating denitrification could be occurring (Figure 17).

Figure 16. Floating DO instrumentation

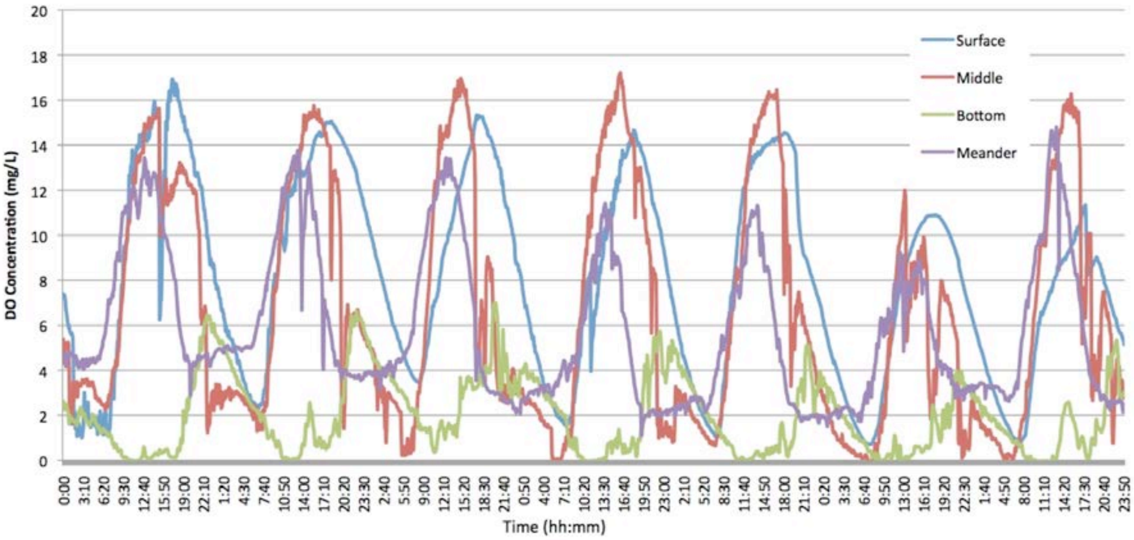


Figure 17. DO concentrations August 20-27, 2012

FINDINGS & RECOMMENDATIONS – Year 1-10

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 (new / revised findings for 2012 are <u>underlined</u>):

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. When designed and built correctly, they should be expected to operate with minimal maintenance for long periods of time.

Effectiveness of Small Storm Capture: The efficiency of designing for small storms has been proven. Results from both the infiltration trench and bioinfiltration raingarden have shown that because the majority of the region's rainfall is produced by smaller storms, BMPs designed for smaller storms are extremely effective in reducing runoff volume and capturing surface pollutants in regions with similar climates. <u>While only having a surface volume capture equaling ½" of runoff from impervious surfaces, 100% of the runoff from the first ½" of rain is removed, 97% of from the next ½" and 50% from larger storms is removed. There should not be any discount for green infrastructure performance for back to back storms.</u>

Variability of Infiltration Rate: Results from all three 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. Note that on a yearly basis, this variation has not interfered with performance, but must be considered when conducting municipal inspection / monitoring programs.

Longevity: A study based on the results of this project has shown that there is no statistical reduction in performance for the bioinfiltration rain garden after 7 years, or from the pervious concrete site after 4 years (Emerson and Traver 2008). As long as the site is protected from large sediment loads (i.e., from upstream erosion) there is every expectation that these sites will remain effective for a very long time. Longevity is achieved through proper design, construction, and siting (characteristics of the drainage area). For the bioinfiltration BMP, freeze - thaw, soil processes and root systems are aiding in maintaining the infiltration capacity. For the pervious concrete site, the lack of suspended sediments in the rooftop runoff, the filtering through the pervious concrete, and the large surface area support its longevity. Conversely, a considerable change in performance has been seen at the infiltration trench due to the theorized clogging of the bottom layer. It should be noted that the drainage area to the infiltration trench greatly exceeds that of "normal" sites. Using the drainage area sizing recommendations of the Pennsylvania BMP manual, the infiltration trench has experienced a pollutant load equivalent to 80 years during its *initial* 5-year lifetime. More recent readings demonstrate that while performance is reduced, volume reduction continues.

Robustness of Green Infrastructure: Continuing performance of the Villanova University stormwater BMPs with minimal maintenance demonstrates the robustness of green infrastructure practices, as long as the systems are sited, designed, and constructed appropriately. After ten years, no major maintenance has been required of the bioinfiltration sites, and only street sweeping for the porous concrete/porous asphalt site.

Variation in Pollutant Loading Rate / First Flush: Runoff from different contributing areas has been found to vary considerably in quality. For example, roof runoff from taller buildings has been found to be remarkably free of TSS, which makes it an ideal candidate for infiltration. In contrast, runoff from the parking deck has delivered extremely high pollutant loads to the infiltration trench. Clearly pretreatment devices would extend the life of infiltration BMPs in high loading areas.

Raingarden Volume Removal Repeatability and Predictability – Analysis of data from bioretention / bioinfiltration raingardens at Villanova University, NC State University, and the University of Maryland show repeatability of performance of volume reduction. This has lead to a Journal Article that presents methods / equations to predict the removal of volume in the soil media, and provide guidance on how to size / configure the site to remove a set volume from the overwhelming majority of events.

Porous Asphalt/ Pervious Concrete- Thermal Benefit - Analysis of data has clearly demonstrated the effectiveness of temperature reduction for the PAPC site. Multiple conference presentations and a Journal Paper is under development.

Porous Asphalt/ Pervious Concrete- Water Quality - Analysis of data has clearly demonstrated the effectiveness of pollutant abatement for this site. Multiple conference presentations and a Journal Paper are under development.

BioInfiltration Soil Media – Phosphorous. The site has been shown to be effective in reducing phosphorus with a slow infiltrating media mix. The volume of phosphorous 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 – Nitrogen. A current master's thesis under review has found that nitrification reduction is occurring at the site, possibly due to the slow movement through the media. This starts to make us question the current practice of high infiltration rate soil media regardless of the native soil infiltration rates. As shown earlier in the monitoring results, NOX levels are a magnitude higher in the grass areas adjacent to the SCM then below the media within the SCM.

Importance of ET – A companion Growing Greener Study has demonstrated the importance of evapotranspiration (ET) for the Green Roof, Rain Garden, Bioretention and Stormwater Wetland. Research is continuing, on the subject but the chief limitation on ET is lack of available water. Maintaining moisture over longer times is needed to increase the ET component. One article has been published, and multiple conference presentations and a journal paper are under development.

Sustainable Design – Life Cycle analysis – A life cycle approach is needed for SCM evaluation of ancillary benefits. For example the energy and pollutants produced when quarrying sand (energy, carbon, etc.) for the Bioinfiltration Rain Garden negated it's sustainability impact for the first two years of it's life. A Master's study predicts it now reduces the equivalent of one car per year of carbon impact (Flynn 2011). Note Villanova now has 13 raingardens. It is questionable whether the green roof would ever overcome the non stormwater impacts of the aluminum flashing used along the edges. Multiple conference presentations and a Journal Paper are under development.

Back to Back Storms: It is clear that the occurrence of back to back storms is not an issue for green infrastructure in this region when viewed from a pollutant or volume perspective. From an examination of the record of rainfall, rarely do we have a storm event on a second or third day large enough to effect the volume reduction capacity of smaller storms. This will be the subject of a future publication.

Recommendations

Targeted Raingarden Design – Analysis of data from bioretention / bioinfiltration raingardens at Villanova University, NC State University, and the University of Maryland has lead to equations relating volume reduction to the site design to include root depth. It is recommended that this publication be considered during the revision of the Pennsylvania Stormwater BMP manual.

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. 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.

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.

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 raingardens 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.

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 Perspective. The results of this work have lead to requests for presentations to Congress, EPA Office of water and many others. Villanova co hosted 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* (Note that the research from this project is heavily referenced in this report).

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 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 raingardens as part of new building projects. Including ARRA projects, Villanova now has 15+ raingardens, and five pervious pavement sites. The Stormwater wetland is visited and used by other deparments and is an admired feature on campus.

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. In addition, free or low cost seminars are held locally, and many groups request to visit and tour the research sites. Finally, all project reports and theses are available on the web (www.villanova.edu/VUSP). It should be noted that the work is incorporated in the graduate and undergraduate classes at Villanova, and that graduate students working on the project gain a wealth of experience.

FUTURE DIRECTIONS AND RECOMENDATIONS

The Villanova Stormwater Research and Demonstration Park remains a viable and valuable research tool. The proximity of the on-campus BMPs 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 BMPs. While great strides have been made, the relations between site characteristics, load and volume to BMP design are just becoming understood. As the understanding of the processes involved advances, the VUSP expects that the design methods used for these BMPs will change to more accurately represent the hydrologic, chemical and biological processes involved. These changes will advance our ability to protect our waters. Currently, funding is in place through 2014/15, and it is the expectation of the researchers to continue this work on both current and future BMPs at the Villanova campus.

For 2012, the focus of the 319 program is to evaluate the effect of the changes to the Storm Water Wetlands, and to continue the research on the Bioinfiltration Rain Garden equating volumetric reduction to quality enhancements.

Published Major Works

Traver, R., “Comments on Proposed National Rulemaking to Strengthen the Stormwater Program; Testimony to USEPA Office of Water”, Washington DC. 28 January 2010

Traver, R. “Efforts to Address Urban Stormwater Runoff”, Testimony to Subcommittee on Water Resources and Environment, Committee on Transportation and Infrastructure, U.S. House of Representatives. Washington DC March 2009

NRC 2008 Urban Stormwater Management in the United States. Washington. DC: National Academies Press. (Committee Report)

Published Refereed Journal Articles (Since 2002)

1. Lee, R., Traver, R., and Welker, A. "Continuous Modeling of Bioinfiltration Stormwater Control Measures using Green and Ampt," Journal of Irrigation and Drainage Engineering, in press

2. Flynn, K., Traver, R., (2013) “Green Infrastructure Life Cycle Assessment: A Bio-Infiltration Case Study”, Journal of Ecological Engineering, Volume 55, pp 9-22.

3. Welker, A., Mandarano, L., Greising, K., Mastrocola, K. (2013) “Application of a Monitoring Plan for Stormwater Control Measures in the Philadelphia Region,” J. Environ. Eng., 139(8), 1108–1118.

4. Wadzuk, B., Schneider, D., Feller, M., Traver, R. (2013) “Evapotranspiration from a Green Roof

Stormwater Control Measure” J. Irrig. Drain Eng., 10.1061/(ASCE)IR.1943-4774.0000643 (Jun. 6, 2013).

5. Welker, A., Mandarano, L., Greising, K., Mastrocola, K. (2013) “Application of a Monitoring Plan for Stormwater Control Measures in the Philadelphia Region,” J. Environ. Eng., 139(8), 1108–1118.

6. Welker, Andrea L., Jennifer K. Gilbert Jenkins, Leslie McCarthy, and Evgeny Nemirovsky. "Examination of the Material Found in the Pore Spaces of Two Permeable Pavements." *J. Irrig. Drain Eng*., (2012).

7. Welker, Andrea L., James D. Barbis, and Patrick A. Jeffers. "A Side-by-Side Comparison of Pervious Concrete and Porous Asphalt." *JAWRA Journal of the American Water Resources Association* (2012).

8. Radlińska, Aleksandra, Welker, A., Greising, K., Campbell, B. and Littlewood, D. “Long-Term Field Performance of Pervious Concrete Pavement.” *Advances in Civil Engineering* (2012)

9. Nemirovsky, E., Welker, A., and Lee, R. (2012) “Quantifying Evaporation from Pervious Concrete Systems: Methodology and Hydrologic Perspective.” *J. Irrig. Drain Eng*., In Press 2012.

10. Komlos, J. and Traver, R. (2012). ”Long-Term Orthophosphate Removal in a Field-Scale Storm-Water Bioinfiltration Rain Garden.” *J. Environ. Eng., 138(10), 991–998.*

11. Hunt, W.F., Davis, A.P., and Traver, R.G. (2011) “Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design,” *J. Environ. Eng* , June 2012.

12. Davis, A.P., Traver, R.G., Hunt, W.F., Brown, R.A., Lee, R. and Olszewski, J.M. (2011). “Hydrologic Performance of Bioretention Stormwater Control Measures.” Journal Hydrologic Eng, ASCE., accepted for publication, June 2011.

13. Gilbert Jenkins, J.K., Wadzuk, B.M. and Welker, A.L., (2010) “Fines Accumulation and Distribution in a Stormwater Rain Garden Nine Years Post Construction.” *J. Irrig. Drain Eng*. Vol. 136, No. 12, pp. 862-869.

14. Horst, M., Welker, A., Traver, R., “Multi Year Performance of a Pervious Concrete Infiltration Basin BMP”, *J. Irrig. Drain Eng* , June 2011.

15. Machusick, M., Traver, R., Welker, A., Traver, R., “Groundwater Mounding At A Stormwater Infiltration Bmp”, ASCE Journal of Irrigation and Drainage, ASCE March 2011.

16. Davis, A. Hunt, W. Traver, R, “Improving Urban Stormwater Quality: UCOWR Applying Fundamental Principles.” Journal of Contemporary Water Research and Education, December 2010.

17. Welker, A., Wadzuk, B., Traver, R. “Integration of Education, Scholarship and Service Through Stormwater Management.” UCOWR, Journal of Contemporary Water Research and Education, December 2010.

18. Wadzuk, B., Rea, M., Woodruff, G., Flynn, K. Traver, R., “Water Quality Performance of a Constructed Stormwater Wetland for All Flow Conditions”, AWRA, Volume 46, Issue 2, pages 385–394, April 2010.

19. Emerson, C., Wadzuk, B., Traver, R., “Hydraulic Evolution and Total Suspended Solids Capture of an Infiltration Trench” Hydrologic Processes, Wiley Jan 2010

20. Batroney, T., Wadzuk, B., Traver, R., “A Parking Deck's First Flush” ASCE Journal of Hydrologic Engineering, February 2010

21. Davis, A. Hunt, W. Traver, R., "Bioretention Technology: An Overview of Current Practice and Future Needs." ASCE Journal of Environmental Engineering – ASCE Journal of Environmental Engineering, ASCE March 2009

22. Emerson, C., Traver, R., Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices, ASCE Journal of Irrigation and Drainage, ASCE Sep\Oct 2008

23. Braga, A., Horst, M., Traver, R. "Temperature Effects on the Infiltration Rate through an Infiltration Basin BMP", Journal of Irrigation and Drainage, ASCE, Nov\Dec 2007

24. Kwiatkowski, M, Welker, A., Traver, R., Vanacore, M., Ladd, T. "Evaluation of an Infiltration Best Management Practice (BMP) Utilizing Pervious Concrete", AWRA, Oct 2007

25. Welker, A., Gore, M., Traver, R. "Evaluation Of The Long Term Impacts Of An Infiltration Bmp", ICHE The 7th In. Conf. on Hydroscience and Engineering (ICHE-2006).

26. Emerson C. ,Welty, C., Traver, R. "Closure of A Watershed-scale Evaluation of a System of Stormwater Detention Basins", Journal of Hydrologic Engineering, ASCE, November 2006

27. Heasom, W., Traver, R. Welker, A., "Hydrologic Modeling of a Bioinfiltration Best Management Practice", Journal of the American Water Resources Association. Oct 2006

28. Emerson C. ,Welty, C., Traver, R. "A Watershed-scale Evaluation of a System of Stormwater Detention Basins", Journal of Hydrologic Engineering, ASCE, May 2005

29. Syed A. Hashsham, S.A., Alm, E. W., Stedtfeld, R. D., Traver, R. G., and Duran, M., "Detection and Occurrence of Indicator Organisms and Pathogens",Water Environment Research, Vol: 75, No: 6. 2004.

30. Traver, R.G., Chadderton, R.A. "Effectiveness of a Wetland Best Management Practice: First Phase," (with R. Chadderton), Treatment Wetlands for Water Quality Improvement – Selected papers from Intecol Quebec 2000 Wetlands Conference, CH2M HILL Canada Limited – Editor John Pries, 2002

Conference Proceedings (since 2002)

1. Lord, L., Komlos, J., and Traver, R. (2013) Evaluation of Nitrogen Removal and Fate within a Bioinfiltration SCM. World Environmental and Water Resources Congress 2013: pp. 174-185.

2. Dovel, E. and Welker, A. (2013) The Use of Temperature as a Proxy for Nutrient Reduction: a Low-Cost Inspection Tool for Stormwater Control Measures. World Environmental and Water Resources Congress 2013: pp. 3031-3041.

3. Wadzuk, B., and Traver, R., "Design, Construction and Evaluation of a Stormwater Control Measure Treatment Train," World Environmental and Water Resources Congress 2012

4. Vacca, K. Wadzuk, B., "An Analysis of Soluble Reactive Phosphorus Removal Mechanisms in Surface-Flow Constructed Stormwater Wetlands," World Environmental and Water Resources Congress 2012

5. Hickman, J, Wadzuk, B., Traver,R., "Evaluating the Role of Evapotranspiration in the Hydrology of a Bioinfiltration Basin Using a Weighing Lysimeter," World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability.

6. Flynn, F., and Traver R. "Methodology for the Evaluation and Comparison of Benefits and Impacts of Green Infrastructure Practices Using a Life Cycle Approach", World Environmental and Water

Resources Congress 2011: Bearing Knowledge for Sustainability

7. Lee, R. and Traver, R., “Unit Process Simulation of a Bioinfiltration Stormwater Control Measure” World Environmental and Water Resources Congress 2010

8. Komlos, J., Rowe, A., Clark, S., Traver, R. Stinson, M., “Assessing BMP Performance Using Microtox Toxicity Analysis” World Environmental and Water Resources Congress 2010

9. Hickman, J. Schneider, D. Wadzuk, B. Traver, R., “Determination of Evapotranspiration in SCM’s Using a Weighing Lysimeter: An Experimental Approach” World Environmental and Water Resources Congress 2010

10. Feller, M., Traver, R. Wadzuk, B., “Estimation of Green Roof Evapotranspiration—Experimental Results”; EWRI Low Impact Development National Symposium 2010

11. Traver, R.,”Stormwater Infiltration Retrofits Experience Gained through Long Term Monitoring”, World Environmental and Water Resources Congress 2009

12. Machusick, M., Traver, R.,”The Observed Effects of Stormwater Infiltration on Groundwater”, World Environmental and Water Resources Congress 2009

13. Brown,R. Et al,” Bioretention/Bioinfiltration Performance in the Mid-”, World Environmental and Water Resources Congress 2009

14. Traver, R., Et al. “Stormwater Concepts – No Adverse Impact”, EWRI Low Impact Development National Symposium 2008

15. Horst, M., Traver, R., Tokarz, E. “BMP Pollutant Removal Efficiency”, ASCE EWRI National Symposium 2008

16. Emerson, C., Traver, R. “Long-Term Characteristics of Infiltration Best Management Practices”, ASCE EWRI National Symposium 2008

17. Wadzuk, B. Traver, R. “Nutrient Loading In A Mature Constructed Stormwater Wetland”, ASCE EWRI National Symposium 2008

18. Wadzuk, B. Traver, R. “Nutrient Loading In A Mature Constructed Stormwater Wetland”, ASCE EWRI National Symposium 2008

19. LeBoon, M., Traver, R. “An Infiltration Model Of An Underground Rock Storage Bed Infiltration Bmp”, ASCE EWRI National Symposium 2007

20. Wadzuk, B, Heasom, W., Traver, R.,”Re-conceiving the Villanova University Constructed Stormwater Wetland”, ASCE EWRI National Symposium 2007

21. Davis A, Hunt, W., Traver R. Clar, M. “Bioretention Technology: An Overview of Current Practice and Future Needs” LID National Symposium, 2007 (Extended Abstract)

22. Tokarz, E. Traver, R., Heasom, W. “Experiences from Long Term Monitoring of Stormwater Infiltration BMPs”, LID National Symposium, ASCE 2007 (Extended Abstract)

23. Gore, M., Welker, A. Traver, R., “Evaluation of the Long Term Impacts of an Infiltration BMP” ICHE 2007

24. Heasom, W., Traver R., “Modeling a BioInfiltration Best Management Practice “ LID National Symposium, ASCE 2007 (Extended Abstract)

25. Ermilio, J., Traver, R, "Hydrologic and Pollutant Removal Performance of a Bio-Infiltration BMP", EWRI 2006 – National Symposium

26. Rea, M., Traver, R. Performance Monitoring of a Stormwater Wetland Best Management Practice, National Conference, World Water & Environmental Resources Congress 2005 (EWRI/ASCE)

27. Emerson, C., Traver, R., The Villanova Bio-Infiltration Traffic Island: Project Overview, National Conference, World Water & Environmental Resources Congress 2004 (EWRI/ASCE)

28. Traver, R., Infiltration Strategies for Low Impact Development, National Conference, World Water & Environmental Resources Congress 2004 (EWRI/ASCE)

29. Designing for Infiltration – (Primary Author) A Perspective EWRI (ASCE 2003) World Water & Environmental Resources Congress, Philadelphia, PA

30. "Development of a BMP Research and Demonstration Park," *9th International Conference on Urban Storm Drainag*e, Environmental and Water Research Institute, ASCE, 2002

Ph.D. Dissertations (available through the VUSP website)

Evaluation of Infiltration Practices as a Means to Control Stormwater Runoff, Clay Emerson, May 2008

An Experimental and Numerical Analysis of Soluble Reactive Phosphorus Removal Mechanisms in Surface-Flow Constructed Stormwater Wetlands Using Soil Amendment Strategies, Kaitlin Vacca May 2013

Masters Theses (available through the VUSP website)

Evaluating Nutrient Removal and Hydraulic Efficiency in a Free Water Surface Flow Constructed Stormwater Wetland, Michael Rinker (2013)

Evaluation Of Nitrogen Removal And Fate Within A Bioinfiltration Stormwater Control Measure. Lord, Laura (2013)

Evaluation of Stormwater Control Measures from the Micro and Macro Perspectives: Low Cost Monitoring of Nutrients in Non-Vegetated Systems and Watershed-Scale Effects of Rain Gardens, Erin Dovel (2013)

A MODELING APPROACH TO THE PERFORMANCE OF AN INFILTRATION SCM DESIGN AND THE POTENTIAL IMPLICATIONS OF CLIMATE CHANGE, JACLYN MARGE (2013)

The Implementation and Evaluation of Stormwater Control Measures in Series, Cara Lyons (2013)

Evaluation Of Green Infrastructure Practices Using Life Cycle Assessment, Kevin Flynn, (2012)

Evaluating the Role of Evapotranspiration in the Hydrology of Bioinfiltration and Bioretention Basins Using Weighing Lysimeters, John Hickman Jr., 2011

Evaporation from A Pervious Concrete Stormwater SCM: Estimating the Quantity and its Role in the Yearly Water Budget, Evgeny Nemirovsky, 2011

The Application Of An Integrated Monitoring Plan On Stormwater Control Measures, Kathryn Greising, 2011

Modeling Infiltration In A Stormwater Control Measure Using Modified Green And Ampt, Ryan Lee, 2011

Urban Hydrology Modeling With EPA's Stormwater Management Model (SWMM) and Analysis of Water Quality in a Newly Constructed Stormwater Wetland, James Pittman, 2011

Quantifying Evapotranspiration From a Green Roof Analytically, Dominik Schneider, 2011

Quantifying Evapotranspiration in Green Infrastructure: A Green Roof Case Study, Meghan Feller, 2011

A Randomization Process for Modeling Constructed Wetlands with an Optimization Example, Gerrard Jones, 2010

A Side by Side Water Quality Comparison of Pervious Concrete and Porous Asphalt, and an Investigation into the Effects of Underground Infiltration Basins on Stormwater Temperature James Barbis, Dec 2009

Continuous Simulation of an Infiltration Trench Best Management Practice, Hans Benford, May 2009

The Observed Effects of Stormwater Infiltration on Groundwater, Matthew Machusick, May 2009

Water Quantity Comparison of Pervious Concrete and Porous Asphalt Products for Infiltration Best Management Practices, Patrick Jeffers , Jan 2009

Pollutant Removal Efficiency of a Mature Constructed Wetland Over the Course of a Year -Kelly Flynn , Dec 2008

A Soil Profile Characterization of a Bioinfiltration BMP, Keisha Isaac-Ricketts Aug, 2008

Pollutant Removal Efficiency of Three Infiltration BMPs during Storm Events, Erika Tokarz, June 2008

An Integrated Monitoring Plan for Best Management Practices, Krista Hankins, May 2008

The Implications of the First Flush Phenomenon on Infiltration BMP Design, Tom Batroney, May 2007

An Infiltration Model of an Underground Rock Storage Bed Infiltration, Megan Vanacore, Jan 2007

Stormwater Total Hydrocarbon and Hydrologic Mass Balance and a Chloride Mass Balance of the VU Stormwater Wetland, D. Salas-DeLaCruz Chemical Eng, 2007

Evaluation and Restoration of Two Seepage Pits with Special Considerations for Nutrient, Metal, and Bacterial Contents, Matt Gore, Oct 2007

An Examination of the Effect of Plant Density on Low Reynolds Number Flow in a Wetland, Erin Burke, Aug 2007

Characterization Study of a Bio-Infiltration Stormwater BMP, Jordan Ermilio, Dec 2005

Pollutant Removal Efficiency and Seasonal Variation of a Storm Water Wetland BMP, Gregg Woodruff, Sep 2005

A Hydrologic Analysis Of An Infiltration BMP, Erika Dean, Sep 2005

An Infiltration Analysis of the Villanova Porous Concrete Infiltration Basin BMP, Andrea Braga, Sep 2005

Pollutant Removal Efficiency of a Stormwater Wetland BMP during Baseflow and Storm Events, Matthew Rea, Sep 2004

Water Quality Study of a Porous Concrete Infiltration BMP, Michael Kwiatkowski, May 2004

Water Quantity Study of a Porous Concrete Infiltration BMP, Tyler Ladd, June 2004

TOTAL PROJECT BUDGET

Note: several of these grants had differing starting dates, this is an estimate. Grants other then the NMP funds are supplemental and also address other project goals.

Year 1: Oct 2003 – Sep 2004	
VUSP – PaDep Growing Greener	$170,000
NMP – PaDep (319 Funds)	$ 53,933
NMP – PaDep (319 Funds)	$ 11,733
Year 2: Oct 2004 – Sep 2005	
EPA Region III – 104b.3. funds	$160,000
NMP – PaDep (319 Funds)	$ 56,630
Year 3: Oct 2005 – Sep 2006	
NMP – PaDep (319 Funds)	$ 58,561
VUSP - PaDep Growing Greener	$175,000
Year 4: Oct 2006 – Sep 2007.	
NMP - PaDep (319 Funds)	$ 61,000
VUSP Corporate Donations	
Note PC/ PA funds not included	
Year 5: Oct 2007 – Sep 2008.	
NMP – PaDep (319 Funds)	$ 63,990
VUSP Corporate Donations	
Note PC/ PA funds not included	
Year 6: Oct 2008 – Sep 2009	
PaDep (319 Funds)	$ 68,910
VUSP Corporate Donations	
Year 7: Oct 2009 – Sep 2010	
PaDep (319 Funds)	$ 72273
VUSP Corporate Donations	
Year 8: Oct 2010 – Sep 2011	
PaDep (319 Funds)	$ 74628
VUSP Corporate Donations	
Year 9: Oct 2011 – Sep 2012	
PaDep (319 Funds)	$ 78098
VUSP Corporate Donations	
Year 10: Oct 2012 – Sep 2013	
PaDep (319 Funds)	$ 85,000
VUSP Corporate Donations	

IMPACT OF OTHER FEDERAL AND STATE PROGRAMS

State Impact – Current State regulations in general terms requires the two year storm to be infiltrated, evaporated or reused on site

Federal Impact – The Chesapeake Bay Nutrient TMDL and the recent requirement to manage storm volume for new federal facilities combined with the commonwealth requirements has raised interest on green infrastructure volume reduction SCMs which is the focus of this project. The volume requirement is defined as the 95% storm occurrence which is roughly 1.7 +/- inches in the Philadelphia area.

Philadelphia Water Department CSO Long Term Control Plan requires properties to remove one inch of rainfall volume.

OTHER PERTINENT INFORMATION

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 on innovative stormwater Best Management Practices, directed studies, technology transfer and education.

* Research and directed studies will emphasize comprehensive watershed stormwater management planning, implementation, and evaluation.

* Technology transfer will provide tools, guidance and education for the professional.

* Partnership Goal is to promote cooperation amongst the private, public and academic sectors.

http://www.villanova.edu/VUSP

Deliverables – 2012-2013

- Participated in the 2012 and 2013 319 NPS Monitoring Workshop as a planner, and presenter. In October 2012, besides representing Pennsylvania on the planning committee, we participated presenting results from our research on the bioinfiltration site, “Advancements in Sustainable in Rain Garden Design: Adding Evapotranspiration to the Tool Box.” In addition, Dr. Traver ran a workshop on monitoring for the workshop. For October 2013, Dr. Traver is scheduled to present “Long-term Nutrient Reduction Results in an Urban Rain Garden” and to present a workshop “Fundamentals of Green Infrastructure — Lessons from the 319 Monitoring Program.”

- Presented work on the Bioinfiltration Traffic Island nitrogen performance at the National EWRI conference in Cincinnati Ohio, and the LID National Conference in Minnesota.

- Scheduled to host the 2013 Pennsylvania VUSP Stormwater Symposium in October 2013. There are scheduled research presentations on the 319 demonstration sites, and they will be visited by the tours. We are also scheduled to host a tour during “Green Build”

- Hosted MANY local groups to visit the research sites

Bioinfiltration Site. As per the contract documents, focus has continued to be on the quality / quantity interface. Note that a revised QAAP was submitted and has been approved and the water monitoring system has been updated, partially funded through the VUSP partners. The number of publications delivered based on this work GREATLY exceeds the deliverables promised.

- Referred Journal Publications on the Bioinfiltration Site.
    - Lee, R., Traver, R., and Welker, A. "Continuous Modeling of Bioinfiltration Stormwater Control Measures using Green and Ampt," Journal of Irrigation and Drainage Engineering, in press
    - Komlos, J. and Traver, R.G. (2012). "Long Term Orthophosphate Removal in a Field-Scale Stormwater Bioinfiltration Raingarden" Journal of Environmental Engineering, 138, 991-998.
    - Komlos, J., A. Welker, V. Punzi and R. Traver (2013) "Feasibility Study of As-Received and Modified (Dried/Baked) Water Treatment Plant Residuals for use in Stormwater Control Measures (SCMs)" Journal of Environmental Engineering. J. Environ. Eng., 139(10), 1237–1245.
    - Flynn, K., Traver, R., (2013) "Green Infrastructure Life Cycle Assessment: A Bio-Infiltration Case Study", Journal of Ecological Engineering, Volume 55, pp 9-22.
    - Welker, A., Mandarano, L., Greising, K., Mastrocola, K. (2013) "Application of a Monitoring Plan for Stormwater Control Measures in the Philadelphia Region," J. Environ. Eng., 139(8), 1108–1118.

Master's Thesis Developed: *Note – these are to be turned into articles in the future.*

Lord, Laura (2013) Evaluation Of Nitrogen Removal And Fate Within A Bioinfiltration Stormwater Control Measure.

Stormwater Wetland Site.

- Referred Journal Publications on VCASE Sites supported through 319.
    - Jones, G. and Wadzuk, B. (2013). "Predicting Performance for Constructed Storm-Water Wetlands." J. Hydraulic. Eng., 139(11), 1158–1164.

Master's Thesis Developed: *Note – these are to be turned into articles in the future.*
Michael Rinker (2013) Evaluating Nutrient Removal and Hydraulic Efficiency in a Free Water Surface Flow.

The only challenge with the deliverables is to update the USEPA / ASCE Stormwater BMP Database. When funding is available for the management team, we provide the data requested.

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National Research Council. 2008. Urban Stormwater Management in the United States. National Academies Press, Washington DC

North Carolina State University, NWQEP Notes 115:1-6, http://www.bae.ncsu.edu/programs/extension/wqg/issues/notes115.pdf [accessed July 26, 2010]