Tracking the Rain: Can we Use Remote in situ Sensors to Evaluate the Effectiveness of Green Infrastructure?

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Tracking the Rain: Can we use remote *in situ* sensors to evaluate green infrastructure?

A Capstone Project Submitted in Partial Fulfillment of the Requirements of the Renée Crown University Honors Program at Syracuse University

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May 2016

Honors Capstone Project in Civil Engineering

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ABSTRACT

For decades Onondaga County and the City of Syracuse, New York, have struggled with water quality issues involving combined sewer overflows. These combined sewer overflows and the lack of an appropriate system to mitigate storm water runoff have continually contributed to the degradation of Onondaga Lake and the streams draining into it. To combat the issues presented by combined sewer overflows, Onondaga County implemented the storm water reduction program known as "Save the Rain". The Save the Rain program aims to utilize various forms of green infrastructure to reduce storm water flows into the combined sewer system. Examples of green infrastructure technologies include, but are not limited to: green roofs, porous pavement lots, rain gardens and bio swales. In this Honors thesis I aimed to observe and evaluate the effectiveness of porous pavement lots, rain gardens and bio swales associated with Save the Rain program. Various water quantity and quality instrumentation were placed in the catch basins of these technologies in Syracuse. Three different types of sampling technologies were utilized. Water level loggers were installed in order to monitor the quantity of water processed through measurements of change in water stage (height). Water quality sondes equipped with pH, turbidity, conductivity, oxidation-reduction potential (ORP), fluorescent dissolved organic matter (fDOM), and temperature sensing probes were placed in the catch basin of the system to monitor water quality. Finally, a 1 liter bottle sampling system, consisting of 3 bottles positioned vertically, was used to collect and analyze water quality at different positions of water stage in the catch basin. From this study it was observed that porous pavement systems have the ability to capture large quantities of stormwater, but may have negative effects on water quality. Rain garden and bioswale systems functioned with varying capture performance but showed a greater ability to filter water and improve water quality.
EXECUTIVE SUMMARY

Aging civil infrastructure has become a critical issue for many cities across the United States. Of this aging infrastructure, sewer systems are one of the more critical areas in need of improvement. Older cities, primarily in the eastern U.S., were built with combined sewer infrastructure. Combined sewers carry waste from domestic and industrial inputs as well as the inputs from storm water. It is this combination of flows that can cause a system exceedance otherwise known as combined sewer overflows. A combined sewer overflow occurs when the waste water treatment facilities cannot process excessive flows experienced when these systems receive high runoff associated with precipitation events or snowmelt. As a result, the surplus mixed sewage is discharged directly into surface water bodies. For public health and safety as well as preservation of the environment, it has become important to replace or alter these sewer systems in order to prevent these occurrences.

To eradicate combined sewer overflows, there are two common approaches. The first is a complete replacement of the existing infrastructure to allow for two systems with one conveying storm water while the other carries the domestic and industrial waste. The second option is to implement technologies that divert the storm water at the source of the input. This diversion can be accomplished through capture, storage and potential processing of the stormwater by the means of surface infiltration into subsurface porous areas and/or promoting enhanced evapotranspiration. Because of the economic and environmental benefits, the second option has become a popular choice. This modification of the urban landscape for stormwater capture is referred to as green infrastructure.
Green infrastructure is an emerging network of technologies that aims to reduce and delay stormwater inputs into the combined sewer system. These technologies all incorporate a modification of the surface and subsurface characteristics of the local landscape in order to improve infiltration, evapotranspiration and storage capacities. Typical technologies used are rain gardens, porous pavements and bioswales.

With the increasing popularity and use of green infrastructure, it has become important to further understand, characterize and quantify how each type of technology functions and the degree to which they mitigate combined sewer overflows. In addition, green infrastructure has the potential to improve water quality, which represents a co-benefit of this approach to stormwater management. Given the widespread implementation of green infrastructure, it is important to quantitatively evaluate and assess the performance of these technologies in the field. The overall goal of my Capstone was to instrument and evaluate the ability of green infrastructure facilities to process stormwater quantity and quality across runoff events of varying magnitude in Syracuse, New York.

To achieve this goal, I instrumented multiple facilities, including porous pavement, bioswales and rain gardens with sensors that were used to track the amount and the quality of the water processed for a series of storm events during 2014. In particular, the ability of these systems to reduce stormwater inputs was determined by measuring the water inflow and the depth of water or stage at each system using a weir and a continuous water level recorder. Water quality was determined in the same facilities using in situ water quality sensors or sondes and
traditional collection of water samples following by laboratory analysis to monitor the changes in water quality during storm events.

The results of this study indicate green infrastructure technologies have varying capacities to reduce stormwater inputs into the combined sewer systems. Porous pavement systems had high capacities at reducing stormwater inputs, while rain gardens and bioswales had variable capacities to process stormwater inflows. The effectiveness for reduction and capture by the porous pavements may indicate a possible overdesign issue which should be considered in future designs. I observed that green infrastructure does alter water quality. For some porous pavements, deterioration in water quality characteristics was evident. This water quality issue may be related to overdesign. Because the green infrastructure systems rarely overflow, there is no opportunity to “flush” contaminants which can lead to an accumulation in these systems. Future work is needed to characterize and quantify the long-term processing of contaminants by green infrastructure technologies.

In conclusion, green infrastructure systems can be a cost-effective tool for reducing stormwater inputs that can be monitored with \textit{in situ} sensors. Results on stormwater capture indicate that porous pavement systems are the most effective at stormwater reduction and capture, but all green infrastructure technologies performed well. Poor water quality patterns that were observed in porous pavement systems should be evaluated further. To improve performance and longevity across the board, it is suggested that more attention be taken towards implementing an effective and manageable maintenance plan.
ACKNOWLEDGEMENTS

I would like to extend my deepest gratitude to my two advisors Dr. Charles Driscoll and Dr. David Chandler who have provided guidance and mentoring throughout this process. Without their patience and encouragement this project would not have been completed. I would also like to thank Mario Montesdeoca for his assistance and all graduate students who provided knowledge and assistance throughout this process.
CHAPTER 1: INTRODUCTION

In Syracuse, New York, more than 86% of current sanitary sewer systems were constructed between 1875 and 1950\(^1\). Sanitary sewer systems transport wastewater from residences, commercial operations and industrial complexes to a wastewater treatment facility. Prior to modern construction advancements, sewer systems conveyed storm water, together with domestic and industrial sewage water. This approach to water conveyance is a combined sewer system. During high flow (rain, snowmelt) events, combined wastewater can exceed the capacity of the wastewater treatment plant. Under this condition the treatment facility is bypassed and these combined sewer overflows directly discharge dilute raw sewage to surface waters contributing to water quality problems. Onondaga County has 46 combined sewer overflow (CSO) discharge locations on designated surface water bodies\(^2\). Many of these discharge locations are located on direct tributaries to Onondaga Lake, which have contributed to the degradation of the 4.6 square mile (11.9 square kilometers) lake located north of Syracuse.

In an effort to reduce occurrences of combined sewer overflows, Onondaga County originally focused on rehabilitating and replacing portions of the existing gray infrastructure. However, in 2009 the County altered this approach to stormwater management by adopting a plan of using green infrastructure as a primary tool for reducing storm water flows. Onondaga County named

\(^1\) (City of Syracuse Comprehensive Plan 2040, 2014)
\(^2\) (Combined Sewer Overflow Notification, 2016)
this green infrastructure program “Save the Rain”. By 2018, this program aims to reduce combined sewer overflows by 95% or 247,000,000 gallons/year\(^3\) (935,000 m\(^3\)/year).

The purpose of green infrastructure is to capture stormwater by providing additional storage and promoting infiltration or evapotranspiration through modification of the natural landscape of a given area. Depending on the type of green infrastructure installed and the size of the area, the rate and amount of capture, storage and loss varies substantially. In Syracuse, New York, the most widely used green infrastructure technologies are porous pavements, green roofs, rain gardens, and bioswales. Other technologies such as tree plantings are used, but were not considered in this study.

With the increasing popularity of green infrastructure as a method of reducing combined sewer flows, there has become a critical need for information pertaining to the hydraulic performance of these technologies. It is also of interest to monitor the water quality in these systems for the purpose of monitoring pollutant transport. Depending on the type of system, green infrastructure has the ability to remove trace metals, nutrients, sediment, pathogens and other contaminants which can lead to improved water quality\(^4\). The extent to which given infrastructure effectively remove these pollutants depends on technology used, design, location, season, climate and the event characteristics.

In this study I aimed to determine the ability of different types of green infrastructure in Syracuse to reduce stormwater inputs into the combined sewer. In addition, I evaluated patterns of water quality during draining of different types of green infrastructure systems. The

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\(^3\) (CH2MHILL, 2012)

\(^4\) (Driscoll, C.T., et. al, 2015)
water quality response over the duration of storm events of varying magnitudes was also evaluated.
CHAPTER 2: SITE DESCRIPTIONS AND METHODS

BACKGROUND

Each green infrastructure system in Syracuse has a central catch basin where stormwater drains through a weir. The weir is the final component limiting stormwater transport into the combined sewer. This catch basin was chosen as the study location for multiple sites because of the ability to understand water quantity and quality passing into the combined sewer during a weir overflow. In some cases, it was not practical to instrument the central catch basin and alternative catch basins were monitored.

Each monitored catch basin used a combination of at least two technologies to measure water quality and catch basin depth. A HOBO water level logger (P/N: U20L-04) manufactured by Onset Technologies was used to obtain measurements for depth of the water column in the catch basin. Sensor measurements of water quality were collected with an EXO1 Water Quality Sonde (SKU: 599501-00), equipped with conductivity (salinity), turbidity (suspended matter), temperature, pH, oxidation reduction potential (ORP), and fluorescent dissolved organic matter (fDOM) sensors. Grab samples were also collected at sites in a vertical suite of one liter bottles. These bottles were positioned to sample with variations in water stage (height). The grab samples and sonde data provide complementary water quality observations. Sondes provide continuous record of observations through the duration of an event, allowing for an understanding dynamics of fine scale changes in water quality. The grab samples provide a discrete record of routine water quality measurements not supported by the sondes.
SITES

Seven built and operating green infrastructure sites were monitored during this study. The sites were chosen based on type, location, and ease of access. The sites selected for the study included three porous pavement, two bioswales, and one rain garden. A summary of salient information regarding each type of green infrastructure technology as described by the US Environmental Protection Agency is provided in Table 1.

The approximate location of these sites in the City of Syracuse and the type of green infrastructure at each location is shown in Figure 1. Shown in blue is a reference site where grab samples were collected in storm water drain adjacent to the road surface of Wilkinson Street.

Table 1: Description of technologies investigated in this research.5

<table>
<thead>
<tr>
<th>Green Infrastructure System</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioswale</td>
<td>Channels that are vegetated or xeriscaped which slow, absorb, and filter storm water flows.</td>
</tr>
<tr>
<td>Rain Garden</td>
<td>Vegetated basins which collect and absorb stormwater through infiltration. Rain gardens allow for natural processes of evaporation and transpiration to occur.</td>
</tr>
<tr>
<td>Porous Pavement</td>
<td>Allow for infiltration, capture, and treatment of the rainwater where it falls. Typical solutions are porous concrete or porous asphalt.</td>
</tr>
</tbody>
</table>

Adapted from (US EPA)

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5 (US EPA, 2015)
**Figure 1:** Site study locations; shown in black are porous pavement sites; green are rain gardens; orange are bioswales; blue is a reference site. Figure not to scale. Map source: Google Maps Engine.

**GENERAL SITE FEATURES**

Each green infrastructure site studied has a similar means of subsurface stormwater collection. Each site has a permeable surface through which the stormwater infiltrates. Under the surface, depending on the type of green infrastructure, there is a varying depth of porous media. At the base of the porous media section typically there is a porous pipe through which stormwater is conveyed that is not removed by the green infrastructure. In many facilities, there is an impermeable layer underneath the porous media which prevents stormwater from infiltrating into the native soils. The central catch basin captures water from the porous pipe sections as well as some overflow from the surface of the green infrastructure. During high flow events, stormwater from both the surface and the porous inlets were sampled in the catch basin. If the
stormwater flow did not cause an overflow of the weir, the quality of the catch basin water was monitored as it drains to the porous media system.

POROUS PAVEMENT SITES

The porous pavement sites shown with black markers in Figure 1 are located at the Rosamond Gifford Zoo in Syracuse. The Rosamond Gifford Zoo parking lot has a capture area of 224,800 sq. ft. (20,884 m²), which equates to an estimated runoff reduction of 3,772,000 gal/year (14,278 m³). The parking lot uses both bioswale medians (see Figure 3) and porous sections to capture stormwater\(^6\). The locations of sampling relative to the green infrastructure technologies studied are shown in Figure 2. Point ZENE (Zoo Elephant northeast) included bottle and depth sampling, Points ZESW (Zoo Elephant southwest) and ZT (Zoo Tiger) had depth and sonde sampling.

Point ZENE was located in a porous pavement section which drains to the combined sewer in the event of a weir overflow. Point ZESW was also located on a porous section which is connected to the lower lot with an unidentified pipe section. Point ZT is located at a higher elevation that drains a bioswale and the porous piping under the porous pavement.

\(^6\) (Onondaga County, Save the Rain: Green Projects, 2011)
Figure 2: Rosamond Gifford Zoo sampling locations. Figure not to scale. ZENE was located in a porous pavement section which drains to the combined sewer in the event of a weir overflow.

ZESW was also located on a porous section which is connected to the lower lot with an unidentified pipe section. ZT is located at a higher elevation that drains a bioswale and the porous piping under the porous pavement.
Figure 3: Zoo bioswale during winter season. Adjacent to bioswale is porous pavement sections.

BIOSWALE SITES

Represented by the orange markers in Figure 1, the bioswale sites are located on East Washington Street adjacent to the Syracuse Center of Excellence and on East Adams Street on the south side of the OnCenter Parking Facility. The East Washington Street site featured an interlocking porous paver section on the road surface, and bioswales on either side of East Washington Street. In total, the East Washington site has a capture area of 76,900 sq. ft. (7144 m$^2$) and a runoff reduction of 933,000 gal/year$^7$ (3530 m$^3$/year). The sampling location relative to the Center of Excellence and East Washington St is shown in Figure 4.

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$^7$ (Onondaga County, Save the Rain: Green Projects, 2011)
Figure 4: East Washington St. Green Corridor. Shown in Green is monitored bioswale with EWCOE being the sampling location of depth and bottle samples.

The OnCenter parking garage has a total surface area of 72,500 sq. ft. (6735 m²) and a total capture of 1,277,000 gal/year\(^8\) (4834 m³). This bioswale site was sampled with depth sensors, an EXO1 water quality sonde, and bottle sampling technologies. The bioswale accepts the runoff from the exposed parking surfaces of the parking garage and rainfall infiltrating from the surface. The parking garage drainage is transferred to the swale via multiple outlet pipes that drain the collected storm water onto a flat granite surface to disperse the flow before it enters the swale. The sample location relative to the garage and the swale is shown in Figure 5.

\(^8\) (Onondaga County, Save the Rain: Green Projects, 2011)
Figure 5: OnCenter bioswale indicated by green section. Label OCO shows the sampling location. East Adams Street is shown in the foreground.

Rain Garden Sites

Represented by the blue and green markers in Figure 1, the Barker Park rain garden which is part of a larger system that has a total surface area of 24,000 sq. ft. (2230 m²) and a total runoff reduction of 1,574,000 gal/year (5958 m³). The rain garden has a central catch basin which is an outlet for Tracy St. runoff and Wilkinson St. runoff. This catch basin was sampled with depth sensors, an EXO1 water quality sonde, and bottle sampling technologies. The sampling location relative to Tracy and Wilkinson streets is shown in Figure 6.
Figure 6: Barker Park rain garden. Rain garden is represented by dotted line. Inlet catch basins are indicated on the adjacent streets, site BPI is the reference catch basin. Site BPO is the central catch basin.

METHODS

CALIBRATION AND PROGRAMMING METHODS

HOBO water level loggers require programming with the HOBOware software package to launch. Following the procedure described in the reference manual, the HOBO water level logger was programmed to sample data points at a five minute interval. The HOBO Data logging coupler for the water level logger uses a portable optic interface to communicate with device which allowed for data collection at site.

The EXO1 water quality sondes required programming and calibration. Each sensor was calibrated according to the manual and the adapted methods described in Appendix 1. When
launching the EXO1 water quality sonde with the KOR-EXO software package, it was set at a fifteen minute logging interval.

**INSTALLATION METHODS**

At each site, a water level logger was installed by placing it at the base of the catch basin. In some instances, the water level logger was placed in a PVC pipe section with a slotted section at the base to prevent movement during turbulent conditions. In the sites where the water level loggers were not placed in a PVC section, they were secured to the top of the catch basin with twine.

For the EXO1 water quality sonde, a metal conduit bracket was installed approximately 12 inches (30.48 cm) above the base of the catch basin. A PVC reducing coupler was mounted in this bracket that allowed the sonde to be placed from the surface. This allowed for a repeatable installation in deep catch basins that otherwise could not have been achieved. A collection of installation photos is shown in the Appendix.

The one liter bottle sampling system was installed to allow for sampling collection at various conditions of stage as shown in Figure 7. Mounted on a threaded rod, each bottle was set at predetermined heights based on the catch basin specifications. A bottle was positioned at the lowest elevation below the inlet, the middle bottle was placed below the height of the weir, and the upper bottle was placed above the weir. Each bottle had a rubber stopper installed at the top and a plastic ball inside which would plug the stopper when the bottle became full. This ensured that further mixing of the sample did not occur after the bottle was filled.
**Figure 7:** Conceptual diagram illustrating collection of water samples in one liter bottles with increasing stage in catch basin.

**Collection Methods**

After a rain event of size greater than 1/4” (0.64 cm) total, the bottles with water samples were collected and capped. If the runoff event was not large enough to fill the lower bottle completely, the samples were discarded and a new bottle was placed for sampling. Sonde data were retrieved every 30 days, when the sondes were extracted for calibration.

The collected grab samples were returned to the laboratory and then split into smaller bottles for water quality analysis. The samples remained refrigerated while still in the process of being
tested for water quality constituents. The one liter bottles were cleaned using a standard process of three Milli-Q water rinses, filling with 0.05M sulfuric acid, and cured in the oven for 24 hours.

**ANALYSIS METHODS**

In the event of a weir overflow, depth data were used in conjunction with the Kindsvater and Carter equation (Equation 1) to estimate the volume of the overflow.

Equation 1: \[ Q = C_e \cdot \frac{2}{3} \sqrt{2gb_e h_e^{1.5}} \] (Kindsvater and Carter, 1980)

Where:
- \( C_e \) = Discharge Coefficient
- \( g \) = Gravitational constant
- \( b_e \) = Effective weir width
- \( h_e \) = head (height of water over weir)

The discharge coefficient was estimated using Equation 2.

Equation 2: \[ C_e = .602 + .075 \left( \frac{h_e}{P} \right) \]

Where:
- \( C_e \) = Discharge Coefficient
- \( h_e \) = head (height of water over weir)
- \( P \) = height of weir from base of catch basin

Inflow volumes were estimated from the size of the catch basin tributary area and precipitation depth.
CHAPTER 3: EXPERIMENTAL RESULTS

RESULTS: SYSTEM RESPONSE TO PRECIPITATION EVENTS

Continuous catch basin depth was monitored at each site from April 2014 until October 2014. During this period, the City of Syracuse experienced 22 rain events with precipitation in excess of one centimeter. Of these 22 storms, six were in excess of two centimeters, and three were in excess of three centimeters of precipitation\(^9\). Overall precipitation depth for April 2014 to October 2014 storms is shown in Table 2. Annual precipitation for Syracuse is 102.87 cm or 40.5”.

**Table 2: Precipitation depth for April 2014 to October 2014 storms in Syracuse, New York. Data obtained from NOAA station at SUNY ESF.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation Depth (cm)</th>
<th>Date</th>
<th>Precipitation Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/30/2014</td>
<td>1.02</td>
<td>7/29/2014</td>
<td>3.86</td>
</tr>
<tr>
<td>5/10/2014</td>
<td>1.12</td>
<td>7/31/2014</td>
<td>1.6</td>
</tr>
<tr>
<td>5/14/2014</td>
<td>2.18</td>
<td>8/3/2014</td>
<td>1.19</td>
</tr>
<tr>
<td>5/17/2014</td>
<td>2.92</td>
<td>8/13/2014</td>
<td>1.19</td>
</tr>
<tr>
<td>6/25/2014</td>
<td>3.02</td>
<td>8/17/2014</td>
<td>1.04</td>
</tr>
<tr>
<td>6/26/2014</td>
<td>1.85</td>
<td>8/22/2014</td>
<td>2.72</td>
</tr>
<tr>
<td>7/9/2014</td>
<td>1.42</td>
<td>9/22/2014</td>
<td>1.83</td>
</tr>
<tr>
<td>7/15/2014</td>
<td>1.14</td>
<td>10/1/2014</td>
<td>1.07</td>
</tr>
<tr>
<td>7/24/2014</td>
<td>1.19</td>
<td>10/8/2014</td>
<td>1.19</td>
</tr>
<tr>
<td>7/27/2014</td>
<td>1.14</td>
<td>10/16/2014</td>
<td>3.68</td>
</tr>
</tbody>
</table>

Precipitation quantity did not always correspond to a high stage response in the catch basin. A continuous record of precipitation depth and the response of the stage in the catch basin for

\(^9\) (NOAA, 2014)
Barker Park rain garden, Zoo Elephant parking lot, and OnCenter parking garage and be shown in Figures 8, 9 and 10 respectively.

**Figure 8: Barker Park rain garden precipitation (upper panel) and runoff stage (lower panel) record April 28, 2014 to October 27, 2014. The stage of the three grab sample bottles is shown as is the height of the weir. Runoff stage exceeding the weir height discharges into the combined sewer system.**

During the study period, there were 14 weir overflows at the Barker Park rain garden. The greatest weir overflows were observed during high volume storms that occurred within three days after the previous storm. The event on October 16, 2014 measured at 3.68 centimeters of rain, the second largest event of the study period, did not produce a significant weir overflow.
Figure 9: Zoo Elephant northeast parking lot time series: Precipitation (upper panel) and stage (lower panel) record of events April 28, 2014 to October 27, 2014. The stage of the three grab sample bottles is shown as is the height of the weir. Runoff stage exceeding the weir height discharges into the combined sewer system.

There was one observed overflow event at the Zoo Elephant NE parking lot, which occurred on August 3, 2014. Like Barker Park rain garden, high volume events usually produced the largest change in stage in the catch basin. The overflow that occurred on August 3, 2014 was for a storm of 1.14 centimeters. This result indicates that other factors such as saturation of the subsurface porous voids which were not monitored in this study affect the overflow occurrence rate of these systems.
Figure 10: OnCenter Parking Garage bioswale time series: Precipitation (upper panel) and runoff stage (lower panel) record May 11, 2014 to August 17, 2014. The stage of the three grab sample bottles is shown as is the height of the weir. Runoff stage exceeding the weir height discharges into the combined sewer system.

Due to inadequate data collection from the East Washington St. bioswale site, depth data were not presented. Grab samples were not collected at the remaining Zoo sites, so the overall precipitation record is not provided.

Depth data collected at each site were analyzed using the Kindsvater and Carter equation to determine for weir discharge in an overflow event. All observed systems, with the exception of Barker Park Rain Garden (Figure 8), had one overflow event between April 2014 and October
2014. Inflow values were estimated from tributary areas and precipitation depth from the day of the event.

Estimates for the inflow from Barker Park Inlet (BPI), one of the inlets for Barker Park Outlet (BPO, See Figure 6) as well as estimates for total inflow BPO from all inlets are shown in Figure 11. If one of the selected events overflowed the weir, then outflow was estimated as shown in Figure 11. Note that the outflow from Barker Park outlet does not discharge directly into the combined sewer, but instead continues further into the green infrastructure system. Therefore a weir overflow at this site (BPO) does not necessarily correspond to a reduction in stormwater inflow to the combined sewer system.
RESULTS: WATER QUALITY

Water quality varied based on site type and site characteristics. Observed EXO-1 Sonde data are shown for ranges of observed values (Figure 12, 13, and 14) and hysteresis loops for specific conductivity, fluorescent dissolved organic matter (fDOM) and pH (Figures 17-22) associated with changes in stage during individual runoff events. Considering weir overflows were rare with the exception of Barker Park Rain garden, values of outflow (overflow) loadings were not determined.

Figure 11: Inflow and outflow volumes for Barker Park Rain inlet and outlet for 2014 precipitation events.
Figures 12, 13, and 14: Boxplots for data during rain events for green infrastructure sites monitored with EXO-1 water quality sonde from June-August 2014. OCO is OnCenter outlet. ZT is Zoo Tiger. BPO is Barker Park outlet. ZE is Zoo Elephant.

Specific conductivity was highest at Zoo sites with average values of 229μS/cm at Zoo Elephant and 186μS/cm at Zoo Tiger. Specific conductivity at the two swale sites was significantly lower than the porous pavement Zoo sites, with average values of 84μS/cm and 60μS/cm at the OnCenter and Barker Park outlet, respectively. Average values for pH were all slightly basic, with average values of 7.9 and 8.3 at Zoo Elephant and Zoo Tiger, respectively. The OnCenter site had the lowest average pH value with 7.6, and Barker Park outlet had an average value of 8.0.
The Zoo sites had the highest values of fluorescent dissolved organic matter (fDOM) with mean values of 113 QSU at Zoo Tiger and 81 QSU at Zoo Elephant. OnCenter bioswale and Barker Park rain garden had fDOM mean values of 13 QSU and 40 QSU, respectively. Standard deviations for these sites were large, but only because of the nature of the collected data. Water quality values obtained during the filling of the catch basin are shown in Figures 12, 13 and 14. In most instances, the value was low during the onset of the precipitation event in the low stage bottle and the water quality parameter increased with increases in stage from the measured concentrations in the higher stage bottles giving a wide range of values explaining the high standard deviation.

Data collected from bottle sampling were weighted by contributing area. Dissolved organic carbon (DOC) loadings are shown in Figure 15. Zoo Elephant northeast had the highest DOC loading with a mean value of 41 mol C/event. Both Barker Park sites had low DOC loadings in comparison to the Zoo site. Barker Park inlet had a mean value of 3.1 mol C/event and Barker Park outlet had a mean value 8.0 mol C/event. The loading of DOC at Barker Park outlet was nearly double the loading of Barker Park inlet, which indicates that the outlet most likely receives identical loadings from each adjacent street and that it receives minimal input from the rain garden. Based on area footprint, the rain garden occupies 13% of the total tributary area.

Of the ions analyzed, chloride was also evaluated because of the large number of observations. Chloride loadings were the highest at Barker Park outlet (mean value of 3 mol/event) and the lowest at Barker Park inlet (mean value of 0.9 mol/event). Unlike DOC trends, chloride loading
was lower at the Zoo Elephant lot (mean value of 2.1 mol/event.) than the loading at Barker Park rain garden.

At all sites except Barker Park, rain garden weir overflows were rare. As a result only inflow water quality values are presented for rain garden sites. Inflows represent a direct loading to the green infrastructure system.

Due to varying infrastructure type, the systematic response of water quality solute loadings to catch basins displayed distinct differences from site to site. Barker Park rain garden demonstrated a tendency to rapidly increase in specific conductance during the storm onset. After the catch basin reached maximum depth, specific conductance at Barker Park rain garden began to decrease (Figure 17). Zoo Tiger and Zoo Elephant lots both initially decreased in
specific conductance and then increase after the stage reached a maximum depth (Figures 18 and 19). The specific conductance was observed to not decrease as stage reached its maximum in the catch basin like Barker Park rain garden, but instead continue to increase at the end of the event.

Similar patterns were observed for fluorescent dissolved organic matter (fDOM). At the Barker Park rain garden catch basin, fDOM increased as stage increased until the maximum stage, when fDOM generally decreased or remained the same, with the exception of June 26, 2014 event 2. At the Zoo Tiger lot, fDOM gradually decreased as stage increased and then began to increase after maximum stage was attained. fDOM demonstrated a tendency to rapidly decrease at the Zoo Elephant lot and then remain steady as stage began to decrease.

Amongst both specific conductivity and fDOM observations, the June 25, 2014 event two was an anomaly. The event surge which occurred four hours after the conclusion of the prior event did not cause an initial increase in any of the three water quality observations from sondes. After stage reached a peak, both specific conductance and fDOM gradually increased.
Figure 17: Specific conductivity response changes in stage to runoff events in the Barker Park Catch Basin (June 17, 2014 to June 26, 2014 rain events).

Figure 18: Specific conductivity response to changes in stage during runoff events at the Zoo Tiger Catch Basin (June 25, 2014 to July 9, 2014).
Figure 19: Specific conductivity response to changes in stage during runoff events at Zoo Elephant catch basin (June 25, 2014 to July 9, 2014).

Figure 20: fDOM response to changes in stage during runoff events in the Barker Park Catch Basin (June 17, 2014 to June 26, 2014 rain events).
Figure 21: fDOM response to changes in stage during runoff events at the Zoo Tiger Catch Basin (June 25, 2014 to July 9, 2014).

Figure 22: fDOM response to changes in stage during runoff events at the Zoo Elephant Catch Basin (June 25, 2014 to July 9, 2014).
CHAPTER 4: DISCUSSION

DISCUSSION: SYSTEM RESPONSE TO PRECIPITATION EVENTS

Green infrastructure response to precipitation varied based on the system characteristics. The porous pavement systems at the zoo rarely overflowed, whereas Barker Park overflowed frequently. Barker Park rain garden displayed a distinct pattern of a similar retention rate after filling in which the gradual decrease in catch basin stage typically occurred over a 2 to 3 day period. This difference in rate of retention from the other monitored sites is thought to be a function of the condition of saturation of the subsurface media at Barker Park prior to the event.

The OnCenter bioswale was expected to respond in a similar manner to Barker Park rain garden, but rather exhibited very few overflows during the study period. But upon inspection after rain events all bottles were frequently filled at the OnCenter catch basin. Because the top bottle of the system was placed at the height of the weir, this repeated filling of the bottle suggests that there was a bypass of the green infrastructure and a direct system input from the surface. During the June 25, 2014 storm, it was observed that the proximity of the parking garage discharge pipes (within 20’ for most locations) leads to direct loading of stormwater to the system without passing into the subsurface media. This bypass resulted in the filling of the bottles without the catch basin stage reaching the appropriate level. In future designs, the location of discharge pipes should be positioned at a distance far enough away to allow the system adequate time to allow for stormwater infiltration and capture.
Shown as grey lines in Figures 8, 9 and 10 are the heights at which the grab samples were collected. For certain events at the OnCenter Parking Garage (Figure 10) as well as at the Zoo Elephant NE parking lot (Figure 9) the top bottle was filled despite the stage not registering that height. It was observed in July 2015, that at the Zoo Elephant NE parking lot high intensity events produce sheetflow on the surface of the porous pavement. This sheetflow contributed discharge to the upper grab sample bottle and therefore likely contaminated that sample for the purposes of this study. These samples were therefore omitted from consideration.

At the Zoo sites, the rapid decline in catch basin depth indicates a rapid retention of inflowing water by the system. Because overflows rarely occurred at the Zoo, most stormwater capture at the Zoo occurred by retention within the green infrastructure. This repeated stormwater retention with no adequate flushing of the system likely is indicative that the structure was overdesigned. The rapid rate of retention of large quantities of stormwater also is an indication of overdesign. Although these systems are intended to absorb large quantities of stormwater, this study also indicated that there is a need for a repeated flushing to prevent significant buildup of organic and inorganic matter.

When overflows occurred at Barker Park they were small volumes in comparison to total inputs (Figure 11). This difference in total input and weir outflow volume indicates that even when overflows occur, the system has the capacity to capture and absorb significant quantities. The event that occurred on August 3, 2014 produced an overflow equal to approximately half of the total input. Considering the total input was 1.19 cm, it was not expected that an event of this magnitude would produce a large overflow. Close examination revealed that this event did not
follow the pattern of a standard hydrograph (see Figure 23 for the actual hydrograph on August 3, 2014).

![Figure 23: Hydrograph for precipitation on August 3rd, 2014.]

This event began with high intensity of 0.11 cm for the initial five minutes of the event. This initial high intensity was not adequately absorbed because of the difference in rainfall rate and infiltration capacity of the system. This immediate high intensity was shown to produce sheetflow and direct loading of the catch basin without a significant capture by the system.

**DISCUSSION: WATER QUALITY**

Barker Park rain garden and the OnCenter bioswale were expected to have high values of fDOM and acidic pH values because of the presence of organic material in the subsurface media. The presence of significant plant and detrital matter and the nutrient loading associated with organic matter decay was expected to supply elevated fDOM. However, fDOM and pH were lowest at the OnCenter. Rain garden pH was generally basic which was not anticipated because
of the presence of organic material and the tendency of rainwater in the Central New York area to be acidic with values between 5.5 and 6.

Crushed limestone comprises a large portion of the subsurface media at the porous pavement sites at the Zoo. When limestone becomes mobilized by the means of infiltration of surface stormwater, the limestone will generate an increase in pH making it more basic. This phenomenon was observed at the Zoo Tiger site where the average pH was 8.3. At the other Zoo site pH was not significantly basic, which is suggestive of higher presence of organic matter which should limit pH. Observations at this site indicate that stormwater primarily entered this site directly into the catch basin from surface sheetflow. Therefore this water bypasses the subsurface limestone storage not allowing for adequate residence time to alter pH. At the upper Zoo site, large amounts of tree cover and plant matter lead to the more acidic observed pH. Specific conductance and fDOM loadings were greater at the Zoo sites. Higher values of specific conductance and fDOM are an indication of higher salinity waters and organic material, respectively, to be stored in the matrix of porous pavements and leached in draining waters.

Dissolved organic carbon loading varied by the type of green infrastructure. The greatest loading of DOC was observed at the Zoo. This observation is in accordance with the high values of fDOM observed at these facilities. This trend between organic matter and site characteristics was expected at the Zoo Tiger lot. At the Zoo Tiger lot there was observation of runoff from the parking area around the adjacent bioswale entering the bioswale and reworking the soil through erosion and infiltration into the deep storage via the domed risers. This processing would be indicative of a high concentration of organic matter. At the Zoo Elephant lot, the only
paths into the catch basin were through the porous pavement or directly into the catch basin from the surface. Therefore any infiltration through the porous pavement should have had low dissolved organic matter concentration and high pH. It was regularly observed that there was direct input of surface water and litter from adjacent pine trees entering the catch basin at the Zoo Elephant lot. This resulted in regular accumulation of organic material in the catch basin filter bag and observed accumulation of organic matter in the catch basin. This response of accumulated organic matter is therefore correlated to the lack of precipitation storage in the system and the direct loading of surface water into the catch basin.

Field observations at the Zoo showed that the intermittent observation wells and final catch basins had a tendency to capture grass clippings. These grass clippings were loaded into the system when the height of water in the system decreased back to its original pre-event value. This loading could cause significant increases in the presence of organic matter in samples as well as lead to potential clogging of porous pipes which could lead to an issue with the systems efficiency to absorb storm water.

Chloride loading at Barker Park is likely the result of the composition of the subsurface media of the rain garden. Barker Park inlet (BPI) shows low values of chloride. The increase in chloride concentrations observed is thought to be due to the system’s ability to store chloride. The loadings of chloride at the zoo show comparable values to those of Barker Park. This result indicates that in order to conduct a study of salinity effects each site would need to be evaluated to determine the relationship between ions of interest and conductivity.
To gain further understanding of system performance of salt and organic matter processing, events were plotted against catch basin stage as shown in Figures 17-22. These hysteresis patterns indicated distinct differences in processing of water quality during events in green infrastructure at the Zoo and Barker Park. Specific conductance and fDOM loadings at Barker Park over the total period of the event show general tendencies to steadily increase in concentration and then decrease as the stage in catch basin decreased. Exceptions to this general pattern occurred on June 26 for both events. This difference is likely due to the fact that the facilities were affected by solute inflows from two events the day before and the system did not have adequate time to absorb and process the stormwater from the events that followed.

Event loading patterns at the Zoo Tiger lot began with a general dilution of the observed measurements, indicating a priming of the system with low concentrations of solutes and organic matter in the stormwater. After catch basin stage reached a peak, there was a continued increase of organic matter (fDOM) and ions (conductivity). This is likely due to the ability of porous pavements to accumulate and store solutes in their matrix and release them after repeated infiltration. Zoo Elephant lot displayed differences in the processing of fDOM and conductivity. fDOM at the Elephant lot for events that were not closely preceded by previous events (less than one day) started at high values indicating a storage of organic material and then a dilution during events. This pattern suggests a post-event gradual accumulation of organic material in the system. Conductivity at the Elephant lot for most events displayed a general dilution in measured concentration at the beginning of the event. As the stage continued to increase, an increase in concentration was observed indicating a delay in
the mobilization of ions. Similar to Barker Park, the Elephant lot showed a decrease in conductivity at the conclusion of the event, often to the original level of conductivity in the system. This pattern differs from Zoo Tiger because Zoo Elephant did not appear to capture and store ions as the event persisted. This is likely the case because the Zoo Elephant often displayed clogging of the porous matrix causing a bypass of the surface infiltration media.

**DISCUSSION: SUGGESTIONS FOR SYSTEM IMPROVEMENT**

Visual inspection of the green infrastructure facilities studied during rain events allows for the following suggestions for system efficiency improvement. Green infrastructures, especially those that rely on infiltration through porous pavement require significant annual maintenance to maintain adequate infiltration. As a part of the Onondaga County Green Infrastructure program, vacuuming of these sites is to occur biannually. This process aims to remove surface clogging, and been proven to be effective at the removal of debris clogging. Porous pavements display a tendency to decrease in infiltration capacity as a result of continued clogging throughout their service life. In order to achieve the full benefit of the economic investment and promise of the system to attain full service life, intensive maintenance is needed to prevent significant economic investment to replace the systems.

The effect of inadequate maintenance is illustrated in Figure 24 which shows the Zoo Elephant NE Parking lot ponding in the northeast corner where the study catch basin is located. During high volume events, this ponding extends to the location of the catch basin causing filling of the top bottle from the surface similar to the prior discussed sheetflow. This ponding allows for collected stormwater to pass over the curb and down the adjacent hill; which has led to
continued erosion of this area. Careful design considerations should be made to place catch basins in locations that are not subjected to significant surface clogging.

*Figure 24: Ponding of precipitation at the corner of the Zoo Elephant NE lot on July 9, 2015, after a 1.24 centimeter rain event.*

For bioswales, it was observed that at plants selected for the facility did not always thrive in the environment. Selection of replacement plants that achieve the same stormwater and nutrient retention is suggested as well as continued maintenance. To preserve the aesthetic appeal of green infrastructure the sites should be monitored to prevent overgrowth and deterioration of appearance.
CHAPTER 5: CONCLUSIONS

The results of this study indicate that green infrastructure technologies in Syracuse, New York have varying capacities at reducing stormwater inputs into the combined sewer systems. Porous pavement systems at the Zoo had high capacities at retaining stormwater inputs, while rain gardens and bioswales had variable capacities to process stormwater inflows. The effectiveness for reduction and capture by the porous pavements may indicate a possible overdesign issue which should be considered in future designs. Barker Park rain garden displayed frequent weir overflows, but the volume of overflow was a small percentage of the total inflow. The Barker Park rain garden design performed the best, which indicates that these design practices should be mimicked at other sites.

It was observed that green infrastructure alters water quality. For some porous pavements deterioration in water quality characteristics was evident. This water quality issue is likely related to overdesign. Because the stormwater systems rarely overflow, there is no opportunity to “flush” contaminants which can lead to an accumulation in these systems. Future work is needed to characterize and quantify the long-term processing of contaminants by green infrastructure technologies.

In conclusion, green infrastructure systems can be a cost-effective tool for reducing stormwater inputs and can be effectively monitored with in situ sensors. Results on stormwater capture indicate that porous pavement systems are the most effective at stormwater reduction and capture, but all green infrastructure technologies performed well. Poor water quality patterns that were observed in porous pavement systems should be evaluated further. To improve
performance and longevity across the board, it is suggested that more attention be taken
towards implementing an effective and manageable maintenance plan.
### Table 3: Solution preparation and sonde calibration procedures

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<tr>
<th>Probe</th>
<th>Calibration Method</th>
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<tr>
<td><strong>pH /ORP</strong></td>
<td>Although integrated into the same sensor, ORP and pH require separate calibrations. For ORP, a Zobell solution should be used. Zobell solution can be purchased as a powder and then mixed with 150mL DI water. A suggested product is YSI 3682 Zobell Solution. The pH calibration can be completed as a 1,2, or 3 point calibration. For a three point calibration, three pH buffer solutions such as pH-4, pH-7, and pH-10 were used.</td>
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<td><strong>Turbidity</strong></td>
<td>A three point calibration was used for the turbidity sensor. The three point calibration should include a blank DI water, a 5-200 NTU sample, and 200-4200 NTU standard. All standards were prepared in accordance with a standard preparation reference. A sample standard preparation is shown below</td>
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<tr>
<td><strong>fDOM</strong></td>
<td>Solution Preparation: There are two principal ingredients in an NTU solution. These are hydrazine sulfate and hexamethylenetetramine. This solution was prepared in advance because at least 24 hours of setting time is required prior to use. In accordance to Appendix 1, these solutions when prepared on a monthly basis. fDOM calibration can either be a one point or two point calibration. For increased accuracy, was a two point calibration be used. The two calibration solutions should be clear, deionized water and 300 mg/L Quinine Sulfate solution.</td>
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Solution Preperation: Obtain solid Quinine Sulfate dihydrate with a high purity (>99%), and (0.05 M) sulfuric acid. Weigh .100 g of solid Quinine Sulfate dihydrate and transfer the solid to a 100-mL volumetric flask. Dissolve the solid in the about 50-mL of the 0.05-mL sulfuric acid and then dilute to the solution mark with 0.05-mL sulfuric acid. Mix well by inversion, and this solution is 1000 ppm in quinine sulfate (.1%). Transfer 0.3 mL of the 1000 ppm solution to a 1000 mL volumetric and then fill the flask to the top graduation with 0.05 M sulfuric acid. Mix well to obtain a solution of 300 μg/L (300 QSU or 100 RFU). Store this solution in a darkened glass bottle for up to (5) days.

Conductivity

Prior to calibration the orifices of the sensor were cleaned with the supplied brush. Using a 1000 μS/cm solution, the calibration cup was filled to cover all sampling orifices. During the process, the sonde was rotated in order to remove any bubbles from the cell. Bubbles could alter the reading of the sensor and lead to a faulty calibration. During calibrating, at least one minute was allowed to pass before accepting a reading.
Figure 25: Sensor installation at Barker Park rain garden. Shown in the foreground is the weir. The water quality sonde is located on the right, the three sampling bottles in the center and the HOBO water level logger in the PVC tube on the left.
Figure 26: Sensor installation at Zoo Tiger parking lot. The water quality sonde is located on the left with the HOBO water level logger in the PVC tube on the left. Bottle sampling was not deployed at this site.
Figure 27: Sensor installation at OnCenter parking garage. The water quality sonde is located on the right with the HOBO water level logger in the PVC tube in the foreground. Bottle sampling is shown on the left.
REFERENCES


NOAA. (2014). Daily Rain Data-ESF.
