Control of Urban Runoff: The Role of Bioretention Systems

Perrin Falkner, Breanna Mariano, Kathryn Jaquish, Emily Xu, Raleigh Heap, advisor Dr. Teresa Culver

For Community Based Undergraduate Research Grant

Final Report
April 14, 2017

University of Virginia
Civil & Environmental Engineering

Abstract

Increasing volumes of urban runoff have become a growing concern due to the effects of erosion on stormwater quality. In response, the usages of bioretention cells has greatly increased. The purpose of this investigation was to research the impacts of the bioretention cell at Charlottesville High School, to see if 1) bioretention performance decreases over time, 2) bioretention performance at the site meets specified Chesapeake Bay environmental quality standards, and 3) an enhanced bioretention cell at Venable Elementary School shows significant improvement compared to a traditional bioretention cell. In order to do this, we performed lab analyses on rain samples taken through robotic samplers at the inlet and outlet of the bioretention cell. Phosphorus and nitrate kits were used to determine nutrient concentrations, and samples were dried, filtered, and weighed for sediment concentrations. Using flow data collected from the samplers, the nitrate (N), phosphate (P), total nitrogen (TN), and total phosphorus (TP) mass loads were calculated for both the inlet and outlet. Percent removal was then calculated for all the nutrients and sediments in terms of mass and concentration. It was found that over time, the system had greater removal of nitrates and phosphates. Removal standards were met for sediments and phosphorus, but do not consistently meet nitrogen removal standards. The enhanced system performed better in nitrogen and phosphorus removal, but TN, TP, and sediment removal showed no significant improvement.

Introduction

The urban environment is characterized by high densities of people, which are associated with large amounts of impervious surfaces, such as roadways, buildings, and parking facilities (U.S. Department of Transportation). Due to the lack of pervious spaces available for water infiltration, greater volumes of stormwater runoff find its way into local surface waters (U.S. Department of Transportation). According to the U.S. Department of Transportation Federal Highway Administration, "[t]he greatly increased runoff volumes and the subsequent erosion and sediment loadings to surface waters that accompany these changes are of concern." It is important for federal, state, and local agencies in charge of maintaining watersheds and pollution control to be aware of "the natural balance between stormwater runoff and the ecosystem of wetland and stream systems" (U.S. Department of Transportation). By controlling urban runoff, this prevents stormwater pollution from damaging local waterways.

Within the City of Charlottesville, increased development has affected stormwater runoff which in turn affects water flowing to the Rivanna River. Eventually, this contaminated water, with high levels of nitrates, phosphates and debris, drains to the Chesapeake Bay. Urban stormwater runoff is the fastest growing source of pollutants to the Bay (Chesapeake Bay Program). In order to comply with state and federal regulations and reduce stormwater runoff, Charlottesville uses systems called Best Management Practices (BMPs). BMPs are stormwater management systems that "replicate hydrologic cycle elements that have been lost in urban areas to meet stormwater management objectives" such as reduced stormwater volumes and removal of pollutants ("Using Green Stormwater BMPs in Urban Areas").

Central Question and Previous Research

With the intention of reducing stormwater pollutants draining to local waterways within Charlottesville, and for the purpose of the Community Based Undergraduate Research Grant, the central question that drove this study was: do local bioretention systems protect Charlottesville from the impacts of stormwater runoff? A bioretention system is a BMP that uses vegetation, a ponding area, and subsurface media to reduce stormwater volumes and remove pollutants, such as nitrates and phosphates, and total suspended solids. Along with the main question, three sub-questions were created to fully answer the main question. The three sub-questions include: 1) Do enhancements to traditional bioretention systems improve performance? 2) How do bioretention systems perform over time? and 3) Do the systems meet environmental quality standards?

Previous research on this study began in 2009 with the installation of a traditional bioretention system (non-modified media composition) at Charlottesville High School (CHS) and then in 2015 with the construction of an enhanced bioretention system (modified media composition never used before in the field) at Venable Elementary School. The modified media composition consisted of biochar and zero-valent iron which was intended to substantially increase the removal of nitrogen and phosphorus nutrients (Chiu et al.). In the fall of 2015, a team of undergraduate University of Virginia students began monitoring the performance of the enhanced Venable system and sampled a small number of storm events (Furr et al.). However, long-term observation over many storm events and multiple seasons is necessary to effectively assess the system’s performance.

Since the spring of 2016, multiple storm samples have been collected, both from CHS and Venable, and analyzed for stormwater pollutant removal. This paper explains the analysis that was conducted during the spring of 2016 to the spring of 2017 and addresses the central question of: Do local bioretention systems protect Charlottesville from the impacts of stormwater runoff?

Methods

Robotic samplers in the field were used to collect rain flow information and water samples. Before each storm, both the inlet and outlet samplers were set to collect individual water samples at certain volume intervals. These intervals were estimated based on the predicted depth of the storm, from sources such as the National Weather Service; the bigger the storm, the longer the sampling intervals. Each site had a rain gauge to record the actual storm depth, plus stormwater inflow and outflow flow data through the flumes was recorded in the sampling systems.

After the storm, the samples from the samplers needed to be brought back to the lab within 24 hours and analyzed for nutrients within 48 hours. In the lab, water from each sample's plastic sampling bag was analyzed for nitrate, phosphate, total nitrogen, and total phosphorus levels. This was done using phosphorus kits (HACH TNTplus 843) and nitrate kits (Nitrate Vacu-vials kit), as well as a spectrometer (HACH DR 3900). Total nitrogen and total phosphorus also required digestion (heating the sample) in a test tube digester (Hach DRB200). Each sample was also analyzed for sediment mass. ASTM standard for sediments in water was followed (ASTM 2000). Briefly, this was done by funneling water through a glass fiber filter to separate suspended solids larger than 1.5 microns. The filter was then dried overnight in an oven at 105°C and weighed. The weight of the original clean filter was subtracted to determine the final mass of the suspended sediments.

The approve information was processed to understand the performance of the systems for each storm event. With the rain levels and water flow recorded at five minute intervals, hyetographs and flow graphs were made. Then each sample was delegated a volume fraction of the storm (representative volume). If different number of samples were analyzed for nutrients than for sediments, then representative volumes were determined for each case. Nitrate, phosphate, total nitrogen, total phosphorus and sediment masses were calculated for each sample, then summed up for the whole storm. The event mean concentrations (EMCs) were determined by dividing the pollutant masses by the flow volumes. This process was repeated for the samples and data from both the inlet and the outlet.

The percent mass removal and percent concentration changes between the inlet and outlet were then calculated for sediments and each nutrient. The nitrate load, phosphate load, total nitrogen mass load, total phosphorus mass load, total sediments, nitrate event mean concentration (EMC), phosphorus EMC, and total sediments EMC percent changes were calculated from inflow and outflow data by Equation 1 and Equation 2.

$$\%\ removal\ by\ mass\ load\ =\ \frac{Mass_{in} - Mass_{out}}{Mass_{in}}$$

Equation 1

$$\%\ removal\ EMC\ =\ \frac{Concentration_{in} - Concentration_{out}}{Concentration_{in}}$$

Equation 2

Results

Do enhancements to traditional bioretention systems improve performance?

For this comparison, the enhanced bioretention system at Venable Elementary School and the Charlottesville High School (CHS) with a traditional design were chosen. Only one storm event (9/27/16), was successfully captured at both Venable and CHS in 2016. The single storm can be used as a preliminary comparison in an attempt to understand the data that was collected.

The total nitrogen mass load percent removal was the only criterion that produced potentially significant results. Venable had a much higher total nitrogen removal (39% versus an 18% removal at CHS). The zero-valent iron biochar layer at Venable may have contributed to this high removal because during an anaerobic reaction with water, zero-valent iron produces iron ions as shown below in Reaction 1.

$$Fe^0 + 2H_2O \rightarrow Fe^{2+} + H_2 + 2OH^-$$

Reaction 1

The positive iron ions react with negative nitrate ions in the water to form iron(II) nitrate as shown in Reaction 2. Nitrate is a prevalent form of dissolved nitrogen in stormwater runoff, and it acts as a nutrient (ChesapeakeBay.net).

$$Fe^{2+} + 2NO_3^- \rightarrow Fe(NO_3)_2$$

Reaction 2

The iron(II) nitrate precipitates from the water and is ideally captured in the porous biochar or soil of the bioretention system. However, although the removal is seemingly better at Venable, it does not meet the Virginia Department of Environmental Quality (DEQ) performance standard for total nitrogen removal for this event. A further analysis on performance standards is explained later in the results and discussion for the third research question.

The percent removal for total suspended sediments was not largely different between sites. CHS performed slightly better according to the values in Table 1. It was expected that the biochar layer would help trap more sediments, yet, because the Venable bioretention system is newer than the one at CHS, it has had less time to settle. Often, settling can be great enough that additional material is needed to keep the system from sinking below a desired elevation (United States, New Jersey). As a bioretention system grows more compact, the pore size shrinks. While it may take more time for water to pass through it, smaller sediments will be trapped than a lesser compact system. Since CHS has had five additional years to settle, a slightly higher amount of trapped sediments aligns with this logic.

For the nitrate load percent removal, Venable removed some nitrate, however, the percent removal of nitrate for CHS was negative. A negative value means that nitrogen was added to the outflow as it passed through the system. One potential explanation for this could be that nitrogen trapped in the soil was released into the effluent or that either the inflow or outflow values were not accurate.

Nitrate EMC, phosphate EMC, total nitrogen EMC and total phosphorus EMC resulted in negative values for both Venable and CHS. The EMC is a ratio of mass to volume, so if the mass of nutrient decreased by a lesser amount than the volume of water, then the percent removal would result in a negative value. For example, if 2 mg of nitrogen were present in 100 L of water and then as the water passed through the bioretention system, 0.1 mg of nitrogen and 50 L were retained, the concentration of nitrogen to volume of water would be almost twice the amount in the outflow than the inflow. Therefore, the system could potentially still be removing a significant mass of nitrogen, even if the percent removal of nitrogen EMC is negative.

The phosphate EMC and total phosphorus EMC at the inlet were below the detection limit (BDL) so total mass could not be estimated therefore neither could removal rates for concentrations nor load be estimated. A small value for total mass is desirable in that it means the stormwater entering the bioretention system is almost void of the nutrient. In urban areas, larger concentrations of phosphorus often come from lawn fertilizer runoff. In the case of CHS, the stormwater entering the system came directly from the asphalt parking lot, and little, if any, came from surrounding areas of grass or other vegetation. Future testing should be completed to state with further confidence the reasons behind low levels of phosphorus as well as the reasons behind the negative values in Table 1, and an overall definitive conclusion about which performed better cannot be made at this time.

Table 1. Storm event (9/27/16) percent removals for Venable and CHS

Storm event (9/27/16) sites	**Venable**	**CHS**
Nitrate Load (%)	49	-69
Phosphate Load (%)	BDL	BDL
Total Nitrogen Mass Load (%)	39	18
Total Phosphorus Mass Load (%)	70	BDL
Total Suspended Sediments (%)	96	99
Nitrate EMC (%)	-119	-332
Phosphate EMC (%)	BDL	BDL
Total Nitrogen EMC (%)	-163	-108
Total Phosphorus EMC (%)	-29	BDL
Total Sediments EMC (%)	81	97

How do bioretention systems perform over time?

To assess how the Charlottesville High School bioretention unit performs over time, three storm events analyzed during 2016 were compared to older, similarly sized storms from 2010 and 2011. Storm size was determined based on rain depth in inches (in), and older storm events were determined to be of similar size if the difference of the rain depths was no larger than 0.05 in. For each comparison, the load removal percentages for TSS, nitrates, and phosphates were considered. The EMC efficiencies were initially included in this comparison, but were ultimately excluded because many of the EMC load removal percentages that were calculated returned negative values and no conclusions could confidently be drawn from them.

The first storm analyzed was from 5/1/2016 (0.66 in rain depth), and it was compared to two storms from November 2011 (Figure 1). For TSS load removal, both the older storms and the 2016 storm performed similarly with 91.67%, 96.30%, and 89.03% removal respectively. The nitrate removal percentage for the 2016 is storm is greater than the 2011 storm with 44.66% removal compared to 36.1%.

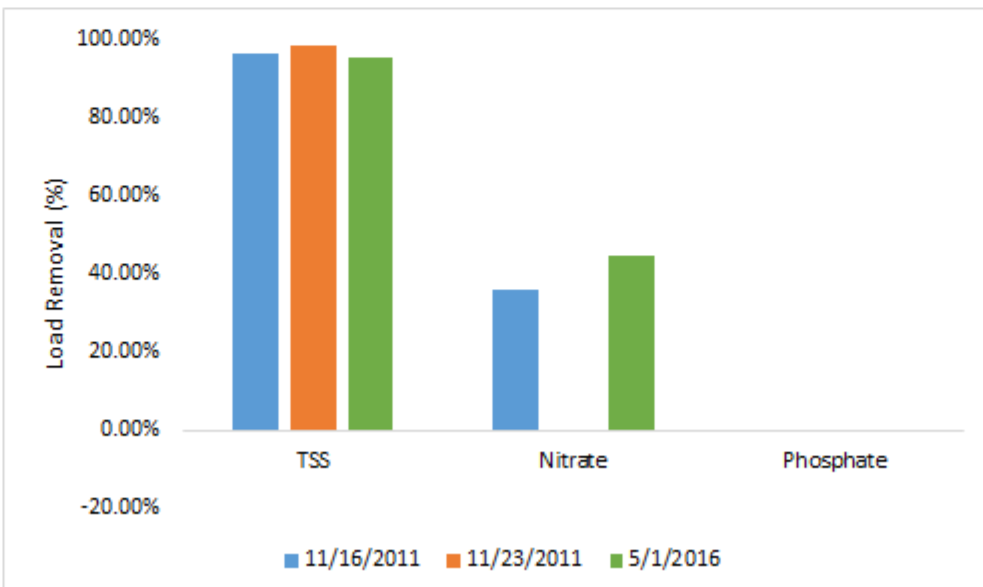

Figure 1: Load Removals in 5/1/16 (0.66 in rain depth) storm to 11/16/11 (0.67 in) and 11/23/11 (0.68) storms

The second storm event comparison looked at one storm from 9/19/2016 (0.59 in) and one from 8/25/2011 (0.56 in) (Figure 2). The nitrate and phosphate load removals for the 2016 storm were 48.82% and 93.10% respectively, while the 2011 storm had 21.79% nitrate and 64.87% phosphate load removals. This shows that both the percentages of nitrate and phosphate load removal were greater during the September 2016 storm event.

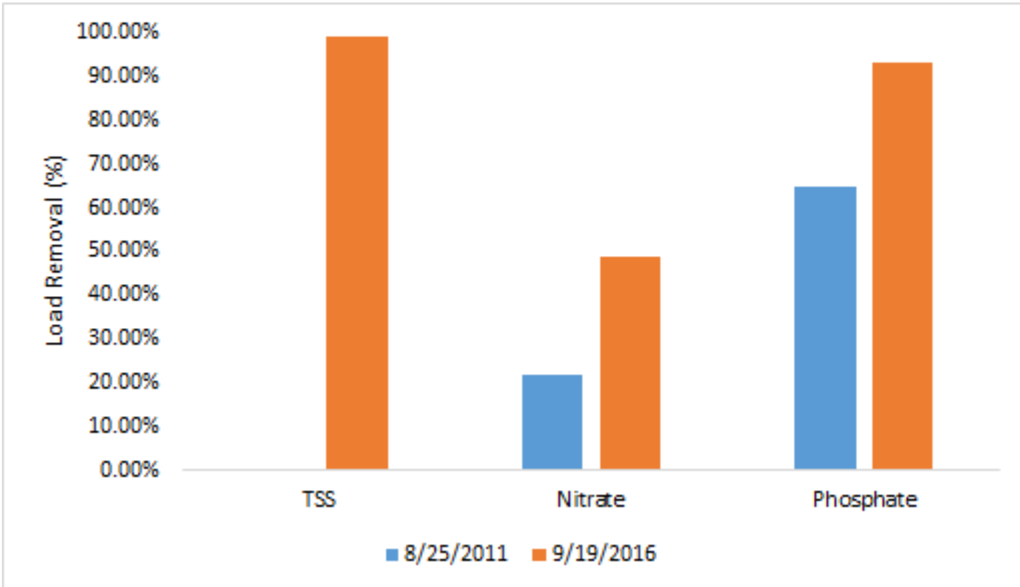

Figure 2: Load Removals in 9/19/16 (0.59 in) storm to 8/25/11 (0.56 in) storm

For the final storm event comparisons, a recent storm from 9/27/2016 (0.69 in) and two older storms, one from 9/28/2010 (0.73 in) and one from 5/3/2011 (0.74 in), were used (Figure 3). This comparison shows that the TSS removal for the 2010 and 2016 storms were about the same, but higher for the 2016 storm at 98.72% compared to 95.38%. The phosphate load removal was also slightly greater for the September 2016 storm at 88.22% removal compared to 36.05% and 84.12%.

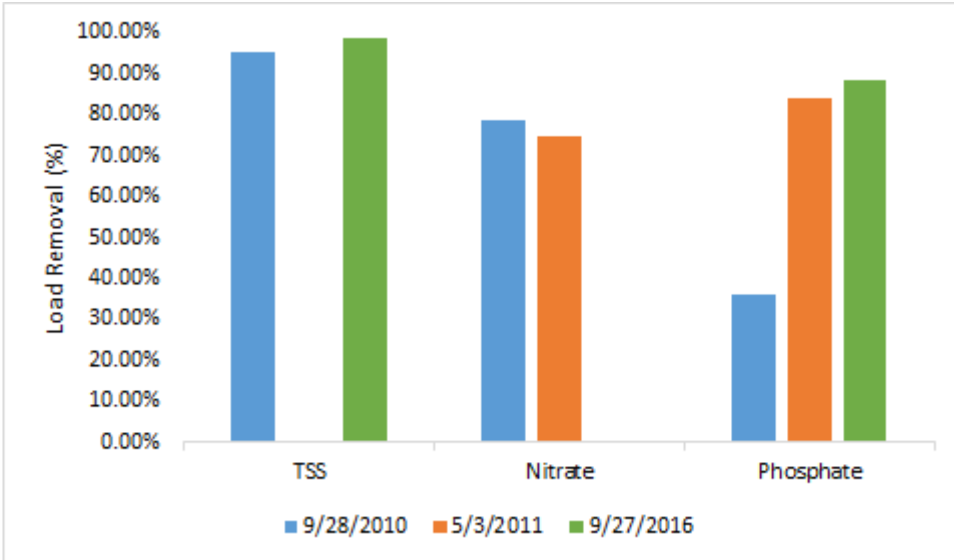

Figure 3: Load Removals in 9/27/16 (0.69 in) storm to 9/28/2010 (0.73 in) and 5/3/11 (0.74 in) storms

Based on the nitrate load removal percentages for the May 1 and September 19, 2016 storm events, and the load removal percentages of phosphate for the two September 2016 storms, it appears that the CHS bioretention unit is performing just as well, if not better, than it was five years ago. This is consistent with the expectations of bioretention units because as the plants within the unit become established and grow, they contribute to greater uptake of nutrients and pollutant removal (Dehais, 2011). However, the occurrence of storm events are variable, stormwater samples must be analyzed within 48 hours of the storm event, and sometimes the robotic samplers at the bioretention site fail. Due to these limitations, only three usable storms events were captured at CHS during 2016 that could be used for this comparison. Additionally, the data available on older storms is limited, and storms must be of similar size for the comparison of load removal percentages to be fair. Therefore, further observation and comparisons of storm events for the CHS bioretention unit are recommended in order to have a stronger conclusion on its performance over time.

Do systems meet environmental quality standards?

In order to assess the performance of the CHS bioretention system, nutrient and sediment levels in the inflow and outflow streams of each storm were tested and compared to percent removal expectations established by the Virginia DEQ and the University of Maryland Mid-Atlantic Water Program. Percent removals were calculated using Equation 1 and Equation 2, and results for storm events captured at CHS are shown in Table 2.

Table 2: Percent removals for CHS bioretention cite for 4 storm events compared to expectations established by Virginia DEQ and University of Maryland Mid-Atlantic Water Program. Red numbers indicate that the percent removal was below the performance standard, while green means that it met or exceeded the standard. BDL is defined as below detection level.

Event	**Total Nitrogen Mass Load (%)**	**Total Phosphorus Mass Load (%)**	**Total Sediments (%)**	**Total Nitrogen EMC (%)**	**Total Phosphorus EMC (%)**	**Total Sediments EMC (%)**
5/1/16	46	BDL	95	2.34	BDL	89
5/2/16	61	92	88	48	89	80
9/19/16	67	80	99	-21	25	98
9/27/16	18	BDL	99	-108	BDL	97
Expected (%)	**64**	**55**	**80**	**40**	**25**	**80**

According to the results in Table 2, the CHS bioretention system met or exceeded removal standards for total phosphorous and sediments in all cases, but failed to meet removal standards for total nitrogen in most cases. This is because it is very hard for soil to retain nitrate, which as mentioned before, is the primary source of nitrogen in the system. Soil containing clay, like that in Charlottesville, is generally negatively charged. Therefore, negative nutrient-containing ions like nitrate do not incorporate themselves into the soil and can be easily washed out. In order to meet the nutrient removal standards, specific soils containing more organic matter or zero-valent iron would need to be added to the CHS system. Or regions with anoxic conditions should be added to facilitate denitrification. The Venable system is considered enhanced because it incorporates these aspects in an effort to increase nutrient retention. Regarding total phosphorous, in half of the storm events, the inlet level was below the detection levels. This means that the amount of nutrient in the system is negligible. This indicates that phosphorus is not a current concern in Charlottesville City stormwater. Finally, sediments showed the highest percentage removal between inlet and outlet streams. This is because the bioretention system acts like a filter and blocks the larger sediment particles from passing through the system. Overall, the CHS bioretention system is functioning as efficiently as expected for reducing stormwater volume and trapping sediment runoff, but could use some improvement in order to further remove nitrates from stormwater.

Discussion

Overall, the research proved successful with a few limitations. The first is that the enhanced bioretention system with zero-valent iron has the possibility of drying out and then reacting with oxygen. Because the summer and fall of 2016 were unusually dry and because Virginia weather is often periods of intense storms followed by dry periods, there is the possibility that the layer dried out. A zero-valent layer may perform better in regions with more consistent rainfall where the system stays moist and does not dry out as often. Another limitation is that during the May storms, the robotic samplers' batteries died and as a result data was printed out on paper instead of recorded electronically. This resulted in extracting flow information from paper printouts, which was less accurate than if the digital data had been available.

The use of bioretention systems in removing pollutants in stormwater has proven successful in protecting Charlottesville from the impacts of stormwater runoff. According to results shown above, both the traditional bioretention system (CHS) and the enhanced bioretention system (Venable) removed nitrates, phosphates, total nitrogen, total phosphorus, and sediments from stormwater events. In both systems, removal standards were met for sediments and phosphorus, but not met consistently for nitrogen. The traditional system proved to have greater removal of nitrate and phosphate. However, the enhanced system seemed to perform better than the traditional system in removing nitrogen and phosphorus, but the total suspended sediments percent removal was not largely different between the two sites, with both demonstrating excellent removal rates. The expectation that the biochar would trap more sediment was not as successful because it was found that over time the CHS traditional system settled and grew more compact and therefore trapped more sediment particles.

In terms of the total suspended sediments EMC, both CHS and Venable performed excellently. The slight difference might be attributed to a different volume of water absorbed by the system at Venable as compared to CHS, creating a lesser difference in EMC from the inflow to the outflow and therefore appearing to reduce less sediment. To add, when comparing older and newer storm events, it was found that the CHS bioretention unit performed well, if not better, than it was five years ago. The expectation is that as plants within the unit become established and grow, they contribute to greater uptake of nutrients and pollutant removal (Dehais, 2011).

Using local bioretention systems (both traditional and enhanced) in Charlottesville are a way of meeting environmental stormwater runoff standards. Not only do the systems successfully remove pollutants from stormwater before draining to the Chesapeake Bay, but they do so in an environmentally friendly way by representing the natural landscape before development in urban areas.

References

American Society for Testing and Materials (ASTM), 2000, Standard test methods for determining sediment concentration in water samples: D 3977-97, vol. 11.02, Water (II), 395-400

Chiu, P., Imhoff, P.T., & Culver, T.B. (2015, April). Simultaneous Removal of Nitrogen and Phosphorus from Stormwater by Zero-Valent Iron and Biochar in Bioretention nitrogen -and-phosphorus-from-stormwater-by-zero-valent-iron-and-biochar-in-bioretention-cells.

Dehais, Mary, "Bioretention: Evaluating their Effectiveness for Improving Water Quality in New England Urban Environments." MA thesis, University of Massachusetts Amherst, 2011. http://scholarworks.umass.edu/theses/595

Furr, B., Johnson, Z., Lassiter, D., Long, G., Patrick, K., Sankowski, A., Wong, K., Evaluation of *Enhanced Venable Elementary Bioretention System*, CE2990 Final Report, December 18, 2015.

Simpson, T., and Weammert, S. (2009, Dec.). *Developing best management practice definitions and effectiveness estimates for nitrogen, phosphorus, and sediment in the Chesapeake Bay Watershed.* Retrieved from https://collab.itc.virginia.edu

"Stormwater Runoff." *Chesapeakebay.net*. Chesapeake Bay Program, 2012. Web. 13 Apr. 2017. http://www.chesapeakebay.net/issues/issuestormwater runoff#inline

United States, New Jersey. (2007, November). *New Jersey Stormwater Best Management Practices Manual*. Retrieved April 13, 2017, from http://www.njstormwater.org/docs/bioretention_11_08_07.pdf

U.S. Department of Transportation. *Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring.* Federal Highway Administration, 2000. Web. 13 Apr. 2017.

"Using Green Stormwater BMPs in Urban Areas." *Water Environment Research Foundation*. Water Environment Research Foundation, 2009. Web. 13 Apr. 2017.

Virginia DEQ stormwater design specification No. 9. Bioretention (2011, March 1). Retrieved from Virginia Stormwater BMP Clearinghouse, http://www.vwrrc.vt.edu/swc/documents/2013/DEQ BMP Spec No 9_BIORETENTION_FinalDraft_v1-9_03012011.pdf