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Hydraulic Efficiency of a Penn State Stormwater Bioswale during Rain Events

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ABSTRACT

Background. Stormwater contamination and flooding are common concerns in many populated areas across the globe. Green Stormwater Infrastructure has been introduced to leverage ecological processes to reduce the impact of runoff on urban systems. The following study was conducted to calculate an average percent reduction from stormwater inflow versus outflow at a 16-year-old stormwater infiltration swale on the Penn State campus. Additionally, the data investigated the lag time from rainfall to underground flow in the runoff system. **Methods.** Precipitation data was gathered in the State College, PA, area for each rainfall event. This data was used to model inflow volume using. A pressure sensor in the underdrain outflow pipe was used to calculate water depth in the drainage pipes, which allowed for an outflowing pipe-flow volume to be found. This data was compared in time and quantity to determine any reduction in volume as well as lag time between the events. **Results.** The average percent reduction in flow volume, found using data from 4 different events, was 97.77 percent. The loss of water volume is assumed to be from evaporation and infiltration into underlying soil. Also, the sensor data showed an average lag flow time of 4 hours and 30 minutes after precipitation began. This time is accounted for through surface flow across the basin and ground seepage and transport. **Conclusions.** It is shown that infiltration-based stormwater basins could be effective at reducing the flow volume running off impervious surfaces, even many years past initial installation. They also can significantly delay the flow, to prevent overwhelming sewer systems and downstream flooding.

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Chapter 1: Introduction

Urban Flooding

Stormwater runoff creates a list of problems across the globe. In my hometown of Northport, New York we have massive flooding from steep gradient roads and inadequate drainage. Flowing into the lowest elevation of the town, any high intensity storm creates streams where children blow up tubes and ride down the flooded street. However, as the runoff flows, it takes with it all sorts of contaminants. The water pours down the road, just outside of the residents' windows, carrying garbage cans, grocery bags, fertilizer, pesticides, and heavy metals, and occasionally causes physical damage to cars, homes, and infrastructure.

Runoff and flood hazards are an issue that is particularly relevant in urban areas, especially those within a small watershed. Urbanization increases the amount of impervious land in an area which can lead to intense flooding episodes during storms that last even a short duration if that runoff is not detained and/or retained. Regions that occupy space near small streams and those that are at lower elevations are especially susceptible to property damage that is a result of flooding and runoff. This issue is common in areas where urban growth is on the rise (Barnard).

A case study performed in the Ralston Creek Watershed of Iowa illustrates these facts. The North and South Branch of Ralston Creek flow into the main stream which eventually empties into the Iowa River. The South Branch Ralston Creek was subject to a 20-year period of urbanization that began in the 1950s. When the project began in 1950 only 5% of the region was urbanized, compared to the 30% of the region that was urbanized as of 1978. The changes made to impervious land in the Southern Branch led to incrementally more flooding issues downstream as evidenced by the increase in the estimated probability of discharge on a given day in the region. While the South Branch saw much change, the Northern Branch remained relatively unchanged; henceforth, it was the drastic changes in the landscape Southern Branch that led to these changes in runoff (Barnard).

The hydrologic results, as recorded by five precipitation stations and one continuous rainfall recorder that the watershed housed from 1924 to 1978, provided researchers with an accurate account of rainfall in the region over a period of many years. This data, compared with flooding and urbanization data, points to the urbanization of the South Branch as the culprit for the flood hazard increase. As a result of intense flooding episodes, property values in the lower sections of the watershed had decreased as of 1978 due to the wear and tear the land experienced during large storms in the region (Barnard). These patterns are not just isolated to this watershed. Across the United States, increases in flood magnitude have been consistently documented with increases in impervious surface (*Causal Effect of Impervious Cover on Annual Flood Magnitude for the United States - Blum - 2020 - Geophysical Research Letters - Wiley Online Library*).

Runoff Contamination

Depending on where it rains there are various sources of runoff contamination. Suburban landscapes may have large amounts of herbicides and pesticides from tending to their gardens or lawns. When precipitation wipes these chemicals away, they often run into streams, ponds, rivers, or lakes and create problems in ecosystems downstream. These chemicals are created to destroy living organisms and they often aren't very selective. They damage the population of a small organism in a large food chain, disrupting the inhabitants of that entire biome.

Nitrogen and phosphorous are two nutrients which can come from fertilizer to lawns as well as deposition from vehicle exhaust. As they flow to larger bodies of water, they often lead to a phenomenon known as eutrophication (*Nutrients and Eutrophication | U.S. Geological Survey*). The direct meaning of "eutrophic" is "well-nourished" and almost seems like a beneficial term for the aquatic system (Yang et al.). However, this increase in nutrients leads to the extreme overproduction of phyto-plankton. Algal blooms are created and cover lakes and ponds, preventing sunlight from penetrating the surface layer as well as reducing the capability of oxygen absorption of the organisms below. When human activity directly increases the growth rate of algae in these systems it is known as cultural eutrophication (*Eutrophication | Definition, Types, Causes, & Effects | Britannica*). The lack of sunlight and oxygen is devastating to the entire food chain below and often results in an almost complete removal of life from the ecosystem. This has had damaging effects on fisheries, freshwater sources, and recreational areas across the country.

A study was conducted in the Sarno River Basin, a creek in Southwest Italy, to find changes in contaminant levels over time. Samples were taken at 6 different sites at the same location of a study conducted in 1975 and 1985 to allow for base contamination levels to refer to. Twelve samples were gathered at each site in 1998 and the results provided strong evidence that the urbanization around the area has led to drastic increases in various contamination levels. For example, the five-day Biological Oxygen Demand (BOD) values were 5 to 10 times greater at some sites after the 13-year period and the Chemical Oxygen Demand (COD) doubled at every site (Arienzo et al.). These values indicate increases in chemical organic materials and organic wastewater constituents.

The study concludes that the recent industrial and urban growth have contributed to the increased pollution of the river. Aside from the BOD and COD changes, there were noticeable increases in settleable solids at all sites and there were bacterial densities that exceeded allowable water quality standards (Arienzo et al.). The results were astounding, and the water quality was proven to have degraded through increased electrical conductivity, up to 87% increases in COD, and up to 200% increases in settleable solids at two of the sites (Arienzo et al.).

Cities and mass infrastructure create hundreds of additional sources for contaminating runoff. These include vehicle transportation, construction and demolition, washing and maintenance, gardening, and littering (Müller et al.). For example, heavy metals and Polychlorinated Biphenyls (PCBs) are found in waterways across the country and often contributed to construction activity and demolition of old buildings in cities (Müller et al.). These PCBs are prohibited for manufacture in the US and have been since 1978 due to their damaging effects. However, they remain in old infrastructure and are still produced in many other countries and used in electrical equipment (Bench). Additionally, microplastics are frequently sourced from the PVC and Polyethylene during construction and maintenance work. As plastics break down, they get smaller and smaller until they are invisible to the human eye. However, they are not biodegradable and remain to damage our world for thousands of years. Over 150 fish species have been found to have ingested microplastics, damaging aquatic ecosystems and potentially connecting the effects directly back to the humans who caused the problem (*Bioavailability and Toxicity of Microplastics to Fish Species: A Review - ScienceDirect*). However, if small construction materials were removed from their transport to the sewers and streams, if they were prevented from ever leaving the block they come from, we could limit the contamination of runoff in urban settings.

Metals are also a common urban pollutant (Hwang et al.). Metals like zinc and copper can be shed from roofs or vehicle brake pads. Metals are of particular concern due to their neurotoxic effects on aquatic fauna. Additional types of urban contaminants include large debris and garbage, copper, lead, and other heavy metals, personal care products and medications, and in some places PFAS (Poly- and Perfluoroalkyl Substances) from industrial plants.

When it comes to urban land, especially crowded cities, many contamination sources are diffuse and difficult to identify. This type of pollution is known as ‘non-point source’ pollution and benefits from distributed solutions that can help detain and treat runoff in various locations around the city before it reaches downstream waterbodies.

Green Stormwater Infrastructure as a Solution

Green Stormwater Infrastructure (GSI) can help address both flooding and urban water quality issues. GSI like bioswales, green roofs, permeable pavement, and rainwater harvesting systems all offer an alternative location for the water to flow to, reducing the total flow and lowering stress on the existing rainwater infrastructure, all while introducing the rainwater back into the hydrologic cycle and filtering it into the groundwater system.

Stormwater runoff is a large contributor to the contamination of water in our hydrological cycle. Manmade trash, herbicides and pesticide, fertilizers with high phosphorous and nitrogen levels, and heavy metals and debris from our roadways all act as sources of pollutants from our urban runoff. The addition of hard, impermeable surfaces covering the soil of cities has created problems and forced the increased transport of stormwater runoff. With nowhere to infiltrate, our existing infrastructure has created flooding problems in and outside of cities worldwide. The traditional mentality of mitigating impacts of stormwater runoff in urban areas has been to quickly and efficiently remove the water and transport it away via sewer pipes or ditches to reduce flooding issues around roads and buildings. However, this method causes various other problems such as hydrological disturbances, stream damage, groundwater depletion, and downstream flooding (Walsh et al.; Dhakal and Chevalier). Green stormwater infrastructure (GSI), including rain gardens or bioswales, were created to prevent the discharge of this runoff and to try to mimic those hydrologic conditions that existed before urban development occurred. This could mean the infiltration of water into the soil and vegetation, the reuse of water for various purposes later or trickling the runoff into the existing pipes at a slower rate. In older, combined-sewage systems, methods like these can help limit any system from becoming overwhelmed in quick storm events by elongating the time of runoff introduction and limiting the flow volume into the pipes. GSI acts to delay and reduce the outflow of precipitation accumulation and create less stress on these systems (US EPA).

Although newer urban areas are designed with separate sewer and storm sewers, GSI can still be incredibly useful (*Bioswales | Hixon Center for Urban Ecology*). In fact, GSI like bioswales have been shown to reduce pollutant retention, removal or sediment, and nutrient and soil transport from cities to water ways downstream, and GSI has also been found to have beneficial impacts for the hydrology and water quality of downstream water bodies (Hopkins et al.). This has allowed GSI to grow to a common practice in benefiting the sewer system and surrounding ecosystems while adding a pleasant aesthetic to the surrounding area. In cities, where precipitation often causes roadside rapids, water picks up debris, garbage, and all sorts of chemical contaminants to damage our water sources. By adding GSI, it is possible to implement some nature and greenery into the concrete jungles to help prevent flooding, reduce the contamination of our waterways and drinking water sources, and can change the mood and mentality of the human population nearby.

As the 2018 Water Infrastructure Improvement Acts defines, Green Infrastructure is "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters" (US EPA). This definition allows for various methods and includes much more than bioswales. Infrastructure such as green roofs, bioswales, rain gardens, and permeable pavement have all been studied to help reduce flow in varied ways. In addition, some of these GSI techniques have been studied to impact much more than just flow and water quality.

Besides the physical benefits of GSI, various separate studies suggest that the inclusion of nature in urban areas is beneficial in the everyday attitude and mood of the people passing by. (Suppakittpaisarn et al.). To many, city biomes are considered dreary, gray, and gloomy. With trees and wildlife few and far between, it can brighten the day of the average person and benefit their mental health to include nature in the land. Multiple published studies have indicated that green spaces produce increased health and social activity, from better cardiovascular health to lower crime rates (Suppakittpaisarn et al.).

Bioswales

’Bioretention’ GSI like bioswales or rain gardens can be both aesthetically beautiful and provide multiple hydrology and water quality improvement benefits. Typical design for these GSI includes an engineered soil media that is well-draining with limited organic matter to help sustain plants and sorb contaminants (Hunt et al.). The soil may be top-dressed with mulch or gravel. There are typically several types of vegetation which are critical for water and nutrient uptake, maintaining soil infiltration capacity, and aesthetic benefits. Thicker grasses, plants, and other vegetation have been shown to increase efficiency in the infiltration basin’s contaminant removal (*Bioswales*). In areas of high precipitation rates, water intensive vegetation could be optimal if they can be preserved by the rain frequency. Water typically enters GSI features like bioswales through surface inlets at the edge of impervious surface such as a parking lot or road. Inlets typically have energy attenuation built in through a rough surface such as cobbles. slows the runoff and allows the water to seep into the ground and be utilized in the photosynthesis of surrounding vegetation. Physical debris and selected contaminants are filtered out as the water moves through the soil media. Contaminants like metals, certain organics, and phosphorus may be adsorbed to soil particles, and nitrogen is taken up by plants and microbes as the water interacts with the soil and vegetation.

Additionally, the surface is equipped with an overflow drain. Located at an elevation slightly below the perimeter of the garden but above the soil on the ground, this drain permits pooling of rainwater while preventing flooding onto the road or surrounding area. If the water level in the swale gets to an unacceptable height, potentially flooding roadways or other surrounding infrastructure, the lowest point of elevation for the water to flow would be directly into the pipe below.

The infiltrated water may eventually seep down to a buried, perforated pipe, if not directly inflowed through the overflow drain. This pipe would then accumulate the water and transport it off site as a typical storm drain would. In combined sewer systems, this drained water is routed to a treatment plant, but more commonly released to a nearby stream or river. This makes it crucial that the water in transport is not heavily polluted and will not damage our environment or surrounding ecosystems with any potentially harmful contaminants. A large proportion of infiltrated runoff may also continue to seep into underlying groundwater, providing long term retention and treatment.

To manage this unmitigated runoff, and its associated flooding and water quality issues, stormwater management solutions can be implemented that can help detain, retain, and/or treat the runoff. Bioswale design is particularly important during new urban development, when the ease and accessibility of implementing green infrastructure of any scale is at its cheapest and most convenient. In older, condensed cities, it can be challenging to find space to develop a bioswale. However, there often can be retrofit opportunities to add GSI. If roadways are reorganized or intermediate street barriers are added, bioswales can be an extremely useful asset to prevent the increased flooding associated with the urban layout of the surrounding environment.

Typical designs of GSI are associated with assumed hydrologic, water quality, and other benefits. However, it is critical that function is also directly evaluated for selected GSI, to ensure that we are meeting intended goals. If hydrologic and water quality goals are not being met, then changes in design could be made. Additionally, basins may function as intended initially, but their function could evolve over time, due to accumulation of material and/or inadequate maintenance practices. Thus, it is critical to gather field insights on GSI function for various types and ages of GSI.

Previous research indicates that hydrologic function can vary widely for different types of GSI. For bioretention GSI such as bioswales, 50 to nearly 100% reductions in runoff volume have been documented. In a swale in Virginia, installed in 2007, 28 rain events were monitored. The bioretention cell had inflow from a parking lot and reduced flow volume by 97% and peak flow rates by 99% (DeBusk and Wynn). A similar study gathered data from various studies and found bioretention cells, like the bioswales on Penn State's campus, had a mean retention of 90 percent (Driscoll et al.).

However, there is still a need for continued insights, especially on GSI that are older. Thus, our research documents the hydrologic function of a 16-year-old bioswale on Penn State University campus. With the knowledge that bioswales can reduce flood disturbances and lower contamination of State College runoff, the hydraulic efficiency of this bioswale will be measured through the percent reduction of runoff volume. This reduction is valuable information to determine the impact that one bioswale of this size and age can have on mitigating runoff damage. Additionally, future studies need to be conducted to measure the reduction in contaminant levels using this bioswale. By observing the changes that a bioswale can create after 16 years, we can determine the reductions necessary for effective bioswales, how to increase longevity of a bioretention cell, and how they correlate to runoff mitigation and environmental protection.

Hypothesis

We hypothesize that the infiltration basin under study can infiltrate a substantial proportion of incoming runoff to underlying groundwater. Thus, through analysis of data, we expect to determine a significant percent reduction in the flow volume from inflow of precipitation to outflow through the pipes. This inflow value will already account for infiltration into surrounding ground using a curve number approximation, so any reduction in the collected data will be through bioswale action.

Additionally, through transport time on the surface and through ground seepage, it is expected that there will be a time difference between precipitation downfall and the point when outflow water exits the underdrain pipe. This lag time may alter based on storm intensity due to changes in remaining ground storage.

Chapter 2: Methods

The following study was conducted on one specific bioswale on the Penn State campus. Over the duration of 2 years, data was collected, and select rainfall events were analyzed. The following are the specifics of the basin, the data collection methods utilized, as well as the analysis and calculations performed to compare the data and create the graphs seen in the Results.

Basin Site

The Penn State bioswale focused on in this study is located off Hastings Road on the South-East corner of Hastings and University Drive. This location has an approximate area of .40 acres of land in its watershed. A considerable amount of this land is a paved, slightly sloped parking lot, making much of the water run towards the basin. The Curve Number of this highly impervious watershed, which will be further discussed in Data Analysis, is estimated to be 97.

The swale is approximately 350 m^2. Two inlet pipes route water from the parking lot watershed into one end of the swale. At the opposite end of the swale is an overflow grate which allows water to pond to the top of grate, and then overflow directly into the storm sewer connection to prevent flooding of the surrounding area. The swale was constructed with 42 inches of engineered soil media, below which is 6 inches of pea gravel, and 12 inches of 2B gravel. In the 2B gravel is a 6-inch perforated underdrain pipe which routes to the overflow grate catch basin. The swale is not lined, allowing some water to infiltrate into underlying soils and groundwater. The originally planted vegetation consisted of a mix of typical bioretention plantings, including *Iris versicolor, Sparganium Americanum, Juncus effusus, and Scirpus pungens*.

Figure 2.1: The monitored Penn State bioswale at Upper Grad Circle parking lot during late winter (when vegetation is dormant)

Data Collection

To facilitate measurement of outflow from the underdrain below the swale, we inserted a 6-inch pipe weir into the end of the drainpipe where it discharges to the overflow catch basin. Behind the weir, we utilized an Onset HOBO MX2001 Bluetooth pressure sensor to gather pressure values caused by flowing water in the pipe. These pressures were then converted via the hydrostatic pressure equation into water height at five-minute intervals. A statistical relationship from the weir manufacturer (Thel-Mar) was then used to convert water height into flow rates. Data has been collected for over two years through a Bluetooth device to transfer the information from sensor to an excel file for further analysis. For my investigation, I focused on specific rain events during this time for storms of varying size.

Figure 2.2 Onset HOBO MX2001 Bluetooth pressure transducer and Thel-Mar pipe weir

Inflow to the swale was not directly monitored due to concerns that water in the basin could backflow into the inflow pipes and cause inaccurate flow measurements during large events. Instead, precipitation data was used to make a simple model of inflowing runoff. The precipitation data from the storms was gathered through the weather station – a HOBO RX3000 Station located in the study basin. This data, starting in May 2019, was recorded in 2 minutes intervals and indicates the depth of rainfall for each time interval. Although the time intervals were different from each data collection, we were only concerned about the total volume of water for the event, so the time interval differential was neglected.

One consideration in the data from the swale was to remove all values or rainfall events from our analysis if the temperature of the area was below freezing during or recently before that time. This was included to remove the impact of snow or frozen topsoil. Snow could potentially alter our data drastically, melting at a much later date than accumulated, or even remaining frozen until the subsequent precipitation assisted in the melting process. Also, frozen land would limit or entirely prevent infiltration of the precipitation, forcing pooling, flooding, or direct flow from basin through the overflow drain into the basin below.

Data Analysis

Weather data collected at the basin recorded various variables including rain depth, temperature, wind speed and direction, etc. For our purposes we only utilized the rain depth, as well as temperature to confirm the ground was not frozen and the precipitation was not snow. Calculating the inflow to the bioswale is a combination of precipitation depth, watershed area, and the Curve Number of the area. The watershed area for this bioswale is .40 acres or 17,424 square feet. This value remains constant for each event. The US Natural Resources Conservation Service Curve Number equation is a tool used to determine approximate infiltration based on the type of soil or land use in the area. The equations below show how this is used. The Curve Number for our area is estimated to be 97 of a potential 100 maximum. This value was determined to be 97 because of the land percentage used for parking lot covered with impervious pavement. The Curve Number, CN, determines the intermediate values of S, potential max retention, and I, initial abstraction before ponding. The initial abstraction value is equal to one twentieth of the S value. The D value calculated from the final equation gives us the rainfall excess, or estimated runoff of water that proceeds into the bioswale.

$$S = \left(\frac{1000}{CN}\right) - 10) \qquad D = \frac{(P - Ia)^2}{(P - Ia) + S}$$

Equation 2.1 and 2.2: *Curve Number Equations used to determine runoff depth*

Using the new D value for runoff depth, we can calculate the volume of water through the by simply multiplying the new runoff depth by the area of the watershed. This gives us an approximate inflow volume from the storm in total cubic feet of water.

Outflow will be found using data from the sensor in the underdrain pipe. This sensor measures pressure and calculates that value into a water height in the pipe. Using this water level, measure in feet, we can apply the weir equation to calculate the volumetric flow rate in cubic feet per second. These equations are shown below, with Equation 2.3 coming from the manufacturer and Equation 2.4 determined in a previous lab test, both of which x is the water level in feet. The intent of the lab test was to correct any disruption of water depth behind the pipe weir by the sensor during very shallow flows.

For Water Level of .08 ft or greater : $\mathbf{Q = 1.1902x^2 + .113x - .0151}$ (Equation 2.3)

For Water Level between 0 and .08 ft : $\mathbf{Q = 1.8307x^2 = .0498x + .0005}$ (Equation 2.4)

With the flow rate now calculated in cubic feet per second, we can multiply each 2-minute interval's outflow discharge rate (Q) by 120 seconds to get a volume for that interval. By summing the volumes throughout the storm and post storm data we achieve a total volume of outflow runoff (Equation 2.5). Below, in Figure 2.5, a visual representation of the flow rate over the course of a storm is seen. To calculate total outflow from this bioswale each data point was multiplied by 120 seconds to account for the 2-minute intervals. In the equation below, Q is the flow rate in cubic feet per second, and t is the time (120 seconds for the 2-minute intervals).

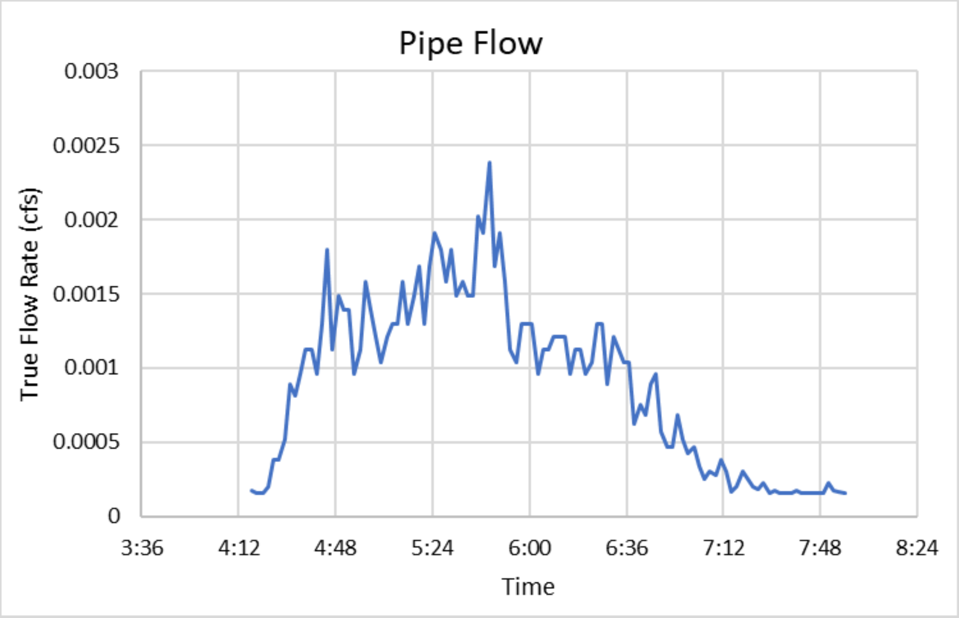


Figure 2.5: Flow Rate of a specific rain event over time

$$\sum_{t}^{f} Q(cfs) * t(sec)$$

Equation 2.5: Volume Equation from t = initial time to f = final time

For each event analyzed, the modeled inflow volume was compared to the measured outflow volume. The difference between those volumes is considered the amount of water that has been retained and treated, either by infiltration to underlying soils or by evapotranspiration. For each event analyzed, additional characteristics about the event were considered, such as the total precipitation depth and duration of the event, as these factors could affect the swale's ability to manage incoming runoff.

Chapter 3: Results

The following is a culmination of the tables, results, and statistics put together through the analysis of # different rain events. Each uses the data recorded and analyzed by the same sensor and the same weather station. For average values such as average percent reduction found and average lag time, values from every event were considered.

The following Figures, Figures 3.5 to 3.6, are examples of the Pipe Flow and Precipitation data over time. These graphs were created for each of the four events and can be seen in the Appendix, Figures 3.1 through 3.8. Although the precipitation data seems somewhat uniform, the peak between 5:30 and 8:30 am and the peak between 10:15 to 1:15pm show increased rainfall for those two periods. This can be seen in the two peaks in Figure 3.5. For about three hours, between 10:30am and 1:30 pm, there is increased flow in the pipe, correlating to the 3-hour increase in precipitation intensity 5 hours prior. The same connection can be seen with the second peak in flow.

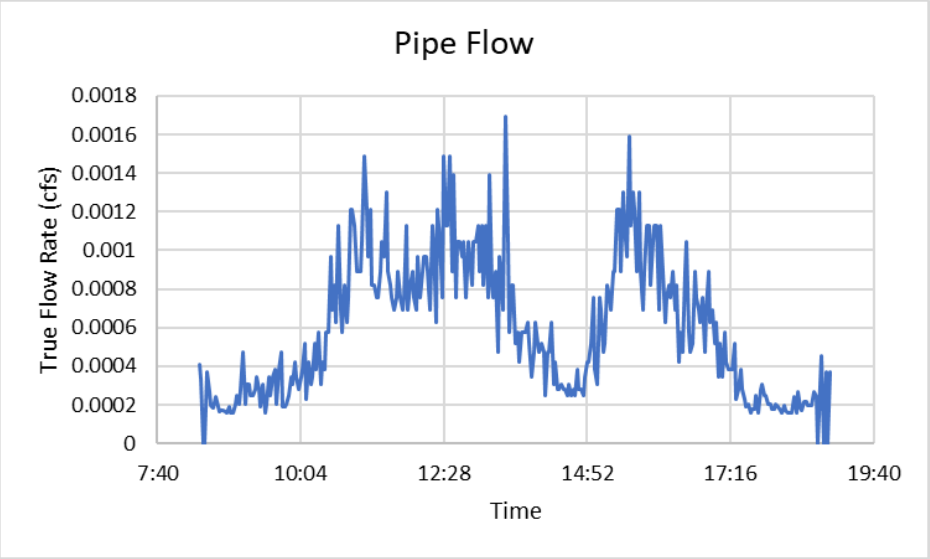


Figure 3.5: Pipe Flow Calculating Flow Rate vs Time (October 29, 2020)

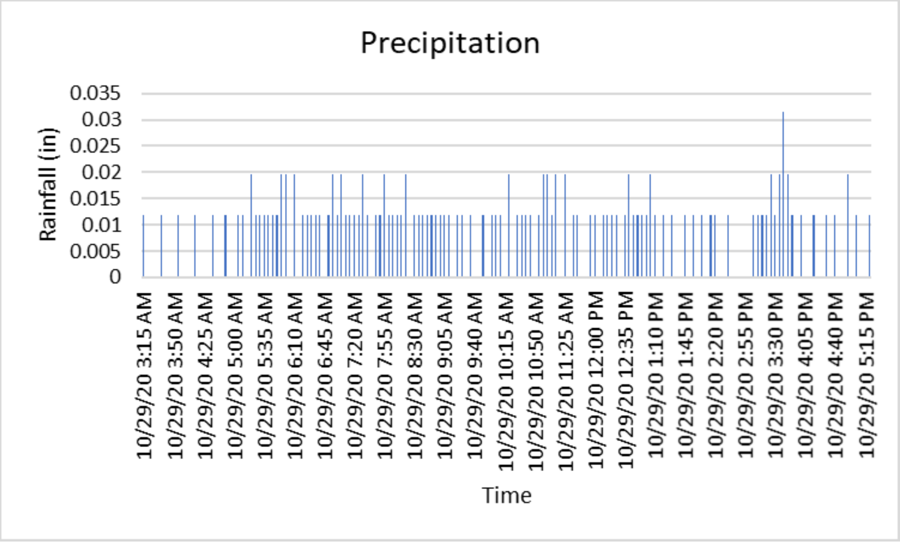


Figure 3.6: Precipitation vs Time (October 29, 2020)

The following Table, Table 3.1, is a culmination of data from the four precipitation events investigated. This was constructed to observe any potential correlation between the average rainfall intensity during a given storm, the duration of the storm, the percent reduction in flow, and the lag time. This table also provides an average percent reduction and an average lag time between precipitation and flow in the pipe.

Table 3.1: Summary of four rain events, providing percent reduction in runoff volume between inflow and outflow, and lag time between start of precipitation and start of pipe outflow.

Date	Approximate Duration (hr)	Total Rainfall (in)	Intensity (in/hr)	Percent Reduction	Approximate Lag Time (hr)
29-Sep-20	7	1.732	0.247	96.66	6
12-Oct-20	6	0.772	0.129	98.41	4
29-Oct-20	13	1.465	0.113	98.66	5
11-Nov-20	10	1.26	0.126	97.34	3
			Average	**97.77**	**4.50**

As seen above, the average percent reduction found throughout the four events is 97.77 percent. Additionally, the average lag time is four and a half hours, with a maximum variation of 1.5 hours.

Chapter 4: Discussion

Prevention of precipitation infiltration is an issue urban development has created through the excessive use of impervious pavement and infrastructure. Now, many cities struggle with problems caused by rain and storm events and must implement methods to limit the flooding and contamination hazards that runoff creates. GSI like bioswales offer a potential solution by retaining large volumes of runoff in infiltration basins and filtering out contaminants in the process. However, based on size, vegetation, precipitation frequency, and storm intensity, each bioswale differs in efficiency. Through the study of one bioswale on Penn State's campus, I calculated a value of average reduction in runoff volume. This value, 97.77 % reduction, shows that this basin is extremely efficient in mitigating potential flood waters and can be implemented in urban areas as a vital asset to lower stress on their existing stormwater systems. Additionally, basins like this can function to delay runoff from various parts of an area, extending the period of runoff inflow into a sewer system, allowing for a much more manageable rate.

When observing the results from the study, the most expected outcome is that as the storms intensify (i.e. larger rainfall per hour) the percentage reduction of flow decreases. This was expected due to the finite soil storage and the infiltration rate of the ground. When introduced to a surplus of precipitation, the storage of the bioswale's soil was saturated more quickly, forcing more flow of excess runoff into the pipes. We would expect larger total rainfall volumes to produce smaller reduction percentages, being the case in the September event, providing one and three quarters inches of rain. However, October 29th, with 1.465 inches, has the highest percent reduction in volume. I believe this can be explained by the duration of the storm. Although a large volume of water was input into the area, the lowest intensity also occurred, allowing the soil time to infiltrate and transport the runoff at a rate like the precipitation. Although these high intensity storm events are when most problems occur, GSI is still effective in assisting the storm management system. Our basin still had a volume reduction of over 95 percent with the largest storm intensity, as well as a delay of 4+ hours from precipitation to outflow.

Comparing the Penn State bioswale study with other bioswale studies, we see that 97.77 percent is a high rate of runoff reduction, but not at all unprecedented. For example, a study of a stormwater basin in the Stroubles Creek Watershed in Blacksburg Virginia measured the change in volume as well over 28 events. This similar study showed a volume reduction average of 97 percent and 99 percent peak flow reductions (DeBusk and Wynn). This, along with many other studies leads me to believe that my calculations have led to accurate results with little discrepancy based on exterior variables.

Another study, led by Syracuse University, researched the existing literature of various stormwater mitigation techniques. Over all observations they found that “bioretention cells”, a very similar GSI to our system, had an average of 90.3 percent volumetric reduction. This reduction was the highest among all GSI methods including porous pavement, green roofs, and detention ponds (Driscoll et al.). The comparison in efficiency can be seen in Figure 3.9 in Appendix A.

Based on this study, bioswales can be an environmentally friendly and low energy way to lower runoff catastrophes while introducing nature back into urban landscapes. Additionally, besides installation costs, these systems require little maintenance annually and a periodic sediment replacement to promote proper flow and contaminant removal (*Bioswales – Naturally*

Resilient Communities). The possibility of reducing runoff volumes by over 90 percent could save millions in disaster damage and will assist in creating healthy ecosystems around our cities.

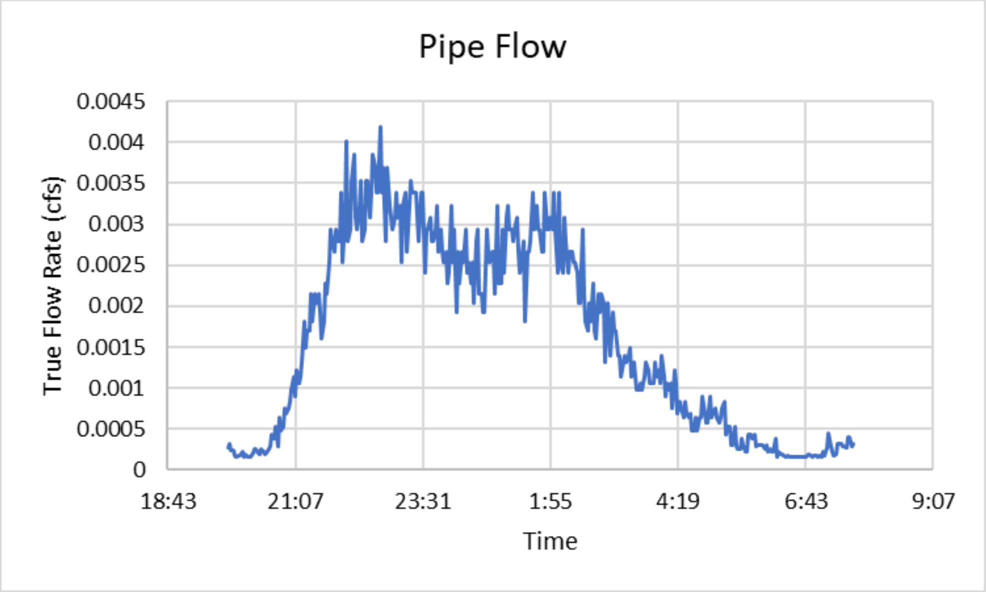
Because our study only included volume and flow of one basin and looked at a relatively limited set of storm events, it is difficult to determine that the efficiency of all bioswales in a climate such as this would function equally. Additionally, water quality samples were not taken from the inflow and outflow water, so the actual reduction in contaminants is unknown. We would assume that the large volume reduction would be proportional to the reduction in pollution, if not greater due to adsorption. However, we cannot say for sure that 97 percent of the contamination from this runoff is also removed from transport and stored in the swale.

Future research should address the contaminants input into this basin sourced from the parking lot above. By testing the inflow pollution levels to the outflow, we can determine the effectiveness of our bioretention cell in removing contaminants. Additionally, monitoring the changes of volume reduction in this bioswale and the other two on Penn State’s campus moving forward will provide valuable information on the longevity of the system and the differences in efficiency between the three. Future work could also investigate specific mechanisms of volume reduction, since both infiltration and evapotranspiration could be playing a role. Finally, the swale inflow and outflow water should continue to be tested for the possibility of the bioswale soil becoming “spent”, or unable to conduct further adhesion of chemical contaminants such as VOCs, pesticides, nitrates, and other organic pollutants or heavy metals, no longer preventing the transport of such contaminants

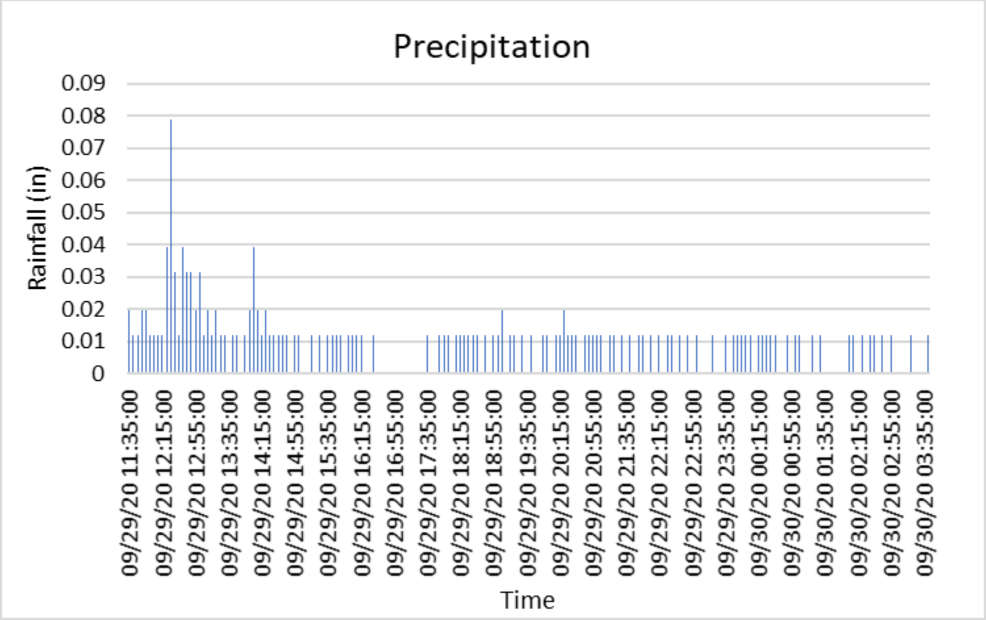
Chapter 5: Conclusion

The goal of this research was to evaluate the hydrologic performance of a 16-year-old bioswale on Penn State University campus. Data was collected to allow comparison of inflowing runoff volumes to the outflow volumes of water continuing into the storm drain system. Our results indicate that the bioswale is extremely effective in reducing the volume of precipitation in the area that still makes its way into the storm sewer system. With an average of 97.77 percent volume reduced, this bioswale significantly reduces the flood hazards caused by the implementation of impermeable pavement over this .4-acre lot. The substantial runoff reduction through the ability of the bioswale to infiltrate water into underlying soils, as well as evapotranspiration action, creates a significant impact on reducing runoff that must be dealt with. Additionally, the bioswale showed an average lag time of 4.5 hours between precipitation in the area and outflow from the storm drain. This time differential can be beneficial in lowering stress of a larger storm runoff system by delaying the introduction of additional water volume. Urban issues with flooding and water contamination could be heavily reduced by implementing bioswales in effective locations that limit and delay precipitation volume from becoming problematic runoff.

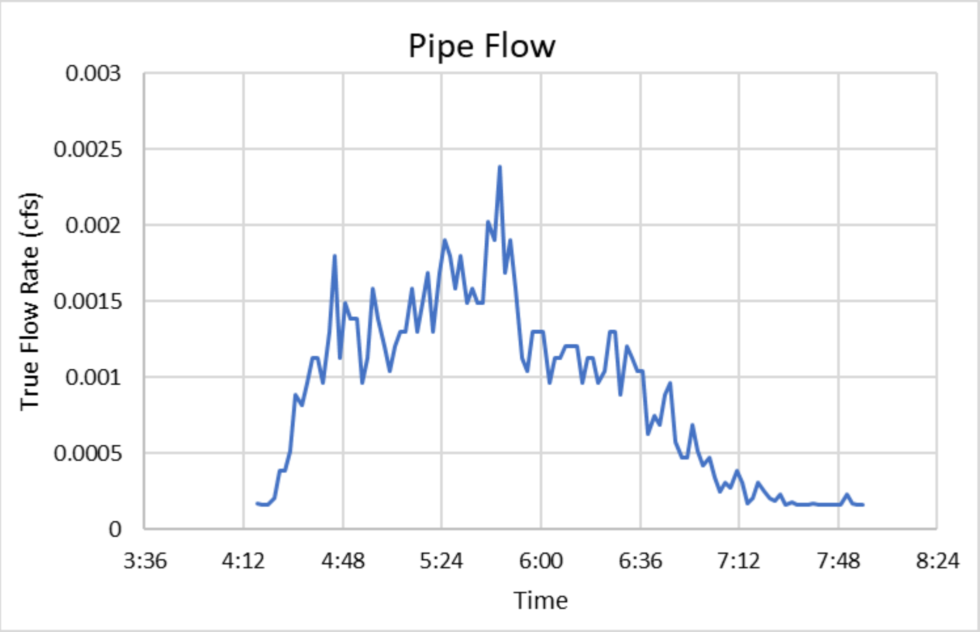
Appendix A Figures



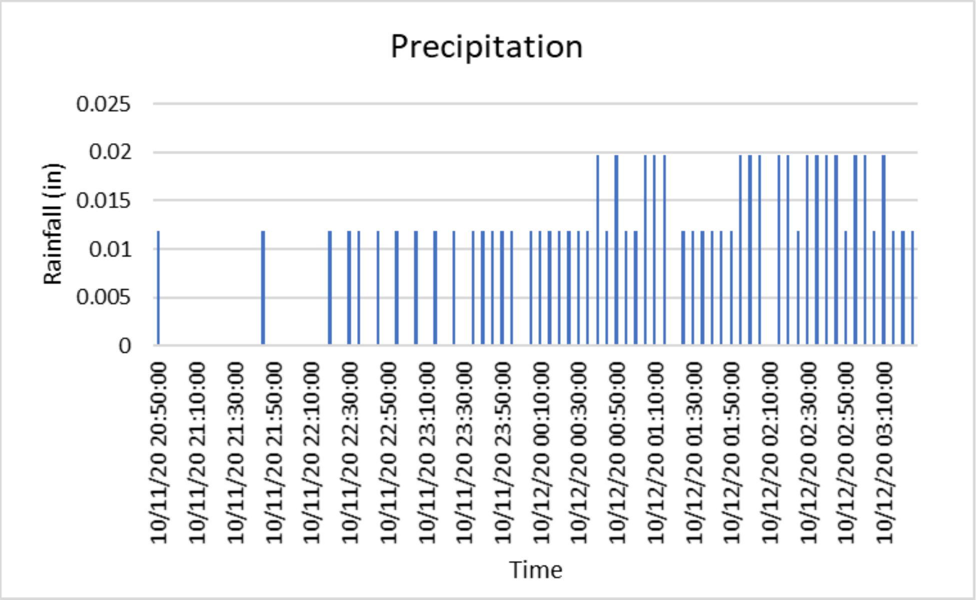
3.1



3.2


Pipe Flow
True Flow Rate (cfs)
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
3:36
4:12
4:48
5:24
6:00
6:36
7:12
7:48
8:24
Time

3.3


Precipitation
Rainfall (in)
0.025
0.02
0.015
0.01
0.005
0
10/11/20 20:50:00
10/11/20 21:10:00
10/11/20 21:30:00
10/11/20 21:50:00
10/11/20 22:10:00
10/11/20 22:30:00
10/11/20 22:50:00
10/11/20 23:10:00
10/11/20 23:30:00
10/11/20 23:50:00
10/12/20 00:10:00
10/12/20 00:30:00
10/12/20 00:50:00
10/12/20 01:10:00
10/12/20 01:30:00
10/12/20 01:50:00
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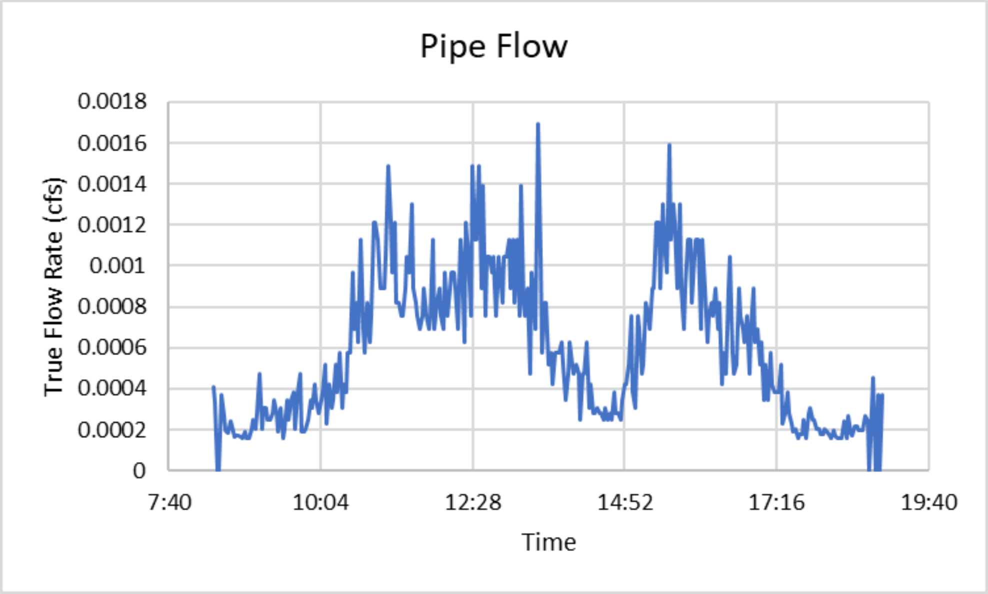
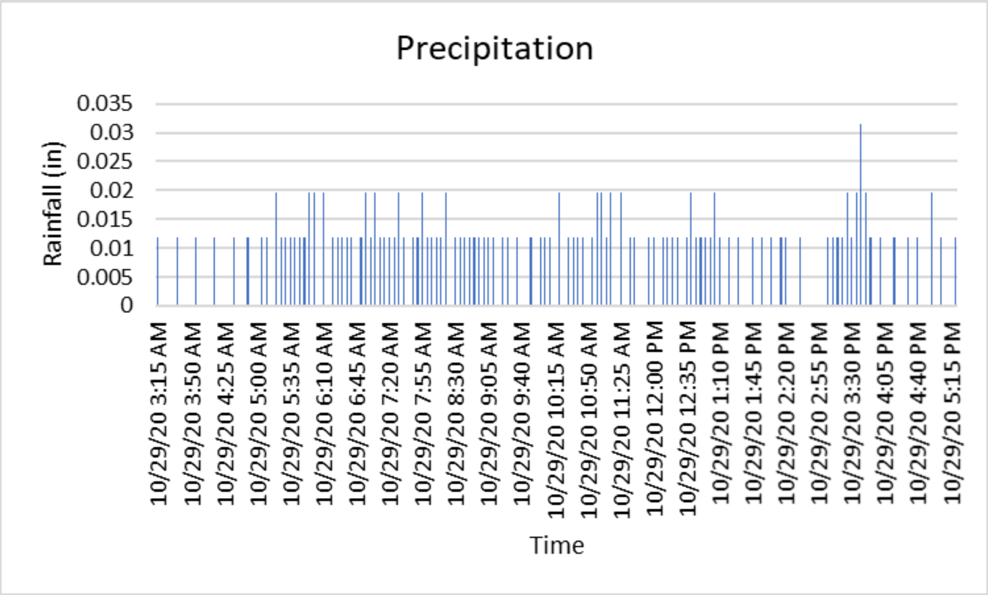
10/12/20 02:30:00
10/12/20 02:50:00
10/12/20 03:10:00
Time

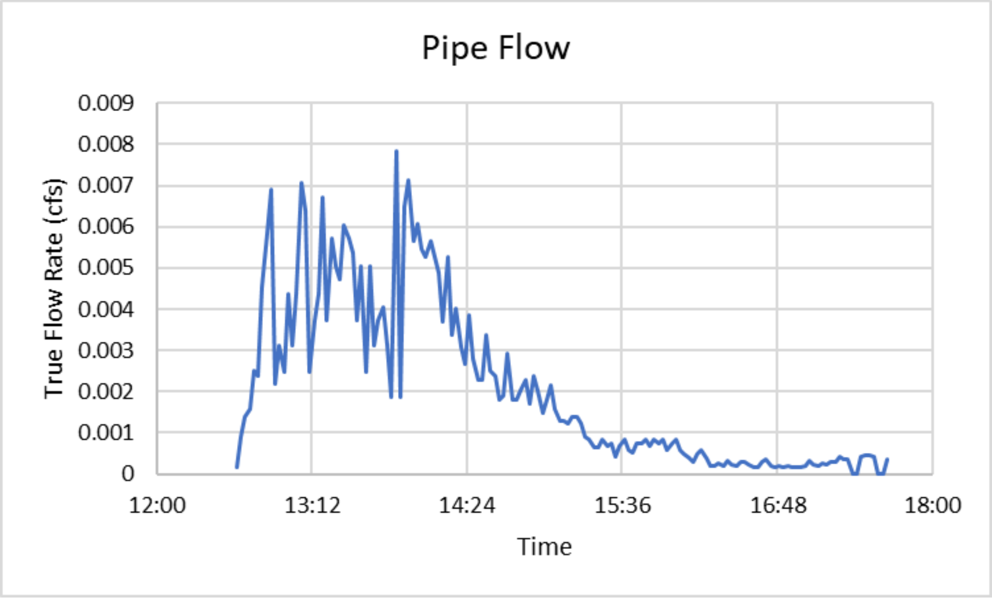
3.4


Pipe Flow
True Flow Rate (cfs)
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
7:40
10:04
12:28
14:52
17:16
19:40
Time

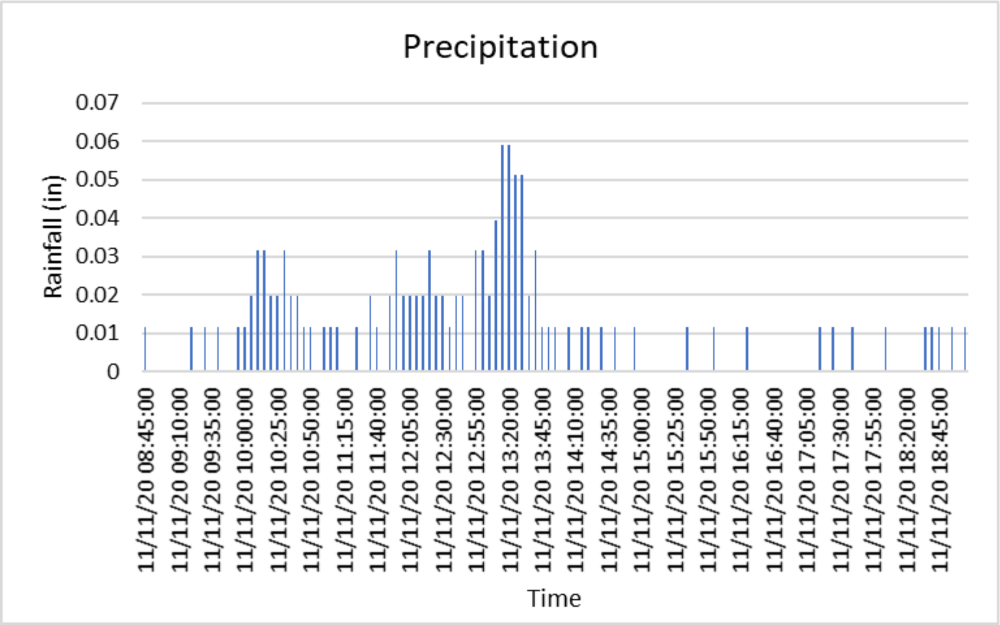
3.5


Precipitation
Rainfall (in)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
10/29/20 3:15 AM
10/29/20 3:50 AM
10/29/20 4:25 AM
10/29/20 5:00 AM
10/29/20 5:35 AM
10/29/20 6:10 AM
10/29/20 6:45 AM
10/29/20 7:20 AM
10/29/20 7:55 AM
10/29/20 8:30 AM
10/29/20 9:05 AM
10/29/20 9:40 AM
10/29/20 10:15 AM
10/29/20 10:50 AM
10/29/20 11:25 AM
10/29/20 12:00 PM
10/29/20 12:35 PM
10/29/20 1:10 PM
10/29/20 1:45 PM
10/29/20 2:20 PM
10/29/20 2:55 PM
10/29/20 3:30 PM
10/29/20 4:05 PM
10/29/20 4:40 PM
10/29/20 5:15 PM
Time

3.6



3.7



3.8

Figures 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8: Graphs of Flow Rate vs Time and Precipitation vs Time for each of the four rain events

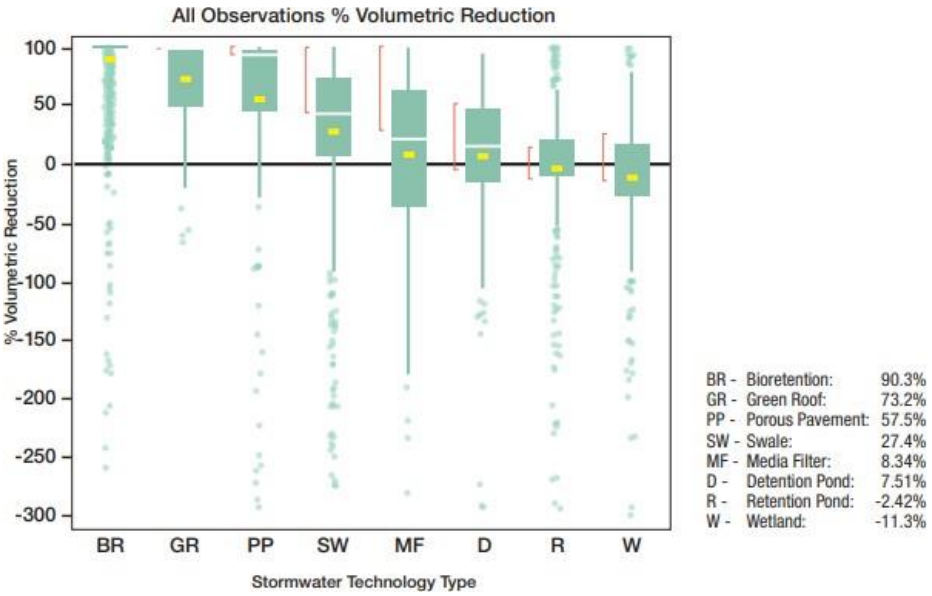
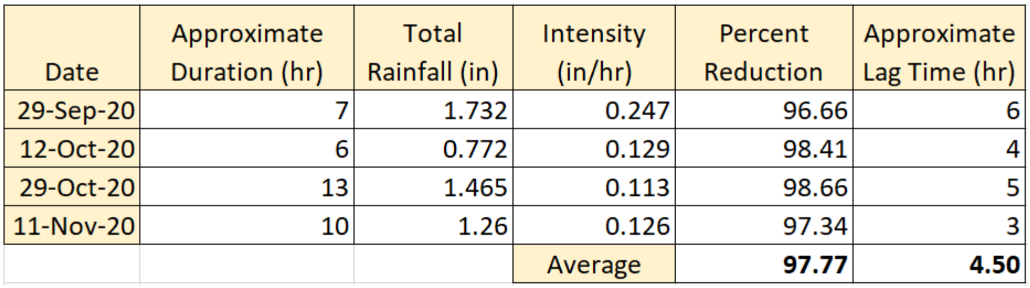


Figure 3.9: Volumetric Reductions based on GSI type (Driscoll 2015)

Appendix B Tables

Table 3.1: Summary of four rain events, providing percent reduction in runoff volume between inflow and outflow, and lag time between start of precipitation and start of pipe outflow.



Date	Approximate Duration (hr)	Total Rainfall (in)	Intensity (in/hr)	Percent Reduction	Approximate Lag Time (hr)
29-Sep-20	7	1.732	0.247	96.66	6
12-Oct-20	6	0.772	0.129	98.41	4
29-Oct-20	13	1.465	0.113	98.66	5
11-Nov-20	10	1.26	0.126	97.34	3
			Average	**97.77**	**4.50**

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ACADEMIC VITA

Daniel C. Lennon

Education:

Penn State University, Schreyer Honors Scholar **2018 – Present**
Major in Civil Engineering and a Minor in Environmental Engineering Graduation, May 2022

Relevant Experience:

Research in Penn State– College of Engineering **September 2021-April 2022**
Analyzed Inflow and Outflow Data for bioswale - GSI on Penn State's campus *State College, PA*
Calculated the volumetric changes through the basin after individual storm events

Internship with Whiting-Turner, General Contractor **June 2021-Aug 2021**
Communicated with Architects, Owners, and Subcontractors to resolve various issues *Woodbury, NY*
Sorted, reviewed, and transferred hundreds of submittals, RFI's, and subcontracts
Coordinated between multiple teams to discuss scheduling, design, and expectations

Backyard Builders **May 2020 – August 2020**
Learned the foundational basics of construction through playset assembly *Suffolk County, NY*
Brainstormed solutions to due to site issues, lack of materials, or team disagreements

Technical Skills:

Proficient in Excel, Procore, Bluebeam, and various AutoCAD modeling software
Experience in the bidding, contract writing, site preparing, and supervision of construction projects
Intermediate Spanish skills (reading, writing, and speaking)

Leadership and Activities:

Studied abroad in San Sebastian and Madrid, Spain ***Summer 2019 & Spring 2020***
Competed in an Engineering design showcase with the goal of enhancing customer PMV experiences
Spoke in Spanish to locals in order to identify customer needs and product design flaws
Improved my language skills by immersing myself in the culture in the capital of Spain

Member of the American Solar Energy Society ***2019 - 2021***
Furthered my knowledge and interest in Solar Energy and its possibilities

Co-Founder of the Alpha Sigma Phi – Upsilon Chapter ***2019 - Present***
Conducted interviews with new potential members to evaluate compatibility
Organized brotherhood events to create social networks for Penn State students interested in joining

Volunteering:
Alpha Sigma Phi THON Fundraising ***2019 - Present***
La Fortuna Orphanage, Costa Rica ***Summer 2016***
Peanut Butter and Jelly Gang ***2011 - 2020***