THE PENNSYLVANIA STATE UNIVERSITY
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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

# Modeling Hydrological Performance of Rain Garden Design Scenarios across Pennsylvania

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# ABSTRACT

Traditional stormwater management has focused on reducing urban flooding through the collection and channeling of stormwater; however, this has led to a series of undesirable environmental impacts downstream. More modern stormwater managements are now beginning to be utilized, known as green infrastructure. Rain gardens are green infrastructure features used to remove stormwater in urban areas by detaining and retaining runoff. GIFMod was used to model the hydrological performance of residential rain gardens based on the predominant soil characteristics in regions of Pennsylvania. The objectives of these simulations were to analyze the sensitivity of basic rain garden design factors and explore the variability in rain garden performance throughout Pennsylvania, based on the maximum ponding depth and ponding time of the rain garden. While rain garden hydrological performance varies depending on native soil, it was found that Pennsylvania soils can often accommodate stormwater loading ratios much larger than those currently recommended. Additionally, it was concluded that evapotranspiration provides negligible contributions to runoff reduction in residential rain gardens. It is recommended that the rain garden design sizing guidelines outlined in the Pennsylvania Stormwater Best Management Practices manual be revised, and rain garden sizing be determined based on the infiltration rates of the native soil compositions.

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# Chapter 1

# Introduction

## Need for Stormwater Management

Urbanization is rapidly increasing. The global urban population has grown from 34% in 1960, to 55% in 2018, and is expected to increase to 68% by 2050 (UN DESA 2018). Over time, urban development has had a significant impact on the natural environment; most notably, permeable land surfaces have been changed to impermeable surfaces through the mass construction of paved roads, driveways, and buildings (Alyaseri et al. 2017). This has resulted in a chain of negative water resource effects termed the “urban stream syndrome” (Walsh et al. 2005).

The urban evolution of water throughout the past three centuries can be described as three sequential stages: the “Industrial City”, the “Sanitary City”, and the “Sustainable City” (Kaushal et al. 2015). At the start of the Industrial Revolution, cities developed around rivers because they played a major role in sustaining the city itself. These water sources supported natural processes, such as flood prevention, and were needed for transportation, power, and trade. The Industrial City was characterized by the use of water for manufacturing; in turn, these industrial processes caused point and nonpoint source pollution in urban waters.

As society evolved, cities grew further and further away from these water sources, which drove the need for clean water; the Sanitary City is characterized by centralized sanitary sewer and drinking water distribution systems. The inhabiting of previously undeveloped land caused a significant increase in coverage by impervious surfaces, which successively caused the need for stormwater management. In uncultivated areas, surface water flows through pervious surfaces, where it is naturally removed through infiltration and evapotranspiration. However, impervious surfaces inhibit these natural processes and generate runoff. Traditional stormwater management used engineered drainage networks, which created a hydrological connectivity between terrestrial and aquatic environments through a system of ditches, storm drains, and pipes to reduce stormwater runoff. This led to a series of undesirable impacts, now known as urban stream syndrome.

Routing runoff from urbanized catchments into natural stream ecosystems causes both hydrological and water quality concerns. When large volumes of water are discharged into streams, it causes the streams to have flashier hydrographs: “more frequent, larger flow events with faster ascending and descending” times (Walsh et al. 2005). This increases the frequency of erosion and flooding. Additionally, nonpoint source contaminants and pollutants are picked up through runoff and discharged into the streams, resulting in water chemistry change and an array of undesirable health effects on aquatic ecosystems, among other environmental consequences.

In addition to direct discharge of storm sewer into streams, some older cities have combined sanitary and storm sewer systems that periodically have combined sewer overflows (CSOs) into streams. In these cities, wastewater treatment plants can treat stormwater with wastewater during smaller storm events, but larger storms cause CSOs, which cause highly polluted water to be discharged into receiving water bodies.

The recognition of urban stream syndrome drives the present-day stage in the urban evolution of water, where society is transitioning from the Sanitary City to the Sustainable City, which focuses on ecosystem restoration. Growing research has demonstrated that traditional stormwater management systems that focused on reducing urban flooding through the conveyance of stormwater or combination of wastewater and storm sewers have deteriorated water sources. More modern approaches, with a focus on slowing and retaining stormwater, are essential in reducing water pollution and protecting and restoring urban streams.

## History

The first U.S. law to address water pollution was the Federal Water Pollution Control Act of 1948 (US EPA 2013). The original statute was designed in an attempt to reduce the pollution in interstate waters and improve the sanitary conditions of underground and surface waters (FWS 2013). However, pollution control was not a priority for state and federal governments at the time. As the Industrial Age began, factories expanded and there were no regulations on what to do with the waste. Industries, sewers, and residents continued to dump their waste into rivers, until June 22, 1969, when the Cuyahoga River in Cleveland, Ohio caught on fire. The cause of the fire is still unknown; however, the prevailing theory is that sparks from a railroad bridge ignited an oil slick below the bridge. This was not the first time the Cuyahoga River caught on fire, however, the fire of 1969 drew national attention, which led to amendments of the law (RCAP 2021).

In 1972, the Federal Water Pollution Control Act was amended and became known as the Clean Water Act (CWA). The 1972 amendments established the basic structure for regulating pollutant discharges and made it unlawful to discharge pollutants into U.S. waters unless a permit was obtained, among other things. However, most significantly, this amendment recognized the need for planning to address the problems associated with nonpoint source pollution (US EPA 2013). The act has undergone many changes since then, and now defines green infrastructure as a stormwater management approach to reduce water pollution.

In 1990, the National Pollution Discharge Elimination System (NPDES) program began under the CWA, which mandates stormwater management for municipal separate storm sewer systems (MS4s) and combined sewer systems (CSS). This program was intended to mitigate some of the negative environmental effects of runoff, by requiring stormwater control measures (SCMs) that detain or retain stormwater. Green infrastructure has been an essential SCM for cities with either type of sewer system, but its acceptance was motivated due to CSS. Under the NPDES program, cities with CSS were federally mandated to implement CSO control plans to reduce stormwater inflows to the sewer systems. These cities were required to make consent decrees, committing large amounts of money towards stormwater management, aimed to reduce CSOs (McPhillips and Matsler 2018).

## Green Infrastructure

The United States Environmental Protection Agency (EPA) classifies water management systems into two categories: gray infrastructure and green infrastructure. Gray infrastructure is the traditional water management systems that rely on hard infrastructure to collect and channel stormwater (Denchak 2019). In municipal separate storm sewer systems, stormwater runoff drains through engineered collection systems and the untreated water is discharged into local water bodies. Stormwater runoff is a primary cause of water pollution, for it carries trash and pollutants from its source (US EPA 2015a).

The National Resources Defense Council (NRDC) estimates that 10 trillion gallons of untreated stormwater runoff enter the U.S. waterways from sewer systems every year (Denchak 2019). The American Society of Civil Engineers (ASCE) releases an annual 'Report Card for America's Infrastructure', in which it assesses the infrastructure conditions in the U.S. using an A to F school report card scale. The United States' stormwater systems received a grade of D, emphasizing the need for infrastructure improvements (ASCE 2021). According to the EPA, upgrading the water systems will require at least $434 billion in additional investments over the next decade, with approximately one-quarter going specifically towards stormwater management (Denchak 2019). The EPA is encouraging communities to use this need for improvement as an opportunity to incorporate green infrastructure into their stormwater management systems (US EPA 2015b).

In Section 502 of the CWA, green infrastructure is defined as "...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". Green infrastructure is designed to mimic the natural absorption and filtration of stormwater through the use of vegetation, soils, and other natural elements. It reduces and treats stormwater at its source while providing environmental, economic, and health benefits (US EPA 2015a).

## Rain Gardens

Rain gardens are a green infrastructure feature used to reduce stormwater runoff and remove pollutants. Terms such as bioinfiltration basin, bioretention basin, or bioswale may also be used as synonyms to rain gardens. A bioinfiltration rain garden consists of four main layers: a ponding area, a substrate soil layer (also known as a filter media), a native soil layer, and a groundwater layer (see Figure 1). Vegetation is also a key component of these green infrastructure features.

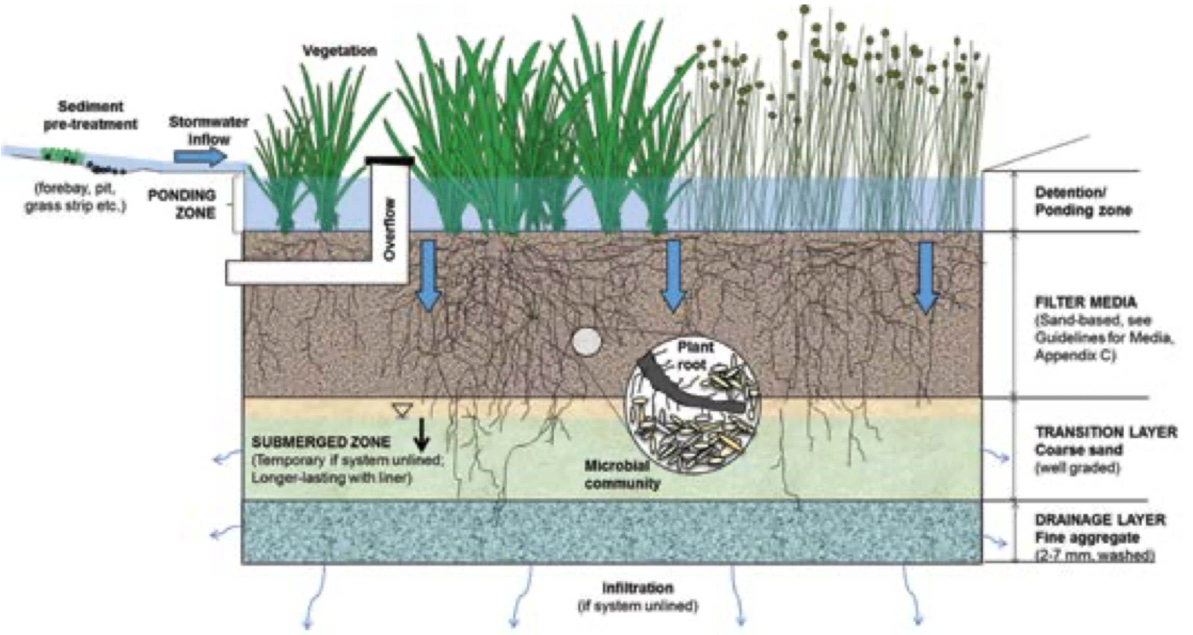


**Figure 1. Bioinfiltration Rain Garden (Payne et al. 2015)**

The ponding area is a depressed, vegetated basin into which stormwater flows and temporarily ponds on the surface. The flow entrance design varies depending on the site use. Inflow could enter the ponding area via diffuse surface water runoff, as common in residential applications, or via an inlet, used predominantly for larger scale commercial or industrial applications. The ponding zone provides temporary storage of stormwater runoff. The surface area of the pond is variable depending on the volume of water it needs to accommodate; however, the depth of the pond is limited to ensure optimal aesthetics and safety.

The stormwater then infiltrates into the substrate soil layer. The substrate soil layer generally has three sublayers: a planting soil medium, a transition layer, and a storage layer (Payne et al. 2015). The primary purpose of the planting soil medium is to promote and sustain a robust vegetive cover throughout the ponding area, so there is typically some organic matter in this layer (Philadelphia Water Department 2020). Vegetation is crucial to rain gardens, as it influences both its hydrologic and water quality performance. Plants transpire water through their roots, aiding in runoff reduction. Additionally, plant roots and rhizomes open pathways throughout the soil medium, which helps promote infiltration (DEP 2006). In terms of water pollution, plants can absorb much of the incoming nutrient pollutants (nitrogen and phosphorus) to improve the water quality (Philadelphia Water Department 2020).

The transition sublayer is intended to increase infiltration, provide additional water storage, and prevent washout of filter media. It provides a bridging layer to prevent migration of fine particles from the upper filter media to the gravel drainage layer (Payne et al. 2015). The depth and texture of this layer vary depending on the site condition. Typically, a sand texture is used to maximize the rain garden's infiltration rate and storage capacity. As stormwater infiltrates through this sublayer, pollutants are filtered out, further improving water quality.

Depending on the native soil conditions, a storage sublayer may need to be incorporated into the rain garden design, beneath the transition sublayer. This is a gravel layer that allows the system to either drain into a collection pipe or infiltrate into surrounding soils. It also provides higher porosity to temporarily store stormwater between pores (Payne et al. 2015). However, this layer is intended for soils where infiltration is limited. It is generally only included when runoff cannot be removed entirely through infiltration.

Rain gardens may be configured to drain in two key ways:  The ideal ‘bioinfiltration’ configuration is to maximize removal of runoff via infiltration into the surrounding soils. An alternative configuration, sometimes referred to as bioretention, is a combined green and gray infrastructure that has an underdrain (perforated pipe) in the lower gravel storage layer which connects to the storm sewer system. While a portion of the water will still infiltrate into the surrounding soils, excess water is retained and released into the storm sewer at a controlled pace. This is intended to reduce the pond’s drainage time. Sometimes there is also an impermeable liner below the lowest media layer, in cases when no infiltration can be permitted. (Philadelphia Water Department 2020). When the underlying soils are tested and determined to be infiltration-feasible, the standard bioinfiltration design can be used and a storage sublayer is not necessary. The Philadelphia Water Department recommends that the soils underlying infiltration practices have a mean tested infiltration rate between 0.4 and 10 inches per hour (Philadelphia Water Department 2020). For slower infiltration rates, a bioretention design is recommended (see Figure 2). Other situations may also prohibit infiltration-focused designs, such as situations where karst geology is present and sinkholes may form, or where the water table is too high.

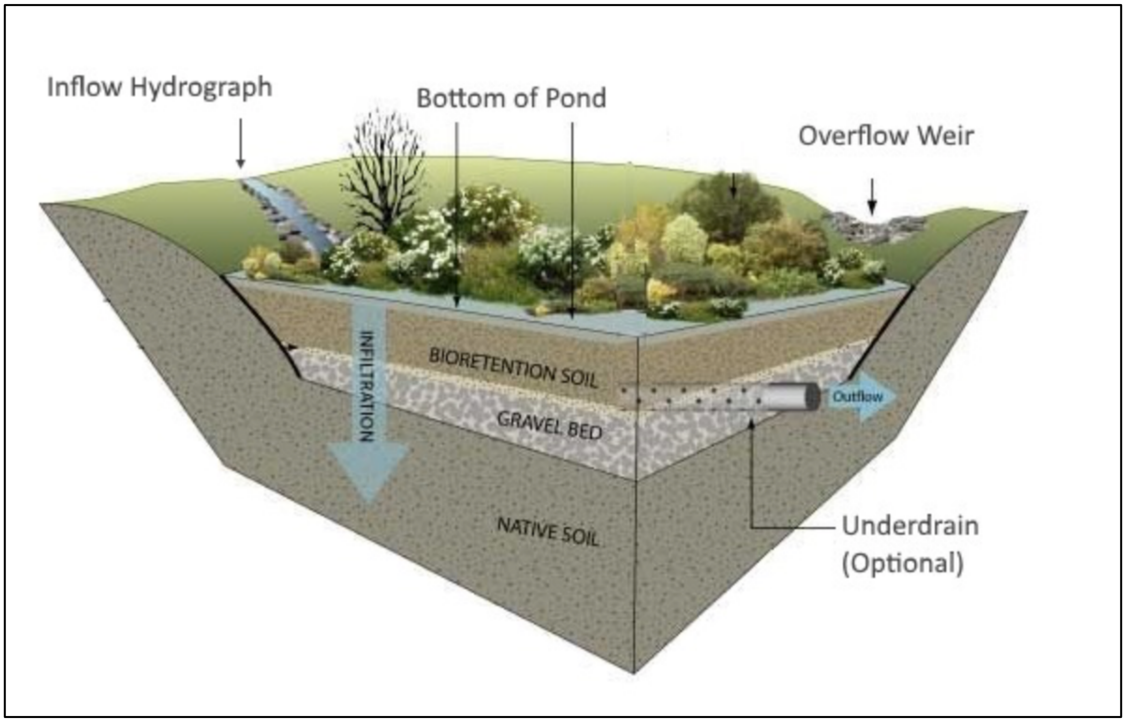


**Figure 2. Bioretention Rain Garden (“Bioretention Pond Design” 2021)**

Beneath these design layers are the native soils and the groundwater table. These are dependent on the conditions and location of the site and cannot be altered. These are the most restrictive layers and are typically the limiting factor for the rain garden’s hydrological performance.

While rain garden design standards vary in different states and municipalities, most areas require the incorporation of an overflow pipe. Overflow structures are provided for large storm events, up to a 100-year, 24-hour storm, where flooding and excess runoff is a concern. Overflow pipes stick up out of the ponding area, as seen in Figure 1, and in the event of a large storm, drain excess runoff into an existing stormwater system, bypassing treatment via the rain garden soil media layers.

# Chapter 2

# Green Infrastructure Flexible Model

## Overview

The EPA has developed numerous models, tools, and technologies to help communities manage water runoff in a more sustainable way, increasing resilience to future changes (US EPA 2014). One of their newest, most versatile programs is the Green Infrastructure Flexible Model (GIFMod). GIFMod is a computer program that can be used to evaluate the hydrological and water quality performance of stormwater green infrastructure. The process-based mathematical modeling program allows users to examine the effects of various different design guidelines on green infrastructure performance. This provides a cost-effective way to analyze the hydraulic and water quality performance tailored to specific sites and geographies (Massoudieh et al. 2017).

## Model Components

In GIFMod, hydrological and hydraulic elements are represented as "blocks" and "connectors". The program contains seven types of blocks used for representing different media: pond, plant block, soil, Darcy block, storage, catchment, and stream. The connectors are used as conduit elements, conveying flow through open channels or pressurized pipes (Kaykhosravi et al. 2018). Blocks are imported from the upper toolbar into the Model Space, as seen in the Graphical User Interface (GUI) in Figure 3, where connectors can be attached, and the block properties can be adjusted.

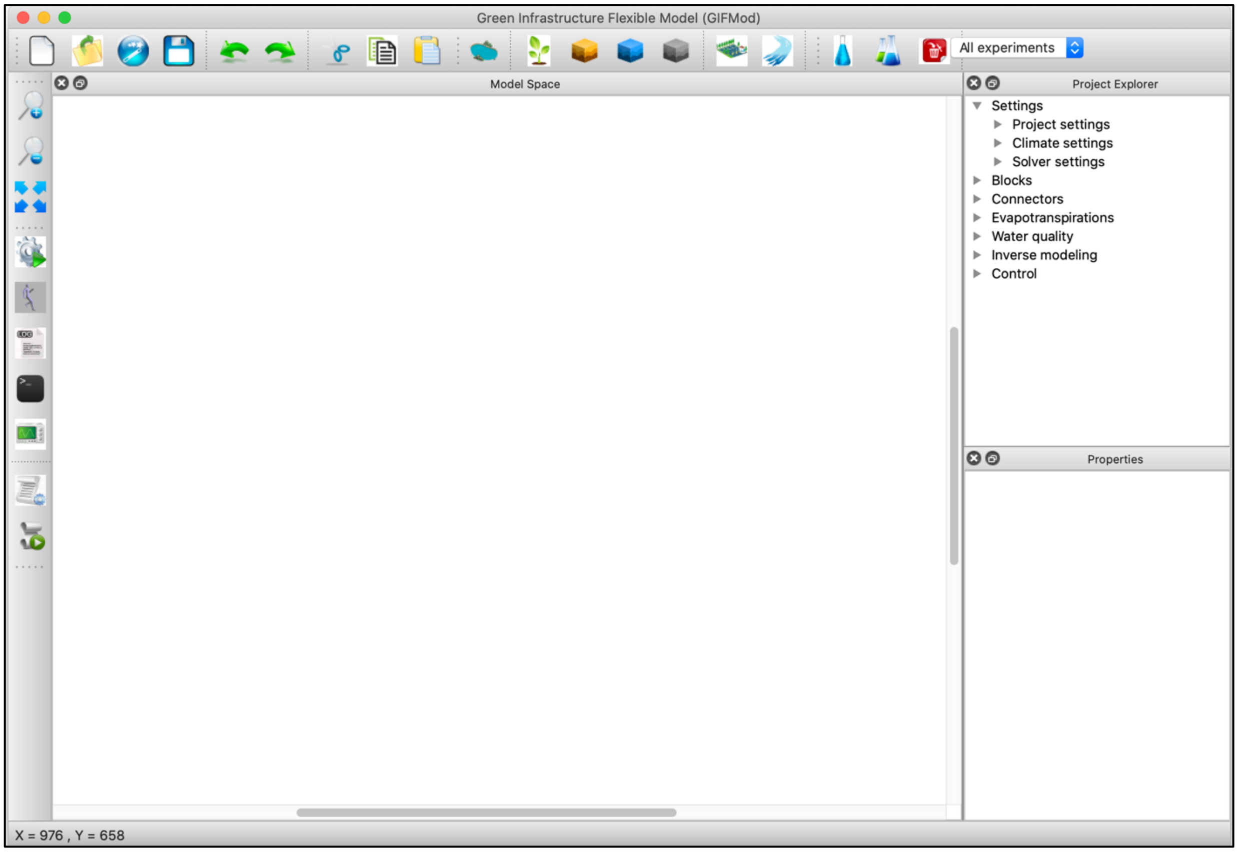


**Figure 3. GIFMod Graphical User Interface**

To construct a simple rain garden model in GIFMod, three primary block types are needed. A pond block is imported first, representing the uppermost ponding area. Soil blocks are used to represent both the substrate and native soil layers. A Darcy block is used to portray the groundwater table. A storage block can also be incorporated for more complex models. The storage block can be used within the native soil to represent a bedrock layer. Additionally, in the bioretention design, a storage block is used to depict the gravel storage layer to which an underdrain connects.

GIFMod allows the user flexibility in setting up the model configuration. Each block has user-defined properties that can be inputted into the model, allowing the program to accurately model specific soil conditions. Table 1 lists the block input properties required to model a rain garden, and the available units associated with each property.

**Table 1. GIFMod Rain Garden Input Properties**

| Block Type | Required Input Properties | Units Available | | | |
|---|---|---|---|---|---|
| Pond | Bottom Area | $m^2$ | $cm^2$ | $ft^2$ | |
| | Bottom Elevation | m | cm | ft | in |
| Soil | Subtype | unitless | | | |
| | Bottom Area | $m^2$ | $cm^2$ | $ft^2$ | |
| | Bottom Elevation | m | cm | ft | in |
| | Depth | m | cm | ft | in |
| Darcy | Bottom Area | $m^2$ | $cm^2$ | $ft^2$ | |
| | Bottom Elevation | m | cm | ft | in |
| | Head-Storage Relationship | unitless | | | |
| | Initial Moisture Content | unitless | | | |
| | Depth | m | cm | ft | in |
| | Saturated Moisture Content | unitless | | | |
| Storage | Bottom Area | $m^2$ | $cm^2$ | $ft^2$ | |
| | Bottom Elevation | m | cm | ft | in |
| | Depth | m | cm | ft | in |
| | Saturated Hydraulic Conductivity ($k_S$) | m/day<br>ft/day | cm/day<br>in/day | cm/s<br>in/s | mm/s |
| | Saturated Moisture Content ($\theta_S$) | unitless | | | |

GIFMod provides further flexibility within the soil block subtype property. In soil blocks specifically, the subtype determines the soil type, from which the program assigns default soil parameters; these parameters can be manually altered by the user (Massoudieh and Aflaki 2017). Alternatively, the 'user defined' subtype can be selected, in which no default parameters are assigned, and all soil properties must be manually input. The default values for the soil hydraulic properties are based on (Carsel and Parrish 1988) and are listed in Table 2 for each available soil type.

**Table 2. GIFMod Default Soil Parameters**

| **Soil Type** | **Residual Moisture Content ($\theta_R$)** | **Saturated Hydraulic Conductivity ($k_S$)** | **Saturated Moisture Content ($\theta_S$)** | **Van-Genuchten Parameters** | | |
|---|---|---|---|---|---|---|
| | | | | $\alpha$ | $\lambda$ | $n$ |
| Sand | 0.045 | 7.128 m/day | 0.43 | 14.5 1/m | 0.5 | 2.68 |
| Loam | 0.078 | 0.2496 m/day | 0.43 | 3.6 1/m | 0.5 | 1.56 |
| Silt | 0.034 | 0.06 m/day | 0.46 | 1.6 1/m | 0.5 | 1.37 |
| Silt Loam | 0.067 | 0.108 m/day | 0.45 | 2 1/m | 0.5 | 1.41 |
| Sandy Clay Loam | 0.1 | 0.3144 m/day | 0.39 | 5.9 1/m | 0.5 | 1.48 |
| Clay Loam | 0.095 | 0.0624 m/day | 0.41 | 1.9 1/m | 0.5 | 1.31 |
| Silty Clay Loam | 0.089 | 0.0168 m/day | 0.43 | 1 1/m | 0.5 | 1.23 |
| Sandy Clay | 0.1 | 0.0288 m/day | 0.38 | 2.7 1/m | 0.5 | 1.23 |
| Silty Clay | 0.07 | 0.0048 m/day | 0.36 | 0.5 1/m | 0.5 | 1.09 |
| Clay | 0.068 | 0.048 m/day | 0.38 | 0.8 1/m | 0.5 | 1.09 |
| Loamy Sand | 0.057 | 3.5016 m/day | 0.41 | 12.4 1/m | 0.5 | 2.28 |
| Sandy Loam | 0.065 | 1.0608 m/day | 0.41 | 7.5 1/m | 0.5 | 1.89 |

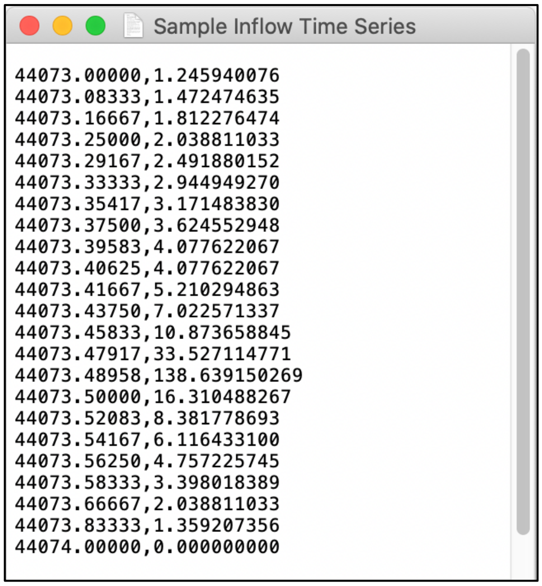
When using GIFMod to model rain gardens, connectors are used to represent stormwater flow. To model the infiltration through each soil layer, connectors are placed in between each layer, connecting all of the blocks. In modeling infiltration, there are two primary connector properties that need to be input: direction and length. The direction of each connector indicates the flow direction. For rain gardens, the connectors should be directed downwards, from the above block to the below block. The length represents the distance between the centroids of the blocks being connected and is used to calculate hydraulic gradients in flow relationships (Massoudieh and Aflaki 2017).

As discussed previously, the primary runoff reduction process in rain gardens is infiltration. GIFMod uses different relationships to simulate infiltration, depending on the type of blocks that are connected. When water is flowing to an unsaturated soil block, the Van Genuchten-Mualen (VGM) equations regulate flow rate. The Darcy equation controls flow to saturated soil blocks and storage blocks. Table 3 shows the default governing equations when two blocks of a certain type are connected.

**Table 3. Equations Governing Flow Between Blocks**

| **Bottom Layer** | **Top Layer** | | |
|---|---|---|---|
| | **Pond** | **Saturated Soil** | **Storage** |
| **Unsaturated Soil** | VGM | VGM | VGM |
| **Saturated Soil** | Darcy | Darcy | Darcy |
| **Storage** | Darcy | Darcy | Darcy |

Climate settings are can be incorporated into GIFMod using time series. Time series are external, comma separated value (.csv), text files that can be applied to all, or selected, blocks (Massoudieh and Aflaki 2017). When analyzing the hydrological performance of rain gardens in terms of infiltration capacity, the inflow rate of stormwater into the pond is introduced using an inflow time series. To quantify the water inflow rate, a two-column text file can be inputted into the program and attached to the pond block. The first column indicates the time the inflow begins, in units of days past 1/1/1900, while the second column indicates the inflow rate, in units of cubic meters per day. An example showing the format of the text file containing the inflow time series is shown in Figure 4. This file depicts a 2-inch, 24-hour storm beginning at midnight on 9/1/2020, over a 1000-square foot drainage area.



```
44073.00000,1.245940076
44073.08333,1.472474635
44073.16667,1.812276474
44073.25000,2.038811033
44073.29167,2.491880152
44073.33333,2.944949270
44073.35417,3.171483830
44073.37500,3.624552948
44073.39583,4.077622067
44073.40625,4.077622067
44073.41667,5.210294863
44073.43750,7.022571337
44073.45833,10.873658845
44073.47917,33.527114771
44073.48958,138.639150269
44073.50000,16.310488267
44073.52083,8.381778693
44073.54167,6.116433100
44073.56250,4.757225745
44073.58333,3.398018389
44073.66667,2.038811033
44073.83333,1.359207356
44074.00000,0.000000000
```

**Figure 4. Sample Inflow Time Series**

Additional time series can also be incorporated into the model to simulate evapotranspiration. GIFMod provides five alternative evaporation and transpiration models: Priestly-Taylor, Aerodynamic, Penman, transpiration based on soil moisture content, and transpiration based on soil matric potential. These models require additional climate information that can be provided as time series, including light, humidity, temperature, and wind.

In GIFMod, hydraulic simulations are modeled over a set period of time, as defined by the user. Before the model can be run, the simulation start and end times must be specified in the project settings. The time units within this setting are the same as for the time series, in days past 1/1/1900. If these numbers are not entered by the user, default values of zero (equivalent to 1/1/1900) and one (equivalent to 1/2/1900) will be assigned for the start and end time, respectively. The simulation start and end times must coincide with the times in the time series files for the model to run properly.

# Chapter 3

## Sensitivity Analysis of Basic Rain Garden Design Factors

To analyze the hydrological performance of residential rain gardens, preliminary simulations were conducted first to determine which variables have the largest influence on the rain gardens' infiltration capacity. Six variables were tested: inflow time series, substrate soil texture, substrate soil depth, native soil texture, native soil depth, and surface area. The objectives of these preliminary simulations were to determine which variables have the largest influence on the rain gardens hydrological performance and to identify any relationships between variables.

### Stormwater Management Requirements

The Pennsylvania Stormwater Best Management Practices (BMP) manual was published on December 30, 2006 to provide guidance, options, and tools for effective stormwater management. The manual provides design standards and planning concepts, intended to mitigate stormwater problems. It is important to note that this manual has no independent regulatory authority, and residential stormwater management methods must abide to the ordinances and rules established by their local municipalities (DEP 2006).

Chapter 6.4.5 of the BMP manual provides detailed rain garden design considerations, from which the rain gardens modeled in these simulations were based off. The rain gardens' hydrological performance was evaluated based on the manual's requirement that the surface ponding depth should not exceed 6-inches and should empty within 72-hours (DEP 2006). These recommendations were developed to minimize hazards associated with standing water. Ponding depths in excess of 6-inches could cause safely concerns, particularly in areas with children. Long durations of stagnant water was found to cause health issues, as it allows for mosquitos to breed and algae to grow, among other concerns. Additionally, excess water is detrimental to vegetation and will prohibit plant life. The manual also states that underdrains should not be used except where in-situ soils fail to effectively drain surface water. Based on this recommendation, the rain gardens in this chapter were modeled without the incorporation of a storage layer and underdrain. Lastly, it is stated that the impervious drainage area to infiltration area should not exceed a maximum loading ratio of 5:1, from which the rain garden surface area and catchment area were based off of.

## Statistical Indicators

The influence of each variable and the relationships between variables were evaluated based on statistical indicators. The relative standard deviation (RSD), also known as the coefficient of variation (CV), was used to indicate the variability of hydrologic parameters (maximum ponding depth and ponding time) as related to each input variable manipulated (substrate soil texture, substrate soil depth, native soil texture, and native soil depth). Relative standard deviation measures precision in data analysis. It is derived from the standard deviation (SD), which measures the variance of each value from the mean. The standard deviation was calculated based on Equation 1.

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad (1)$$

The relative standard deviation is a more versatile form of the standard deviation. It expresses the variance from the mean as a percent, allowing variation in different data sets to be compared. The relative standard deviations in both the maximum ponding depth and ponding time as related to each input variable were calculated based on Equation 2 and used to indicate the sensitivity of the hydrologic parameters to each variable. In this analysis, high RSDs indicate that the rain garden's hydrological performance is strongly influenced by the variable measured, while lower RSDs suggest that the influence is minimal.

$$RSD = \frac{100S}{\bar{x}} \tag{2}$$

The relationships between variables and hydrologic parameters were also analyzed. The significance of each relationship was measured based on the coefficient of determination ($R^2$). The coefficient of determination measures the proportion of the variance in the dependent variable that is predictable from the independent variable. These values range from 0 to 1, in which higher values indicate a stronger relationship between the two variables.

## Base Rain Garden Model

A base rain garden model was designed; this model was intended to represent a standard residential rain garden. The base rain garden model had four layers: a ponding area, a substrate soil layer, a native soil layer, and a groundwater layer. The representation of the base rain garden model in GIFMod is presented in Figure 5.

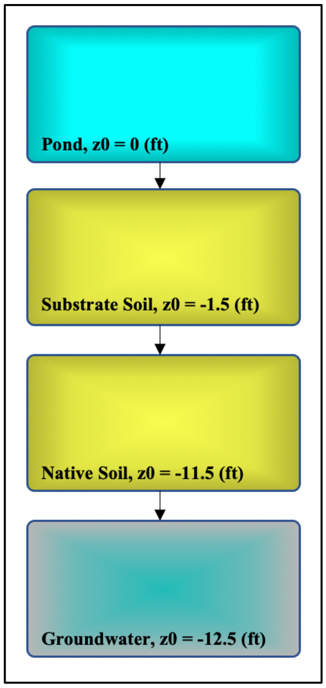


**Figure 5. GIFMod Base Rain Garden Model**

Existing design guidance indicates that common residential rain garden areas are between 100 and 300 $ft^2$, so a median area of 200 $ft^2$ was selected for the base model (Jennings et al. 2015). The substrate soil properties were selected based on the Pennsylvania Stormwater BMP guidelines. The BMP manual determines the substrate properties based on the plants utilized in the rain garden; they recommend this layer being a loam soil capable of supporting a healthy, vegetative cover, having a depth of at least 18-inches. In these simulations, the substrate soil was represented as a single layer, rather than the multiple sublayers discussed in Chapter 1. The planting medium is intended to promote vegetation; it is a thin, organic layer with minimal effect on infiltration. The influence of plants was not modeled in these simulations; therefore, the planting medium was not included. The storage layer is intended for the bioretention rain garden design, in which excess water is routed to an existing sewer system. The objective of these simulations was to analyze the sensitivity of infiltration on rain garden design factors; therefore, the storage layer was also not included. In the optimal bioinfiltration rain garden configuration, infiltration is dependent on the transition layer, which was modeled in these simulations.

The native soil layer and depth to the groundwater table is dependent on the soil conditions at the location the rain garden is built. A clay loam native soil texture with a 10-foot depth to the groundwater table was arbitrarily chosen. Additionally, it was assumed that the water table will not be affected by the recharge from the rain garden and will remain constant. This was done by setting head-storage relationship for the groundwater block to a fixed head representing the groundwater table (Massoudieh and Aflaki 2017). The base rain garden model property values input into GIFMod are listed in Table 4.

### Table 4. Base Rain Garden Model Properties

| Block Type | Block Name | Input Property | Input Value |
|---|---|---|---|
| Pond | Pond | Bottom Area | 200 $ft^2$ |
| | | Bottom Elevation | 0 ft |
| Connector | Pond – Substrate Soil | Length | 9 in |
| Soil | Substrate Soil | Subtype | Loam |
| | | Bottom Area | 200 $ft^2$ |
| | | Bottom Elevation | -1.5 ft |
| | | Depth | 1.5 ft |
| Connector | Substrate Soil – Native Soil | Length | 69 in |
| Soil | Native Soil | Subtype | Clay Loam |
| | | Bottom Area | 200 $ft^2$ |
| | | Bottom Elevation | -11.5 ft |
| | | Depth | 10 ft |
| Connector | Native Soil - Groundwater | Length | 5 ft |
| Darcy | Groundwater | Bottom Area | 200 $ft^2$ |
| | | Bottom Elevation | -12.5 ft |
| | | Head-Storage Relationship | -11.5 |
| | | Initial Moisture Content | 0.35 |
| | | Depth | 1 ft |
| | | Saturated Moisture Content | 0.35 |

The preliminary simulations were conducted without incorporating evapotranspiration into the model. Evapotranspiration rates are highly variable from day to day; these simulations were intended to analyze how different variables influenced a rain garden's runoff reduction capacity, solely through infiltration.

## Varying Inflow Time Series

The first variation tested was varying the inflow time series. As explained in Chapter 2, inflow time series are external text files that indicate the different inflow rates into the pond over time. In these simulations, two parameters were used in creating the inflow time series: storm depth and catchment area. The catchment, service, or drainage area is referring to both the rain garden area ($A_g$) and the impervious surface area ($A_r$). The incremental precipitation was determined based on the Soil Conservation Service (SCS) Type II Storm Distribution and the precipitation depth ($P$). The incremental precipitation was then multiplied by the drainage area to determine the inflow rates into the pond during 24-hour storm events. The inflow volume ($Q$) was calculated based on Equation 3.

$$Q = \left(A_g + A_r\right) * P \tag{3}$$

Five different inflow time series variations were tested. The parameters used in creating these inflow time series are outlined in Table 5.

**Table 5. Inflow Time Series Variations**

| Storm Depth | Catchment Area | Inflow Volume |
|---|---|---|
| 2.73-inches | 1,000 ft$^2$ | 227.5 ft$^3$ |
| | 10,000 ft$^2$ | 2275 ft$^3$ |
| 3.37-inches | 1,000 ft$^2$ | 280.83 ft$^3$ |
| | 10,000 ft$^2$ | 2808.33 ft$^3$ |
| 2.40-inches | 1,000 ft$^2$ | 200 ft$^3$ |

The inflow time series were input into the model by attaching the external text file to the pond block, through the block ‘inflow time series’ property. These time series outlined the varying inflow rates throughout the 24-hour storm event. The inflow volumes, calculated based on Equation 3, were not used as a model input. The inflow volumes were only calculated to quantify the total volume of runoff accumulated from the precipitation timeseries over the contributing area during the 24-hour storm events, for analysis purposes.

It was found that the maximum ponding depth is linearly related to the inflow water volume. The inflow water volume ($ft^3$) was plotted on the x-axis, the maximum ponding depth (in) was plotted on the y-axis, and a linear trendline was added. The linear relationship between maximum ponding depth and inflow water volume for the base model is depicted in Figure 6. The coefficient of determination of this linear trendline from the five inflow volumes tested is 0.9997, indicating a very strong linear fit.

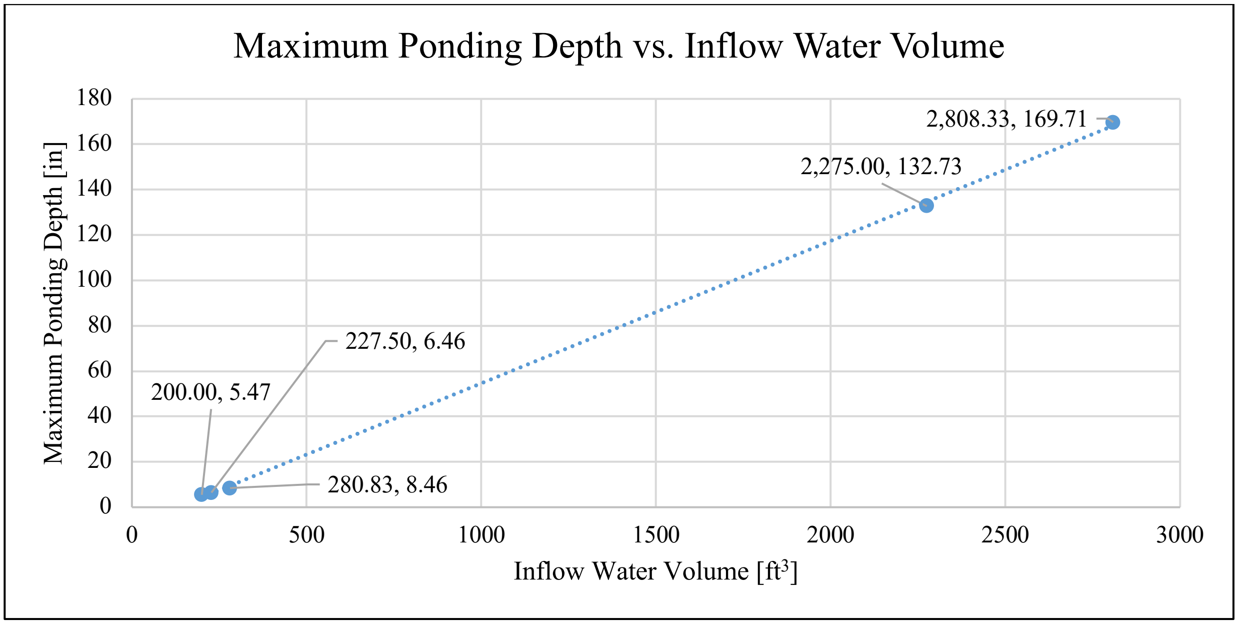


**Figure 6. Linear Relationship Between Inflow Water Volume and Maximum Ponding Depth**

It is important to note, however, that GIFMod does not require the depth of the ponding layer to be specified. In these simulations, it was assumed that the ponding area was infinitely deep. In reality, the pond would be designed for a specific water depth, and when that depth is exceeded, the basin would overflow. Therefore, the two maximum ponding depths on the higher end of Figure 6 are unrealistic, as a residential rain garden would overflow from depths of this size, and were only included for hypothetical analysis.

A linear relationship was found between the duration of water in the pond and the inflow water volume as well. As the inflow water volume increases, the time for the pond to empty increases. Two different catchment areas were used in creating the inflow time series used in these simulations: 1,000 $ft^2$ and 10,000 $ft^2$. In the simulations run with the 1,000 $ft^2$ service area, all of the ponds emptied within the 9-day time frame of the simulation. However, in the simulations run with the 10,000 $ft^2$ service area, water was still in the pond at the end of the 9-days. As a result, those inflow water volumes will not be included in this analysis. The 10,000 $ft^2$ service areas modeled 49:1 loading ratios and generated ponding depths in excess of 11 feet. These inflow rates are drastically larger than those a residential rain garden would be designed to accommodate, therefore do not represent a realistic storm event. The linear relationship between the duration water is in the pond and inflow water volume is depicted in Figure 7. The coefficient of determination of this linear trendline from the three inflow volumes used is 0.9979, again indicating a strong linear fit.

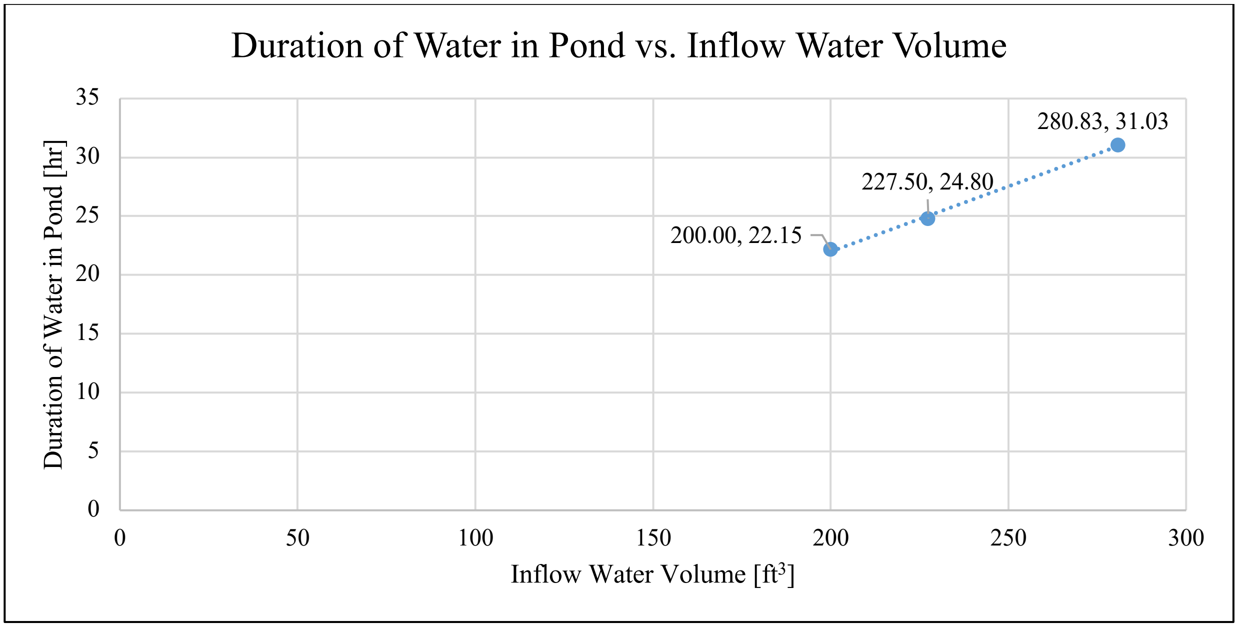


**Figure 7. Linear Relationship Between Inflow Water Volume and Duration of Water in Pond**

It is apparent that the 6-inch maximum ponding depth requirement is more restrictive than the requirement that the pond must empty within 72-hours. As can been seen through comparing Figure 6 and Figure 7, the ponding depth exceeds 6-inches long before the duration of water in the pond exceeds 72-hours. Of the inflows tested, the maximum ponding depth exceeds 6-inches with an inflow water volume of 227.50 ft$^3$, yet the pond empties within less than 25-hours. This draws the conclusion that the maximum ponding depth is the limiting factor in rain garden design.

## Varying Substrate Soil Layer

To measure the influence of the substrate soil layer on rain gardens' hydrological performance, experiments were conducted in GIFMod varying both the substrate soil texture and depth. Four different soil textures were tested, each subject to two different inflow water volumes. Four different soil depths were analyzed as well, each of which was subject to two different inflow volumes. The substrate soil layer variations are outlined in Table 6.

**Table 6. Substrate Soil Layer Variations**

| Varying Substrate Texture | | Varying Substrate Depth | |
|---|---|---|---|
| **Soil Textures** | **Inflow Water Volumes** | **Soil Depths** | **Inflow Water Volumes** |
| Loam<br>Clay<br>Sand<br>Silt | 227.50 $ft^3$<br>280.83 $ft^3$ | 1.5 ft<br>3.0 ft<br>4.5 ft<br>6.0 ft | 227.50 $ft^3$<br>280.83 $ft^3$ |

The maximum ponding depths and times for the ponds to empty found for the substrate soil variations outlined in Table 6 are presented in Appendix B. The relative standard deviations in maximum ponding depth and ponding time due to varying the substrate soil texture and depth were calculated for both inflow water volumes. The average RSD for each input variable and parameter was then calculated between the two inflow water volumes to indicate the variability of the hydrologic parameters related to each input variable manipulated.

The maximum ponding depth is strongly influenced by the substrate soil texture; for both inflow water volumes tested, the maximum ponding depth varied significantly in different substrate textures. The average relative standard deviation for both inflow water volumes was over 50%, indicating large deviations between each soil texture.

To determine which soil texture most effectively reduces ponding depth, the percent change in maximum ponding depth for each soil texture was calculated from the base model substrate soil texture: loam. It was found that sand is the most effective substrate soil texture in terms of ponding depth; on average, the maximum depth of water in the pond is reduced by over 65% when a sand substrate texture is used instead of loam. On the contrary, clay and silt were determined to be the least effective substrate textures; their hydrological performance is comparable and increases the maximum ponding depth by over 45% from the loam base model. The influence of the substrate soil texture on the maximum depth of water in the pond is outlined in Table 7.

**Table 7. Influence of Substrate Soil Texture on Maximum Ponding Depth**

| **Soil Texture** | **Percent Change in Maximum Ponding Depth** | | |
|---|---|---|---|
| | **Inflow Water Volume** | | |
| | **227.50 ft$^3$** | **280.83 ft$^3$** | **Average** |
| Clay | 45.35 % | 46.24 % | 45.80 % |
| Sand | - 40.09 % | - 92.41 % | - 66.25 % |
| Silt | 46.55 % | 46.36 % | 46.45 % |
| ***RSD*** | 36.72 % | 65.36 % | 51.04 % |

The time for the pond to empty is also highly dependent on the substrate soil texture. The average relative standard deviation for both inflow water volumes was almost 65%, again indicating large deviations between each soil texture. The percent change from the loam base model was once again used to analyze which soil texture is most effective. Similar to with the maximum ponding depth, sand performed the best, reducing the duration of water in the pond by over 25% on average. Clay and silt again had comparable results and increased the time for the pond to empty by over 195%. The influence of the substrate soil texture on the time for the pond to empty is outlined in Table 8.

**Table 8. Influence of Substrate Soil Texture on Time for Pond to Empty**

| **Soil Texture** | **Percent Change in Time for Pond to Empty** | | |
|---|---|---|---|
| | **Inflow Water Volume** | | |
| | **227.50 ft$^3$** | **280.83 ft$^3$** | **Average** |
| Clay | 220.63 % | 207.25 % | 213.94 % |
| Sand | - 18.41 % | - 34.05 % | - 26.23 % |
| Silt | 198.39 % | 191.78 % | 195.09 % |
| ***RSD*** | 63.36 % | 65.86 % | 64.61 % |

Choosing an effective substrate soil texture is crucial to maximizing the inflow water volume a rain garden can accommodate, without exceeding the maximum ponding depth and ponding time thresholds recommended by the BMP manual. As seen in Appendix B, sand was the only substrate soil texture in which the ponding depth did not exceed 6-inches and ponding time did not exceed 72-hours, for both inflow volumes analyzed. The loam soil emptied within the 72-hour threshold, however, its ponding depth surpassed 6-inches, while the clay and silt soils exceeded both recommendations, for both inflow volumes. To optimize a rain garden's hydrological capabilities, a sand substrate texture should be utilized.

The substrate soil depth was found to have minimal influence on both the maximum ponding depth and the time for the pond to empty; the average relative standard deviations were calculated to be 3.25% and 5.23%, respectively. As seen in Appendix B, with all four substrate soil depths analyzed, the maximum ponding depth exceeded 6-inches; however, the ponding time remained less than 72-hours. For most soil compositions, the maximum ponding depth will likely exceed 6-inches before the ponding time exceeds 72-hours, further emphasizing the ponding depth as the stricter recommendation to adhere to.

There was no clear correlation between substrate soil depth and maximum ponding depth or the time for the pond to empty. This is likely due to the fact that loam was used as the substrate soil texture in these simulations. It was found that sand is the most effective substrate soil texture in minimizing the maximum depth of water in the pond and the duration of water in the pond. It is expected that if sand were to be used as the substrate soil texture, the maximum ponding depth and ponding time would both decrease as the substrate soil depth increases, due to sand's high hydraulic conductivity (see Table 2).

## Varying Native Soil Layer

The native soil layer is the most variable rain garden property, given that it changes with each site location. To determine which native conditions rain gardens are most effective in, six different native soil textures and five depths were tested, each of which was subject to two different inflow water volumes. The native soil variations are outlined in Table 9.

**Table 9. Native Soil Layer Variations**

| Native Soil Texture | Native Soil Depth | Storm Depth | Catchment Area | Inflow Water Volume |
|---|---|---|---|---|
| Clay Loam<br>Loam<br>Sand<br>Clay<br>Silt<br>Silt Loam | 5 ft<br>10 ft<br>15 ft<br>20 ft | 2.73-inches | 1,000 ft$^2$ | 227.5 ft$^3$ |
| | | | 10,000 ft$^2$ | 2275 ft$^3$ |

The maximum ponding depths and ponding times found for the native soil variations outlined in Table 9 are presented in Appendix C. It was found that the native soil layer has a moderate influence on the rain garden's hydrological performance. In regard to the maximum ponding depth, the simulations varying the native soil texture had a relative standard deviation of 6.33%, compared to the simulations varying the native soil depth, which had a relative standard deviation of 1.01%. This indicates that surface ponding is more influenced by the native soil texture than by the depth to the water table. The percent change in maximum ponding depth for each native soil texture and depth analyzed was calculated from the base model native soil layer: clay loam with a 10-foot depth. The influence of the native soil layer on the maximum ponding depth is presented in Table 10.

**Table 10. Influence of Native Soil Layer on Maximum Ponding Depth**

| **Native Soil Texture** | **Percent Change in Maximum Ponding Depth** | | |
|---|---|---|---|
| | **Inflow Water Volume** | | |
| | **227.5 ft$^3$** | **2275 ft$^3$** | **Average** |
| Loam | 0.20 % | - 12.78 % | - 6.29 % |
| Sand | - 9.41 % | - 19.48 % | - 14.45 % |
| Clay | - 2.54 % | 1.03 % | - 0.75 % |
| Silt | 0.57 % | - 1.32 % | - 0.37 % |
| Silt Loam | - 0.30 % | - 4.62 % | - 2.46 % |
| ***RSD*** | 3.91 % | 8.75 % | 6.33 % |
| **Native Soil Depth** | | | |
| 5 ft | 1.05 % | 2.48 % | 1.76 % |
| 15 ft | 0.05 % | - 0.60 % | - 0.27 % |
| 20 ft | 0.29 % | - 0.91 % | - 0.31 % |
| ***RSD*** | 0.48 % | 1.54 % | 1.01 % |

As seen in Appendix C, sand was the only native soil texture in which the maximum ponding depth did not exceed 6-inches for the 1,000 ft$^2$ catchment area (227.5 ft$^3$ inflow water volume). The maximum ponding depth surpassed 6-inches for all of the soil textures analyzed with the 10,000 ft$^2$ catchment area (2275 ft$^3$ inflow water volume); however, as discussed previously, this loading ratio is far larger than that a residential rain garden would be designed to accommodate. Overall, the more permeable the native soil texture, the larger inflow volume the rain garden can accommodate.

For all four native soil depths tested, the maximum ponding depths exceeded 6-inches slightly for the 1,000 ft$^2$ drainage area, ranging from 6.46-inches to 6.52-inches. This is likely due to the fact that clay loam was modeled as the native soil texture in these simulations, which has a very low hydraulic conductivity. It would be expected that if a more permeable native soil was used, the maximum ponding depths for the 1,000 ft$^2$ catchment area would meet the 6-inch threshold recommendation.

Limited data was available for analyzing the effect of the native soil layer on the ponding time. The pond emptied within the duration of the simulations for all of the models tested having a 1,000 $ft^2$ service area, however, it did not empty in 7 out of the 10 simulations run having a 10,000 $ft^2$ service area. Furthermore, the pond did not empty in the base model simulation when subject to a 2275 $ft^3$ inflow water volume, so the percent change could not be calculated for this inflow volume. The available data regarding the influence of the native soil layer on the time for the pond to empty is summarized in Table 11.

**Table 11. Influence of Native Soil Layer on Time for Pond to Empty**

| **Native Soil Texture** | **Percent Change in Time for Pond to Empty** | | |
|---|---|---|---|
| | **Inflow Water Volume** | | |
| | **227.5 $ft^3$** | **2275 $ft^3$** | **Average** |
| Loam | - 11.19 % | - | - 11.19 % |
| Sand | - 26.10 % | - | - 26.10 % |
| Clay | - 10.22 % | - | - 10.22 % |
| Silt | - 2.21 % | - | - 2.21 % |
| Silt Loam | - 7.18 % | - | - 7.18 % |
| ***RSD*** | 10.22 % | 41.83 % | 26.02 % |
| **Native Soil Depth** | | | |
| 5 ft | 18.35 % | - | 18.35 % |
| 15 ft | - 2.96 % | - | - 2.96 % |
| 20 ft | - 3.90 % | - | - 3.90 % |
| ***RSD*** | 10.16 % | - | 10.16 % |

As seen in Table 10 and Table 11, the native soil layer has a greater influence on the ponding time than the ponding depth. The relative standard deviations in the time for the pond to empty are more than triple those for the maximum ponding depth. Additionally, the effects of the native soil layer on the rain gardens hydrological performance are greater for larger inflow volumes.

It is apparent that rain gardens perform best with native soils having high saturated hydraulic conductivities. The native soil textures that most effectively reduced both the maximum ponding depth and the duration of water in the pond were sand and loam, which also have the highest hydraulic conductivities (see Table 2). On the contrary, the rain gardens that exhibited the highest ponding depths and took the longest to empty were those with clay, silt, and clay loam native soil textures, which have the lowest saturated hydraulic conductivities of the six textures tested.

In terms of the native soil depth, rain gardens with longer depths to the groundwater table generally perform better. However, this could be due to the substrate and native soil textures selected for the base model. If the groundwater table was overlaid by a less permeable soil texture, it would be expected that the native soil layer would hinder infiltration.

## Varying Rain Garden Surface Area

The final variation tested was varying the surface area of the rain garden. As mentioned previously, residential rain gardens are typically between 100 ft$^2$ and 300 ft$^2$. Three different surface areas were tested, each exposed to two differently sized storm events. The surface area variations are presented in Table 12.

**Table 12. Surface Area Variations**

| Surface Area | Catchment Area | Storm Depth | Inflow Water Volume |
|---|---|---|---|
| 100 ft$^2$<br>200 ft$^2$<br>300 ft$^3$ | 1,000 ft$^2$ | 2.73-inches | 227.5 ft$^3$ |
| | | 3.37-inches | 280.83 ft$^3$ |

As expected, for a given inflow water volume, the maximum ponding depth decreases as the surface area increases. However, it was found that the maximum ponding depth decreases at an increasing rate (i.e., the function is concave-up). The relationship between the maximum ponding depth and the rain garden surface area is depicted in Figure 8. This relationship indicates that the effect of the surface area on the maximum ponding depth decreases as the surface area increases.

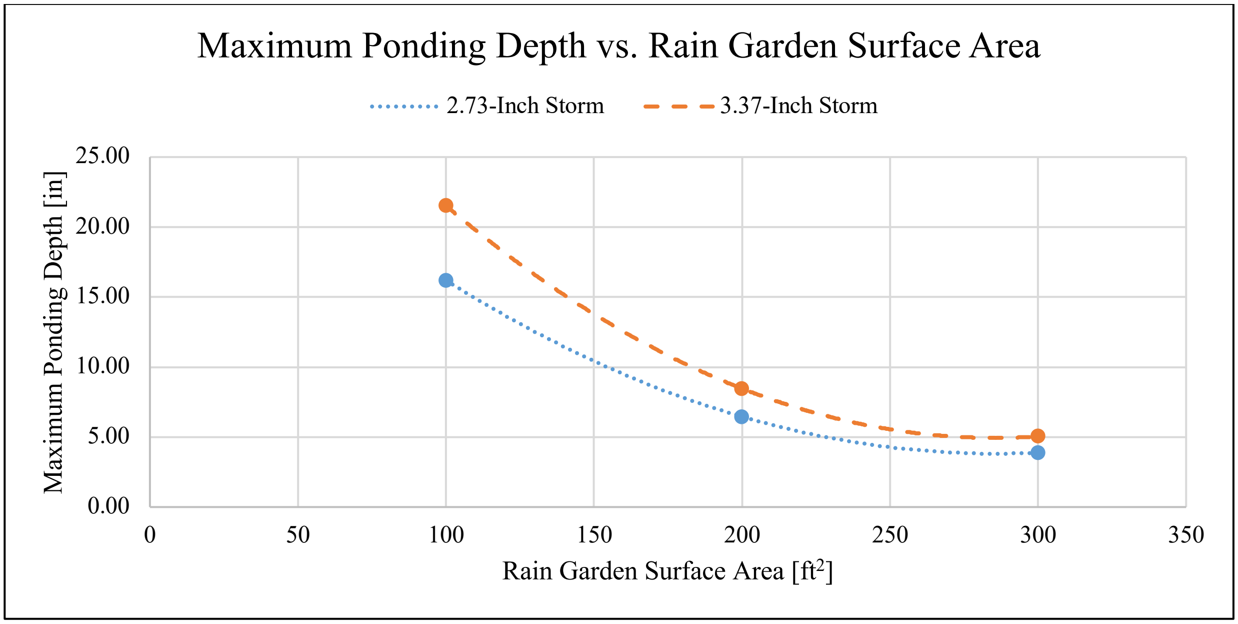


**Figure 8. Relationship Between Rain Garden Surface Area and Maximum Ponding Depth**

It can be seen in Figure 8 that as the surface area increases, the influence of the inflow water volume on the maximum ponding depth decreases. Assuming there is a linear relationship between the inflow water volume and the maximum ponding depth (as found when varying the inflow time series), the maximum inflow water volume can be calculated for a given maximum ponding depth and compared among varying surface areas. The linear relationship between the inflow water volume and the maximum ponding depth for each surface area was first plotted, as shown in Figure 9. It is important to note, however, that the functions illustrated in Figure 9 were each created with only two points. These relationships were developed based on the assumption that the maximum ponding depth is linearly related to the inflow water volume, as discussed previously in the chapter. The limited data available for each surface area could potentially have caused inaccuracy in these results. If the linear relationship found between the maximum ponding depth and inflow water volume does not hold true, the functions shown in Figure 9 would be incorrect. Assuming the maximum ponding depth is linearly dependent on the inflow water volume, the relationships in Figure 9 are likely marginally inaccurate, and could vary slightly if more data was incorporated.

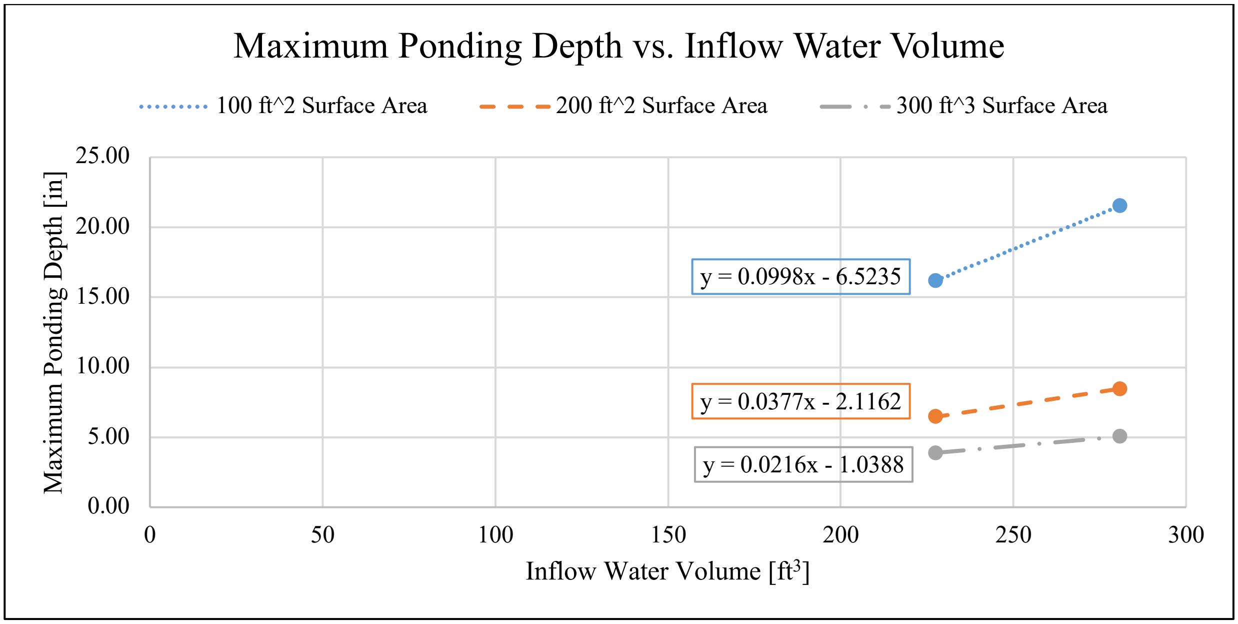


**Figure 9. Relationship Between Inflow Water Volume and Maximum Ponding Depth Among Varying Surface Areas**

It can be seen that the slope of this relationship decreases as the surface area increases, further illustrating that the influence of the inflow water volume on the maximum ponding depth decreases as the surface area increases. The relationships plotted above can then be used to calculate the inflow water volume corresponding to a given maximum ponding depth for each surface area. Based on the Pennsylvania Stormwater BMP manual, a maximum ponding depth of

6-inches was used to determine the maximum inflow water volume each surface area can accommodate before surpassing this requirement. The maximum inflow water volumes were then plotted against their corresponding rain garden surface areas, as depicted in Figure 10. It was found that the maximum inflow water volume a rain garden can accommodate increases linearly as the rain garden surface area increases, for a given maximum ponding depth.

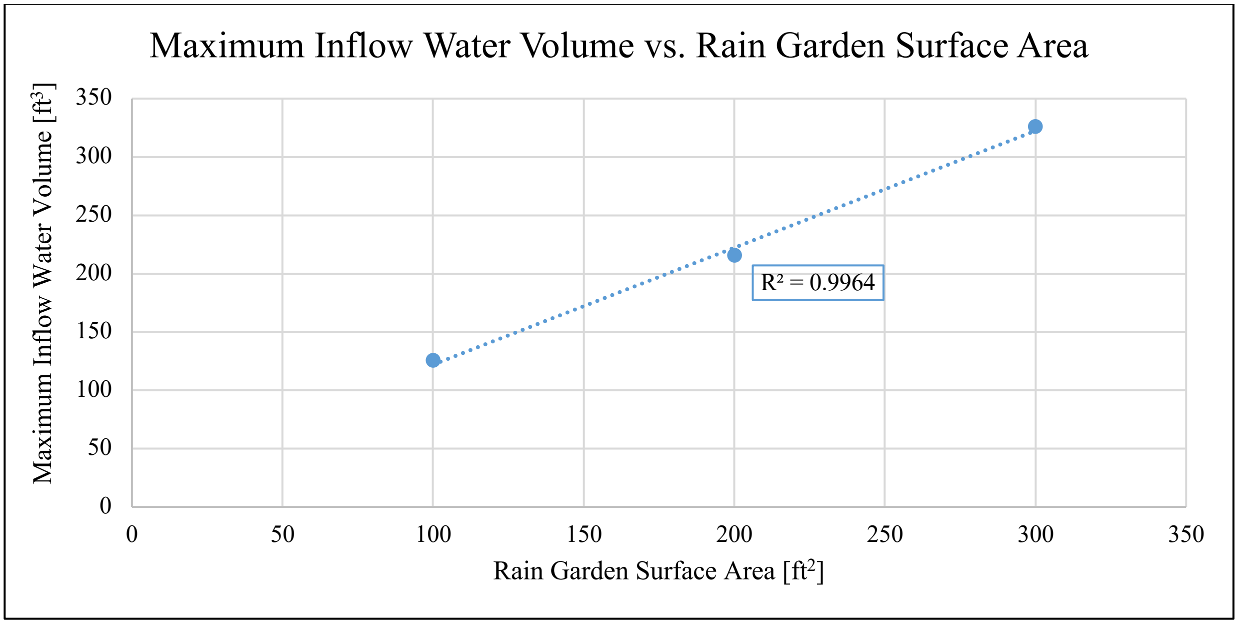


**Figure 10. Relationship Between Rain Garden Surface Area and Maximum Inflow Water Volume**

Similarly, it was found that the time for the pond to empty decreases as the surface area increases, also at an increasing rate. This relationship is illustrated in Figure 11. Once again, it can be seen that as the surface area increases, the influence of the inflow water volume on the duration of water in the pond decreases. However, even in the rain gardens simulated with small surface areas subject to large inflow water volumes, the pond emptied in less than 72-hours as required by the Pennsylvania BMP manual. The maximum ponding depth exceeds 6-inches far before the duration of water in the pond exceeds 72-hours. As a result, this relationship is less significant to the rain gardens hydrological performance, for the maximum ponding depth is the limiting design factor.

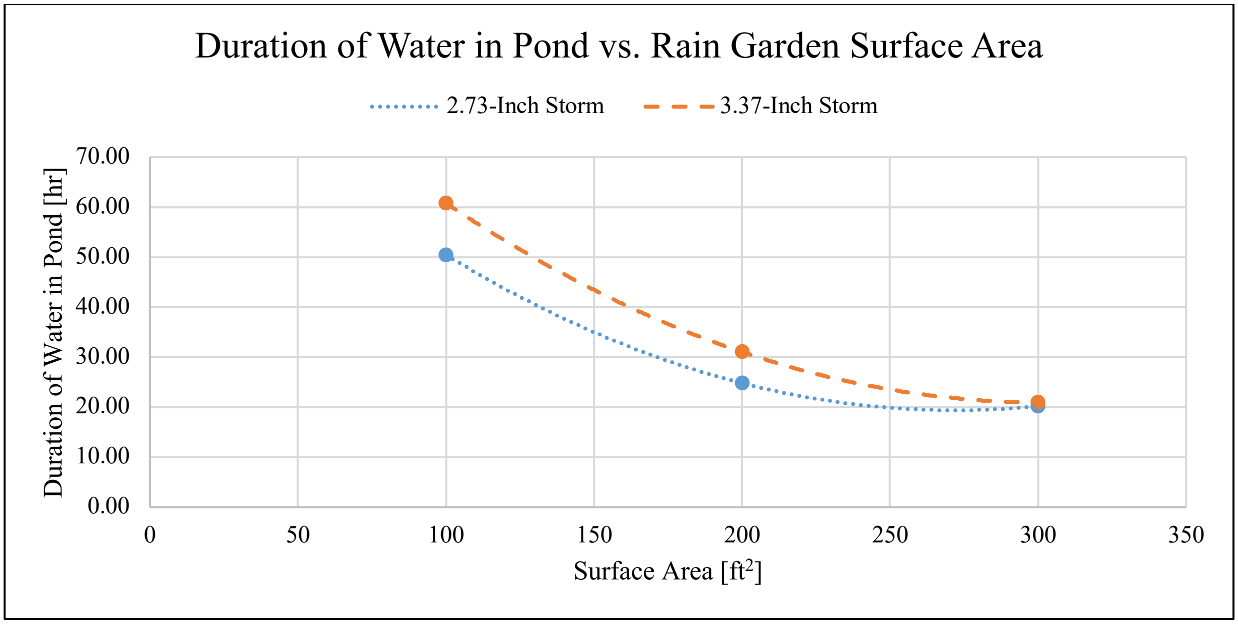


**Figure 11. Relationship Between Rain Garden Surface Area and Duration of Water in Pond**

## Conclusions

To determine the influence of each variable tested on the hydrological performance of the rain garden, the relative standard deviation of each variable was compared. Higher standard deviations indicate that the variation had a large influence on the rain gardens' infiltration capacity, while lower standard deviations indicate smaller effects. The relative standard deviations of the four soil parameters tested are summarized in Table 13.

**Table 13. Influence of Soil Parameters on Hydrological Performance**

| Rank | Maximum Ponding Depth | | Time for Pond to Empty | |
|---|---|---|---|---|
| | Variable | RSD | Variable | RSD |
| 1 | Substrate Soil Texture | 51.04 % | Substrate Soil Texture | 64.61 % |
| 2 | Native Soil Texture | 6.33 % | Native Soil Texture | 26.02 % |
| 3 | Substrate Soil Depth | 3.25 % | Native Soil Depth | 10.16 % |
| 4 | Native Soil Depth | 1.01 % | Substrate Soil Depth | 5.23 % |

It is evident that the soil texture has a more significant impact on both ponding depth and ponding time than the soil depth. For the substrate soil layer, a sand or a soil texture with a comparable saturated hydraulic conductivity and porosity should be used to optimize the rain gardens infiltration capacity. The simulations modeled with a sand substrate layer had the lowest maximum ponding depths and durations of water in the pond. Sand substrate layers can accommodate the largest inflow water volumes without exceeding the Pennsylvania BMP manual requirements, making it the most effective soil choice. However, sand alone cannot sustain vegetation. To maintain a robust vegetative cover, small amounts of organic matter, or a shallow topsoil layer, would need to be incorporated as well. The substrate soil depth had minimal effects on the rain garden's hydrological performance. The depth of this layer should be chosen based on the vegetation that will be incorporated into the rain garden. A minimum depth of 18-inches is required, but larger depths may be needed if larger plants will be utilized, such as trees or shrubs.

The native soil texture influences the rain garden's hydrologic capability as well. Rain gardens perform significantly better in sandy and loamy native soil conditions than in clayey and silty conditions. While many states and municipalities provide guidelines on the impervious drainage areas rain gardens can accommodate for runoff reduction, they are not the most important factor to focus on, as the rain gardens’ performance is highly dependent on the native soil. The high variability in rain garden performance with differing native soil conditions suggests that it would be more effective to determine drainage areas based on the site soil conditions, rather than general guidelines. It is likely that areas with infiltration-feasible native soil can effectively reduce runoff from much larger areas, while areas with less permeable native soils will experience higher ponding depths and longer drainage times than recommended.

The relationships found involving inflow water volume and surface area could provide a more effective method for calculating the maximum drainage area. Assuming the results represented by GIFMod are accurate and the relationship holds true with all soil textures, the maximum inflow water volume a rain garden could accommodate without exceeding the maximum ponding depth could be calculated based on the basin surface area and site-specific conditions.

# Chapter 4

# Exploring Variability in Rain Garden Performance in Different Regions of Pennsylvania

In this chapter, the relationships identified between the inflow water volume and rain garden surface area on the maximum ponding depth will be further evaluated, based on the stormwater and soil conditions in Pennsylvania. The geographical focal areas analyzed were Philadelphia, Pittsburgh, Scranton, State College, and Erie.

## Rainfall Distribution

In Pennsylvania, nearly all of the annual rainfall occurs in small storm events; precipitation of an inch or less is frequent and well distributed throughout the year. However, stormwater management typically focuses on managing flooding from less frequent, more extreme storm events. Regulatory criteria are often based on controlling runoff generated from 2-year through 100-year storm events. These storm frequencies are based on the statistical probability of a storm being exceeded in any year (DEP 2006). The statistical storm frequency events for the five locations analyzed in these simulations, provided by the BMP manual, are presented in Table 14. The storm frequency that a residential rain garden needs to accommodate varies depending on its usage and the regulations set by the local municipality where it is being implemented.

**Table 14. Rainfall Events of 24-Hour Duration in Pennsylvania**

| Location | Rainfall Depth [Inches] | | | | |
|---|---|---|---|---|---|
| | Frequency of Occurrence | | | | |
| | 2-Year | 5-Year | 10-Year | 50-Year | 100-Year |
| Philadelphia | 3.3 | 4.1 | 4.8 | 6.7 | 7.6 |
| Pittsburgh | 2.4 | 2.9 | 3.3 | 4.4 | 4.9 |
| Scranton | 2.6 | 3.2 | 3.7 | 5.4 | 6.4 |
| State College | 2.7 | 3.3 | 3.8 | 5.2 | 5.9 |
| Erie | 2.6 | 3.2 | 3.7 | 5.1 | 5.8 |

The inflow time series used in these simulations were created based on the storm depths outlined in Table 14. The rainfall intensity in Pennsylvania can be estimated based on the SCS Type II synthetic 24-hour rainfall distribution (USDA 1986). The inflow time series were created based on the SCS Type II 24-hour storm cumulative fractions presented in (Mays 2019) and a 1,000 $ft^2$ total drainage area. The inflow water volumes used for each location and corresponding storm frequency are presented in Table 15.

**Table 15. Inflow Water Volumes for Each Location and Storm Frequency**

| Location | Inflow Water Volume [Cubic Feet] | | | | |
|---|---|---|---|---|---|
| | Frequency of Occurrence | | | | |
| | 2-Year | 5-Year | 10-Year | 50-Year | 100-Year |
| Philadelphia | 275.00 | 341.67 | 400.00 | 558.33 | 633.33 |
| Pittsburgh | 200.00 | 241.67 | 275.00 | 366.67 | 408.33 |
| Scranton | 216.67 | 266.67 | 308.33 | 450.00 | 533.33 |
| State College | 225.00 | 275.00 | 316.67 | 433.33 | 491.67 |
| Erie | 216.67 | 266.67 | 308.33 | 425.00 | 483.33 |

## Soil Information

Soil conditions vary significantly across different locations. The Web Soil Survey (WSS) was used to determine the predominant soil conditions in each area of interest. The WSS is operated by the US Department of Agriculture Natural Resources Conservation Service (NRCS) and provides soil data and information produced by the National Cooperative Soil Survey. It has soil maps and data available from more than 95% of the nation's counties which can be used for general planning, although onsite investigation is often required for engineering applications (USDA 2019).

For each of the cities evaluated, the most predominant soil composition was selected based on the data provided by the WSS. The WSS requires you to set an area of interest (AOI), and then provides the soil map within that AOI. In these simulations, the AOIs were set as the county each city is located in and the most relevant soil composition within each county was used to model the native soil conditions for each location. The AOIs used, predominant soil composition within that AOI, and its relevance are presented in Table 16.

**Table 16. Most Predominant Soil Compositions in Areas of Interest**

| AOI | City of Interest | Soil Symbol | Soil Name | Acres in AOI | Percent of AOI |
|---|---|---|---|---|---|
| Allegheny County | Pittsburgh | GQF | Gilpin-Upshur complex, very steep | 50,642.1 | 10.6 % |
| Centre County | State College | VrF | Varilla-Laidig complex, 25 to 60 percent slopes, very rubbly | 49,778.7 | 7.0 % |
| Erie County | Erie | VeB | Venango silt loam, 3 to 8 percent slopes | 105,972.4 | 20.5 % |
| Lackawanna County | Scranton | UA | Udorthents, strip mine | 12,951.9 | 4.4 % |
| Philadelphia County | Philadelphia | UdB | Urban land-Chester complex, 0 to 8 percent slopes | 21,146.5 | 23.3 % |

Two of the soil compositions listed in Table 16 are representative of two different soil profiles: the Gilpin-Upshur complex and the Varilla-Laidig complex. The varying soil profiles and their relevance within each composition are outlined in Table 17.

**Table 17. Soil Compositions with Multiple Profiles**

| Soil Symbol | Soil Profile | Relevance within Soil Composition |
|---|---|---|
| GQF | Gilpin | 45% |
| | Upshur | 35% |
| VrF | Varilla | 58% |
| | Laidig | 34% |

After determining the main soil composition in each area, the soil profiles, also provided by the WSS, were used to establish the native soil properties to be inputted into GIFMod. The typical profiles of each soil type are outlined in Table 18.

**Table 18. Predominant Soil Profiles in Selected Geographical Focal Areas**

| Soil Profile | Soil Texture | Soil Depths | Depth to Water Table |
|---|---|---|---|
| GQF – Gilpin | Silt Loam<br>Loam<br>Bedrock | 0 to 24 inches<br>24 to 30 inches<br>30 to 40 inches | More than 80 inches |
| GQF – Upshur | Silty Clay Loam<br>Silty Clay<br>Silty Clay Loam<br>Bedrock | 0 to 6 inches<br>6 to 35 inches<br>35 to 50 inches<br>50 to 60 inches | More than 80 inches |
| VrF – Varilla | Sandy Loam<br>Loamy Sand | 0 to 42 inches<br>42 to 60 inches | More than 80 inches |
| VrF – Laidig | Loam<br>Sandy Loam | 0 to 39 inches<br>39 to 80 inches | 30 to 47 inches |
| VeB | Silt Loam<br>Loam | 0 to 20 inches<br>20 to 72 inches | More than 80 inches |
| UA | Loam | 0 to 60 inches | More than 80 inches |
| UdB | Silt Loam<br>Sandy Loam | 0 to 42 inches<br>42 to 68 inches | More than 80 inches |

Limited soil information is available beyond depths of 40 to 80 inches below ground, so various assumptions needed to be made in modeling these soil profiles. For soils with water tables listed at depths of "more than 80 inches", a water table depth of 80 inches was assumed. Additionally, when information was not available about the soil textures all the way to the water table, it was assumed that the bottommost soil texture provided extended to the water table. When modeling the Laidig soil profile, in which the water table ranges from depths of 30 to 47 inches, a depth of 47 inches was used for modeling purposes. As discussed in Chapter 2, throughout the GIFMod simulations, it was assumed that the water table will not be affected by the recharge from the rain garden and will remain at a constant depth (i.e., once water reaches the water table, it is removed from the simulation). As a result, the assumptions made about the depths to the water table likely have minimal influence on the rain garden's hydrologic performance.

To model a bedrock layer in GIFMod, the physical properties of the bedrock must be manually input. These properties were not provided by the WSS and instead would need to be determined based on US Geological Survey datasets. These properties can be highly variable, depending on the type of rock and fractures within the rock. As a result, assumptions needed to be made about the porosity and permeability of the bedrock layer for the Gilpin-Upshur complex soil composition. To most accurately represent these layers, values were chosen based on the median value of typical ranges. Sedimentary rocks generally have porosities in the range of 10% to 30%, so a porosity, or saturated moisture content, of 20% (0.2) was selected. There is a wide range of permeability in geological materials from $10^{-12}$ m/s to around 1 m/s; a median value of $10^{-6}$ m/s (0.0864 m/day) was selected for the saturated hydraulic conductivity (Earle 2015).

## Incorporating a Substrate Soil Layer

The initial objective of these simulations was to analyze how effectively the incorporation of a substrate soil layer reduces the maximum ponding depth. To begin, rain gardens underlaid with the soil conditions outlined in Table 18 were modeled in GIFMod to be used as baseline measurements. These simulations determined the infiltration capacity of the native soils, before the incorporation of a substrate soil layer. Each of the soil types were subject to five different inflow water volumes, based on the storm depths listed in Table 14 corresponding to the location of the soil, and a 1,000 $ft^2$ drainage area. An initial rain garden surface area of 200 ft$^2$ was used, modeling a 4:1 loading ratio. The results from these baseline simulations are presented in Table 19.

**Table 19. Maximum Ponding Depths of Pennsylvania Native Soil Compositions**

| Soil Type | Location | Maximum Ponding Depth [Inches] | | | | |
|---|---|---|---|---|---|---|
| | | Frequency of Occurrence | | | | |
| | | 2-Year | 5-Year | 10-Year | 50-Year | 100-Year |
| GQF – Gilpin | Pittsburgh | 6.94 | 9.23 | 11.24 | 16.86 | 19.45 |
| GQF – Upshur | Pittsburgh | 9.54 | 12.35 | 14.68 | 21.21 | 24.21 |
| VrF – Varilla | State College | 4.47 | 5.82 | 7.00 | 10.42 | 12.21 |
| VrF – Laidig | State College | 6.14 | 7.98 | 9.58 | 14.28 | 16.77 |
| VeB | Erie | 6.70 | 8.74 | 10.52 | 15.83 | 18.64 |
| UA | Scranton | 3.15 | 4.93 | 5.95 | 6.70 | 8.36 |
| UdB | Philadelphia | 8.91 | 11.83 | 14.54 | 22.37 | 26.34 |

The top 18-inches of the native soil layer was then removed and replaced with a sand substrate soil. The same simulations were run again to analyze how effectively the incorporation of a substrate layer reduced the maximum ponding depth. The reduction in maximum ponding depths found are presented in Table 20, and the maximum ponding depths with and without the incorporation of a sand substrate layer are outlined in Appendix D.

### Table 20. Reduction in Maximum Ponding Depth from the Incorporation of a Sand Substrate Soil Layer

| Soil Type | Location | Percent Reduction in Maximum Ponding Depth | | | | | |
|---|---|---|---|---|---|---|---|
| | | Frequency of Occurrence | | | | | |
| | | 2-Year | 5-Year | 10-Year | 50-Year | 100-Year | Average |
| GQF – Gilpin | Pittsburgh | 29.86 % | 30.57 % | 27.22 % | 20.95 % | 20.98 % | 25.92 % |
| GQF – Upshur | Pittsburgh | 57.71 % | 43.83 % | 35.30 % | 25.84 % | 22.97 % | 37.13% |
| VrF – Varilla | State College | 44.29 % | 87.13 % | 77.55 % | 47.71 % | 58.08 % | 62.95 % |
| VrF – Laidig | State College | 62.05 % | 93.59 % | 85.77 % | 73.68 % | 70.25 % | 77.07 % |
| VeB | Erie | 70.86 % | 69.29 % | 69.18 % | 79.97 % | 75.69 % | 73.00 % |
| UA | Scranton | 26.87 % | 23.45 % | 24.74 % | 21.02 % | 19.60 % | 23.14 % |
| UdB | Philadelphia | 64.66 % | 88.04 % | 81.17 % | 72.75 % | 70.61 % | 75.44 % |

It is evident that the incorporation of a sand substrate significantly reduces the maximum ponding depth. The sand layer has a higher hydraulic conductivity than the native soils, allowing water to infiltrate out of the pond at a faster rate initially. The sand also provides additional storage; once infiltration reaches the native soil where the infiltration rate decreases, 69 $ft^3$ of water is stored in the sand rather than the pond, reducing both the maximum ponding depth and the time for the pond to empty.

In the soil conditions representing State College, Erie, and Philadelphia, the average maximum ponding depth was reduced between 60 and 80 percent when a substrate layer was added, indicating that rain gardens could be a very effective stormwater management method in these areas. It was found that, for the soil conditions in both State College and Erie, a 200 $ft^2$ rain garden can easily accommodate up to a 100-year storm without the ponding depth exceeding 6-inches. The maximum ponding depths from a 100-year storm for the Varilla and Laidig soil profiles in State College and the Erie soil conditions were found to be 5.12, 4.99, and 4.53-inches, respectively.

The incorporation of a substrate layer was least effective in the soil conditions representing Pittsburgh and Scranton, from which the average maximum ponding depth was reduced between 20 and 40 percent. The Pittsburgh soil conditions displayed the weakest hydrological performance. In both the Gilpin and Upshur soil profiles, the ponding depth exceeded 6-inches from only a 5-year storm when a substrate layer was added, with maximum ponding depths of 6.41 and 6.94-inches, respectively. Additionally, these were the only soil conditions in which the pond did not empty within 72-hours. The ponding depth versus time curves generated by GIFMod for the Gilpin and Upshur soils from a 2-year storm and a 5-year storm are shown in Figure 12.

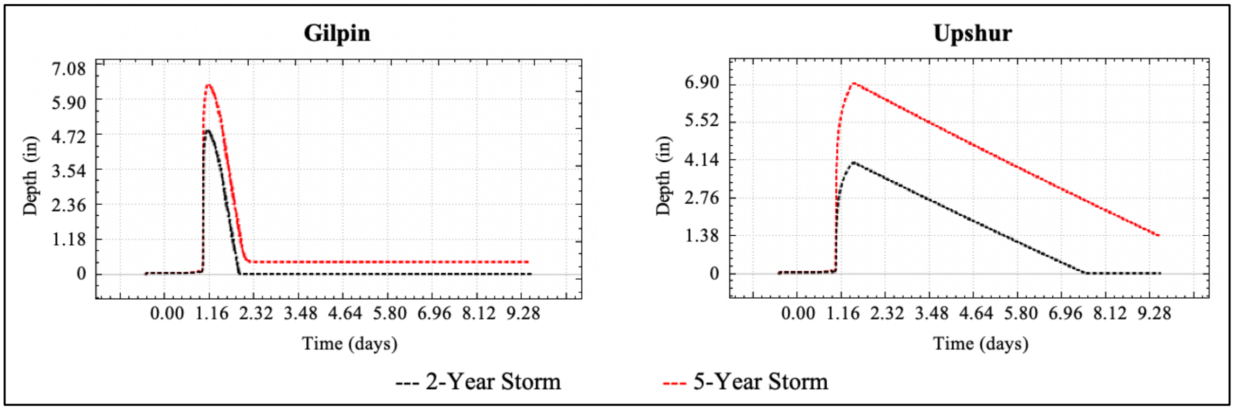


**Figure 12. Ponding Depths for the Pittsburgh Soil Conditions Over Time**

The ponding time of the Gilpin soil profile was 30.07-hours after a 2-year storm event, but the pond did not empty within the simulation time (9-days) after a storm frequency of 5-years or larger. It can be seen that the ponding depth quickly increases to its maximum depth and then decreases; however, infiltration in this soil profile is limited. For inflow water volumes larger than those from a 2-year storm (200 $ft^3$), the ponding depth decreases to a minimum value and then remains relatively constant for the duration of the simulation. This is likely due to the bedrock layer located only 30-inches below the pond. Bedrock is typically impermeable, and infiltration only occurs through fractures in the rock. Presumably, during the 2-year storm event, the pond empties before infiltration reaches the bedrock layer. During larger storms, the inflow water volume exceeds the storage capacity of the soils overlaying the bedrock, at which point infiltration essentially stops.

The ponding time of the Upshur soil profile exceeded 72-hours from a 2-year storm, having a ponding time of 165.43-hours. The ponding depth again increased quickly to its maximum depth, but then decreased very slowly, at a rate of approximately 0.6633 inches per day. This is probably due to the low permeability of the native soils. Even though there is a bedrock layer beneath this pond, it is located much deeper underground, at a depth of 50-inches. The bedrock layer is overlaid by a silty clay loam soil, which has a saturated hydraulic conductivity of 0.0168 meters per day, or approximately 0.66 inches per day. For the duration of these simulations, infiltration never reached the bedrock layer, therefore the rate at which the pond emptied was based on the infiltration rate of the silty clay loam native soil layer.

Nonetheless, the duration of water in the pond is a concern with the Pittsburgh soil conditions. The ponding time exceeded 72-hours before the maximum ponding depth exceeded 6-inches, and both requirements were surpassed in the Gilpin and Upshur soil profiles from a 2-year storm and a 5-year storm, respectively. This indicates that an underdrain needs to be incorporated into the rain garden design for these soil conditions to effectively reduce runoff.

## Varying the Rain Garden Surface Area

After completing the baseline simulations for each soil condition and measuring the effects of incorporating a sand substrate soil layer, varying surface areas were tested to further analyze the relationships found in Chapter 3 between the inflow water volume and rain garden surface area on the maximum ponding depth. Rain gardens with each of the native soil conditions were modeled having four different surface areas (100 ft$^2$, 150 ft$^2$, 200 ft$^2$, and 250 ft$^2$), each subject to the five different inflow water volumes listed in Table 15. The loading ratios modeled for each surface area are outlined in Table 21.

**Table 21. Loading Ratio for Each Rain Garden Surface Area**

| **Rain Garden Surface Area ($A_g$)** | **Catchment Area ($A_T$)** | **Impervious Surface Area ($A_r$)** | **Loading Ratio** |
|---|---|---|---|
| 100 ft$^2$ | 1,000 ft$^2$ | 900 ft$^2$ | 9:1 |
| 150 ft$^2$ | 1,000 ft$^2$ | 850 ft$^2$ | 6:1 |
| 200 ft$^2$ | 1,000 ft$^2$ | 800 ft$^2$ | 4:1 |
| 250 ft$^2$ | 1,000 ft$^2$ | 750 ft$^2$ | 3:1 |

## Inflow Water Volume vs. Maximum Ponding Depth

It was found that the maximum ponding depth is linearly related to the inflow water volume, but the linear relationship varies within different inflow ranges. The relationship between the maximum ponding depth and the inflow water volume for the Erie soil conditions having a 200 ft$^2$ surface area is depicted in Figure 13. There is a linear relationship with the inflow water volumes from the 2-year storm to the 10-year storm, and then a different relationship for the inflow water volumes from the 50-year storm and larger. This is likely due to the different infiltration rates of each of the soil layers. For inflow water volumes less than or equal to a 10-year storm, the pond reaches its maximum depth while the water is infiltrating through the sand substrate layer. However, for storms larger than this, the pond reaches its maximum depth while the water is infiltrating through the first native soil layer, silt loam in this case. Since silt loam has a lower hydraulic conductivity than sand, water will infiltrate slower once it reaches this layer. In turn, the maximum ponding depth will be more sensitive to an increase in inflow water volumes at this point, as depicted by the larger slope in this linear segment.

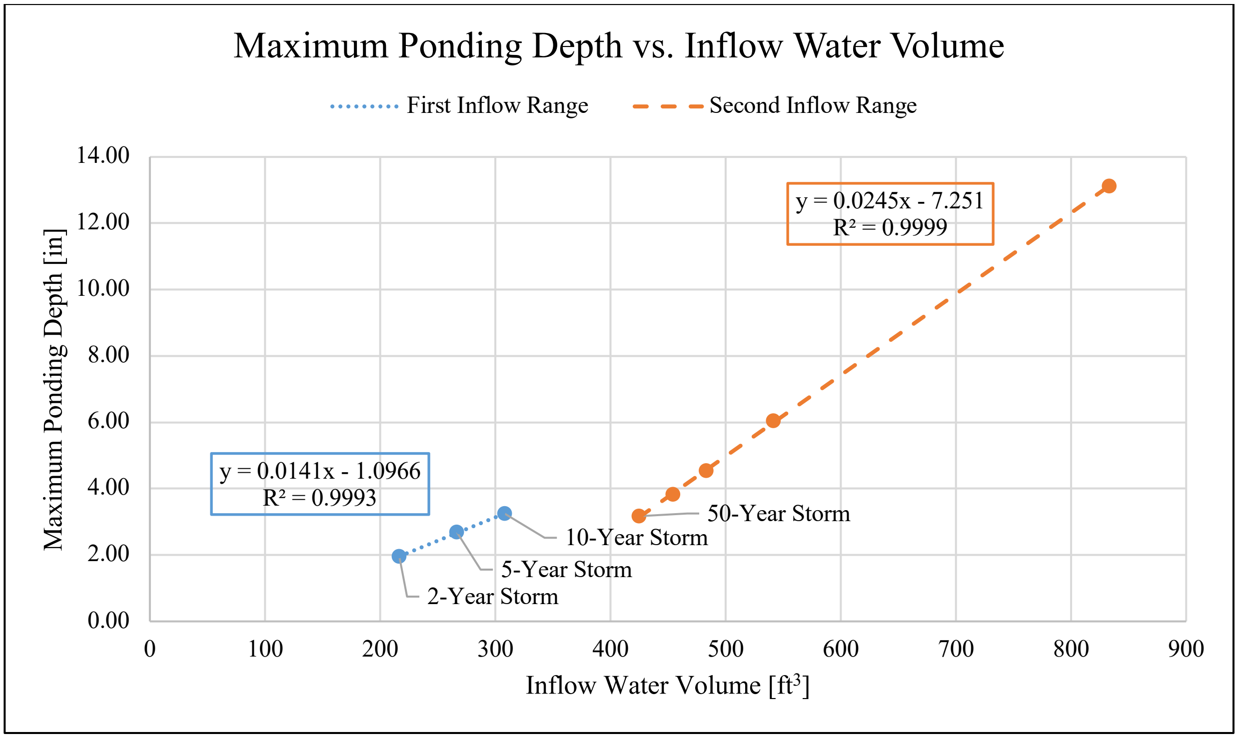


**Figure 13. The Varying Linear Relationships Between Inflow Water Volume and Maximum Ponding Depth for Different Inflow Ranges**

The linear relationship between the maximum ponding depth and inflow water volume that encompassed a maximum ponding depth of 6-inches was found for all five soil conditions with all four surface areas tested. Standards were set for determining these relationships to ensure they were accurate, and the inflow ranges used were correct. A minimum of four values were used in each linear fit, with at least one representing a maximum ponding depth less than and greater than 6-inches. These relationships can be found in Appendix E.

The coefficient of determination was used to measure the accuracy of each linear fit. These values ranged from 0.9907 to 1.0000, indicating a strong linear correlation between the inflow water volume and the maximum ponding depth. However, there is a potential error in the relationships illustrated in Appendix E for the Scranton soil conditions. The relationship between the maximum ponding depth and the inflow water volume with the Scranton soil conditions for a rain garden surface area of 100 $ft^2$ is illustrated in Figure 14. A maximum ponding depth of 6-inches is located between two different inflow ranges. The lower inflow range was used for all succeeding calculations because it contained the maximum ponding depth closest to 6-inches, however, it is uncertain which linear fit encompasses a maximum ponding depth of 6-inches for this particular scenario.

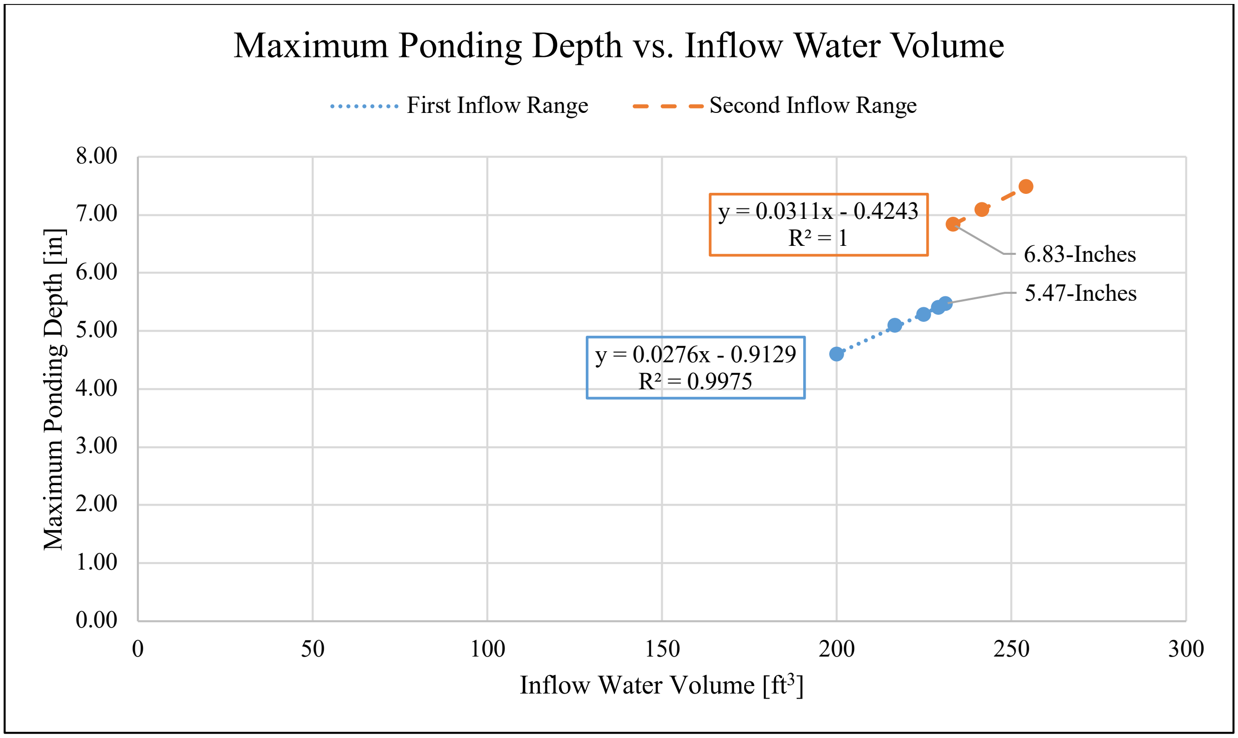


**Figure 14. Potential Inaccuracy in the Scranton Soil Conditions due to 6-Inch Maximum Ponding Depth Falling Between Two Inflow Ranges**

## Maximum Inflow Water Volume

The linear relationship between the inflow water volume and maximum ponding depth found for each native soil texture and surface area was then used to determine the maximum inflow water volume each rain garden configuration can accommodate before the maximum ponding depth exceeding 6-inches. The trendline equations in Appendix E were used to calculate the inflow water volume corresponding to a maximum ponding depth of 6 inches. The maximum inflow water volumes each soil condition and surface area can accommodate before the ponding depth exceeds 6-inches are summarized in Table 22.

### Table 22. Maximum Inflow Water Volume for Each Soil Condition and Surface Area

| Location (Soil Type) | Maximum Inflow Water Volume [Cubic Feet] | | | |
|---|---|---|---|---|
| | Surface Area | | | |
| | 100 ft$^2$ | 150 ft$^2$ | 200 ft$^2$ | 250 ft$^2$ |
| Pittsburgh (GQF – Gilpin) | 118 | 175 | 228 | 295 |
| Pittsburgh (GQF – Upshur) | 114 | 170 | 227 | 282 |
| State College (VrF – Varilla) | 266 | 398 | 533 | 664 |
| State College (VrF – Laidig) | 296 | 403 | 539 | 672 |
| Erie (VeB) | 269 | 404 | 542 | 675 |
| Scranton (UA) | 250 | 357 | 490 | 619 |
| Philadelphia (UdB) | 279 | 417 | 553 | 694 |

As expected, it was found that the Pittsburgh soil conditions can accommodate the smallest volumes of water, likely due to their highly impermeable bedrock layer. The maximum inflow water volumes for the Gilpin and Upshur soil profiles were, on average, 43.82% and 42.60% of those of the other five soil conditions, respectively. The remaining soil conditions all performed comparably. The maximum inflow water volume for the five remaining soil conditions varied between 3.83% and 5.73% for the four surface areas analyzed, having an average relative standard deviation of 4.58%.

### Surface Area vs. Maximum Inflow Water Volume

The maximum inflow water volumes were then plotted against their corresponding surface areas to evaluate the linear relationship found between rain garden surface area and maximum inflow water volume in Chapter 3. These plots are depicted in Figure 15.

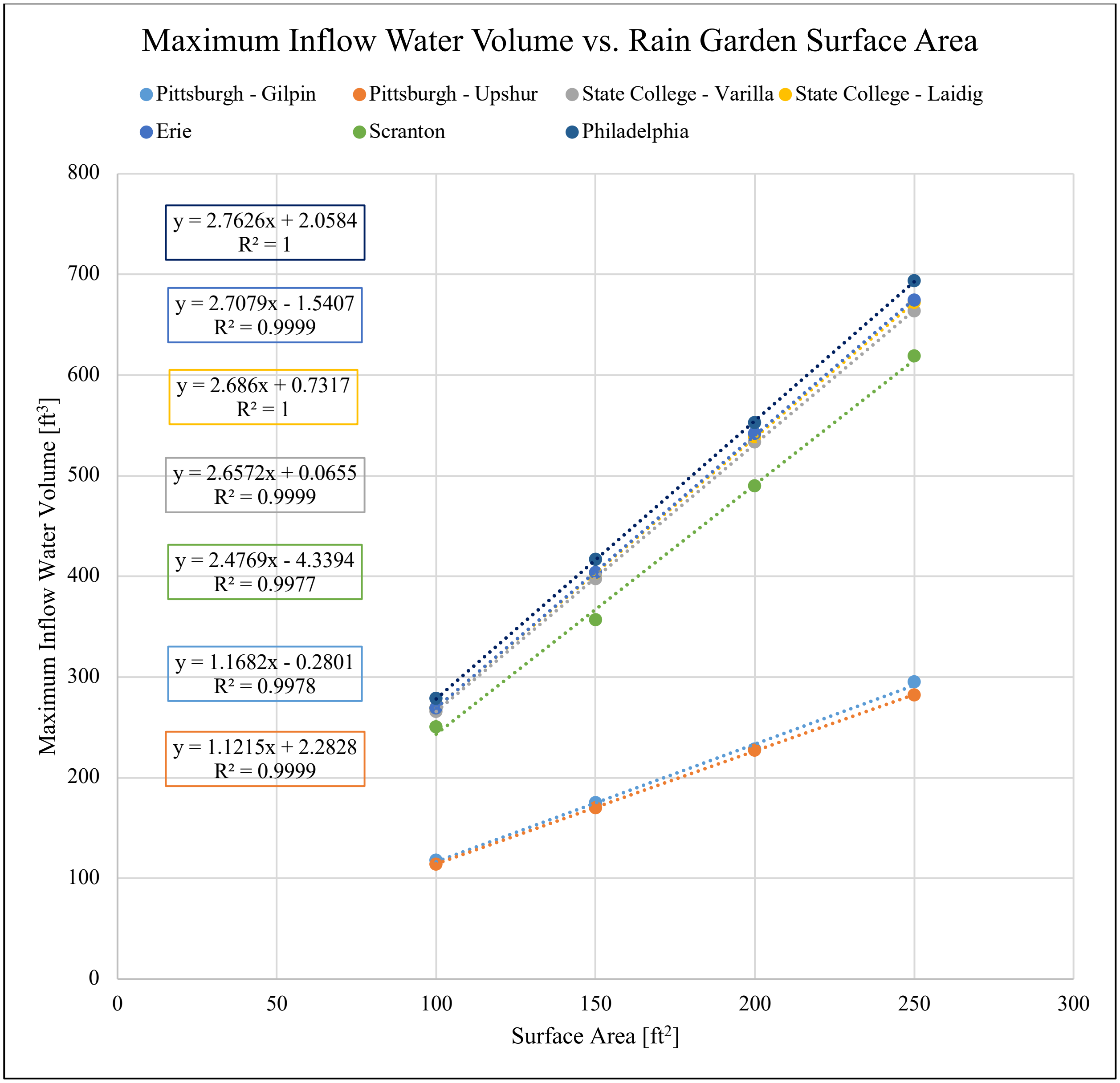


**Figure 15. Relationship Between Rain Garden Surface Area and Maximum Inflow Water Volume for Pennsylvania Soil Conditions**

The maximum inflow water volume is linearly related to the basin surface area for all soil conditions, although the relationship varies between different conditions. These relationships could be beneficial in rain garden design, for the required rain garden surface area can be calculated based on the inflow water volume it needs to accommodate, or vice versa. The slope of these relationships represents how much additional inflow the rain gardens can accommodate [$ft^3$] per additional surface area [$ft^2$].

The Pittsburgh soil conditions again performed the weakest in this evaluation. The slopes of the Gilpin and Upshur soil profile trendlines were, on average, 44.01% and 42.25% of those of the other soil conditions. Overall, rain gardens underlaid by the predominant Pittsburgh native soil conditions can accommodate less than half the inflow the other soil conditions can initially with a minimum 100 $ft^2$ rain garden surface area, then require more than double the additional surface area for an increase in inflow, further emphasizing the need for an underdrain in these conditions.

The remaining five soil profiles again performed comparably. The slopes ranged from approximately 2.48 to 2.76 cubic feet of inflow per square feet of rain garden surface area, with a relative standard deviation of 4.08%. The Philadelphia soil conditions were found to have the largest allowable inflow volume for a 100 $ft^2$ rain garden surface area and highest slope, followed by Erie, State College – Laidig, State College – Varilla, and Scranton, respectively. However, the low range and relative standard deviation in the slopes indicates that the difference in hydrologic performance between these five rain garden configurations is minimal.

## Maximum Total Drainage Area and Maximum Loading Ratio

The maximum inflow water volumes ($Q_{max}$) found were then used to determine the maximum total drainage area ($A_{T,max}$) each rain garden can accommodate before the maximum ponding depth exceeding 6-inches, based on the rain garden's surface area and the storm frequency it needs to be able to contain. Equation 3 can be rearranged to solve for the maximum drainage area as shown in Equation 4.

$$A_{T,max} = \frac{Q_{max}}{P} \tag{4}$$

The maximum drainage areas found for each soil condition, rain garden surface area, and storm frequency are presented in Appendix F. For a 2-year storm event, these areas range between 572 and 3,113 square feet. In 2018, the average lot size for a new single-family detached home sold was 8,567 square feet (Siniavskaia 2019). Zoning requirements vary among municipalities and zoning districts, however, the maximum impervious surface cover allowed for a property of this size is typically 45% (Pennsylvania Lower Merion Township Administration 2020). Assuming the average residential property has approximately 3,855 square feet of impervious land cover, the rain gardens analyzed could remove between 15 and 80% of the runoff generated from impervious surfaces in a 2-year storm event.

It was found that for a given storm frequency, the Erie soil conditions can accommodate the largest catchment area, followed by State College, Scranton, Philadelphia, and Pittsburgh, respectively. It is important to note however that these catchment areas take into account the variation in storm frequency depths for each location, outlined in Table 14.

The Pittsburgh soil conditions were able to accommodate significantly smaller service areas than the other soil conditions. The maximum service areas for the Gilpin and Upshur soil profiles were, on average, 53.48% and 52.03% of those for the other soil conditions, respectively. Again, the remaining five soil profiles were found to have similar hydrological performances, with an average relative standard deviation of 8.22%. Considering the differences in storm frequency depths between the remaining four locations, this variation in maximum drainage areas is minimal. The storm depths corresponding to the 2 through 100-year storm events modeled vary an average of 12.84% between Philadelphia, Scranton, State College, and Erie. If equivalent storm depths were analyzed, the five remaining soil profiles would likely have analogous maximum drainage areas.

The maximum catchment areas found were lastly used to calculate the corresponding maximum loading ratios ($R_{max}$:1). The maximum loading ratios were calculated based on Equation 5:

$$R_{max} = \frac{A_{T,max} - A_g}{A_g} \tag{5}$$

The maximum loading ratios for each soil condition and rain garden surface area for a 2-year storm event are outlined in Table 23. The loading ratios for larger storm events, through the 100-year storm frequency, are presented in Appendix G.

**Table 23. Maximum Loading Ratios for a 2-Year Storm Event**

| Location | Rain Garden Surface Area | | | |
|---|---|---|---|---|
| | 100 ft$^2$ | 150 ft$^2$ | 200 ft$^2$ | 250 ft$^2$ |
| Pittsburgh (Gilpin) | 5:1 | 5:1 | 5:1 | 5:1 |
| Pittsburgh (Upshur) | 5:1 | 5:1 | 5:1 | 5:1 |
| State College (Varilla) | 11:1 | 11:1 | 11:1 | 11:1 |
| State College (Laidig) | 11:1 | 11:1 | 11:1 | 11:1 |
| Erie | 11:1 | 11:1 | 11:1 | 11:1 |
| Scranton | 11:1 | 10:1 | 10:1 | 10:1 |
| Philadelphia | 9:1 | 9:1 | 9:1 | 9:1 |

As expected, the maximum loading ratios for the Pittsburgh soil conditions were significantly smaller than those of the other soil condition. On average, the maximum loading ratios for the Gilpin and Upshur soil profiles were less than half of those of the other soil conditions: 46.10% and 44.41%, respectively. During a 2-year storm event, both of the Pittsburgh soil profiles could accommodate a maximum loading ratio of 5:1 before ponding depth exceeds 6 inches: the same maximum loading ratio recommended in the Pennsylvania

BMP manual. However, as emphasized throughout the chapter, these soil profiles hydrologically performed considerably worse than the other five profiles analyzed. The Pennsylvania BMP manual also recommends the incorporation of an underdrain into the rain garden design for similar native soils, in which infiltration is limited. An underdrain would reduce both the ponding time and maximum ponding depth. It would be expected that the Pittsburgh soil profiles analyzed would be able to accommodate larger inflow water volumes if an underdrain were incorporated, and in turn, larger maximum loading ratios. The fact that worst performing native soil compositions were able to accommodate loading ratios of 5:1, without the influence of an underdrain or evapotranspiration, suggests that this recommendation is far too conservative.

Again, the remaining soil profiles analyzed had comparable maximum loading ratios, with an overall relative standard deviation of 10.74%. On average, these soil compositions could accommodate a maximum loading ratio of 11:1 during a 2-year storm event: more than double what is recommended in the Pennsylvania BMP manual. These soil compositions can accommodate loading ratios larger than 5:1 up until a 100-year storm event, in which the average maximum loading ratio between the five soil profiles is 4:1. However, outlet structures, such as emergency spillways or overflow drains, are customarily incorporated into stormwater management to prevent flooding in the event of infrequent, high intensity storms. For typical precipitation events in Pennsylvania, rain gardens can accommodate loading ratios much larger than 5:1.

## Assumptions

Numerous assumptions were made throughout these simulations that could influence the results found. Most significantly, the inflow time series were calculated based on two key assumptions: the runoff depth was equal to the rainfall depth and the runoff immediately drained into the ponding area. The runoff curve number method is the most commonly used tool for estimating runoff volumes (DEP 2006). With this method, runoff is calculated based on the land conditions and rainfall depth. Curve numbers (CN) are used to quantify the watershed soil and cover conditions, based on land cover type, hydrologic conditions, antecedent moisture condition, and hydrologic soil group. The potential maximum retention after runoff begins ($S$) is calculated based on Equation 6:

$$S = \frac{1000}{CN} - 10 \tag{6}$$

The runoff depth in inches ($Q_{depth}$) can then be calculated based on Equation 7:

$$Q_{depth} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{7}$$

The inflow time series used in these simulations were created assuming that the runoff depth was equal to the rainfall depth (i.e., the curve number was equal to 100). However, according to (USDA 1986), the runoff curve numbers for urban areas with impervious land cover range from 72 to 98, depending on the cover type and hydrological soil group. As a result, the inflow water volumes used corresponding to each storm frequency are likely larger than they would be in practice. In turn, it is probable that the maximum drainage areas and loading ratios calculated are very conservative, and the rain gardens modeled can accommodate larger impervious surface areas and loading ratios.

The inflow time series used were also based on the assumption that the time of concentration is equal to zero. In this situation, the travel time is the time it takes stormwater to travel from where it lands within the watershed to the ponding area. The time of concentration is the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the ponding area, which is calculated based on the sum of the various travel times (USDA 1986). The time of concentration is dependent on the surface roughness, flow patterns, and slopes within the watershed, therefore it varies with each site. Typically, in practice, a minimum time of concentration of 5 minutes is used in calculations for urbanized areas (UDFCD 2018). Although runoff generally travels very quickly through impervious surfaces, it would still take a small amount of time for the runoff to reach the ponding area. As a result, the rate at which inflow entered the rain garden used in these simulations is likely inaccurate, which could vary the results found.

Assumptions were also made about the rain garden itself. When modeling ponds with GIFMod, it is assumed that the pond has vertical sides, therefore the ponding depth is even throughout the entire pond. However, most local jurisdictions set requirements on the maximum surface side slopes, based on safety concerns. Generally, a maximum side slope of 3 to 1 (horizontal to vertical) is recommended (Philadelphia Water Department 2020). Consequently, the storage volume of the ponding area for each rain garden surface area in these simulations was likely larger than it would be in reality. Assuming a 3 to 1 side slope and 6-inch depth is utilized, the rain garden surface areas would have to be adjusted according to Table 24 to have the same storage capacity as the surface areas used in these simulations and be able to accommodate the same inflow water volumes. For depths greater than 6-inches, the adjusted radius would need to be increased by 3-inches for every additional inch of depth, and the adjusted surface area calculated accordingly.

**Table 24. Adjusted Surface Areas for 3:1 Side Slopes**

| Simulation | | Adjusted for 3:1 Side Slopes | | Percent Increase in Surface Area |
|---|---|---|---|---|
| Surface Area | Radius | Surface Area | Radius | |
| 100 $ft^2$ | 5.64 ft | 127.68 $ft^2$ | 6.38 ft | 27.68 % |
| 150 $ft^2$ | 6.91 ft | 183.68 $ft^2$ | 7.65 ft | 22.45 % |
| 200 $ft^2$ | 7.98 ft | 238.72 $ft^2$ | 8.72 ft | 19.36 % |
| 250 $ft^2$ | 8.92 ft | 293.17 $ft^2$ | 9.66 ft | 17.27 % |

## Conclusion

Although stormwater management requirements vary by municipality, the Pennsylvania Stormwater Management Act of 1978, or Act 167, created regularity within the state. This act required counties to develop and follow a stormwater management plan, or ‘Act 167 Plan’, approved by the Department of Environmental Protection (DEP) (DEP 2020). While these plans vary slightly between counties, the stormwater management ordinances in all five counties evaluated require similar volume control measures. Overall, the most restrictive requirement states that new impervious surfaces should not “increase the post-development total runoff volume for all storms equal to or less than the two-year, twenty-four-hour duration rainfall” (City Council of the City of Scranton 1997). To meet this requirement, additional runoff generated from new impervious surfaces must be removed through infiltration, evaporation, or transpiration.

Evaporation and transpiration were not included in these simulations. The values found throughout this chapter were based on runoff being removed solely through infiltration. As a result, the maximum inflow water volumes, drainage areas, and loading ratios found are likely conservative, for evaporation and transpiration will reduce additional runoff. However, municipalities typically do not account for evapotranspiration in stormwater reduction calculations, due to its high variability. Consequently, the stormwater management ordinances generally require the additional runoff generated from new impervious surfaces, due a 2-year storm event, to be removed entirely through infiltration. Overall, it was found that rain gardens are highly effective stormwater management methods.

The hydrological performances of seven native soil profiles, prominent in five major cities in Pennsylvania, were analyzed based on their ability to remove runoff from intense storm events, purely through infiltration. Hydrological performance was evaluated primarily on the rain gardens maximum ponding depth, which according to the Pennsylvania BMP manual should not exceed 6 inches. The incorporation of an 18-inch sand substrate layer was found to be highly effective. This layer allows water to initially infiltrate faster out of the pond and provides temporary storage while the water infiltrates through the less permeable native soil layers, reducing the maximum ponding depth 53.52% on average.

Additionally, the relationships between the inflow water volume, the maximum ponding depth, and the surface area were analyzed to determine a more effective rain garden design method. It was found that within a particular range of inflows, the maximum ponding depth is linearly related to the inflow volume. This relationship could be used to calculate the inflow volume corresponding to a maximum ponding depth of 6 inches, or the maximum inflow volume. Ergo, the maximum inflow volume is linearly related to the rain garden surface area. This relationship could then be used to determine the maximum inflow volume a given surface area can accommodate, or vice versa. Consequently, the maximum service area and loading ratio a specific rain garden configuration can manage can be calculated.

These relationships were analyzed for all seven soil profiles, each of which was modeled with at least five different inflow volumes and four surface areas. It was found that the linear relationships between the inflow volume and maximum ponding depth and between the surface area and maximum inflow volume had average coefficients of determinations of 0.9992 and 0.9993, respectively, indicating a strong linear fit.

Lastly, these relationships were used to measure the variation in hydrological performance between the different soil profiles, based on their calculated maximum inflow water volumes, drainage areas, and loading ratios. It was found that the two soil profiles representative of Pittsburgh, Gilpin and Upshur, performed the weakest hydrologically. In these soil profiles, the water table is overlaid by a highly impermeable bedrock layer, which essentially halts infiltration. For rain gardens built in similar soil compositions, an underdrain would likely need to be incorporated to reduce the maximum ponding depth and ponding time.

The remaining five soil profiles all performed comparably and could effectively remove runoff from large storm events solely through infiltration. The overall relative standard deviations between the five soil profiles in maximum inflow water volume, drainage area, and loading ratio ranged between 4.08% and 10.74%, which is minimal considering the variation in storm frequency depths. On average, these soil profiles could remove the entirety of runoff due to a 2-year storm event generated from an 11:1 loading ratio.

Overall, these findings suggest that the recommendations provided by the current (2006 version) Pennsylvania BMP manual are too conservative and universal. Infiltration feasible native soils can accommodate loading ratios much larger than the recommended maximum loading ratio of 5:1 suggested by the BMP. Additionally, rain garden hydrological performance is highly variable, based on the design and site-specific conditions. Assuming the relationships found hold true, it would be much more effective to base rain garden design on their unique site conditions, rather than general, state-wide recommendations. Universal sizing recommendations could result in undesirable environmental consequences; if sizing is designed too cautiously, the rain gardens hydrological capabilities will be underutilized, whereas if sizing is over estimated, it could cause flooding, among other negative effects.

# Chapter 5

## Evapotranspiration

Evapotranspiration is the process by which water is transferred from the land to the atmosphere and can be broken down into two categories: evaporation and transpiration. Water is removed directly from soil and vegetated surfaces through evaporation and from plant leaves through transpiration (Mays 2019). Neither of these processes were modeled within the GIFMod simulations, due to their high variability and the programs limited functionality. Instead, the influence of evapotranspiration on rain gardens' hydrological performances was considered based on published data and studies.

### Evaporation

Evaporation is a runoff reduction process, in which surface water is converted from liquid into vapor and returned to the atmosphere. Energy is required to change the state of the stormwater from liquid to vapor, which is provided predominantly through solar radiation. Essentially, water vapor is removed from the evaporating surface due to the difference between the water vapor pressure at the evaporating surface and that of the surrounding atmosphere (Pereira et al. 1998). Evaporation is governed by the climate, therefore, varies significantly with location and time.

Numerous methods have been developed to estimate evapotranspiration based on the available climatic data. Currently, the ASCE recommends the Penman-Monteith method, which calculates evaporation and transpiration rates based on solar radiation, air temperature, air humidity, and wind speed (Pereira et al. 1998). However, these parameters are highly variable. To avoid assumptions that may be false, evaporation was not included in the GIFMod simulations discussed in Chapter 3 and Chapter 4. Similarly, runoff reduction from evaporation is not accounted for in most stormwater management ordinances, likely also due to its high variability, and the fact that most stormwater design recommendations are focused on managing discrete storm events; evaporation is very minimal during the short time period of a precipitation event, but rather can contribute more to overall water volume reduction in inter-event periods.

To analyze the influence of evaporation on residential rain gardens, actual available evaporation data was used. The Pennsylvania State Climatologist is a service run by the College of Earth and Mineral Sciences and Penn State that provides climatological data for the Commonwealth of Pennsylvania ("Pennsylvania State Climatologist" 2021). This service measures the daily evaporation at six distributed locations throughout the state, representative of north eastern, south eastern, central, north western, west central, and south western Pennsylvania. The data provided by the Pennsylvania State Climatologist was used to evaluate the potential influence of evaporation on runoff reduction in rain gardens.

The locations evaluated in Chapter 4 were categorized into each of the representative regions, to determine the approximate daily evaporation at each location. The region corresponding to each location used is listed in Table 25.

**Table 25. Representative Region Corresponding to Each City**

| City | Representative Region |
|---|---|
| Pittsburgh | West Central Pennsylvania |
| State College | Central Pennsylvania |
| Erie | North Western Pennsylvania |
| Scranton | North Eastern Pennsylvania |
| Philadelphia | South Eastern Pennsylvania |

The Pennsylvania State Climatologist provides the daily evaporation data for each of the five regions throughout the months of May through October. From this data, the average daily evaporation each month was calculated in each location, as illustrated in Figure 16.

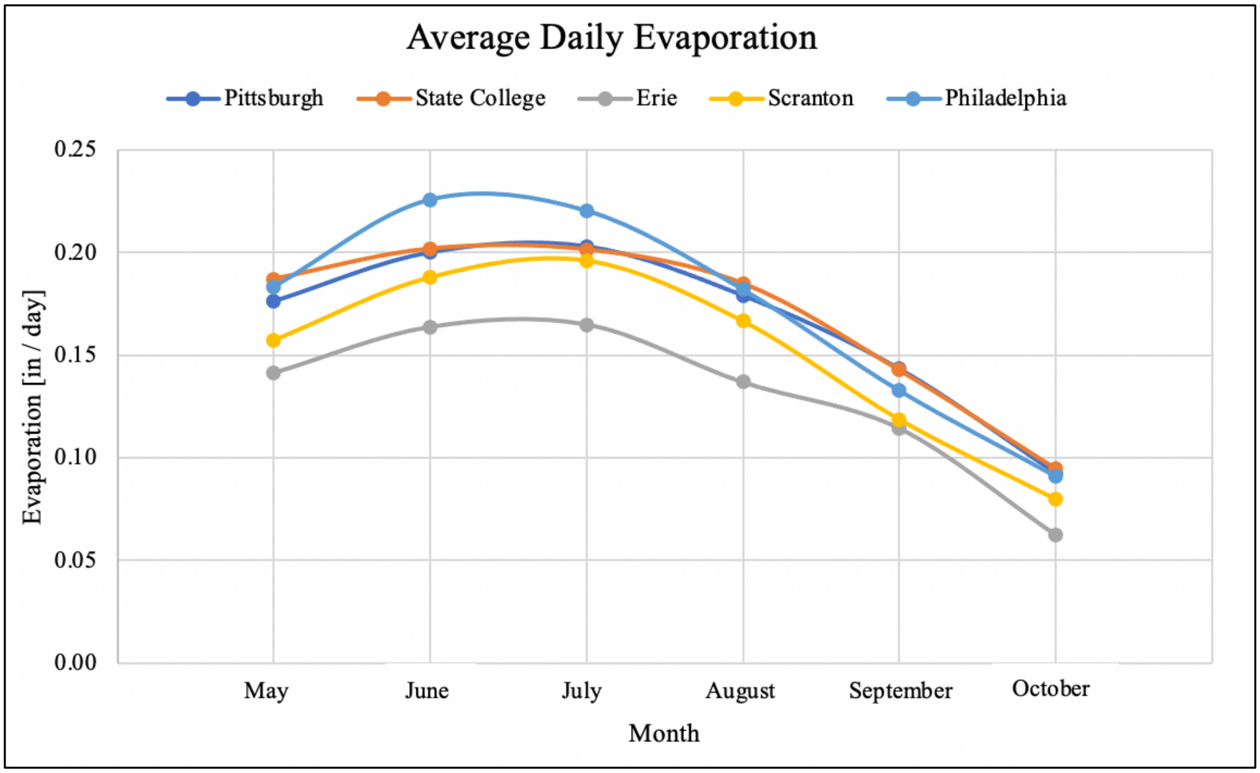


**Figure 16. Average Daily Evaporation**

The average daily evaporation varies slightly between locations. The evaporation rate is generally higher in central and southern Pennsylvania than it is in the norther regions. However, the range between average evaporation rates is at most 0.06 inches per day, which is minimal. For simplicity, the average rate was calculated each month for all five regions combined to approximate the influence of evaporation on runoff reduction in residential rain gardens. The average evaporation is highest during the months of May through August, with average values ranging between 0.17 and 0.20 inches per day. Evaporation is lowest during the months of September and October, with average values of 0.13 and 0.08 inches, respectively.

Based on the data provided, it is likely that evaporation has minimal impact on runoff volume reduction in residential rain gardens. As discussed previously, runoff from impervious surfaces drains into the rain garden ponding area very quickly. Although the time of concentration is not equal to zero, values ranging from 5 to 10 minutes are generally assumed for impervious surfaces. Based on this assumption, evaporation within the surrounding watershed is negligible, and the runoff is evaporating solely from the rain garden ponding area. Within the ponding area, the impact of evaporation on runoff reduction is based on the ponding depth. The daily percent change in runoff volume from evaporation, based on the average daily evaporation rate each month and the ponding depth, are summarized in Table 26.

**Table 26. Daily Percent Change in Runoff Volume from Evaporation**

| **Month** | **Average Evaporation** | **Ponding Depth** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **1 in** | **2 in** | **3 in** | **4 in** | **5 in** | **6 in** |
| May | 0.17 in | 17.00% | 8.50% | 5.67% | 4.25% | 3.40% | 2.83% |
| June | 0.20 in | 20.00% | 10.00% | 6.67% | 5.00% | 4.00% | 3.33% |
| July | 0.20 in | 20.00% | 10.00% | 6.67% | 5.00% | 4.00% | 3.33% |
| August | 0.17 in | 17.00% | 8.50% | 5.67% | 4.25% | 3.40% | 2.83% |
| September | 0.13 in | 13.00% | 6.50% | 4.33% | 3.25% | 2.60% | 2.17% |
| October | 0.08 in | 8.00% | 4.00% | 2.67% | 2.00% | 1.60% | 1.33% |
| **Average** | | **15.83%** | **7.92%** | **5.28%** | **3.96%** | **3.17%** | **2.64%** |

Evaporation has a larger influence on runoff reduction in rain gardens with lower ponding depths. To increase runoff reduction through evaporation, larger rain garden surface areas could be implemented, which would in turn reduce the ponding depth and increase the volume of water evaporated. Based on the data provided by the Pennsylvania State Climatologist, it can be concluded that evaporation reduces a moderate amount of runoff in small storm events. However, stormwater management design criteria are typically based on larger, less frequent storm events. If a rain garden is designed having a maximum impervious drainage area and loading ratio based on a 6-inch maximum ponding depth, evaporation will have minimal influence on runoff reduction in the design storm.

## Transpiration

Transpiration is a process in which water is transferred from land to the atmosphere via plants; it consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere (Pereira et al. 1998). Water, along with some nutrients, are taken up from the saturated soil by plant roots and transported through the plants to their leaves. Plant leaves contain stomata, which are openings in the aerial part of plants that control gas exchange and water transpiration between the plant interior and the environment (Melotto et al. 2008). The aperture of stomata allows for water to evaporate within the leaf, increasing the vapor pressure in the intercellular space and causing a vapor pressure gradient between the leaf and the atmosphere. Consequently, vapor is diffused out of the leaf stomata and into the atmosphere, at which point more water is drawn up from the underlying root system to sustain the plant (Feller 2011).

Similar to evaporation, transpiration rates are highly variable. Transpiration is governed by the same climatological factors as evaporation: solar radiation, air temperature, air humidity, and wind speed. However, the available amount of water is limited by the moisture content of the underlying soil and the ability of the soil to conduct water to the roots (Hess 2014). The transpiration rate is also influenced by crop characteristics, environmental aspects, and cultivation practices; the type of crop, crop development, environment, and management all influence transpiration (Pereira et al. 1998).

Vegetation enhances rain gardens' hydrological performance; additional runoff is removed from the system through transpiration and the plant root systems promote infiltration through their influence on soil physical structure. Hydrological modeling of watersheds is governed by the water balance model used, which should cover all processes in the water cycle, including transpiration. However, due to model simplifications, some of these processes are often neglected. Processes associated with plants are important in GIs, especially those with a significant vegetative cover, such as rain gardens. Despite GIFMod's high versatility, the program does not model any of these processes (Kaykhosravi et al. 2018). As a result, transpiration could not be included in the simulations modeled throughout Chapter 3 and Chapter 4. Although this is a major disadvantage of GIFMod compared to other hydrological modeling programs, transpiration rates are most accurately predicted based on variables that are not readily available, making it extremely difficult to estimate. Similar to with evaporation, numerous climatological factors would have to be assumed, as well as environmental and agricultural factors, which could provide inaccurate results. To optimize accuracy, the influence of transpiration on rain gardens' hydrological performance was analyzed based on published literature.

Many studies have been conducted investigating the effects of transpiration on the hydrologic capabilities of rain gardens. However, evaporation and transpiration occur simultaneously, making the two processes often indistinguishable. As a result, evaporation and transpiration are typically analyzed together, as evapotranspiration. Plants develop over time in what is commonly referred to as the crop cycle. Generally, this cycle goes from the sowing period, through the growing period, and to harvest period: from when the crops are first planted through when they are fully developed. Transpiration rates are influenced by the crop development, therefore vary significantly throughout this cycle. In turn, the portion of evapotranspiration due to evaporation and transpiration can be estimated based on the crop development phase and the vegetation density.

Apart from water availability, evaporation is primarily based on the fraction of solar radiation reaching the soil surface. In vegetated areas, this fraction is dependent on the crop cover. The leaf area index (LAI) is used to quantify the crop cover, representing the total one sided leaf area per unit ground surface area (Chen and Black 1992). When crops are first planted and during early development, the LAI is low, and water is predominantly removed through evaporation. Throughout the growing period, the crop canopy shades an increasing amount of the ground, decreasing the fraction of solar radiation reaching the surface. Once the crop is fully developed, the majority of the soil is covered, making transpiration the main process (Pereira et al. 1998). The partitioning of evapotranspiration into evaporation and transpiration based on the leaf area per unit surface area is illustrated in Figure 17. At sowing, almost 100% of evapotranspiration is due to evaporation, while at the peak LAI, over 90% is due to transpiration (Pereira et al. 1998).

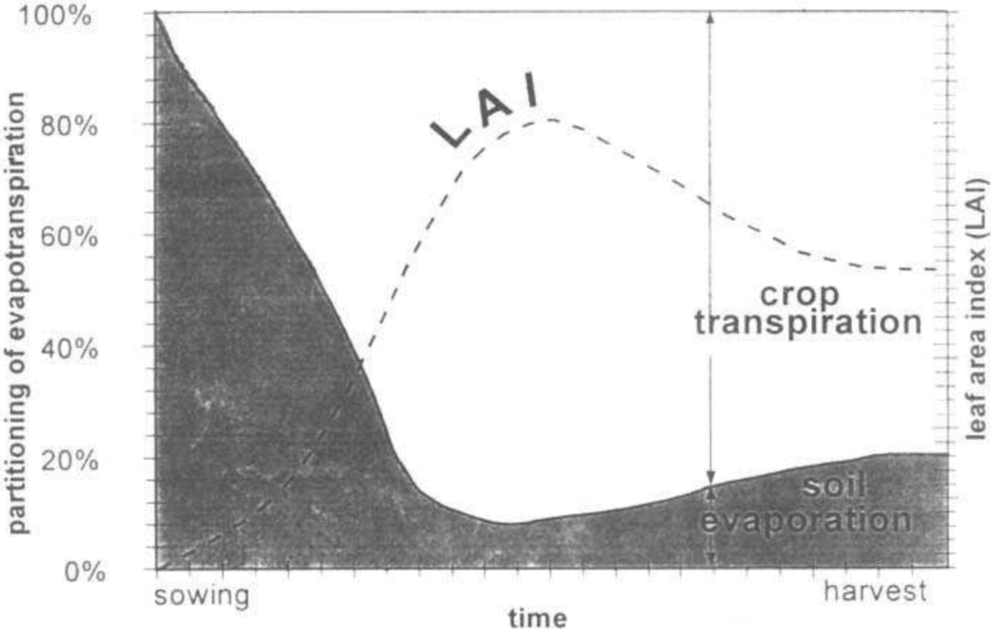


**Figure 17. Partitioning of Evapotranspiration Based on Leaf Area Index (Pereira et al. 1998)**

(Jennings 2016) evaluated the hydrological performance of 35 identical rain gardens in different climate zones in the United States, simulated based on their recorded hourly climate and precipitation data over a two-year time period, in order to analyze the impact of transpiration on rain garden hydrology. This study modeled a 100 $ft^2$ rain garden surface area having a 1,000 $ft^2$ catchment area. The pond was underlaid with a 6 in. soil having an infiltration potential of 6.35 mm/h (0.152 m/day), comparable to the silt loam soil texture in GIFMod. The inflow was based on the hourly precipitation data in each of the 35 areas, ranging from 0.1 to 3.9 m/ year (3.9 to 153.5 in./ year). Pennsylvania has an average annual precipitation ranging from 37 to 45 in./ year, suggesting that the results would be comparable (DEP 2006). A LAI of 50% was used; based on Figure 17, it can be estimated that evapotranspiration was approximately 20% evaporation and 80% transpiration.

(Jennings 2016) found that only 0.16 to 1.06% of runoff reduction was due to evapotranspiration. Assuming 20% of that was from evaporation, this suggests that transpiration removes between 0.13 and 0.85% of runoff in this particular rain garden model. This is a negligible contribution. Additionally, the infiltration potential of the soil used is often cited as the lowest allowable rate. If a more permeable soil texture was utilized, such as the sand modeled in Chapter 4, water would infiltrate much faster, reducing the amount of available water. In turn, it would be expected that the runoff reduction accomplished by evapotranspiration would decrease as the infiltration potential increased.

Although rain garden transpiration was not modeled throughout the GIFMod simulations, literature review suggests that it has negligible contribution to rain gardens' hydrological performance. Even though vegetation is a primary component in rain garden design, garden effectiveness is dominated by infiltration (Jennings et al. 2015). To optimize rain gardens' hydrologic capabilities, design should be focused on maximizing their infiltration capacity. While the contribution of transpiration to runoff reduction in rain gardens is minimal, vegetation provides additional hydrological benefits. Plants help maintain healthy soil structure, while their roots open pathways throughout the soil, aiding infiltration. Although transpiration is not crucial to the hydrological performance of rain gardens, vegetation is essential in optimizing infiltration.

# Chapter 6

# Conclusion

Rain gardens are highly effective stormwater management methods for reducing urban flooding while providing environmental benefits. However, their hydrological performance is extremely variable, depending on certain environmental and design parameters. In terms of the physical soil properties, the media texture has the strongest influence on rain gardens' runoff reduction capacity; most significantly, the texture of the substrate soil layer. Rain gardens perform the best hydrologically when a permeable substrate layer, such as sand, is incorporated into the design. Based on the seven native soil profiles and five storm frequencies analyzed, the incorporation of an 18-inch sand substrate layer reduced the maximum ponding depth 53.52% on average. The substrate layer allows water to initially infiltrate faster out of the ponding area and provides temporary storage while the water infiltrates through the less permeable native soil textures. Although most design guidelines recommend the depth and texture of the substrate layer be chosen based on the plants that will be incorporated into the rain garden, this work also emphasizes the importance of these factors in ultimate hydrological function. While vegetation is a critical element of the aesthetic appeal of rain gardens, there needs to be a careful balance between designing soil media to support plants while also ensuring adequate infiltration and storage for desired runoff reduction benefits.

A brief review of relevant literature found that transpiration has negligible effects on runoff reduction, contributing to less than 1% of runoff reduction. To maximize the rain gardens hydrologic capabilities, a sandy soil would be optimal, and the depth should be chosen based on the inflow water volume it needs to accommodate.

Infiltration capacity is strongly dependent on the native soil conditions, and therefore the location of the rain garden. For the five storm frequencies analyzed, the maximum ponding depth varied 33.98% with the seven native soil profiles modeled. Predominantly sandy and loamy native soil textures can infiltrate larger volumes of water faster, therefore can remove runoff from larger drainage areas than clayey and silty textures. While the depth of the native soils to the water table was found to have minimal influence on maximum ponding depth, the depth of each native soil texture is significant. In six of the seven Pennsylvania soil profiles analyzed, the water table was more than 6-feet below ground; in turn, the pond typically emptied before infiltration reached the water table. Native soils with thicker, more permeable, uppermost soil layers and thinner less permeable soil layers generally performed better.

For a given native soil profile, the maximum ponding depth is linearly related to the inflow water volume (i.e., the drainage area and storm depth) within specific inflow ranges. This relationship can be used to calculate the maximum inflow water volume a specific rain garden configuration can remove before the ponding depth exceeds 6-inches. The maximum inflow water volumes are then linearly related to the corresponding rain garden surface areas. Assuming the simulated results are representative of reality, these relationships can be used to calculate the maximum drainage area and loading ratio a rain garden can accommodate, based on its surface area and native soil profile.

## Future Research Needs

Historical accounts of ancient civilizations suggest stormwater management and urban drainage systems were utilized long before recorded history, possibly as early as the third millennium BC (Burian and Edwards 2002). The current vision of nature-based water resources management as ‘green infrastructure’ is still a relatively new concept though. A 1995 issue of the EPA’s newsletter *Nonpoint Source News- Notes* (Beier 1995) attributes the first use of rain gardens to a Maryland residential developer, who proposed the idea in 1990 (Jennings et al. 2015). As such, design recommendations continue to evolve, as do our models for planning and evaluating them. GIFMod is also a newly developed model, released in 2016, that has not been used widely in other studies (Kaykhosravi et al. 2018). These modern stormwater management approaches and modeling programs create the need for much future research.

The rain gardens simulated throughout this study were based on very specific scenarios and numerous assumptions needed to be made about the inflow rates in the gardens. In all of the models simulated, inflow rates were calculated based on the 24-hour SCS Type II storm distribution and assuming a time of concentration of zero minutes. Although the SCS storm distributions were created based on typical weather pattens throughout the U.S. and the Type II category is representative of Pennsylvania, it is only a hypothetical storm; it is unlikely that rainfall patterns will replicate that exact distribution and duration. Research has found that the SCS Type II rainfall distribution does not match historical records for short-duration thunderstorms and long-duration winter storms (Bakotich 2014). While this model likely provides accurate results on how rain gardens will perform in the event of a specific, 24-hour storm, their hydrologic capabilities in differing rainfall distributions, such as short, high intensity storms and consecutive storms, are still unknown. Additionally, in real life application, runoff would not immediately drain into the rain garden, and the travel times from different locations within the drainage area would vary depending on the topography of the site. As a result, the inflow rates created based on these two assumptions likely differ from what they would be in reality. Historical precipitation data and calculated, site specific time of concentrations could be incorporated into the inflow time series to replicate more accurate inflow rates and varying storm distributions.

The inflow rates were also created assuming that, throughout the entire drainage area, the runoff depth was equal to the rainfall depth. However, this assumption is highly unlikely. The runoff curve number method was developed by the NRCS (known as the SCS at the time) for estimating direct runoff from storm rainfall. This method was developed around the concept that there is some amount of rainfall for which no runoff will occur, known as the initial abstraction, which can be calculated based on the curve number (Mays 2019). However, the NRCS also developed a table outlining the varying curve numbers based on land use, in which the maximum curve number for impervious urban areas is 98 (USDA 1986). This value indicates that even in highly impervious areas, the initial 0.04 in. of rainfall is not converted to runoff. As a result, the inflow volumes calculated based on this assumption are likely larger than they would be for each storm depth. Additionally, the simulations modeled did not account for drainage areas with varying land covers, in which additional rainfall would be removed. Hydraulic modeling programs with the ability to calculate hydrographs based on land cover, such as HydroCAD, could be used in creating the inflow time series, to more accurately model the influence of land cover on inflow volumes and rates.

As noted, GIFMod is a relatively new modeling program that is not yet widely used, therefore, resources on the program are limited. In all of the simulations run, the values input into the model were based on the information provided in the User’s Manual (Massoudieh and Aflaki 2017). While multiple studies have been conducted evaluating the functionality of the program, little to no information is available about the accuracy of its results. However, GIFMod has inverse modeling capabilities, in which parameters can be estimated both deterministically and probabilistically (Massoudieh and Aflaki 2017). The program’s inverse modeling features could be used to compare the modeled results with field data and measure how well the program actually represents reality based on statistical indicators.

Additionally, GIFMod has water quality modeling capabilities that have yet to be broadly utilized. While rain gardens provide many hydraulic and hydrologic benefits, research suggests they are also an effective method for improving water quality. Rain gardens remove pollutants from runoff through a suite of biological and physico-chemical processes, such as plant uptake, microbial metabolism, and sorption. GIFMod has the ability to model these processes, which could be used to analyze the effect of different rain garden configurations on water quality.

## Recommendations

The current Pennsylvania Stormwater Best Management Practices manual was published in 2006, intended to “ensure effective stormwater management to minimize the adverse impacts of stormwater on ground water and surface water resources to support and sustain the social, economic and environmental quality of the Commonwealth” (DEP 2006). Since then, water resources engineering research has advanced and some of the design details of BMPs outlined throughout the manual are now outdated. As a result, the Pennsylvania Department of Environmental Protection is currently in the process of revising the BMP manual to better reflect recent findings. The results found through simulating various residential rain garden configurations with GIFMod draw the conclusion that current rain garden design recommendations are too universal and often too conservative.

The hydrological performance of residential rain gardens is highly variable depending on the physical soil properties. Since the native soil composition varies significantly in different locations throughout Pennsylvania, the hydrologic capacity of a rain garden is strongly dependent on where it is located. Therefore, it is almost arbitrary to provide universal, state-wide rain garden design recommendations, for some locations will be able to manage much larger volumes of water than others. It is recommended that rain garden sizing be designed based on the specific native soil composition of the project site, rather than broad state guidelines.

The current BMP manual recommends a maximum loading ratio of 5:1 (impervious area to infiltration area). Assuming the GIFMod models produced accurate results, some rain gardens can manage much larger drainage areas, while others much smaller, depending on site conditions and usage. Between 1926 and 2003, 92% of precipitation events in Pennsylvania had a rainfall depth of 2 inches or less (DEP 2006). The seven rain gardens modeled in Chapter 4, underlaid by each of the common Pennsylvania soil profiles, were all able to remove 100% of runoff from a 2-inch precipitation event and 5:1 loading ratio, without the maximum ponding depth exceeding 6 inches. Even the native soils with low infiltration capacities could remove runoff from this drainage area solely through infiltration. Besides the two soil profiles representative of Pittsburgh, in which an underdrain would likely be incorporated, the rain gardens modeled were able to remove runoff from drainage areas more than twice the recommended ratio, without the ponding depth exceeding 6 inches. For average rainfall events, the recommended maximum loading ratio is far too conservative.

However, depending on the usage of the rain garden, it may be required to manage less frequent, high intensity storm events, up to a 100-year storm. Typically, outlet structures, such as an emergency spillway or overflow drain, are incorporated into the rain garden design to prevent flooding in the unlikely event of one of these storms. Nonetheless, if rain gardens are the sole stormwater management system for the site, ponding depths would exceed 6 inches from much smaller loading ratios during large storm events.

Overall, it is recommended that rain garden design sizing guidelines be developed based on the native soil composition, rather than universal state-wide guidelines. Although the current recommendations are often too conservative, this is not always the case. Rain gardens' hydrological performance is highly variable, depending on the location, site conditions, and scope of the project. Infiltration-feasible soils can manage much larger drainage areas while remaining within the maximum ponding depth and ponding time requirements, but the current recommended maximum loading ratio may be accurate for less permeable soil compositions. It is proposed that, rather than providing a single maximum loading ratio recommendation, differing loading ratios be provided based on the permeability and porosity of the native soils. With this proposition, soil logs and permeability tests could be conducted at the site to determine the infiltration rate of the native soils. The updated BMP manual would then provide differing maximum loading ratio recommendations between 5:1 and 10:1, each corresponding to a range of infiltration rates. In turn, rain garden sizing would be designed based on the site-specific conditions, optimizing rain gardens' hydrological benefits.

# Appendix A

## Notations

| Parameter | Description |
|---|---|
| $A_g$ | Impervious Surface Area [Square Feet] |
| $A_r$ | Rain Garden Surface Area [Square Feet] |
| $A_T$ | Total Drainage Area [Square Feet] |
| $A_{T,max}$ | Maximum Total Drainage Area [Square Feet] |
| $CN$ | Curve Number |
| $k_S$ | Saturated Hydraulic Conductivity |
| $N$ | Number of Data Points in the Data Set |
| $P$ | Precipitation Depth [Inches] |
| $Q$ | Inflow Water Volume [Cubic Feet] |
| $Q_{depth}$ | Runoff Depth [Inches] |
| $Q_{max}$ | Maximum Inflow Water Volume [Cubic Feet] |
| $R^2$ | Coefficient of Determination |
| $R_{max}$ | Maximum Loading Ratio |
| $RSD$ | Relative Standard Deviation [Percent] |
| $S$ | Potential Maximum Retention After Runoff Begins [Inches] |
| $SD$ | Standard Deviation |
| $\bar{x}$ | Mean of the Data Set |
| $x_i$ | Individual Value in the Data Set |
| $\alpha, \lambda, n$ | Van-Genuchten Parameters |
| $\theta_R$ | Residual Moisture Content |
| $\theta_S$ | Saturated Moisture Content |

# Appendix B

## Variations in Maximum Ponding Depth and Time for Pond to Empty due to Substrate Soil Layer

### Substrate Soil Texture

| Substrate Soil Texture | Inflow Water Volume | | | |
|---|---|---|---|---|
| | 227.5 ft$^3$ | | 280.83 ft$^3$ | |
| | Maximum Ponding Depth [Inches] | Time for Pond to Empty [Hours] | Maximum Ponding Depth [Inches] | Time for Pond to Empty [Hours] |
| Loam | 6.46 | 24.80 | 8.46 | 31.03 |
| Clay | 9.38 | 79.52 | 12.38 | 95.35 |
| Sand | 3.87 | 20.23 | 0.64 | 20.47 |
| Silt | 9.46 | 74.00 | 12.39 | 90.55 |

### Substrate Soil Depth

| Substrate Soil Depth [Feet] | Inflow Water Volume | | | |
|---|---|---|---|---|
| | 227.5 ft$^3$ | | 280.83 ft$^3$ | |
| | Maximum Ponding Depth [Inches] | Time for Pond to Empty [Hours] | Maximum Ponding Depth [Inches] | Time for Pond to Empty [Hours] |
| 1.5 | 6.46 | 24.80 | 8.46 | 31.03 |
| 3 | 6.79 | 23.58 | 8.74 | 28.15 |
| 4.5 | 6.94 | 24.07 | 9.03 | 28.15 |
| 6 | 6.90 | 26.72 | 9.08 | 30.07 |

# Appendix C

## Variations in Maximum Ponding Depth and Time for Pond to Empty due to Native Soil Layer

### Native Soil Texture

| Native Soil Texture | Inflow Water Volume | | | |
|---|---|---|---|---|
| | 227.5 ft$^3$ | | 2275 ft$^3$ | |
| | Maximum Ponding Depth [Inches] | Time for Pond to Empty [Hours] | Maximum Ponding Depth [Inches] | Time for Pond to Empty [Hours] |
| Clay Loam | 6.46 | 24.13 | 132.73 | - |
| Loam | 6.47 | 21.43 | 115.77 | 105.92 |
| Sand | 5.85 | 17.83 | 106.88 | 77.12 |
| Clay | 6.29 | 21.67 | 134.10 | - |
| Silt | 6.49 | 23.60 | 130.98 | - |
| Silt Loam | 6.44 | 22.40 | 126.60 | 174.07 |

### Native Soil Depth

| Native Soil Depth [Feet] | Inflow Water Volume | | | |
|---|---|---|---|---|
| | 227.5 ft$^3$ | | 2275 ft$^3$ | |
| | Maximum Ponding Depth [inches] | Time for Pond to Empty [Hours] | Maximum Ponding Depth [inches] | Time for Pond to Empty [Hours] |
| 5 | 6.52 | 29.35 | 136.03 | - |
| 10 | 6.46 | 24.80 | 132.73 | - |
| 15 | 6.46 | 24.07 | 131.94 | - |
| 20 | 6.47 | 23.83 | 131.52 | - |

# Appendix D

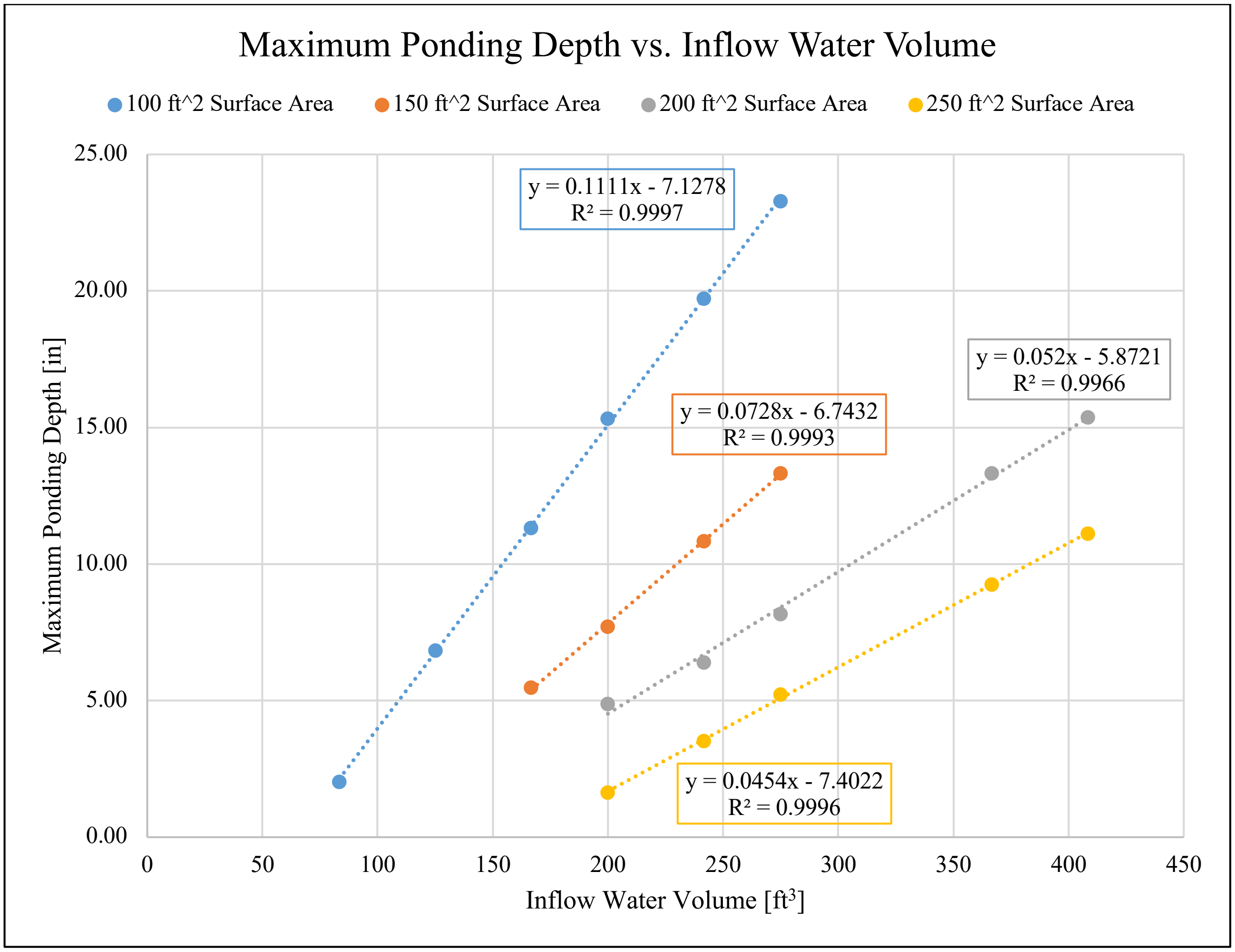
## Maximum Ponding Depths of 200 ft$^2$ Rain Gardens with Pennsylvania Native Soil Conditions

| Location | Soil Composition | Storm Frequency | Storm Depth [Inches] | Inflow Water Volume [Cubic Feet] | Maximum Ponding Depth [Inches] | | Percent Reduction |
|---|---|---|---|---|---|---|---|
| | | | | | Native Soil Composition | 18-Inch Sand Substrate | |
| Pittsburgh | GQF - Gilpin | 2-Year | 2.4 | 200.00 | 6.94 | 4.87 | 29.86% |
| | | 5-Year | 2.9 | 241.67 | 9.23 | 6.41 | 30.57% |
| | | 10-Year | 3.3 | 275.00 | 11.24 | 8.18 | 27.22% |
| | | 50-Year | 4.4 | 366.67 | 16.86 | 13.33 | 20.95% |
| | | 100-Year | 4.9 | 408.33 | 19.45 | 15.37 | 20.98% |
| | GQF - Upshur | 2-Year | 2.4 | 200.00 | 9.54 | 4.04 | 57.71% |
| | | 5-Year | 2.9 | 241.67 | 12.35 | 6.94 | 43.83% |
| | | 10-Year | 3.3 | 275.00 | 14.68 | 9.50 | 35.30% |
| | | 50-Year | 4.4 | 366.67 | 21.21 | 15.73 | 25.84% |
| | | 100-Year | 4.9 | 408.33 | 24.21 | 18.65 | 22.97% |
| State College | VrF - Varilla | 2-Year | 2.7 | 225.00 | 4.47 | 2.49 | 44.29% |
| | | 5-Year | 3.3 | 275.00 | 5.82 | 0.75 | 87.13% |
| | | 10-Year | 3.8 | 316.67 | 7.00 | 1.57 | 77.55% |
| | | 50-Year | 5.2 | 433.33 | 10.42 | 5.45 | 47.71% |
| | | 100-Year | 5.9 | 491.67 | 12.21 | 5.12 | 58.08% |
| | VrF - Laidig | 2-Year | 2.7 | 225.00 | 6.14 | 2.33 | 62.05% |
| | | 5-Year | 3.3 | 275.00 | 7.98 | 0.51 | 93.59% |
| | | 10-Year | 3.8 | 316.67 | 9.58 | 1.36 | 85.77% |
| | | 50-Year | 5.2 | 433.33 | 14.28 | 3.76 | 73.68% |
| | | 100-Year | 5.9 | 491.67 | 16.77 | 4.99 | 70.25% |
| Erie | VeB | 2-Year | 2.6 | 216.67 | 6.70 | 1.95 | 70.86% |
| | | 5-Year | 3.2 | 266.67 | 8.74 | 2.69 | 69.29% |
| | | 10-Year | 3.7 | 308.33 | 10.52 | 3.24 | 69.18% |
| | | 50-Year | 5.1 | 425.00 | 15.83 | 3.17 | 79.97% |
| | | 100-Year | 5.8 | 483.33 | 18.64 | 4.53 | 75.69% |
| Scranton | UA | 2-Year | 2.6 | 216.67 | 3.15 | 2.30 | 26.87% |
| | | 5-Year | 3.2 | 266.67 | 4.93 | 3.77 | 23.45% |
| | | 10-Year | 3.7 | 308.33 | 5.95 | 4.48 | 24.74% |
| | | 50-Year | 5.4 | 450.00 | 6.70 | 5.29 | 21.02% |
| | | 100-Year | 6.4 | 533.33 | 8.36 | 6.72 | 19.60% |
| Philadelphia | UdB | 2-Year | 3.3 | 275.00 | 8.91 | 3.15 | 64.66% |
| | | 5-Year | 4.1 | 341.67 | 11.83 | 1.42 | 88.04% |
| | | 10-Year | 4.8 | 400.00 | 14.54 | 2.74 | 81.17% |
| | | 50-Year | 6.7 | 558.33 | 22.37 | 6.10 | 72.75% |
| | | 100-Year | 7.6 | 633.33 | 26.34 | 7.74 | 70.61% |

# Appendix E

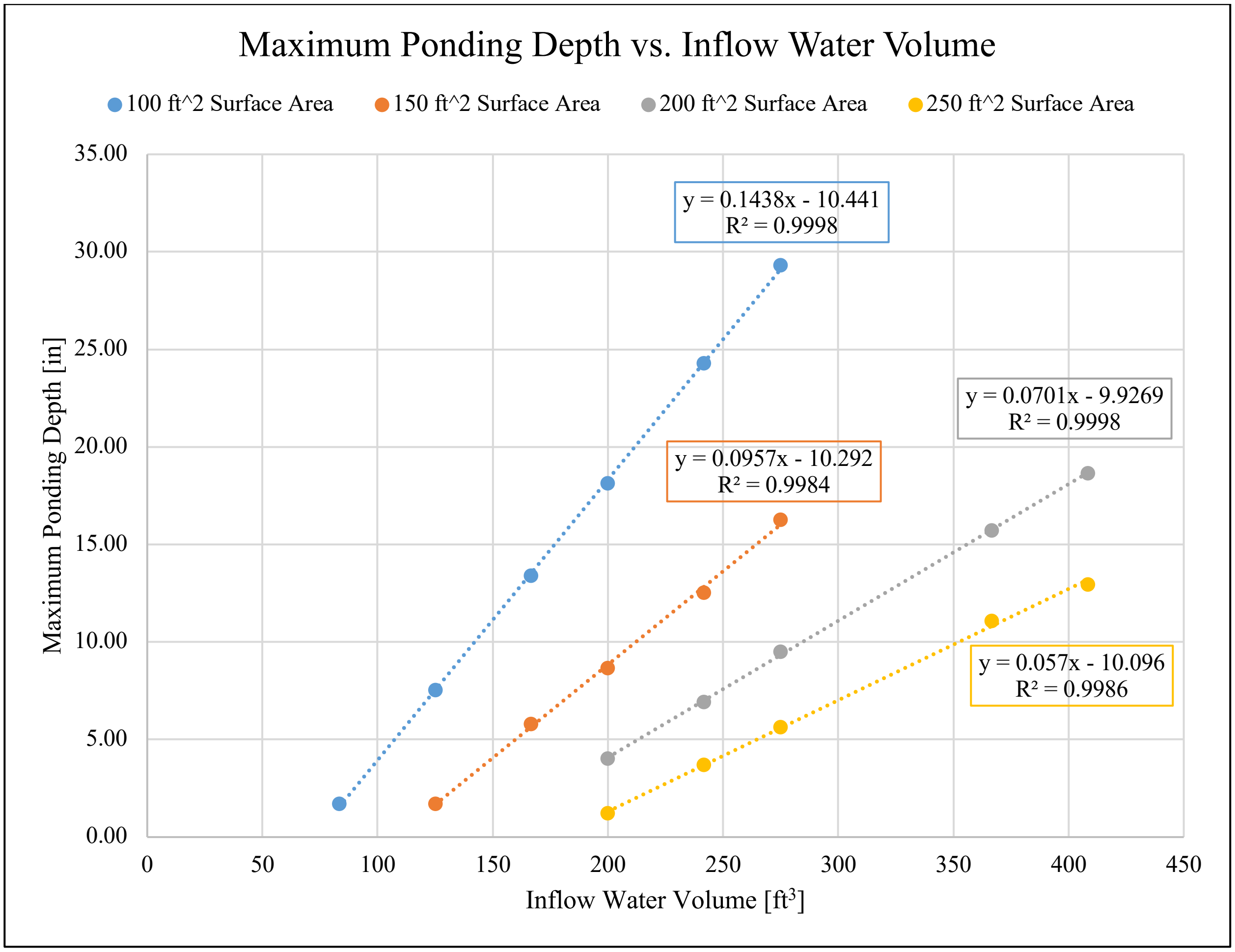
## Relationships Between Inflow Water Volume and Maximum Ponding Depth

### Pittsburgh (Gilpin)



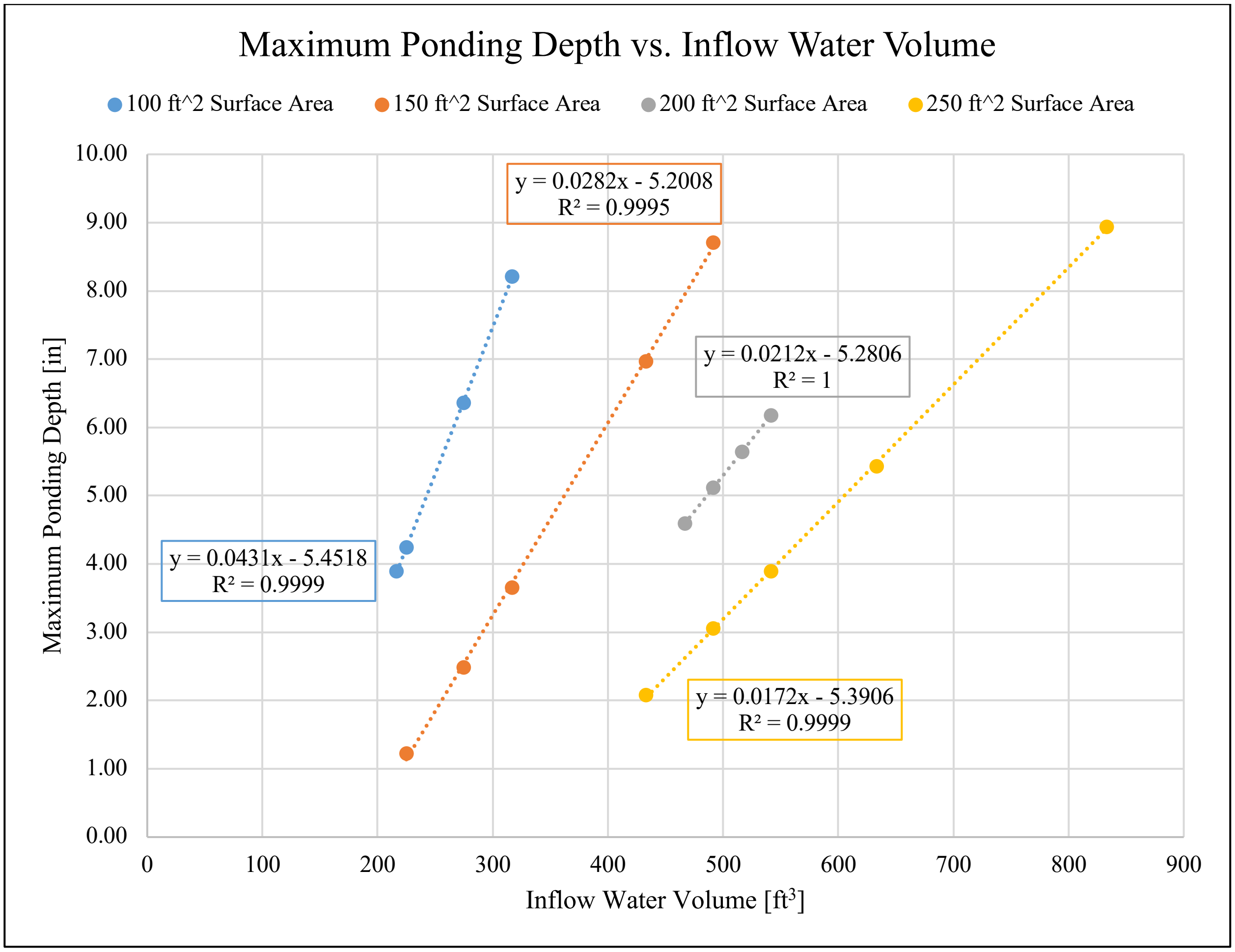
| Surface Area | Slope | Y-Intercept | $R^2$ |
|---|---|---|---|
| **100 ft$^2$** | 0.1111 | -7.1278 | 0.9997 |
| **150 ft$^2$** | 0.0728 | -6.7432 | 0.9993 |
| **200 ft$^2$** | 0.0520 | -5.8721 | 0.9966 |
| **250 ft$^2$** | 0.0454 | -7.4022 | 0.9996 |

**Pittsburgh (Upshur)**



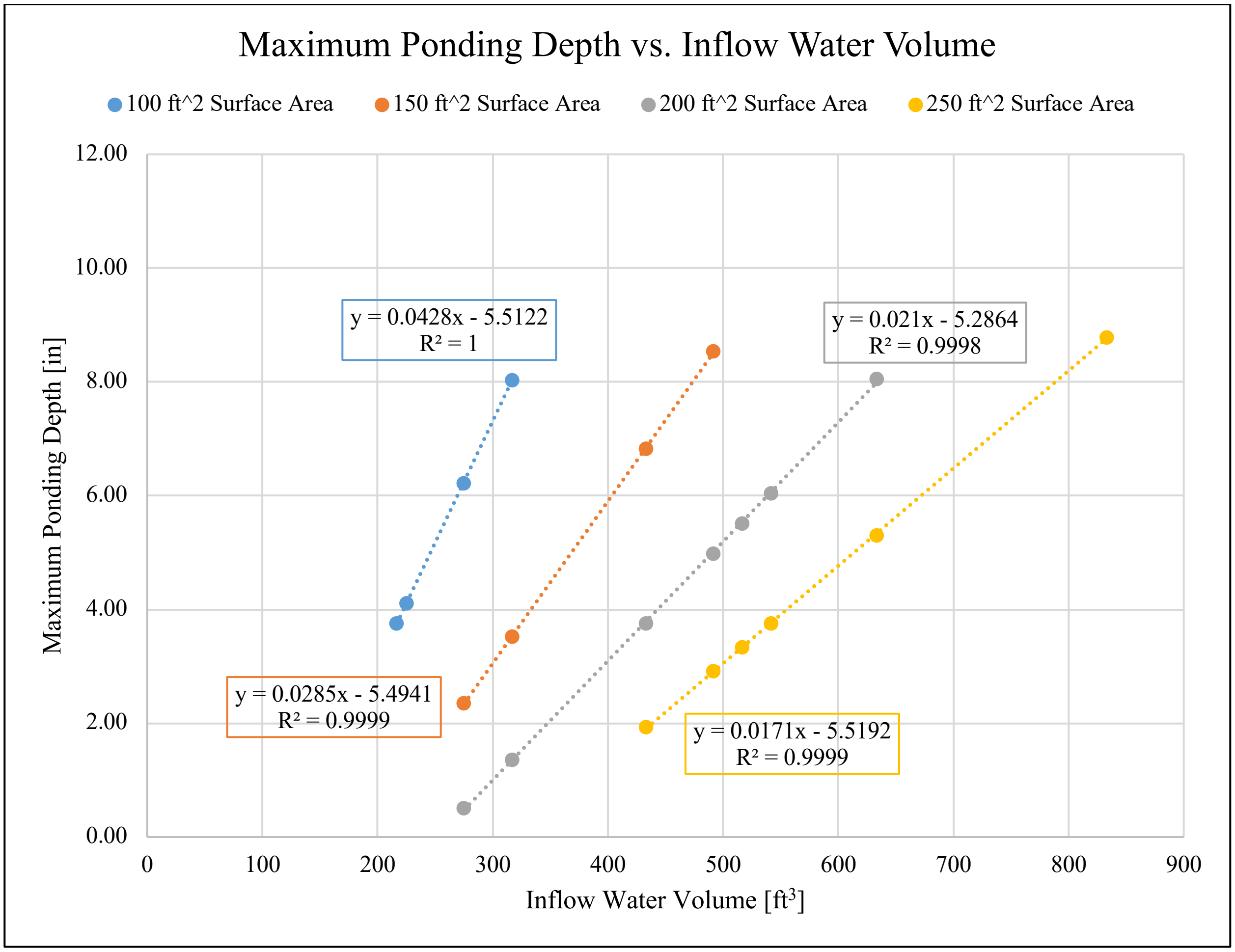
| **Surface Area** | **Slope** | **Y-Intercept** | **$R^2$** |
|---|---|---|---|
| **100 ft$^2$** | 0.1438 | -10.4414 | 0.9998 |
| **150 ft$^2$** | 0.0957 | -10.2923 | 0.9984 |
| **200 ft$^2$** | 0.0701 | -9.9269 | 0.9998 |
| **250 ft$^2$** | 0.0570 | -10.0962 | 0.9986 |

## State College (Varilla)



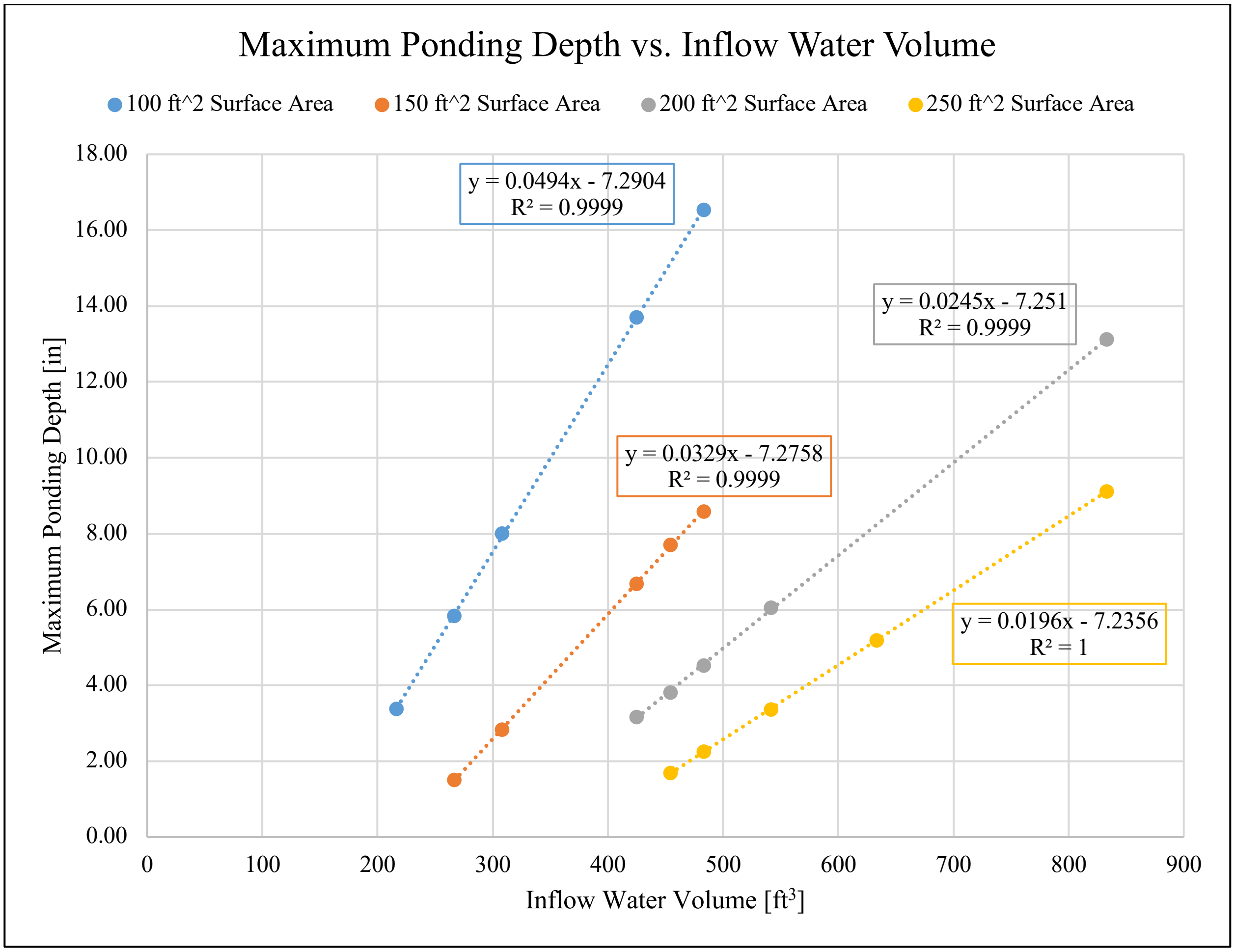
| **Surface Area** | **Slope** | **Y-Intercept** | **R$^2$** |
|---|---|---|---|
| **100 ft$^2$** | 0.0431 | -5.4518 | 0.9999 |
| **150 ft$^2$** | 0.0282 | -5.2008 | 0.9995 |
| **200 ft$^2$** | 0.0212 | -5.2806 | 1.0000 |
| **250 ft$^2$** | 0.0172 | -5.3906 | 0.9999 |

## State College (Laidig)



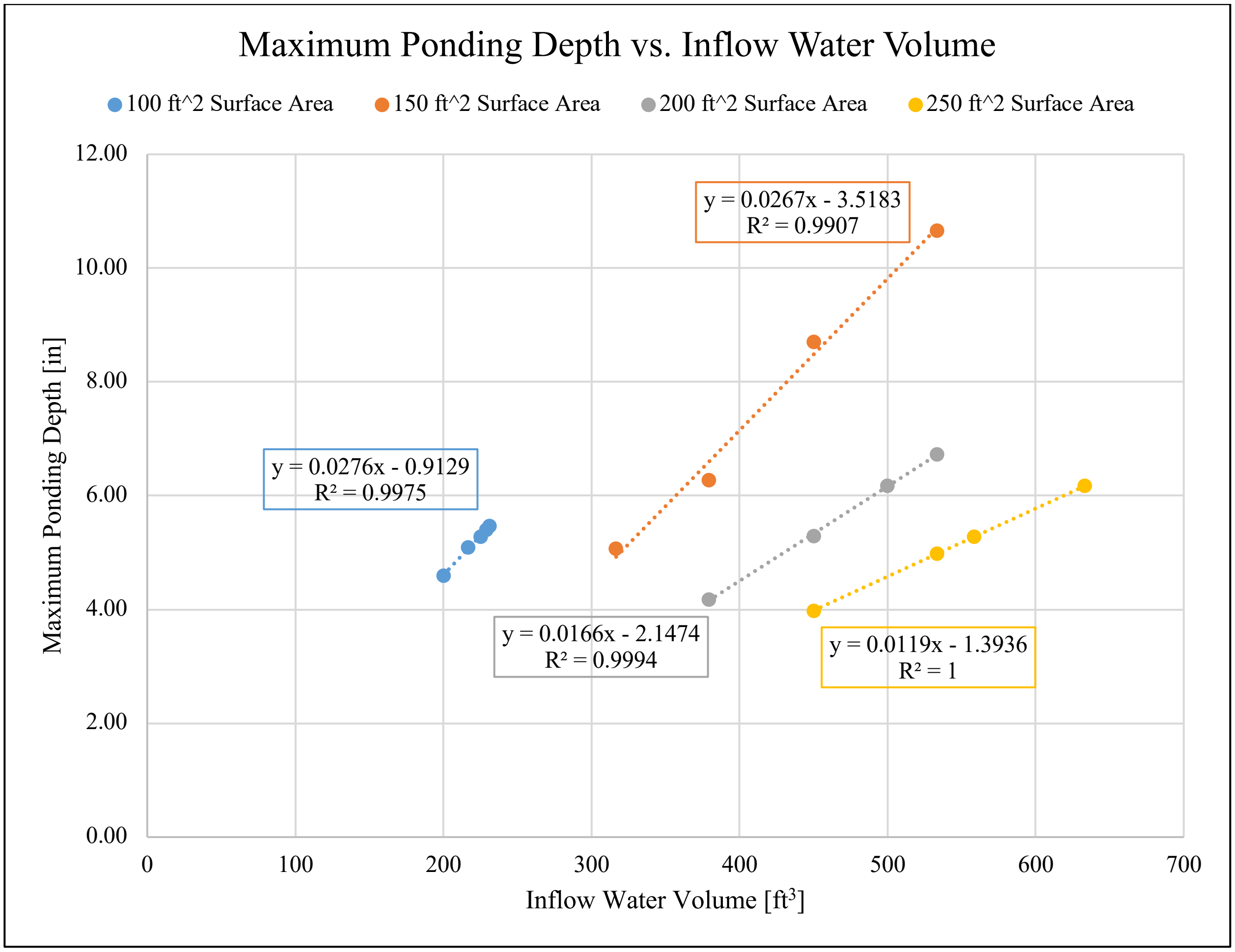
| **Surface Area** | **Slope** | **Y-Intercept** | **$R^2$** |
|---|---|---|---|
| **100 $ft^2$** | 0.0428 | -5.5122 | 1.0000 |
| **150 $ft^2$** | 0.0285 | -5.4941 | 0.9999 |
| **200 $ft^2$** | 0.0210 | -5.2864 | 0.9998 |
| **250 $ft^2$** | 0.0171 | -5.5192 | 0.9999 |

## Erie



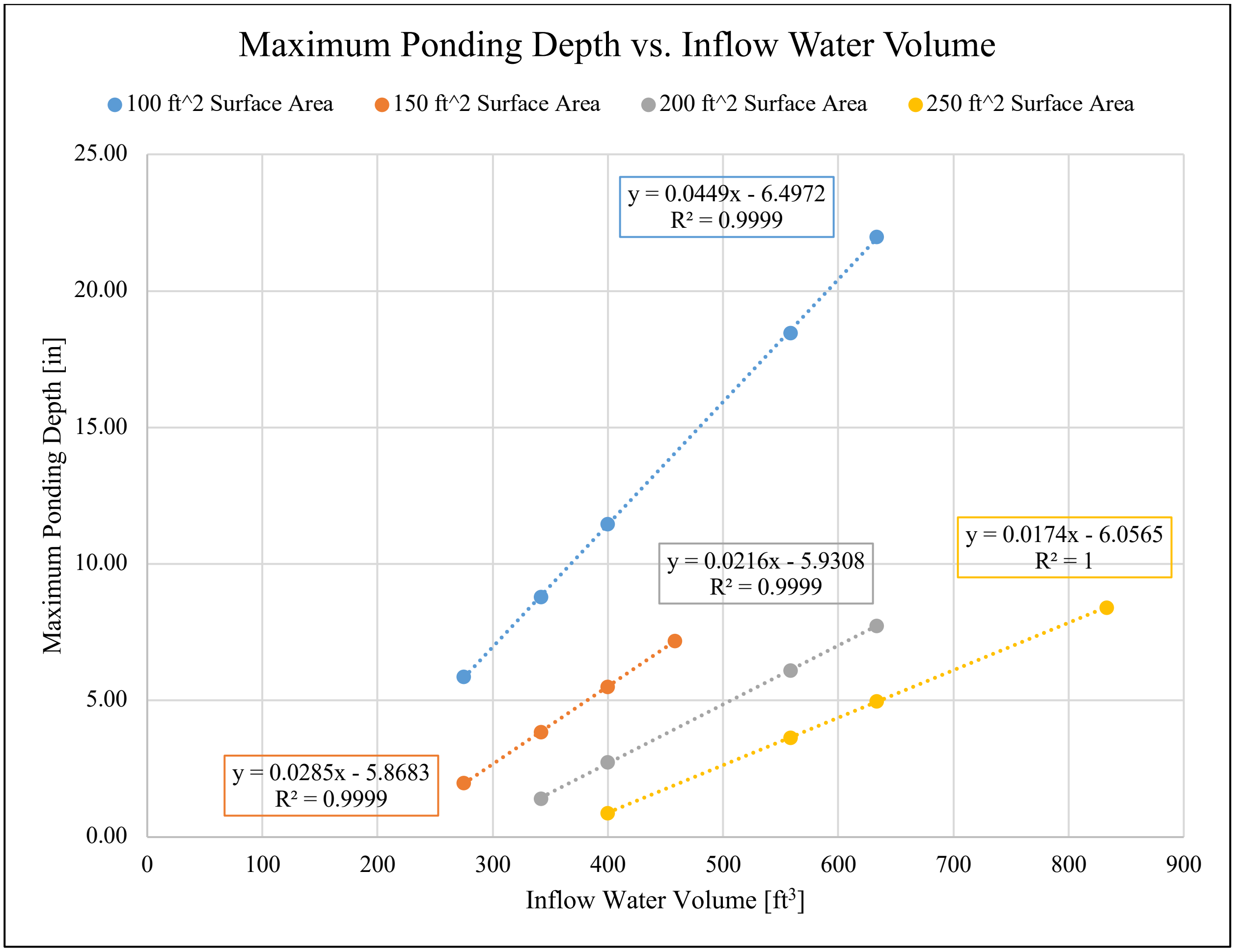
| Surface Area | Slope | Y-Intercept | $R^2$ |
|---|---|---|---|
| **100 $ft^2$** | 0.0494 | -7.2904 | 0.9999 |
| **150 $ft^2$** | 0.0329 | -7.2758 | 0.9999 |
| **200 $ft^2$** | 0.0245 | -7.2510 | 0.9999 |
| **250 $ft^2$** | 0.0196 | -7.2356 | 1.0000 |

## Scranton



| **Surface Area** | **Slope** | **Y-Intercept** | **$R^2$** |
|---|---|---|---|
| **100 $ft^2$** | 0.0276 | -0.9129 | 0.9975 |
| **150 $ft^2$** | 0.0267 | -3.5183 | 0.9907 |
| **200 $ft^2$** | 0.0166 | -2.1474 | 0.9994 |
| **250 $ft^2$** | 0.0119 | -1.3936 | 1.0000 |

## Philadelphia



| **Surface Area** | **Slope** | **Y-Intercept** | **$R^2$** |
|---|---|---|---|
| **100 $ft^2$** | 0.0449 | -6.4972 | 0.9999 |
| **150 $ft^2$** | 0.0285 | -5.8683 | 0.9999 |
| **200 $ft^2$** | 0.0216 | -5.9308 | 0.9999 |
| **250 $ft^2$** | 0.0174 | -6.0565 | 1.0000 |

# Appendix F

## Maximum Catchment Area

| Storm Frequency | Storm Depth [inches] | Maximum Catchment Area [Cubic Feet]<br>Rain Garden Surface Area<br>100 ft$^2$ | 150 ft$^2$ | 200 ft$^2$ | 250 ft$^2$ |
|---|---|---|---|---|---|
| **Pittsburgh (Gilpin)** | | | | | |
| **2-Year Storm** | 2.4 | 591 | 875 | 1142 | 1475 |
| **5-Year Storm** | 2.9 | 489 | 724 | 945 | 1221 |
| **10-Year Storm** | 3.3 | 430 | 636 | 831 | 1073 |
| **50-Year Storm** | 4.4 | 322 | 477 | 623 | 805 |
| **100-Year Storm** | 4.9 | 289 | 429 | 559 | 723 |
| **Pittsburgh (Upshur)** | | | | | |
| **2-Year Storm** | 2.4 | 572 | 851 | 1137 | 1411 |
| **5-Year Storm** | 2.9 | 473 | 705 | 941 | 1168 |
| **10-Year Storm** | 3.3 | 416 | 619 | 827 | 1026 |
| **50-Year Storm** | 4.4 | 312 | 464 | 620 | 770 |
| **100-Year Storm** | 4.9 | 280 | 417 | 557 | 691 |
| **State College (Varilla)** | | | | | |
| **2-Year Storm** | 2.7 | 1182 | 1767 | 2370 | 2949 |
| **5-Year Storm** | 3.3 | 967 | 1446 | 1939 | 2413 |
| **10-Year Storm** | 3.8 | 840 | 1256 | 1684 | 2095 |
| **50-Year Storm** | 5.2 | 614 | 918 | 1231 | 1531 |
| **100-Year Storm** | 5.9 | 541 | 809 | 1085 | 1350 |
| **State College (Laidig)** | | | | | |
| **2-Year Storm** | 2.7 | 1197 | 1793 | 2393 | 2986 |
| **5-Year Storm** | 3.3 | 979 | 1467 | 1958 | 2443 |
| **10-Year Storm** | 3.8 | 850 | 1274 | 1701 | 2122 |
| **50-Year Storm** | 5.2 | 621 | 931 | 1243 | 1551 |
| **100-Year Storm** | 5.9 | 548 | 820 | 1095 | 1367 |
| **Erie** | | | | | |
| **2-Year Storm** | 2.6 | 1243 | 1863 | 2501 | 3113 |
| **5-Year Storm** | 3.2 | 1010 | 1514 | 2032 | 2529 |
| **10-Year Storm** | 3.7 | 873 | 1309 | 1757 | 2188 |
| **50-Year Storm** | 5.1 | 634 | 950 | 1275 | 1587 |
| **100-Year Storm** | 5.8 | 557 | 835 | 1121 | 1396 |
| **Scranton** | | | | | |
| **2-Year Storm** | 2.6 | 1156 | 1647 | 2262 | 2856 |
| **5-Year Storm** | 3.2 | 939 | 1339 | 1838 | 2321 |
| **10-Year Storm** | 3.7 | 812 | 1158 | 1590 | 2007 |
| **50-Year Storm** | 5.4 | 557 | 793 | 1089 | 1375 |
| **100-Year Storm** | 6.4 | 470 | 669 | 919 | 1160 |
| **Philadelphia** | | | | | |
| **2-Year Storm** | 3.3 | 1013 | 1516 | 2011 | 2522 |
| **5-Year Storm** | 4.1 | 815 | 1220 | 1618 | 2030 |
| **10-Year Storm** | 4.8 | 696 | 1042 | 1382 | 1734 |
| **50-Year Storm** | 6.7 | 499 | 747 | 990 | 1242 |
| **100-Year Storm** | 7.6 | 440 | 658 | 873 | 1095 |

# Appendix G

## Maximum Loading Ratios

| **Storm Frequency** | **Storm Depth [inches]** | **Rain Garden Surface Area** | | | |
|---|---|---|---|---|---|
| | | **100 ft$^2$** | **150 ft$^2$** | **200 ft$^2$** | **250 ft$^2$** |
| **Pittsburgh (Gilpin)** | | | | | |
| **2-Year Storm** | 2.4 | 5:1 | 5:1 | 5:1 | 5:1 |
| **5-Year Storm** | 2.9 | 4:1 | 4:1 | 4:1 | 4:1 |
| **10-Year Storm** | 3.3 | 3:1 | 3:1 | 3:1 | 3:1 |
| **50-Year Storm** | 4.4 | 2:1 | 2:1 | 2:1 | 2:1 |
| **100-Year Storm** | 4.9 | 2:1 | 2:1 | 2:1 | 2:1 |
| **Pittsburgh (Upshur)** | | | | | |
| **2-Year Storm** | 2.4 | 5:1 | 5:1 | 5:1 | 5:1 |
| **5-Year Storm** | 2.9 | 4:1 | 4:1 | 4:1 | 4:1 |
| **10-Year Storm** | 3.3 | 3:1 | 3:1 | 3:1 | 3:1 |
| **50-Year Storm** | 4.4 | 2:1 | 2:1 | 2:1 | 2:1 |
| **100-Year Storm** | 4.9 | 2:1 | 2:1 | 2:1 | 2:1 |
| **State College (Varilla)** | | | | | |
| **2-Year Storm** | 2.7 | 11:1 | 11:1 | 11:1 | 11:1 |
| **5-Year Storm** | 3.3 | 9:1 | 9:1 | 9:1 | 9:1 |
| **10-Year Storm** | 3.8 | 7:1 | 7:1 | 7:1 | 7:1 |
| **50-Year Storm** | 5.2 | 5:1 | 5:1 | 5:1 | 5:1 |
| **100-Year Storm** | 5.9 | 4:1 | 4:1 | 4:1 | 4:1 |
| **State College (Laidig)** | | | | | |
| **2-Year Storm** | 2.7 | 11:1 | 11:1 | 11:1 | 11:1 |
| **5-Year Storm** | 3.3 | 9:1 | 9:1 | 9:1 | 9:1 |
| **10-Year Storm** | 3.8 | 8:1 | 7:1 | 8:1 | 7:1 |
| **50-Year Storm** | 5.2 | 5:1 | 5:1 | 5:1 | 5:1 |
| **100-Year Storm** | 5.9 | 4:1 | 4:1 | 4:1 | 4:1 |
| **Erie** | | | | | |
| **2-Year Storm** | 2.6 | 11:1 | 11:1 | 11:1 | 11:1 |
| **5-Year Storm** | 3.2 | 9:1 | 9:1 | 9:1 | 9:1 |
| **10-Year Storm** | 3.7 | 8:1 | 8:1 | 8:1 | 8:1 |
| **50-Year Storm** | 5.1 | 5:1 | 5:1 | 5:1 | 5:1 |
| **100-Year Storm** | 5.8 | 5:1 | 5:1 | 5:1 | 5:1 |
| **Scranton** | | | | | |
| **2-Year Storm** | 2.6 | 11:1 | 10:1 | 10:1 | 10:1 |
| **5-Year Storm** | 3.2 | 8:1 | 8:1 | 8:1 | 8:1 |
| **10-Year Storm** | 3.7 | 7:1 | 7:1 | 7:1 | 7:1 |
| **50-Year Storm** | 5.4 | 5:1 | 4:1 | 4:1 | 5:1 |
| **100-Year Storm** | 6.4 | 4:1 | 3:1 | 4:1 | 4:1 |
| **Philadelphia** | | | | | |
| **2-Year Storm** | 3.3 | 9:1 | 9:1 | 9:1 | 9:1 |
| **5-Year Storm** | 4.1 | 7:1 | 7:1 | 7:1 | 7:1 |
| **10-Year Storm** | 4.8 | 6:1 | 6:1 | 6:1 | 6:1 |
| **50-Year Storm** | 6.7 | 4:1 | 4:1 | 4:1 | 4:1 |
| **100-Year Storm** | 7.6 | 3:1 | 3:1 | 3:1 | 3:1 |

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# ACADEMIC VITA

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## Education

**Bachelor of Science in Civil Engineering**
***Schreyer Honors College***
*The Pennsylvania State University, University Park, PA*
Dean's List: Fall 2017, Spring 2018, Fall 2018, Spring 2019, Fall 2019, Spring 2020, Fall 2021
Anticipated Graduation: May 2021

## Work Experience

**Two River Engineering** **Summer 2018 and 2019**
*Colts Neck, NJ*

- Performed site reconnaissance work, including site evaluations, soil logs, permeability tests, and surveys
- Drafted plots to prepare base maps for site plans and other engineering design drawings
- Managed office work, including assembling application packages, reproducing necessary plans and delivering legal permits
- Assisted on a variety of engineering projects including subdivisions, septic tank and disposal field designs, storm water management system design, and variance applications

**Kimley-Horn – Virtual Internship Program** **Summer 2020**
*Philadelphia, PA*

- Shadowed employees to learn about the current projects the company is working on and the technologies utilized in completing them
- Participated in a design challenge, in which we worked with other interns to create a land development, transportation, and landscape architect plan for a commercial property
- Met with the executive officers of the company to learn how the business aspect of the company is run

## Honors

**Carpenter and Masland Engineering Scholarship** **2021**

**Kinsey Honors Scholarship** **2020**

**Tau Beta Pi Engineering Honors Society** **2019**

- Top one twelfth of Penn State engineering students

**Chi Epsilon Civil Engineering Honors Society** **2019**

- Top one third of Penn State civil engineering students

**Alpha Lambda Delta and Phi Eta Sigma Honors Society** **2018**

- Penn State student who maintained a GPA over a 3.5

## Software

SolidWorks
MATLAB
R
AutoCAD
Microsoft Office
GIFMod
HEC-HMS
HEC-RAS

## Activities

**Kappa Alpha Theta Sorority** **2018-Present**
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