ANALYSIS OF A FLOW REGIME:
Understanding the Effectiveness of the Headwaters Approach to Restoration and Investigating how an Imperfect Rain Gauge Influences that Understanding

By

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ABSTRACT

This research is part of the Delaware River Watershed Initiative (DRWI), funded by the William Penn Foundation (WPF). The ultimate goal of this research was to establish an increased understanding of how to restore the headwaters of the East Branch of Indian Creek to the extent that there is a notable change in flow regime. This goal was accomplished in a two-part process. The first step of this research involved increasing understanding of how an imperfect rain gauge influences analysis of a particular flow regime. After establishing an increased understanding of how the limitations of various rain gauges influence the US Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM), the second step of this research was to increase the understanding of the effectiveness of rain garden installation as a means of stream restoration.

The rain gauge evaluation revealed the importance of checking recorded data with independent sources, calibrating installed instruments, and installing instrumentation in a location that can be easily accessed for regular maintenance. These processes allow for malfunctioning equipment to be identified and addressed in a timely manner. Rain garden analysis concluded that the volume reduction resulting from the identified, practical rain garden opportunities in Narberth Borough would be insufficient to cause significant peak flow reduction immediately downstream in the headwaters of the East Branch of Indian Creek. Therefore, it is suggested that future research be conducted to investigate alternative benefits of SCM installation. Although it was concluded that the impact of the proposed rain gardens on peak flow in the East Branch of Indian Creek would be insignificant, the characterization of the current health of the creek remains unclear. When using various flow metrics to quantify the pre-restoration health of the East Branch of Indian Creek, it was determined that a thorough understanding of base flow is necessary to accurately analyze the

health of the given flow regime. Thus, it is suggested the future research be conducted to develop a more comprehensive base flow profile for the East Branch of Indian Creek.

PROBLEM STATEMENT

This research is part of the Delaware River Watershed Initiative (DRWI), funded by the William Penn Foundation (WPF). The ultimate goal of this research is to establish an increased understanding of how to restore the headwaters of a particular creek to the extent that there is a notable change in flow regime. This will be accomplished in a two-part process.

The first step of this research will be to increase understanding of how an imperfect rain gauge influences analysis of a particular flow regime. To complete this task, three versions of the US Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM) will be created for the East Branch of Indian Creek watershed. All aspects of the three models will be kept the same, except that each model will be calibrated to a unique rain gage. This is a case where no one rain gauge is obviously preferable. The three uniquely calibrated models will then be used to evaluate the flow regime for a typical water year. It is expected that the distinctions in the flow regimes for the three models will demonstrate how the imperfections associated with each rain gauge alters the user's understanding of the health of the watershed. Thus, this research aims to provide insight into the extent to which an imperfect rain gauge will alter the researcher's understanding of restoration success in terms of water quantity. Furthermore, this research aims to assist restoration professionals who may not have access to an ideal rain gauge.

After establishing an increased understanding of how the limitations of each rain gauge influence SWMM, the second step of this research will be to increase the understanding of the effectiveness of a particular approach to stream restoration. After meeting with key municipal officials from the watershed in question, various opportunities for storm water control measure (SCM) implementation were identified. These opportunities included both implementation on public land

and potentially providing subsides for installation on private, residential land. This research aims to evaluate whether a notable change in flow regime can be observed after addressing only those SCM opportunities on public land. If such opportunities are insufficient to cause a significant change in flow regime, this research aims to identify how many homeowners must embrace a rain garden on their property in order to establish a notable change in flow regime for the creek in question.

CHAPTER 1: BACKGROUND AND LITERATURE REVIEW

I. Site Description

A. Overview

The research evaluates the East Brach of Indian Creek, in Narberth Borough and Lower Merion, Pennsylvania. The East Branch of Indian Creek is a tributary of Cobbs Creek in the Philadelphia area of Pennsylvania in the United States. Figure 1 displays an image of the East Branch of Indian Creek Watershed.

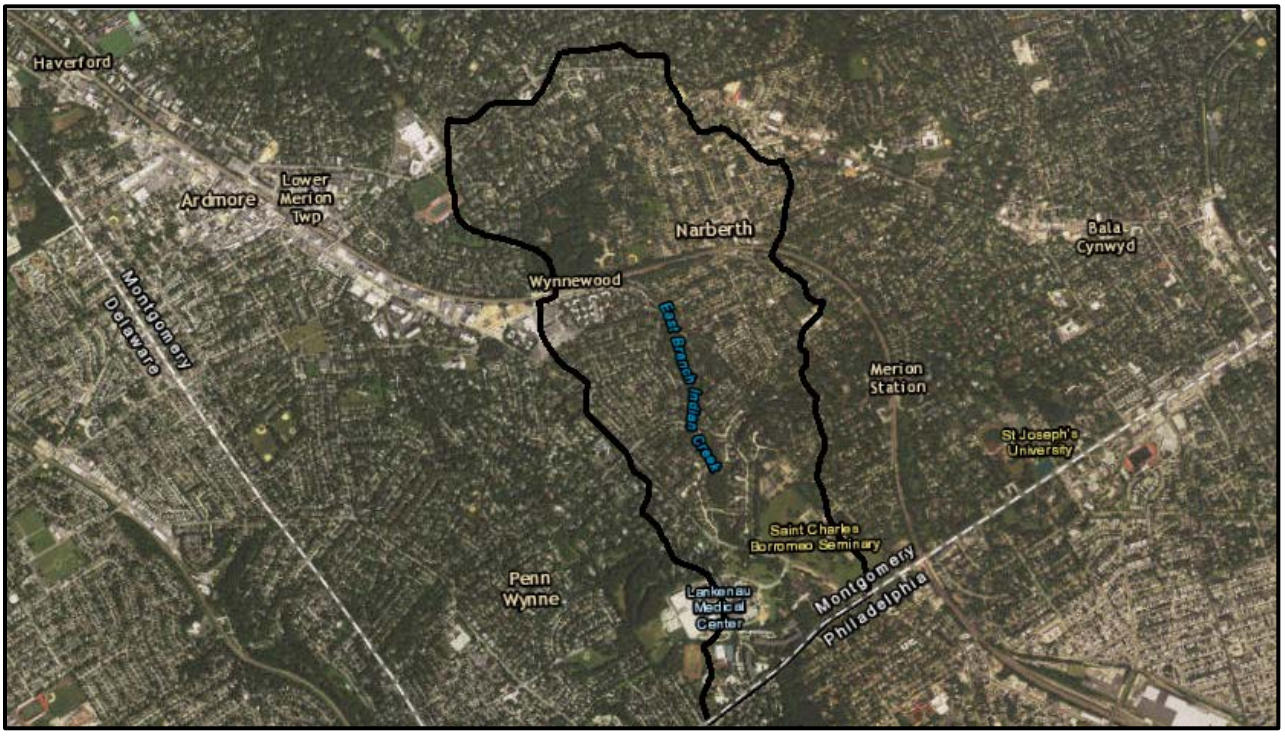

Figure 1: East Branch of Indian Creek Watershed

The watershed draining into the creek is made up of approximately 2,200 diverse properties, ranging from parks to single family homes to large institutional structures (Lower Merion Conservancy 2014). The portion of the East Branch of Indian Creek watershed being evaluated in this study is approximately 3.15 km^2 and 31% impervious. The creek itself ranges from

approximately 1 to 6 meters in width, and the creek bed ranges from concrete culvert to vegetated, unchannelized flow. In general, the creek's depth is between 3 cm and 30 cm, with some pockets of deeper water. The portion of the creek being evaluated is approximately 2.5 km long. Figure 2 displays images of three diverse sections of the creek.

Figure 2: Varying Sections of the East Branch of Indian Creek

To provide some social context for the area, Narberth Borough is approximately 1.3 km^2 and had a 2010 Census population of 4,282 (Narberth Borough 2008; U. S. Census Bureau 2015). As of the 2010 census, the median age in Narberth was 37.4, approximately 97.5% of residents attained a high school degree or higher, and the median household income was $88,090 (U. S. Census Bureau 2015). Lower Merion Township is a larger area, covering approximately 61.2 km2 with total 2010 Census population of 57,825 (Lower Merion Conservancy 2014; U. S. Census Bureau 2015). As of the 2010 Census, the median age in Lower Merion was 43.5, approximately 97.0% of residents attained a high school degree or higher, and the median household income was $115,657 (U. S. Census Bureau 2015).

B. Site Significance

The East Branch of Indian Creek watershed is of particular interest, because it is located at the headwaters of Cobbs Creek. Improving the ability to effectively model headwaters areas is important for improving the effectiveness of the headwaters approach to restoration. The headwaters approach to restoration is discussed in greater detail in the *Overview of Stream Restoration* section of this Literature Review.

When this research began, restoration plans were already underway in the headwaters of the East Branch of Indian Creek. In 2014, the National Fish and Wildlife Foundation awarded a grant to the Lower Merion Conservancy to improve water quality in the creek (Pennsylvania Environmental Council and William Penn Foundation 2015). As of August 2016, as part of this grant, a riparian buffer has been implemented along portions of the creek running through Narbrook Park, a private residential neighborhood in Narberth Borough. The estimated costs of the buffer were approximately $15K. There are design plans to construct a swale system that would run between a baseball field in Narberth Park and Windsor Ave. The estimated costs of the swale system were $180K (Pennsylvania Environmental Council and William Penn Foundation 2015). All restoration efforts described in this report are part of DRWI, funded by the William Penn Foundation.

II. Overview of Stream Impairment

A. Brief History of Stream Impairment

Improving the effectiveness of restoration efforts is relevant, because the current state of river impairment is significant. For instance, as of 2007, “of the 5.3 million kilometers of rivers in the coterminous United States, about 79% are affected by human activities and another 19% drowned by reservoirs, leaving only 2% relatively unimpacted…and more than one-third of the rivers are

officially listed as impaired or polluted" (Palmer et al. 2007). As a result of this degradation of stream health, in the United States, stream restoration has become a "major business with over one billion dollars spent on projects annually" (Schwartz et al. 2009). Despite wide-spread efforts towards stream restoration, impairment of stream ecosystems in urbanized watersheds remains a worldwide problem (Walsh et al. 2005).

Streams are low elevation points in their surrounding landscape, and, therefore, are strongly influenced by the warming, pollutants, and stormwater that typify catchment urbanization (Violin et al. 2011). Since the mid-20th century, when many countries experienced rapid urbanization and a significant increase in impervious land cover (Burns et al. 2012), the negative effects of urbanization on stream ecosystems have been well documented (Booth and Jackson 1997; Meyer et al. 2005; Paul and Meyer 2001; Walsh et al. 2005).

B. Disturbance to Flow Regimes

Urbanization disturbs natural flow regimes in a number of ways. For instance, the negative effects of urbanization on stream ecosystems "include altered base flow and unstable hydrology with frequent, short duration, high-peak floods" (Violin et al. 2011). This is because the replacement of vegetation with impervious surfaces results in reduced infiltration and evaporation, and thus an increase in total volume of stormwater runoff. Reduced infiltration results in less water available to recharge the groundwater table and, therefore, lower magnitude base flows. It is also known that the "ecological consequences of reduced base flows are likely to be large, given their importance in providing habitat for instream biota" (Burns et al. 2012). Adding to the hydrologic disturbance, the conventional method of handling urban stormwater is known as the "drainage efficiency approach." Using the drainage efficiency approach, engineers rout stormwater runoff directly to receiving waters using pipes and channels that provide limited detention time. This results in an

increased volume of water reaching the reviving waters at much faster paces than those of pre-development (Burns et al. 2012).

As an example of the disturbance to flow regimes being experienced in the particular watershed being evaluated in this study, Figure 3 depicts groundwater levels from 2011 through 2016. The figure displays a steady decrease in groundwater levels over time, which may be the result of reduced infiltration and less water available to recharge the groundwater table. Data was taken from a U.S. Geological Survey monitoring well, approximately 2 km from the outlet of the East Branch of Indian Creek watershed (2016)

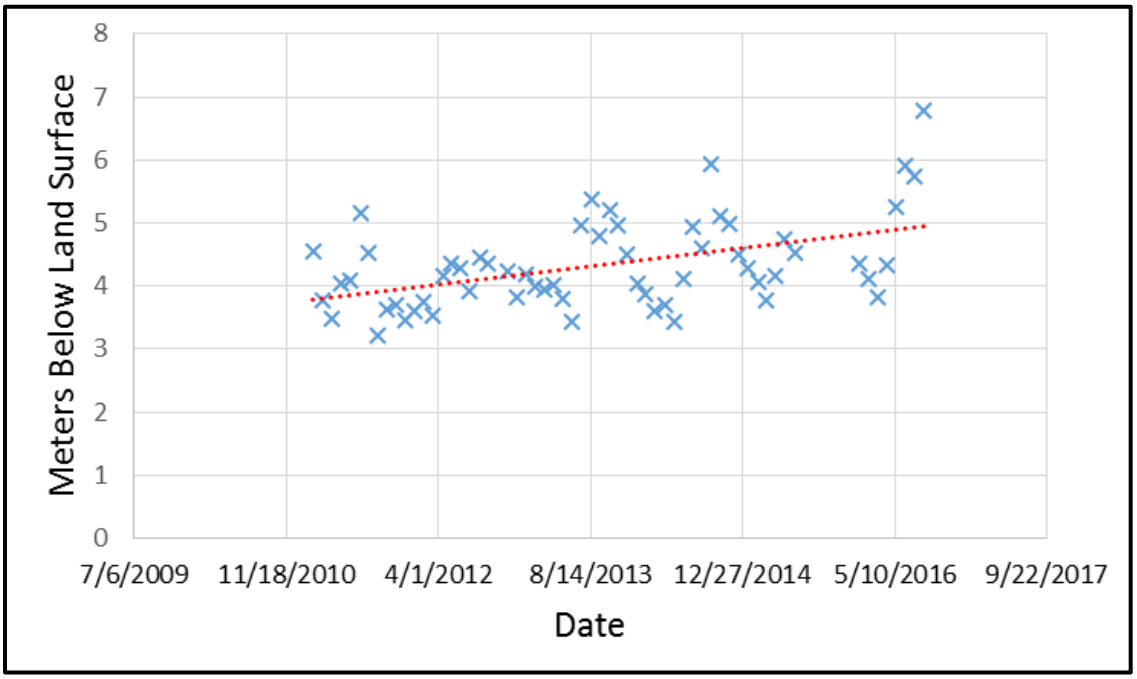

Figure 3: Groundwater Levels

C. Water Pollution

In addition to causing disturbances in flow regimes, urbanization also causes an increase in water pollution, primarily in the form of nonpoint source pollution. As defined by the EPA (2016),

nonpoint source pollution comes from many diffuse sources, as opposed to one specific source, and it is "caused by rainfall or snowmelt moving over and through the ground." This precipitation is able to mobilize a variety of pollutants, and, when the precipitation reaches receiving water bodies, any pollutants carried by the precipitation are deposited into the receiving water bodies. Thus, the increase in stormwater volume flowing into urbanized water bodies has resulted in an increase in non-point source pollution. In a number of states, nonpoint source pollution is the leading cause of water pollution. In suburban areas, such as the site evaluated in this study, common pollutants transported via precipitation can include fertilizers, herbicides, and insecticides from residential areas; oil, grease and toxic chemicals from urban areas; sediment from eroding streambanks; or bacteria and nutrients from pet wastes. Importantly, it is known that the pollutants transported via stormwater have detrimental effects on wildlife, fisheries, recreation, and drinking water supplies (EPA 2016). Thus, the increased volume of stormwater reaching local creeks, streams, and rivers both alters natural flow regimes and degrades water quality.

III. Overview of Stream Restoration

A. Water Quality versus Water Quantity

Although urbanization can affect aquatic ecosystems in a number of ways, "flow regimes, in particular, are an important pathway by which urbanization influences biotic conditions" (Booth 2005). This premise is founded in the abundance of research linking urbanization with hydrologic alteration (Booth and Jackson 1997; Hollis 1975; Konrad and Booth 2005; Leopold 1968) and, and, in turn, hydrologic alteration to biological health (May et al. 1999; Poff and Allan 1995; Poff and Ward 1989; Power et al. 1988; Resh et al. 1988; Roy et al. 2005). Thus, although a large number of new restoration projects are focused on improving water quality rather than quantity (Burns et al. 2012; Wohl et al. 2015); the two metrics are intimately related. Water quantity is a

critical metric when gauging the health of a creek, and previous research has concluded that, without taking steps to achieve a pre-development flow regime, “protection of urban streams is unlikely” (Burns et al. 2012). It has also been suggested that hydrologic alteration is the primary cause of declining biological richness and benthic index of biotic integrity (B-IBI) scores as basins become urbanized (DeGasperi et al. 2009). The B-IBI index is a uniform tool for characterizing the condition of the ecological region at the lowest level of a body of water. This tool compares various benthic ecosystem characteristic to values that would be expected under pre-development conditions, and the results reflect the overall habitat conditions in the aquatic system (Llansó et al. 2003; Tetra Tech/KCM, Inc. 2005).

B. Headwaters Approach to Restoration

In an attempt to restore the health of natural water bodies, major restoration groups throughout the country are focusing their efforts on the headwaters (Allen 2011; Chattahoochee Riverkeeper 2015; Cruz 2010; Fair and Hunt 2015; Fripp and Weber 2013; Minnesota Pollution Control Agency 2011; Rio Grande Headwaters Restoration Project 2015). For instance, the Minnesota Pollution Control Agency, who has been given jurisdiction over pollution control problems by Minnesota legislature, was scheduled to commence intensive monitoring of its headwaters watershed in 2015 (Minnesota Pollution Control Agency 2011). In Pennsylvania, Project Headwaters was initiated by well-established organizations including the Philadelphia Water Department Office of Watersheds (PWD), Temple University’s Center for Sustainable Communities, and the Pennsylvania Environmental Council (PEC). Project Headwaters prioritized headwaters restoration as a means of stream restoration, and they commenced five headwaters projects in the Philadelphia suburbs between the years of 2007 and 2010 (Cruz 2010).

The headwaters approach to restoration is largely based on the River Continuum Concept, a dominant concept in the modern understanding of stream ecosystems. The River Continuum Concept asserts that from "headwaters to mouth, the physical variables within the river system present a continuous gradient of physical conditions" (Vannote et al. 1980). One major implication of the River Continuum Concept is that to understand what is happening at any location along a river, one must also understand what is happening upstream (Stroud Water Research Center 2015). This concept of protecting small and vulnerable headwater streams, because they provide important ecological services and are closely linked to downstream ecosystems, is echoed in other publications (Burns et al. 2012; Doppelt 1993; Meyer and Wallace 2001).

C. Volume Reductions due to Stormwater Control Measures

Stormwater control measures (SCMs), also known as best management practices (BMPs) or green infrastructure, are features that facilitate a combination of water storage, infiltration, and evaporation in an attempt to counter the impacts of increased imperviousness and to return the hydrologic cycle to a more natural state. As communities learn about the effects of urbanization on their local water bodies, many have implemented SCMs as a form of volume control.

Because of SCMs' ability to store, infiltrate, and evaporate stormwater, they are known for their ability to decrease peak discharges resulting from urbanization (Bain et al. 2014). Much research has been conducted to verify the ability of SCMs to facilitate volume reductions (e.g. Ahiablame et al. 2012; Clary et al. 2011; Debo and Reese 2003; Dovel et al. 2015; Finnemore and Lynard 1982). For instance, studies at Villanova University have demonstrated that both vegetated and non-vegetated SCMs have significant stormwater volume control capacity. As one example, eight years of data collected for a bio-infiltration rain garden revealed that the rain garden removed an average of 973 m3 of stormwater annually (Flynn and Traver 2013). Also at Villanova University,

a two-year study demonstrated that a pervious concrete infiltration basin had over a 91% efficiency at capturing and storing excess stormwater runoff (Horst et al. 2011). Furthermore, research has demonstrated that there are watershed scale benefits to Low Impact Development (LID) (Ahiablame et al. 2012; Bedan and Clausen 2009). LID includes SCM implementation, such as grass swales and rain gardens, and it also encompasses additional urban planning aspects such as cluster housing and shared driveways (Bedan and Clausen 2009). Despite these success stories, there is limited research demonstrating the success of SCMs on a watershed scale (Roy et al. 2014a)

IV. Introduction to SWMM

This project focuses on the use of SWMM as a tool to evaluate restoration success. SWMM is dynamic rainfall-runoff model that is widely accepted both in the US and in other parts of the world. It has been used for various applications, including research, planning, and design related to stormwater runoff (Ahiablame et al. 2012; Barco et al. 2008; Larson et al. 2008).

SWMM is primarily intended for use in urban areas, and it has a variety of capabilities related to stormwater management. For example, the program has the capability to model various aspects of urban hydrologic water cycles, “including rainfall, snow melt, surface runoff, transport through the drainage network, storage and treatment, and receiving water effects” (Barco et al. 2008). Also related to precipitation, the model can be set up to simulate stormwater quantity and quality for long term or single events. Once precipitation reaches the subcatchments, the user can adjust how the model accounts for both infiltration and evaporation losses. SWMM also has the ability to model a wide range of drainage networks such as storm drains, pipes, channels, combined sewers, storage/treatment devices, orifices, weirs, regulators, or natural drainage (Ahiablame et al. 2012;

Barco et al. 2008). Finally, the model allows for easy distinction of the connected and disconnected impervious surfaces within a watershed (Blansett 2011).

Given its functionality, SWMM has the potential to be a significant resource for stream restoration. First, the ability to distinguish between connected and disconnected impervious surfaces is valuable, because connected impervious area is a key parameter in stormwater management (Blansett 2011). Additionally, if calibrated properly, the program has the potential to provide detailed, catchment specific knowledge of stormwater runoff generation (Guan et al. 2015). Furthermore, one current challenge to restoration efforts is that, because of the high interannual variability of most flow regimes, it can be challenging to detect trends in streamflow. Especially over a short period of time, it may be difficult to determine whether a specific stream restoration effort is effective, because the effects may be hidden by interannual changes to precipitation totals or precipitation patterns (Baker et al. 2004). A watershed model has the potential to make the assessment clearer, because all factors other than the improved management practices can be held constant.

V. Sensitivity of Hydrologic Models to Uncertainty in Rainfall Input

A. Overview

Rainfall is a primary source of uncertainty in many hydrologic models. Much research has been completed to develop a better understanding of the sensitivity of hydrologic models to rainfall distribution and uncertainty in rainfall input (Andréassian et al. 2001; Berndtsson and Niemczynowicz 1988; Dawdy and Bergmann 1969; Krajewski et al. 1991; Kuczera and Williams 1992; Obled et al. 1994; Schilling 1984; Troutman 1983; Volpi et al. 2012; Wilson et al. 1979; Younger et al. 2009).

Two primary types of uncertainty surrounding rain gauge selection are related to the accuracy of the rain gauge instrument and how the location of the instrument affects whether the data recorded is representative of what is occurring on site. Therefore, to minimize the amount of uncertainty associated with a hydrologic model, it is ideal to select a rain gauge that is both a high accuracy and local instrument. In many cases, such an instrument is not available. In a hydrologic model, it is possible to compensate for rainfall uncertainties by recalibrating other parameters. The disadvantage of this approach is that the other parameters in question may completely lose physical meaning (Arnaud et al. 2011). Any level of uncertainties in the rainfall used for calibration result in uncertainties in calibrating the input parameters (Andréassian et al. 2001; Kuczera and Williams 1992; Obled et al. 1994).

B. Influence of Spatial Variability

Rainfall spatial variability refers to the large inconsistencies that rainfall can exhibit over space and time. It is known that spatial variability has an impact on streamflow and the shape of the hydrologic response (Volpi et al. 2012). It is also known that ignoring spatial variability of rainfall will decrease the accuracy of a rainfall-runoff model (Nicotina et al. 2008; Zhao et al. 2013).

Spatial variability is particularly important as it applies to rainfall pattern. For instance, Xue and Gavin (2008) found that both infiltration loss and runoff production for a given event are sensitive to rainfall pattern. Specifically, their research discovered that rainfall pattern has more influence than the mean rainfall intensity on the volume of infiltration and runoff during a storm event (2008). Furthermore, research by Dunkerly (2012) noticed that when rainfall intensity is held constant, total runoff, low peak flow, and the ratio between runoff and rainfall are all strongly influenced by rainfall patterns.

The extent to which spatial variability influences streamflow is highly complex and highly dependent on specific catchment characteristics. For instance, some catchments have characteristics, such as the heterogeneity of flow paths, which override the influence of spatial variability. Previous conclusions on the influence of the spatial variability of rainfall are highly site specific, and there does not appear to be a way to generalize the results (Volpi et al. 2012). For instance, Nicotina et al. (2008) found that the spatial variability of rainfall does not have a significant effect on flood response for watersheds smaller than 3500 km^2. Contrastingly, Faurès et al. (1995) reported that rainfall variability must be taken into account even for watersheds as small as 0.05 km2. Faurès et al. (1995) reasoned that, regardless of the application, measurements taken from solely one point are not always representative. Overall, it is evident that there is a great potential for there to be an error in model calibration related to spatial variability, but the extent of the error is unclear.

Arnaud et al. (2011) conducted a study to investigate the influence of various rainfall sampling methods on rainfall-runoff modeling. It was discovered that larger catchments are more sensitive to rainfall spatial variability, but small catchments are more sensitive to uncertainty in rainfall estimates. As the catchment being evaluated in this model is relatively small, it is possible that is will be more sensitive to uncertainty in rainfall estimates than spatial variability. However, due to the influence of specific catchment characteristics on the studies described above, for the purposes of this report it will be assumed that both rainfall spatial variability and uncertainty will have an equal opportunity to influence model results.

VI. Need for Research

Despite the increasing investments in river restoration, the health of the associated ecosystems is continuing to decline (Beechie et al. 2010), and river restoration is proving to be more difficult

than anticipated (Bernhardt and Palmer 2011). This disappointment is creating a need within the restoration community to determine “which methods in which settings are most ecologically effective” (Palmer et al. 2007).

The lack of quantifiable improvements may be a result of a number of different factors, including a lack of understanding of the problem, or the selection of solutions being inappropriate for the context specific problem (Palmer et al. 2007). For instance, Roy et al. (Roy et al. 2014b) investigated if the retrofit stormwater management would result in measureable shifts in the ecological condition of streams in a given catchment. The authors expected minimal responses, due to the relatively small change in hydrology and small reduction in the percent of streams directly connected impervious area. As expected, when rain barrels and rain gardens were installed on 30% of properties in the experimental catchments, there were “few responses in stream water quality, periphyton, and macroinvertebrate metrics relative to the control site” (Roy et al. 2014b). This study suggests that retrofit stormwater management may be an inappropriate or incomplete solution to the problem of impaired streams.

Similarly, a study completed on the 27.5 square mile Aberjona River watershed in Massachusetts concluded that it would be nearly impossible to achieve a peak flow reduction in the watershed greater than 30% using infiltration base SCMs (Perez-Pedini et al. 2005; Winchester, MA 2016). A portion of the results from the study are displayed in Figure 4 below, demonstrating that after a certain threshold, as more infiltration based SCMs are installed, the ratio of benefit to cost exponentially decreases (Perez-Pedini et al. 2005). This, and other, similar limitations would be important to consider before setting restoration goals for the Aberjona River watershed or choosing infiltration base SCMs as the means of restoration for the watershed.

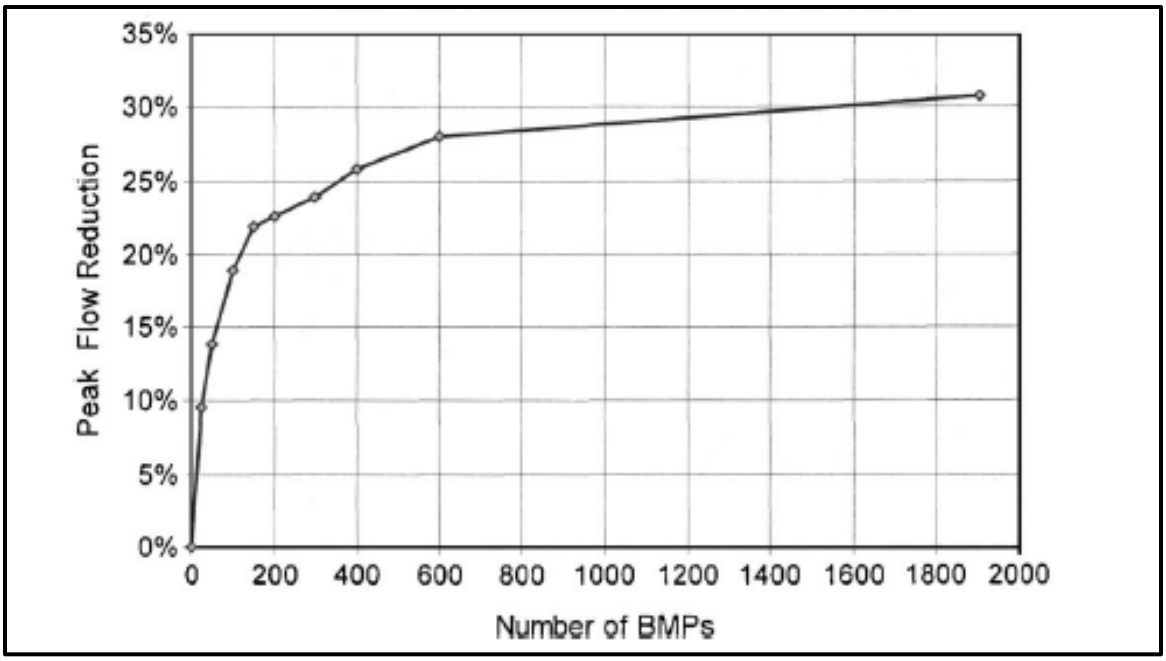

Figure 4:Trade-off between peak flow reduction and number of best management practices (Perez-Pedini et al. 2005)

Walsh et al. (2012) "demonstrated that it is possible for streams with approximately 10% imperviousness to have good ecological condition if stormwater is infiltrated throughout the catchment." Though a success story of stormwater control measures on a watershed scale, the study has limited relevance for stream restoration in developed areas, which generally have land cover with significantly more than 10% imperviousness (Roy et al. 2014b).

Limitations to possible restoration outcomes, such as those described by Figure 4 above, are not identical for each restoration site. River restoration planning should include an understanding of site specific environmental degradation, of which aspects of the degradation are possible to fix through river restoration, and of the local community (Beechie et al. 2010; Palmer et al. 2007). However, if more research is completed on the subject, perhaps trends will emerge that can aid communities in their restoration efforts. Additionally, an increase in reports of restoration practice effectiveness monitoring and restoration outcome, which are currently rare, would enable

communities to learn from past mistakes and to become more effective moving forward (Bernhardt and Palmer 2011).

When selecting restoration goals, it is known that restoring a stream to natural conditions is highly unlikely (Schwartz et al. 2009; Wohl et al. 2015); however, "there is an obvious need for additional controlled studies where stormwater management practices are installed at higher densities to capture a greater volume of stormwater to determine the extent of stormwater management necessary to improve ecosystem health" (Roy et al. 2014b). There is currently much uncertainty as to setting appropriate restoration expectations.

In response to the needs outlined above, this study aims to use modeling methods to evaluate how implementing SCMs at the headwaters of a given creek will influence the flow regime of that creek. In doing so, this work aims to provide an increased understanding of what types of restoration outcomes might be expected from similar projects. Furthermore, this research involves interviewing key members of the local community, and, in doing so, this study aims to provide insight into non-technical boundaries that might prohibit restoration success.

CHAPTER 2: METHODS

I. Methods Overview

The general approach to this research consists of constructing three unique models of the East Branch of Indian Creek Watershed. Each of the three models will be calibrated to one of three rain gauges. Each model will be calibrated to a set of representative, diverse storm events rather than to one continuous data set.

After calibrating the three models, the implications of changing the rain gauge was evaluated by calculating the High Pulse Count, the High Pulse Range, and the Richard Baker Flashiness Index for a "typical year" in each model (Baker et al. 2004; DeGasperi et al. 2009). These metrics are described in greater detail in the Selecting an Appropriate Hydrologic Metric portion of this Methods section. Rainfall data for a typical year were assigned based on a study by the Pennsylvania Water Department (2009).

This model was created as part of the Delaware River Watershed Initiative (DRWI), funded by the William Penn Foundation (WPF). As such, the selection of methods was strongly guided by methods previously used by other key players in the DWRI. Specifically, at the onset of this project, Temple University had already used SWMM for another site in suburban Philadelphia for the DRWI. Methods for this thesis research were selected to be compatible with Temple's methods, to maintain consistency throughout the DRWI.

II. Establishing a Baseline Model

The first step in this project was to establish baseline model. The same baseline model was used for all three final models. In other words, all three of the final models started with the same baseline prior to calibration, to isolate the influence of changing the rain gauge to the greatest extent

possible. The original pre-calibration estimation of SWMM parameters is a critical step in model development to simulate rainfall-runoff behavior as closely as possible (Tan et al. 2008). This step provides a frame of reference during the calibration process for which input parameters are reasonable. The following sections detail how the baseline model was established. The final input parameters for the baseline model are described in Table 1 and 2.

Table 1: Part A of SWMM Input Parameters for the Baseline Model

Subcatchment	Area (ac)	Width (ft)	% Slope	% Impervious	Impervious Area		
					Manning's N	Depth of Depression Storage (in)	% of Area with No Depression Storage
SB1	88	2,741	2.9%	33%	0.011	0.075	0.25
SB2	132	6,763	3.0%	22%	0.011	0.075	0.25
SB3	30	1,064	5.2%	26%	0.011	0.075	0.25
SB4	180	4,772	3.3%	36%	0.011	0.075	0.25
SB5	165	9,313	3.1%	37%	0.011	0.075	0.25
SB6	150	4,595	2.7%	29%	0.011	0.075	0.25
SB7	34	908	4.9%	9%	0.011	0.075	0.25

Table 2: Part B of SWMM Input Parameters for the Baseline Model

Subcatchment	Pervious Area			Subbarea Routing	% Runoff Routed	Groundwater	Ks (in/hour)	Drying Time (days)
	Manning's N	Depth of Depression Storage (in)	Curve Number					
SB1	0.25	0	61	Pervious	25%	No	0.1950	7
SB2	0.25	0	61	Pervious	25%	No	0.1000	10
SB3	0.25	0	63	Pervious	25%	No	0.2080	7
SB4	0.25	0	62	Pervious	25%	No	0.1530	8
SB5	0.25	0	62	Pervious	25%	No	0.1000	10
SB6	0.25	0	68	Pervious	25%	No	0.1100	9
SB7	0.25	0	66	Pervious	25%	No	0.1515	8

A. GIS versus Google Earth

When obtaining the elevations, lengths, and areas of various SWMM inputs, there were two tools available to the authors: Google Earth Pro (Google Earth) and Esri's GIS (GIS). While Google Earth is a widely accepted teaching tool, and it is very useful for getting a feel of a site, for specific

data analysis or cartography, GIS should be used (U.S. Fish and Wildlife Service 2012). This is because the accuracy on Google earth has a wide range, and Google does not guarantee any range of accuracy (Google 2009). Therefore, Google Earth is incredibly useful for initial characterization of an area, but not for data analysis or final design. For these reasons, GIS was used characterize many of the SWMM inputs.

B. Hydraulics

1. Overview

In SWMM, the hydraulics are represented by a series of links and nodes. To collect information about links and nodes for the model, the author walked the creek from the location where the headwaters daylights to the outflow of the East Branch of the Indian Creek Watershed. In the field, a map of the creek and visual inspection of landmarks were used to assign a location to each significant change in channel characteristics. The author measured and recorded creek bed width, creek depth, and visual observations of the channel bed. A summary of the field measurements obtained while walking the creek is presented in Table 3: Walking the Creek Nodes and Table 4: Walking Indian Creek Links. Note that the names assigned to the links indicate the corresponding inlet and outlet nodes. For instance, for the *#7-2* link, the corresponding inlet node is *#7n* and the corresponding outlet node is *#2n*.

Table 3: Walking the East Branch of Indian Creek Nodes

SWMM Junction ID	Channel Description	Invert El. (ft)	Max Depth (ft)
East Branch of Headwaters			
#6n	Start of Creek - Concrete Pipe upstream of this location, but no knowledge of the path of this pipe	273	3
#4n	Channelized Flow Ends	270	5
#3n	Creek Goes Under Narberth Park	260	5
West Branch of Headwaters			
#7n	End of circular culvert under road - Concrete Pipe upstream of this location, but no knowledge of the path of this pipe	260	8
Downstream of Where Headwater Branches Converge			
#2n	Creek Divides	258	4
#1n	Changes from rocky channel bed to concrete channel bed	255	4
FM1	Flow Meter #1	254	4
#13n	Downstream of Narberth Park - underground, circular channel ends	253	14
#14n	Creek Comes out from Under Train Tracks - narrows	251	4
#15a	Start of Bridge under Parkview Drive	241	5
#15b	End of Bridge under Parkview Drive	240	5
#16n	Uncahnnelized Stream Narrows	235	5
#17n	Unchannelized stream narrows	231	5
#18n	Chanelized(ish) flow begins again	228	5
#19n	Unchannelized	226	5
#20	Beginning of Two Channel Bridge	225	6
#20.2n	End of Two Channel Bridge	224	6
#21n	End of Last Section of Park/Start of Remington Rd Bridge	221	6
#22n	End of Remington Rd Bridge	220	6
#23a	Start of Bowman Ave Bridge	216	10
#23b	End of Bowman Ave Bridge	215	10
#24a	Start of Violet Lane Bridge	206	10
#24b	End of Violet Lane Bridge	205	10
#25a	Start of Lancaster Ave Bridge	201	15
#25b	End of Lancaster Ave Bridge	200	15
#26	Start of Lankenau Bridge	190	7
FM2	Location of Flow Meter #2/ Start of Bridge under Road to Lankenau Medical Center	190	7

Table 4: Walking Indian Creek Links

Link ID	Description	Shape	Barrels (#)	Max Depth (ft)	Bottom Width (ft)	Sidewalls Removed	Length (ft)	Manning's Roughness Coefficient	Manning's Channel Description
East Branch of Headwaters									
#6-4	Concrete Channel	Rectangular, Open	1	3	4	none	76	0.02	Concrete bottom float finish with sides of random stone in mortar
#4-3	Unchannelized Flow	Rectangular, Open	1	5	1.5	none	697	0.045	clean, winding, some pools and shoals, some weeds and stones
#3-2	Concrete Pipe	Circular	1	4	NA	NA	126	0.013	Concrete culvert with bends, connections, and some debris
West Branch of Headwaters									
#7-2	Rocky Bed, Channelized Flow	Rectangular, Open	1	8	3	none	101	0.027	Earth, straight, and uniform, with short grass, few weeds
Upstream of Flow Meter #1									
#2-1	Rocky Bed, Channelized Flow	Rectangular, Open	1	4	7.75	none	125	0.035	clean, straight, full stage, no rifts or deep pools, more stones and weeds
#1-FM1	Concrete Rectangular Channel	Rectangular, Open	1	4	7.75	none	140	0.02	Concrete bottom float finish with sides of random stone in mortar
Between Flow Meter #1 and Flow Meter #2									
FM1-13	Circular Channel Under Narberth Park	Arch	1	4	7.75	NA	427	0.013	Concrete culvert with bends, connections, and some debris
#13n-14	Channel under railroad	Arch	1	4	11	NA	187	0.02	Concrete bottom float finish with sides of random stone in mortar
#14n-15.1	Rectangular Channel in Residential Area	Rectangular, Open	1	4	8	none	657	0.045	clean, winding, some pools and shoals, some weeds and stones
#15.1-15.2	Bridge under Parkview Drive	Closed Rectangular	1	5	8	none	130	0.013	Concrete culvert with bends, connections, and some debris
#15.2-16	Rocky and vegetated channel	Rectangular, Open	1	5	10	none	359	0.045	clean, winding, some pools and shoals, some weeds and stones
#16-17	Channel narrows	Rectangular, Open	1	5	7	none	400	0.045	clean, winding, some pools and shoals, some weeds and (more) stones
#17-18	Channel narrows and becomes rockier	Rectangular, Open	1	5	5	none	272	0.05	clean, winding, some pools and shoals, some weeds and (more) stones
#18-19	Channelized(ish) flow begins again	Rectangular, Open	1	5	7	none	191	0.05	clean, winding, some pools and shoals, some weeds and (more) stones
#19-20.1	Unchannelized Flow	Rectangular, Open	1	5	7	none	223	0.05	clean, winding, some pools and shoals, some weeds and (more) stones
#20.1-20.2	Two Channel Bridge	Closed Rectangular	2	6	5	none	44	0.013	Concrete culvert with bends, connections, and some debris
#20.2-21	Last Section of Park	Rectangular, Open	1	6	5	none	577	0.045	clean, winding, some pools and shoals, some weeds and stones
#21-22	Remington Rd Bridge	Closed Rectangular	2	6	3.5	none	61	0.013	Concrete culvert with bends, connections, and some debris
#22-23.1	Creek between Remington and Bownman	Rectangular, Open	1	10	15	none	255	0.045	clean, winding, some pools and shoals, some weeds and stones
#23.1-23.2	Bowman Ave Bridge	Closed Rectangular	1	10	15	none	46	0.013	Concrete culvert with bends, connections, and some debris
#23.2-24.1	Creek between Bowman and Violet	Rectangular, Open	1	10	10	none	1403	0.045	clean, winding, some pools and shoals, some weeds and stones
#24.1-24.2	Violet Lane Bridge	Rectangular, Open	1	10	10	none	60	0.013	Concrete culvert with bends, connections, and some debris
#24.2-25.1	Creek Between Violet and Lancaster	Rectangular, Open	1	10	15	none	737	0.045	clean, winding, some pools and shoals, some weeds and stones
#25.1-25.2	Lancaster Ave Bridge	Rectangular, Open	1	15	15	none	59	0.013	Concrete culvert with bends, connections, and some debris
#25.2-FM2.2	Creek Between Lancaster and FM2	Rectangular, Open	1	7	15	none	5	0.011	Coment, neat surface

The measurements and observations collected while walking the creek were then used in combination with a number of other sources to assign hydraulic properties in SWMM. Table 5 briefly summarizes the various parameters that were assigned as part of the Hydraulics portion of the East Branch of Indian Creek model.

Table 5: Summary of Hydraulic Input Parameters

Object	Model-Specific Object Description	Assigned Input Parameters	Source
Node	Junction of natural surface channels or a location within a channel where characteristics change notably	Node Selection	Field observations, GIS, municipal storm sewer data
		Node Invert Elevation	2005 DVRPC Montgomery County five foot contours, GIS & field visits
		Node Maximum Depth	Field measurements
Link (Conduit)	Represent the creek itself, connecting sequential nodes	Geometric Shape	Field observations
		Maximum Depth	Assigned properties for adjacent nodes
		Bottom Width	Field measurements and observations
		Length	GIS
		Manning's Roughness Coefficient	Field observation and typical values from literature

2. Nodes

a. Node Selection

Nodes were assigned to all stream locations between where the stream headwaters daylights and the outflow of the East Branch of Indian Creek watershed where there was a notable change in channel characteristics. The creek was observed for bridges, stormwater outfalls, slope changes, vegetation, channel bed material, and channel geometry (Schwartz et al. 2009). When possible, nodes were selected through site visits, and in SWMM the prefix “WC” on the majority of nodes

denotes that the information for that particular location was obtained by walking the creek. The nodes were labeled to correspond to walking the creek points for consistency in records. In locations where the river was inaccessible, due to being on private property or being underground in a pipe making it too small for safe student entry, the author used GIS images and storm sewer system data provided by Lower Merion Township. The uppermost portions of the headwaters of this watershed are contained in pipes below the surface that are not represented as part of this model. They were not represented because of the high level of uncertainty associated with both the pipe characteristics and the micro drainage areas created by the inclusion of these pipes.

b. Node Properties

For simplicity, invert elevation and maximum depth were the only node parameters that were adjusted for the watershed. To assign invert elevation, field notes were used to label nodes of interest on a base map in GIS. Elevations for each node were then determined using 2005 DVRPC Montgomery County five foot contours, downloaded from the PASDA database (DVRPC 2005). Maximum node depth is defined as the node's depth from the ground surface, and an approximate maximum depth for each node was assigned based on field measurements and observations. For unchannelized areas, a maximum depth of 1.5 m (5 ft) was assigned. This was assigned as an overestimate to prevent the depth from limiting the amount of flow that was allowed to travel through each node in SWMM. This overestimate was noted, and node depth was checked during storm simulations for reasonability during the calibration period of the model development.

For each node, the author assumed an initial depth of 0, no treatment, no surcharge depth, no internal inflows, no ponded water during flooding, and that flooding occurs when water levels reach the assigned maximum depth. Specifically, the author chose not to specify any initial flow

to remain consistent with Temple University's methods, which calibrated the model based on storm flows alone.

For the outflow of the model, for model simplicity, there was assumed to be "FREE" outflows with no tide gate. Based on field visits to the watershed outlet, this assumption appeared to be physically accurate. Therefore, the only parameter that was assigned for outfalls was the invert elevation, which was assigned as described above.

3. Links (Conduits)

Conduits were assigned to this model to connect each of the sequential nodes and to represent the creek itself. The properties that the authors assigned to each of the conduits are geometric shape, maximum depth, bottom width, length, and Manning's roughness coefficient.

Input parameters were assigned using a combination of field observations and measurements, values from literature, and GIS. For instance, the geometric shape of each section of the creek (conduit) was determined from field observations. Bottom width of the conduit was determined by field measurements, or, when access was limited, visual approximations. Conduit maximum depth was assigned based on the maximum depth for the adjacent, connected nodes, which were assigned as described in the *Nodes* section above. Field observations were used in combination with values from literature to assign Manning's roughness coefficients for each length of the creek (between each node). The Manning's coefficients were assigned based on *Manning's n for Channels* (Chow 1959). Conduit lengths were determined in GIS. To do this, a polyline shape file was created for each conduit, by tracing the creek between each set of nodes. Then, the geometry was calculated for each conduit by GIS.

In addition, inlet offset, outlet offset, initial flow, max flow, entry loss coefficient, exit loss coefficients, average loss coefficient, and seepage loss rate were all assumed to be as 0, the default value for these parameters in SWMM, for all conduits.

C. Hydrology

1. Overview

Table 6 summarizes the various parameters that were assigned as part of the Hydrology portion of the East Branch of Indian Creek model.

Table 6: Summary of Hydrologic Input Parameters

Object	Model-Specific Object Description	Assigned Input Parameters	Source
Rain Gauge	Supplies rainfall data to the subcatchments (Rossman 2015)	Rain Format	Formatted to match weather station output
		Time Interval	Formatted to match weather station output
		Data Source	VUSP weather stations
Subcatchment	An area of land consisting of both impervious and pervious surfaces, whose runoff drains to a common outlet point (Rossman 2015)	Geometric Shape	Field observations
		Maximum Depth	Assigned properties for adjacent nodes
		Bottom Width	Field measurements and observations
		Length	GIS
		Manning's Roughness Coefficient	Field observation and typical values from literature

2. Subcatchment Development

A subcatchment is defined as an area of land consisting of both impervious and pervious surfaces, whose runoff drains to a common outlet point (Rossman 2015). The model presented in this report

consists of seven distinct subcatchments, whose properties were assigned as described in the following sections.

a. Delineation and Area Calculations

The first step in creating this model was to obtain a delineation of the East Branch of Indian Creek watershed. This GIS data was provided by the Lower Merion Township Building and Planning Department's Planner-GIS Technician.

Next, it was necessary to determine how many subcatchments to create within the East Branch of Indian Creek watershed. It is known that model scale has a significant impact both input parameter assignment and simulation result. Additionally, it is known that a microscale model is particularly useful for simulating and evaluating the effects of stormwater control measure implementation (Sun et al. 2014). However, the East Branch of Indian Creek is a relatively flat watershed. This flat terrain limits the extent to which the watershed could be broken up into smaller catchments while maintaining confidence in the delineation and resulting direction of water flow. It was judged that the watershed should only subdivided where the water flow boundaries appeared to be relatively clear. It was assumed that inaccuracies accumulated by a relatively arbitrary delineation process would negatively outweigh any benefits gained from a microscale model. This resulted in the creation of eight subcatchments within the watershed. This delineation is depicted in Figure 5.

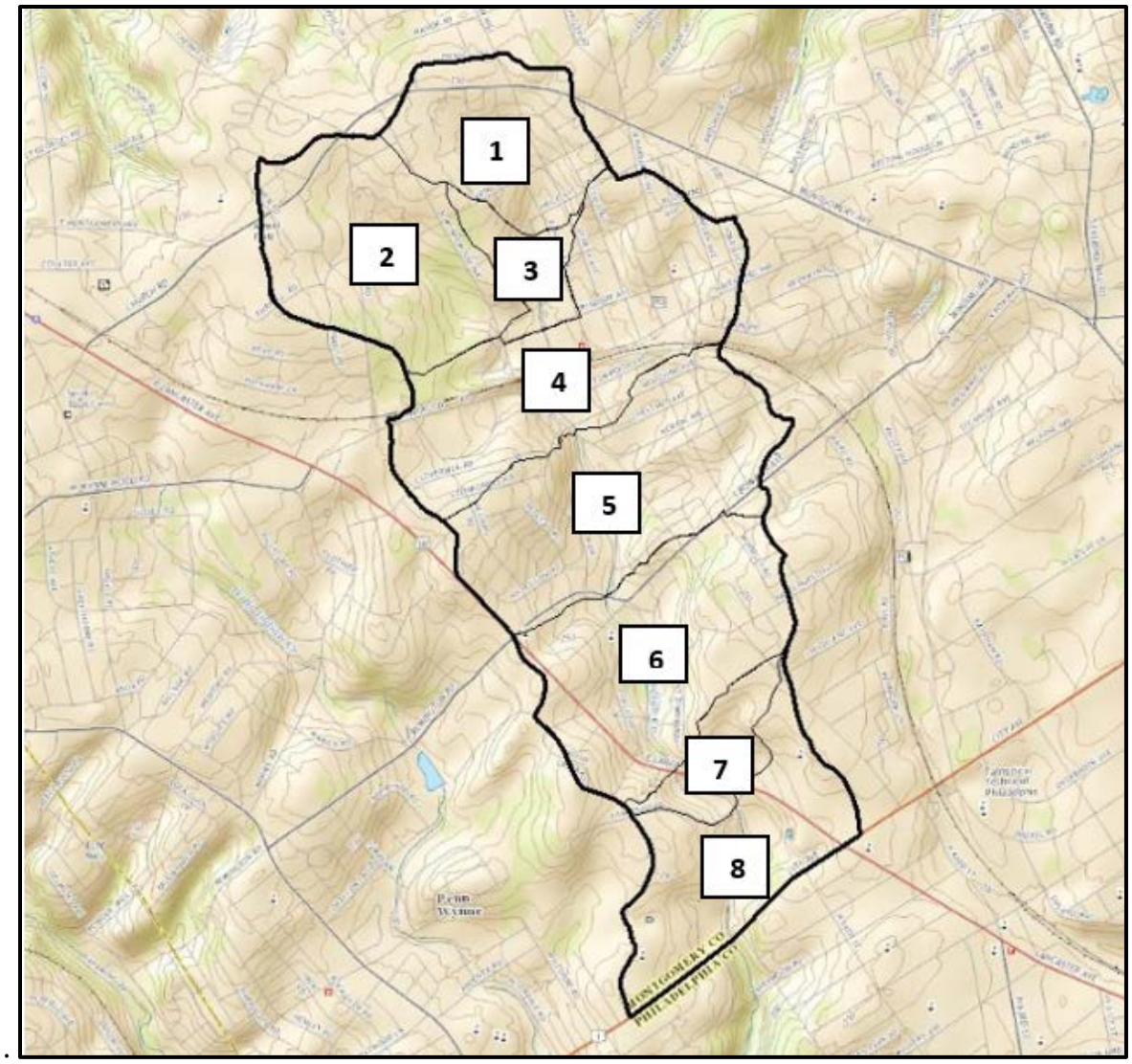

Figure 5: East Branch of Indian Creek Subcatchment Delineation

Delineation of the eight subcatchments was completed manually in GIS using a combination of contour and sewer maps. Manual delineation was chosen, because it allowed for the consideration of non-digitized storm sewer maps. Additionally, the watershed is small enough that manual delineation was manageable. 1.5 m (5 ft) contour maps for the watershed were provided by Lower Merion Township. Storm sewer maps were provided by Narberth Borough and Lower Merion Township, respectively. Both sets of storm sewer data were spot checked in the field as a form of verification. Contour maps were verified using DVRPC 2005 contour data for Montgomery, PA

(DVRPC 2005). Areas for each subcatchment were measured in GIS and were verified using Google Earth measurements.

It is important to note that the downstream outfall location for subcatchments 3 and 7 were assigned to match the location of two installed flow meters that were installed by VUSP. These flow meters are discussed in greater detail in the *Flow Data Collection for Calibration* section of this report. It is also important to note that only subcatchments 1 through 7 were evaluated as part of this research. This is because, due to the location of the installed flow meters, only subcatchments 1 through 7 could be calibrated.

b. Routing

It was assumed that the runoff from each subcatchment's pervious and impervious areas was routed to a pervious section of the subcatchment, and then to the outlet. This is to account for the residential areas within the watershed, where runoff from driveways etc. may runoff and collect in homeowner's yards or other lawn areas. The percent of the impervious areas routed to the pervious areas was initially set as 25%, with the remaining 75% of impervious areas being routed directly to the outfall. This percent routed was then adjusted as a calibration parameter. This approach was selected to remain consistent with Temple University's modeling efforts.

Additionally, Kinematic Wave routing was selected as the overall routing method for the model. This method was selected to remain consistent with Temple University's approach. Furthermore, this routing methods was selected for a similar study completed by Tan et al. (2008).

c. Percent Impervious Cover

The percent impervious cover in each subcatchment was determined using GIS. To complete this calculation, the impervious areas were grouped into three major categories: buildings, private

roads and drives, and public roads. After calculating the total impervious area in each subcatchment, percent impervious area was estimated by dividing the impervious area by the total area of the subcatchment.

The area covered by buildings and private drives/roads was determined using GIS data provided by both Narberth Borough and Lower Merion Township. The accuracy of the provided data was verified using GIS base maps of the area.

The area covered by public local roads was determined by using a combination of linear GIS features provided by both Narberth Borough and Lower Merion Township and shapefiles created by tracing GIS base maps of the area. To determine the total area of public roads in each watershed the measured length of the roads were multiplied by a width. Given Narberth and Lower Merion's narrow roads, the local lane width of 2.7 m determined using the minimum acceptable lane width for local roadways as specified by the FHWA for local roadways (FHWA 2014b). Similarly, the collector lane width of 3.0 m was determined using the minimum acceptable width for collector roadways as specified by the FHWA (FHWA 2014b). Average sidewalk width was also determined based on information presented by the FHWA (FHWA 2014a).

Using the information described above, for all public local roads, the average road width was estimated by assuming three 2.7 m lanes (two driving lanes, one parking lane), and two 1.525 m (60") sidewalks, for a total average width of 11.15 m. For all public collector roads, the average road width was estimated by assuming four 3.0 m lanes (four driving lanes), and one 1.525 m (60") sidewalk, for a total width of 13.525 m. The total calculated width for both local and collector roads was verified using a combination of Google Earth, field measurements, and field

observations. As a calculation check, the impervious area for each subcatchment was compared against the weighted average curve number for the subcatchment.

d. Curve Numbers

It is significant to note that SWMM interprets curve numbers as only representing pervious areas. Therefore, all discussion of assigning curve numbers in this report is referring to assigning a pervious curve number: a curve number exclusively for the pervious area of each subcatchment.

The curve number method was chosen as the infiltration model for this project to remain consistent with the methods used by Temple University. The curve number method was originally selected by Temple University, because it can be very difficult to find data for the Horton or Green-Ampt methods that is representative of an entire subcatchment. Furthermore, one method of modeling SCMs in SWMM employs the curve number method (Ahiablame et al. 2013). The author of this report were interested in creating a model that would be compatible with this method of SCM modeling, to maximize the model's adaptability to future uses.

To determine the curve number for each subcatchment, both soil and land cover data were obtained for the watershed. Soil data were obtained from the Web Soil Survey, a service provided by the United States Department of Agriculture's Natural Conservation Resource Service (USDA 2013). This method of obtaining soil data is not only consistent with Temple University's methods, but also with previously published models (Ahiablame et al. 2013). Output from the Web Soil Survey describes soil as belonging to one of fourteen different USDA soil classifications. Using engineering judgement and information from the soil report, the author of this report grouped each of the fourteen soil types into one of the four hydrologic soil groups. These groupings are described in Table 7. The full report from Web Soil Survey can be found in Appendix I: Web Soil Survey

Report. To determine land cover for the watershed, a PASDA 2012 Land Cover Data set was obtained from Villanova's Geography Department's GIS Technician.

Table 7: Soil Classification for Curve Number Calculation

Hydrologic Soil Group	Soil Survey Classification
A	
B	PaB, Ch, GnB, GsB, UrmB, UdsB, UrlB
C	CaA, Ha, UugB, UgB, UgD, UugD, UdsD
D	

After both soil and land cover data sets were obtained, GIS was used to overlay the soil data set and the land cover data set, to obtain a new dataset of each unique combination of soil type and land cover that exists within each subcatchment. This paper will refer to each of these hundreds of unique areas as "micro areas." The attributes tables for the new data sets were then exported from GIS to Microsoft Excel, where a mass balance was completed to determine the overall pervious curve number for each of the seven subcatchments.

To complete the mass balance and assign an overall pervious curve number for each subcatchment, the hundreds of micro areas were sorted into 28 unique "categories." These categories consisted of each of the four hydrologic soil groups (A, B, C, and D) for each of the seven different types of land cover that exist with the subcatchment (Developed, Open Space; Developed, Low Intensity; Developed, Medium Intensity; Developed, High Intensity; Deciduous Forests; Mixed Forest; and Woody Wetland). From here, a pervious curve number was applied to each category. All curve numbers were assigned based on Table 8.7.3 in *Water Resources Engineering* (Mays 2011). The curve numbers assigned for each of these categories are summarized Table 8 below.

Table 8: Pervious Curve Number Selection

Category	Impervious Surfaces	Selected Pervious Curve Number	
		Curve Number	Description
Developed, Open Space	<20%	A=39, B=61, C=74, D=80	Lawns, open spaces, parks, golf courses, cemeteries, etc. Open space, good condition (>75% grass cover)
Developed, Low Intensity	20-49%		
Developed, Medium Intensity	50-79%		
Developed, High Intensity	80-100%		
Deciduous Forests	0%	A=36, B=60, C=73, D=79	Woods; Fair Soil
Mixed Forest	0%	A=36, B=60, C=73, D=79	Woods; Fair Soil
Woody Wetland	0%	A=35.5, B=58, C=71.5, D=78	50% Woods, Fair Soil; 50% Brush; Fair Soil

Next, a specific percent pervious value was assigned to each category for each subcatchment. These values were assigned based on a range defined by the National Land Cover Database (NLCD) 2001 Land Cover Class Definitions, as described in Table 8 above (Irwin et al. 2006). The overall percent pervious for each subcatchment was calculated as a weighted average of the area and the percent pervious for each category.

This percent pervious value for each category, calculated based on typical values from literature, was then calibrated to the percent pervious measured directly in GIS (described in the *Percent Impervious Cover*) section above. This calibration was performed by adjusting the assigned percent pervious for each category within the ranges presented in Table 8.

Finally, the pervious curve number for the subcatchment was calculated from the area of each category, the percent pervious assigned to each category, the pervious curve number for each category, the area of the overall subcatchment, and the percent pervious assigned to the overall subcatchment. The equation used for this calculation is displayed below.

$$\frac{Category\ Area * Category\ \%\ Pervious\ *\ Category\ Pervious\ CN}{Subbasin\ Area * Subbasin\ \%\ Pervious} = Subbasin\ Pervious\ CN$$

(Equation 2)

e. Drying Time

Drying time for each subcatchment was calculated as instructed in the SWMM Manual. The SWMM Manual, Volume I suggests using this approach when the curve number method is being employed as the infiltration model, which is true for this project. This method relates the soil's drying time (T_{dry}) in days to the soil's saturated hydraulic conductivity (Ks) in in/hr. The equation used for this method is presented below (Rossman and Huber 2016)

$$T_{dry} = \frac{3.125}{\sqrt{K_s}} \quad \text{(Equation 3)}$$

To complete this equation, a K_s value was assigned to each subcatchment. This was completed by using the Web Soil Survey Data, described in the *Curve Numbers* section of this report above, to assign a predominant soil type for each subcatchment. Then, Table 9, provided by the SWMM Manual, Volume I, was used to estimate a K_s from soil type. Note that numbers in parentheses in the table are ± one standard deviation from the parameter value shown (Rossman and Huber 2016).

Table 9: Assigning Ks from Soil Type (Rawls et al. 1983)

Soil Class	Porosity, ϕ	Effective Porosity, ϕ_e*	Wetting Front Suction Head, ψ_s (in)	Saturated Hydraulic Conductivity, K_s (in/hr)
Sand	0.437 (0.374–0.500)	0.417 (0.354–0.480)	1.95 (0.38–9.98)	4.74
Loamy sand	0.437 (0.363–0.506)	0.401 (0.329–0.473)	2.41 (0.53–11.00)	1.18
Sandy loam	0.453 (0.351–0.555)	0.412 (0.283–0.541)	4.33 (1.05–17.90)	0.43
Loam	0.463 (0.375–0.551)	0.434 (0.334–0.534)	3.50 (0.52–23.38)	0.13
Silt loam	0.501 (0.420–0.582)	0.486 (0.394–0.578)	6.57 (1.15–37.56)	0.26
Sandy clay loam	0.398 (0.332–0.464)	0.330 (0.235–0.425)	8.60 (1.74–42.52)	0.06
Clay loam	0.464 (0.409–0.519)	0.309 (0.279–0.501)	8.22 (1.89–35.87)	0.04
Silty clay loam	0.471 (0.418–0.524)	0.432 (0.347–0.517)	10.75 (2.23–51.77)	0.04
Sandy clay	0.430 (0.370–0.490)	0.321 (0.207–0.435)	9.41 (1.61–55.20)	0.02
Silty clay	0.479 (0.425–0.533)	0.423 (0.334–0.512)	11.50 (2.41–54.88)	0.02
Clay	0.475 (0.427–0.523)	0.385 (0.269–0.501)	12.45 (2.52–61.61)	0.01

*Effective porosity is the difference between the porosity ϕ and the residual moisture content ϕ_r that remains after a saturated soil is allowed to drain thoroughly.

f. Manning's Roughness Coefficients for Overland Flow

Manning's N values were assigned using Table 5.4 from Design and Construction of Urban Stormwater Management Systems (ASCE 1993). This table was sourced from Crawford and Linsley (1966) and Engman (1986), and a copy is presented as Table 10. Impervious surfaces in the subcatchments were assumed to behave as concrete or asphalt, which has a recommended Manning's Roughness Coefficient of 0.011 for overland flow. Pervious areas in the subcatchments were assumed to behave as lawns, which has a recommended Manning's Roughness Coefficient

of 0.25. The general land cover types were assigned based on site visits and knowledge that the land within the subcatchments is highly residential. The assigned coefficients were adjusted within the provided range as part of the calibration process.

Table 10: Estimates of Manning's Roughness Coefficients for Overland Flow (Crawford and Linsley 1966; Engman 1986)

Surface Type (1)	Manning's *n* (2)	Range (3)
Concrete/Asphalt**	0.011	0.01–0.013
Bare Sand**	0.01	0.01–0.016
Bare Clay—Loam (eroded)**	0.02	0.012–0.033
Gravelled Surface**	0.02	0.012–0.03
Packed Clay*	0.03	
Short Grass Prairie**	0.15	0.10–0.20
Light Turf*	0.20	
Lawns*	0.25	0.20–0.30
Dense Turf*	0.35	
Pasture*	0.35	0.30–0.40
Dense Shrubbery and Forest Litter*	0.40	
Bluegrass Sod**	0.45	0.39–0.63

*From Crawford and Linsley (1966)—obtained by calibration of Stanford Watershed Model.
**From Engman (1986) by kinematic wave and storage analysis of measured rainfall-runoff data.

g. Depth of Depression Storage

The depth of depression storage is one component of initial abstractions during rain events (Sample et al. 2001). Depth of depression storage is defined as "the volume of water that can be held in natural depressions in the land surface," or "the depth of water that has to be exceeded on the subcatchment before runoff occurs" (Sun et al. 2014). To assign a depth of depression storage for the impervious and pervious areas, Table A.5 from the SWMM Manual 5.1 was used (Rossman 2015). The table was sourced from ASCE (1993), and a copy is presented as Table 11. A value for 0.075 inches was selected as the depression storage value for impervious surfaces, as it is the average of the range provided in Table 11. A value of 0.00 inches was selected as the initial

depression storage value for pervious surfaces, as the curve number method already accounts for initial abstractions for pervious surfaces. Assigned depression storage values for impervious surfaces were adjusted within the provided range during the calibration portion of this project.

Table 11: Typical Values for Depression Storage (ASCE 1993)

Impervious surfaces	0.05 – 0.10 inches
Lawns	0.10 – 0.20 inches
Pasture	0.20 inches
Forest litter	0.30 inches

To run SWMM, it is necessary to assign the percent of impervious area with no depression storage. The default SWMM value of 25% was used. Engineering judgement was used to assign this value based on knowledge of the conditions of the local roadways. This value was then adjusted between 0% and 50% as part of the calibration process. This method is consistent with Temple University's methods for assigning the same parameter.

h. Watershed Width

Watershed widths were calculated following instructions from the SWMM Manual, Volume I. Width was calculated by dividing the area of a subcatchment by the maximum overland flow length. The maximum overland flow length is defined as the farthest distance that flow might travel in the subcatchment before it becomes channelized. This length should represent relatively slow flow over primarily pervious surfaces. For the majority of subcatchments, the area was large enough that there were numerous possibilities for a maximum overland flow length. Therefore, an average flow length was used (Rossman and Huber 2016). Possible flow lengths for each subcatchment were measured in GIS. When assigning these flow lengths, location of storm sewer inlets was considered. Overland flow lengths do not include distance traveled through storm sewers. Lengths were verified using Google Earth.

Due to the high levels of uncertainty associated with identifying overland flow paths, width was used as a calibration parameter. This is consistent with the methods used by Temple University and those suggested by the SWMM Manual, Volume I (Rossman and Huber 2016). While the baseline width was assigned as the average maximum flow length, for the width calibration range was defined using the upper and lower bounds of the possible maximum flow lengths for each subcatchment.

i. Watershed Slope

The SWMM Manual defines watershed slope as the "slope of the land surface over which runoff flows and is the same for both the pervious and impervious surfaces. It is the slope of what one considers to be the overland flow path" (Gironás et al. 2009). For the model presented in this paper, slope was calculated using the maximum flow lengths described in the *Watershed Width* section above and the elevations for the high and low points of each maximum flow length. These elevations were determined using 2005 DVRPC Montgomery County 1.5 m (5 ft) contours, downloaded from the PASDA database (DVRPC 2005). The slopes calculated from the maximum flow lengths in each subcatchment were averaged to obtain an average slope for the subcatchment. The slope calibration range was defined using the upper and lower bounds of the possible slopes for each subcatchment.

j. Groundwater Table

For modeling purposes, it was assumed that the groundwater table was far enough from the surface not to significantly influence the creek in this model. This assumption is primarily based on information collected by the USGS 395942075144301 MG 2164 gauge station. This station is located at Latitude 39°59'41.50", Longitude 75°14'42.50" NAD83, which is about a mile from the model's outfall. According to this gauge station, the average annual maximum groundwater level between the years of 2011 and 2015 was 3.74 m (12.26 ft) below land surface. The annual

maximum groundwater level ranged from 3.21 m (10.52 ft) below ground surface in 2011 to 5.04 m (16.53 ft) below land surface in 2016 (U.S. Geological Survey 2016).

Figure 3 in the *Background and Literature Review* section of this report displays the groundwater data gathered from a local USGS gauge station. Groundwater levels appear to be decreasing as time passes. As discussed in the *Background and Literature Review* section of this report, this may be the result of increased impervious surfaces over time and less water being available to recharge the groundwater table.

Note that the groundwater table is much closer to the land surface at the top of the headwaters, adjacent Narberth Park. Field infiltration tests performed by the author demonstrated that the groundwater table is approximately 0.76 m (2.5 ft) below land surface in this area. The high water table will be critical for SCM design; however, the authors decided to proceed with the assumption that the height of the groundwater table has a negligible influence on the model itself. This is because the single data point does not provide enough information to characterize complex groundwater patterns throughout the entire watershed. When looking at the scale of the model, it was judged that the data point directly adjacent to the creek in the headwaters is not characteristic of the watershed as whole. The time and resources allotted for this study did not allow for a thorough and accurate groundwater characterization for each of the seven subcatchments. Furthermore, the creek at the location of the identified high water table is characterized by a concrete, rectangular channel, and is therefore unable to be influenced by the groundwater table.

D. Climatology

1. Overview

To complete the baseline model, various climatology parameters were assigned. An overview of the assigned site-specific parameters and their sources is included as Table 12 below.

Table 12: Overview of Climatology Input Parameters

Parameter	Source
Temperature	VUSP Narberth weather station
Evapotranspiration	Hargreaves equation & VUSP Villanova University weather station
Wind Speed	VUSP Narberth weather station

2. Wind Speed and Snow Melt

Monthly average wind speed was computed using data recorded by the VUSP Narberth weather station from June 2015 to May 2016. The monthly average wind speeds used for calibration and validation are displayed in Table 13. Wind speed was not considered to be a highly influential, as it is only used to compute snow melt (Rossman 2015). No snow occurs during the calibration period for this model. As such, the snow melt input parameters were assigned as SWMM's default values.

Table 13: Monthly Average Wind Speed (mph)

Jan	Feb	March	April	May	June
3.04	2.04	3.24	2.52	1.59	1.67

July	August	Sept	Oct	Nov	Dec
1.44	1.51	1.22	1.53	2.03	2.33

3. Evapotranspiration

Daily evapotranspiration (ET) values were computed using the Hargreaves equation and a VUSP Villanova University weather station. Villanova University is located approximately 5 miles from the location of the VUSP Narberth Park weather station. Prior to the start of this project, members of the VUSP team had calculated daily ET values for 2015 and 2016 using the weather station at Villanova University. It was assumed that 5 miles was not a significant enough distance to effect the site's temperature, solar radiation or relative humidity at the resolution anticipated by this model. Temperature, solar radiation, and relative humidity are the inputs influencing the Hargreaves equation. Daily ET was added to the model as a time series.

4. Temperature

Temperature was added to the baseline model as a time series. The temperature data was obtained in five minute increments from the VUSP Narberth Park weather station.

III. Flow Data Collection for Calibration

A. Overview

To maximize the reliability of a watershed model, the model was calibrated by comparing the flow regime predicted by SWMM to the flow regime measured in the field for a particular storm. The two locations where flow data were collected to calibrate the model are depicted with stars on Figure 6. The locations are marked by the Headwaters Flow Meter and the Downstream Flow Meter and are referred to as the Headwaters Calibration Point and the Downstream Calibration Point, respectively. Both flow meters are Starflow Ultrasonic Doppler Instruments: 6526H Starflow (Starflow flow meters). These instruments were programed by VUSP to report the following parameters every five minutes: depth, velocity, temperature, and quartile. Assuming the

width of the channel in these locations is constant, the instrument also uses its recorded depth and velocity measurements to calculate area and flow rate for each five minute interval.

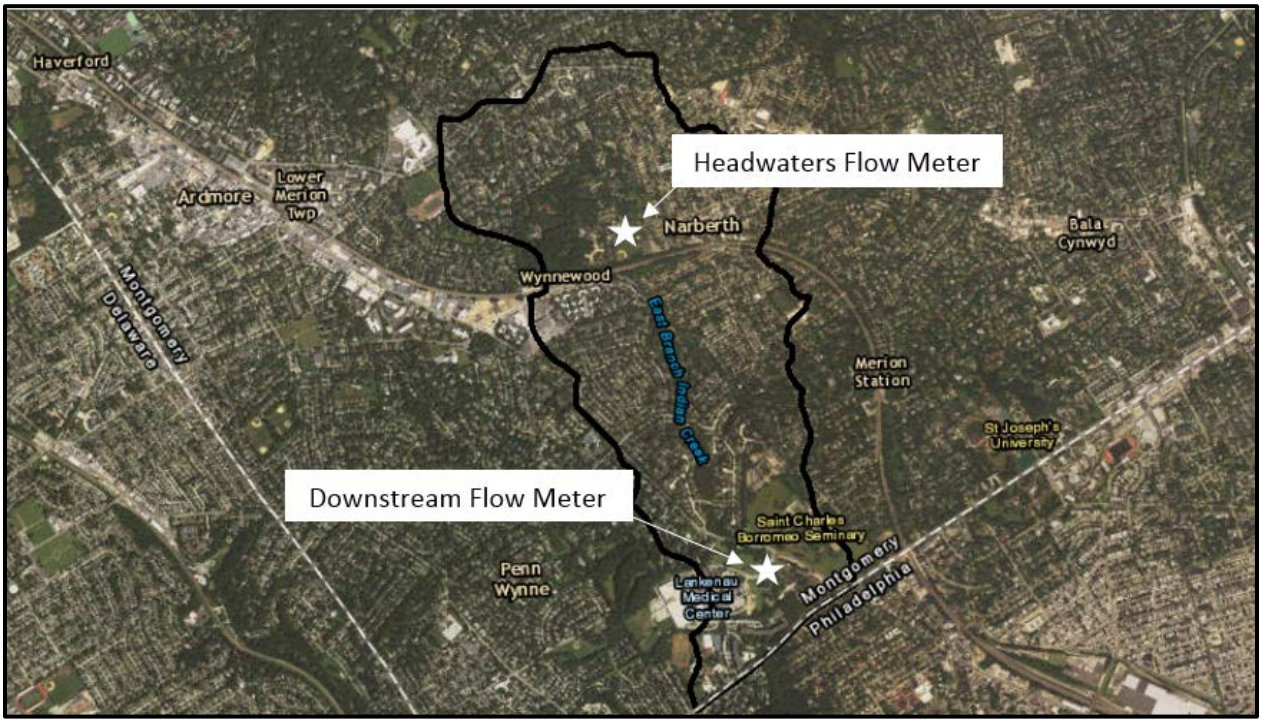

Figure 6: SWMM Calibration Points

B. The Headwaters Flow Meter

The Headwaters Flow Meter is located at Narberth Park, directly downstream of the proposed swale system discussed in the background section of this report. This calibration point will ultimately enable the VUSP team to quantify the immediate water quantity impacts of the swale system on the creek. Additionally, the Headwaters Flow Meter will allow for a highly calibrated model of the upper most headwaters of the East Branch of the Indian Creek. Understanding the way that the headwaters behaves allows the authors to better analyze the headwaters approach to restoration.

The Headwaters Flow Meter was installed by VUSP in February 2015 and is located in a storm sewer pipe beneath Narberth Playground in Narberth, PA. The creek at this location exists as a concrete, arch shaped channel, about 1.2 m (4 ft) tall and 2.9 m (9.5 ft) wide. The Manning's channel description for this area was determined to be a concrete culvert with bends, connections, and some debris (Mays 2011). A picture of the location of the Headwaters Flow Meter is shown as Figure 7.

Figure 7: VUSP Members Installing the Headwaters Flow Meter

C. The Downstream Flow Meter

The Downstream Flow Meter is located approximately 0.5 km (0.3 miles) upstream of the watershed outfall. This instrument allows for the calibration of the subcatchments downstream of the Headwaters Flow Meter. Ultimately, this instrument will assist the VUSP team to determine how installed SCMs affect the creek as a whole. This location represents the outfall of the SWMM model.

The Downstream Flow Meter was installed in October 2015 and is located beneath the bridge to Lankenau hospital in Wynnewood, PA. The Downstream Flow Meter is approximately 2 km (1.25 miles) downstream of the Headwaters Flow Meter. The creek at this location exists as a concrete, rectangular shaped channel, about 1.8 m (6 ft) tall and 4.6 m (15 ft) wide. The Manning's channel description for this area was determined to be a concrete culvert with bends, connections, and some debris (Mays 2011). A picture of the location of the Downstream Flow Meter is shown as Figure 8.

Figure 8: Thesis Author at the Location of the Downstream Flow Meter

D. Quartile Analysis

1. Overview

The Starflow flow meters take samples 200 times every five minutes, and the value reported every five minutes is an average of those 200 readings. The quartile reading indicates the range within

those 200 samples. The greater the quartile reading, the greater the range within the 200 samples and the less representative the reported average value is. The Starflow Support Team suggests that the only valid data occurs when the quartile reading is reduced to between 15 and 40. The Starflow flow meter manual suggests that data is unreliable if a quartile greater than 100 is recorded (Unidata 2016). Given this information, flow data from both meters was analyzed to determine the most appropriate quartile filter. It is critical to ensure that the flow data recorded by the flow meters is reliable, because it is the single data set to which the accuracy of this model is compared against.

2. Headwaters Flow Meter

Figures 9 and 10 depict a summary of the completed quartile analysis for the Headwaters Flow Meter at two different scales. In the figures, upper quartile limits of 40, 55, 60 and 80 are represented in the legend as Q40, Q55, Q60, and Q80, respectively. For the Upstream Flowmeter, an upper quartile limit of 60 appears to record all of the peak flows from storms while maintaining flow values that are reasonable compared against field visits and engineering judgement. For the Headwaters Flow Meter, raising the quartile significantly above 60 appears to collect only outliers that do not appear to be reasonable when checked against engineering judgement. Thus, for the Headwaters Flow Meter, an upper quartile limit of 60 was used whenever Starflow flow data from the field was required for analysis.

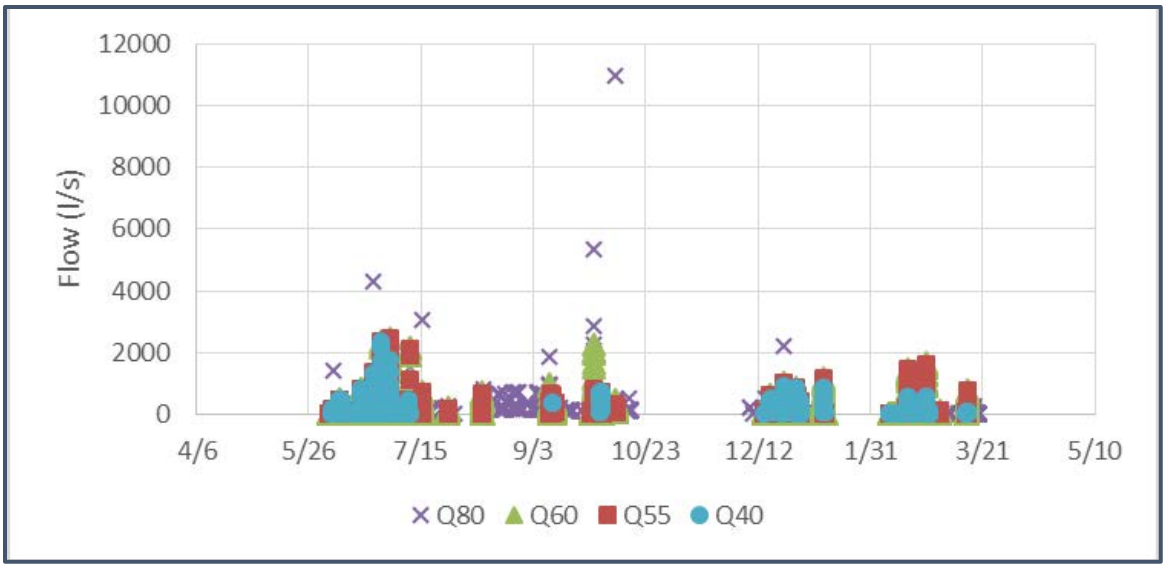

Figure 9: Comparison I of 2015-2016 Flow Data Collected by the Headwaters Flow Meter when the Upper Quartile Limit is Adjusted from 40 (Q40) to 80 (Q80)

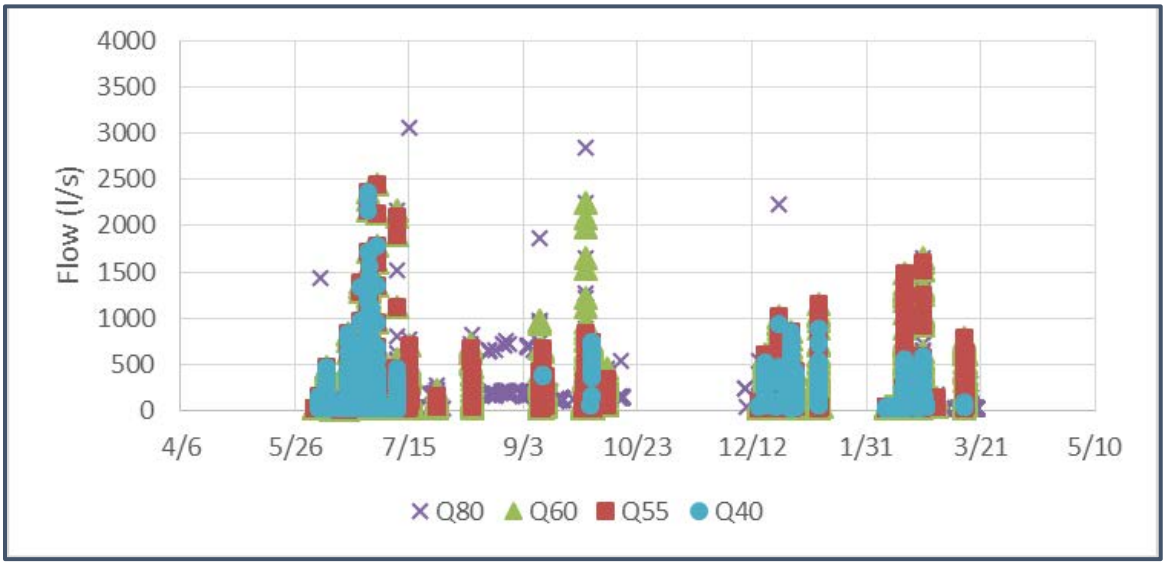

Figure 10: Comparison II of 2015-2016 Flow Data Collected by the Headwaters Flow Meter when the Upper Quartile Limit is Adjusted from 40 (Q40) to 80 (Q80)

Because an upper quartile limit of 60 can be considered to be significantly higher than the upper quartile limit of 40 recommended by the Starflow Support Team, once individual storms were selected for calibration purposes (as described in the *Rain Gauge Selection for Calibration*

section), individual storms were analyzed to examine the difference between data collected with an upper quartile limit of 40 versus data collected with an upper quartile limit of 60 in greater detail. Under close inspection, engineering judgement was used to determine that the data collected with an upper quartile limit of 60 are reasonable and that the models can be calibrated to these data with a reasonable amount of confidence. Figures 11-17 depict this quartile analysis for individual storms for the Headwaters Flow Meter. Note that in Figures 11-17, upper quartile limits of 40 and 60 are represented in the legends as Q40 and Q60, respectively. Additionally, for any storm that lasts for more than one day, the storm is identified by the date when the storm began.

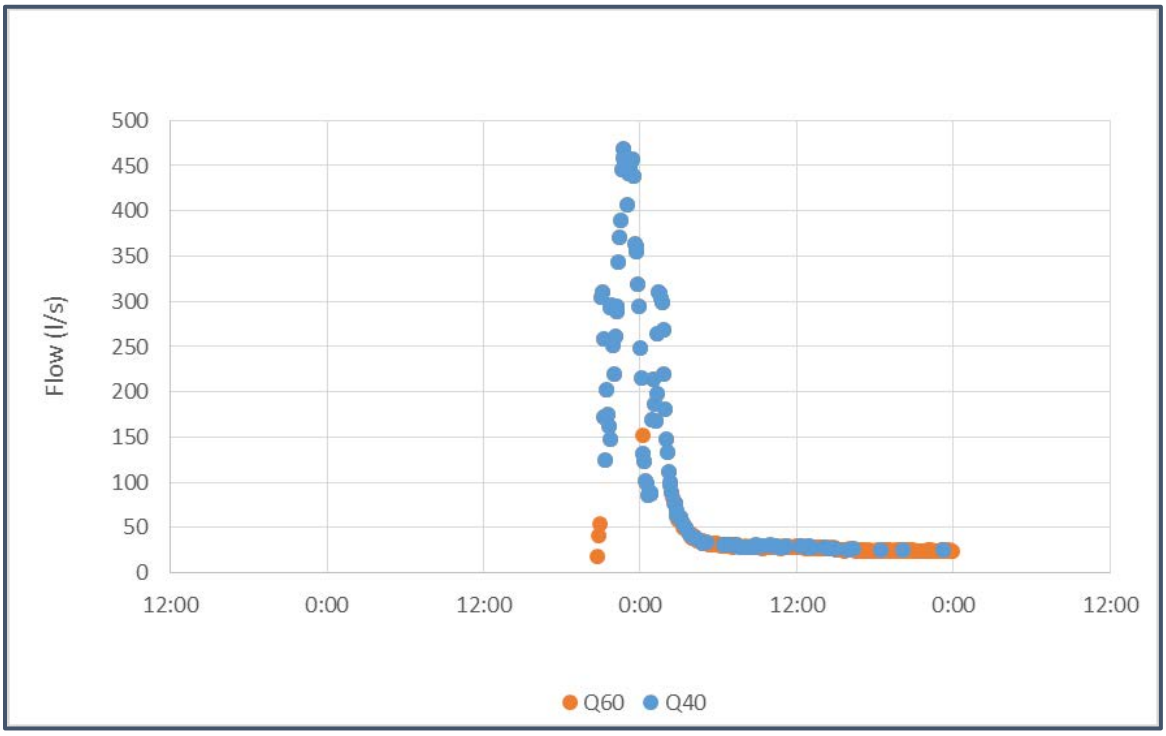

Figure 11: 6/8/2015 Quartile Analysis for the Headwaters Flow Meter

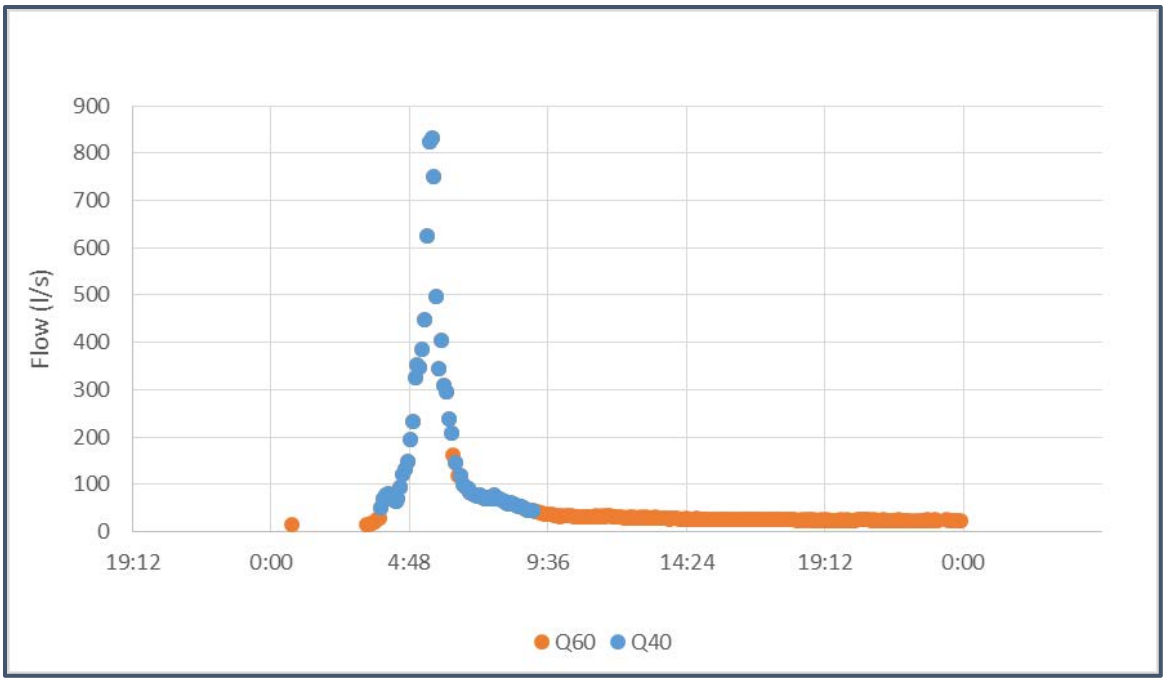

Figure 12:6/18/2015 Quartile Analysis for the Headwaters Flow Meter

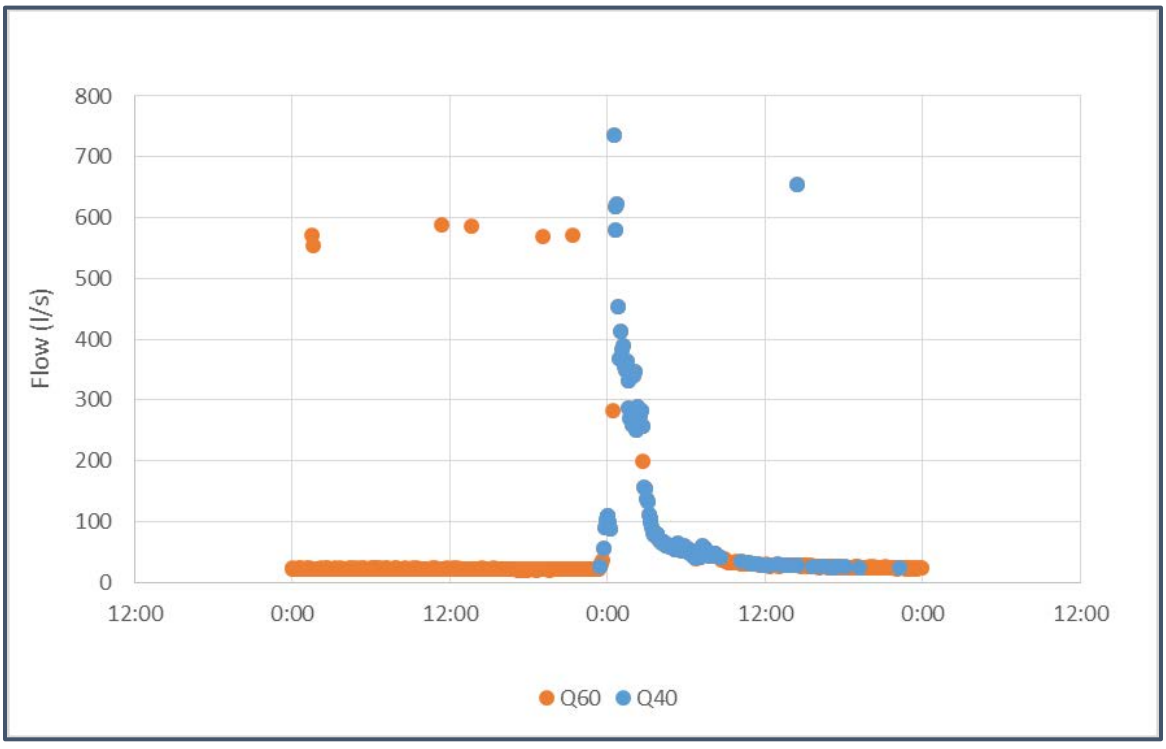

Figure 13: 6/20/2015 Quartile Analysis for the Headwaters Flow Meter

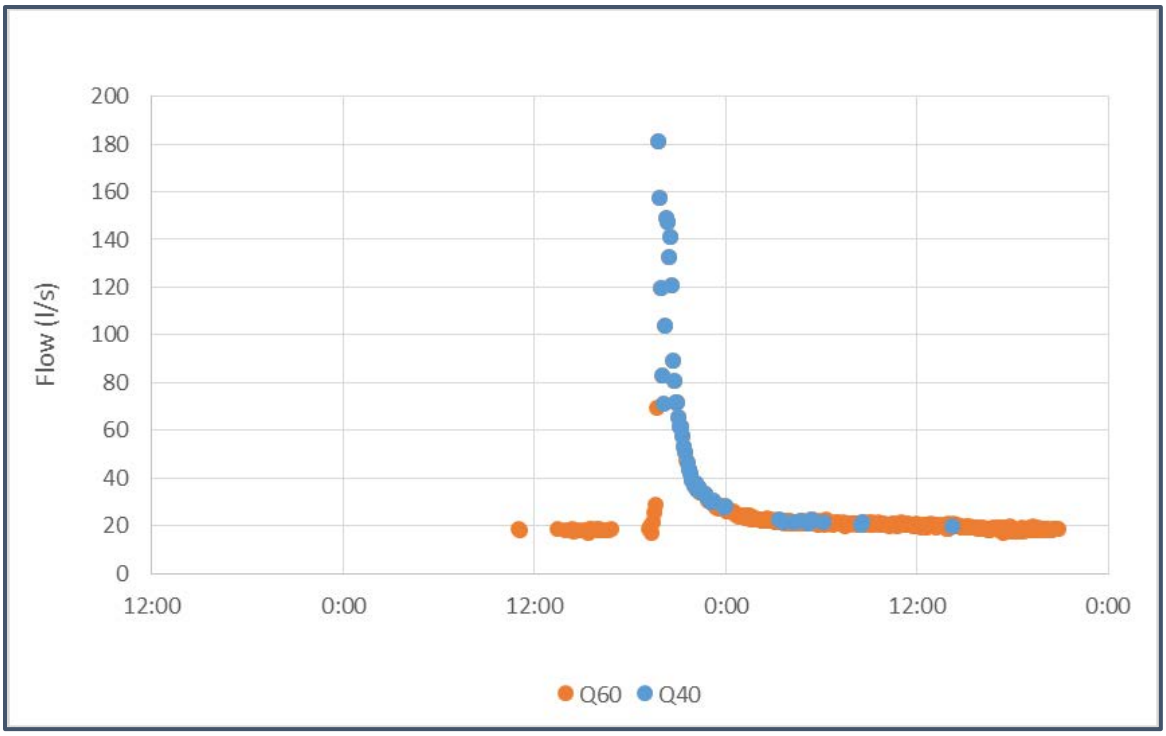

Figure 14: 6/25/2015 Quartile Analysis for the Headwaters Flow Meter

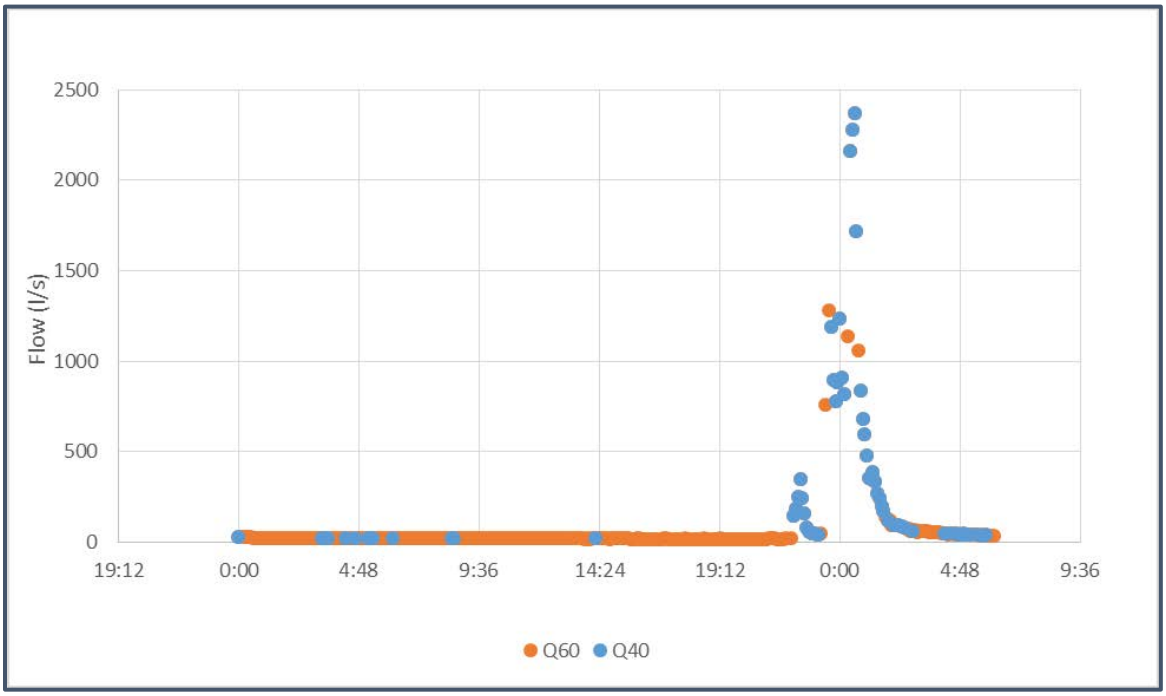

Figure 15: 6/26/2015 Quartile Analysis for the Headwaters Flow Meter

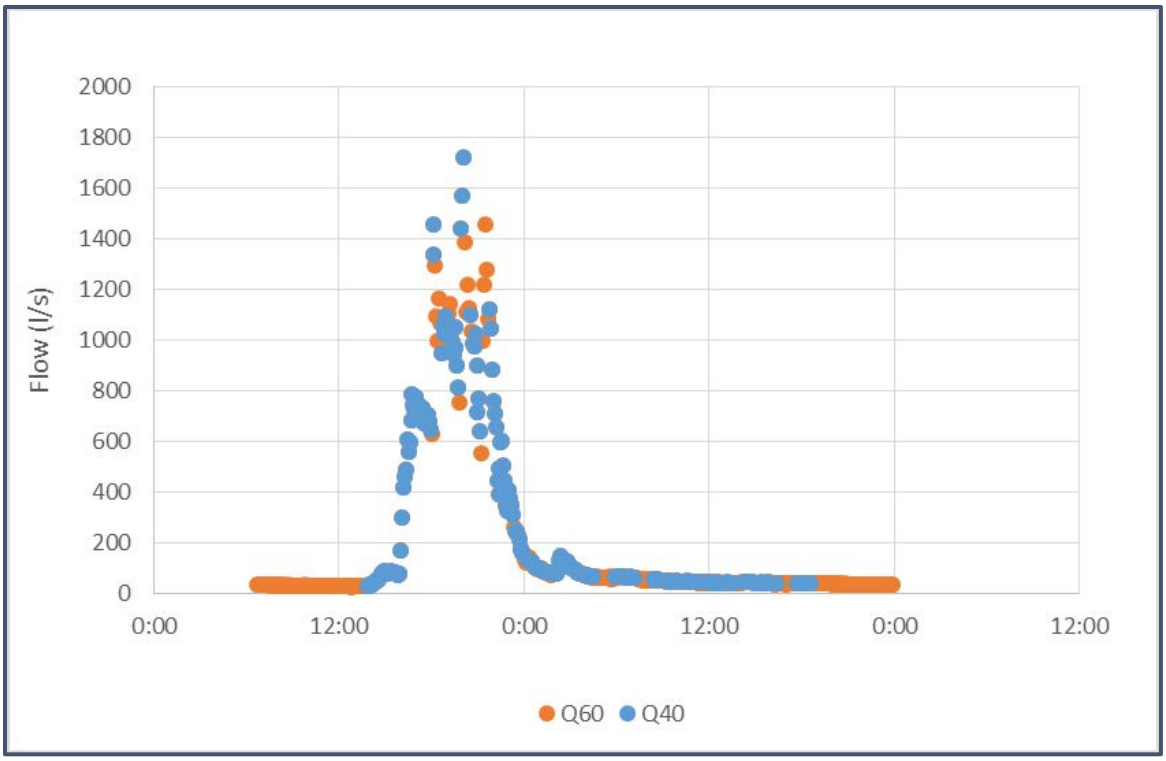

Figure 16: 6/27/2015 Quartile Analysis for the Headwaters Flow Meter

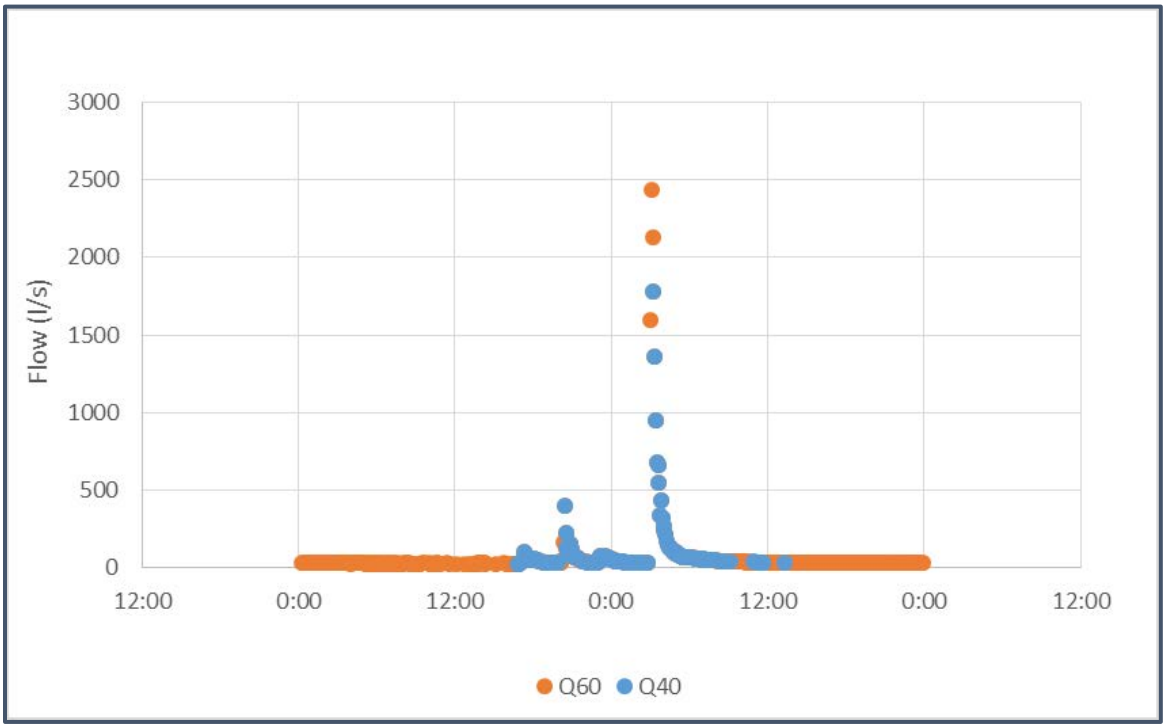

Figure 17: 6/30/2015 Quartile Analysis for the Headwaters Flow Meter

3. Downstream Flow Meter

Figures 18 - 20 depict a summary of the completed quartile analysis for the Downstream Flow Meter. Note that Figures 18 and 19 present the same data at different scales. In the figures, upper quartile limits of 40, 45, 50, 60, and 70 are represented in the legend as Q40, Q45, Q50, Q60, and Q70, respectively. For the Downstream Flow Meter, an upper quartile limit of 45 appears to record all of the peak flows from storms while maintaining flow values that are reasonable compared against field visits and engineering judgement. For the Downstream Flow Meter, raising the quartile significantly above 45 appears to collect only outliers that do not appear to be reasonable when checked against engineering judgement. Thus, for the Downstream Flow Meter, an upper quartile limit of 45 was used whenever Starflow flow data from the field was required for analysis.

Figure 18: Comparison of 2015-2016 Flow Data Collected by the Downstream Flow Meter when the Upper Quartile Limit is Adjusted from 40 (Q40) to 60 (Q60)

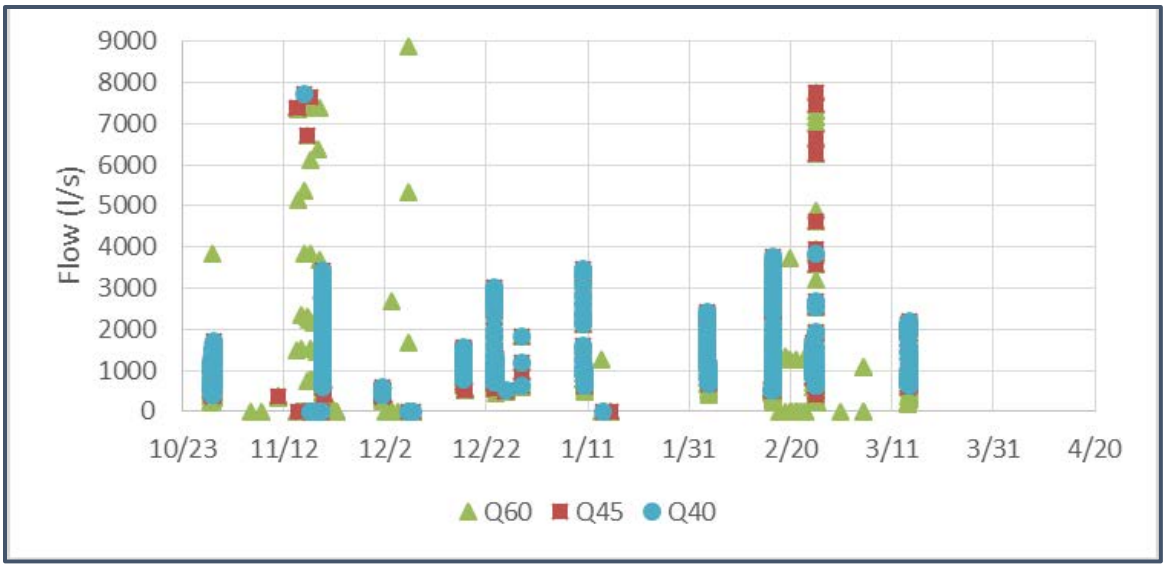

Figure 19: Comparison II of 2015-2016 Flow Data Collected by the Downstream Flow Meter when the Upper Quartile Limit is Adjusted from 40 (Q40) to 60 (Q60)

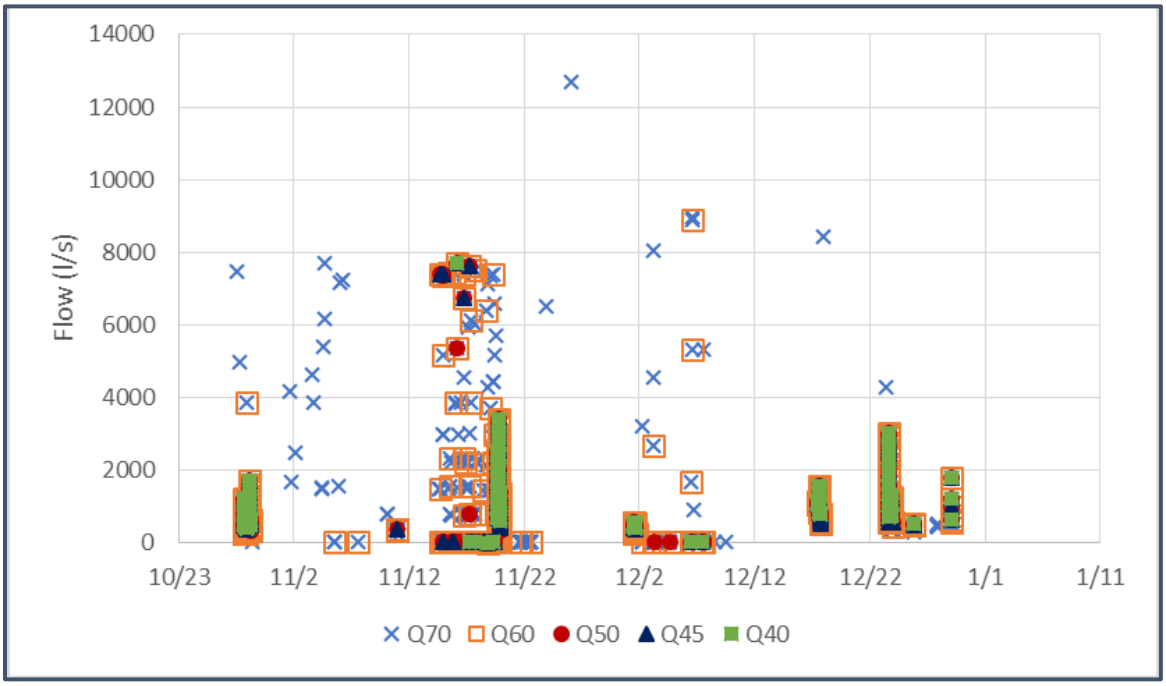

Figure 20: Comparison of 2015 Flow Data Collected by the Downstream Flow Meter when the Upper Quartile Limit is Adjusted from 40 (Q40) to 70 (Q70)

Because an upper quartile limit of 45 can be considered to be reasonably close to the upper quartile limit of 40 recommended by the Starflow Support Team, unlike the Headwaters Flow Meter,

individual storms were not analyzed to examine the difference between data collected with an upper quartile limit of 40 versus data collected with an upper quartile limit of 45 in greater detail.

E. Base Flow

1. General Incorporation of Base Flow in Model

For the purposes of this report, base flow refers loosely to stream flow in between storm events. This is opposed to the definition of base flow used for VUSP water quality testing, which requires 72 hours without precipitation.

Base flow was not calibrated as part of this work. The approach of only calibrating the model to storm flow has been used successfully in earlier research (Ahiablame et al. 2013). To account for not including base flow in SWMM, a base flow value was subtracted from each non-zero Starflow flow data point prior to calibration. In situations where the established base flow value was greater than the flow recorded by Starflow (and adjusting the data point would result in a negative value), the data point was set to zero. The following section describes how a base flow value for each calibration storm event was established. This is consistent with the approach used by Temple University.

2. Base Flow Establishment

a. Starflow Base Flow

When available, Starflow data was used to establish a base flow associated with each calibration storm. Specifically, if the Headwaters Flow Meter recorded any base flow readings within 24 hours from the start of the storm event (and at least 6 hours after the end of the previous storm event) then the base flow reading that was recorded closest to the start of the storm was considered to be the base flow for that storm. This allowed for the establishment of a storm specific base flow.

These base flow readings were checked for reasonability against base flow measurements recorded in the field. This approach was used for all Headwaters Flow Meter calibrations except for the June 8, 2015 storm. For the June 8, 2015 storm, no pre-storm base flow readings were available from the Headwaters Flow Meter (The specific storm selection process for calibration is described in the *Rain Gauge Selection for Calibration* section of this report). The Downstream Flow Meter did not record any base flow data points. In general, the Starflow flow meters have difficulty reading low flows.

b. Manually Measured Base Flow

When Starflow data were not available for a given calibration storm, an average base flow was calculated from velocity, depth and width readings manually collected in the field. Depth and width measurements (Narberth is consistently 2.9 m wide, and Lankenau is 4.5 m wide) were collected with a tape measure and velocity readings were collected using both a Global Water Instruments (GWI) Flow Probe model FP111 and a ping pong ball approach. The ping pong ball approach involved using a ping pong ball, a tape measure, and a timer to calculate creek velocity. Although the ping pong ball approach only measures surface velocity, this was considered to be a reasonably estimate the full velocity profile for the creek when considering the very shallow creek depth relative to the diameter for a ping pong ball. For instance, the diameter of a ping pong ball is approximately 40 mm. Average creek depths for the headwaters and downstream calibration points are displayed in Table 14. The ping pong ball approach was used when water depths were too shallow for use of the GWI Flow Probe or when the GWI Flow Probe was unavailable.

Manual base flow measurements were taken from 12/7/15 to 12/2/2016. Data points were collected bi-weekly by VUSP and the Lower Merion Conservancy from 12/7/15 to 7/6/16. Data points were

collected monthly by VUSP from 7/6/16 to 12/2/2016. A summary of this collected data is displayed in Table 14.

Table 14: Summary of Manual Measurements at Headwaters and Downstream Calibration Points

	Headwaters			Downstream		
	Depth (cm)	**Velocity (cm/s)**	**Flow (l/s)**	**Depth (cm)**	**Velocity (cm/s)**	**Flow (l/s)**
Number of Readings	19			22		
Maximum	9	87	87	6	65	176
Minimum	1	12	17	1	12	17
Average	4	36	34	4	31	54

For both the Headwaters and the Downstream Calibration Points, manual base flow measurements were assigned as an average of the manual measurements collected in the field for the respective calibration point. This is to account for the variability of the manual measurements and that the majority of measurements could not be correlated to specific storm events. Thus the same base flow was assigned for all seven downstream calibration storm events. All manual base flow readings for both the Headwaters and the Downstream Calibration points are depicted on Figure 21 and Figure 22.

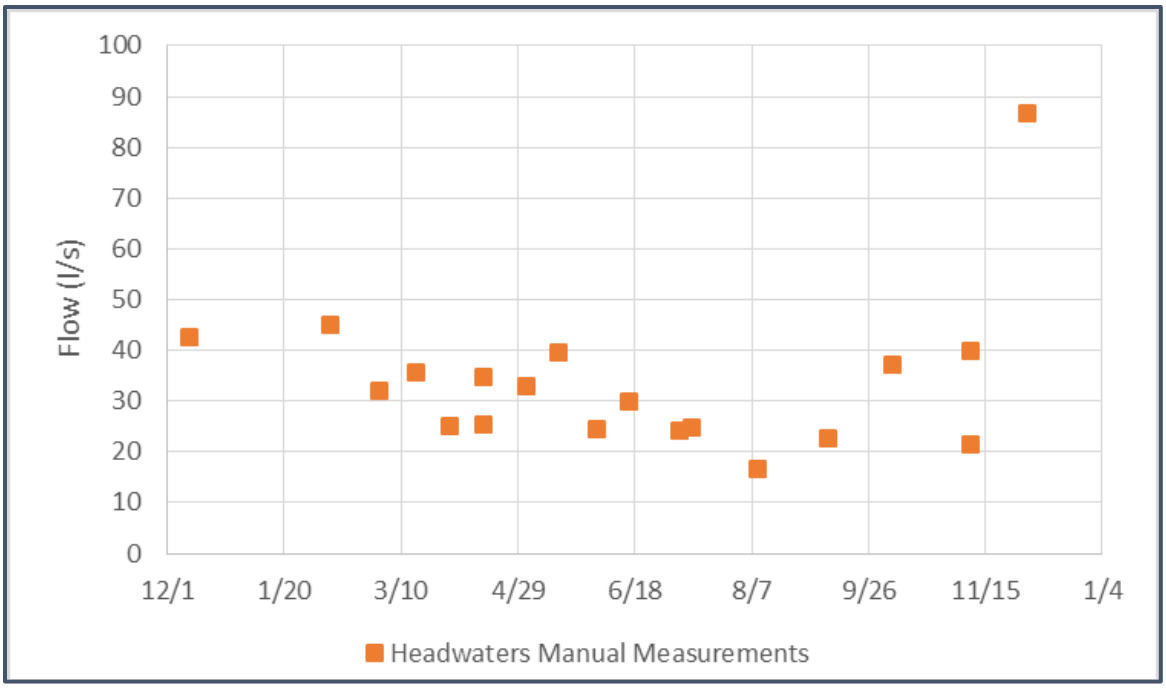

Figure 21: Manual Base Flow Readings Collected at the Headwaters Calibration Point (2015-2016)

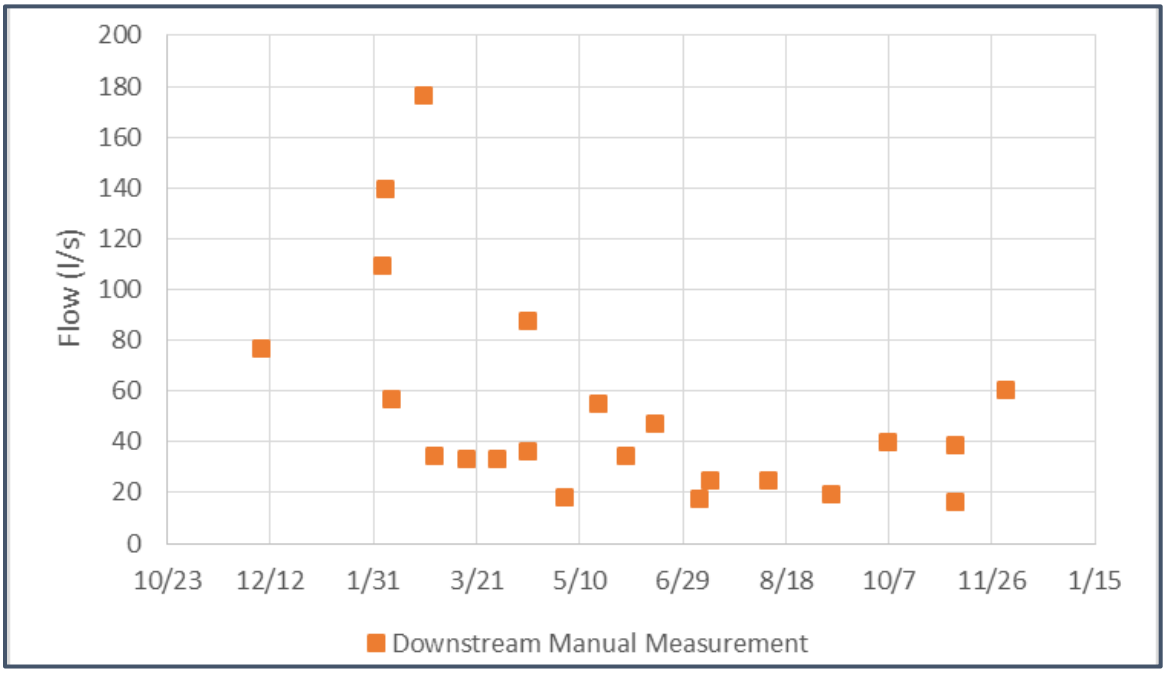

Figure 22: Manual Base Flow Readings Collected at the Downstream Calibration Point (2015-2016)

For both Figure 21 and Figure 22, the most recent data point collected for both calibration points was collected on 12/2/2016. These two data points were measured only about 38 hours after an (approximately) 1 in storm event. Following VUSP protocol, at least 72 hours must pass after a storm event to declare base flow conditions. This explains the upward trend in flow rate for the 12/2/2016 reading. Although the 12/2/2016 data point does not represent base flow conditions, it is still valuable for determining the type of flows that the creek is experiencing between storm events. Due to the 72 hour rule for base flow, the creek does not reach base flow conditions between every storm event.

Figures 23 and 24 displays the variation in manual base flow measurements relative to Starflow data collected during storm events for both the Headwaters and the Downstream Calibration Points. From these figures, it was concluded that, for the purposes of this thesis work, variations in base flow could be considered to be negligible relative to storm flows.

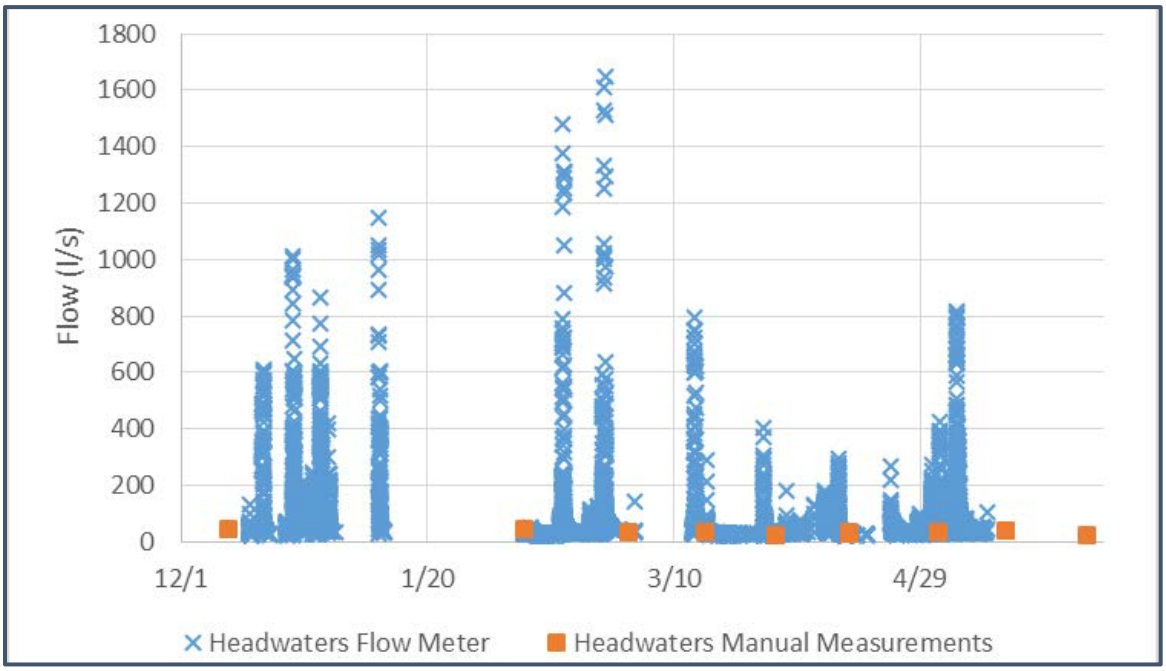

Figure 23: 2015-2016 Variations in Base Flow (Manual Measurements) Relative to Stormflow (Headwaters Flow Meter) for the Headwaters Calibration Point

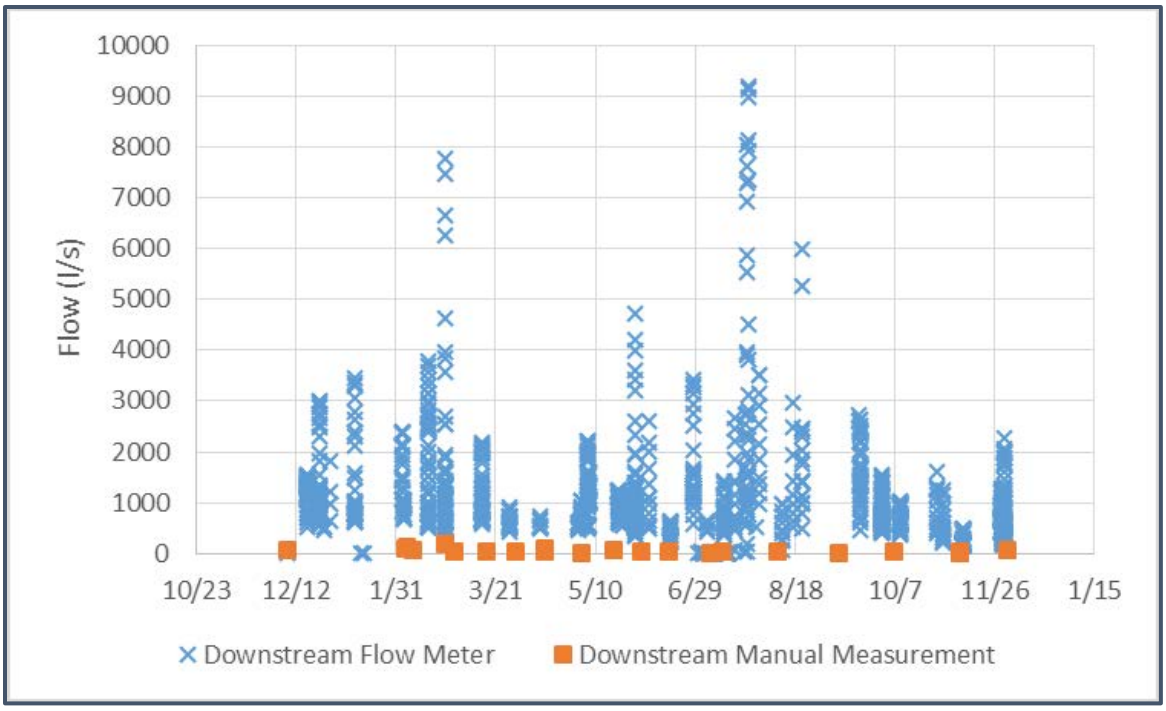

Figure 24: 2015-2016 Variations in Base Flow (Manual Measurements) Relative to Stormflow (Downstream Flow Meter) for the Downstream Calibration Point

IV. Rain Gauge Selection for Calibration and Validation

A. Overview

The purpose of the rain gauge in SWMM is to supply rainfall data to the subcatchments (Rossman 2015). As described by Barco et al. (2008), "Rainfall data drive the model and produce runoff, which means that an accurate estimation of rainfall data determines the success of the modeling effort". Thus the rain gauge for a model must be as accurate as possible.

Another key factor in selecting a rain gauge is to select an instrument with an appropriate time step. Having a 5 minute time step is important for accuracy, particularly for storms with rapidly varying intensities. In a past study by MacKenzie et al. (2007), it was determined that "raingage data collected on a 60-minute time step, or even a 15-minute time step will not capture the true characteristics of a rainfall event of rapidly varying intensity…[and the data] can result in

misleading conclusions". Thus, all three rain gauges selected for use as part of this model record precipitation in five minute intervals.

Rain gauge density and location are also large considerations when setting up a rainfall-runoff model. For instance, the same study by MacKenzie et al. (2007) demonstrated that the location of rain gauge within a 3.09 square mile watershed "had a noticeable impact on how the simulated results varied from the field-observed data". This demonstrates that spatial variability of rainfall can have an impact on relatively small rainfall runoff models. Also, in the same study Mackenzie et al. (2007) found that "when the gauge density exceeded approximately one gage per square mile, very little change occurred in the range of variations in the results". As discussed in the *Background and Literature Review*, the specific impact of spatial variability on rainfall runoff models is largely unknown. However, based on the MacKenzie et al. (2007) study, it can be assumed that the spatial variability of a rainfall runoff model has a negligible impact within one square mile from the rain gauge.

B. Continuous Data versus Representative Storms

Two common approaches to calibrating SWMM models are to calibrate to a continuous data set and to calibrate to a set of representative storms. Calibrating to a continuous data set refers to calibrating to a set of continuous weather data that includes both rain events and dry periods, rather than individual storms. For this thesis work, SWMM was calibrated to a set of representative storms. Justification for this approach is provided below.

1. Calibrating to a Continuous Data Set

Calibrating to a continuous data set is often the preferred calibration approach, because past research has demonstrated that the "reliability of the single-event calibrated model was lower than

those calibrated over continuous events, suggesting that event based modeling depends strongly on initial conditions" (Tan et al. 2008). A model calibrated to a continuous data set has the unique advantage of accounting for any lingering effects of previous storms. A study completed at Villanova University makes the case for continuous modeling in SWMM, concluding that "overall the model hydrology is substantially different than the actual watershed during short periods of time" and that model hydrology with a continuous data set proved to be more representative of the actual watershed. The ability to model continuous data sets is one of the advantages of using SWMM (Pittman 2011). Furthermore, if one month of data represents a large variety of rain event characteristics and peak flow responses, it is possible to use just one month of continuous data for calibration. Tan et al. (2008) set the precedent for this approach.

2. Calibrating to a Set of Representative Storms

Despite the many benefits of calibrating to a continuous data set, calibrating to a set of representative storms is also a viable option, or even a better option, for some watersheds. For instance, "for a small watershed [such as the one being presented in this study] having a moderate impact of initial soil moisture memory, rainfall-runoff models can still be calibrated reliably over a set of representative events, provided that the events cover a wide range of peak flow" (Tan et al. 2008). The study found that hydrograph characteristics for such watersheds were "generally insensitive to the infiltration parameters of the low permeable in situ soils that are mainly responsible for the soil moisture memory" (Tan et al. 2008). The Tan et al. (2008) approach involved creating a model that was calibrated to ten different representative rain events. Each of the events was calibrated individually and "the event-based parameter set was obtained by averaging the parameter sets for the ten selected events" (Tan et al. 2008).

Not only did Tan et al. (2008) find the representative event calibration approach to be viable, but also, the study concluded that the event based calibration approach provided more accurate results in terms of overall hydrograph shape, time to peak, and peak flow rate. One goal of this thesis work is to find a suitable metric to evaluate stream health in terms of water quantity metrics. As discussed in the *Background and Literature Review* section of this report, flow regimes disturbed by urbanization are characterized by a reduced base flow and short duration, high-peak floods. To evaluate the extent of such disturbances, accurate results in terms of hydrograph shape, time to peak, and peak flow rate are important. Note that the same study by Tan et al. (2008) found continuous event calibration to be more accurate at predicting runoff volume. This is one example of the importance of knowing the end goal of the model before selecting a calibration approach, as detailed in the *Calibration Approach* section.

Data obtained from the Web Soil Survey, as discussed in the *Curve Number* section of this report, revealed that soil for this watershed consists primarily of different kinds of loam ranging from gravely loam (with gravely clay loam) to silty clay loam (USDA 2013). In the Tan et al. (2008) study, the watershed considered to have a moderate impact of initial soil moisture memory consisted of primarily loamy soils. Therefore, it was assumed that the East Branch of the Indian Creek model also has a moderate impact of initial soil moisture memory.

The calibration approach using a set of representative storms has been used successfully in other models. For instance, a SWMM study of the Fox Hollow watershed by Zhang (2009) set calibration parameters for eight individual events and then used an average of those terms for the calibrated model. Although Zhang (2009) had higher errors for the calibration events [relative to a model calibrated using a continuous data set], the errors for validation events were smaller (Blansett 2011).

Furthermore, if an appropriate range of storms is selected for calibration, the event-based approach allowed the author to evenly balance parameter adjustments between different kinds of storm events. This is significant because, as found in the early stages of creating the East Branch of Indian Creek model, during the calibration process, "a point was reached where parameter value adjustments to achieve a better match between simulated and observed data for one event increased the error for another event…A better match could be made for a single event but those parameters could result in a poorer match for another event"(Blansett 2011). With a continuous data set, it may be difficult to ensure that the final calibration parameters are not favoring one type of storm.

C. Summary of Storm Selection

Storm selection was completed before the evaluation of rain gauge specific data. This was done because the same set of calibration storms was used for all three rain gauges for a better comparison across the three models. Two sets of storms were collected. One set of representative storms was used to calibrate the headwaters portion of the model (Subcatchments 1-3), and a second set of representative storms was used to calibrate the downstream portion of the model (Subcatchments 4-7). When selecting a set of calibration storms, it is preferable to include a wide range of storms and peak flows so that "the calibrated parameters are unbiased to a particular flow regime"(Tan et al. 2008).

1. Defining a Typical or Representative Storm

To improve the author's understanding of rainfall patterns in the Greater Philadelphia Area, historical rain data were analyzed to define a typical storm for the area. These typical storm data were then used as a baseline for defining what would qualify as a large or small event to create a full range of representative storms. An awareness of what storms are most typical allowed for an informed decision of selecting storms that are representative of the watershed.

To determine what a typical event was, the authors evaluated historical data from the VUSP Villanova Rain Gauge at the Constructed Stormwater Wetland in Villanova, PA. This is one of the same rain gauges that is used for the model calibration portion of this thesis work. Rain data were evaluated from 2012 through 2016. This allowed for enough storm data to accumulate to prevent especially wet or dry periods from obscuring the perception of what defines a typical storm. As discussed in the *Rain Gauge 2: VUSP Villanova University* section of this report, the time series data form this gauge is geographically far enough away from the site that spatial variability may influence the results of a 5-minute time step model. However, it can be assumed that general climate trends and typical storms are the same throughout the Greater Philadelphia Area, which comprises Villanova and the East Branch of Indian Creek watershed.

As part of this analysis, 210 storms were analyzed. Following VUSP protocol, storm events were defined as any rain event with a rainfall volume greater than 0.25 in. Tables 15 – 17 below provide a breakdown of storm volumes and durations for the 210 events analyzed. The blue, red, and green bars in Tables 15, 16, and 17, respectively, provide a visual representation of the number of storms within each total rainfall or duration category. From the data, it can be concluded that the most typical storm for the Greater Philadelphia Area has a total volume of 0.25 – 0.50 in and lasts for about 10 – 11 hours.

Table 15: 2012-2016 Storm Volumes in 0.05 Inch Increments

Total Rainfall (in)	Number of Storms	Percent of Total Storms
0.25 - 0.30	25	12%
0.30 - 0.35	11	5%
0.35 - 0.4	26	12%
0.40 - 0.45	10	5%
0.45 - 0.50	9	4%
0.50 - 0.55	10	5%
0.55 - 0.60	10	5%
0.60 - 0.65	11	5%
0.65 - 0.70	10	5%
0.70 - 0.75	10	5%
0.75 - 0.80	11	5%
0.80 - 0.85	10	5%
0.85 - 0.90	9	4%
0.90 - 0.95	3	1%
0.95 - 1.00	9	4%
1.00 - 1.05	4	2%
1.05 - 1.10	3	1%
1.10 - 1.15	2	1%
1.15 - 1.20	5	2%
1.20 - 1.25	3	1%
1.25 - 1.30	4	2%
1.30 - 1.35	6	3%
1.35 - 1.4	2	1%
1.40 - 1.45	4	2%
1.45 - 1.50	3	1%

Table 16: 2012-2016 Storm Volumes in 0.25 Inch Increments

Total Rainfall (in)	Number of Storms	Percent of Total Storms
0.25 - 0.50	81	39%
0.50 - 0.75	51	24%
0.75 - 1.00	42	20%
1.00 - 1.25	17	8%
1.25 - 1.50	19	9%

Table 17: 2012-2016 Storm Durations in Hourly Increments

Duration (hours)	Number of Storms	Percent of Total Storms
0.0 - 1.0	0	0%
1.0 - 2.0	0	0%
2.0 - 3.0	0	0%
3.0 - 4.0	0	0%
4.0 - 5.0	0	0%
5.0 - 6.0	0	0%
6.0 - 7.0	2	2%
7.0 - 8.0	9	11%
8.0 - 9.0	4	5%
9.0 - 10.0	5	6%
10.0 - 11.0	15	19%
11.0 - 12.0	7	9%
12.0 - 13.0	3	4%
13.0 - 14.0	5	6%
14.0 - 15.0	5	6%
15.0 - 16.0	6	7%
16.0 - 17.0	2	2%
17.0 - 18.0	2	2%
18.0 - 19.0	7	9%
19.0 - 20.0	2	2%
20.0 - 21.0	0	0%
21.0 - 22.0	2	2%
22.0 - 23.0	0	0%
23.0 - 24.0	2	2%
24.0 - 25.0	0	0%

2. Defining the Calibration Periods

Next, calibration and validation periods were defined for each flow meter. These periods were selected based on both flow meter and rain data availability.

For the Headwaters Calibration/Validation Location, this was determined to be from June 3, 2015 to July 9, 2015. This period was used for the areas draining into the Headwaters Flow Meter (Subcatchments 1-3). This period was selected because, as depicted in Figure 25 below, the month of June had the highest percentage of flow data with quartile readings less than or equal to 40

between the time that the flow meter was installed on June 3, 2015, and the beginning of April 2016. In the figure, upper quartile limits of 40 and 60 are represented in the legend as Q40 and Q60, respectively. April 2016 is when the first SCM was installed in the headwaters of the East Branch of Indian Creek. After April 2016, the Headwaters Calibration/Validation Point stopped experiencing baseline conditions. As described in the *Quartile Analysis* section of this report above, data points with quartile readings less than 60 are considered to be acceptable, but data points with quartile readings less than or equal to 40 are those that guarantee the highest level on confidence in the flow data. Additionally, there was a diverse enough variation of rain events from June 3, 2015 to July 9, 2015 that is was assumed this time frame would result in a well-rounded calibration/validation.

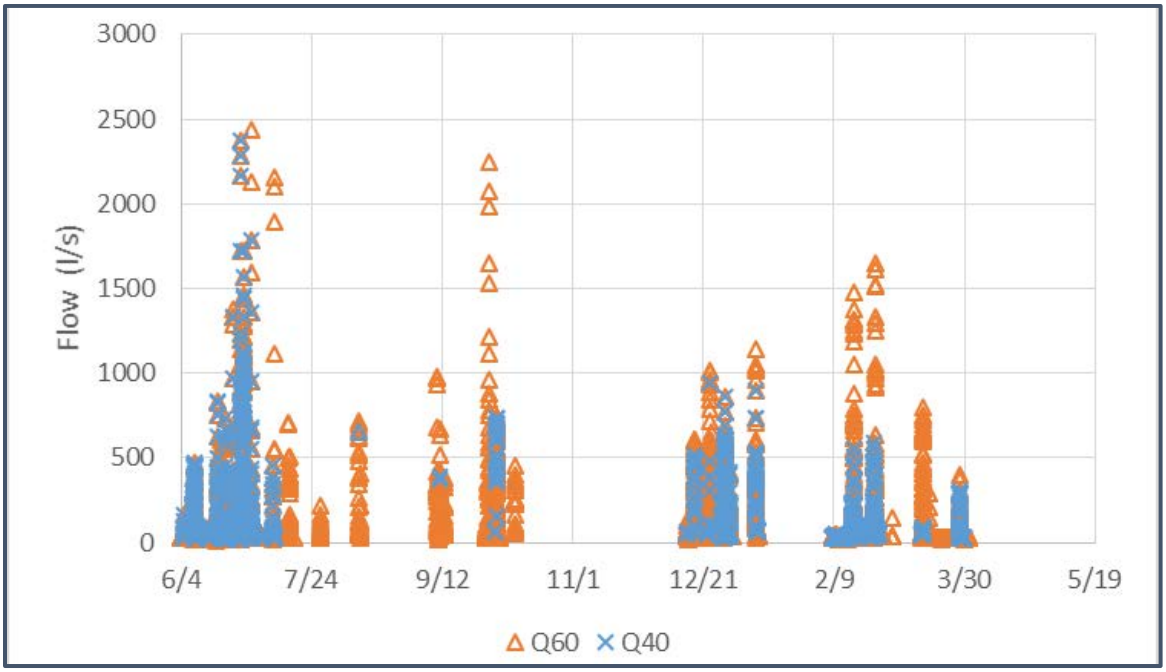

Figure 25: Analysis of which Time Period has the Highest Percentage of Quartile Readings Less than 40

For the Downstream Flow Meter, the calibration/validation period was determined to be from October 26, 2015 to December 30, 2015. This period was used for the areas draining into the

Downstream Calibration/Validation Point (Subcatchment 4-7). This period represents the time from when the Downstream Flow Meter was first installed to the beginning of the winter months where precipitation was in the form of snow. Snow fall adds an added level of complication to rainfall-runoff models that was not addressed as part of this thesis work. This period of time is roughly the same length as the period selected for the Headwaters Calibration/Validation Point. There was a diverse enough variation of rain events from October 26, 2015 to December 30, 2015 that is was assumed this time frame would result in a well-rounded calibration/validation.

The validation periods were not extended into 2016. This was determined to be the best approach because only two rain events were recorded by the VUSP Narberth Rain Gauge between December 31, 2015 and April 16, 2016, and both events were less than 0.2 inches. This is not a sufficient range of storms to determine whether the calibration efforts provide reasonable results for a range of storms. The validation must be completed before April 16, 2016, because after the riparian buffer was installed, the location of the Headwaters Flow Meters could no longer be described as experiencing baseline or pre-construction conditions. When considering the two other rain gauges, 2016 rain data is only unavailable for one third of the total SWMM work completed as part of this thesis. However, it is the author's goal to keep the methods for each portion of the model as consistent as possible. Ideally, this will provide an accurate understanding of how the rain gauge itself, rather than the calibration approach or other various factors, influences interpretation of the selected hydrologic metrics.

3. Final Selection

After defining the calibration/validation periods, individual storm selection was based primarily on the percent of null readings in the Starflow data set for a given storm and the diversity of the storms selected. Diversity of storms was ensured in terms of storm duration and total rainfall

volume. Storms were selected to represent a range of conditions, so that the model calibrated model was not partial to any particular type of storm.

Storms were selected to minimize the amount of null Starflow readings recorded during the storm. Null flow meter readings are any point when the data recorded by the flow meter had a quartile reading greater than 60 or 45 (for the Headwaters or Downstream Flow Meter, respectively), for reasons described in the *Quartile Analysis* section of this report. The larger the percent of null flow meter readings, the less complete the Starflow data set for a given storm, and the less confidence the author had in her understanding of what actually happened in the stream for that storm event. For the Headwaters Calibration/Validation Point, storms with very small percent of null flow Starflow readings (i.e. 1% or 2% null readings) were prioritized for selection. Storms with null flow meter readings greater than 15% were excluded from calibration/validation. The percent of null readings for each storm is provided as part of Table 18.

For the Downstream Calibration/Validation Point, it was not appropriate to use the same standards for percent null Starflow readings. This is because storms recorded during the Downstream Calibration/Validation Period had null readings varying from 63% to 98% of the total Starflow data set for a given storm. The percent of null readings for each storm is provided as part of Table 18. As discussed in the *Continuous Data versus Representative Storm Events* section of this report, this research is more concerned with hydrograph shape and peak flows than total flow volume. Therefore, calibration to the Downstream Flow Meter data is still valuable, as the flow meter was able to capture peak flows during the storm and time to peak after initial rainfall. However, more detailed, final analysis, the results from the Headwaters Calibration/Validation Point may be more reliable than the results from the Downstream Calibration/Validation Point.

Upon closer investigation, it was determined that many of the storm events that occurred during the Downstream Calibration Period did not have sufficient flow meter data to complete a meaningful calibration or validation. This occurred for the 11/30/2015 storm, the 12/25/2015 storm, and the 12/28/2015 storm. Figures 26-28 depicts the flow meter data recorded for these storms relative to the SWMM output for the Downstream Calibration Point in the baseline model.

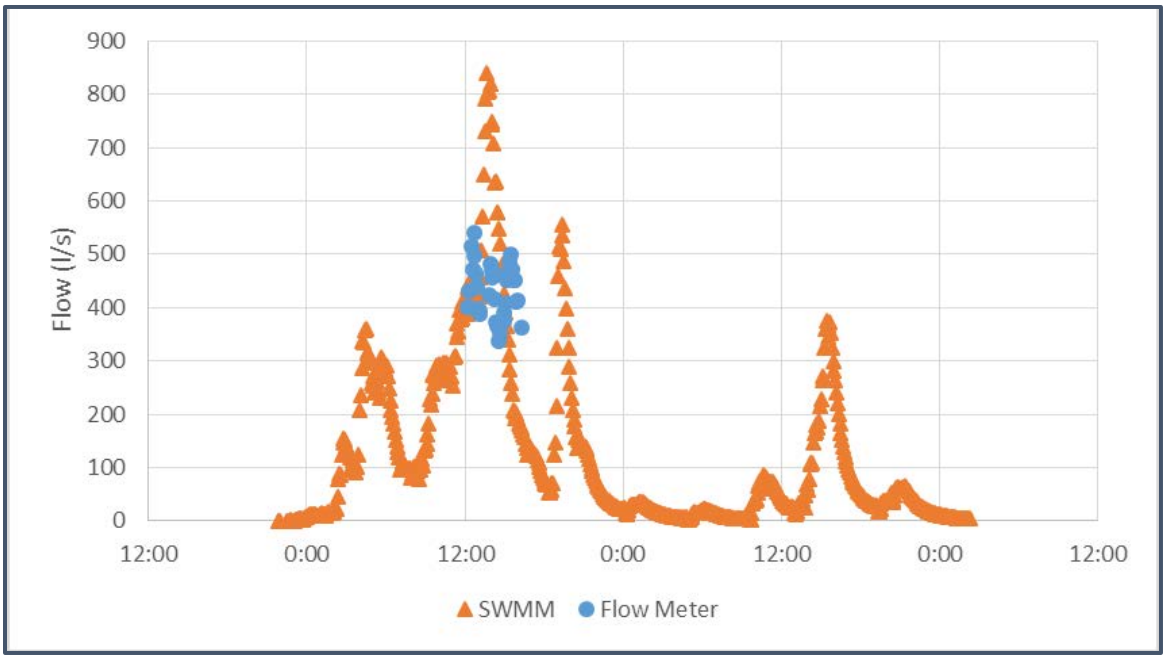

Figure 26: 11/30/2015 Storm Event with Insufficient Data for Downstream Calibration

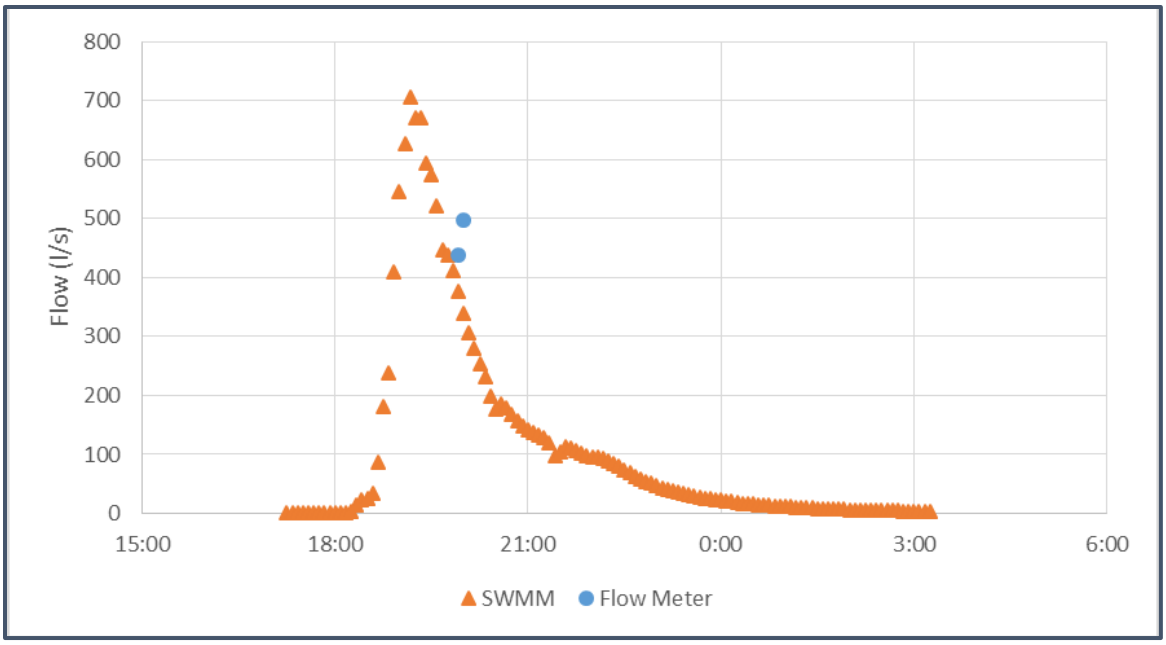

Figure 27: 12/25/2015 Storm Event with Insufficient Data for Downstream Calibration

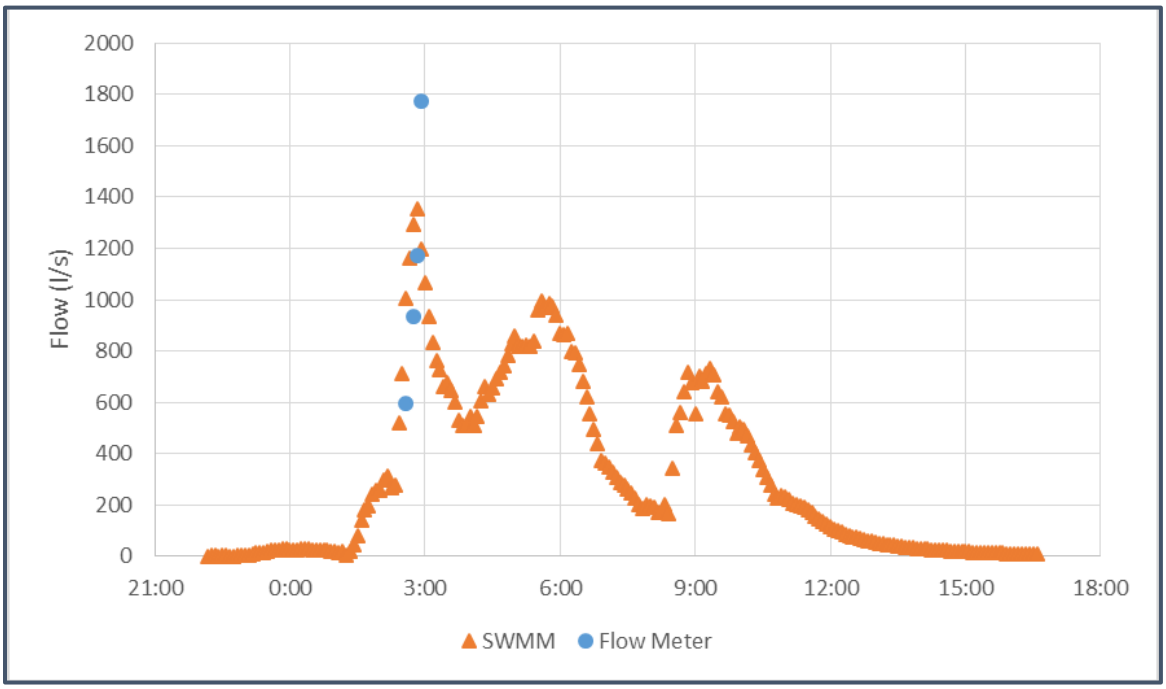

Figure 28: 12/28/2015 Storm Event with Insufficient Data for Downstream Calibration

Table 18 below displays the final storms selected for calibration and validation of the Headwaters and Downstream Calibration/Validation Points. Note that the total flow for each storm is defined

as the total flow moving past the respective flow meter (Headwaters or Downstream, depending on the storm being assessed) from the beginning of the storm until 6 hours after the last precipitation.

Table 18: Storms Selected for Headwaters and Downstream Calibration and Validation

HEADWATERS CALIBRATION AND VALIDATION

Date	Headwaters Flow Meter		Villanova Rain Gauge		Narberth Rain Gauge		Wynnewood Rain Gauge	
	Total Flow	% Null Readings	Storm Duration	Total Rainfall	Storm Duration	Total Rainfall	Storm Duration	Total Rainfall
	L	*%*	*hours*	*inches*	*hours*	*inches*	*hours*	*inches*
6/8/2015	5,764,154	12%	5	0.75	4	0.55	5	0.73
6/18/2015	4,157,428	11%	9	0.47	2	0.21	9	0.59
6/20/2015	4,965,212	1%	6	0.61	2	0.29	6	0.59
6/25/2015	1,490,865	14%	7	0.20	NA	NA	5	0.20
6/26/2015	8,874,781	4%	3	0.99	3	0.83	NA	NA
6/27/2015	26,679,912	2%	21	1.96	6	1.10	23	1.59
6/30/2015	6,472,488	1%	7	0.64	11	0.48	13	0.70

*If storm continues for more than one day, *Date* is the first day of the storm

DOWNSTREAM CALIBRATION AND VALIDATION

Date	Downstream Flow Meter		Villanova Rain Gauge		Narberth Rain Gauge		Wynnewood Rain Gauge	
	Total Flow	% Null Readings	Storm Duration	Total Rainfall	Storm Duration	Total Rainfall	Storm Duration	Total Rainfall
	L	*%*	*hours*	*inches*	*hours*	*inches*	*hours*	*inches*
10/28/2015	14,871,362	81%	21	1.32	14	0.47	24	1.11
11/19/2015	38,020,963	63%	10	1.35	5	0.54	13	1.57
12/17/2015	17,670,018	69%	7	0.86	6	0.48	7	0.89
12/23/2015	17,941,430	83%	16	0.96	10	0.63	16	0.99

*If storm continues for more than one day, *Date* is the first day of the storm

Two distinct sets of storms were used for the calibration and validation of each model variation. After the final selection of storms for calibration/validation, events were grouped into two categories: storms to be used for calibration and storms to be used for validation.

When assigning each final storm as a calibration or validation event, following the set of representative storms method, the author prioritized having a range of storms for both the calibration and validation of each model variation, to minimize the bias of each model variation. Additionally, storms were grouped so that the characteristics of the validation storms were similar to the characteristics of the calibration storms for each model variation. The final grouping of storms is displayed in Tables 19 and 20. To check the similarity of the group of calibration storms compared to the group of validation storms selected for each model variation, the average volume of rainfall (inches), the average duration of rainfall (hours) and the average total creek flow (L) were calculated for each group of calibration or validation storms. These averages are displayed in Tables 19 and 20. The author prioritized assigning similar average rainfall volumes to the calibration and validation groups, then average storm duration, and finally, average total creek flow.

Storms with the most complete data sets (or smallest % null readings) were prioritized for calibration. As described in the *Calibration Approach* section of this report, calibration is a quantitative process that is dependent on individual data points. As described in the *Validation* section of this report, below, a qualitative approach was used for the validation of the SWMM models. Thus, the validation process was not dependent on individual data points and would be les influenced by null readings.

It is important to note how the averages in Tables 19 and 20 compare to the typical storm defined in the *Defining a Typical or Representative Storm* section of this report. For the Headwaters Calibration/Validation Point, the calibration and validation storms, on average, exhibit a higher rainfall volume and a shorter rainfall duration than the previously defined typical storm. For the Downstream Calibration/Validation Point, the calibration and validation storms, on average, exhibit higher rainfall volumes and longer rainfall durations than the defined typical storm. Therefore, the models calibrated as part of this research may be biased to higher volume rain events.

Table 19: Average Event Statistics for Headwaters Calibration and Validation Events

VUSP Villanova Rain Gauge							
Headwaters Calibration Events				Headwaters Validation Events			
Date	Average Event Statistics			Date	Average Event Statistics		
	inches	*hours*	*L*		*inches*	*hours*	*L*
6/8/2015	0.83	9.0	9,074,526	6/18/2015	0.73	5.92	6,516,104
6/20/2015				6/26/2015			
6/25/2015							
6/27/2015							
6/30/2015							

VUSP Narberth Rain Gauge							
Headwaters Calibration Events				Headwaters Validation Events			
Date	Average Event Statistics			Date	Average Event Statistics		
	inches	*hours*	*L*		*inches*	*hours*	*L*
6/20/2015	0.62	6.32	12,705,871	6/8/2015	0.53	2.94	6,265,454
6/27/2015				6/18/2015			
6/30/2015				6/26/2015			

WU Wynnewood Rain Gauge							
Headwaters Calibration Events				Headwaters Validation Events			
Date	Average Event Statistics			Date	Average Event Statistics		
	inches	*hours*	*L*		*inches*	*hours*	*L*
6/20/2015	0.77	11.64	9,902,119	6/8/2015	0.66	7.11	4,960,791
6/27/2015				6/18/2015			
6/30/2015							
6/25/2015							

Table 20: Average Event Statistics for Downstream Calibration and Validation Events

VUSP Villanova Rain Gauge							
Downstream Calibration Events				Downstream Validation Events			
Date	Average Event Statistics			Date	Average Event Statistics		
	inches	*hours*	*L*		*inches*	*hours*	*L*
10/28/2015	0.91	19.00	11,947,117	12/17/2015	0.91	11.33	17,805,724
11/19/2015				12/23/2015			
11/30/2015							
12/25/2015							
12/28/2015							

VUSP Narberth Rain Gauge							
Downstream Calibration Events				Downstream Validation Events			
Date	Average Event Statistics			Date	Average Event Statistics		
	inches	*hours*	*L*		*inches*	*hours*	*L*
10/28/2015	0.50	9.23	26,446,162	12/17/2015	0.55	8.21	17,805,724
11/19/2015				12/23/2015			

WU Wynnewood Rain Gauge							
Downstream Calibration Events				Downstream Validation Events			
Date	Average Event Statistics			Date	Average Event Statistics		
	inches	*hours*	*L*		*inches*	*hours*	*L*
10/28/2015	0.99	20.17	11,947,117	12/17/2015	0.94	11.55	17,805,724
11/19/2015				12/23/2015			
12/25/2015							
12/28/2015							
11/30/2015							

D. Rain Gauge 1: VUSP Narberth

The first model variation was calibrated to the VUSP Narberth Rain Gauge. This rain gauge is a Vaisala Weather Transmitter WXT520. The accuracy for this instrument is better than 5% and is weather dependent (Vaisala 2012). The rain gauge is located in Narberth Park in Narberth, PA approximately 30 meters from the Headwaters Flow Meter, 2 km from the Downstream Flow

Meter, and 0.5 km from the centroid of the watershed. Figure 29 below displays the location of the VUSP Narberth Rain Gauge within the East Branch of Indian Creek watershed.

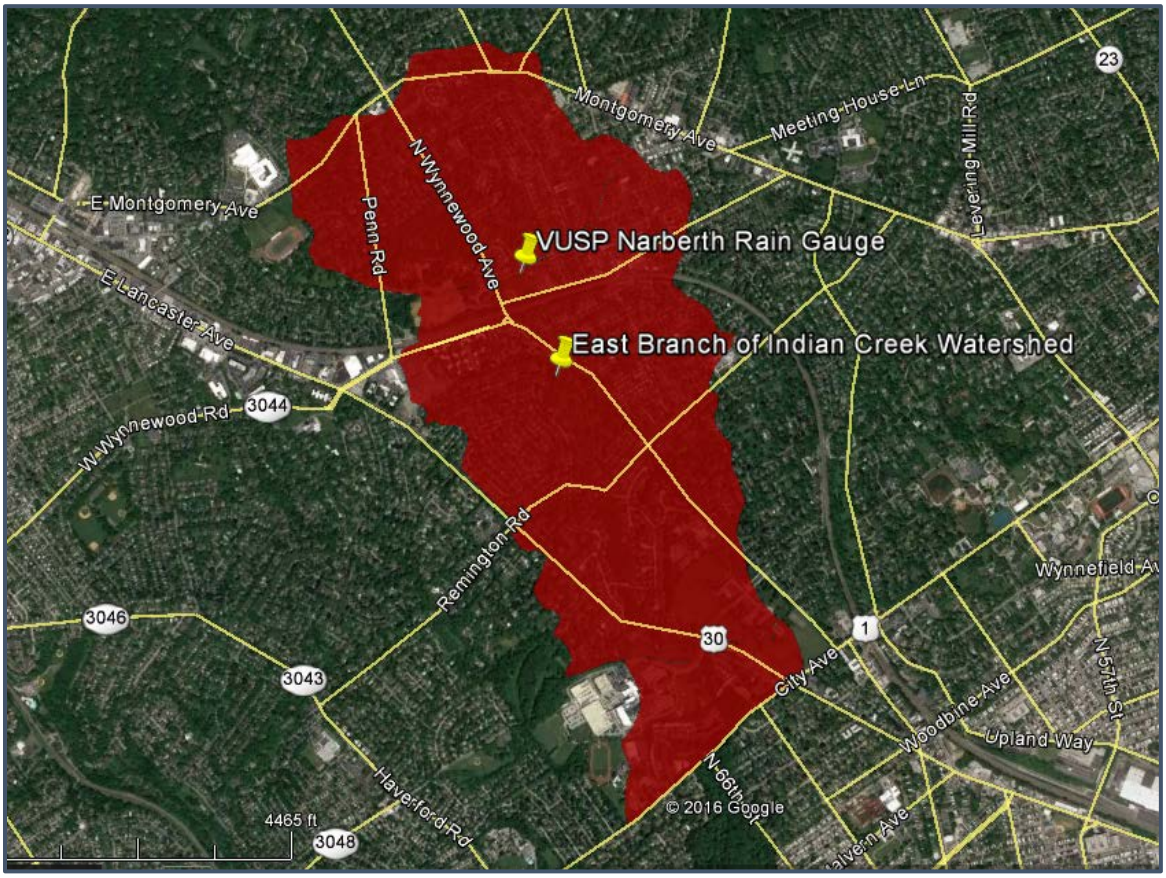

Figure 29: VUSP Narberth Rain Gauge Location

Given that the area of East Branch of the Indian Creek watershed is approximately 1.2 square miles, and that the Narberth Rain Gauge is located within the rain gauge is located within the watershed, it can be assumed that the influence of spatial variability on this model will be negligible (MacKenzie et al. 2007). This is particularly true for the Headwaters Calibration Point approximately 30 m from the rain gauge. Thus, this rain gauge was chosen for its geographic location.

While this rain gauge is assumed to capture rainfall patterns more accurately than the other two rain gauges, collected data suggest that the VUSP Narberth rain gauge significantly under-records rainfall volume. This phenomenon is demonstrated in Table 18 in *Summary of Storm Selection,* where the VUSP Narberth Rain Gauge consistently records rainfall volumes lower than the other two rain gauges. The problem was further confirmed by a preliminary SWMM result. Table 21 below displays the total flow recorded by the Headwaters Flow Meter for a given time period. Table 21 also displays the total flow predicted by SWMM for the same time period using both the VUSP Narberth Rain Gauge and the VUSP Villanova Rain Gauge. When all other SWMM input parameters remain the same, the VUSP Narberth Rain Gauge predicts less than half of the flow as the VUSP Villanova Rain Gauge. With these preliminary SWMM results, the VUSP Villanova Rain Gauge is close to predicting the total flow measured in the field. The VUSP Narberth Rain gauge was located on the top of a telephone pole and any trouble shooting required renting a lift. Although this is a VUSP rain gauge, technical difficulties were unable to be swiftly addressed due to an inability to access the rain gauge.

Table 21: Data Source versus Total Flow past Headwaters Flow Meter

	Starflow Data	SWMM Data	
	Quartile Limit = 65	VUSP Villanova Rain Gauge	VUSP Narberth Rain Gauge
Total Flow (l) for Calibration Period	65,218,290	63,758,269	26,407,215

E. Rain Gauge 2: VUSP Villanova

The second model variation was calibrated to the VUSP Villanova Rain Gauge. This rain gauge is a Met One 375C Electric Heated Tipping Bucket Rain/ Snow Gauge. The accuracy for this piece of equipment is ±1% at 1 inch to 3 inches per hour at 70 degrees Fahrenheit (Met One Instruments

2014). The VUSP has many rain gauges located on Villanova University's campus, and the specific rain gauge used for this calibration is located at the Constructed Stormwater Wetland. The advantage of this rain gauge is that it is easily accessed and consistently maintained by the VUSP. Additionally, it is known that this rain gauge is calibrated. Thus, this rain gauge can be considered to have the most accurate and most reliable instrumentation of the three rain gauges used for this model. The VUSP Villanova Rain Gauge is located approximately 7.5 km from the centroid of the watershed. About 7 km from the Headwaters Flow Meter and about 8.5 km from the Downstream Flow Meter. Thus, this rain gauge is the farthest from the East Branch of Indian Creek watershed, and spatial variability will have the largest effect on this model variation. The location of the VUSP Villanova Rain Gauge relative to the East Branch of Indian Creek Watershed is displayed in Figure 30 below.

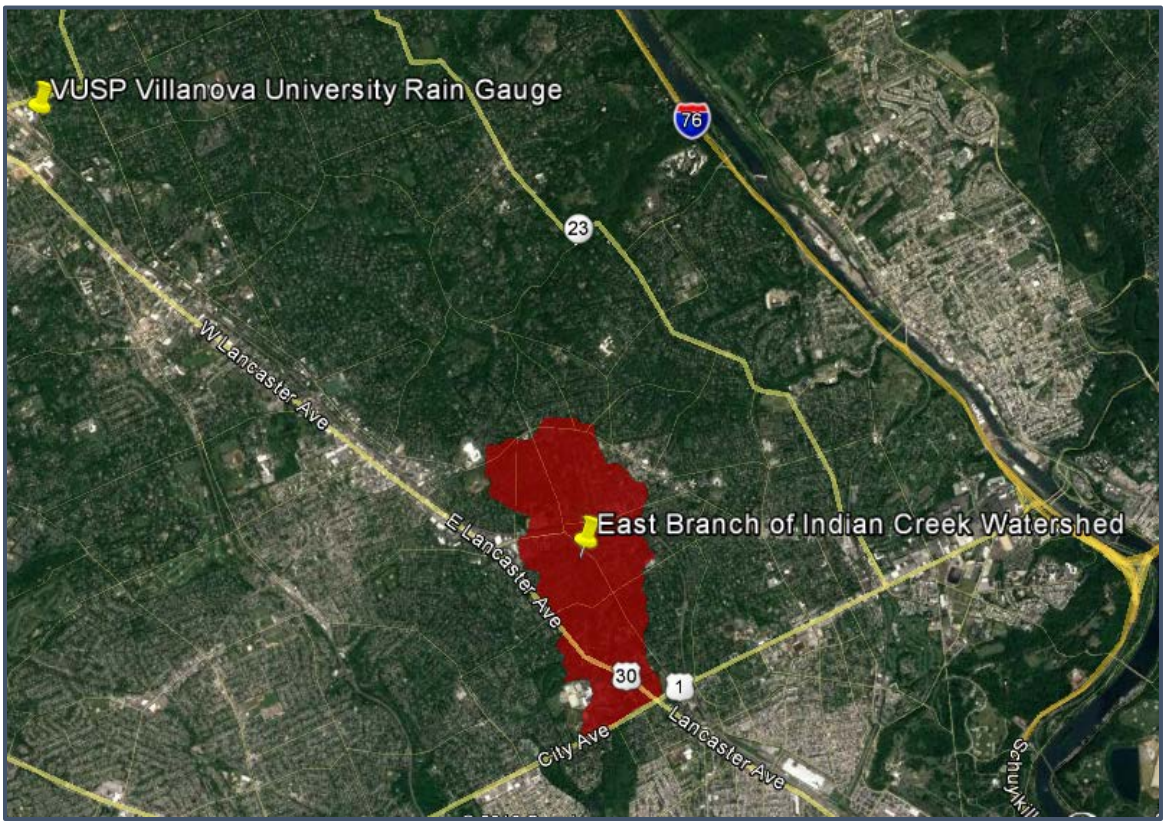

Figure 30: VUSP Villanova Rain Gauge Location

F. Rain Gauge 3: WU Wynnewood

The third model variation was calibrated using the Weather Underground (WU) Rain Gauge in Wynnewood, PA. This rain gauge is a Ambient Weather WS1200IP OBSERVER and has an accuracy of ± 10% (Ambient Weather 2016). No information is known about quality assurance, quality control or maintenance for this system. On paper, this instrument is the least accurate of the three rain gauges. However, when comparing rainfall volumes and durations for each storm in Table 18 engineering judgement suggests that, because the VUSP Narberth Rain Gauge appears to be significantly under-recording rain events, the WU Wynnewood rain gauge may be a more accurate choice in terms of volume and duration.

This rain gauge is located approximately 2 km from the centroid of the watershed, 2.5 km from the Headwaters Flow Meter, and 2.5 km from the Downstream Flow Meter. Though this location is not as close to the calibration points as the VUSP Narberth Rain Gauge, it is twice as close as the VUSP Villanova Rain Gauge. Figure 31 below displays the location of the WU Wynnewood Rain Gauge relative to the East Branch of Indian Creek Watershed. While the VUSP Villanova Rain Gauge is the best choice in terms of accuracy and the VUSP Narberth Rain Gauge is the best choice in terms of location, the WU Wynnewood appears to provide a compromise between location and accuracy.

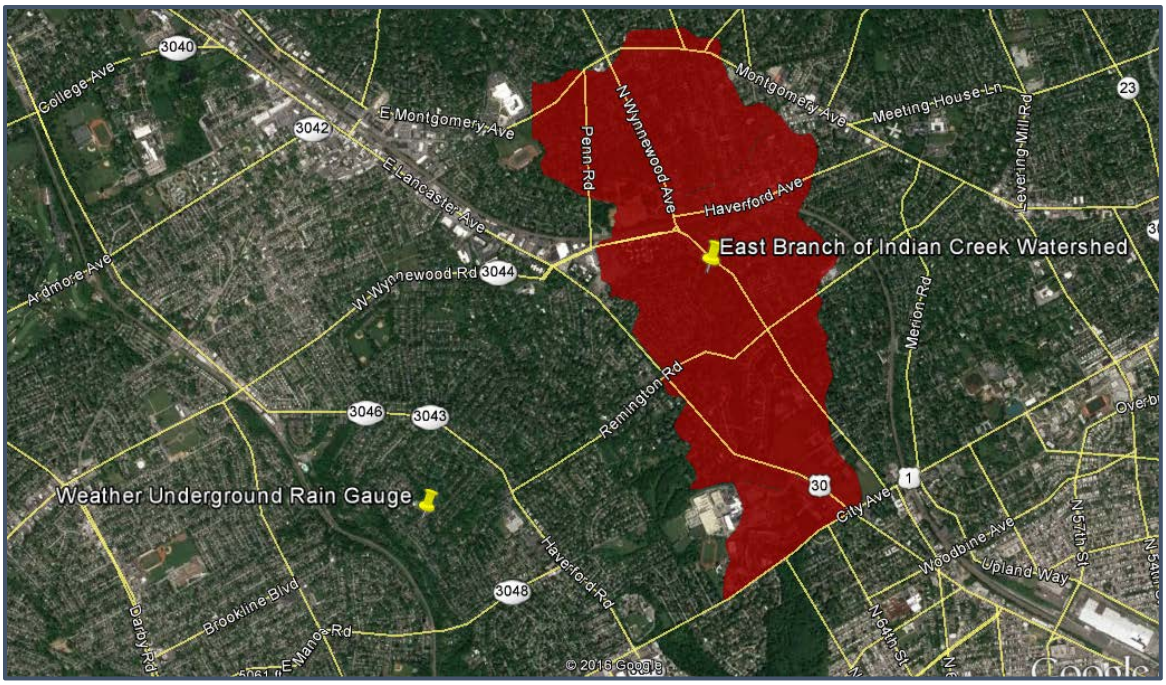

Figure 31: WU Wynnewood Rain Gauge Location

V. Calibration Approach

Calibration is an important step in model development. This is because although the baseline input parameters for subcatchment characteristics were estimated to the author's best ability, it is never possible to truly predict such parameters for an entire subcatchment. Thus, "parameter estimation must be performed by calibration against observed data" (Madsen et al. 2002).

A. General Approach

For this model, the three upstream subcatchments (Subcatchments 1-3) were calibrated based on flow passing through a single node in the model, the Headwaters Calibration Point. The Headwaters Calibration point is representative of the Headwaters Flow Meter. The four downstream subcatchments (Subcatchments 4-7) will be calibrated based on flow passing through a separate, single node in the model, the Downstream Calibration Point. The Downstream Calibration Point is representative of the Downstream Flow Meter. Calibration parameters were

adjusted to optimize model specific calibration objectives, described in greater detail in the Non-Unique Solutions section below. These parameters were adjusted based on reasonable ranges of values based on either engineering judgement or SWMM documentation (Blansett 2011). The parameters adjusted as part of calibration were as follows:

- Width of Overland Flow
- Subcatchment Slope
- Percent of Impervious Land Cover
- Manning's N for Impervious Land
- Manning's N for Pervious Land
- Depth of Depression Storage on Impervious Area
- Percent of Impervious Area with No Depression Storage
- Percent of Runoff Routed to Pervious Area
- Subcatchment Curve Number

The parameters listed above were systematically adjusted one at a time until the difference between the simulated and observed values were minimized. The adjustment process for each parameter was completed when either the best match between observed and simulated results was obtained or when the parameter value reached the extent of its acceptable range (Rosa et al. 2015). The parameters most strongly influencing the model (as described in the Parameter Sensitivity section below) were adjusted first, attempting to match the field runoff volume and peak rate to the SWMM values. Once the runoff volume and peak rate started approaching the calibration targets, other, more minor parameters (or parameters that SWMM is less sensitive to) were adjusted to achieve an optimized calibration (Blansett 2011).

All calibration was done by hand. This allowed for engineering judgement to determine which of the non-unique solutions was best for this project's calibration goals (Madsen 2000). This concept is described in greater detail in the *Non-Unique Solutions* section. As described in greater detail in the *Rain Gauge Selection for Calibration* section, final parameters for each model were assigned by averaging the parameter sets from representative events (Tan et al. 2008).

B. Parameter Sensitivity

1) When approaching calibration, it was noted that SWMM is more sensitive to some input parameters than others. For instance, a study completed by Li et al. (2016) demonstrated that Width of Overland Flow, Depth of Depression Storage on Impervious Area, and the Percent of Impervious Area with No Depression Storage (in that order) had the largest influence on runoff volume. Li et al.'s (2008) study also concluded that Width of Overland Flow Path, Manning's N for Impervious Land, and Depth of Depression Storage on Impervious Area had the largest influences on peak flow. In a similar study, Tan et al. (2008) concluded that Percent of Impervious Area, Width of Overland Flow, Subcatchment Slope, and Manning's N for Impervious Land had the largest influences on hydrograph characteristics. More specifically, the study found that Manning's N for Impervious Land most strongly influenced time to peak flow, while Percent of Impervious Area (followed by Width of Overland Flow and Manning's N for Impervious Land) has the largest influence on Peak Flow and Total Runoff Volume.

C. Non-Unique Solutions

Madsen et al. (2002) define four primary objectives for optimizing a SWMM model, to put the general goal of calibration into more quantifiable terms. They are to achieve an agreement between the simulated and observed:

1) water volume
2) hydrograph shape
3) peak flows (with respect to timing, rate, and volume)
4) low flows (with respect to timing, rate, and volume)

Madsen et al.'s (2002) research further demonstrated that it is impossible to achieve a single calibration solution that optimizes all four calibration objectives simultaneously. There are multiple "parameter combinations that are equally good according to trade-offs between different objectives" (Madsen et al. 2002). Thus, it is critical to know the objective of the model before the calibration process begins. Similarly, past research has advised that rain gauge selection should be governed by whether the primary calibration objective is hydrograph shape or volume (Tan et al. 2008)

As discussed in the *Continuous Data versus Representative Storm Events* and *Summary of Storm Selection* sections of this report, this research is most concerned with hydrograph shape and peak flows than total flow volume. So, in general this model will focus on portraying peak flows accurately and hydrograph shape accurately. Low flows will not be calibrated, for reasons discussed in the *Base Flow* portion of this report above. This model will also play into the strengths of the specific grain gauges selected. For instance:

- The VUSP Narberth Park Rain Gauge model will prioritize hydrograph shape, because it is at the same location as the Headwaters Flow Meter, and therefore is assumed to portray rainfall patterns most accurately. However, it is suspected that this rain gauge will not produce an accurate rainfall volume or peak flow.

- The VUSP Villanova University Rain Gauge model will focus more heavily on peak flow and runoff volume than on hydrograph shape. This is because it is geographically the farthest from the Headwaters Flow Meter and is therefore expected to predict rainfall pattern less accurately. However, the rainfall volume collected by the VUSP Villanova University Rain Gauge could be considered to record the most accurate rainfall volume of the three rain gauges.
- The WU Wynnewood Rain Gauge will attempt to equally prioritize hydrograph shape and peak flow. This approach represents a compromise between the three calibration objectives. This approach was selected because, as described in the *Rain Gauge Selection for Calibration* section, this rain gauge was selected because it represents a compromise between spatially accurate rainfall pattern and accurate rainfall volume readings.

D. Nash-Sutcliff Model Efficiency (NSE) Coefficient

The Nash-Sutcliff Model Efficiency (NSE) Coefficient was used to quantify the success of calibration. The NSE coefficient is a tool that "indicates how well simulated data match observed data compared to a 1:1 line; it can range between negative infinity and 1, with NSE=1 indicating a perfect fit" (Rosa et al. 2015). Generally speaking, for SWMM applications, an NSE coefficient greater than 0.5 indicates acceptable model performance (Dongquan et al. 2009). This coefficient was chosen to be used as part of this thesis work, because it was used by Temple University to calibrate a SWMM model for another site in suburban Philadelphia for the DRWI. This coefficient has also been used successfully in other, similar applications. For instance, it was used in Tan et al.'s (2008) analysis of using a continuous rain gage versus using multiple, representative storm events for calibration.

VI. Validation

Precipitation data from the validation storms were used as an input in the calibrated models. The SWMM results from the validation storm events were then compared to field data collected during the same storm events to check for reasonability (Blansett 2011). Additionally, the Nash-Sutcliff Model Efficiency (NSE) Coefficient was used to quantify the success of validation for each storm. A summary of the storms used for this process can be found in Table 18. The results of this process are discussed in *Chapter 3: Analysis.*

VII. Evaluation

A. Rain Gauge Selection for Evaluation

The calibrated models were then used to evaluate the watershed for a typical precipitation year. The first step in the evaluation process is to define exactly what a typical precipitation year looks like for the Greater Philadelphia Area. For this project, the typical precipitation year was defined based on a study completed by the Philadelphia Water Department (PWD). The goal of the PWD study was to assign a typical precipitation year to simulate combined sewer outfall (CSO) statistics necessary for the evaluation of CSOs in the city (Philadelphia Water Department. 2009). It was assumed that the results from the PWD study would be applicable to this work, as the East Branch of Indian Creek is located in suburban Philadelphia.

1. Determine a Most Typical Precipitation Year

In their study, PWD evaluated data from 1948 to 2006 to determine characteristics such as annual number of storm events, total annual rainfall volume, and the best fit cumulative distribution function (CDF) plot of event peak hourly rainfall intensity. This information was then used to evaluate precipitation data from 1990 to 2006 to determine which of those 17 years was most typical. The study concluded that 2005 data best represented the long term average hydrologic

conditions for Philadelphia (Philadelphia Water Department. 2009). In response to this conclusion, the author selected 2005 data for use in the evaluation portion of this project. The rain data was taken from VUSP's Rain Gauge at the Bio-Infiltration Traffic Island (BTI) at Villanova University. The BTI Rain Gauge was chosen for the evaluation portion of this project, because it is the only VUSP rain gauge that has a complete rain data set for 2005.

2. Adjust Abnormal Peak Rainfall Volumes for Individual Events

There is one aspect of the 2005 precipitation year that is particularly unique. PWD's evaluation found that an October 8, 2005 storm, which lasted from October 7 at 12:15 PM and October 9 at 8:45 AM, reported an average rainfall volume of 5.40 inches across PWD's 24 rain gauges. This rainfall event was "the third largest annual peak rainfall volume recorded at the Philadelphia International Airport (PIA) station over the long-term period of 1948- 2006" (Philadelphia Water Department 2009). There was concern that the largeness of this storm would skew the city's understanding of the average performance of the CSOs. Therefore, from October 7 at 12:15 PM and October 9 at 8:45 AM, precipitation data was adjusted by a factor of 0.630. This scaling factor was determined "as the ratio of the average median peak annual rainfall volume estimated for PWD 24-raingage network over the long-term period of 1948-2006 (3.40 inches), to the average rainfall volume for PWD 24-raingage network during the October 8, 2005 event (5.40 inches)" (Philadelphia Water Department. 2009). This scaling was completed so that the rainfall volume for the October 8 event was equal to the medial peak annual rainfall volume estimated by the PWD study. For this thesis, the author also scaled all precipitation data from October 7 at 12:15 PM and October 9 at 8:45 AM by a factor of 0.630.

3. Adjust Total Annual Rainfall Volume

In the PWD study, a third step was completed to further adjust the 2005 precipitation year. The third step was to scale all precipitation data for the year up, so that the total rainfall for the year matched the long term average annual rainfall, as measured from 1948 to 2006 by the Philadelphia International Airport. In the PWD study, it was determined that, after the 2005 rainfall was adjusted for the October 8 rainfall event, the long term average annual rainfall was about 3% higher than the 2005 specific rainfall. To account for this discrepancy, all 2005 precipitation data points were increased by 3%. For this thesis work, step three was determined to be unnecessary for the data collected by the BTI rain gauge. With the adjustments for the October 8, 2005 storm, the annual rainfall was 44.55 inches for the data collected by the BTI rain gauge. There is only a 0.5% difference between this total annual rainfall volume and the PWD (1948-2006) estimated annual rainfall of 44.79 inches. This difference was assumed to be negligible for the purposes of this work in evaluating stream health for a typical precipitation year.

B. Climatology Inputs for Evaluation

A climate file was created using 2005 daily maximum and minimum temperatures as recorded by the Philadelphia International Airport (Weather Underground 2016). The Philadelphia International Airport is approximately 16 km from the site (about 10 miles). This rain gauge was selected for evaluation, because 2005 air temperature data was not available from VUSP rain gauges. This 2005 variation of the East Branch of Indian Creek model is being used to simulate a typical scenario rather than calibration to a set of site specific data; therefore, it was assumed that spatial variability of the input data was less critical. SWMM used the daily maximum and minimum temperatures in the climate file to calculate the daily evaporation in the model using the Hargreaves Equation (Rossman 2015).

VIII. Selecting an Appropriate Hydrologic Metric

When using water quantity to quantify disturbance to flow regimes, there are numerous well-established hydrologic metrics available for use. One challenge with stream and river monitoring for the purpose of river restoration is selecting a metric that not only responds to urbanization, but also reflects biological conditions in the stream. In past research, DeGasperi et al. (2009) proposed that the most useful hydrologic metric for use as a resource management tool fulfilled four criteria:

1) Possess a sensitivity to urbanization consistent with expected hydrologic response
2) Demonstrate statistically significant trends in urbanizing basins
3) Correlate with measures of biological response to urbanization
4) Exhibit an insensitivity to potentially confounding variables such as watershed slope

In the same research, DeGasperi et al. (2009) investigated 15 unique hydrologic metrics, each with the ability to be calculated from daily average flow data. Similarly to the work presented in this report, the work by DeGasperi et al. (2009) was focused on small streams. The study discovered that the High Pulse Count and the High Pulse Range were the individual hydrologic metrics with the greatest potential for biological relevance (DeGasperi et al. 2009). This study will be used as a guide for the best way to evaluate the East Branch of the Indian Creek's flow metrics.

A. High Pulse Metrics

For the High Pulse Metrics, "high pulse is defined as the occurrence of daily average flows that are equal to or greater than a threshold set at twice the long term daily average flow rate" (DeGasperi et al. 2009). In response to urbanization, "high flow pulses occur more frequently and although flow magnitudes are higher, high pulse durations are shorter" (DeGasperi et al. 2009).

Using the defined high pulse for a given creek, the High Pulse Count is the number of days each water year that discrete high flow pulses occur. This metric is expected in increase in response to urbanization (Richter et al. 1997, 1996, 1998). Similarly, the High Pulse Range is the range in days between the start of the first high flow pulse and the end of the last high flow pulse during a water year. A larger range indicates that more high pulses are occurring. Like the high pulse count, the high pulse range is anticipated to increase in response to urbanization. This metric is measured in days (DeGasperi et al. 2009).

B. Richards Baker Flashiness Index

The Richards Baker Flashiness Index (R-B Index) is a "dimensionless index of flow oscillations relative to total flow based on daily average discharge measured during a water year" (DeGasperi et al. 2009). This metric is expected to increase in response to urbanization (Baker et al. 2004). This metric was originally selected for use as a primary flow metric for this research due to its ability to capture reduced base flows and short duration, high-peak floods. However, as described in the following paragraphs, further analysis found that the RB Flashiness Index may not be appropriate for this study.

The RB Flashiness Index is computed using the following equation:

$$R-B\ Index = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}$$

(Equation 1, Baker et al. 2004)

In the equation, q_i is daily (or hourly) discharge volume. The index is equal to the sum, usually over one year, of the absolute value of day-to-day (or hour-to-hour) changes in daily (or hourly) discharge volumes divided by the sum of the daily (or hourly) discharge volumes for the year (or

selected time frame). Note that the value of the index is the same whether the values of q are treated as discharge volumes (l) or as average flow rates (l/s) (Baker et al. 2004). The calculated RB Flashiness Index for the Headwaters Flow Meter and for the Downstream Flow Meter are displayed in Table 22 below. Note that Baker et al. (2004) suggests calculating the R-B Index on an hourly scale for smaller watersheds. This is because as watersheds become smaller, daily mean flows increasingly underestimate fluctuations in flow caused by stormwater runoff.

Table 22: Computed R-B Index for Headwaters and Downstream Calibration Points

Downstream Flow Meter		
Watershed Area	3	km^2
Daily Flashiness Index	**0.60**	
	Total Daily Readings	218
	Days with 0 Change in Flow	0.80 %
Hourly Flashiness Index	**0.30**	
	Total Hourly Readings	5,231
	Hours with 0 Change in Flow	0.98 %
Headwaters Flow Meter		
Watershed Area	1	km^2
Daily Flashiness Index	**0.31**	
	Total Daily Readings	365
	Days with 0 Change in Flow	0.68 %
Hourly Flashiness Index	**0.14**	
	Total Hourly Readings	8,783
	Hours with 0 Change in Flow	0.88 %

To provide significance to the calculated value, it must be compared to the same index calculated for similar streams. Figure 32 displays a range of calculated R-B Index Values to use for such comparison. A lower R-B Index represents a healthier creek. However, when comparing the calculated R-B Index values to the plot below, especially if considering the hourly index as

suggested by Baker et al. (2004), the East Branch of Indian Creek would appear to have very low R-B Flashiness Index values. This would indicate a low amount of flashiness and a healthy creek. However, if flashiness is equated with rapid rates of change in stream flow in response to storm events, then data collected in the field suggest that the East Branch of Indian Creek is in fact a very flashy creek. These rapid changes in stream flow are depicted for a given storm in Figure 33 below. Therefore, for the initial result comparison using Figure 32, calculated index values are not consistent with field observations. Therefore, the R-B Index did not appear to be the most appropriate hydrologic metric for this research project.

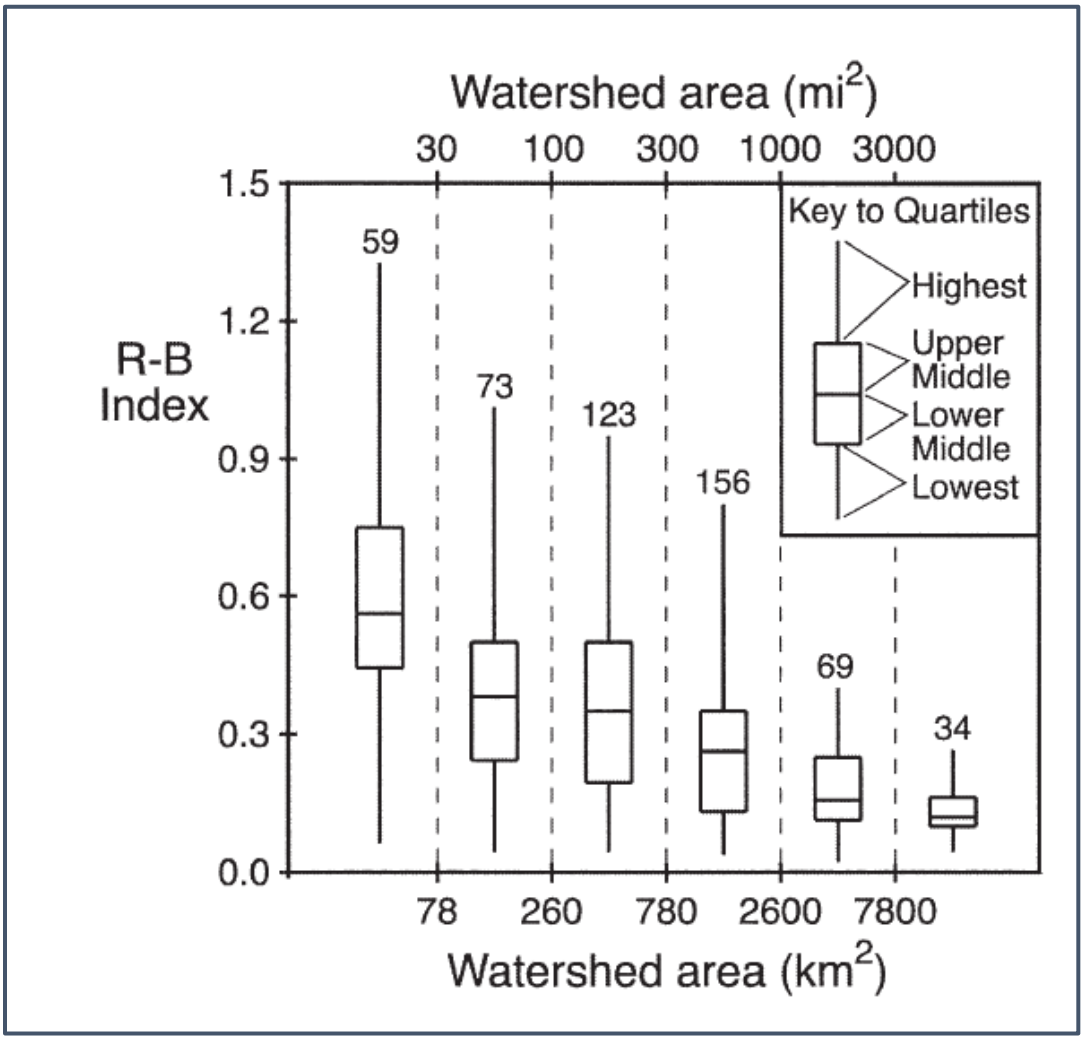

Figure 32: R-B Index for Watersheds of Various Sizes (Baker et al. 2004)

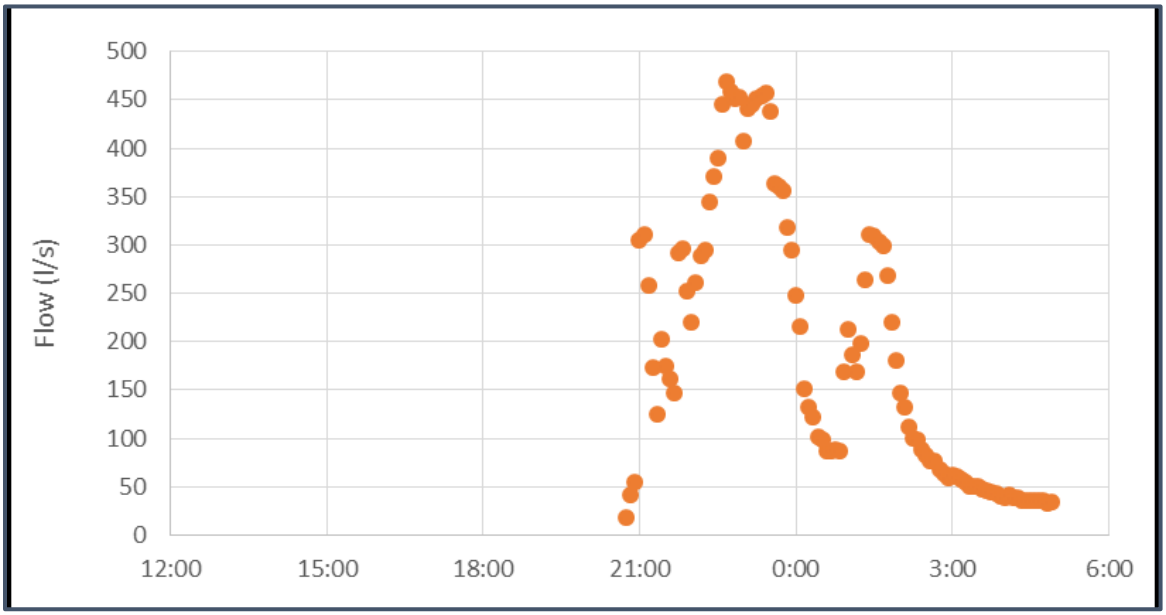

Figure 33: Rapid Changes in Streamflow for the Upstream Calibration Point on June 8, 2015

One potential reason for the R-B Index appearing to be incompatible with this project is that the East Branch of Indian Creek is a significantly smaller watershed than any of those evaluated as part of the Baker et al. (2004) study. As depicted in Figure 32 above, the smallest watershed area noted was 78 km^2. The watershed being evaluated as part of this study is 3 km^2. This theory is further confirmed by evaluating Table 23 in the *Summary Statistics from Past Research* section. The East Branch of Indian Creek has a R-B Index that is similar to the mean of the R-B Index values calculated as part of the DeGasperi et al. study (2009). This is reasonable when considering the characteristics of the other basins considered in the study and that the DeGasperi et al. (2009) considered much smaller watersheds than the Baker et al. (2004) study. This highlights the importance of having a representative baseline against which to compare a calculated hydrologic metric.

An additional potential problem with using the R-B Index is that it is related to total flow volume over the course of an entire year. As described in the *Base Flow Establishment* section, the Starflow flow meters do not accurately measure low flows. While isolated manual base flow measurements or occasional Starflow base flow measurements provide a good base flow estimates for the purposes of calibrating a SWMM model, they do not provide an accurate depiction of how total base flow varies on a daily or hourly basis. Furthermore, as established in the *Summary of Storm Selection*, the Downstream Flow Meter misses a large percentage of data points during storm events. While the data do provide an idea of peak flows and hydrograph shape, they do not provide an accurate runoff volume. Thus, many assumptions had to be made to assign daily and hourly flows for the calculation of the R-B Index. These assumptions may have led to an unrepresentative calculation of the R-B Index for the East Branch of Indian Creek.

Specifically, the following steps were taken to account for null Starflow data points in the R-B Index Calculation:

1) A default base flow was calculated for the site: This base flow calculation is based off of manual velocity measurements. This is the same process as described in the *Base Flow Establishment* section. Based on the average base flow rate for the creek (l/s), an average base flow per Starflow recording interval (l/5 min) and an average base flow per day (l/day) were calculated. These values were used as the default flow measurement when Starflow data were not available.
2) When available, a monthly base flow was calculated from Starflow data: if Starflow base flow readings were available, they were used instead of the manual flow measurements. Manual flow measurements were used to check the reasonability of Starflow readings. Monthly data sets were evaluated to determine if any base flow readings were recorded.

After the author was familiarized with the flow data, a value was selected that could reasonably be upper bounds for base flow. For example, for the Headwaters Calibration Point, based on 2015-2016 data, 35 l/s was selected as the upper limit for base flow boundaries. It was assumed that all readings below 35 l/s would qualify as base flow. For months that were determined to have Starflow base flow readings, an average base flow (l/5 min) was calculated from the Starflow data.

3) Daily and hourly flows were computed: Daily and hourly flows were computed by replacing all null data points with the average (l/ 5 min) base flow value completed from the Starflow data. When Starflow data was not available, the default base flow computed from manual measurements was assigned to the data point.

C. Summary Statistics from Past Research

Table 23 below provides a reference for what type of values might be expected when using the High Pulse Count, the High Pulse Range or the R-B Index to evaluate stream health. The table provides the minimum, mean, and maximum values for each metric calculated when evaluating 16 different stream basins. The characteristics of the stream basins are also described in the table. Note that all of the basins evaluated as part of DeGasperi et al.'s (2009) work were larger than the basin evaluated in this study, which is only approximately 3.15 km^2.

Table 23: Summary Statistics for Basin Characteristics and Hydrologic Metrics Calculated for 16 Stream (DeGasperi et al. 2009)

Variable	Description (units)	Minimum	Mean	Maximum
Basin Characteristics				
Basin area	Drainage basin area (km2)	9.6	28.8	53.5
% TIA	1998 total impervious area (%)	9.5	33.5	58.5
%Outwash	surficial outwash deposits (%)	9.7	24.6	56
%Till	surficial till deposits (%)	18.4	35.3	67.7
%Bedrock	Surficial bedrock cover (%)	0	5.4	31.2
%Urban	1998 urban land cover (%)	15.1	52.8	88.7
%Forest (non-urban)	1998 non-urban forest cover (%)	4.8	38.2	80.8
Basin Elevation	Mean basin elevation (m)	75	146	344
Precipitation	Mean annual precipiation (mm)	891	1192	1833
Basin Slope	Mean basin slope (%)	6.7	10	21.2
Local channel slope	Local channel slope (m/m)	0.004	0.018	0.09
Hydrologic Metrics				
High Pulse Count	Number of high pulse events per year (count)	2	10	22
High Pulse Range	Range each Water Year over which high pulses occur (days)	34	168	306
R-B Index	Richards-Baker Flashiness Index (unitless)	0.08	0.27	0.49

IX. Implementing Stormwater Control Measures

A. Community Importance to Restoration

Successful implementation of a SCM is dependent on the community's receptiveness to it. For instance, Palmer et al. (2007) assert that "citizens can and do have an incredibly important role to play in river restoration…the recommendation is to provide mechanisms for ensuring citizen or stakeholder involvement in all restoration projects". Palmer et al. (2007) continue to explain that "meticulous engineering design plans for a restoration project do not guarantee success. A project whose design is informed by a basic understanding of the science of stream restoration and an understanding of the current and future context of the stream within the watershed is most likely to succeed" (2007). Similarly, Bain et al. (2014) conclude that "any feedback promoting positive community action to sustain restoration success is a potentially powerful benefit that can be utilized to improve management of urban stream restorations".

A significant reason for this emphasis on community involvement and investment is that "actions enhancing the quality of interactions between people and urban streams, particularly those justified in terms of quality of life or by their value as a public amenity, are likely to be supported and maintained; indeed, such actions commonly result in financial outlays far in excess of likely ecosystem benefits" (Booth 2005). Those communities which are receptive to the idea of implementing an SCM are more likely to respect and maintain the SCM over time, thus allowing the SCM to become a long term solution.

B. Taking Steps towards Context Sensitive Solutions

When selecting which SCM implementation scenarios to model in SWMM, the author interviewed both a local municipal official and a local conservation professional. Both of the interviewees have significant experience working with the residents of Narberth Borough. The purpose of these meetings was to gauge community receptiveness to and local feasibility of various, hypothetical SCM implementation scenarios. By considering the real direction and constraints of the borough, the author hoped to produce research results that may be useful for future planning and development.

Possible SCM implementation opportunities considered during the interviews included:

- Rain gardens or swale systems in Narbrook Park. Narbrook Park is grassy park along the East Branch of Indian Creek, directly upstream of the Headwaters Flow Meter. The park is part of a private community.
- Rain gardens installed on private, residential property
- Rain gardens installed on cul-de-sacs, replacing the impervious roadway in the center of each cul-de-sac

- On-street stormwater bumpouts
- Permeable pavement on dead end, low traffic roadways
- Above ground opportunities, such as swale systems or rain gardens, at educational facilities. Educational facilities were considered to be a unique type of opportunity as they have the potential to provide both ecosystem and educational benefits. Specifically, opportunities along the athletic fields at Lower Merion High School and at a Narberth day care center were considered.

1. Interviewing a Local Municipal Official

The author interviewed the Narberth Borough Manager, Sean Metrick on May 26, 2016. Metrick cares about sustainability and he is interested in implementing SCMs within the borough. As Narberth Borough Manager, he also is highly aware of the legislative, social, and financial restrictions that may limit SCM implementation. The conversation with Metrick left the author with the following conclusions about SCM implementation:

- It may be feasible to implement rain gardens in the center of cul-de-sacs. On the cul-de-sac streets, there is a lot of extra impervious surface. Additionally, during the winter months, the cul-de-sac could act as a location to pile snow, creating buy-in from the residents of those streets. Specifically, Hansen Court and Country Lane may be opportunities for such implementation. Country Lane has a current drainage problem. The opportunity to fix that problem may create additional buy-in from residents.
- Wynndale Road may be a good opportunity for stormwater bumpouts. This neighborhood has high lot widths and off street parking and could afford to lose some on-street parking. Contrastingly, Homewood Ave and Elm Terrace are too densely developed for stormwater

bumpouts. These streets have limited off-street parking, and therefore the neighborhood cannot afford to lose any on-street parking to SCMs

- Because of the high cost of installation and maintenance, permeable pavement should only be implemented on a trial basis, paving only a small area at first to evaluate expenses, maintenance, and effectiveness. Homewood Avenue and Elm Terrace, which are too dense for on-street solutions, may be good opportunities for the permeable pavement trial.
- If demonstrated to be feasible, rain garden opportunities on private properties should be prioritized. After further analysis of the restoration and cost effectiveness, the borough may consider providing subsides and construction oversight for such projects.

2. Interviewing a Local Conservation Professional

The author interviewed Lower Merion Conservancy's Conservation Coordinator, Tom Clark on May 18, 2016. As part of the Lower Merion Conservancy, Clark has direct experience working to implement SCMs in Narberth Borough. These restoration plans are described in greater detail in *Chapter 1: Background and Literature Review*. Clark also grew up in Narberth, and therefore is familiar with the community. The conversation with Clark left the author with the following conclusions about SCM implementation:

- Narbrook Park may be a difficult place to implement future SCMs. The community is very supportive of stream restoration efforts. However, community members are protective of their view of the creek and are not receptive to any plantings on the top of the river bank that might obscure that view. Additionally, full access to the river is very important to the community members. Thus, it is difficult to gain full buy in from the community to install planted SCMs on the top of the river bank, as originally suggested by the author of this research.

- The Narberth community would probably be receptive to permeable pavement, as it has potential to boost community pride. When introducing permeable pavement plans to the community, one could emphasize the new, progressive technology, and that the pavement would be placed on low traffic streets, playing into the community's fondness for peaceful neighborhoods. A large factor in gaining community buy-in for permeable pavement would be the current condition of the streets in question. For instance, if the streets are currently in poor physical condition and need to be replaced anyway, it could be an opportunity to insert a SCM without additional construction nuisances to the community. Otherwise, it may be difficult to create buy in from the residents of the dead end streets, because they have no alternative route to return home while there is road work.
- One advantage to pursuing SCM implementation at the day care center is that it is located on private property. Therefore, the implementation process (planning, construction, etc.) would only involve negotiation between the property owners and the contractor. This SCM opportunity would likely be in the front yard of the property. Assuming that the young children do not play in the front yard, this opportunity would not interfere with the children's play space, and it could be assumed that parents would be less concerned about their children falling into the SCM. It is important to note that this property has not always been a day care center and that the business using the property changes.
- Lower Merion High School would likely be receptive to SCM implementation adjacent to their athletic fields, as long as the SCMs are small and do not interfere with field space. The high school offers both an Advanced Placement Environmental Science class and a Landscape Architecture class. It is possible that both classes would be interested in engaging with the installed SCMs.

- Gaining public agreement can be challenging and the process can slow SCM implementation. Therefore, it may be difficult to implement rain gardens on private, residential lots. However, the public may gain interest in this type of opportunity if a stormwater tax was issued. This type of tax exists in neighboring Radnor Township (Township of Radnor 2016). The details of this type of tax varies from town to town, but in general, it charges residents an amount that is proportional to the amount of impervious area on their property. The tax may be designed so that the amount collected is reduced if the owners install a SCM on their property to help control the stormwater runoff generated by neighboring impervious surfaces.

C. Final Scenario Selection

To focus the scope of this research, the author decided only to investigate SCM opportunities in Narberth Borough. This decision was made with community receptiveness in mind and was largely in response to the Narberth Borough Manager's enthusiasm for SCM implementation. This research aims to investigate a future scenario where Narberth Borough takes additional action on its commitment to sustainable stormwater management. Additionally, this research aims to investigate the extent of measurable change in a flow regime that may be observed in response to one borough's actions. To gain an increased understanding of the headwaters approach to restoration, an approach discussed in *Chapter 1: Background and Literature Review*, only opportunities in the headwaters of the East Branch of Indian Creek (i.e. upstream of the Headwaters Flow Meter) were investigated.

After considering the site and information gained from conversations with Sean Metrick and Tom Clark, it was determined that this investigation would only consider rain gardens, specifically, rain gardens without underdrains. Rain gardens are one of the more cost-effective stormwater

management options and they require relatively low maintenance (Philadelphia Water 2017a; Philadelphia Water Department 2016). Contrastingly, in order to maintain permeable pavement functionality, “frequent maintenance with specialized equipment” is necessary (Philadelphia Water 2017b) . It was assumed that the relative low cost and maintenance requirements of rain gardens would facilitate increased buy in from residents who are new to SCMs and municipal officials who are managing complex budgets. Based on suggestions from Metrick and Clark, seven rain garden opportunities were identified on public land. Additionally, 10 residential lots were randomly selected for rain garden implementation on private land. The private, residential lots were selected randomly, because it will be difficult to control or plan which families in the borough may be interested in installing SCMs on their property. Figures 34-36 display the location of each proposed opportunity within Narberth Borough and the corresponding, approximate drainage area.

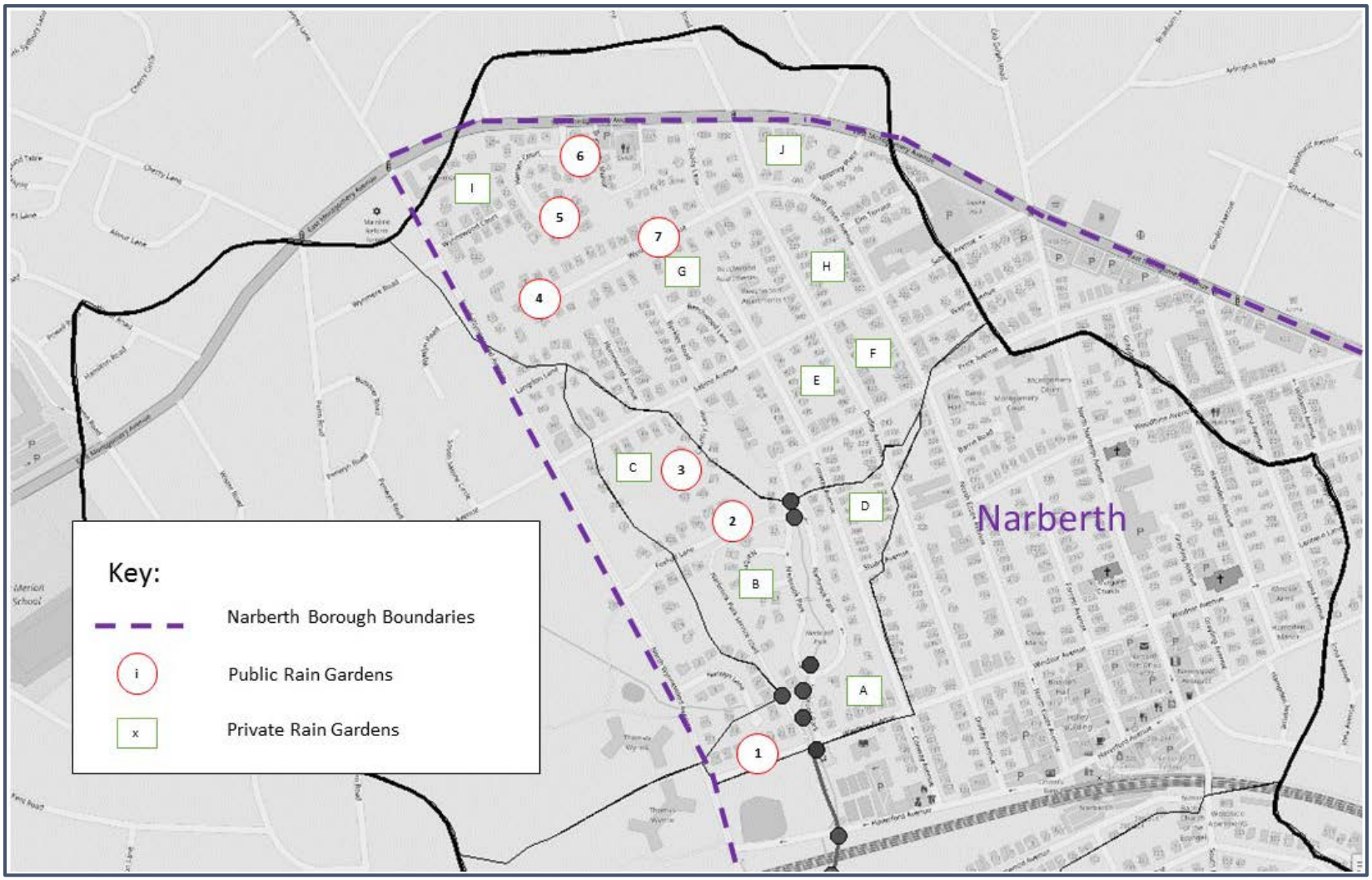

Figure 34: Location of Each Proposed Opportunity within Narberth Borough

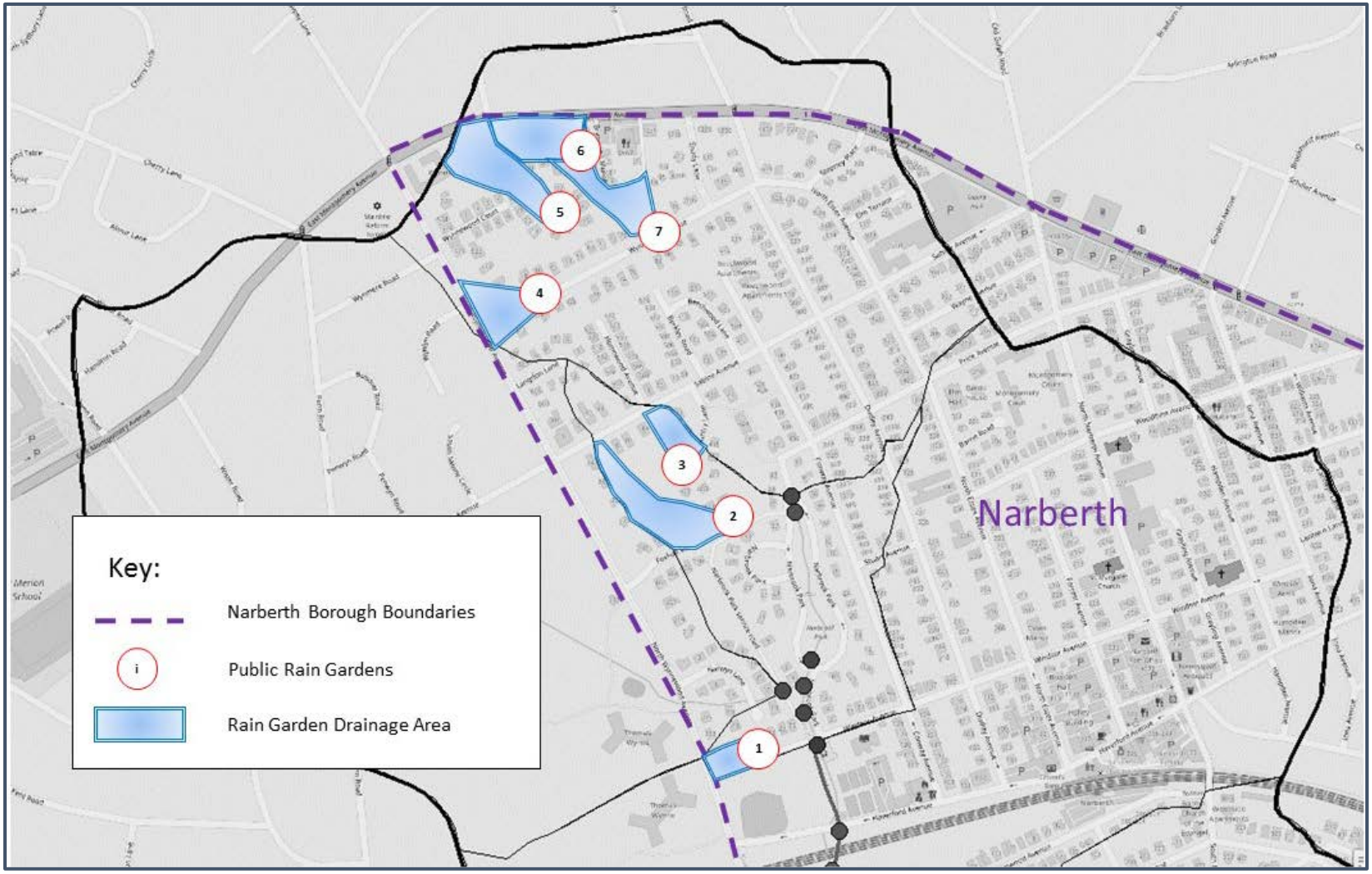

Figure 35: Proposed Public Opportunities and Their Corresponding, Approximate Drainage Areas

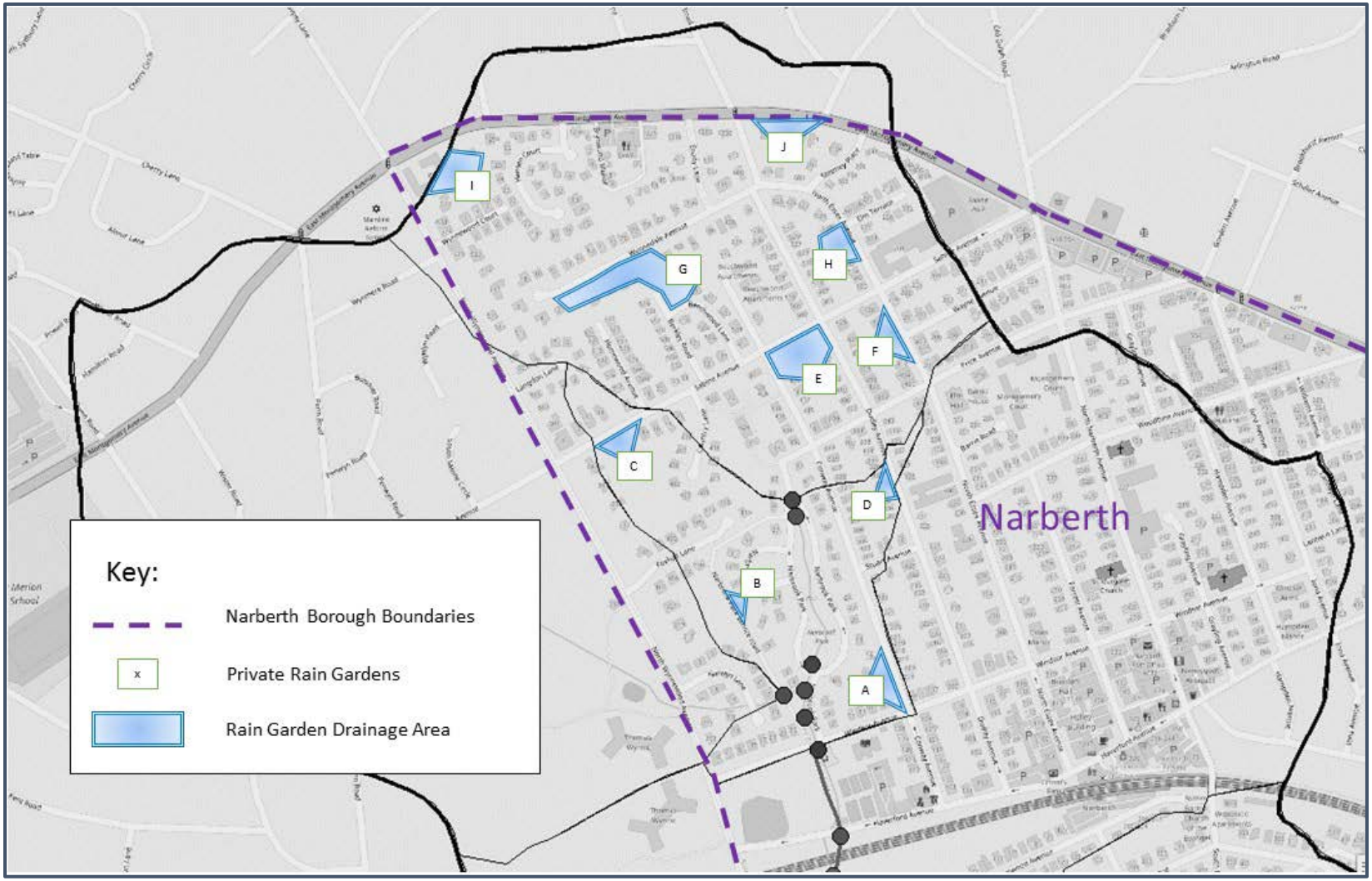

Figure 36: Proposed Private Opportunities and Their Corresponding, Approximate Drainage Areas

With these 17 opportunities in mind, three scenarios were selected for evaluation using SWMM: one scenario modeling the 10 private rain gardens, a second scenario modeling the seven public rain gardens, and a third scenario modeling all 17 public and private rain gardens.

D. Modeling the Scenarios in SWMM

Rain gardens were modeled in SWMM as storage units. Using storage units to simulate the behavior of a SCM is an approach commonly used within the VUSP and has also been used successfully in third party research (Tobio et al. 2015)

Before each new rain garden was added to the model, a new subcatchment was added to SWMM. This new subcatchment represented the area draining into the new rain garden. It was assumed that the new rain garden subcatchment shared the same characteristics as its pre-development subcatchment (i.e. subcatchment 1 or 3, as described in the *Hydrology* section of this chapter), with the exception of area and width. The area of the new rain garden subcatchment was subtracted from the original pre-development subcatchment. In this way, the total area of the East Branch of Indian Creek watershed, as modeled as part of this project, remained the same as each new rain garden was added to the model.

Next, a storage unit was added to SWMM to represent the rain garden itself. Following the parameters presented in Tables 24 – 27, opportunity-specific parameters were assigned to the new storage unit. To connect this storage unit to the model, the outlet of the newly created subcatchment was set as the newly created storage unit. Next, a weir was added to SWMM to connect the newly added storage unit to one of the original junction nodes in the model (i.e. one of the nodes representing the creek itself, as described in the *Hydraulics* section of this chapter). A map of Narberth Borough as well as the 2005 DVRPC Montgomery County five foot contours were

consulted to approximate the location at which overflow from each rain garden would enter the creek (DVRPC 2005).

It was assumed that each rain garden would retain all of the runoff generated by its drainage area during smaller storm events. A weir was used to represent water overflowing from each rain garden during larger storm events, after the storage capacity of the rain garden was reached. The only parameters that were changed from default SWMM weir parameters were length, inlet offset, and height. Inlet offset was set as the total storage depth of the rain garden bowl and media (i.e. the depth to which runoff would be able to fill the rain garden before flooding occurred). Length was set as the approximate perimeter of the rain garden. Height was arbitrarily set at 10 feet, because it was determined that the height of the weir would not influence the results of the model. Because the author was not modeling a specific, designed rain garden, it was less important to model exactly how the water was overflowing from the rain garden than to simulate approximately when the rain garden would overflow and, if it did overflow, where that stormwater runoff would re-enter the model.

The influence of the hypothetical rain garden implementation was evaluated using the same hydrologic metrics used to evaluate the distinctions between rain gauges, as described in the *Selecting an Appropriate Hydrologic Metric* section of this chapter.

E. Assigning Input Parameters

The following methodology was used to assign the input parameters for modeling the 17 rain garden opportunities in SWMM.

1. Drainage Area

The drainage area for each rain garden opportunity was estimated using 2005 DVRPC Montgomery County five foot contours in GIS (DVRPC 2005). It was assumed that rainfall runoff would not cross over any streets. To assign an impervious drainage area to each rain garden, GIS was used to calculate which portion of the impervious area for the subcatchment (as described in *Subcatchment Development* section of this chapter*)* fell within the drainage area for the given rain garden opportunity.

2. Rain Garden Volume

The rain garden storage volume was approximated in SWMM as two rectangular prisms: one representing the rain garden bowl and one representing the rain garden media.

a. Surface Area

For all private and public rain garden opportunities, the surface area was designed to maintain an impervious drainage area to infiltration area (rain garden surface area) ratio of 5:1, as recommended by the Pennsylvania Department of Environmental Protection (Dovel et al. 2015; PADEP 2006). For each public cul-de-sac opportunity, assuming a circular rain garden shape, it was assumed that the maximum surface area was a function of the diameter of the cul-de-sac minus 5.5 m (18 ft). This assumed that that cul-de-sac would be converted into a one-way, circular roadway with a rain garden in the center, and that the roadway would be designed to have the minimum acceptable width for local roadways, 2.7 m (9 ft)/lane as specified by the FHWA (2014b). For private opportunities, it was assumed that the maximum surface area could be between 2,000 and 3,000 ft^2, which is the approximate surface area of the Bio-infiltration Traffic Island on Villanova University's campus. For public, on-street opportunities, particularly the opportunity on Windsor Avenue, it was assumed that the rain garden design would be similar to

current plans for the Windsor Avenue Rain Garden (Whitman Requardt & Associates LLP 2016). For both private and public opportunities, the same surface area (or plan view area) was used to calculate both the rain garden's bowl and media storage volumes.

b. Depth

Rain garden bowl depth and media depth were assigned based on Pennsylvania Department of Environmental Protection (PADEP) rain garden design recommendations (2006). To account for the portion of the media storage occupied by soil, the depth of the media was multiplied by the soil's assumed porosity. This new adjusted media depth was used in SWMM to represent the media storage depth of each rain garden.

3. Soil Characteristics

The underlying soil for each rain garden opportunity was assumed to be the same as the previously assigned soil type for each subcatchment, as described in *Subcatchment Development: Curve Numbers* section of this chapter. Additional necessary soil parameters, specifically suction head and porosity, were assigned based on typical values of the given property for the previously assigned soil compilation (Mays 2011). The initial deficit for all rain garden soil was assumed to be zero. The initial deficit is the difference between the soil's porosity and initial moisture content. In SWMM, an initial deficit of zero represents soil conditions where there is constant seepage equal to the soil's saturated hydraulic conductivity.

4. Summary of Rain Garden Input Parameters

Tables 24 - 27 present all parameters associated with each rain garden opportunity and its implementation in SWMM.

Table 24: Private Rain Garden Parameters Part I

Rain Garden ID	Opportunity Type	Surface Area (ft^2)	Bowl Depth (ft)	Media Depth (ft)	Soil Porosity (n)	Adjusted Media Depth (ft)	Drainage Area (ft^2)	Impervious Drainage Area (ft^2)	Drainage Area Width (ft)
A	Private, Resiential	194	1	2.5	0.471	1.18	13,692	969	85
B	Private, Resiential	46	1	2.5	0.471	1.18	2,789	232	27
C	Private, Resiential	475	1	2.5	0.471	1.18	13,929	2,377	70
D	Private, Resiential	224	1	2.5	0.471	1.18	6,559	1,121	37
E	Private, Resiential	1,611	1	2.5	0.468	1.17	42,824	8,054	161
F	Private, Resiential	501	1	2.5	0.468	1.17	16,033	2,503	73
G	Private, Resiential	1,798	1	2.5	0.468	1.17	66,824	8,988	104
H	Private, Resiential	479	1	2.5	0.468	1.17	10,598	2,397	56
I	Private, Resiential	1,386	1	2.5	0.468	1.17	39,222	6,929	164
J	Private, Resiential	2,656	1	2.5	0.468	1.17	33,381	13,278	134

Table 25: Private Rain Garden Parameters Part II

Rain Garden ID	Subcatchment	Outlet Node	Invert El. (ft)	Ks (in/hour)	Suction Head (in)	Initial Deficit	Soil Type
A	3	FM1	260	0.2080	5.3402	0	3/5 silt loam, 2/5 loam
B	3	WC2	295	0.2080	5.3402	0	3/5 silt loam, 2/5 loam
C	3	WC2	320	0.2080	5.3402	0	3/5 silt loam, 2/5 loam
D	3	WC3	280	0.2080	5.3402	0	3/5 silt loam, 2/5 loam
E	1	WC6	290	0.1950	5.0335	0	Avg between silt loam and loam
F	1	WC6	305	0.1950	5.0335	0	Avg between silt loam and loam
G	1	WC6	310	0.1950	5.0335	0	Avg between silt loam and loam
H	1	WC6	320	0.1950	5.0335	0	Avg between silt loam and loam
I	1	WC6	345	0.1950	5.0335	0	Avg between silt loam and loam
J	1	WC6	330	0.1950	5.0335	0	Avg between silt loam and loam

Table 26: Public Rain Garden Parameters Part I

Rain Garden ID	Opportunity Type	Surface Area (ft^2)	Bowl Depth (ft)	Media Depth (ft)	Soil Porosity (n)	Adjusted Media Depth (ft)	Drainage Area (ft^2)	Impervious Drainage Area (ft^2)	Drainage Area Width (ft)
1	On-Street Solution	159	1	5	0.471	2.36	10,236	NA	28
2	Cul de sac	3,019	1	2.5	0.471	1.18	174,000	22,577	234
3	Cul de sac	1,065	1	2.5	0.471	1.18	24,560	5,326	66
4	Cul de sac	1,893	1	2.5	0.468	1.17	61,090	9,467	144
5	Cul de sac	2,932	1	2.5	0.468	1.17	67,744	14,658	111
6	Cul de sac	2,197	1	2.5	0.468	1.17	43,214	10,985	121
7	On-Street Solution	2,407	1	5	0.468	2.34	89,339	12,035	135

Table 27: Public Rain Garden Parameters Part II

Rain Garden ID	Subcatchment	Outlet Node	Invert El. (ft)	Ks (in/hour)	Suction Head (in)	Initial Deficit	Soil Type
1	3	FM1	257	0.2080	5.3402	0	3/5 silt loam, 2/5 loam
2	3	WC2	300	0.2080	5.3402	0	3/5 silt loam, 2/5 loam
3	3	WC2	315	0.2080	5.3402	0	3/5 silt loam, 2/5 loam
4	1	WC6	340	0.1950	5.0335	0	Avg between silt loam and loam
5	1	WC6	335	0.1950	5.0335	0	Avg between silt loam and loam
6	1	WC6	340	0.1950	5.0335	0	Avg between silt loam and loam
7	1	WC6	320	0.1950	5.0335	0	Avg between silt loam and loam

CHAPTER 3: RAIN GAUGE ANALYSIS

I. Narrowing the Scope of Analysis

A. Insufficient Data for Downstream Analysis

As described in *Chapter 2: Methods,* due to a limited amount of available data, only four storms were available for the calibration and validation of the Downstream Flow Meter: two storms were used for calibration and two storm events were used for validation. The author concluded that the four storms were insufficient to determine an average rain fall runoff and resulting flow regime behavior for the East Branch of Indian Creek.

Calibration of the two individual storms was completed successfully for all model variations. For example, Figure 37 and Figure 38 display the calibration results for the two calibration storms, which occurred on 11/19/2015 and 12/17/2015, for the VUSP Villanova model variation. The NSE coefficients (as discussed in the *Calibration Approach* section of *Chapter 2*) for these two calibrated storms were 0.73 and 0.78, respectively.

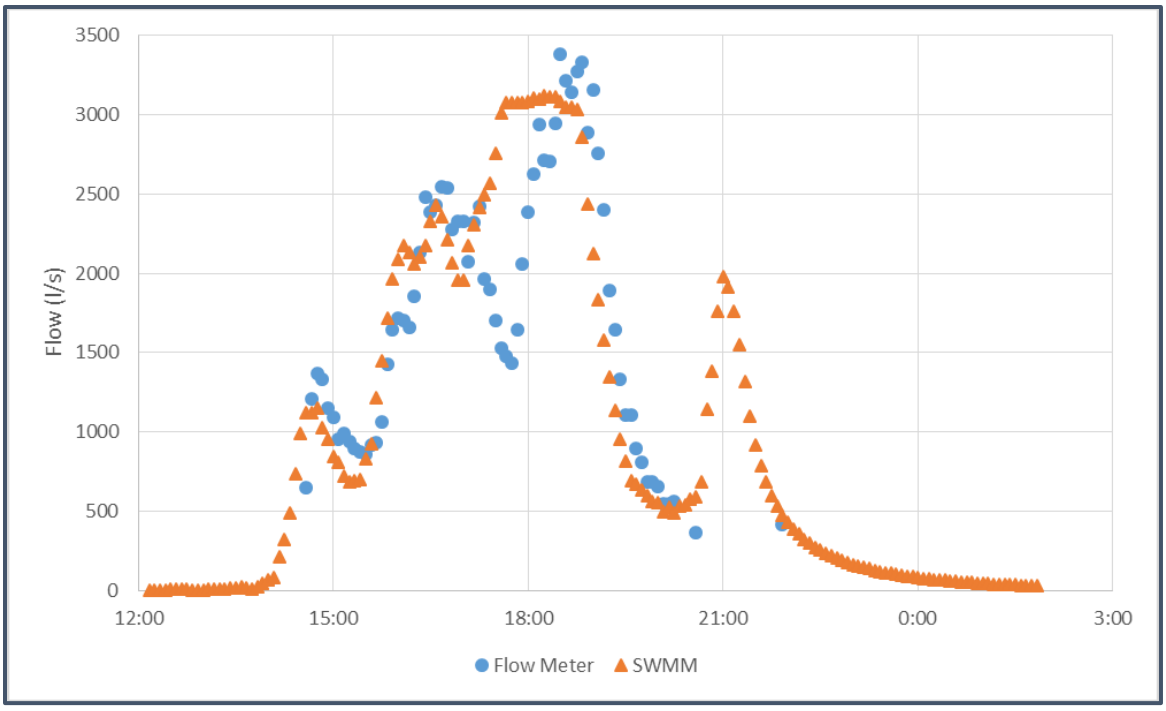

Figure 37: 11/19/2015 Downstream Calibration Results using the VUSP Villanova Rain Gauge

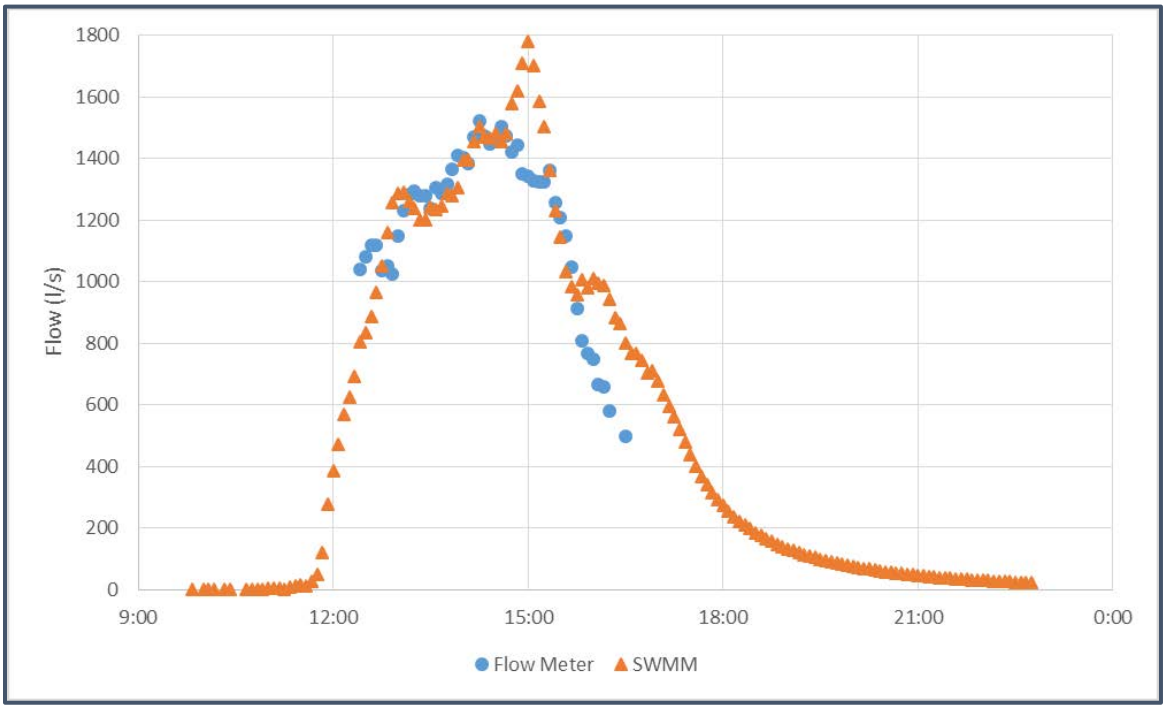

Figure 38: 12/17/2015 Downstream Calibration Results using the VUSP Villanova Rain Gauge

Validation was unsuccessful for the Downstream Flow Meter. Validation results are depicted in Figure 39 and Figure 40. The two storms used for validation of the Downstream Calibration Point occurred on 10/28/2015 and 12/23/2015. The NSE coefficients resulting from the validation of these two storms were (-1.28) and 0.31, respectively. Both of these coefficients are significantly less than 0.50 and therefore are unacceptable.

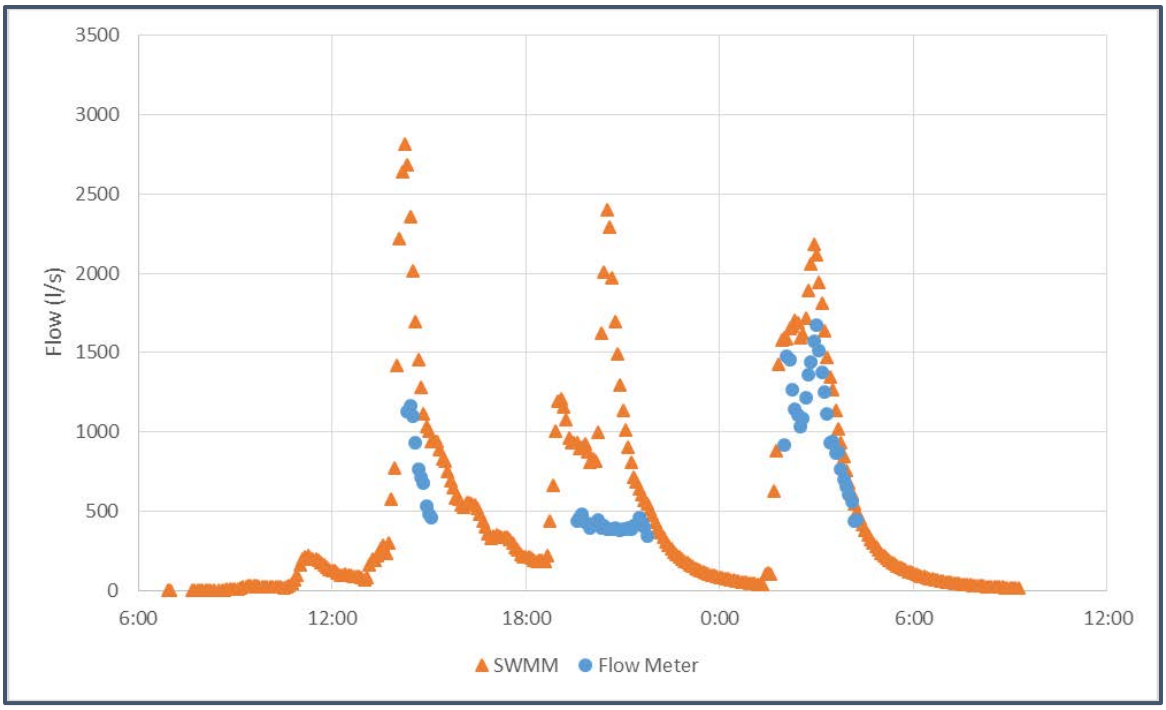

Figure 39: 10/28/2015 Downstream Validation

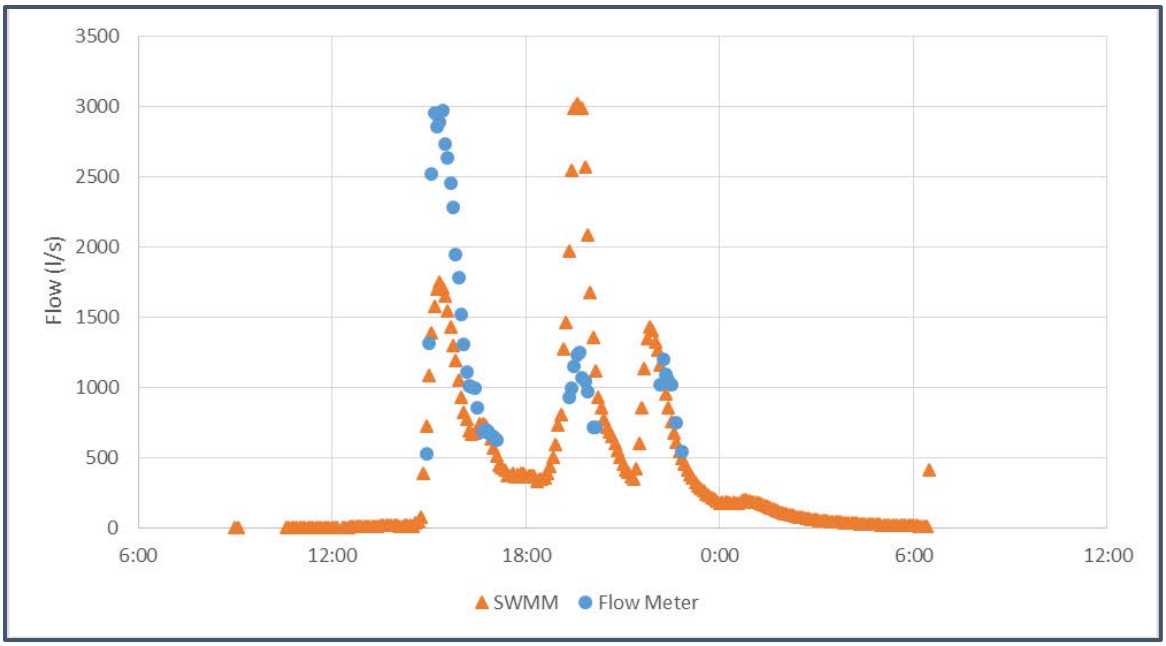

Figure 40: 12/23/2015 Downstream Validation

The author attributes these low NSE coefficients to two primary factors. First, as evidenced by Figure 39 and Figure 40, both of the validation storms appear to have an incomplete set of flow meter data. Specifically, the flow data sets for the two storms are missing 81% and 83% of flow data points, respectively. Therefore, the data do not provide a complete representation of what actually happened in the creek during the two storm events. Second, only two storms were used in the calibration process. Each of the two calibration storms required opposite calibration approaches. Specifically, the baseline model under predicted the peak flows associated with the 11/19/2015 storm event and over predicted the peak flows associated with the 12/17/2017 storm event. These two contrasting storm events provided insufficient data for the author to be comfortable establishing an average behavior for the downstream portion of the watershed. Due to insufficient data being available to confidently predict the behavior of the downstream portion of the watershed, the author decided to cease further analysis involving the Downstream Calibration Point. Therefore, subcatchments draining into the Downstream Flow Meter (i.e.

subcatchments 4-7) for all model variations were not considered to be successfully calibrated and were not used in final analysis for this thesis work.

Tables 28-31 present the baseline values and calibration ranges for each of the parameters used to calibrate subcatchments 4-7. These values are presented for potential use in future work.

Table 28: Subcatchment 4 Calibration Parameters

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value
Width	4772	3600	6700
% Slope	3.3	2.7	3.8
% Impervious	36	29	43
Impervious Manning's N	0.011	0.01	0.13
Pervious Manning's N	0.025	0.02	0.03
Depression Storage for Impervious Area	0.075	0.05	0.1
Depression Storage for Pervious Area	0	0.1	0.2
% Impervious with No Depression Storage	25	0	50
% Routed to Pervious	25	0	50
Curve Number	62	60	75

Table 29: Subcatchment 5 Calibration Parameters

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value
Width	9313	8100	12000
% Slope	3.1	2.1	4.2
% Impervious	37	30	44
Impervious Manning's N	0.011	0.01	0.13
Pervious Manning's N	0.025	0.02	0.03
Depression Storage for Impervious Area	0.075	0.05	0.1
Depression Storage for Pervious Area	0	0.1	0.2
% Impervious with No Depression Storage	25	0	50
% Routed to Pervious	25	0	50
Curve Number	62	60	75

Table 30: Subcatchment 6 Calibration Parameters

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value
Width	4595	3100	8900
% Slope	2.7	2.0	3.3
% Impervious	29	23	35
Impervious Manning's N	0.011	0.01	0.13
Pervious Manning's N	0.025	0.02	0.03
Depression Storage for Impervious Area	0.075	0.05	0.1
Depression Storage for Pervious Area	0	0.1	0.2
% Impervious with No Depression Storage	25	0	50
% Routed to Pervious	25	0	50
Curve Number	68	65	75

Table 31: Subcatchment 7 Calibration Parameters

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value
Width	908	800	1000
% Slope	4.9	3.9	5.9
% Impervious	9	7	11
Impervious Manning's N	0.011	0.01	0.13
Pervious Manning's N	0.025	0.02	0.03
Depression Storage for Impervious Area	0.075	0.05	0.1
Depression Storage for Pervious Area	0	0.1	0.2
% Impervious with No Depression Storage	25	0	50
% Routed to Pervious	25	0	50
Curve Number	66	65	75

B. Elimination of the VUSP Narberth Rain Gauge

Figures 41-43 depict the output from the SWMM baseline model using the VUSP Narberth Rain Gauge versus flow data collected by the Headwaters Flow Meter.

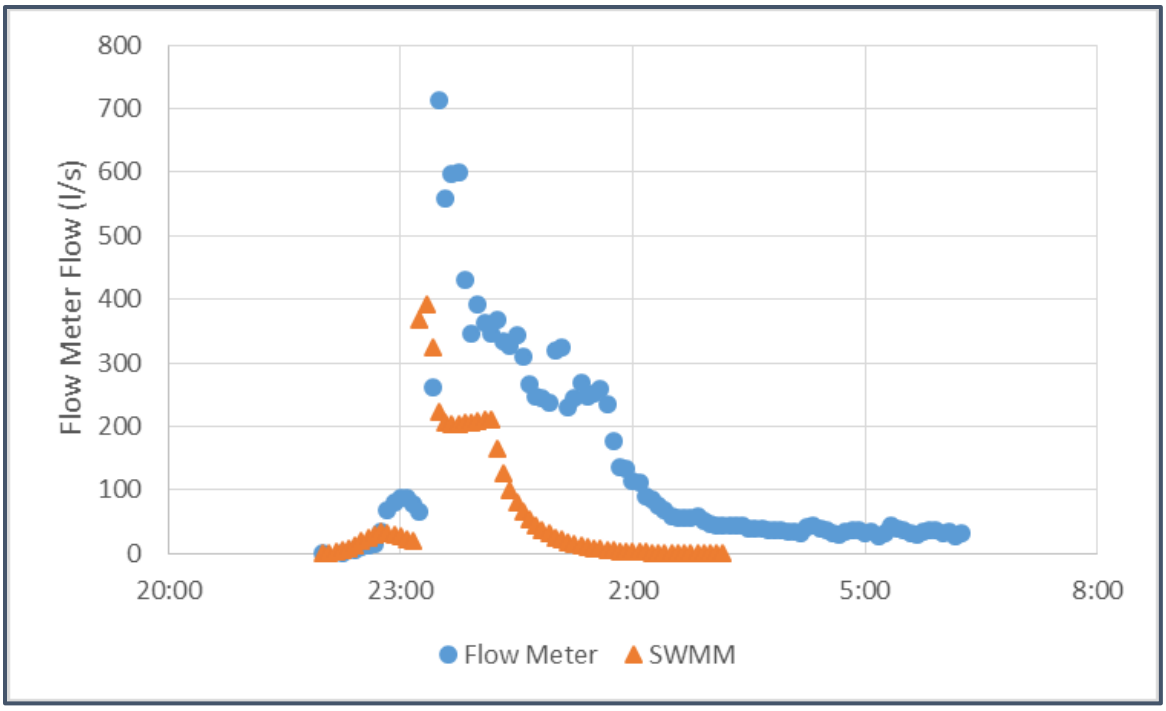

Figure 41: 6/20/2015 VUSP Narberth Headwaters Baseline Results

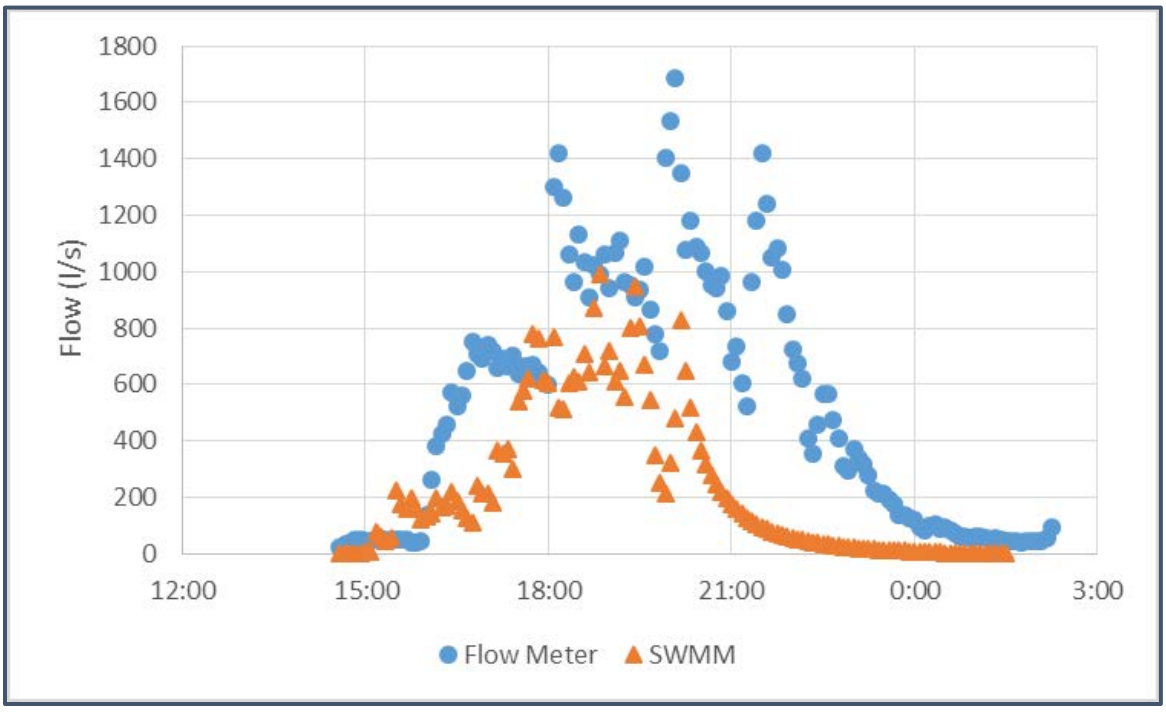

Figure 42: 6/27/2015 VUSP Narberth Headwaters Baseline Results

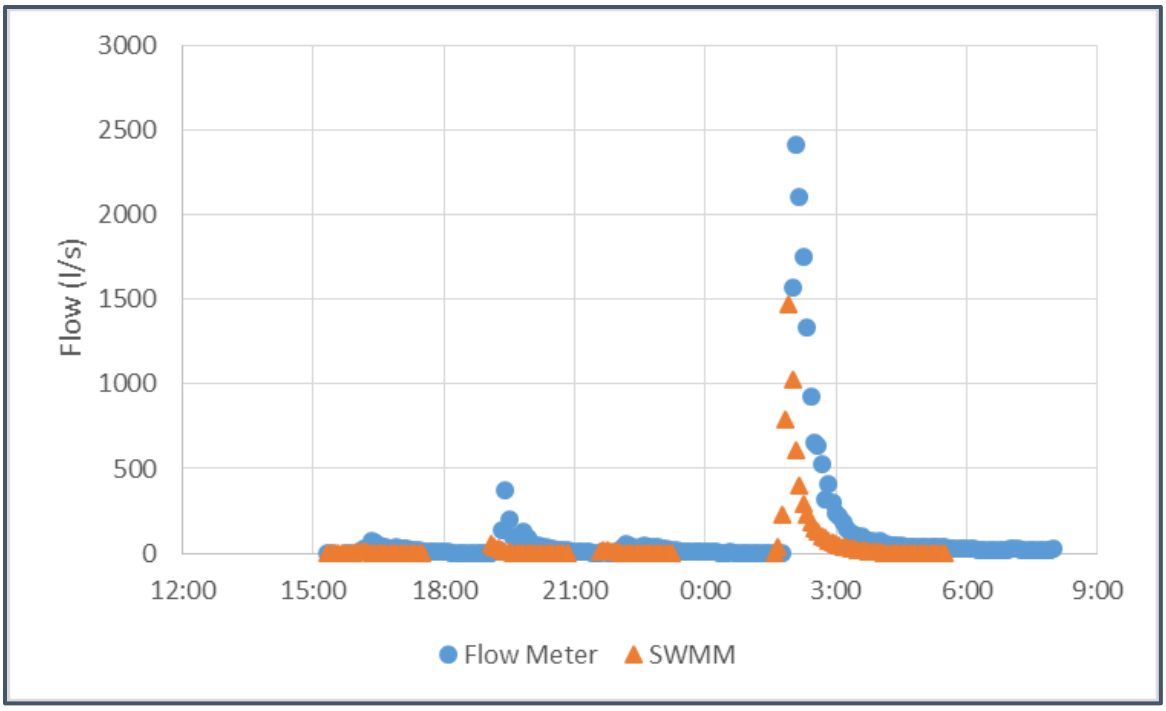

Figure 43: 6/30/2015 VUSP Narberth Headwaters Baseline Results

From Figures 41-43, it is apparent that the VUSP Narberth SWMM variation was able to accurately predict the creek's flow pattern, but not the creek's flow volume. The SWMM input parameters had to be adjusted beyond reasonable values in order for the flow volume predicted by the model to begin approaching the flow volume observed in the field. Therefore, the assumption that the VUSP Narberth Rain Gauge was accurately recording rainfall pattern but under recording rainfall volume, as described in the *Rain Gauge Selection for Calibration* section of *Chapter 2*, was further verified. In order to better understand how to compensate for this volume discrepancy while maintaining reasonable input values, five-minute precipitation data from the VUSP Villanova, the VUSP Narberth, and the WU Wynnewood Rain Gauges were compared for 10 distinct calibration and validation storms. Results of the analysis are presented in Figures 44-53 below.

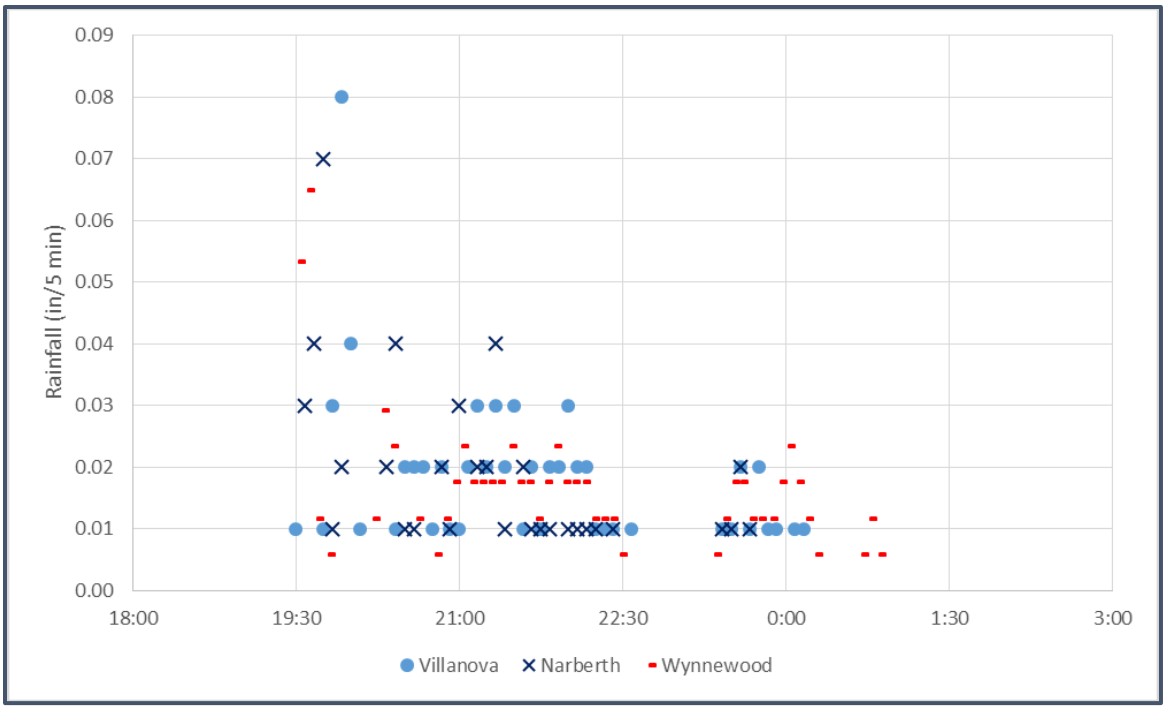

Figure 44: 6/18/2015 Rain Gauge Comparison

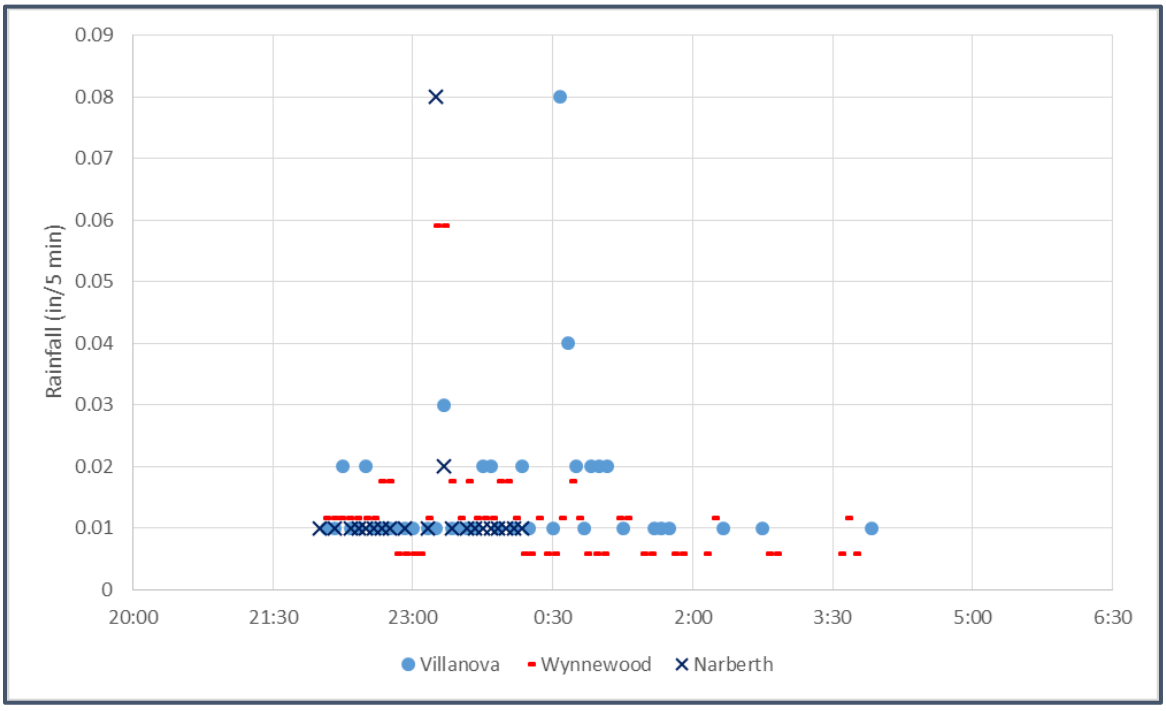

Figure 45: 6/20/2015 Rain Gauge Comparison

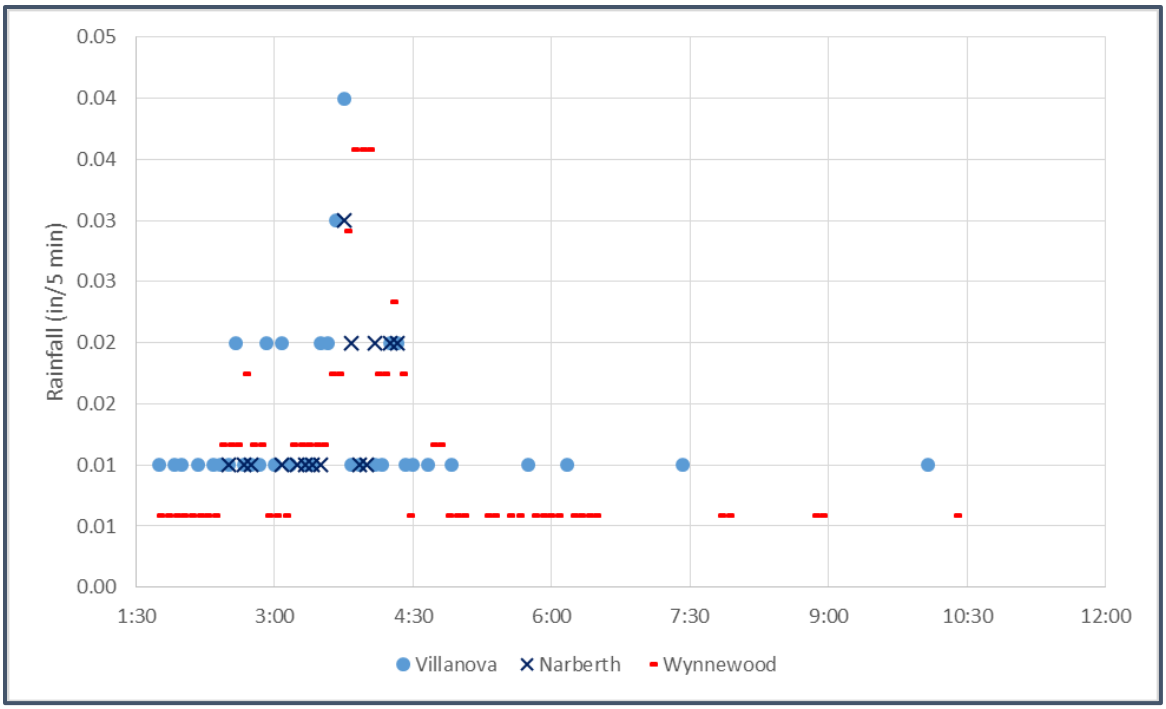

Figure 46: 6/18/2015 Rain Gauge Comparison

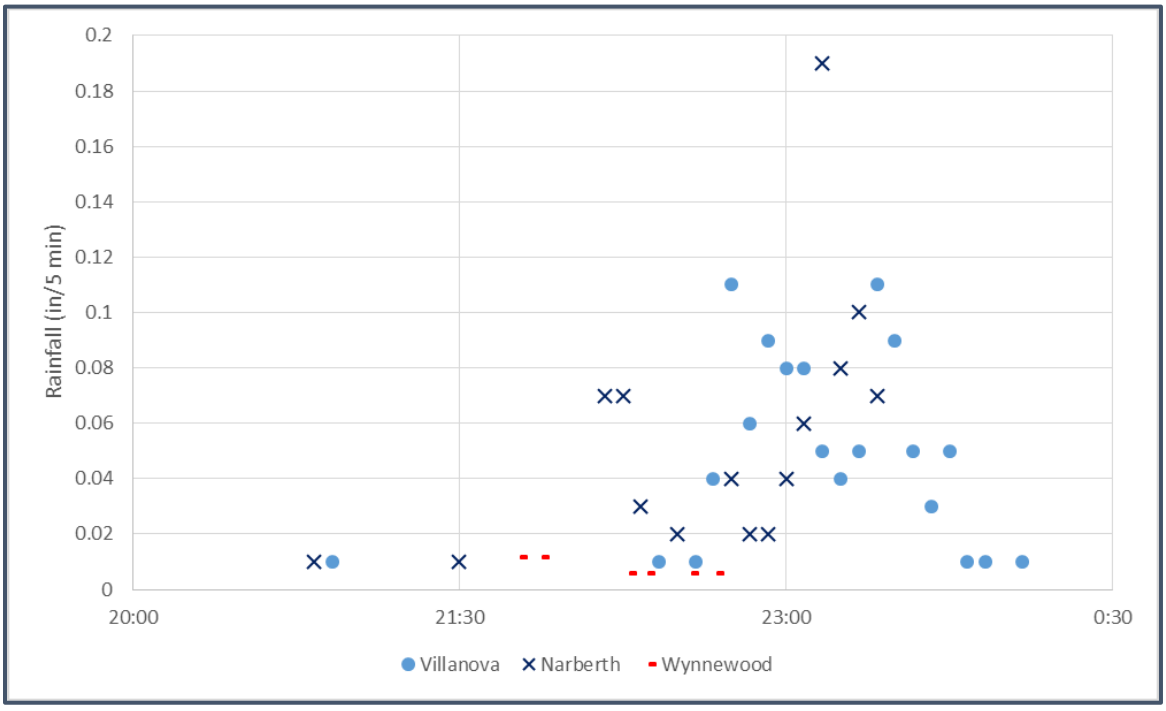

Figure 47: 6/26/2015 Rain Gauge Comparison

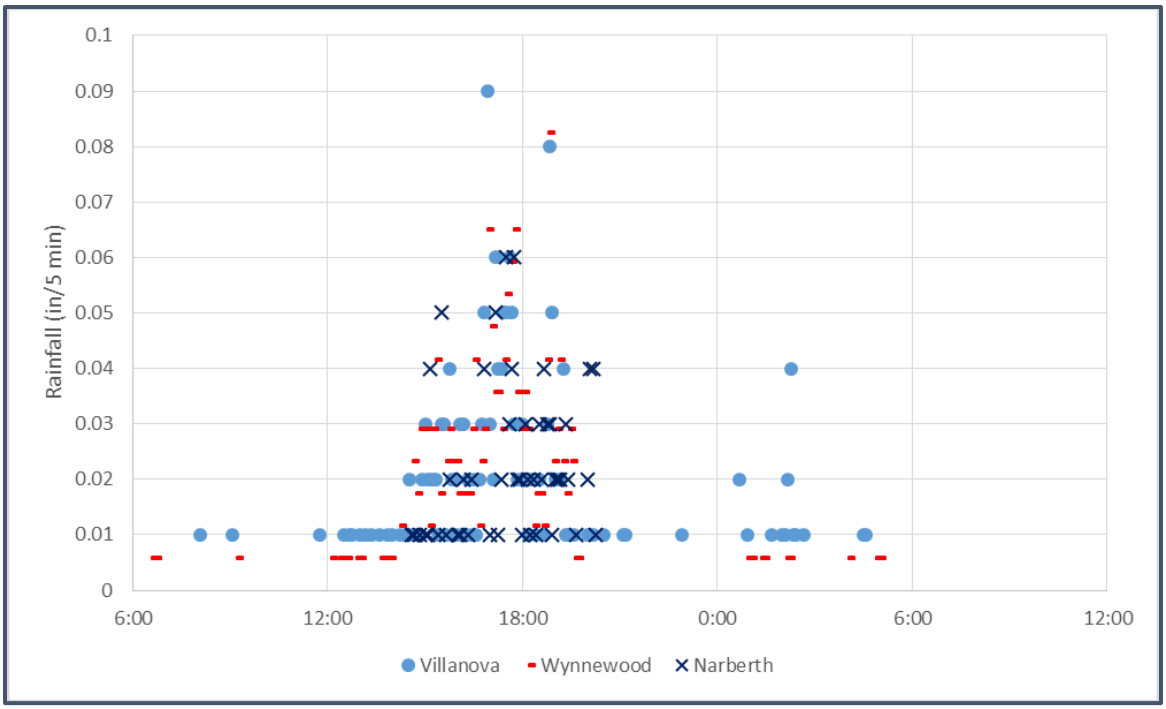

Figure 48: 6/27/2015 Rain Gauge Comparison

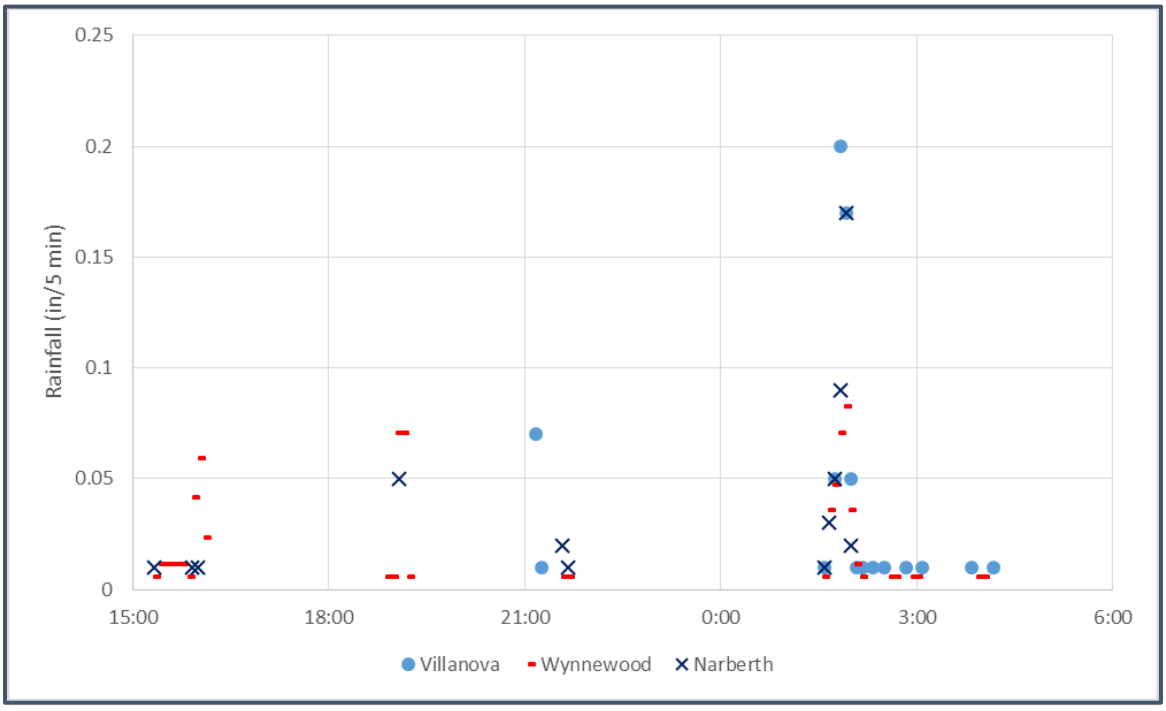

Figure 49: 6/30/2015 Rain Gauge Comparison

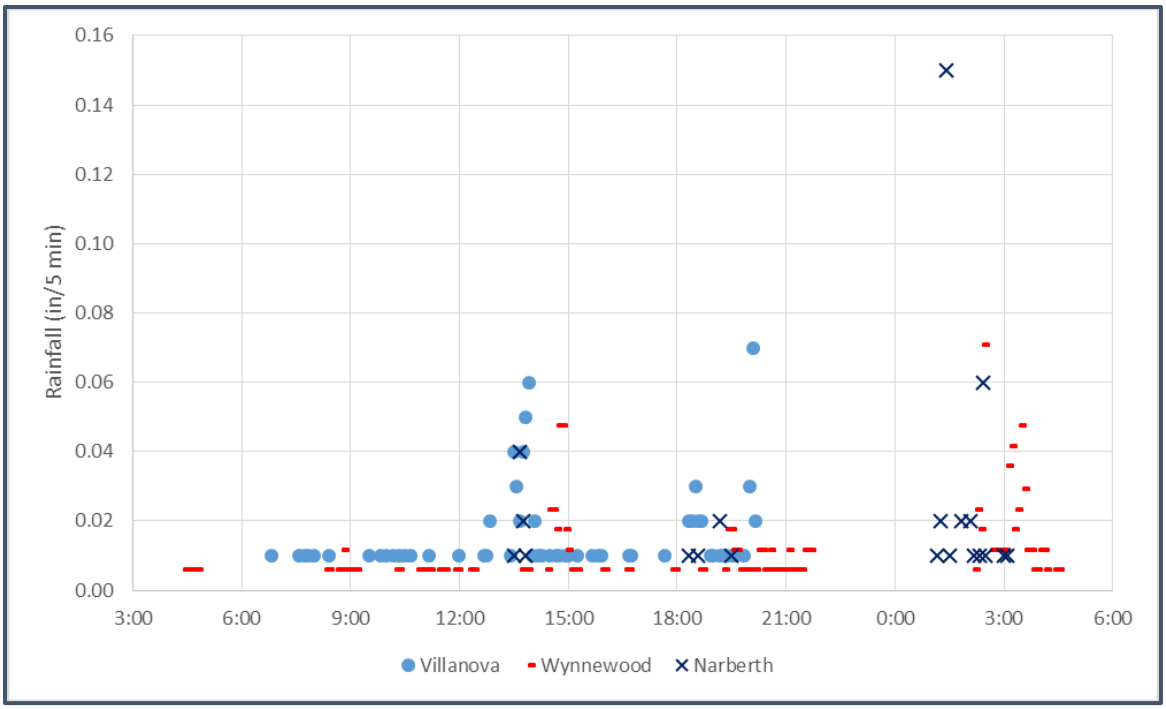

Figure 50: 10/28/2015 Rain Gauge Comparison

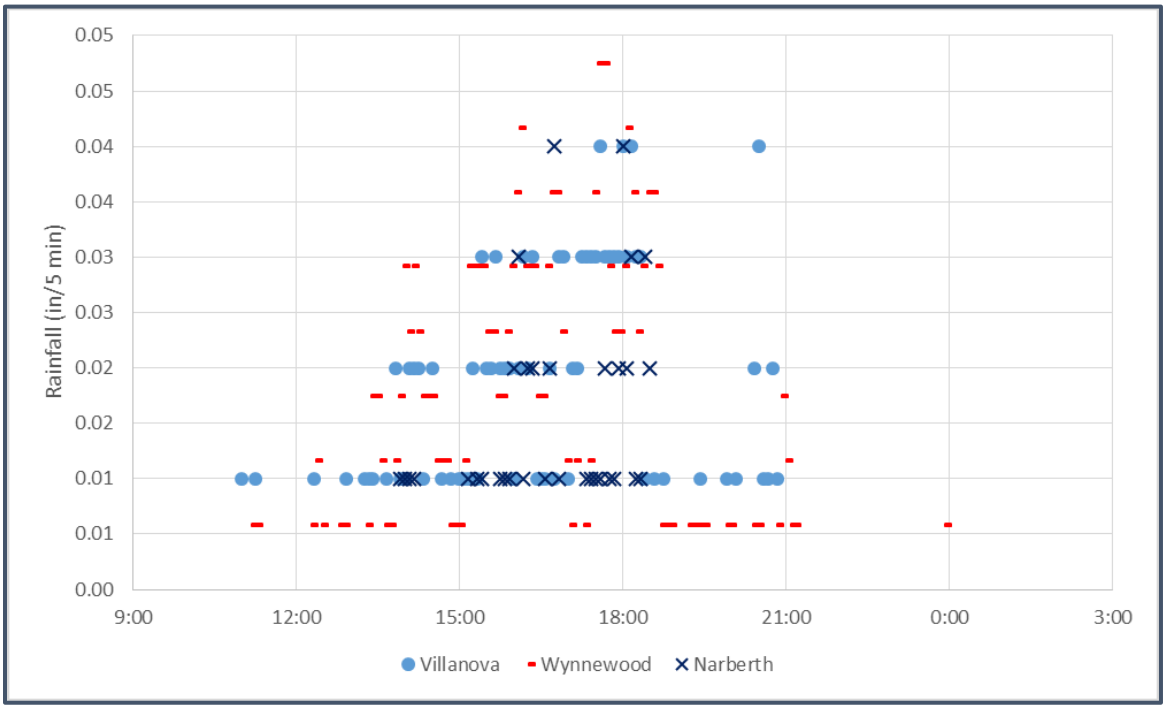

Figure 51: 11/19/2015 Rain Gauge Comparison

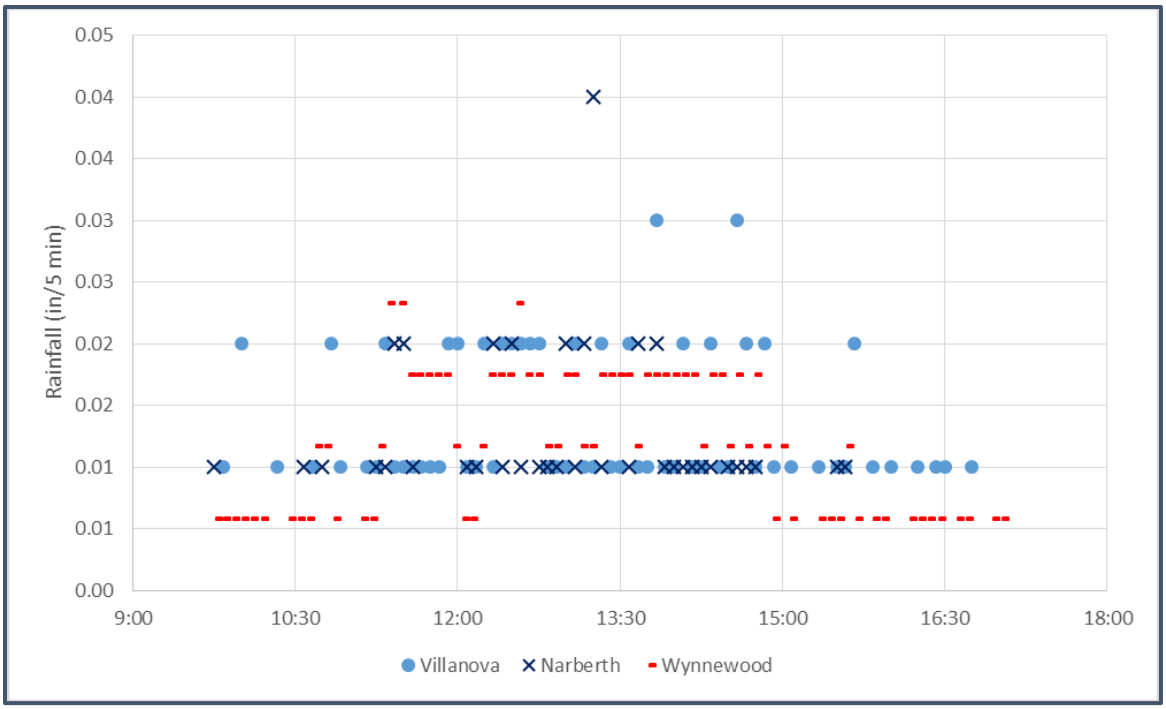

Figure 52: 12/17/2015 Rain Gauge Comparison

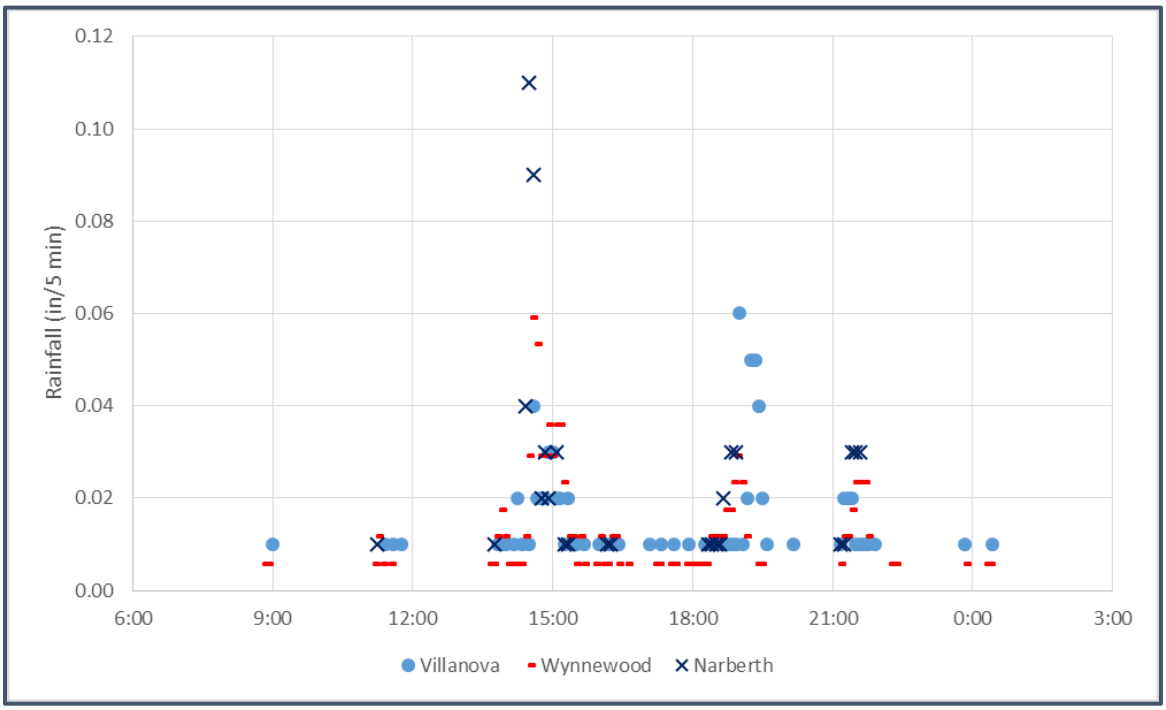

Figure 53: 12/23/2015 Rain Gauge Comparison

Figures 44-53 confirm the author's conclusion that the VUSP Narberth Rain Gauge appears to be accurately recording rainfall pattern. As evidenced by the 10 storm events depicted in Figures 44 – 53, it appears that the individual data points recorded by the VUSP Narberth Rain Gauge are comparable to, if not greater than, individual data points recorded by the other two rain gauges. It appears that the data points recorded by the VUSP Narberth Rain Gauge are reasonable. Therefore, it can be concluded that the VUSP Narberth Rain Gauge is not under-recording every rainfall data point, but it is failing to record a significant number of data points. To compensate for this problem, the author would have to effectively create data points based on the rainfall patterns presented by the other two rain gauges.

As a result of these conclusions, as well as the successful calibration of the VUSP Villanova and VUSP Wynnewood model variations, as discussed in the *Calibration and Validation Results* section of this chapter, it was concluded that using the VUSP Narberth Rain Gauge would not add any value to analysis or to future work. The inability for the author to use the VUSP Narberth Rain Gauge for a detailed analysis due to a long-term mechanical failure of the rain gauge emphasizes the importance of installing weather station instrumentation in a location that can be easily accessed for regular maintenance.

Additionally, because the VUSP Narberth Rain Gauge pattern aligned so well with the flow data collected by the Headwaters and Downstream Flow Meters, when the data was originally being collected by the author, it was assumed that the VUSP Narberth Rain Gauge was functioning successfully. This misconception emphasizes the importance of using multiple methods to check the reasonability of collected data.

II. Calibration and Validation Results

Due to reasons discussed in the *Narrowing the Scope of Analysis* section of this chapter, final assigned values do not exist for the VUSP Narberth model variation or for the Downstream Calibration Point or for the downstream subcatchments (subcatchments 4-7) for any model variation.

A. VUSP Villanova

1. Calibration

Figures 54 – 58 below depict the SWMM calibration results for the VUSP Villanova model variation. All graphs represent flow moving past the Headwaters Calibration Point. Each figure title includes the final NSE coefficient for that calibration storm.

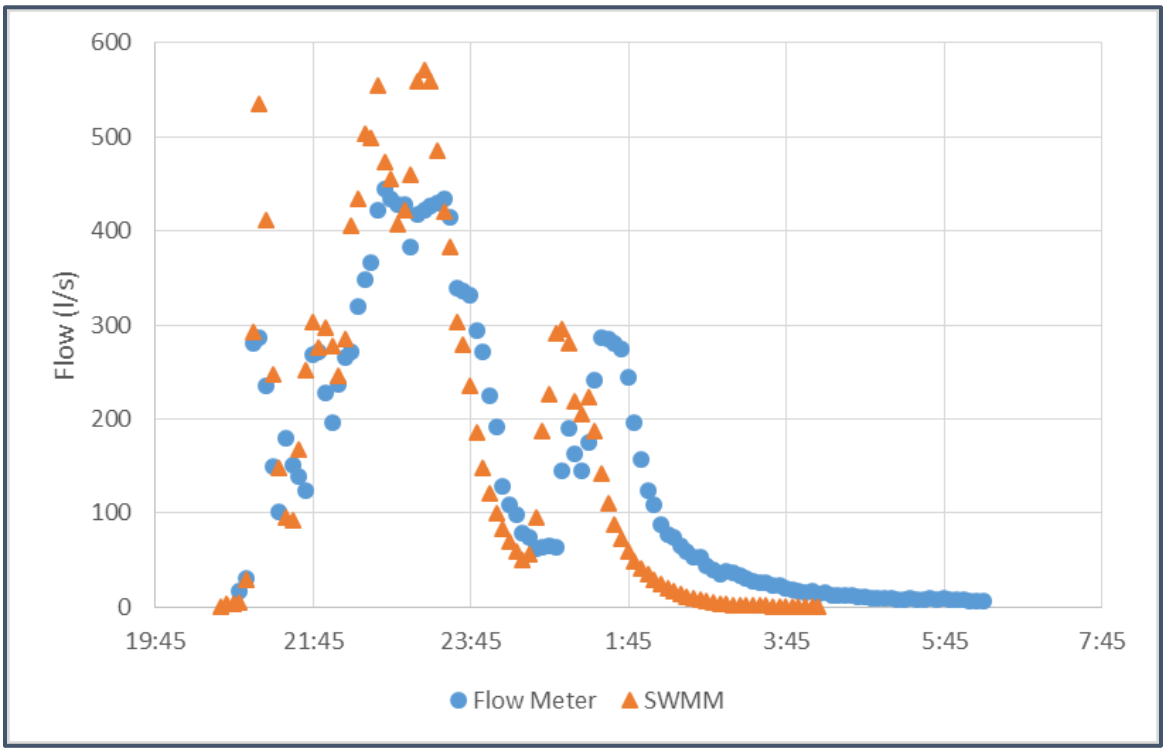

Figure 54: 6/8/2015 VUSP Villanova Calibration (NSE coefficient = 0.67)

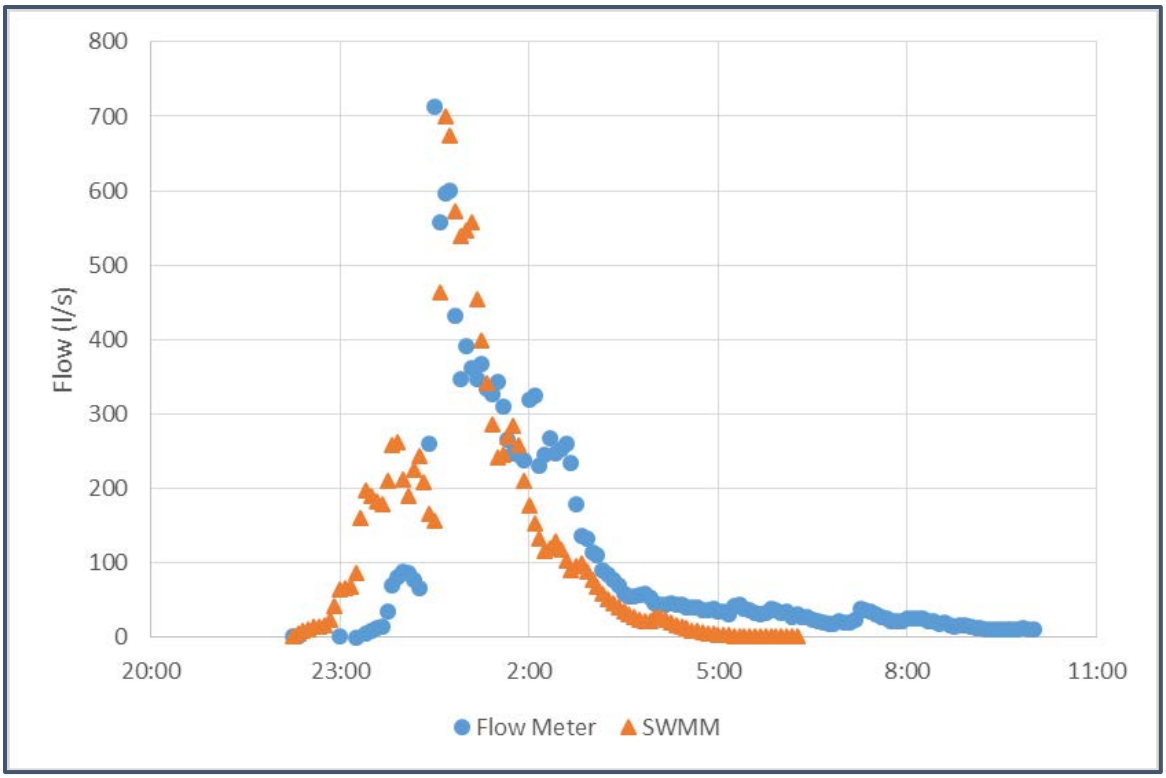

Figure 55: 6/20/2015 VUSP Villanova Calibration (NSE coefficient = 0.59)

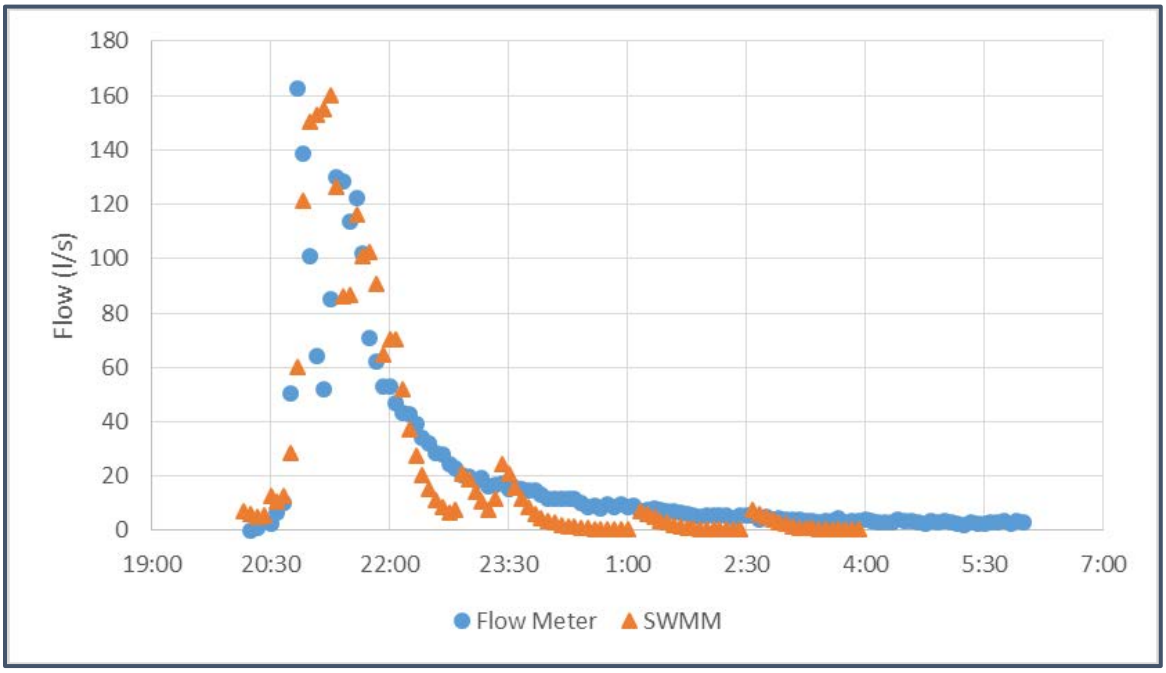

Figure 56: 6/25/2015 Calibration (NSE coefficient = 0.63)

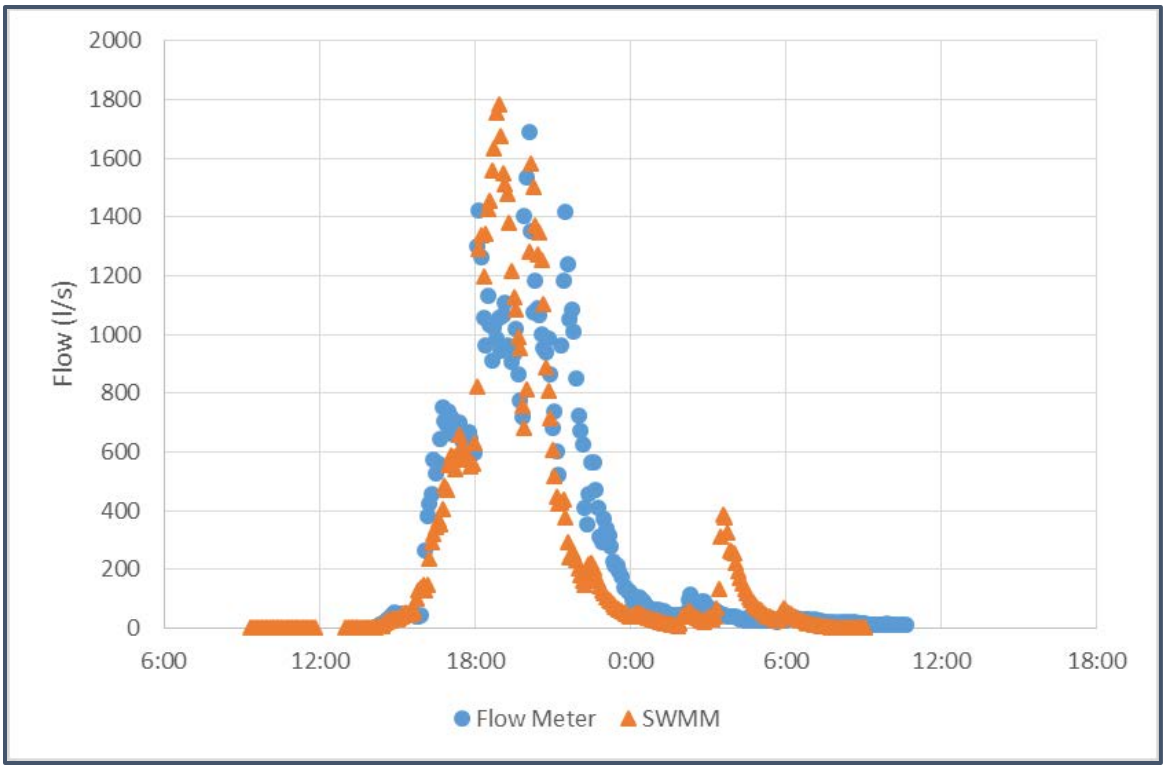

Figure 57: 6/27/2015 VUSP Villanova Calibration (NSE coefficient = 0.70)

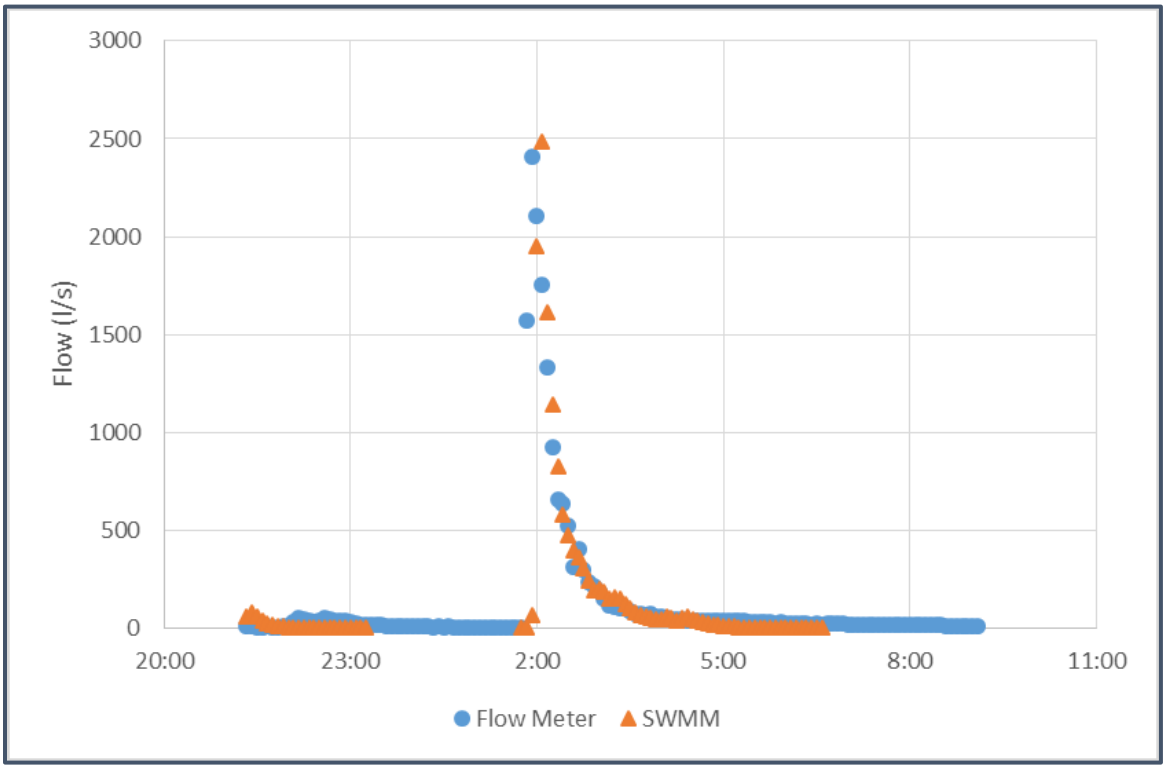

Figure 58: 6/30/2015 VUSP Villanova Calibration (NSE coefficient = 0.52)

Tables 32-34 present the baseline value, the calibration range, and the final assigned value (which was assigned as a result of calibration) for each calibration parameter for each headwaters subcatchment in the VUSP Villanova Model Variation.

Table 32: VUSP Villanova Model, Subcatchment 1

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value	Final Value
Width (ft)	2600	2600	3100	2700
% Slope	2.90	1.9	3.9	2.3
% Impervious	33	26	40	37
Impervious Manning's N	0.011	0.01	0.013	0.012
Pervious Manning's N	0.025	0.02	0.03	0.028
Depression Storage for Impervious Area	0.075	0.05	0.1	0.070
% Impervious with No Depression Storage	25	0	50	30
% Routed to Pervious	25	0	50	30
Curve Number	61	60	75	64

Table 33: VUSP Villanova Model, Subcatchment 2

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value	Final Value
Width	6763	5000	10400	6785
% Slope	3.00	1.8	4.3	2.3
% Impervious	22	18	26	24
Impervious Manning's N	0.011	0.01	0.013	0.012
Pervious Manning's N	0.025	0.02	0.03	0.028
Depression Storage for Impervious Area	0.075	0.05	0.1	0.070
% Impervious with No Depression Storage	25	0	50	30
% Routed to Pervious	25	0	50	30
Curve Number	61	60	75	64

Table 34: VUSP Villanova Model, Subcatchment 3

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value	Final Value
Width	1064	800	1500	1186
% Slope	5.20	4.8	5.7	5.0
% Impervious	26	21	31	25
Impervious Manning's N	0.011	0.01	0.013	0.012
Pervious Manning's N	0.025	0.02	0.03	0.028
Depression Storage for Impervious Area	0.075	0.05	0.1	0.080
% Impervious with No Depression Storage	25	0	50	18
% Routed to Pervious	25	0	50	38
Curve Number	63	60	75	62

2. Validation

Figures 59 and 60 depict the SWMM validation results for the WU Wynnewood model variation. All graphs represent flow moving past the Headwaters Calibration Point. Each figure title includes the final NSE coefficient for that calibration storm.

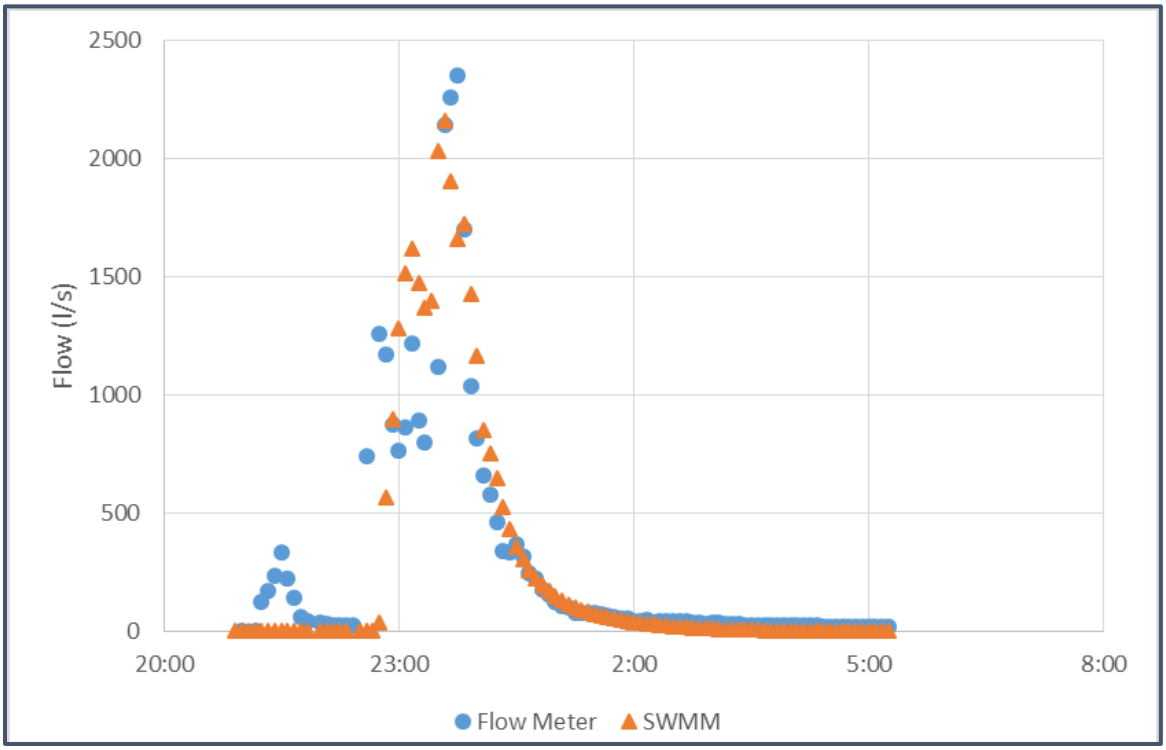

Figure 59: 6/26/2015 VUSP Villanova Validation (NSE coefficient = 0.67)

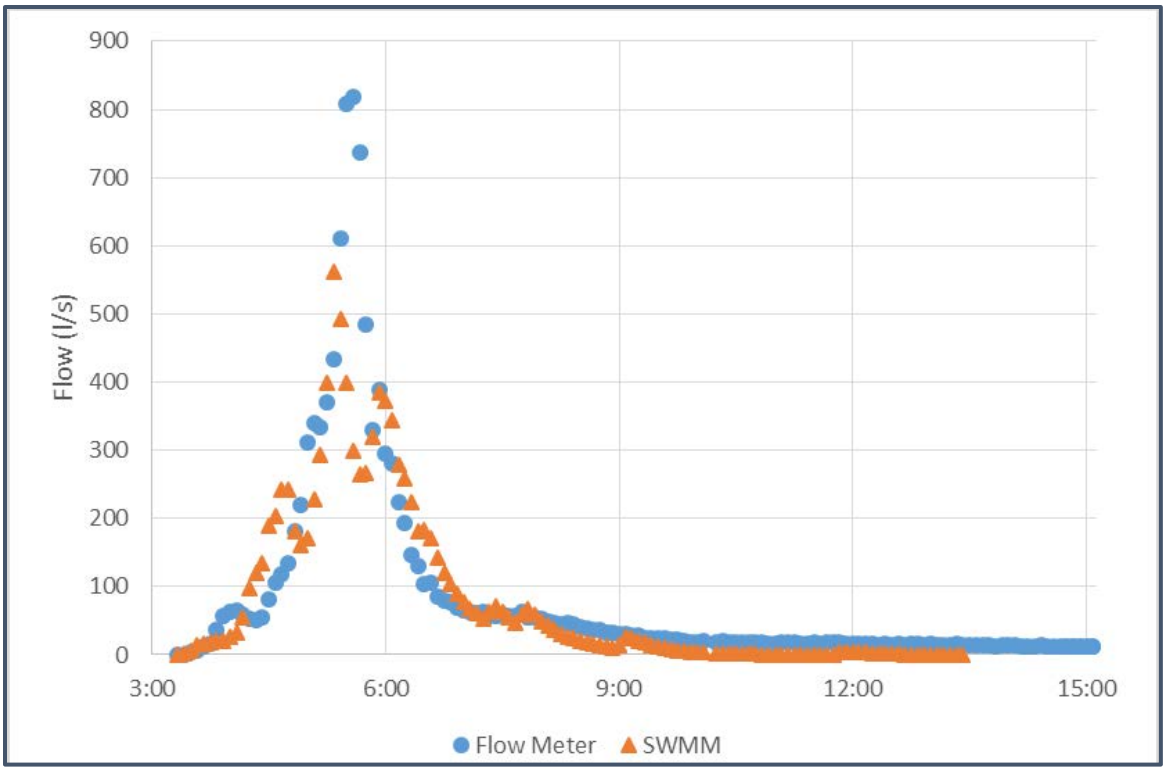

Figure 60: 6/18/2015 VUSP Villanova Validation (NSE coefficient =0.71)

B. WU Wynnewood

1. Calibration

Figures 61 – 64 below depict the SWMM calibration results for the WU Wynnewood model variation. All graphs represent flow moving past the Headwaters Calibration Point. Each figure title includes the final NSE coefficient for that calibration storm.

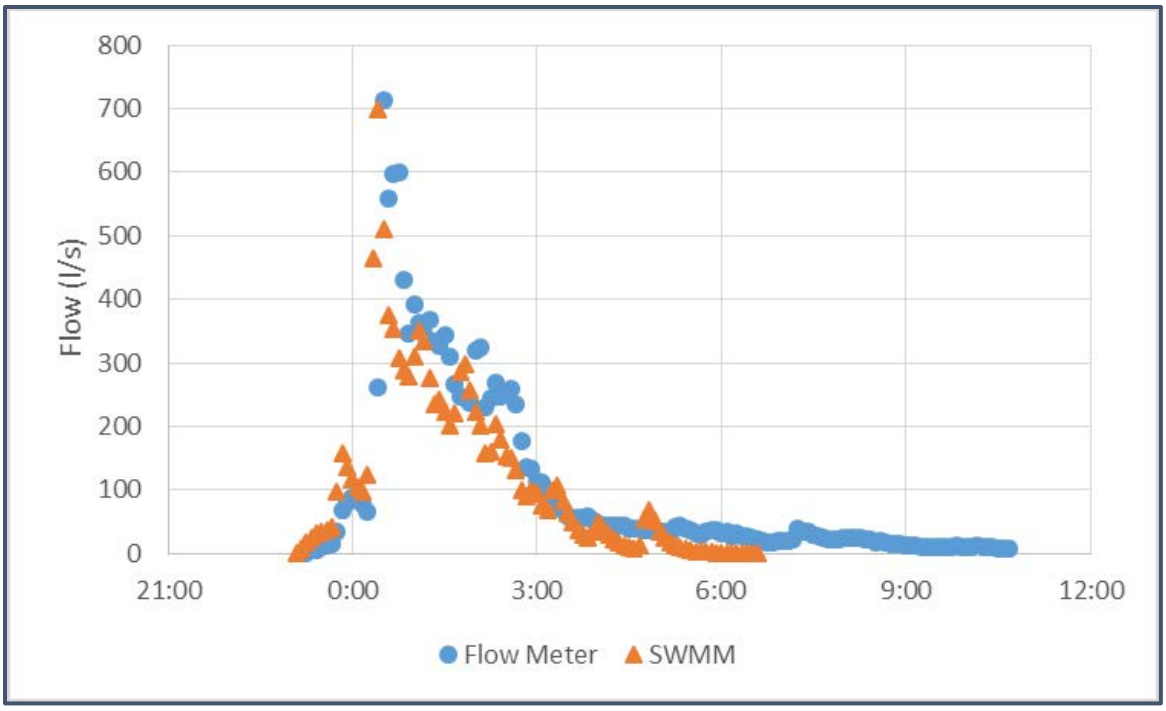

Figure 61: 6/20/2015 WU Wynnewood Calibration (NSE coefficient = 0.68)

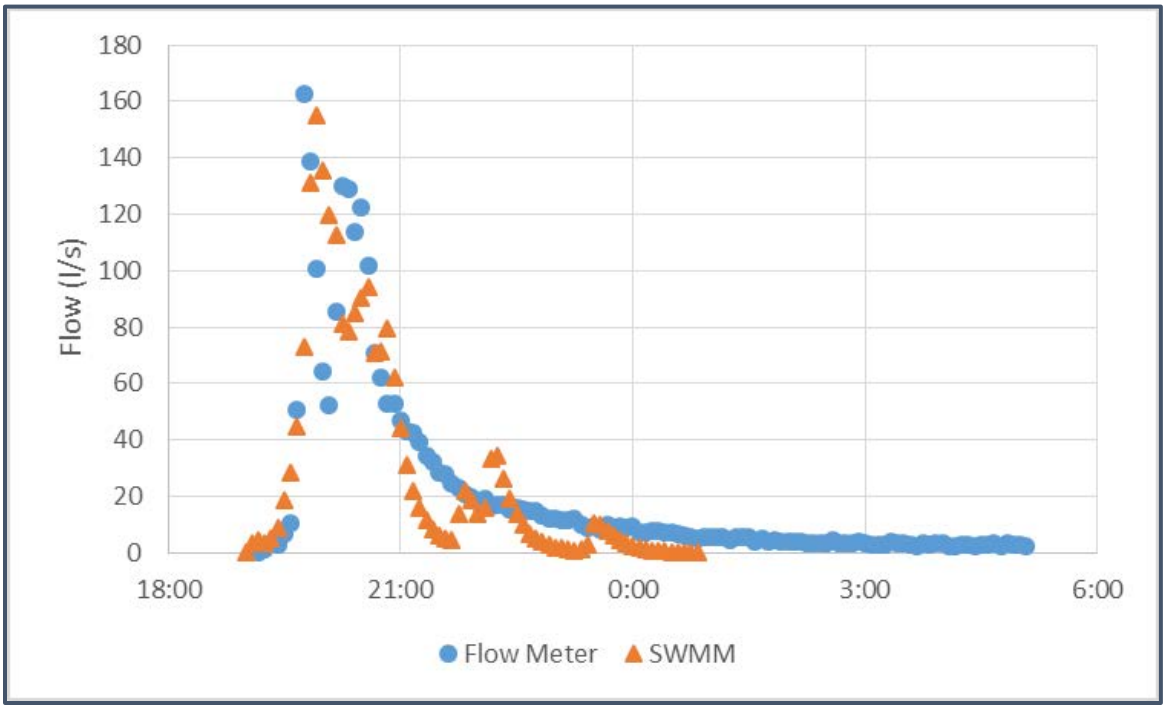

Figure 62: 6/25/2015 WU Wynnewood Calibration (NSE coefficient = 0.58)

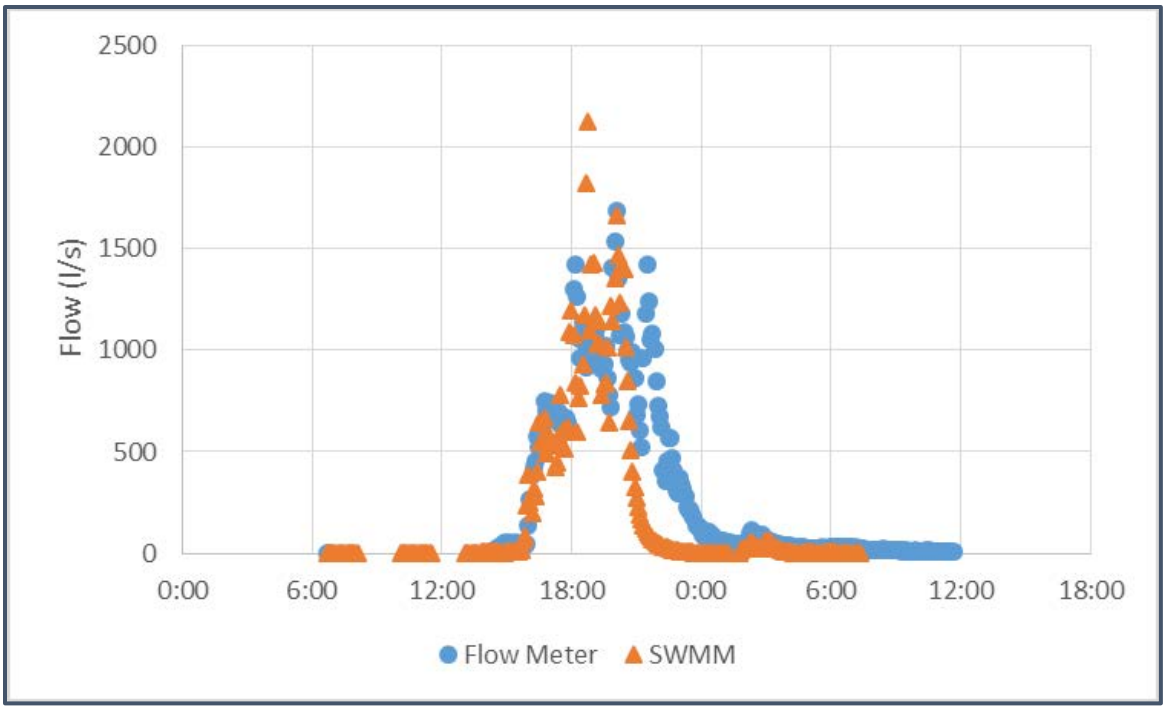

Figure 63: 6/27/2015 WU Wynnewood Calibration (NSE coefficient = 0.62)

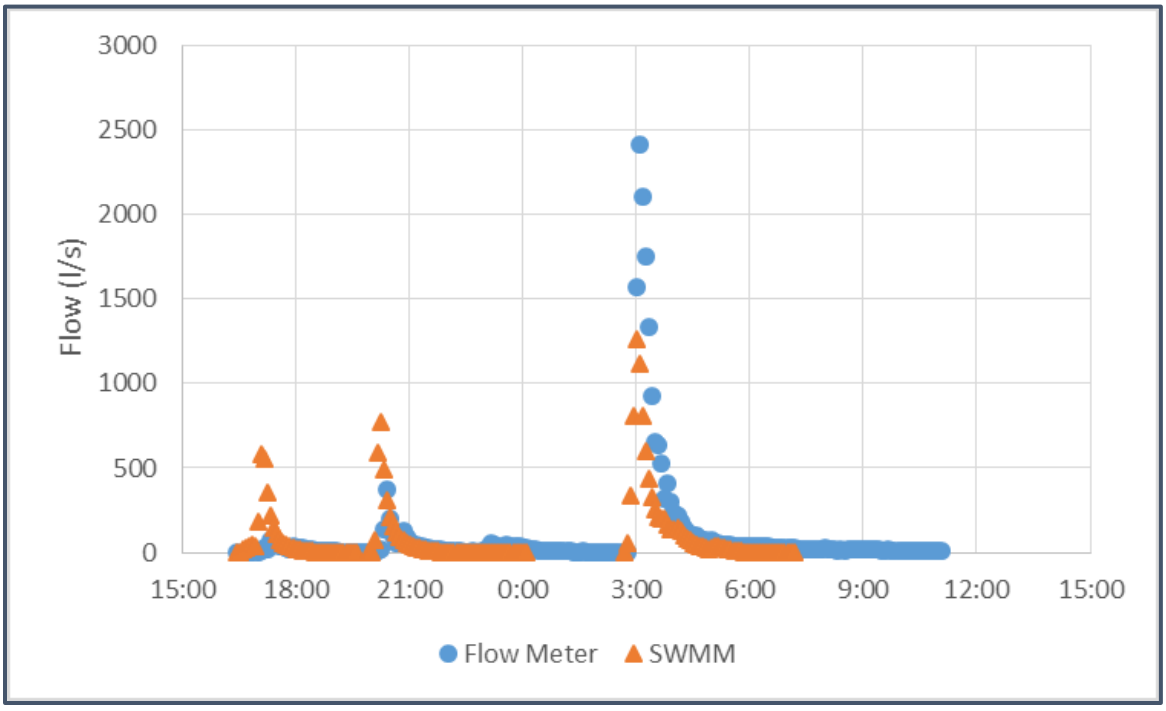

Figure 64: 6/30/2015 WU Wynnewood Calibration (NSE coefficient = 0.52)

Tables 35-37 present the baseline value, the calibration range, and the final assigned value (which was assigned as a result of calibration) for each calibration parameter for each headwaters subcatchment in the WU Wynnewood Model Variation.

Table 35: WU Wynnewood Subcatchment 1

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value	Final Value
Width (ft)	2600	2600	3100	2600
% Slope	2.90	1.9	3.9	2.9
% Impervious	33	26	40	38
Impervious Manning's N	0.011	0.01	0.013	0.012
Pervious Manning's N	0.025	0.02	0.03	0.025
Depression Storage for Impervious Area	0.075	0.05	0.1	0.075
% Impervious with No Depression Storage	25	0	50	25
% Routed to Pervious	25	0	50	25
Curve Number	61	60	75	61

Table 36: WU Wynnewood Model, Subcatchment 2

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value	Final Value
Width	6763	5000	10400	6763
% Slope	3.00	1.8	4.3	3.00
% Impervious	22	18	26	25
Impervious Manning's N	0.011	0.01	0.013	0.012
Pervious Manning's N	0.025	0.02	0.03	0.025
Depression Storage for Impervious Area	0.075	0.05	0.1	0.075
% Impervious with No Depression Storage	25	0	50	25
% Routed to Pervious	25	0	50	25
Curve Number	61	60	75	61

Table 37: WU Wynnewood Model, Subcatchment 3

Parameter	Baseline Value	Lowest Reasonable Value	Highest Reasonable Value	Final Value
Width	1064	800	1500	1064
% Slope	5.20	4.8	5.7	5
% Impervious	26	21	31	29
Impervious Manning's N	0.011	0.01	0.013	0.012
Pervious Manning's N	0.025	0.02	0.03	0.025
Depression Storage for Impervious Area	0.075	0.05	0.1	0.075
% Impervious with No Depression Storage	25	0	50	25
% Routed to Pervious	25	0	50	25
Curve Number	63	60	75	63

2. Validation

Figures 65 and 66 depict the SWMM validation results for the WU Wynnewood model variation. All graphs represent flow moving past the Headwaters Calibration Point. Each figure title includes the final NSE coefficient for that calibration storm.

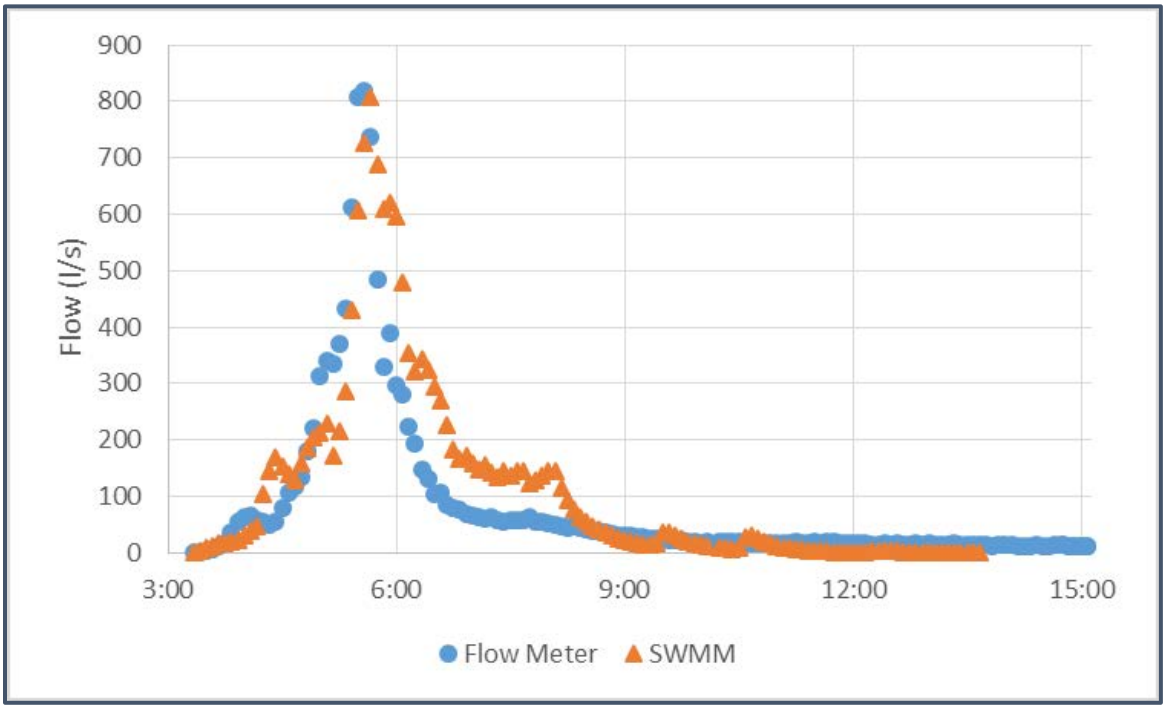

Figure 65: 6/18/2015 WU Wynnewood Validation Results (NSE coefficient = 0.73)

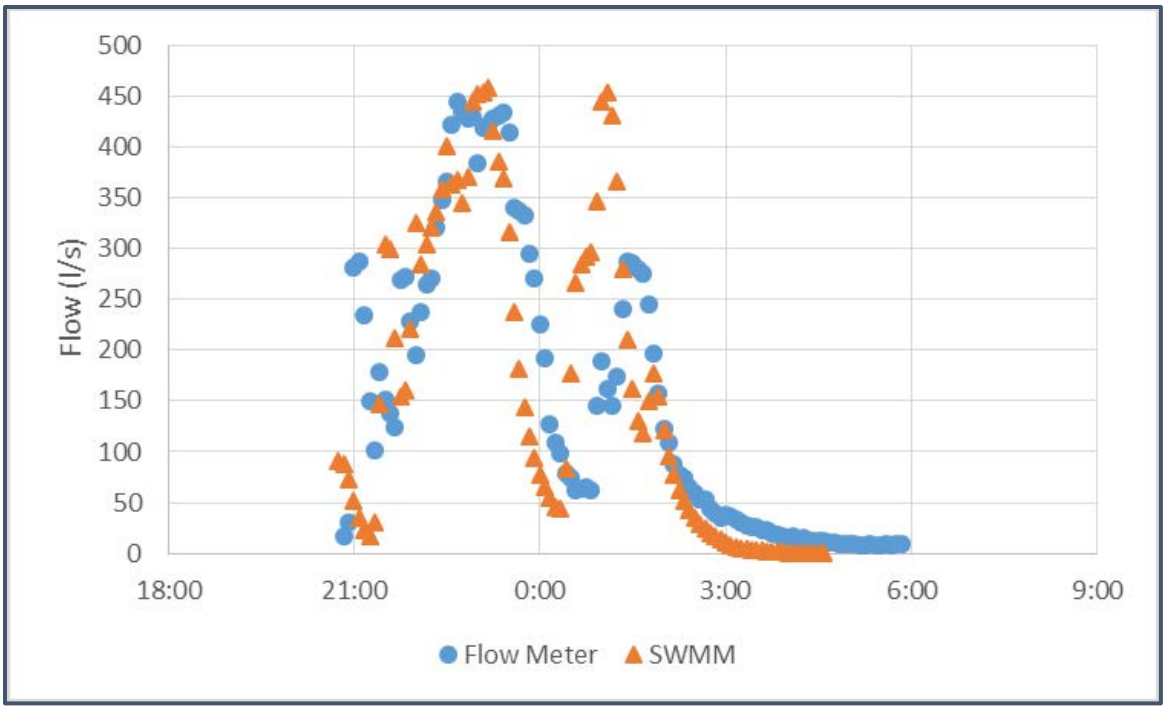

Figure 66: 6/8/2015 WU Wynnewood Validation Results (NSE coefficient = 0.55)

III. Selecting a Single Rain Gauge

The final calibrated inputs for the VUSP Villanova and the WU Wynnewood model variations were similar enough that the author was unable to differentiate between which differences in the calibrated models could be attributed to rain gauge imperfections and which differences could be attributed to a varying calibration approach. The calibration approach used in this research relied heavily on judgement and did not follow a strict methodology. Therefore, after completing the calibration process, the author felt that it would be inappropriate to attribute all of the subtle differences between the model variations to the imperfect rain gauges.

As discussed in *Rain Gauge Selection for Calibration* section of *Chapter 2*, the VUSP Villanova Rain Gauge is the more reliable than the WU Wynnewood Rain Gauge Additionally, because the VUSP owns and maintains the Villanova rain gauge, the author is confident that it will be available for use in future research work. Contrastingly, because the specific location and owner of the WU

Wynnewood Rain Gauge is unknown, the author cannot be confident that the rain gauge will continue to be available and to function reliably for use in future VUSP research. Therefore, to aim for the highest possible level of accuracy and to anticipate consistency with future research, the VUSP Villanova Rain Gauge was selected as the single rain gauge to be used for analysis of the headwaters portion of the East Branch of Indian Creek.

CHAPTER 4: RAIN GARDEN ANALYSIS

I. Checking Reasonability of SWMM Outputs

Before the selected flow metrics were analyzed for each rain garden scenario, each model variation was checked to ensure that the rain gardens' effect on the model output was reasonable. To accomplish this, total flow volume captured by the rain gardens in SWMM was compared to manual calculations. Manual calculations of total runoff volume captured were completed by approximating the runoff from the previous drainage areas using the SCS curve number method and by approximating the runoff from the impervious drainage areas as the total precipitation volume minus subcatchment specific initial abstractions (the Depression Storage for Impervious Area value determined during calibration). Note that only the drainage areas draining into the rain gardens were considered. Figure 67 displays the results of this comparison for a 1.41 inch storm on June 3, 2005. The *Creek Flow Reduction* value displayed on the chart is the reduction effect that each rain garden scenario had on the total water volume moving past the Headwaters Flow Meter.

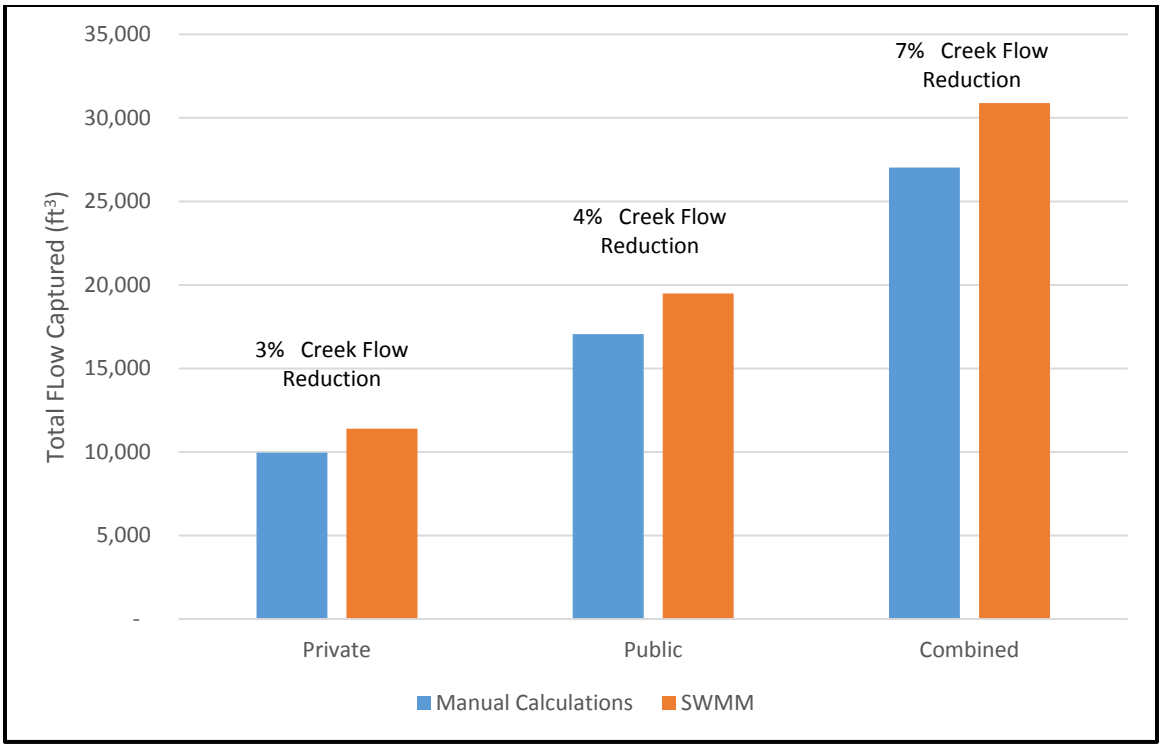

Figure 67: 6/3/2005 Creek Flow Reductions due to Rain Garden Implementation

The results presented in Figure 67 are further quantified in Table 38. The 14% error between the SWMM calculated flow reductions and the manually calculated flow reductions was judged to be reasonable. An error exists because SWMM's runoff calculations do not explicitly follow the SCS Curve Number Method (Reeves et al. 2009).

Table 38: 6/3/2005 Creek Flow Reductions due to Rain Garden Implementation

Rain Garden Scenario	**Total Flow Reduction (ft^3)**		**% Error**
	Manual Calculations	**SWMM**	
Private	9,964	11,396	14%
Public	17,058	19,486	14%
Combined	27,022	30,882	14%

II. Presentation of Flow Metrics

As discussed in *Chapter 2: Methods*, multiple flow metrics were used to evaluate the influence of each rain garden implementation scenario on the headwaters of the East Branch of Indian Creek. High Pulse Count, High Pulse Range, the Richard Baker Flashiness Index were calculated for each of the four scenarios in SWMM: Current Conditions, Implementation of Private Rain Gardens, Implementation of Public Rain Gardens, and Implementation of Private and Public (or Combined) Rain Gardens. Additionally, the Current Conditions Model was run using 2015 - 2016 input data, and the metrics calculated using the resulting SWMM output were compared to metrics calculated using field data collected during the same time period.

A. Calculated High Pulse Metrics

Figures 68 and 69 display the High Pulse Counts and the High Pulse Ranges, respectively, calculated using 2005 SWMM output. The figures display the metrics calculated for current conditions on site ("Do Nothing"), implementation of private rain gardens ("Private"), implementation of public rain gardens ("Public"), and implementation of both public and private rain gardens ("Combined"). The figures depict these results relative to typical values from literature, as discussed in the *Selecting an Appropriate Hydrologic Metric* portion of *Chapter 2: Methods* (DeGasperi et al. 2009). These results are further quantified in Tables 39 and 40.

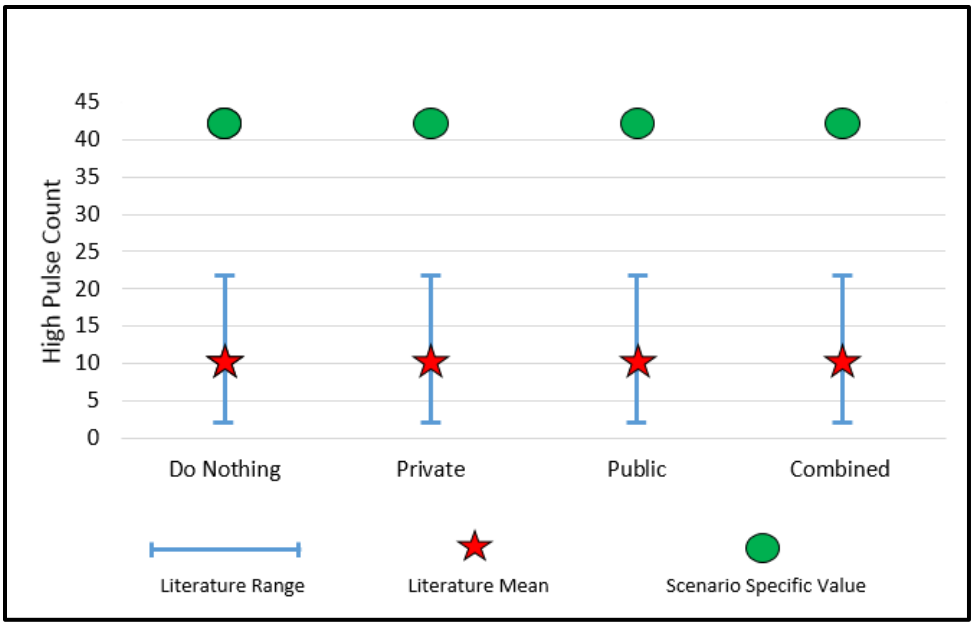

Figure 68: High Pulse Counts Calculated using 2005 SWMM Output for Various Rain Garden Implementation Scenarios

Table 39: High Pulse Counts Calculated using 2005 SWMM Output for Various Rain Garden Implementation Scenarios

Rain Garden Scenario	High Pulse Count			
	Scenario Specific Value	Values from Literature		
		Minimum	Average	Maximum
Do Nothing	42	2	10	22
Private	42			
Public	42			
Combined	42			

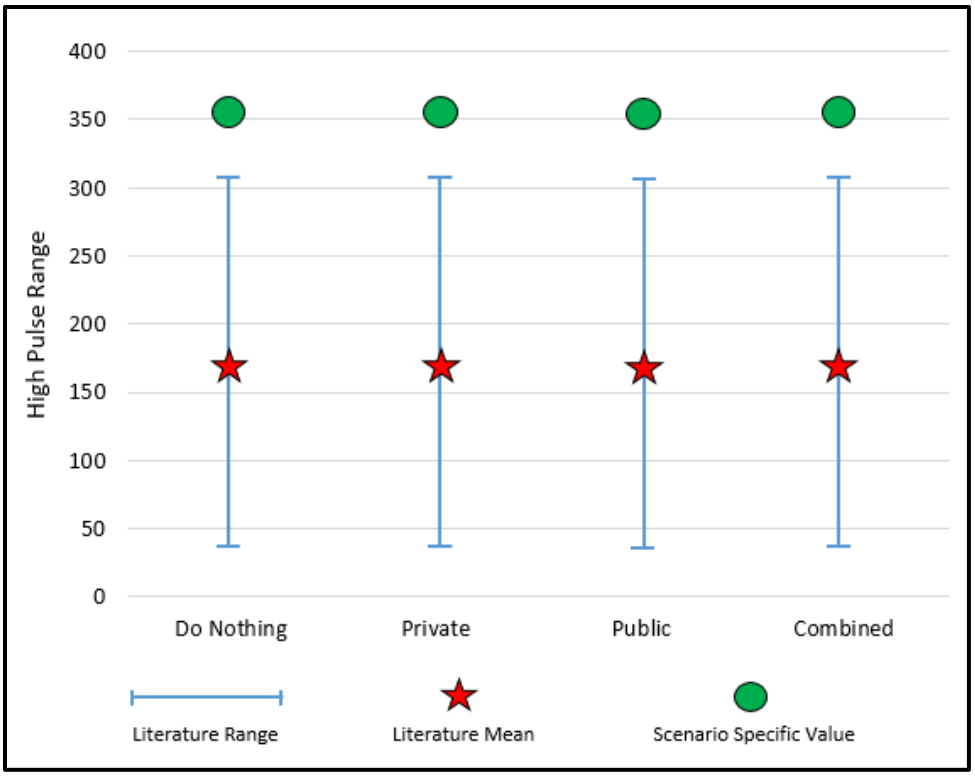

Figure 69: High Pulse Ranges Calculated using 2005 SWMM Output for Various Rain Garden Implementation Scenarios

Table 40: High Pulse Ranges Calculated using 2005 SWMM Output for Various Rain Garden Implementation Scenarios

Rain Garden Scenario	High Pulse Range			
	Scenario Specific Value	Values from Literature		
		Minimum	Average	Maximum
Do Nothing	354	34	168	306
Private	354			
Public	354			
Combined	354			

As demonstrated by Figures 68-69 and Tables 39-40, the rain garden implementation scenarios appear to have no effect on either of the High Pulse Metrics.

B. Calculated Richards Baker Flashiness Index

Figures 70 and 71 display the R-B Index calculated using 2005 SWMM output. The figures display the metrics calculated for current conditions on site ("Do Nothing"), implementation of private rain gardens ("Private"), implementation of public rain gardens ("Public"), and implementation of both public and private rain gardens ("Combined"). The figures depict these results relative to typical values from literature, as discussed in the *Selecting an Appropriate Hydrologic Metric* portion of *Chapter 2: Methods* (DeGasperi et al. 2009). These results are further quantified in Table 41.

Note that Figure 70 displays the R-B Index calculated on an hourly basis, while Figure 71 displays the R-B Index calculated on a daily basis. Both results are compared to the same set of values from literature (DeGasperi et al. 2009). *Chapter 2: Methods* describes how Baker et al. (2004) suggests calculating the R-B Index on an hourly scale for smaller watersheds. Therefore, it can be concluded that the results of Figure 70 are most representative of conditions in the East Branch of Indian Creek. The contrast between the results in Figure 70 and Figure 71 reinforce the significance of choosing to calculate the R-B Index on an hourly versus a daily scale.

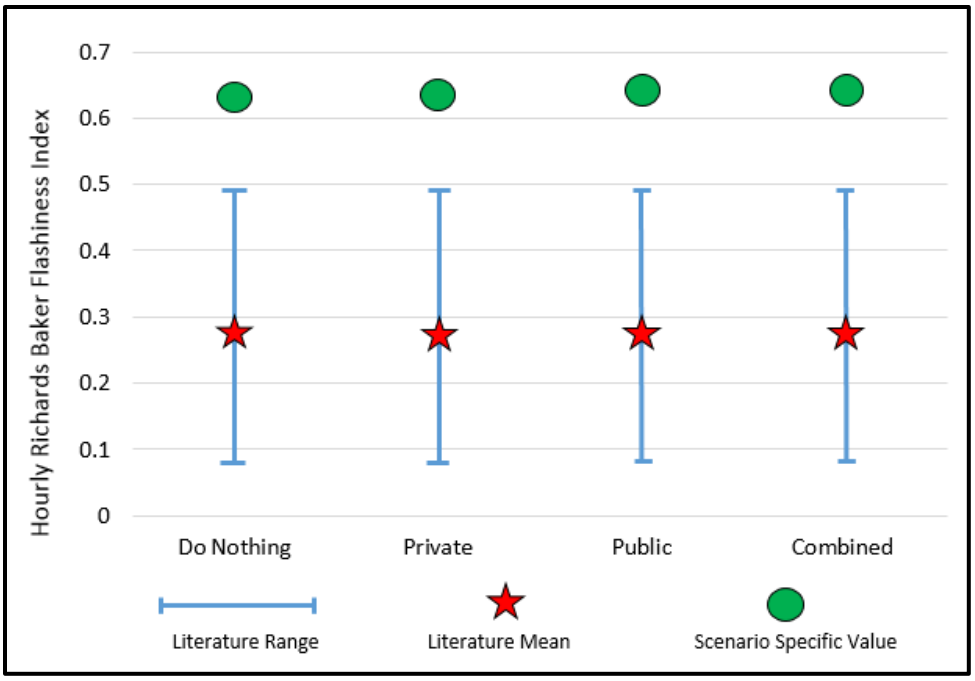

Figure 70: Hourly R-B Index Calculated using 2005 SWMM Output for Various Rain Garden Implementation Scenarios

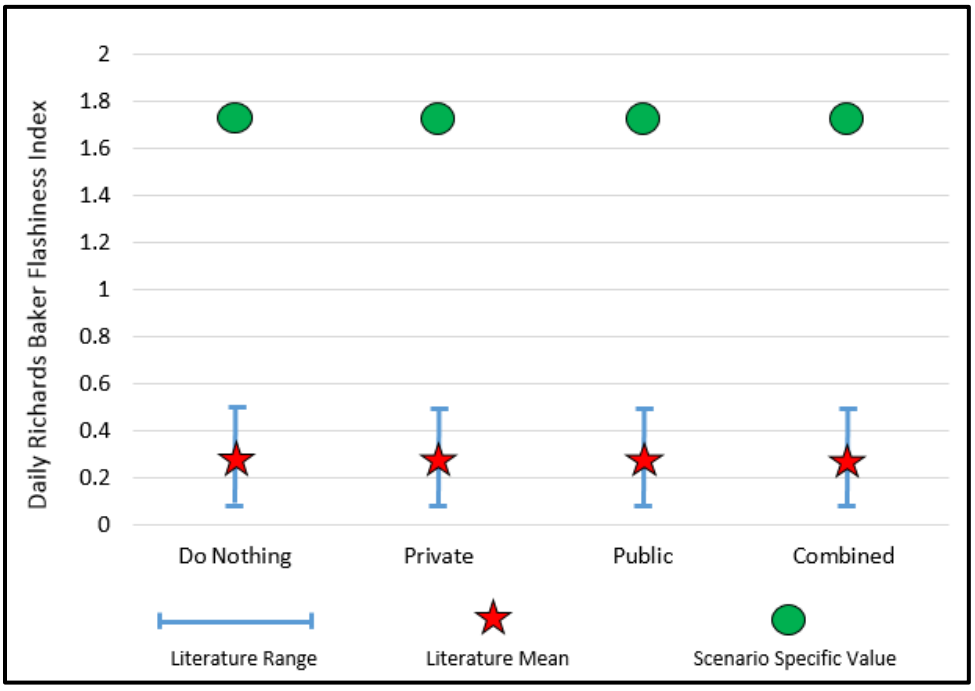

Figure 71: Daily R-B Index Calculated using 2005 SWMM Output for Various Rain Garden Implementation Scenarios

Table 41: R-B Index Calculated using 2005 SWMM Output for Various Rain Garden Implementation Scenarios

Rain Garden Scenario	R-B Index				
	Scenario Specific		Values from Literature		
	Hourly	Daily	Minimum	Average	Maximum
Do Nothing	0.63	1.73	0.08	0.27	0.49
Private	0.63	1.73			
Public	0.64	1.74			
Combined	0.64	1.74			

As demonstrated in Figures 70-71 and Tables 41, the R-B Index is insignificantly affected by the rain garden implementation scenarios. It is notable that although the R-B Index is expected to increase in response to urbanization and decrease in response to restoration, the R-B Index calculated for using the 2005 SWMM output increased in response to restoration. Therefore, this metric, as calculated, may not be accurately representing conditions in the East Branch of Indian Creek. This will be further discussed in *Analysis of Flow Metrics*.

C. Comparison of Metrics Calculated Using Field and SWMM Data

Figures 72-74 compare each of the three flow metrics calculated using the June 1, 2015 to May 31, 2016 SWMM output from the Current Conditions Model to the same flow metrics calculated using field data collected during the same time period. To run the Current Conditions Model from June 1, 2015 to May 31, 2016, precipitation data from the Constructed Stormwater Wetlands rain gauge on Villanova's campus and 2015 -2016 daily maximum and minimum temperatures from the Philadelphia International Airport was used as input in SWMM (Weather Underground 2016). One major source of discrepancy between the two methods is that while the metrics calculated using the SWMM output assumed a base flow of zero, the metrics calculated using field data

assumed a positive base flow. This process of assigning base flow values to the field data is described in the *Selecting an Appropriate Hydrologic Metric* of *Chapter 2: Methods.* These results are further quantified in Table 42.

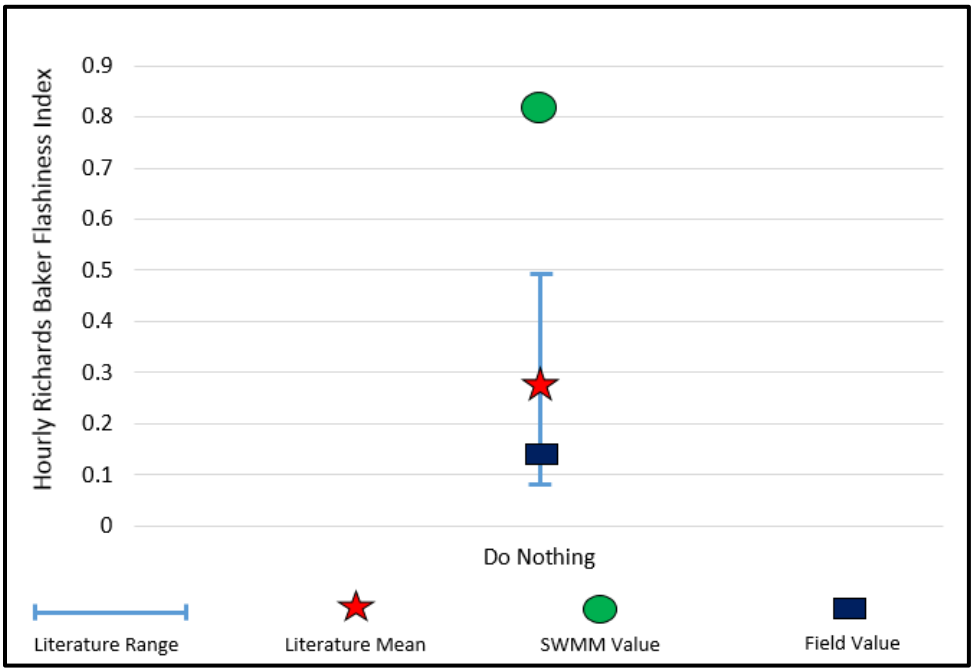

Figure 72: June 2015 – May 2016 R-B Index Calculated for Current Conditions Using SWMM Output and Field Data

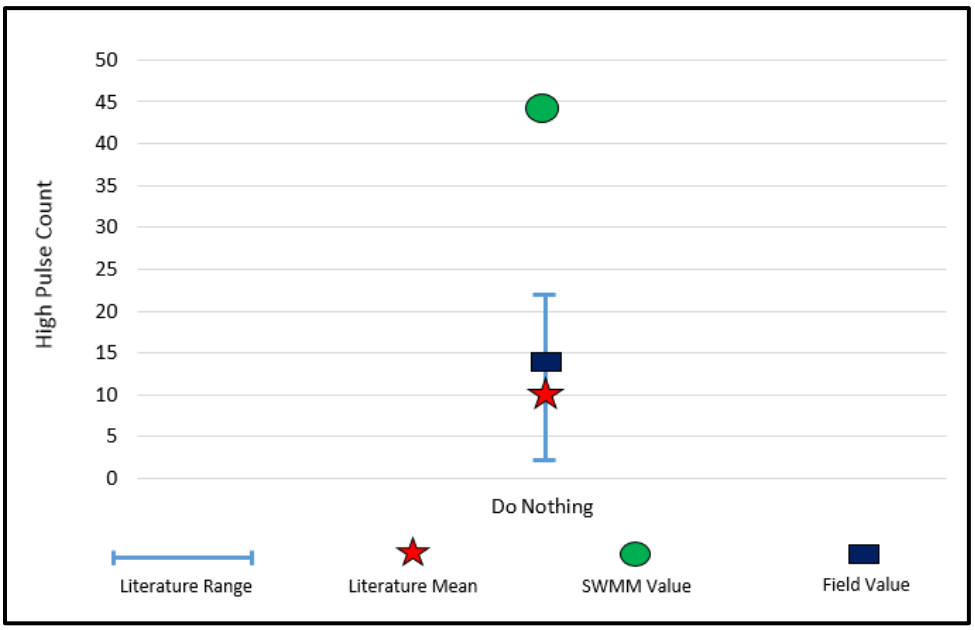

Figure 73: June 2015 – May 216 High Pulse Count Calculated for Current Conditions Using SWMM Output and Field Data

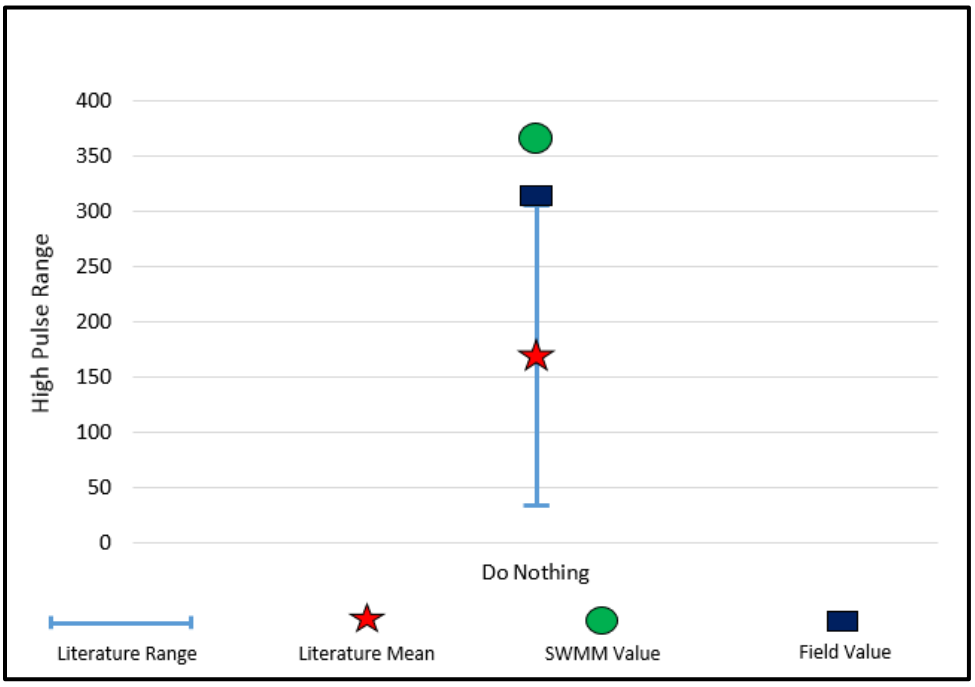

Figure 74: June 2015- May 2016 High Pulse Range Calculated for Current Conditions Using SWMM Output and Field Data

Table 42: Various Flow Metrics Calculated for June 2015- May 2016 Current Conditions Using SWMM Output and Field Data

Flow Metric	Values from Literature			Current Conditions		
	Minimum	Average	Maximum	SWMM Data	Field Data	Error
Hourly RB Flashiness Index	0.08	0.27	0.49	0.81	0.14	83%
High Pulse Count	2	10	22	44	14	68%
High Pulse Range	34	168	306	364	314	14%

Based on the values presented in Table 42, there is an unacceptable discrepancy between the flow metrics calculated using SWMM output data and the flow metrics calculated using field data. The discrepancy is particularly unreasonable considering that all of the storms used in the calibration and validation of this model occurred between June 2015 and May 2016.

III. Analysis of Flow Metrics

A. Insignificant Storage Capacity

As displayed by Figures 68-71, various metrics indicated that the Headwaters of the East Branch of Indian Creek's flow regime experienced no improvement in response to the rain garden implementation scenarios. One factor contributing to this lack of response is that the total amount of rainfall runoff removed from the system was insignificant relative to the total amount of rainfall runoff moving past the Headwaters Flow Meter. As depicted in Figure 75, for the 2005 evaluation, the private rain gardens only captured 2% of total runoff draining to the Headwaters Flow Meter, the public rain gardens only captured 3% of the total runoff, and the public and private rain gardens combined only captured 5% of the total runoff.

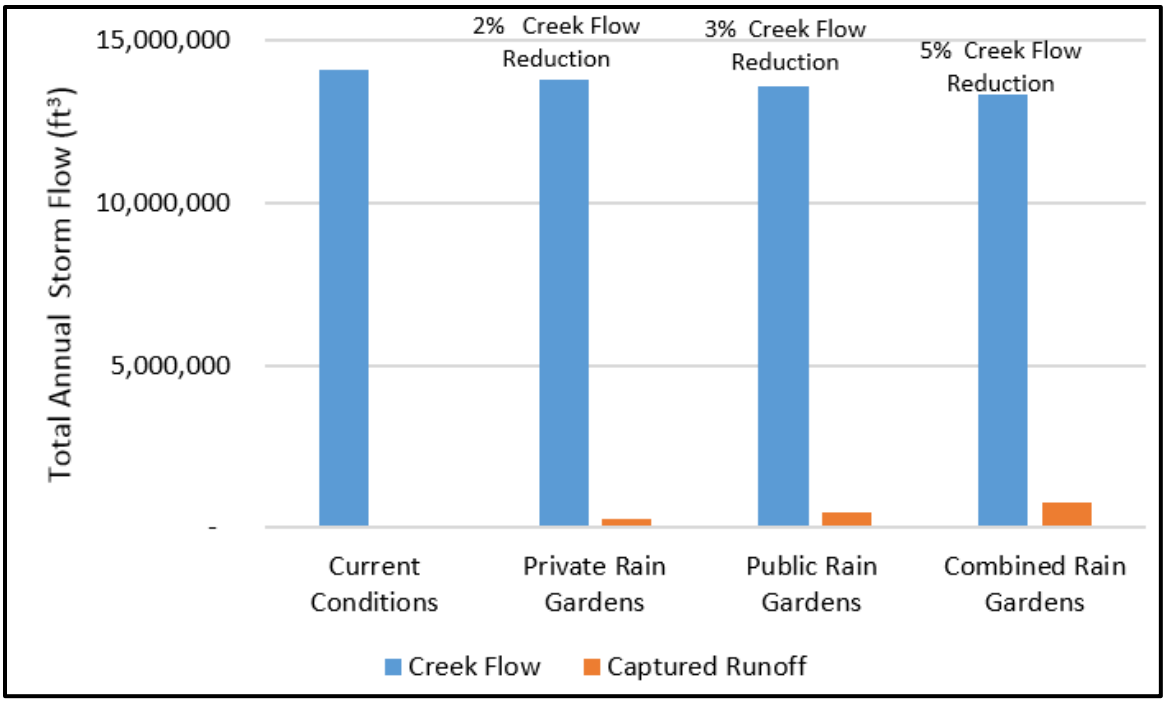

Figure 75: Total Annual Runoff Captured by Implemented Rain Gardens Relative to Total Annual Creek Flow

Putting the volume of water captured by the rain gardens into perspective, the 17 public and private rain gardens presented in this research represent about 53,000 ft^3 (1,500 m^3) of runoff storage. When accounting for subcatchments 1-3, there is a total of 250 acres (1.09e7 ft^2 or 1.01e6 m^2) draining to the Headwaters Flow Meter. Assuming that the total storage volume of the proposed rain gardens was distributed evenly over the entirety of the area draining to the Headwaters Flow Meter, the total storage volume of the rain gardens would be full after 0.06 inches of rainfall. This reinforces the idea that, when quantifying restoration success in terms of peak flow reduction, the identified rain garden opportunities in Narberth, PA represent an insignificant amount of volume reduction.

B. Oversimplifying the System

It is possible that, if the goal is to understand overall stream health, that the current modeling approach is oversimplifying the effect of rain gardens on the system. As discussed in *Chapter 1: Background and Literature Review*, there are three main ways in which urbanization disturbs flow regimes: increased volume of flow reaching the stream, decreased time for runoff in the watershed to reach the stream, and decreased groundwater recharge, which results in decreased base flows in the stream. Thus, the ideal approach to stream restoration would address all three of these disturbances.

The model created as part of this research only addresses one of the three disturbances: the volume of water reaching the creek. Currently, as discussed in *Chapter 2*: *Methods*, rain gardens are modeled in SWMM as storage units. As such, their only effect on the system is to reduce the volume of flow entering the creek during a storm event. This limited effect of rain garden implementation on creek flow, as simulated by SWMM, is depicted in Figure 76. Note that in the figure, "Combined Opportunities" represents the system after implementation of both private and public rain garden opportunities. In SWMM, the rain gardens do not have any effect on the speed at which the runoff reaches the creek during a rain event. In practice, rain gardens may have the potential to affect this speed if runoff is routed towards the rain gardens and away from away storm sewers. Additionally, the current SWMM setup does not take groundwater recharge into account. Thus, the current models do not consider the effects that rain garden implementation may have on base flow.

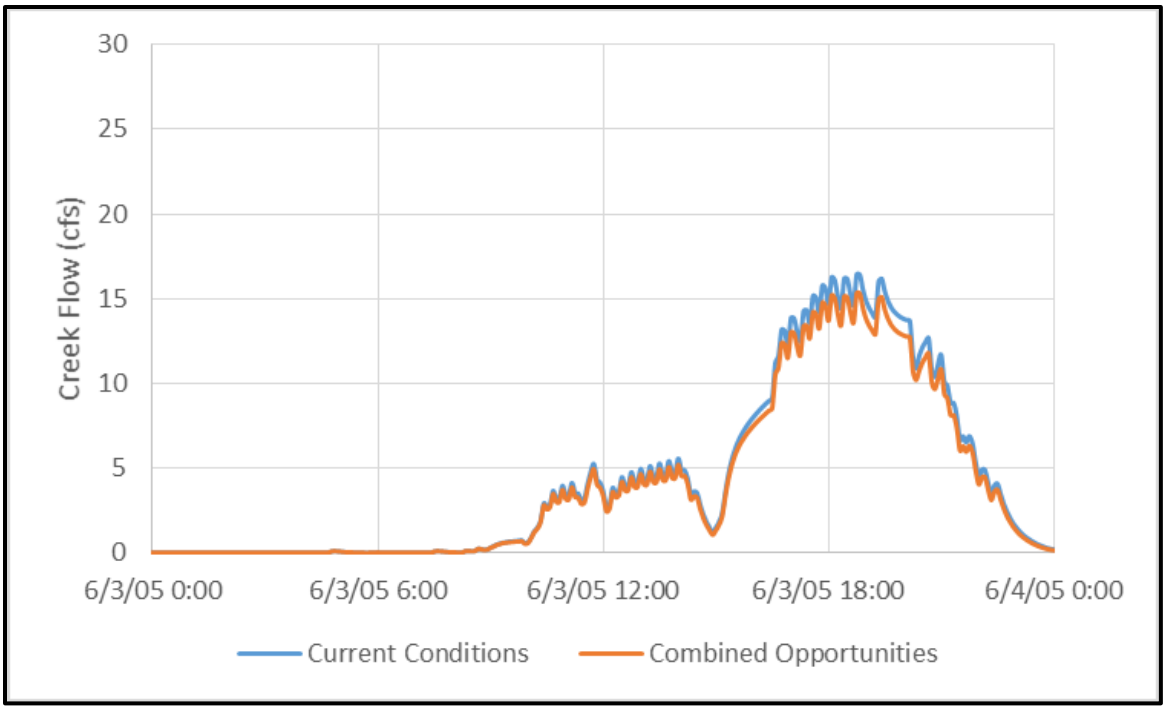

Figure 76: 6/3/2005 Reduced Creek Flow After Rain Garden Implementation

Based on the large discrepancy between the metrics calculated using SWMM output and the metrics calculated using field data collected between June 2015 and May 2016, it can be concluded that base flow in particular plays a significant role in the analysis of a flow regime. This conclusion can be drawn because the primary discrepancy between the two sets of flow data is that while the SWMM output assumed a base flow of zero, the field data assumed a positive base flow. The metrics calculated from the two sets of data, using the two different base flow assumptions, portray the creek very differently. The metrics calculated using field data portray the East Branch of Indian Creek as having a similar level of health to other streams with similar characteristics. The metrics calculated using SWMM output portray the East Branch of Indian Creek as being significantly less healthy than other streams with similar characteristics.

Taking a closer look at the R-B Index value, it is clear why base flow dramatically effects the final metric. Recall from *Chapter 2: Methods*, that the RB Flashiness Index was computed using the following equation:

$$R-B\ Index = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}$$

(Equation 1, Baker et al. 2004)

In the equation, q_i is hourly discharge volume. The index is equal to the sum, over one year, of the absolute value of hour-to-hour changes in hourly discharge volumes divided by the sum of the hourly discharge volumes for the year. During calibration, the volume of flow moving through the creek was scaled down to achieve an effective base flow of zero. As a result of this base flow simplification, the numerator for this index would remain relatively the same, as the hour-to-hour changes in discharge volumes throughout the year would remain relatively the same, regardless of which flow value is used as a baseline. However, the reduction in base flow would significantly affect the denominator of the above equation, which is the sum of hourly discharges for the year.

Given that this R-B Index and the High Pulse Metrics have been demonstrated to be biologically relevant metrics for small streams and that both metrics are significantly impacted by the inclusion of a non-zero base flow in a flow profile, it can be concluded that an accurate representation of base flow is necessary to fully understand the health of a flow regime.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

The ultimate goal of this research was to establish an increased understanding of how to restore the Headwaters of the East Branch of Indian Creek to the extent that there is a notable change in flow regime. This goal was approached in a two part process.

The first step of this research was to increase understanding of how an imperfect rain gauge influenced analysis of a particular flow regime. This research aimed to provide insight into the extent to which an imperfect rain gauge can alter the researcher's understanding of restoration success in terms of water quantity. Furthermore, this research aimed to assist restoration professionals who may not have access to an ideal rain gauge.

During the rain gauge evaluation process, it was realized that an imperfect rain gauge is not to be confused with a malfunctioning rain gauge. While the VUSP Villanova Rain Gauge and the WU Wynnewood Rain Gauge were both imperfect, the VUSP Narberth Rain Gauge was malfunctioning. While the VUSP Villanova Rain Gauge and the WU Wynnewood Rain Gauge were not ideal, due to spatial variability and instrument accuracy, respectively, but both were functional, and the limitations of each instrument were quantifiable. The VUSP Narberth Rain Gauge was ideal, as it was located directly on site, and was a high accuracy instrument on paper, but it was failing to record a significant number of data points. In practice, it is best to avoid using data from a malfunctioning instrument.

The malfunctioning VUSP Narberth Rain Gauge highlighted the importance of checking recorded data with independent sources and calibrating all installed instruments. When observing data from the VUSP Narberth Rain Gauge independently, the rain gauge appeared to be functioning successfully. This was because the patterns of the data collected by the VUSP Narberth Rain Gauge

aligned very well with the flow data collected by the Headwaters and Downstream Flow Meters. Furthermore, the ultimate inability for the author to utilize data from the VUSP Narberth Rain Gauge for a detailed analysis due to a long-term mechanical failure of the rain gauge emphasizes the importance of installing weather station instrumentation in a location that can be easily accessed for regular maintenance.

When comparing the SWMM output of the VUSP Villanova and the WU Wynnewood model variations, it was realized that the final results were similar enough that the author was unable to differentiate between which differences in the calibrated models could be attributed to rain gauge imperfections and which differences could be attributed to a varying calibration approach. The calibration approach used in this research relied heavily on judgement and did not follow a strict methodology. Therefore, after completing the calibration process, the author felt that it would be inappropriate to attribute all of the subtle differences between the model variations to the imperfect rain gauges. Ultimately, because the VUSP Villanova and the WU Wynnewood model variations produced such similar results, the VUSP Villanova Rain Gauge was chosen for use in final analysis, it is more reliable than the WU Wynnewood Rain Gauge Additionally, because the VUSP owns and maintains the Villanova rain gauge, the author is confident that it will be available for use in future research work.

After establishing an increased understanding of how the limitations of each rain gauge influenced SWMM, the second step of this research was to increase the understanding of the effectiveness of rain garden implementation as a form of stream restoration. Overall, it was concluded that the volume reduction resulting from the identified rain garden opportunities in Narberth Borough was insufficient to cause significant peak flow reduction in the Headwaters of the East Branch of Indian Creek. This is consistent with the Perez Pedini et al. (2005) study which concluded that it would

be nearly impossible to achieve a peak flow reduction in the watershed greater than 30% using infiltration base SCMs. Similarly this result supports the suggestion by Roy et al. (2014b) that retrofit stormwater management may be an inappropriate or incomplete solution to the problem of impaired streams.

Although it has been concluded that the impact of the selected rain gardens on the East Branch of Indian Creek is insignificant, the characterization of the current health of the creek remains unclear. When using various flow metrics to quantify the pre-restoration health of the East Branch of Indian Creek, it was determined that an accurate understanding of base flow is necessary to accurately analyze the health of the given flow regime. Thus, it was also concluded that, for the purposes of evaluating stream health, the decision to scale the flows in SWMM to achieve a base flow of zero oversimplified the flow regime.

For future work on the East Branch of Indian Creek, the first step may be to accurately quantify the current health of the stream. This will provide a baseline against which to compare future restoration efforts, whether hypothetical or actual. To accomplish this goal, it would be beneficial to install a flow meter that has the capacity to measure base flows in small creeks. This would allow for the establishment of a complete flow profile and allow for an accurate establishment of the current health of the stream.

Additionally, to evaluate the effectiveness of restoration approaches, both this research and past research have revealed that on a practical scale, SCM volume reduction alone is likely not enough to establish a measurable change in flow regime. Therefore, it is suggested that future research investigate additional benefits of SCM installation in a given watershed. For instance, work may be completed to investigate the effects of SCM installation on the speed at which runoff reaches

the creek, on groundwater recharge, or on public involvement and enthusiasm surrounding stream restoration. This may provide a more complete picture of SCM implementation affects a whole watershed system.

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APPENDIX I: WEB SOIL SURVEY REPORT

United States Department of Agriculture

NRCS

Natural Resources Conservation Service

A product of the National Cooperative Soil Survey, a joint effort of the United States Department of Agriculture and other Federal agencies, State agencies including the Agricultural Experiment Stations, and local participants

Custom Soil Resource Report for Montgomery County, Pennsylvania, and Philadelphia County, Pennsylvania

May 25, 2016

Preface

Soil surveys contain information that affects land use planning in survey areas. They highlight soil limitations that affect various land uses and provide information about the properties of the soils in the survey areas. Soil surveys are designed for many different users, including farmers, ranchers, foresters, agronomists, urban planners, community officials, engineers, developers, builders, and home buyers. Also, conservationists, teachers, students, and specialists in recreation, waste disposal, and pollution control can use the surveys to help them understand, protect, or enhance the environment.

Various land use regulations of Federal, State, and local governments may impose special restrictions on land use or land treatment. Soil surveys identify soil properties that are used in making various land use or land treatment decisions. The information is intended to help the land users identify and reduce the effects of soil limitations on various land uses. The landowner or user is responsible for identifying and complying with existing laws and regulations.

Although soil survey information can be used for general farm, local, and wider area planning, onsite investigation is needed to supplement this information in some cases. Examples include soil quality assessments (http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/) and certain conservation and engineering applications. For more detailed information, contact your local USDA Service Center (http://offices.sc.egov.usda.gov/locator/app?agency=nrcs) or your NRCS State Soil Scientist (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/contactus/?cid=nrcs142p2_053951).

Great differences in soil properties can occur within short distances. Some soils are seasonally wet or subject to flooding. Some are too unstable to be used as a foundation for buildings or roads. Clayey or wet soils are poorly suited to use as septic tank absorption fields. A high water table makes a soil poorly suited to basements or underground installations.

The National Cooperative Soil Survey is a joint effort of the United States Department of Agriculture and other Federal agencies, State agencies including the Agricultural Experiment Stations, and local agencies. The Natural Resources Conservation Service (NRCS) has leadership for the Federal part of the National Cooperative Soil Survey.

Information about soils is updated periodically. Updated information is available through the NRCS Web Soil Survey, the site for official soil survey information.

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How Soil Surveys Are Made

Soil surveys are made to provide information about the soils and miscellaneous areas in a specific area. They include a description of the soils and miscellaneous areas and their location on the landscape and tables that show soil properties and limitations affecting various uses. Soil scientists observed the steepness, length, and shape of the slopes; the general pattern of drainage; the kinds of crops and native plants; and the kinds of bedrock. They observed and described many soil profiles. A soil profile is the sequence of natural layers, or horizons, in a soil. The profile extends from the surface down into the unconsolidated material in which the soil formed or from the surface down to bedrock. The unconsolidated material is devoid of roots and other living organisms and has not been changed by other biological activity.

Currently, soils are mapped according to the boundaries of major land resource areas (MLRAs). MLRAs are geographically associated land resource units that share common characteristics related to physiography, geology, climate, water resources, soils, biological resources, and land uses (USDA, 2006). Soil survey areas typically consist of parts of one or more MLRA.

The soils and miscellaneous areas in a survey area occur in an orderly pattern that is related to the geology, landforms, relief, climate, and natural vegetation of the area. Each kind of soil and miscellaneous area is associated with a particular kind of landform or with a segment of the landform. By observing the soils and miscellaneous areas in the survey area and relating their position to specific segments of the landform, a soil scientist develops a concept, or model, of how they were formed. Thus, during mapping, this model enables the soil scientist to predict with a considerable degree of accuracy the kind of soil or miscellaneous area at a specific location on the landscape.

Commonly, individual soils on the landscape merge into one another as their characteristics gradually change. To construct an accurate soil map, however, soil scientists must determine the boundaries between the soils. They can observe only a limited number of soil profiles. Nevertheless, these observations, supplemented by an understanding of the soil-vegetation-landscape relationship, are sufficient to verify predictions of the kinds of soil in an area and to determine the boundaries.

Soil scientists recorded the characteristics of the soil profiles that they studied. They noted soil color, texture, size and shape of soil aggregates, kind and amount of rock fragments, distribution of plant roots, reaction, and other features that enable them to identify soils. After describing the soils in the survey area and determining their properties, the soil scientists assigned the soils to taxonomic classes (units). Taxonomic classes are concepts. Each taxonomic class has a set of soil characteristics with precisely defined limits. The classes are used as a basis for comparison to classify soils systematically. Soil taxonomy, the system of taxonomic classification used in the United States, is based mainly on the kind and character of soil properties and the arrangement of horizons within the profile. After the soil scientists classified and named the soils in the survey area, they compared the

individual soils with similar soils in the same taxonomic class in other areas so that they could confirm data and assemble additional data based on experience and research.

The objective of soil mapping is not to delineate pure map unit components; the objective is to separate the landscape into landforms or landform segments that have similar use and management requirements. Each map unit is defined by a unique combination of soil components and/or miscellaneous areas in predictable proportions. Some components may be highly contrasting to the other components of the map unit. The presence of minor components in a map unit in no way diminishes the usefulness or accuracy of the data. The delineation of such landforms and landform segments on the map provides sufficient information for the development of resource plans. If intensive use of small areas is planned, onsite investigation is needed to define and locate the soils and miscellaneous areas.

Soil scientists make many field observations in the process of producing a soil map. The frequency of observation is dependent upon several factors, including scale of mapping, intensity of mapping, design of map units, complexity of the landscape, and experience of the soil scientist. Observations are made to test and refine the soil-landscape model and predictions and to verify the classification of the soils at specific locations. Once the soil-landscape model is refined, a significantly smaller number of measurements of individual soil properties are made and recorded. These measurements may include field measurements, such as those for color, depth to bedrock, and texture, and laboratory measurements, such as those for content of sand, silt, clay, salt, and other components. Properties of each soil typically vary from one point to another across the landscape.

Observations for map unit components are aggregated to develop ranges of characteristics for the components. The aggregated values are presented. Direct measurements do not exist for every property presented for every map unit component. Values for some properties are estimated from combinations of other properties.

While a soil survey is in progress, samples of some of the soils in the area generally are collected for laboratory analyses and for engineering tests. Soil scientists interpret the data from these analyses and tests as well as the field-observed characteristics and the soil properties to determine the expected behavior of the soils under different uses. Interpretations for all of the soils are field tested through observation of the soils in different uses and under different levels of management. Some interpretations are modified to fit local conditions, and some new interpretations are developed to meet local needs. Data are assembled from other sources, such as research information, production records, and field experience of specialists. For example, data on crop yields under defined levels of management are assembled from farm records and from field or plot experiments on the same kinds of soil.

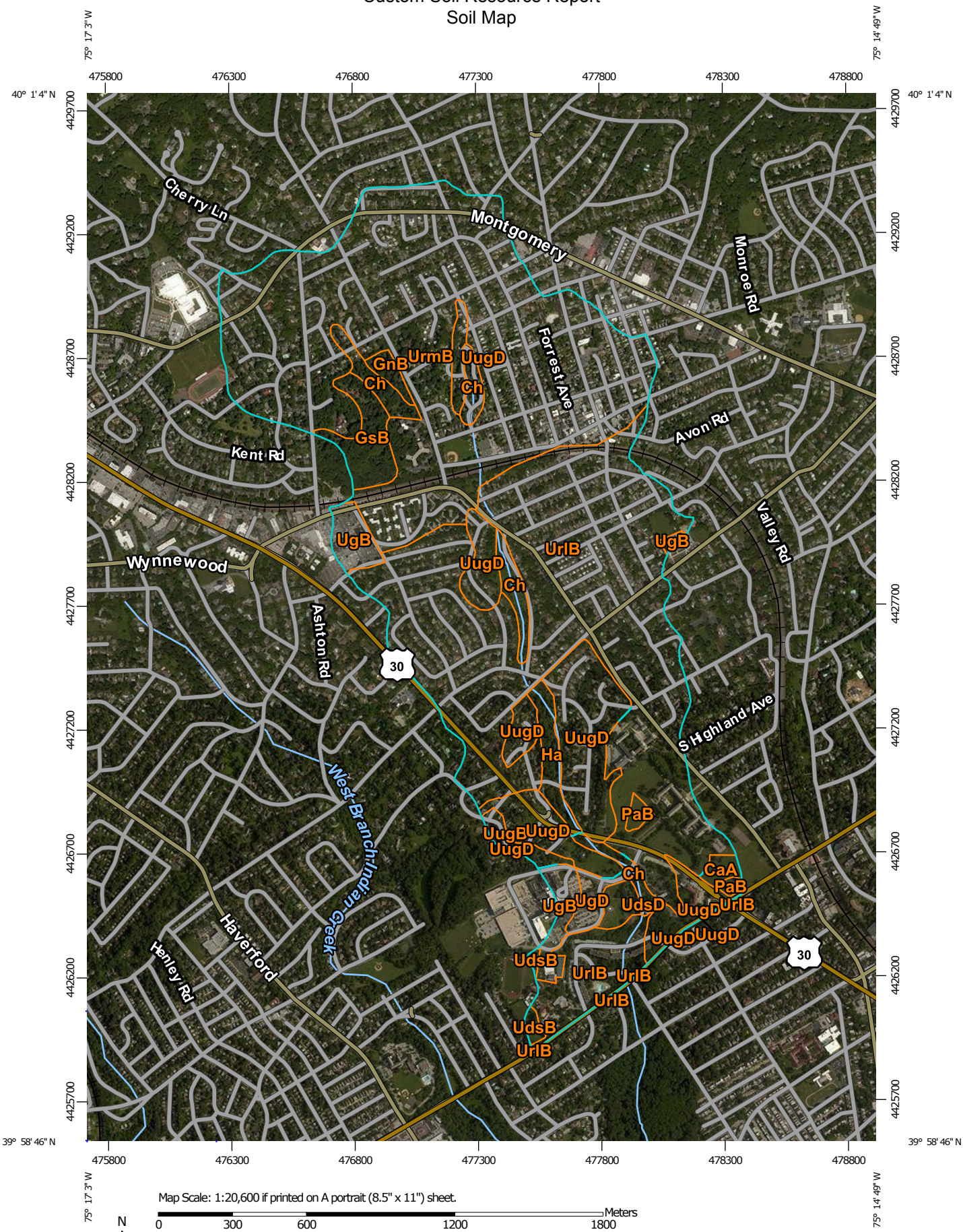
Predictions about soil behavior are based not only on soil properties but also on such variables as climate and biological activity. Soil conditions are predictable over long periods of time, but they are not predictable from year to year. For example, soil scientists can predict with a fairly high degree of accuracy that a given soil will have a high water table within certain depths in most years, but they cannot predict that a high water table will always be at a specific level in the soil on a specific date.

After soil scientists located and identified the significant natural bodies of soil in the survey area, they drew the boundaries of these bodies on aerial photographs and identified each as a specific map unit. Aerial photographs show trees, buildings, fields, roads, and rivers, all of which help in locating boundaries accurately.

Soil Map

The soil map section includes the soil map for the defined area of interest, a list of soil map units on the map and extent of each map unit, and cartographic symbols displayed on the map. Also presented are various metadata about data used to produce the map, and a description of each soil map unit.

Custom Soil Resource Report
Soil Map



MAP LEGEND

Area of Interest (AOI)
- Area of Interest (AOI)

Soils
- Soil Map Unit Polygons
- Soil Map Unit Lines
- Soil Map Unit Points

Special Point Features
- Blowout
- Borrow Pit
- Clay Spot
- Closed Depression
- Gravel Pit
- Gravelly Spot
- Landfill
- Lava Flow
- Marsh or swamp
- Mine or Quarry
- Miscellaneous Water
- Perennial Water
- Rock Outcrop
- Saline Spot
- Sandy Spot
- Severely Eroded Spot
- Sinkhole
- Slide or Slip
- Sodic Spot
- Spoil Area
- Stony Spot
- Very Stony Spot
- Wet Spot
- Other
- Special Line Features

Water Features
- Streams and Canals

Transportation
- Rails
- Interstate Highways
- US Routes
- Major Roads
- Local Roads

Background
- Aerial Photography

MAP INFORMATION

The soil surveys that comprise your AOI were mapped at scales ranging from 1:12,000 to 1:15,800.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Montgomery County, Pennsylvania
Survey Area Data: Version 9, Nov 16, 2015

Soil Survey Area: Philadelphia County, Pennsylvania
Survey Area Data: Version 8, Nov 16, 2015

Your area of interest (AOI) includes more than one soil survey area. These survey areas may have been mapped at different scales, with a different land use in mind, at different times, or at different levels of detail. This may result in map unit symbols, soil properties, and interpretations that do not completely agree across soil survey area boundaries.

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Jun 15, 2014—Jun 24, 2014

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

Map Unit Legend

Montgomery County, Pennsylvania (PA091)			
Map Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI**
CaA	Califon loam, 0 to 3 percent slopes	3.6	0.4%
Ch	Codorus silt loam	26.1	2.9%
GnB	Glenelg silt loam, 3 to 8 percent slopes	3.9	0.4%
GsB	Glenville silt loam, 3 to 8 percent slopes	17.3	1.9%
Ha	Hatboro silt loam	10.9	1.2%
PaB	Parker gravelly loam, 3 to 8 percent slopes	3.6	0.4%
UdsB	Udorthents, schist and gneiss, 0 to 8 percent slopes	2.6	0.3%
UdsD	Udorthents, schist and gneiss, 8 to 25 percent slopes	5.9	0.7%
UgB	Urban land, 0 to 8 percent slopes	22.1	2.5%
UgD	Urban land, 8 to 25 percent slopes	7.0	0.8%
UrlB	Urban land-Gladstone complex, 0 to 8 percent slopes	339.2	38.3%
UrmB	Urban land-Glenelg complex, 0 to 8 percent slopes	342.1	38.6%
UugB	Urban land-Udorthents, schist and gneiss complex, 0 to 8 percent slopes	5.8	0.7%
UugD	Urban land-Udorthents, schist and gneiss complex, 8 to 25 percent slopes	95.8	10.8%
Subtotals for Soil Survey Area		**885.9**	**100.0%**
Totals for Area of Interest		**886.0**	**100.0%**

Philadelphia County, Pennsylvania (PA101)			
Map Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI**
UrlB	Urban land-Gladstone complex, 0 to 8 percent slopes	0.0	0.0%
UugD	Urban land-Udorthents, schist and gneiss complex, 8 to 25 percent slopes	0.0	0.0%
Subtotals for Soil Survey Area		**0.0**	**0.0%**
Totals for Area of Interest		**886.0**	**100.0%**

Map Unit Descriptions

The map units delineated on the detailed soil maps in a soil survey represent the soils or miscellaneous areas in the survey area. The map unit descriptions, along with the maps, can be used to determine the composition and properties of a unit.

A map unit delineation on a soil map represents an area dominated by one or more major kinds of soil or miscellaneous areas. A map unit is identified and named according to the taxonomic classification of the dominant soils. Within a taxonomic class there are precisely defined limits for the properties of the soils. On the landscape, however, the soils are natural phenomena, and they have the characteristic variability of all natural phenomena. Thus, the range of some observed properties may extend beyond the limits defined for a taxonomic class. Areas of soils of a single taxonomic class rarely, if ever, can be mapped without including areas of other taxonomic classes. Consequently, every map unit is made up of the soils or miscellaneous areas for which it is named and some minor components that belong to taxonomic classes other than those of the major soils.

Most minor soils have properties similar to those of the dominant soil or soils in the map unit, and thus they do not affect use and management. These are called noncontrasting, or similar, components. They may or may not be mentioned in a particular map unit description. Other minor components, however, have properties and behavioral characteristics divergent enough to affect use or to require different management. These are called contrasting, or dissimilar, components. They generally are in small areas and could not be mapped separately because of the scale used. Some small areas of strongly contrasting soils or miscellaneous areas are identified by a special symbol on the maps. If included in the database for a given area, the contrasting minor components are identified in the map unit descriptions along with some characteristics of each. A few areas of minor components may not have been observed, and consequently they are not mentioned in the descriptions, especially where the pattern was so complex that it was impractical to make enough observations to identify all the soils and miscellaneous areas on the landscape.

The presence of minor components in a map unit in no way diminishes the usefulness or accuracy of the data. The objective of mapping is not to delineate pure taxonomic classes but rather to separate the landscape into landforms or landform segments that have similar use and management requirements. The delineation of such segments on the map provides sufficient information for the development of resource plans. If intensive use of small areas is planned, however, onsite investigation is needed to define and locate the soils and miscellaneous areas.

An identifying symbol precedes the map unit name in the map unit descriptions. Each description includes general facts about the unit and gives important soil properties and qualities.

Soils that have profiles that are almost alike make up a *soil series*. Except for differences in texture of the surface layer, all the soils of a series have major horizons that are similar in composition, thickness, and arrangement.

Soils of one series can differ in texture of the surface layer, slope, stoniness, salinity, degree of erosion, and other characteristics that affect their use. On the basis of such differences, a soil series is divided into *soil phases*. Most of the areas shown on the detailed soil maps are phases of soil series. The name of a soil phase commonly

indicates a feature that affects use or management. For example, Alpha silt loam, 0 to 2 percent slopes, is a phase of the Alpha series.

Some map units are made up of two or more major soils or miscellaneous areas. These map units are complexes, associations, or undifferentiated groups.

A *complex* consists of two or more soils or miscellaneous areas in such an intricate pattern or in such small areas that they cannot be shown separately on the maps. The pattern and proportion of the soils or miscellaneous areas are somewhat similar in all areas. Alpha-Beta complex, 0 to 6 percent slopes, is an example.

An *association* is made up of two or more geographically associated soils or miscellaneous areas that are shown as one unit on the maps. Because of present or anticipated uses of the map units in the survey area, it was not considered practical or necessary to map the soils or miscellaneous areas separately. The pattern and relative proportion of the soils or miscellaneous areas are somewhat similar. Alpha-Beta association, 0 to 2 percent slopes, is an example.

An *undifferentiated group* is made up of two or more soils or miscellaneous areas that could be mapped individually but are mapped as one unit because similar interpretations can be made for use and management. The pattern and proportion of the soils or miscellaneous areas in a mapped area are not uniform. An area can be made up of only one of the major soils or miscellaneous areas, or it can be made up of all of them. Alpha and Beta soils, 0 to 2 percent slopes, is an example.

Some surveys include *miscellaneous areas*. Such areas have little or no soil material and support little or no vegetation. Rock outcrop is an example.

Montgomery County, Pennsylvania

CaA—Califon loam, 0 to 3 percent slopes

Map Unit Setting

National map unit symbol: 2lfcw
Elevation: 10 to 2,000 feet
Mean annual precipitation: 30 to 50 inches
Mean annual air temperature: 45 to 55 degrees F
Frost-free period: 120 to 220 days
Farmland classification: All areas are prime farmland

Map Unit Composition

Califon and similar soils: 90 percent
Minor components: 10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Califon

Setting

Landform: Hills
Landform position (two-dimensional): Backslope, footslope
Landform position (three-dimensional): Head slope
Down-slope shape: Concave, linear
Across-slope shape: Linear, concave
Parent material: Colluvium derived from granite and gneiss

Typical profile

Ap - 0 to 9 inches: loam
Bt - 9 to 23 inches: clay loam
Bx - 23 to 38 inches: sandy loam
Cx - 38 to 57 inches: sandy loam
2C - 57 to 60 inches: sandy loam

Properties and qualities

Slope: 0 to 3 percent
Depth to restrictive feature: 20 to 30 inches to fragipan; 72 to 99 inches to lithic bedrock
Natural drainage class: Moderately well drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: About 6 to 36 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 4.4 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2w
Hydrologic Soil Group: D

Minor Components

Holly

Percent of map unit: 4 percent

Landform: Flood plains
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave
Across-slope shape: Concave

Fluvaquents

Percent of map unit: 3 percent
Landform: Flood plains
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave
Across-slope shape: Concave

Baile

Percent of map unit: 3 percent
Landform: Depressions
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave, linear
Across-slope shape: Linear, concave

Ch—Codorus silt loam

Map Unit Setting

National map unit symbol: l53x
Elevation: 200 to 2,000 feet
Mean annual precipitation: 35 to 50 inches
Mean annual air temperature: 45 to 57 degrees F
Frost-free period: 120 to 220 days
Farmland classification: All areas are prime farmland

Map Unit Composition

Codorus and similar soils: 85 percent
Minor components: 15 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Codorus

Setting

Landform: Flood plains
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Tread
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Alluvium derived from gneiss and/or alluvium derived from mica schist

Typical profile

Ap - 0 to 12 inches: silt loam
Bw - 12 to 48 inches: silt loam

C - 48 to 60 inches: silt loam

Properties and qualities

Slope: 0 to 3 percent
Depth to restrictive feature: 72 to 99 inches to lithic bedrock
Natural drainage class: Moderately well drained
Runoff class: Low
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.60 to 2.00 in/hr)
Depth to water table: About 18 to 36 inches
Frequency of flooding: Occasional
Frequency of ponding: None
Available water storage in profile: Moderate (about 8.5 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2w
Hydrologic Soil Group: C

Minor Components

Hatboro

Percent of map unit: 8 percent
Landform: Flood plains
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Tread
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear

Glenville

Percent of map unit: 4 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

Baile

Percent of map unit: 3 percent
Landform: Depressions
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

GnB—Glenelg silt loam, 3 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2v7gr
Elevation: 30 to 1,200 feet
Mean annual precipitation: 40 to 55 inches

Mean annual air temperature: 48 to 57 degrees F
Frost-free period: 150 to 192 days
Farmland classification: All areas are prime farmland

Map Unit Composition

Glenelg and similar soils: 85 percent
Minor components: 15 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Glenelg

Setting

Landform: Interfluves, hillslopes
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope
Down-slope shape: Linear
Across-slope shape: Linear, concave, convex
Parent material: Residuum weathered from mica schist

Typical profile

Ap - 0 to 8 inches: silt loam
Bt1 - 8 to 18 inches: clay loam
Bt2 - 18 to 30 inches: clay loam
BCt - 30 to 42 inches: loam
CBt - 42 to 54 inches: loam
C - 54 to 76 inches: channery fine sandy loam

Properties and qualities

Slope: 3 to 8 percent
Depth to restrictive feature: More than 80 inches
Natural drainage class: Well drained
Runoff class: Medium
Capacity of the most limiting layer to transmit water (Ksat): Moderately high (0.20 to 0.57 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: High (about 10.4 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2e
Hydrologic Soil Group: C

Minor Components

Gaila

Percent of map unit: 10 percent
Landform: Ridges, hillslopes
Landform position (two-dimensional): Backslope, shoulder
Landform position (three-dimensional): Side slope
Down-slope shape: Convex
Across-slope shape: Linear

Glenville

Percent of map unit: 5 percent
Landform: Swales, drainageways

Landform position (two-dimensional): Shoulder, backslope
Landform position (three-dimensional): Side slope
Down-slope shape: Concave
Across-slope shape: Linear

GsB—Glenville silt loam, 3 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2tmch
Elevation: 20 to 1,090 feet
Mean annual precipitation: 40 to 55 inches
Mean annual air temperature: 48 to 57 degrees F
Frost-free period: 150 to 192 days
Farmland classification: All areas are prime farmland

Map Unit Composition

Glenville and similar soils: 75 percent
Minor components: 25 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Glenville

Setting

Landform: Swales, drainageways
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Head slope, base slope, interfluve
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear
Parent material: Colluvium derived from metamorphic rock over schist, gneiss or phyllite residuum

Typical profile

Ap - 0 to 11 inches: silt loam
Bt1 - 11 to 20 inches: channery silt loam
Bt2 - 20 to 30 inches: silt loam
Btx - 30 to 40 inches: silt loam
C1 - 40 to 59 inches: loam
C2 - 59 to 82 inches: loam

Properties and qualities

Slope: 3 to 8 percent
Depth to restrictive feature: 29 to 31 inches to fragipan
Natural drainage class: Moderately well drained
Runoff class: Medium
Capacity of the most limiting layer to transmit water (Ksat): Moderately low (0.03 to 0.11 in/hr)
Depth to water table: About 18 to 22 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 5.1 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2e
Hydrologic Soil Group: C/D

Minor Components

Unnamed

Percent of map unit: 15 percent
Landform: Drainageways
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

Baile

Percent of map unit: 10 percent
Landform: Swales, drainageways
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave, linear
Across-slope shape: Linear, concave

Ha—Hatboro silt loam

Map Unit Setting

National map unit symbol: l54h
Elevation: 200 to 800 feet
Mean annual precipitation: 36 to 50 inches
Mean annual air temperature: 48 to 57 degrees F
Frost-free period: 140 to 200 days
Farmland classification: Not prime farmland

Map Unit Composition

Hatboro and similar soils: 95 percent
Minor components: 5 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Hatboro

Setting

Landform: Flood plains
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Tread
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear
Parent material: Alluvium derived from metamorphic and sedimentary rock

Typical profile

Ap - 0 to 9 inches: silt loam

Bg - 9 to 44 inches: silt loam
Cg - 44 to 56 inches: sandy clay loam
C - 56 to 70 inches: stratified gravelly sand to clay

Properties and qualities

Slope: 0 to 3 percent
Depth to restrictive feature: 60 to 99 inches to lithic bedrock
Natural drainage class: Poorly drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.60 to 2.00 in/hr)
Depth to water table: About 0 to 6 inches
Frequency of flooding: Frequent
Frequency of ponding: None
Available water storage in profile: High (about 9.7 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 4w
Hydrologic Soil Group: B/D

Minor Components

Glenville

Percent of map unit: 5 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

PaB—Parker gravelly loam, 3 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2lh8l
Elevation: 250 to 1,200 feet
Mean annual precipitation: 40 to 48 inches
Mean annual air temperature: 45 to 55 degrees F
Frost-free period: 150 to 190 days
Farmland classification: All areas are prime farmland

Map Unit Composition

Parker and similar soils: 96 percent
Minor components: 4 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Parker

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope

Landform position (three-dimensional): Nose slope, interfluve
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Residuum weathered from granite and gneiss

Typical profile

Ap - 0 to 8 inches: gravelly loam
Bw - 8 to 23 inches: very gravelly sandy loam
C - 23 to 72 inches: very gravelly sandy loam
R - 72 to 157 inches: bedrock

Properties and qualities

Slope: 3 to 8 percent
Depth to restrictive feature: 60 to 118 inches to lithic bedrock
Natural drainage class: Somewhat excessively drained
Runoff class: Low
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.20 to 6.00 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 4.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2e
Hydrologic Soil Group: A

Minor Components

Gladstone

Percent of map unit: 4 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex
Across-slope shape: Linear, convex

UdsB—Udorthents, schist and gneiss, 0 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2dtyl
Elevation: 200 to 2,000 feet
Mean annual precipitation: 35 to 55 inches
Mean annual air temperature: 45 to 61 degrees F
Frost-free period: 110 to 235 days
Farmland classification: Not prime farmland

Map Unit Composition

Udorthents, schist and gneiss, and similar soils: 95 percent
Minor components: 5 percent

Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Udorthents, Schist And Gneiss

Setting

Landform: Ridges
Landform position (two-dimensional): Backslope, shoulder, summit
Landform position (three-dimensional): Side slope, nose slope, interfluve
Down-slope shape: Convex, linear
Across-slope shape: Convex, linear
Parent material: Graded areas of schist and/or gneiss

Typical profile

A - 0 to 3 inches: silt loam
C - 3 to 40 inches: gravelly silt loam
2C - 40 to 60 inches: gravelly silt loam

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 40 to 72 inches to paralithic bedrock
Natural drainage class: Well drained
Runoff class: Medium
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: About 60 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: High (about 10.1 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7s
Hydrologic Soil Group: C

Minor Components

Glenville

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

Hatboro

Percent of map unit: 1 percent
Landform: Flood plains
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Tread
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear

Gladstone

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex

Across-slope shape: Linear, convex

Glenelg

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear

Edgemont

Percent of map unit: 1 percent
Landform: Ridges
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Mountaintop
Down-slope shape: Convex, linear
Across-slope shape: Linear, convex

UdsD—Udorthents, schist and gneiss, 8 to 25 percent slopes

Map Unit Setting

National map unit symbol: 2dtym
Elevation: 200 to 2,000 feet
Mean annual precipitation: 35 to 55 inches
Mean annual air temperature: 45 to 61 degrees F
Frost-free period: 110 to 235 days
Farmland classification: Not prime farmland

Map Unit Composition

Udorthents, schist and gneiss, and similar soils: 95 percent
Minor components: 5 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Udorthents, Schist And Gneiss

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Graded areas of schist and/or gneiss

Typical profile

Ap - 0 to 6 inches: silt loam
C - 6 to 60 inches: clay loam
R - 60 to 63 inches: bedrock

Properties and qualities

Slope: 8 to 25 percent
Depth to restrictive feature: 40 to 70 inches to paralithic bedrock

Natural drainage class: Well drained
Runoff class: High
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: About 60 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: High (about 10.1 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e
Hydrologic Soil Group: C

Minor Components

Gladstone

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex
Across-slope shape: Linear, convex

Hatboro

Percent of map unit: 1 percent
Landform: Flood plains
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Tread
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear

Edgemont

Percent of map unit: 1 percent
Landform: Ridges
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Mountaintop
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear

Glenelg

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear

Glenville

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

UgB—Urban land, 0 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2dtyq
Elevation: 800 to 1,500 feet
Mean annual precipitation: 36 to 46 inches
Mean annual air temperature: 41 to 62 degrees F
Frost-free period: 130 to 170 days
Farmland classification: Not prime farmland

Map Unit Composition

Urban land: 90 percent
Minor components: 10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting

Parent material: Pavement, buildings and other artifically covered areas human transported material

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Minor Components

Udorthents, unstable fill

Percent of map unit: 10 percent
Down-slope shape: Linear
Across-slope shape: Linear

UgD—Urban land, 8 to 25 percent slopes

Map Unit Setting

National map unit symbol: 2dtyr
Elevation: 800 to 1,500 feet
Mean annual precipitation: 36 to 46 inches
Mean annual air temperature: 41 to 62 degrees F
Frost-free period: 130 to 180 days
Farmland classification: Not prime farmland

Map Unit Composition

Urban land: 90 percent

Minor components: 10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting
Parent material: Pavement, buildings and other artifically covered areas human transported material

Interpretive groups
Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Minor Components

Udorthents, unstable fill
Percent of map unit: 10 percent
Down-slope shape: Linear
Across-slope shape: Linear

UrlB—Urban land-Gladstone complex, 0 to 8 percent slopes

Map Unit Setting
National map unit symbol: 2l3fs
Elevation: 200 to 1,200 feet
Mean annual precipitation: 36 to 48 inches
Mean annual air temperature: 44 to 57 degrees F
Frost-free period: 130 to 190 days
Farmland classification: Not prime farmland

Map Unit Composition
Urban land: 65 percent
Gladstone and similar soils: 25 percent
Minor components: 10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting
Landform: Hills
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Pavement, buildings and other artifically covered areas

Typical profile
C - 0 to 6 inches: variable

Properties and qualities
Slope: 0 to 8 percent
Depth to restrictive feature: 10 to 100 inches to lithic bedrock
Available water storage in profile: Very low (about 0.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Description of Gladstone

Setting

Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex
Across-slope shape: Linear, convex
Parent material: Local colluvium and residuum weathered from granite and gneiss

Typical profile

A - 0 to 10 inches: gravelly loam
C - 10 to 42 inches: gravelly clay loam
2Ap - 42 to 68 inches: gravelly loam
R - 68 to 78 inches: bedrock

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 60 to 100 inches to lithic bedrock
Natural drainage class: Well drained
Runoff class: Very low
Capacity of the most limiting layer to transmit water (Ksat): Very low to high (0.00 to 6.00 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 6.9 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2e
Hydrologic Soil Group: A

Minor Components

Califon

Percent of map unit: 5 percent
Landform: Hills
Landform position (two-dimensional): Backslope, footslope
Landform position (three-dimensional): Head slope
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear

Cokesbury

Percent of map unit: 5 percent
Landform: Depressions
Landform position (two-dimensional): Toeslope, footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave
Across-slope shape: Concave

UrmB—Urban land-Glenelg complex, 0 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2dtyz
Elevation: 200 to 2,000 feet
Mean annual precipitation: 40 to 55 inches
Mean annual air temperature: 45 to 61 degrees F
Frost-free period: 110 to 235 days
Farmland classification: Not prime farmland

Map Unit Composition

Urban land: 65 percent
Glenelg and similar soils: 30 percent
Minor components: 5 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Pavement, buildings and other artifically covered areas

Typical profile

C - 0 to 6 inches: variable

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 10 to 99 inches to lithic bedrock
Available water storage in profile: Very low (about 0.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Description of Glenelg

Setting

Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Residuum weathered from mica schist

Typical profile

A - 0 to 8 inches: channery silt loam

Bt - 8 to 26 inches: channery silt loam
C - 26 to 60 inches: channery loam

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 60 to 120 inches to paralithic bedrock
Natural drainage class: Well drained
Runoff class: Low
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.60 to 2.00 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: High (about 9.4 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2e
Hydrologic Soil Group: B

Minor Components

Glenville

Percent of map unit: 5 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

UugB—Urban land-Udorthents, schist and gneiss complex, 0 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2dtz7
Elevation: 200 to 2,000 feet
Mean annual precipitation: 35 to 55 inches
Mean annual air temperature: 45 to 61 degrees F
Frost-free period: 110 to 235 days
Farmland classification: Not prime farmland

Map Unit Composition

Urban land: 80 percent
Udorthents, schist and gneiss, and similar soils: 15 percent
Minor components: 5 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Pavement, buildings and other artifically covered areas

Typical profile

C - 0 to 6 inches: variable

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 10 to 99 inches to lithic bedrock
Available water storage in profile: Very low (about 0.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Description of Udorthents, Schist And Gneiss

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Graded areas of schist and/or gneiss

Typical profile

Ap - 0 to 6 inches: loam
C - 6 to 40 inches: silty clay loam
R - 40 to 60 inches: bedrock

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 20 to 70 inches to paralithic bedrock
Natural drainage class: Well drained
Runoff class: Medium
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: About 60 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 6.8 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7s
Hydrologic Soil Group: C

Minor Components

Glenelg

Percent of map unit: 1 percent

Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear

Glenville

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

Gladstone

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex
Across-slope shape: Linear, convex

Edgemont

Percent of map unit: 1 percent
Landform: Ridges
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Mountaintop
Down-slope shape: Convex, linear
Across-slope shape: Linear, convex

Baile

Percent of map unit: 1 percent
Landform: Depressions
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

UugD—Urban land-Udorthents, schist and gneiss complex, 8 to 25 percent slopes

Map Unit Setting

National map unit symbol: 2dtz8
Elevation: 200 to 2,000 feet
Mean annual precipitation: 35 to 55 inches
Mean annual air temperature: 45 to 61 degrees F
Frost-free period: 110 to 235 days
Farmland classification: Not prime farmland

Map Unit Composition

Urban land: 80 percent
Udorthents, schist and gneiss, and similar soils: 15 percent
Minor components: 5 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Pavement, buildings and other artifically covered areas

Typical profile

C - 0 to 6 inches: variable

Properties and qualities

Slope: 8 to 25 percent
Depth to restrictive feature: 10 to 99 inches to lithic bedrock
Available water storage in profile: Very low (about 0.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Description of Udorthents, Schist And Gneiss

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Graded areas of schist and/or gneiss

Typical profile

Ap - 0 to 6 inches: loam
C - 6 to 40 inches: silty clay loam
R - 40 to 60 inches: bedrock

Properties and qualities

Slope: 8 to 25 percent
Depth to restrictive feature: 20 to 70 inches to paralithic bedrock
Natural drainage class: Well drained
Runoff class: High
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: About 60 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 6.8 inches)

Interpretive groups

Land capability classification (irrigated): None specified

Land capability classification (nonirrigated): 7e
Hydrologic Soil Group: C

Minor Components

Glenville
Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

Baile
Percent of map unit: 1 percent
Landform: Depressions
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear

Gladstone
Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex
Across-slope shape: Linear, convex

Glenelg
Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear

Edgemont
Percent of map unit: 1 percent
Landform: Ridges
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Mountaintop
Down-slope shape: Convex, linear
Across-slope shape: Linear, convex

Philadelphia County, Pennsylvania

UrlB—Urban land-Gladstone complex, 0 to 8 percent slopes

Map Unit Setting

National map unit symbol: 2lfgh
Elevation: 200 to 1,200 feet
Mean annual precipitation: 36 to 48 inches
Mean annual air temperature: 44 to 57 degrees F
Frost-free period: 130 to 190 days
Farmland classification: Not prime farmland

Map Unit Composition

Urban land: 65 percent
Gladstone and similar soils: 25 percent
Minor components: 10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting

Landform: Hills
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Pavement, buildings and other artifically covered areas

Typical profile

C - 0 to 6 inches: variable

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 10 to 100 inches to lithic bedrock
Available water storage in profile: Very low (about 0.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Description of Gladstone

Setting

Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex
Across-slope shape: Linear, convex
Parent material: Local colluvium and residuum weathered from granite and gneiss

Typical profile

A - 0 to 10 inches: gravelly loam
C - 10 to 42 inches: gravelly clay loam
2Ap - 42 to 68 inches: gravelly loam
R - 68 to 78 inches: bedrock

Properties and qualities

Slope: 0 to 8 percent
Depth to restrictive feature: 60 to 100 inches to lithic bedrock

Natural drainage class: Well drained
Runoff class: Very low
Capacity of the most limiting layer to transmit water (Ksat): Very low to high (0.00 to 6.00 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 6.9 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 2e
Hydrologic Soil Group: A

Minor Components

Cokesbury

Percent of map unit: 5 percent
Landform: Depressions
Landform position (two-dimensional): Toeslope, footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave
Across-slope shape: Concave

Califon

Percent of map unit: 5 percent
Landform: Hills
Landform position (two-dimensional): Backslope, footslope
Landform position (three-dimensional): Head slope
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear

UugD—Urban land-Udorthents, schist and gneiss complex, 8 to 25 percent slopes

Map Unit Setting

National map unit symbol: 2lfgn
Elevation: 200 to 2,000 feet
Mean annual precipitation: 35 to 55 inches
Mean annual air temperature: 45 to 61 degrees F
Frost-free period: 110 to 235 days
Farmland classification: Not prime farmland

Map Unit Composition

Urban land: 80 percent
Udorthents, schist and gneiss, and similar soils: 15 percent
Minor components: 5 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Urban Land

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Pavement, buildings and other artifically covered areas

Typical profile

C - 0 to 6 inches: variable

Properties and qualities

Slope: 8 to 25 percent
Depth to restrictive feature: 10 to 99 inches to lithic bedrock
Available water storage in profile: Very low (about 0.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8s

Description of Udorthents, Schist And Gneiss

Setting

Landform: Hills
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear
Parent material: Graded areas of schist and/or gneiss

Typical profile

Ap - 0 to 6 inches: loam
C - 6 to 40 inches: silty clay loam
R - 40 to 60 inches: bedrock

Properties and qualities

Slope: 8 to 25 percent
Depth to restrictive feature: 20 to 70 inches to paralithic bedrock
Natural drainage class: Well drained
Runoff class: High
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: About 60 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 6.8 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e
Hydrologic Soil Group: C

Minor Components

Baile

Percent of map unit: 1 percent

Landform: Depressions
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Base slope
Down-slope shape: Concave, linear
Across-slope shape: Concave, linear

Glenville

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Footslope, backslope
Landform position (three-dimensional): Side slope, head slope
Down-slope shape: Linear, concave
Across-slope shape: Concave, linear

Glenelg

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder, backslope
Landform position (three-dimensional): Interfluve, side slope, nose slope
Down-slope shape: Linear, convex
Across-slope shape: Convex, linear

Gladstone

Percent of map unit: 1 percent
Landform: Hillslopes
Landform position (two-dimensional): Summit, shoulder
Landform position (three-dimensional): Nose slope, side slope
Down-slope shape: Linear, convex
Across-slope shape: Linear, convex

Edgemont

Percent of map unit: 1 percent
Landform: Ridges
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Mountaintop
Down-slope shape: Convex, linear
Across-slope shape: Linear, convex

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