Villanova University
The Graduate School
Department of Civil and Environmental Engineering

Continuous Simulation of an Infiltration Trench Best Management Practice

A Thesis in

Civil Engineering

by

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Submitted in partial fulfillment

of the requirements

for the degree of

Master of Science in Water Resources

and Environmental Engineering

May 2009

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Best Management Practice

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A copy of this thesis is available for research purposes at Falvey Memorial Library.

Acknowledgements

I would like to thank those who have supported me in my academic and personal life during my time at Villanova University as a graduate student. Without their continual support, I would not have been able to complete this study.

First of all, I have to thank Dr. Traver for giving me the opportunity to join the Villanova Urban Stormwater Partnership as a graduate student. His ability to motivate and organize people of all types has shown the value of strong leadership as it pertains to progress, specifically in the field of stormwater. In addition to Dr. Traver, I need to thank the entire Villanova University Civil Engineering faculty and staff for my undergraduate education. Dr. Wadzuk, thank you for your valuable advice and guidance through my graduate studies. Bill Heasom, it was always a pleasure working and learning with you. I would like to give a special thanks to Linda DeAngelis and George Pappas for always finding the time to help or talk in their busy days. Clay Emerson and Tom Batroney, thank you for your help in our work at the trench and for your friendships away from school. Keep on fishing. I would also like to thank Mary Ellen and the rest of the VUSP graduate students who I worked with in my time at Villanova.

I am forever grateful for Jane and James Benford who showed me their undying parental support from infancy through my collegiate education. I was blessed to be raised by such great individuals. Also in need of thanks are my six older brothers and sisters who were always supportive of me at all times. Finally, I am grateful of anyone who has been part of my life over the past 6 years as I have grown at Villanova University and become who I am today.

Abstract

The goal of the study is to explore the relationship between contributing watershed size and hydrologic performance for an infiltration trench Best Management Practice (BMP). The following study is a continuation of research performed on the Villanova Urban Stormwater Partnership's (VUSP) infiltration trench BMP, which was constructed in July of 2004. This study builds off of the previous research and instrumentation that has been utilized on the site in an effort to develop a continuous hydrologic model capable of accurately simulating the flow of water through the trench on a long-term basis.

While the development and verification of the hydrologic model are specific to the site, they do provide a methodology for the development of similar models at other such infiltration sites. Examination of simulated infiltration and overflow rates in comparison to measured depth and flow at the site proves that the Environmental Protection Agencies' Storm Water Management Model 5 (EPA SWMM 5) is capable of accurately simulating the infiltration trench hydrology for isolated events. The continuous simulation of water quantity over the course of the entire year of 2006 proves the accuracy of the approach, and is more comprehensive than a single event methodology.

The resulting calibrated and verified model is a functional tool capable of analyzing different sized drainage areas contributing to the infiltration BMP. The model is altered to simulate different scenarios of variously sized drainage areas contributing

to the infiltration trench. Examining various ratios of drainage area to BMP footprint allows the selection of an appropriate drainage area size to achieve infiltration goals. The model is used to demonstrate that an “aged” infiltration trench still meets the goals of stormwater regulations. The flow-duration and depth-duration curves from the continuous flow model provide a more comprehensive understanding of infiltration BMP.

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Chapter 1 - Introduction

1.1 Introduction

The development of a verified continuous hydrologic flow simulation is the basis for evaluation of the performance of an existing infiltration trench. The goal is to explore the effect that the size of the drainage area contributing to an infiltration trench has on its ability to function efficiently in accordance with regulations on a long-term basis. Instrumentation on site and the developed model provide the unique opportunity to compare observed and simulated data. A verified model of the structure is used by varying the size of the drainage area contributing runoff to the BMP. The infiltration trench is located on Villanova University's campus as part of the Villanova Urban Stormwater Partenership (VUSP) Best Management Practice Park. The verified hydrologic model was used to determine the most appropriate drainage area for the size of the trench to achieve maximum infiltration. In the development of future trenches, the model provides a base model to predict the ability of a similar structure to reduce runoff volume. This model is developed from measured data recorded on site and would need to be modified at another site in order to accurately represent the soil conditions, trench geometry, contributing area, and other aspects unique to the specific site and structure. Continuous simulation ensures that the BMP will achieve its infiltration design goals over an extended period of time which is the ultimate objective of such a structure. Continuous simulation provides the opportunity to comprehensively evaluate the structure on a long-term basis and accounts for inter-event effects, which are ignored in isolated event analyses.

The simulation utilizes the Environmental Protection Agency's (EPA) Storm Water Management Model 5 (SWMM 5). Flow data collected from the site is used to calibrate and verify the developed model to ensure its accuracy. Hydrologic data from the year of 2006 from a rain gage on site is utilized for verification. The infiltration rating curve is developed from rates observed over the course of the year 2006 and calculated as an average, independent of age or seasonality. Infiltration BMPs at different locations of various sizes, shapes, drainage areas, and native soil conditions can be modeled similarly with respect to parameters relevant to each site. This type of analysis yields valuable information providing insight pertinent to the inner-mechanisms influencing the effectiveness of infiltration BMPs.

1.2 Stormwater Management and Legislation

Conservation and protection of the natural resources of the United States of America has long been a concern of the federal government in its efforts to protect the public. More specifically, protection of our waterways came through the passing of the Federal Water Pollution Control Act in 1948. Environmental conservation became a much more relevant issue to the public in the 1960's and 1970's as pollution became much more apparent. The general public began to realize the importance of protecting and conserving our natural resources, so the Environmental Protection Agency (EPA) was proposed by President Richard Nixon and was passed by Congress in 1970. The EPA immediately implemented amendments to the original act in 1970 and 1972 in order to address the need to reduce pollutant loads entering our surface waters (US EPA, 2003). More recently stormwater has reached the forefront of environmental engineering concerns. Clean surface water has become an important resource that is becoming harder to find due to the rapid development and urbanization of society.

As more natural meadows and wooded areas are transformed into paved parking lots and buildings, the amount of rain that is able to infiltrate into the ground decreases. Natural soils in pristine environments eliminate a portion of any rain event by absorbing the moisture and allowing rain to infiltrate into the groundwater table. This small amount of infiltration has proven to be significant (Jiang, 2001). In southeastern Pennsylvania, smaller storms comprise a large majority of the annual rainfall as seen in Figure 1-1. This data was recorded in Harrisburg, Pennsylvania which is located in the south central portion of the state and represents a reasonable state average. More than 75 years of data are included in Figure 1-1 and 92% of the storms produced less than two inches of rain. Approximately 65% of the yearly events total less than one inch of rain. Some soils are capable of eliminating all of the first two inches of a precipitation event and other soils are capable of absorbing a large portion of that amount according to the National Resources Conservation Service (NRCS) curve number method (US SCS, 1985). Impervious surfaces channel nearly all precipitation that falls on them directly to traditional stormwater systems which consist of inlets and concrete pipes. The environmentally detrimental effects produced by this lack of infiltration and increase in runoff are seen both on site and downstream.

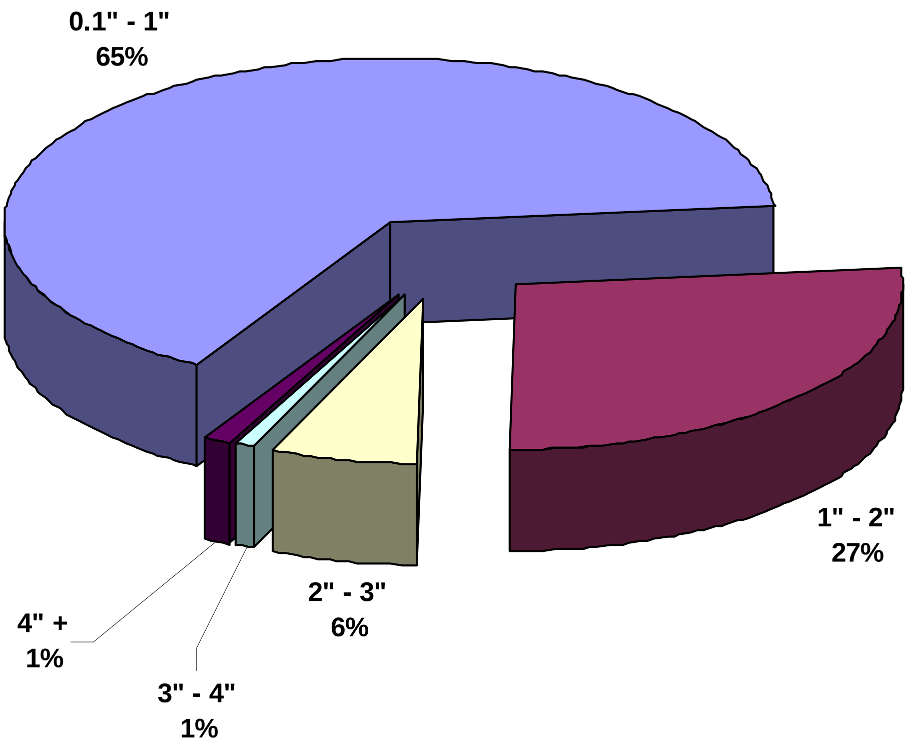

Figure 1-1: Distribution of precipitation by storm magnitude for Harrisburg, PA (PA BMP Manual, 2006)

Developed or impervious surfaces do not allow rain to infiltrate into the groundwater table. The results of an exhausted groundwater table include an increased susceptibility to drought as well as lowered stream base flow levels. The lowered natural stream levels create degraded ecosystems that lack diversity in the species that are able to survive (Paul and Meyer, 2001). Water that had previously soaked into the ground leaves developed sites very quickly over paved surfaces where it is channeled through pipes and directly into natural tributaries. These areas unnaturally contribute large volumes of water to streams quickly during the height of storms which causes peak flows to increase (Beighley et al.; 2002). The increased peak flows in streams and rivers causes large amounts of erosion, which in turn contributes high levels of pollutants in the form of suspended solids and dissolved nutrients.

Additional stress on natural streams and rivers comes in the form of increased water temperature. Paved parking lots become extremely hot during the summer and precipitation contacting the hot surface produces runoff of elevated temperature. This runoff can also contain pollutants related to development, such as fertilizers, animal waste, and leakage from vehicles (Fischer et al, 2003). Many species of fish and macroinvertebrates are highly sensitive to water quality and temperature and the inverse effect that temperature has on dissolved oxygen levels in water. Because of these detrimental effects, it is critical that infiltration of the majority of rainfall reaching these impervious surfaces is redirected back into the natural hydrologic cycle through infiltration on site. This is why the development, research, and use of infiltration BMPs is so important. Infiltration BMPs are not the only type of stormwater management structure, but can be useful tools when used in the correct situation.

In general, stormwater BMPs are designed to treat, retain, or reduce stormwater runoff from developed sites. Infiltration trenches achieve all of the aspects mentioned above by retaining water in a storage space and allow water to enter the ground where it is filtered as it moves through the soil. Among other common volume reduction BMPs are bio-infiltration sites located around existing infrastructure and green roofs which are located on top of buildings. Bio-infiltration sites depend on both infiltration of stormwater into the ground and evapotranspiration which takes place through the plants that grow on the site. Green roofs rely solely on evapotranspiration as they retain stormwater under a media layer. This water is utilized by the plants that grow in the media and effectively reduces the amount of runoff from the roof. Green roofs are specifically designed so that water can be stored in the media on the roof, but so that no leakage occurs through the roofs waterproof membrane beneath the media. Researchers estimate that three to five inches of growth media can eliminate 75% of the roof runoff from storm events of a half inch or less (US EPA, 2007).

Unlike bio-infiltration sites and green roofs, an infiltration trench does not rely on any sort of evapotranspiration, because the water is stored beneath the surface, and is not exposed to significant amounts of air, and should not have any plants growing in or above it. The subterranean trench relies solely on the ability to store water long enough for it to exit through the bottom and sidewalls of the structure and infiltrate back into the groundwater. An infiltration trench is more practical than green BMPs in more urban areas, where minimal area is available for open vegetated spaces.

1.3 Long term performance of infiltration trenches

One of the more common and unavoidable concerns surrounding infiltration trenches, which can be hard to control, is their sustainability and longevity. The ability of an infiltration trench to effectively reduce runoff and move relatively clean water back into the ground depends on the inherent void space present in the rock bed. The rock bed and exfiltrating surfaces of a trench act as a filter for suspended pollutants, such as metals and fine sediment, before entering the groundwater. The concern is that the gradual deposition of fine sediments will eventually clog the exfiltrating surfaces of the trench leading to drastically decreased drainage rates. It is a concern that has been addressed in other studies such as (Dechesne et al. 2005), which examined several different infiltration basins in Lyon, France. Dechesne's study confirmed that similar infiltration rates were observed for multiple trenches of varying age from ten to 21 years. Examination of the data at Villanova's infiltration trench tends to support the idea that infiltration rates of trenches will remain relatively constant over longer periods of time and will be discussed in more detail in Section 1.6.

Sustainability is a primary concern in the design and implementation of infiltration trenches as stormwater BMPs. Infiltration trenches have been proven as effective volume reduction BMPs when utilized in the correct situation. They are not well suited for industrial areas or any other area that is likely to experience a chemical spill, since the spill could quickly enter trench and contaminate groundwater. The remediation of polluted groundwater is much more complicated and expensive than the cleanup of a surface spill. The contamination concern is one that can be addressed easily by choosing the correct BMP for a specific site.

1.4 Hydraulic conductivity and infiltration capacity of infiltration trenches

The infiltration rate of any infiltration structure depends on many factors including temperature and depth of water. The most influential factor in an infiltration BMP's ability to drain is the underlying soil type and condition. Ultimately, it is the hydraulic conductivity of the native soil type that determines how quickly water can exit the BMP. Other factors may speed or slow the rate, but the final destination of the water is the soil and water cannot exit the infiltration structure any faster than it can enter the soil beneath. A very slow infiltration rate would mean that the structure could not drain quickly enough in order to regain its full storage capacity for the next storm. For this reason, the location of infiltration BMP sites is limited to those areas with native soils that are capable of infiltrating water at a rate of at least 0.1 inches per hour (PA BMP Manual, 2006). Another issue surrounding slow infiltration rates is the amount of time it takes for the trench to empty after being filled. The most current stormwater publications impose a maximum draw down time of 72 hours on infiltration trenches in order to address the issue of allowing infiltration trenches to completely drain on a regular basis (PA BMP Manual, 2006).

1.5 Infiltration Trench Site

The VUSP infiltration trench is located in the center of Villanova University's campus and was constructed as a retro-fit in June of 2004. The trench had to be located precisely where it is because of the surrounding building, parking deck, road, and utilities dictating the area available for construction. The site was the location of a few picnic benches for students and faculty to use but was generally considered an eye-sore with an eroding hill and a dying tree. The University wanted to improve the aesthetics of the site and the VUSP took advantage of an opportunity to gain an additional BMP on campus. Figure 1-2 a & b are photographs of the site before and after remodeling of the area.

Figure 1-2 a & b: Site photographs before and after infiltration trench construction.

The eroding hill seen before construction was retained behind a wall while the trench was constructed in the flat lawn area. EP Henry Eco-Pavers were used to cover the trench which maintains the availability of the area for recreation. The PVC pipes seen coming from the upper deck of the parking structure were directed to the trench. This design satisfied the needs of the University in providing a more aesthetically pleasing area for recreation and the VUSP in the addition of a BMP to campus. Before breaking ground on the project, a test pit was excavated at the site in order to determine if the soil was suitable for an infiltration BMP. The soil samples recovered from the test pit were analyzed and it was determined that the soil was in good condition and capable of infiltrating incoming water at a reasonable rate. The soil on the site is classified as a "loamy sand" and the composition of that soil will be discussed in further detail in Section 1.6. An aerial photograph of the site is seen in Figure 1-3, which shows the contributing drainage area and the trench itself.

Figure 1-3: Aerial photograph of the VUSP infiltration trench and contributing area.

The portion of the parking deck outlined in a rectangle is the approximate area that contributes runoff to the infiltration trench, which is located directly next to the parking structure itself. The trench is circled in the lower right side of the aerial photo and as mentioned previously was a retrofit. It is not required as part of the stormwater plan for the site. The trench is primarily an educational structure, which is why it was able to be designed with a largely oversized drainage area. Runoff from half of the parking deck was redirected toward the trench by modifying the existing PVC drainage system. Figure 1-4 shows the previous flow of water from the parking deck to the streets and on to the storm inlets.

Figure 1-4: PVC downspouts before the trench construction and re-routing.

The drainage area contributing to the trench was chosen to be approximately half of the parking deck surface, but could easily be changed. The area could be decreased by diverting some pipes back to the street where they could leave the area via the traditional stormwater system.

Runoff from the upper level of the parking deck is conveyed through the PVC pipe system to the trench. The flows are piped down to ground level on the northwest end of the parking deck. The area contributing to the infiltration trench is 20,400 square feet of impervious area and the trench footprint occupies an area of 130 square feet, which is a ratio of 157:1. This water flows through the pre-treatment sedimentation box and then into the trench where the water is dispersed evenly through a buried perforated pipe. The water travels down through the rock storage bed beneath and fills the trench. When the water depth in the trench reaches 5.2 feet, flows begin to exit the trench via the overflow pipe. This pipe prevents the trench from overflowing through the surface most of the time while the porous pavers above the trench act as an extreme event overflow mechanism. An illustration of the flow of water through the trench is seen in Figure 1-5.

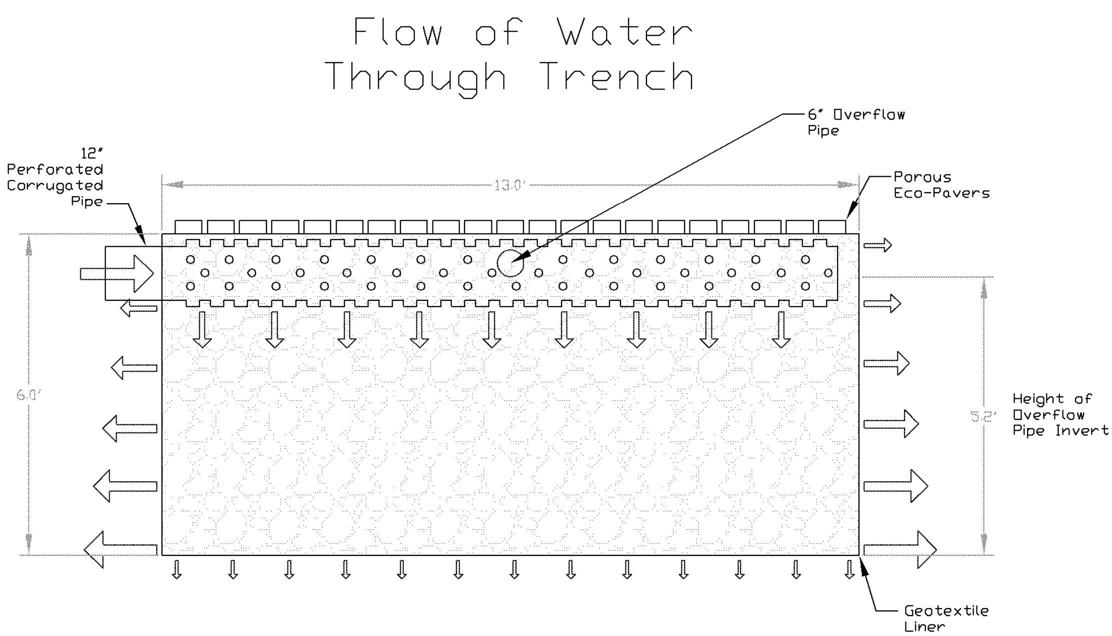

Figure 1-5: Cross section of the flow through the infiltration trench.

As Figure 1-5 shows, runoff leaves the pretreatment structure and flows through a perforated pipe which evenly distributes water into the top of the trench where it percolates down through the storage bed. Exfiltration out of the trench occurs through both the bottom and sides of the trench as illustrated.

1.6 Site Characteristics

Many current studies are based on the theoretical properties of the infiltration trench and the surrounding soil's inherent characteristics (Akan, 2002). Such studies only give the theoretical performance of an infiltration trench in its "new construction" condition. Discussed previously in Section 1.3, a primary concern when dealing with infiltration BMPs is the aging of the structure and its long-term infiltration capacity as the nearly inevitable accumulation of fine sediment occurs over longer periods of time. In order to accelerate the aging process of the studied trench and examine the effectiveness of an aged BMP, the drainage area contributing to it was greatly oversized. The contributing drainage area of 20,400 square feet as compared to the trench footprint of 130 square feet yields a ratio of nearly 157:1 (Table 1-1). Recent general recommendations suggest a ratio 5:1 for impervious areas draining to infiltration areas (PA BMP Manual, 2006) but justification of this ratio is nebulous at best.

Table 1-1: Existing site size compared to recommended size.

	BMP Footprint	**Storage Volume @ 5.2 feet of depth**	**Drainage Area**	**DA:BMP**
	[square feet]	[cubic feet]	[square feet]	[Drainage Area : BMP Footprint]
Existing	130	155	20,400	157
Recommended	130	155	650	5

The large drainage area to BMP ratio (DA:BMP) means that the existing infiltration structure will receive more than 30 times the recommended amount of runoff each year. This increase in runoff volume seen in the trench also means an increase in anything that the water is transporting. Sediments are suspected as the cause of decreasing infiltration rates in infiltration BMPs, thus a pre-treatment sedimentation box at the infiltration trench was designed and installed to remove sediment from inflow (Figure 1-6).

Figure 1-6: Pre-treatment sedimentation box at the infiltration trench.

The large drainage area and minimal pretreatment were chosen to accelerate the aging process of the infiltration trench. It is recommended that infiltration BMPs include a pretreatment sedimentation box, since fine sediment can have such an adverse effect on the structures ability to infiltrate water efficiently. The pre-treatment sedimentation box consists of a series of baffles and screens designed to reduce the amount of suspended solids flowing into the trench. This structure eliminates much of the larger organic debris, such as leaves, and also captures sand and grit from the parking deck surface. It is cleaned several times a year to remove the debris.

However, the pretreatment box at this trench was not designed to remove all of the suspended sediments that pass through it. As exhibited in Figure 1-6, water flows through the pretreatment sedimentation box at this site very rapidly and will transport some suspended solids to the trench in nearly every storm. After water flows from the parking deck and through this sediment collection pretreatment structure, it then enters the trench itself.

Drainage rates have been determined at the trench since its construction. These rates were determined for depth ranges by examining the average slope of the curve when the trench depth was plotted versus time on a storm by storm basis. Plotting storms in this fashion results in plots such as the one seen in Figure 1-7.

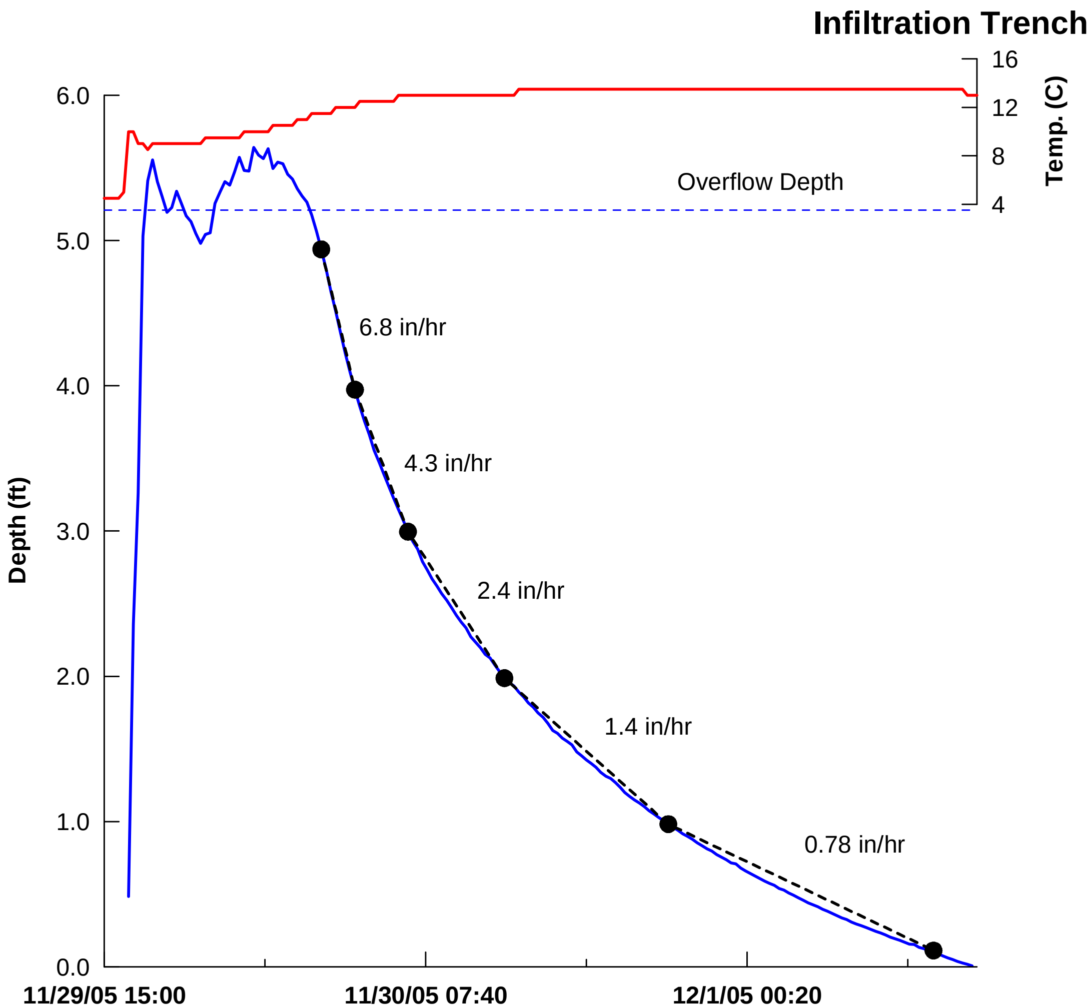

Figure 1-7: Single storm infiltration rates over depth ranges (Emerson, 2008).

Figure 1-7 displays the rate at which the trench drains at various depth ranges. As the depth of water in the trench decreases, the rate at which water leaves the trench also decreases. Two factors contribute to the slowing of infiltration rates as the depth of water in the trench decreases. The first is the decrease of wetted surface available for exfiltration as the depth of water decreases. The second is the decrease in hydrostatic pressure above the bottom and sidewalls of the trench.

Environmental testing demonstrates that substantial amounts of sediment have entered the structure in its four years of operation. The filter fabric, which separates the trench rock bed from the surrounding soil, is almost completely clogged at the bottom; this presumption is based on the decrease in infiltration capacity of the trench over its lifetime (Emerson, 2008). Calculated drainage rates for different depth ranges since the institution of the trench can be seen in Figure 1-8 and shows decreasing drainage rates in the trench.

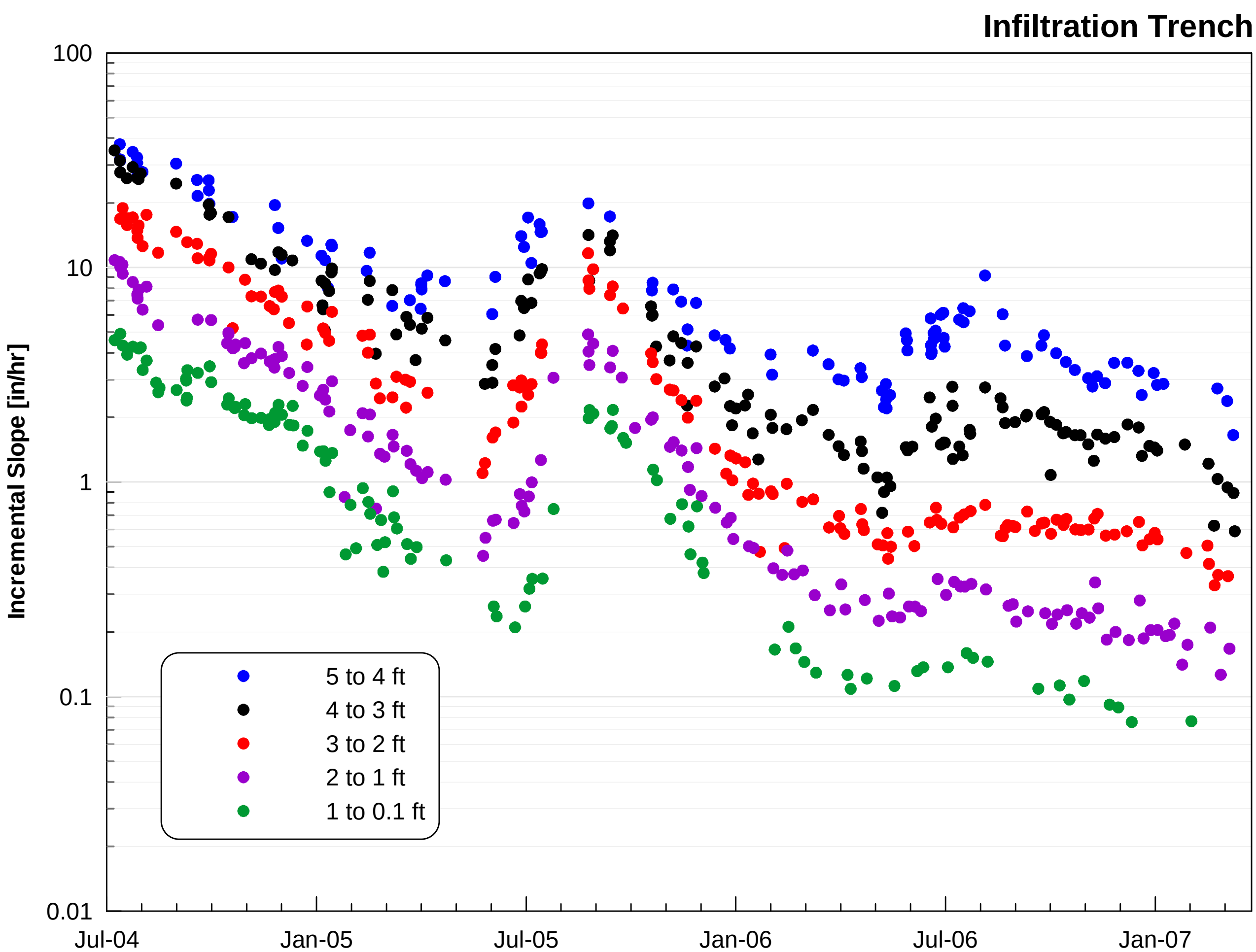

Figure 1-8: Depth decrease rates for ranges over the existence of the trench (Emerson, 2008).

It is important to note that this data is plotted on a log-scale. A first glance shows that there is a general decrease in the drainage rate at the trench over the first few years of its existence and that there is a seasonal variation in the rate as well. Drainage rates seen in the trench should not be mistaken for typical infiltration rates because they are a measure of the time it takes for the trench to empty. This drainage rate is not the hydraulic conductivity of the soil or any other property directly related to the soil on site. The drainage rate is a measure of how quickly the water level in the trench drops and is dependent upon factors such as trench geometry, soil properties, and actual depth of water in the trench. This is why initial drainage rates are seen at nearly 40 inches per hour at the institution of the trench. Typical saturated hydraulic conductivity for a "loamy sand", which is the soil type present on site, should be around 1.2 inches per hour (Rawls et al, 1983). The drainage rate observed is possible because water is exiting the trench in more than one dimension. The bottom and sidewalls of the trench are viable areas for water to infiltrate into the surrounding soil. When the trench is full, the wetted perimeter is maximized and trench depths can decrease most rapidly. Rapid rates decrease quickly as the trench empties as illustrated in Figure 1-7.

The dramatic decrease in this drainage rate over less than three years should be noted. For depths between four and five feet in July 2004 the drainage rates were nearly forty inches per hour, while in July 2007, the rate had decreased to approximately three inches per hour. This can be attributed to the sealing of the bottom of the trench, as discussed previously. Rates at shallower depth ranges also decreased over time, showing that the aging process of the trench was accelerate by overloading it with runoff and suspended solids. The amount of runoff that entered the trench over the first three years was the equivalent volume that would be seen in a more appropriately sized trench (DA:BMP of 5:1) over nearly a century. The amount of sediment entering the trench is also greatly increased especially considering the fact that the runoff comes from a parking deck where there is a relatively high amount of sediment created from wear on the surface. This load is much greater than that which would be seen from a rooftop or structure that does not experience such high traffic. Even with the severe overloading of the trench with sediment, it has been calculated that it would take more than 3,500 years for this trench to completely fill its voids with sediment (Batroney, 2008).

When examining drainage rates over the life of the VUSP infiltration trench, it is evident that drainage rates decreased rapidly over the first few months of its existence but that this rapid "clogging" of the trench did not continue at this rate. It is believed that the rapid decrease in drainage rate observed initially is due to the sealing of the bottom of the trench. The drainage rates observed today are attributed primarily to outflows leaving through the sidewalls of the trench, which have not sealed and are not expected to seal in the near future. For this reason, it is believed that the drainage rate currently observed at the trench will not continue to rapidly decrease as it did in its first few years of existence, but this warrants further study.

CHAPTER 2 - INSTRUMENTATION

2.1 Introduction

The VUSP infiltration trench is a highly monitored BMP. Various instruments are in place to monitor both water quantity and quality at different locations throughout the trench. Instrumentation on site includes weirs, flumes, and pressure transducers for water quantity monitoring as well as lysimeters and autosamplers for water quality monitoring. The following section will focus on the water quantity instrumentation since it is utilized in this study. Figure 2-1 shows a plan view of the trench and the location of the instrumentation.

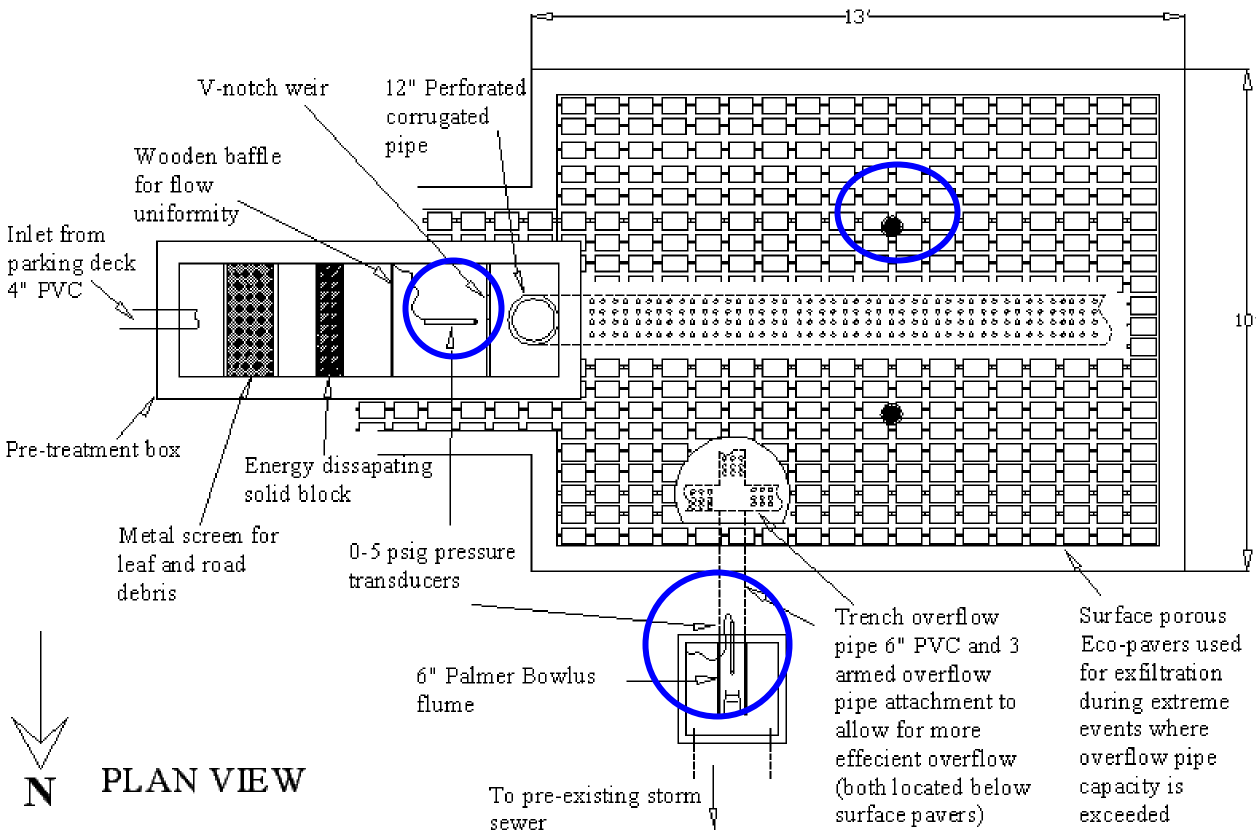

Figure 2-1: Plan view of the infiltration trench and important aspects.

Runoff enters the pretreatment box at the far left and flows from left to right where it enters the trench. When the trench has risen to a depth of 5.2 feet the water overflows to the north through the PVC overflow pipe. The water quantity instruments relevant to this study are circled. The upper dark circle identifies the well that houses a pressure transducer that records water depth readings in the trench.

2.2 Data Logger

All data from the site is currently recorded on a Campbell Scientific CR1000 Measurement and Control System. This data logging device is installed underneath the parking deck within a metal cage to secure it from vandalism. The data logger works in collaboration with a keyboard display, telephone modem, and a battery power supply kit to allow collection of data from the laboratory via the modem. All of the elements are housed within a weather resistant box. All of these elements are shown in Figure 2-2.

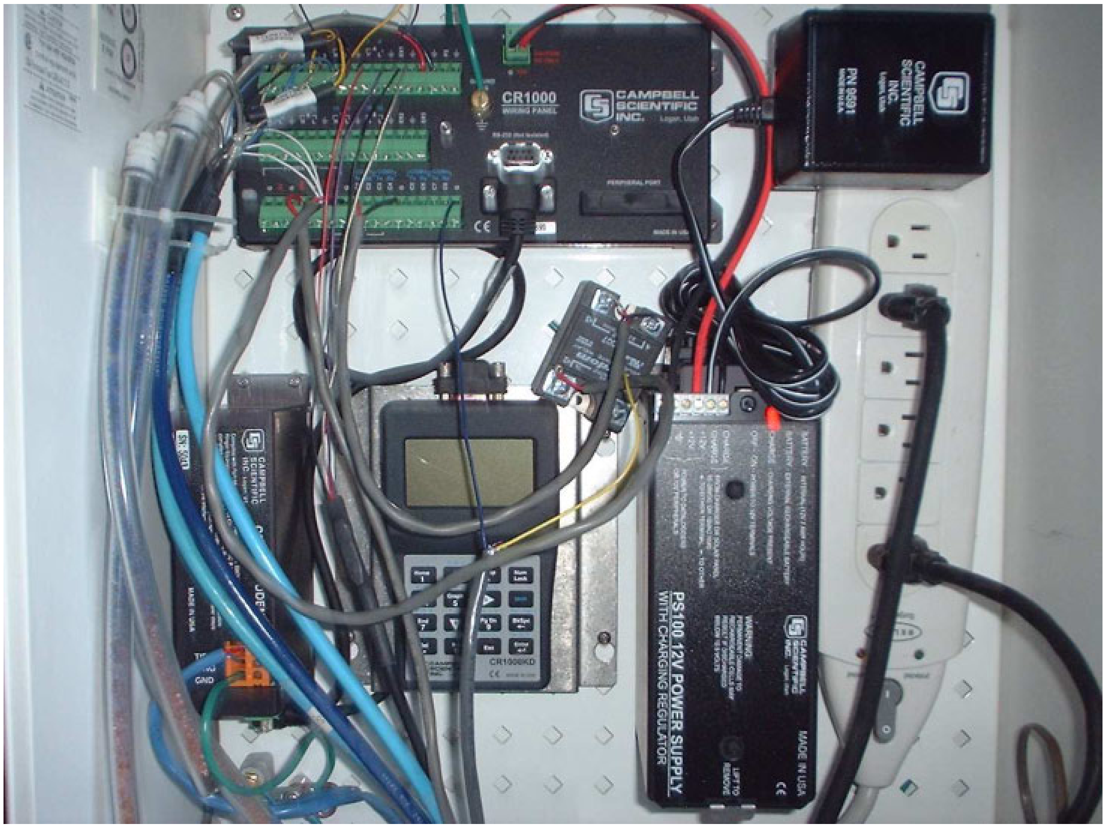

Figure 2-2: Campbell Scientific Data Logging Equipment.

All measurement devices on site from the rain gage to the pressure transducers and auto-samplers run through the data logger. The Campbell Scientific data logger was installed in June of 2006 because of the expanded triggering abilities of the system as compared to its predecessor. These functions allowed automated sampling on a storm by storm basis for water quality studies. For details regarding the logging equipment refer to Batroney (2008).

2.3 Rain Gage

There is a tipping bucket rain gage mounted within the infiltration trench drainage area. The gage was mounted in on one of the support columns of the parking deck as seen in Figure 2-3. It was installed in a location that is least likely to be affected by the presence of any overhead obstructions, such as trees or manmade structures.

Figure 2-3: On site rain gage mounted on the edge of the parking deck.

It should also be noted that the rain gage is not shielded by vehicles since it is on the edge of the parking deck and is elevated above the ground level. This keeps the gage protected from the splash of passing cars and the possibility of physical contact, which could throw off its balance and subsequent accuracy.

2.4 Inflow Thel-Mar Weir and Pressure Transducer

A new Thel-Mar weir shown in Figure 2-4b was installed in June of 2007. The purpose of the new weir is to increase the accuracy of inflow readings at lower flow volumes. The old V-notch weir was determined to be inaccurate at lower flows experienced during the rising limb of the inflow hydrograph. A pipe weir was selected as a low flow measurement device in order to accurately measure inflow at the beginning of events. A 15 inch pipe seen in Figure 2-4a was installed ahead of the pretreatment sedimentation box to fit the new pipe weir. The new pipe replaced a segment of the standard four inch PVC pipe used for the rest of the parking deck drainage system. *Equation 2-1* is an equation developed for the weir that relates the depth of water at the pressure transducer (*h*) to the volume of water overflowing the weir (*Q*) in cfs.

$$Q = -36.164h^4 + 16.416h^3 + 0.9234h^2 - 0.0277h \qquad \textit{Equation 2-1}$$

$$R^2 = 0.9996$$

Figure 2-4 a): Installed 15 inch pipe. **b):** Thel-Mar Weir installed in 15 inch pipe.

Two access doors are cut in the top of the pipe in order to provide access to the weir for maintenance. Sediment accumulated behind the weir can be seen in the Figure 2-4b. The sediment has fallen out of suspension before reaching the pretreatment box. An INW PS9800 pressure transducer is used in conjunction with the pipe weir in order to measure the flow passing through the weir. The pressure transducer is located at the bottom of the pipe behind the weir secured with a bulk-head fitting. The transducer is contained within a ¾ inch PVC pipe. The transducer wire exits through the bottom of the PVC pipe apparatus and is sealed to keep water in the transducer tube. Water flows over the weir and then continues to the pretreatment box through two four inch PVC pipes. After passing through the pretreatment screening and baffling, flows pass over the V-notch weir.

2.5 Inflow V-Notch Weir and Pressure Transducer

The V-notch weir was the original inflow weir installed at the trench. The weir is machined out of ¼" aluminum plate as per ASTM standards (D 5242-92). It is located at the end of the pretreatment box. An INW PS9800 pressure transducer located just upstream of the weir measures the depth of water passing over the weir. The depth of water passing over the weir is used in *Equation 2-2* as H [L].

$$Q = \frac{8}{15} C_d (2g)^{1/2} \tan\frac{\theta}{2} H^{\frac{5}{2}} \qquad \textit{Equation 2-2}$$

In this equation Θ = 90 degrees; Q = Flow Rate [L^3/T]; C_d = Discharge coefficient (0.58). The discharge coefficient (C_d) was chosen from triangular V-notch weir recommendations. The weir discharge coefficient has since been verified by comparing measured rainfall volume to the measured volume of flow passing over the weir. The V-notch weir is seen in Figure 2-5 during a storm event.

Figure 2-5: V-Notch Weir during a storm event.

The V-notch weir had been the sole inflow quantity measuring device on the site, but is now only used for higher flows. The data is still logged every minute as it was before, but the flow values at the V-notch weir will not be used until the maximum flow rate at the Thel-Mar weir is exceeded. The V-notch weir is the inflow measurement device utilized in this study. After flowing over the V-notch weir, flow enters the 12 inch perforated distribution pipe, which delivers water to the trench below the surface.

2.6 Well and Pressure Transducer

A four inch PVC well is located in the trench. The depth of water in the trench is recorded in the well with a calibrated INW PS9800 pressure transducer. The well is as deep as the trench and the transducer sits on the bottom of the well. The volume of water in the trench is calculated using *Equation 2-3*, which is based on trench geometry. The measurements were taken at every foot, before the trench was backfilled with stone. The developed equation accounts for the void space of the trench backfill, which was found to be 35% (Dean, 2005).

$$S = -0.096y^3 + 1.0769y^2 + 24.487y \qquad \textit{Equation 2-3}$$

Where S is the storage volume of water in cubic feet, and y is the depth of water in the trench measured in feet. *Equation 2-2* relates the storage volume to the depth of water.

2.7 Outflow Palmer Bowlus Flume and Pressure Transducer

Outflow at the trench does not occur until the trench fills to the invert of the overflow pipe. The invert of the six inch PVC pipe is located 5.2 feet from the bottom of the trench. The pipe is routed underground into a traditional grated drainage inlet. A six inch Palmer Bowlus flume was installed in June of 2006 and is attached to the pipe in order to measure the volume of water overflowing the trench as seen in Figure 2-6.

Figure 2-6: Palmer-Bowlus Flume attached to the overflow pipe at the trench.

An INW PS9800 5 psi pressure transducer is used to measure the depth of water flowing out of the flume. *Equation 2-4* is the rating curve provided specifically for the flume and is used to calculate the flow.

$$Q = 0.00005y^4 - 0.0007y^3 + 0.0175y^2 + 0.0038y + 0.0001$$

Equation 2-4 (Global Water, Inc.)

Where Q is the flow in cubic feet per second, and y is defined as the depth of water one inch upstream of the contraction in the flume minus the height increase at the contraction. The one inch distance is designated for a six inch diameter flume.

All instruments installed at the infiltration trench continuously log data that is used to analyze the hydrology and hydraulics of the VUSP infiltration trench. The integration of these various devices allows the trench to be continuously monitored and provides data pertinent to studies concerning the infiltration trench.

CHAPTER 3 - SWMM 5 SIMULATION DEVELOPMENT

3.1 Introduction

SWMM 5 is a hydrologic and hydraulic simulation program developed by the United States Environmental Protection Agency. The model is intended for use in urban areas and is capable of routing runoff through a complex drainage system. Hydrologic rain data is applied to a drainage area that is characterized by various soil parameters making up the contributing watershed. The rain that falls on the drainage area is either infiltrated or becomes runoff. The runoff is routed through the drainage system. The simulation model is well suited for urban areas because it is capable of simulating flow through pipes, channels, and other man-made stormwater structures. Both the quantity and quality of runoff are routed from each subcatchment and can be examined at any point in the system. SWMM 5 is capable of simulating single event storms as well as continuous flow simulations. Both time-series and total flow results are available for analysis. In this study, SWMM 5 was utilized primarily because of its continuous simulation capabilities. The completely impervious drainage area is highly urbanized, which is the type of site that SWMM 5 was intended to model. Further water quality analysis can be easily incorporated into the quantity model developed in this study for future research.

3.2 Basic SWMM 5 Modeling Approach

SWMM 5 is a powerful tool capable of analyzing complex hydrologic models, but is just as capable of analyzing less complex systems, such as the one studied here. The site of study for this research is relatively small, so the hydraulic routing is not complex. The configured model is seen in Figure 3-1.

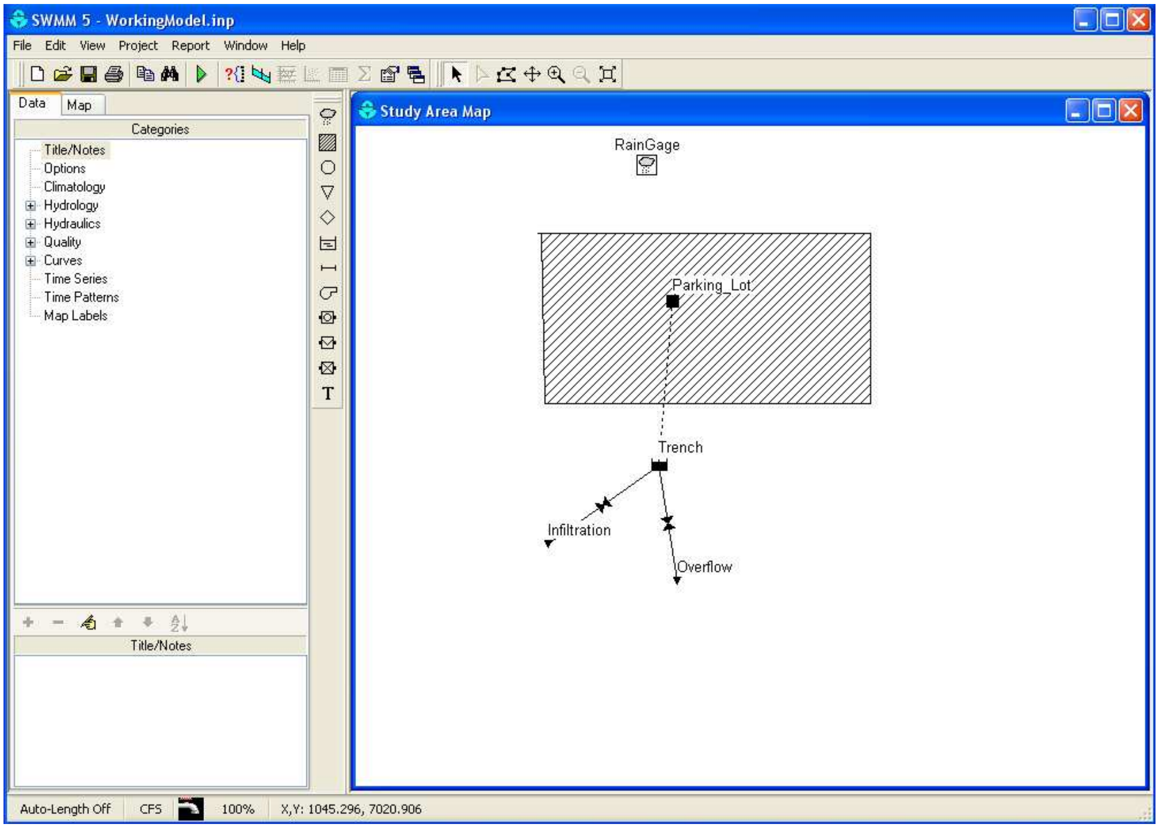

Figure 3-1: SWMM 5 setup.

Rain data from the tipping bucket gage is introduced to the simulation model through a SWMM 5 rain gage (RainGage). This gage simulates precipitation over the subcatchment surface (Parking_Lot). Runoff from the subcatchment enters the storage unit (Trench), which has a stage-storage curve that represents the storage capacity of the trench. The storage unit also has two outlets. The "infiltration" outlet accounts for water leaving the trench as infiltration. The "overflow" outlet is located at the invert of the overflow pipe and accounts for water that leaves the trench via the overflow pipe or through the trench surface. Explained above is the general layout of the model which will be explained in further detail in each of the following sections.

3.3 General SWMM 5 Parameters

General SWMM 5 parameters, such as routing time and infiltration methods, remained the same for the duration of the study. Wet weather runoff was calculated every five minutes while routing took place every five seconds. Values were reported every fifteen minutes. These settings produced accurate results while keeping run times reasonable. The infiltration method used for the subcatchment is the NRCS curve number method, but has little effect on results as the entire subcatchment is impervious. Infiltration at the trench is dependent upon the infiltration rating curve developed specifically for infiltration at the trench in Section 3.7. Kinematic wave routing was chosen as the method for flow routing. All flows in this study are recorded in ft^3/sec. Other general options in SWMM 5 were left as the default settings.

3.4 Subcatchment Characteristics, Methods, and Assumptions

The drainage area developed in SWMM 5 was modeled as a subcatchment that drains to a single point. There are several PVC pipes that comprise the collection system of the parking lot (Appendix A), but the simplified model serves the needs of this study without the loss of accuracy. The simplified system used is acceptable for continuous modeling as the time it takes for water to travel from one drain to the next is in the order of seconds and the model is processing cumulative data every five minutes. The five minute time step eliminates highly variable flows over short periods of time without the loss of mass. It is a rather small time step considering the fact that a year of data from the site is being examined, but does not create an overly-cumbersome simulation time, so it was kept.

The subcatchment "Parking Lot" simulates the parking deck, which is the only drainage area contributing to the trench. The area is entered in acres and is considered to be 100% impervious surface, which is assigned a curve number of 98 and a value of 100 for "%Zero-Imperv" in the SWMM 5 subcatchment characteristic box. A very small portion of the contributing area is the actual footprint of the trench, this area is not considered to be a significant contributor of runoff. The ratio of the contributing area to the area of the trench is 157:1, which makes this area less than 1% of the total area. The surrounding grass area will also contribute runoff, but only in the most intense storm events. In these types of events, the trench is already full and the water simply bypasses the trench altogether by running directly into the grate where it leaves the site as seen in Figure 3-2.

Figure 3-2: Extreme storm event completely overflowing the trench.

The contributing area was originally assumed to be half of the area of the upper level of the parking deck or 20,400 ft^2. A 'dye tracer' study was performed by Dean in 2004 during a rain event in order to verify the drainage boundary. This test was performed by dripping dye near the suspected drainage boundary and observing the direction of flow. The study confirmed that the area was 20,400 ft^2 (0.468 acres). A table of other subcatchment parameters entered into the model can be found in Appendix B.

3.5 Rain Characteristics and Methods

The first step in the development of the model is the input of hydrologic data. The rain data for 2006 used in this model comes from the rain gage on site. The model uses a five minute interval rain data file. This file was created by summing one minute rain gage readings. The data file only contains times in which precipitation occurs because SWMM 5 is capable of reading the file and applying it to the corresponding date and time, eliminating an overly cumbersome rain data file with a majority of "zero" readings. SWMM 5 has the option of inputting rainfall data as an intensity, volume, or cumulative amount. The "Volume" input was selected since rainfall data was recorded as a depth. This depth is converted within the model to a volume of rain falling over the entire subcatchment.

The infiltration trench data logger has had incidents in the past in which the data was not collected for a period of time due to power outage or other technical difficulty. Although flow data was not recoverable for those periods, data from a rain gage located at the VUSP bio-infiltration traffic island was used instead. The traffic island rain gage is located less than half of a mile from the infiltration trench. It is assumed that at this distance, it is reasonable to expect similar rainfall amounts between the two sites.

3.6 Storage Unit Characteristics and Methods

The infiltration trench is developed as a storage unit in the model and is identified as the "Trench." A storage curve was created based upon Emerson's field measurements (Emerson, 2004) taken during construction. The tables used to develop the stage-storage curve are found in Appendix C. The stage-storage curve was developed using the measured perimeter of the trench and the void space of the backfill material. As mentioned previously, the actual void space in the rock bed was determined to be 35%; this was amended from the original assumption of 40%, which was based on the uniformity of the material. The fill had typical variance in the rock size, which leads to lower volumes of void, since more compaction occurs. The storage values were adjusted accordingly in the stage-storage curve.

3.7 Outlet Infiltration Characteristics, Methods, and Assumptions

The first outlet structure named "Infiltration" was created in SWMM 5 in order to separate the infiltration volume from the overflow volume. As is the case with any infiltration facility, the soil directly surrounding the trench is critical to the effectiveness of the structure. In this model, the soil conditions of the site were accounted for in a drainage rating curve, which is explained in this section. It is important to realize that the drainage rates computed are not one-dimensional infiltration rates or hydraulic conductivities. The rates are drainage rates measuring the rate at which the trench empties as water leaves through both the bottom and sidewalls of the structure.

Appreciable decreases in drainage rates have been realized over the first few years of the trench as was seen in Figure 1-8. Infiltration rates have decreased over the life of the trench, but they also fluctuate slightly over the course of each year. The steady decrease has been attributed to the accumulation of fine sediments in the bottom of the trench as discussed previously; this is apparent in Figure 3-3, where it can be seen that it takes several days for the trench to drain from a depth of two feet to a depth of one foot and the rate only decreases slightly more below one foot of depth.

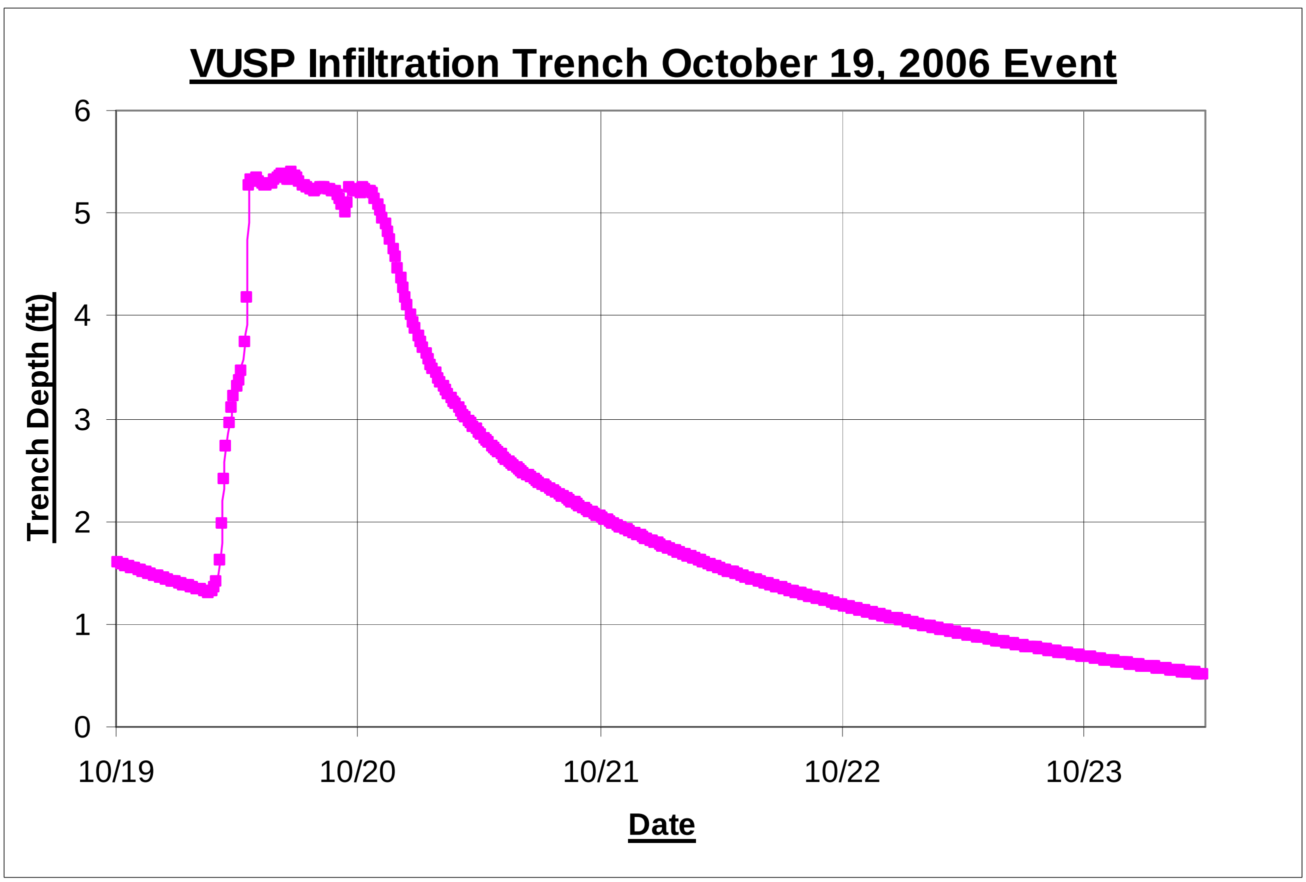

Figure 3-3: Depth of water in the trench for a single storm event.

It also proves that the majority of infiltration currently taking place at the trench is taking place through the sidewalls, since the drainage rate decreases drastically as the bottom infiltration becomes the sole infiltration mechanism.

The drainage rating curve for the model was developed using data collected from the site. Table 3-1 contains the drainage rates used to develop the average annual drainage rates and the average rates are in bold. The calculated average rate from five feet to four feet is assumed to be the rate of infiltration when the depth of water in the trench is 4.5 feet. The rate calculated between four and three feet is designated as the infiltration rate at 3.5 feet, and so on for the other depth ranges.

Table 3-1: Averaged drainage rates at depth ranges for 2006

Midpoint Depth (feet)	1/30/2006	5/2/2006	8/1/2006	10/31/2006	**Average**
4-5	4.01	2.86	6.55	3.32	**4.18**
3-4	1.77	1.11	2.00	2.10	**1.74**
2-3	0.77	0.58	0.66	0.66	**0.67**
1-2	0.45	0.27	0.33	0.33	**0.34**
0.1-1	0.28	0.12	0.14	0.10	**0.16**

The rates above were developed using drainage rates calculated from 2006 data (Emerson, 2008). The range of the data does not include measurements below a depth of 0.1 feet in the trench. It is assumed that there is no water infiltrating at depths below 0.1 feet. The drainage rates were calculated from depth-time relationships as water emptied from the trench for each storm. The values for each date (Table 3-1) are five point moving averages from individual storms around that date. Averaging these rates yields the rates used in the final drainage rating curve values listed in Table 3-1 and is the average rate for the year. Temperature does affect the drainage rate of drainage at the infiltration trench slightly (Emerson, 2008). An average annual infiltration rate does not account for this slight variation on a storm-by-storm basis   The tables used to develop the rating curve for infiltration based on depth of water in the trench is in Appendix C. The infiltration rating curve developed for the model came from 2006 data from the trench. It is important to realize that this infiltration rating curve was calculated using only data from the trench draining and does not include infiltration rates when the trench is overflowing (above 5.2 feet) or has flow entering. A plot of one of the many storms used to develop the rating curve is seen in Figure 3-4.

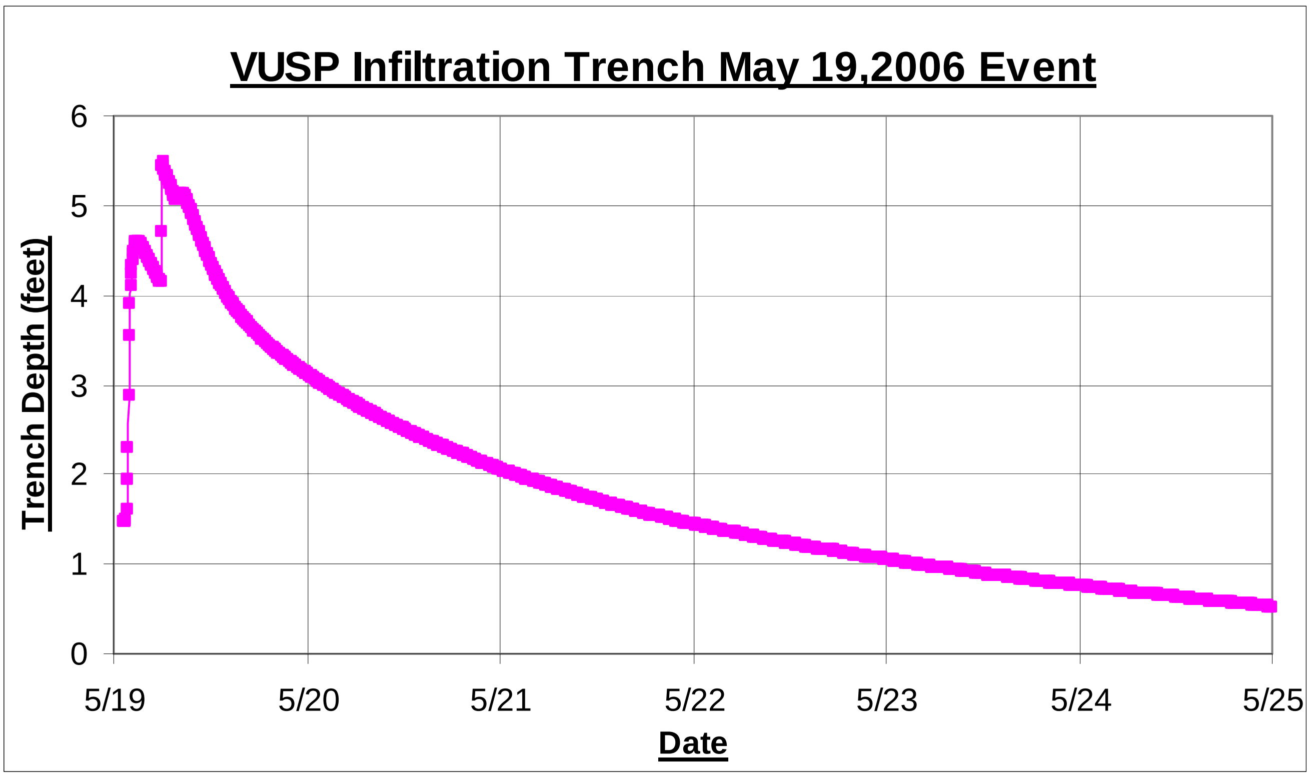

Figure 3-4: Plot of trench depth during a rain event.

The initial portion of the plot in which the depth of water in the trench increases rapidly is not used to develop the infiltration rating curve for the trench because there are multiple flow mechanisms dictating the amount of water that is entering and leaving the trench. It is not possible to accurately calculate the volume exfiltrating through the soil during this portion of any storm. Once the trench is full and drops below the overflow depth of 5.2 feet, then water infiltrating into the soil is the only mechanism by which water is leaving the trench. The rate at which the water depth in the trench drops during this time can be definitively identified as the infiltration rate of water out of the trench and into the ground. For particular storms, discrepancies between simulated and measured data during the trench filling process suggest that there is a difference between infiltration rates when the trench is empty or full. This minor discrepancy does not significantly decrease the accuracy of the model, because the amount of time that it takes the trench to fill is minimal in comparison to the large amount of time examined in the model.

The calculated depth-drainage relationship is applied to the model as a rating curve with the invert of the outlet structure located at the bottom of the trench. The same incremental increase in infiltration rate that was used between 3.5 and 4.5 feet was applied to depths up to the top of the overflow pipe at 5.7 feet. This is a conservative estimation of the infiltration considering that real infiltration rates most likely continue to increase with depth as they do on the rest of the rating curve. It is assumed that after the overflow pipe is totally submerged, that there will be no additional increase in infiltration rate. The rate is assumed constant to a depth of 6.5 feet, which would be a case in which water is ponded above the trench.

3.8 Outlet Overflow characteristics and methods

An outlet structure was created in SWMM 5 and was designated "Outlet." The structure dictates outflows from the trench when water depths reach 5.2 feet. The outflow depth-flow relationship is applied to the model as a rating curve starting at a depth of 5.2 feet from the bottom of the trench. The curve was provided with the Palmer Bowlus flume and was developed by Global Water, Inc. (Equation 2-4). Using this curve assumes that the flume is the condition that limits the amount of water overflowing the trench. Other factors could actually be the limiting factor with respect to the rate at which water is able to exit the trench's overflow structure. The dynamics of the water moving from the inflow dispersion pipe to the overflow pipe could be a factor as water has to move through the upper portion of the rock bed before it reaches the overflow pipe.

Any depth greater than six inches over the invert of the overflow pipe is assumed to produce free flowing overflow. It is assumed that at this point water will leave the trench as quickly as it enters either through the pipe or by exiting through the porous pavers above. A flow rate of ten cfs is assigned to depths greater than 5.7 feet in the trench. This simulates the free flow of water, which comes up through the pavers and flows over the small grass section between the trench and the outlet. Water then leaves the site through the lawn inlet as shown in Figure 2-6. It should be noted that this type of overflow happens only during storms with extremely intense downpours (i.e. 1.2 inches per hour or greater) and is not a regular occurrence. For more detailed drawings, plan and profile views refer to Appendix A.

3.9 Outfalls

Outfalls were created downstream of each structure with corresponding names so that outflow and infiltration could be examined as individual elements at the end of the system. These outfalls were input into the model for the sole purpose of monitoring the total flow exiting via each respective mechanism. Each node can be monitored individually over the course of the simulation in order to determine flows, depths, and volumes leaving the trench instantaneously or cumulatively.

3.10 SWMM 5 Model Development Summary

The simulation model was developed as described in Section 3.2 through Section 3.9, and is capable of simulating flows through the trench for the year of 2006. Verification was the next step to ensure that the model was in fact capable of reproducing actual trench depths, infiltration volumes, and overflow volumes as discussed in Chapter 4. Once the model was verified to accurately simulate the year of 2006 then it was capable of modeling the trench in the future with the input of new meteorological data assuming that the current infiltration rate at the trench does not change drastically. It does not seem likely that a drastic change will take place in the near future since it has not changed significantly over the last two years as proven by Emerson, 2008.

CHAPTER 4 – SIMULATION VERIFICATION

4.1 Introduction

The hydrologic and hydraulic data and physical components of the site were compiled into SWMM 5 as discussed in Chapter 3. This data was recorded by instrumentation on site which is regularly calibrated to ensure accuracy (Emerson, 2008). Comparing simulated trench depths to measured depth readings is the method used to verify the model's accuracy. This verification took place through both visual examination and statistical analysis. A secondary comparison examines the overflow volumes simulated and observed.

4.2 Visual Verification

Verification began with a visual examination of trench depths plotted over time. A graph of simulated trench depths compared to measured trench depths for the year of 2006 is included in Appendix D. Due to the large amount of data, the year was divided into three month periods. Magnifying these periods made the differences between simulated and measured data more clear. Figure 4-1 shows one of the periods spanning from July through September and plots of all four time periods are included in Appendix D.

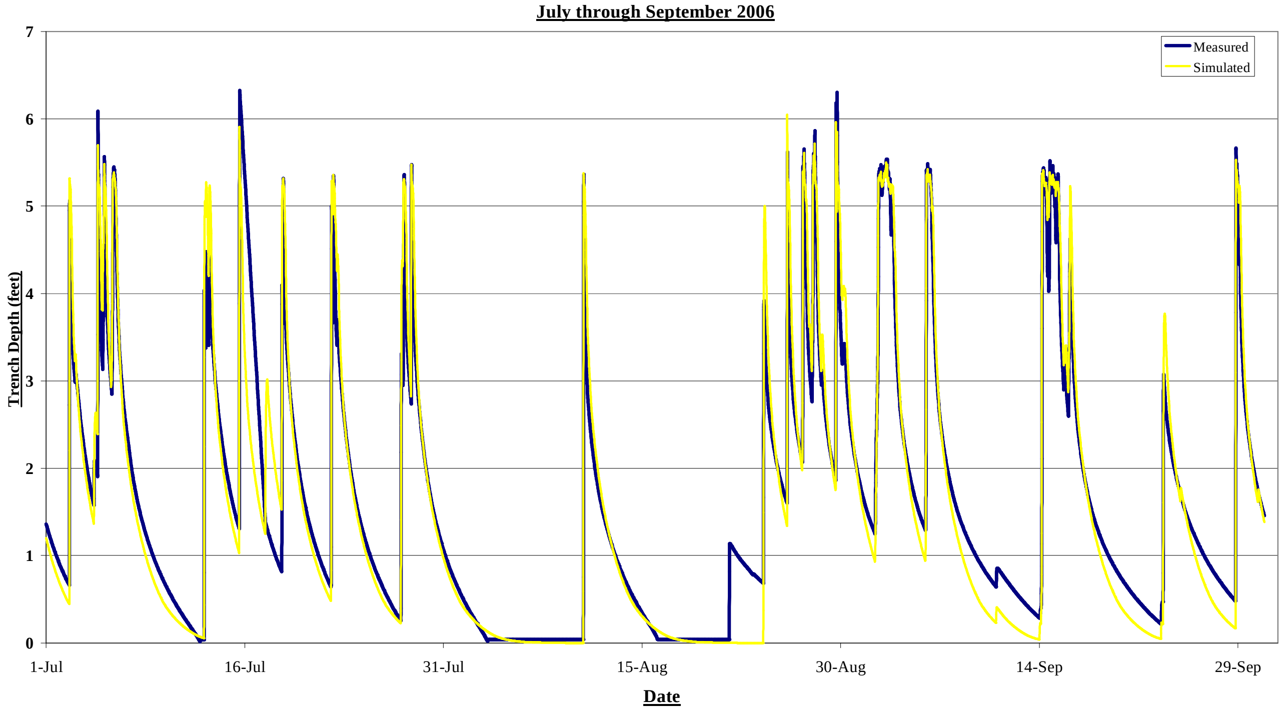

Figure 4-1: July through September trench depth comparison

Examining Figure 4-1 shows that the shape of the simulated depth curve (light) is very similar to the actual depth curve (dark). The rising limb always has a steep slope, which indicates that rain is moving to the trench rapidly from the completely impervious parking deck. The fast conveyance of flow is expected, since the area draining to the trench is small, and it takes no more than a few minutes for water falling on the furthest point of the watershed to reach the trench.

The timing of the runoff from the model matches the measured runoff, which is also seen in the rising limb of each runoff event. The simulated depth of water in the trench begins to increase at the same time as the recorded depth in the trench. The simulated depth of water in the trench also peaks at the same time as the actual trench depth, although there is occasionally some discrepancy between peak depths. The model also is very effective at simulating additional inflow while the trench is draining, which is seen from the sensitivity of the simulated trench depth in back to back events. Some simulated peak depths reach higher than measured peak depths in smaller storms, while some actual peaks reach higher than simulated peaks in larger storms. The slightly higher peaks seen in the model during smaller storms is explained by the fact that the parking deck is not completely impervious. Although the joints between parking deck segments are "sealed", it has been observed that they do leak a portion of the runoff, as seen in Figure 4-2.

Figure 4-2: Leaking parking deck joint.

This loss can be a significant portion of the total runoff for precipitation event with a low constant intensity, because the water slowly moves over these cracks and has more time to seep through the crack. Typical differences in rain and inflow to the trench can be seen for a single month such as September of 2006 in Table 4-1.

Table 4-1: Typical losses from rain to runoff.

Storm Date	**Rain [in]**	**Inflow to Trench [in]**	**Loss [in]**	**Approximate Storm Duration [hours]**	**Max Five-Minute Rain Intensity [in/hr]**	**Percent of Total Rain Entering Trench**
9/1/2006	2.67	2.55	0.12	35	0.08	96
9/5/2006	1.01	1	0.01	12	0.05	99
9/14/2006	1.71	1.39	0.32	55	0.03	81
9/28/2006	0.82	0.79	0.04	7	0.11	95
Total	**6.3**	**5.79**	**0.51**			**92**

Every storm has some sort of loss associated with it, but the loss is dependent on multiple factors, including storm duration and intensity. The percentage lost in September 2006 varies from 25% to nearly 0%. The total lost flow over the course of the month was 8%. The storm on September 14th is the only storm that lost a large percentage of the storm's total volume. This storm was a long storm that produced a large volume of rain, but over a much longer period of time than other storms. The losses seen from the parking deck are not simply depression storage. The losses are somewhat constant over the course of the storm because the runoff flows over the cracks. The drainage area was not changed from 100% impervious in the SWMM 5 simulation model in order to account for this volume, because the purpose of the model is to simulate the theoretical inflow and outflows of the trench for design purposes. Design for construction of new infiltration trenches may account for this variance in construction quality and maintenance of a site, but this model does not account for any such losses.

Examination of larger storms reveals that some of the measured peak depths in the trench exceeded simulated peak depths in larger storms. This is not a concern because the model was designed in such a way to prevent flooding (flows lost in the model) during extreme flow events. When the water is over 5.7 feet deep (the top of the overflow pipe), the infiltration rate remains constant in the model. The overflow rate increases at a constant rate from 5.7 feet to 6.0 feet. The peaks match well in most instances, but it can be seen that simulated trench depths never exceed six feet. This is because the overflow curve jumps from a rate of 1.19 cfs at a trench depth of six feet to a rate of ten cfs at a depth just over six feet, (Appendix C) which simulates the overflow mechanism of water leaving through the surface of the trench pavers, as seen previously in Figure 3-2. This change in flow rate ensures that the overflowing water is accounted for as overflow. The overflow water flows freely over grass to the stormwater inlet a few feet away. The discrepancy in depths here is not a concern because depths are rarely recorded above six feet for more than a couple of minutes at a time. In 2006, the trench depth was recorded above six feet for only five events, and no event was above six feet for more than 15 minutes. It can be assumed that virtually all of that water above a depth of six feet is lost to overflow.

It is critical that an infiltration trench will infiltrate water effectively, and the focus of this study is to determine what amount of rainfall is infiltrated on site. When the depth of water in the trench is below 5.2 feet, infiltration is the only mechanism by which water can leave the trench. Examining simulated recession limbs versus measured recession limbs verifies that the infiltration rating curve is accurately simulating infiltration at the trench. Figures 4-3 a and b show recession limbs that match fairly well, and others that are nearly identical, respectively. Snowmelt events are not accounted for in this model; for example, the 2/12 event in Figure 4-3 b. This will be discussed in more detail in Section 4.5.

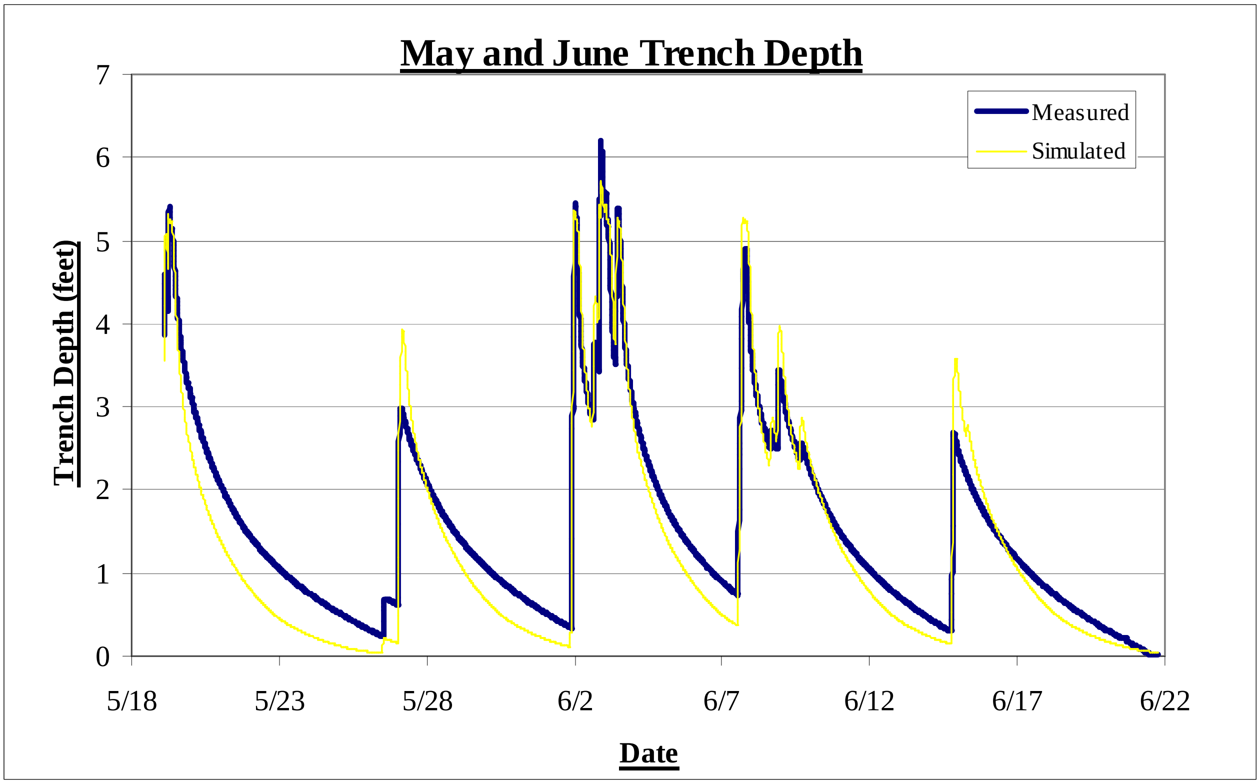

Figure 4-3 a: Trench depth comparison for May/June.

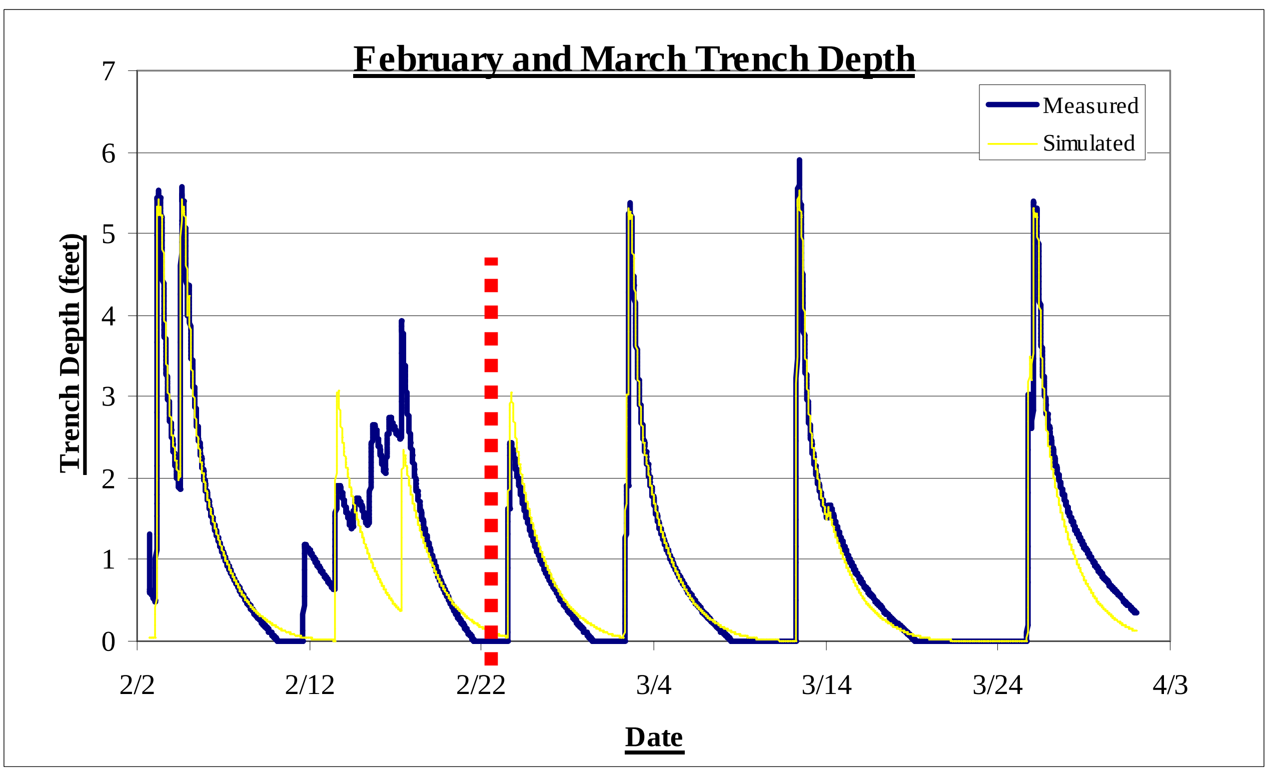

Figure 4-3 b: Trench depths for February/March
(Only data following vertical dashed line is used in the statistical analysis.)

The two periods of time in Figures 4-3 a and b show that infiltration rates at the trench vary over the course of the year. The infiltration rating curve input into the model was developed from average rates calculated for the year of 2006. The simulated recession limb is identical for every storm and does not account for the season or temperature. Figure 4-3a shows some storms in which the calculated infiltration rate is faster than the actual infiltration rate and the opposite is seen in Figure 4-3b, as the simulated recession curve is held constant, it is clear that the actual infiltration rate at the trench varies as was expected. Figures 4-3 a and b will be analyzed further in Section 4.3 for statistical verification. In order to examine the data even more closely, a single storm from each of the 4 three month periods discussed above was plotted individually. Figures 4-4 a, b, c, and d are the plots of the data for these storms.

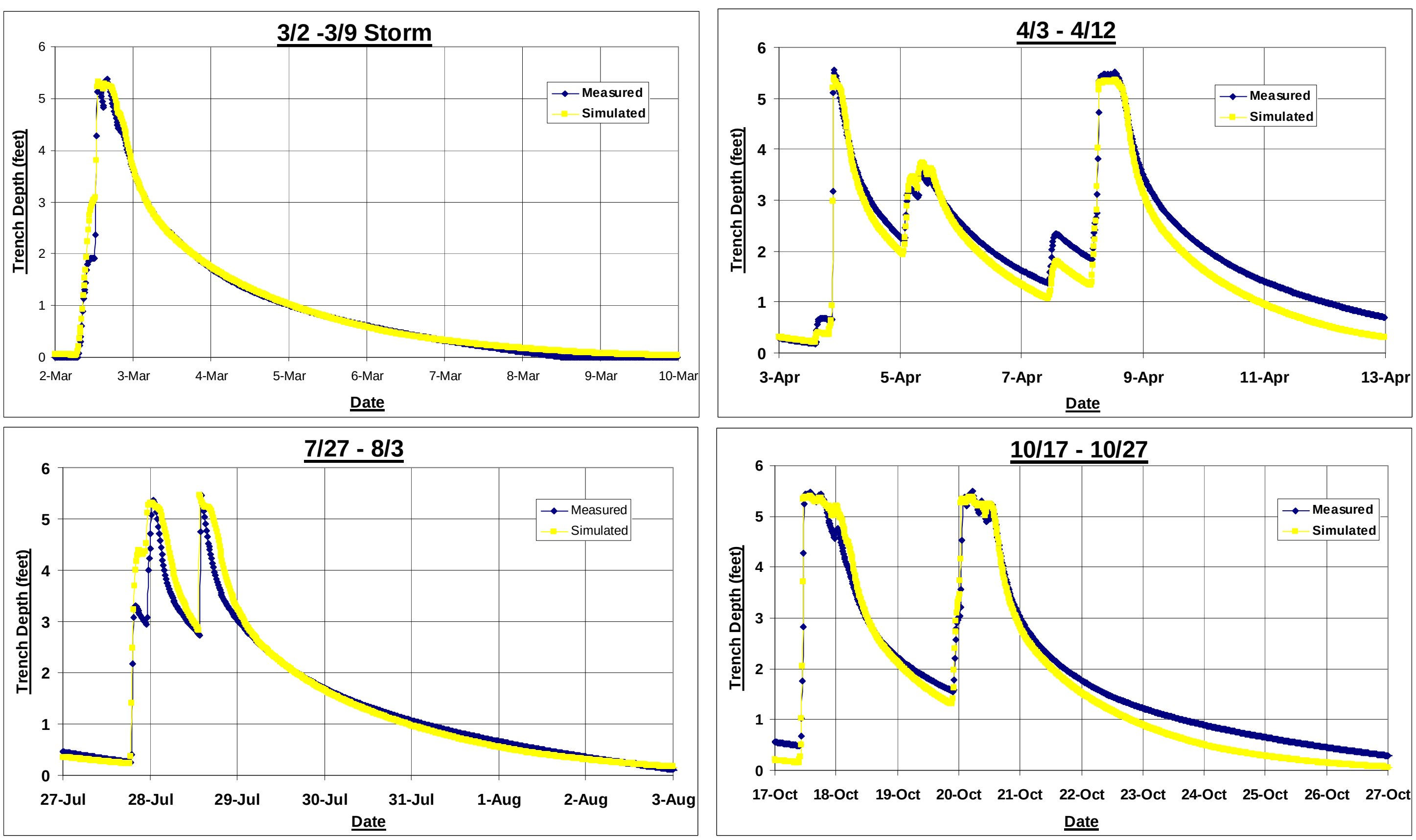

Figure 4-4 a, b, c, & d: Plots of individual storms in different seasons.

The plots cover time periods ranging from seven to ten days which encompasses the trench filling and emptying for each storm. The individual events were chosen to examine the accuracy of the model during each respective time period. Only the event starting on March 2nd is a single peaking event. The April storm has the largest deviations between measured and simulated data. The multiple peaks of the storm were not matched because of the difference in depth of water left in the trench at the beginning of each new peak. The rising limb and peaks of the storms match well the majority of the time. Timing and height of the peaks are similar. The simulated data deviates furthest from observed data as the trench empties in the April 3rd storm and again in the October 17th storm. The difference between measured and simulated depths varies and is never larger than half a foot, but is typically much less. In the lower depths of the trench, where the deviation is the largest, the half foot difference in depth is a 14 cubic foot change in volume. The July 27th storm has measured depths lower than simulated depths, which is contrary to the characteristics exhibited in the previously mentioned storms. While the second recession limb of the October 17th storm underestimates the depth of water in the trench, the first recession limb shows the simulated data above, and matching the measured data at different times. The individual storm examination provides further verification that the model is capable of accurately predicting trench depths.

4.3 Statistical Verification

Statistical verification of the model is the ultimate goal of the verification process to prove that the model is capable of reliably predicting the performance of the trench. Two time periods during the year were chosen to perform the statistical analysis.

4.3.1 Basic Statistical Comparison

The time periods examined were chosen through the visual examination of the data. The first time period was chosen because it appeared to be the worst correlation between the measured and simulated data for the year aside from snowmelt events. This time period runs from May 19th through June 22nd, and can be seen in Figure 4-5 b. The second time period was selected because it appeared to be the time of the year in which the simulated and measured trench depth data matched most closely. This time period runs from February 22nd through March 31st and the compared depths were shown previously in Figure 4-3 b to the right of the vertical dashed line (excluding the snow melt event.) Figures 4-5 a and b compare measured depths (abscissa) to simulated depths (ordinate) for the two time periods.

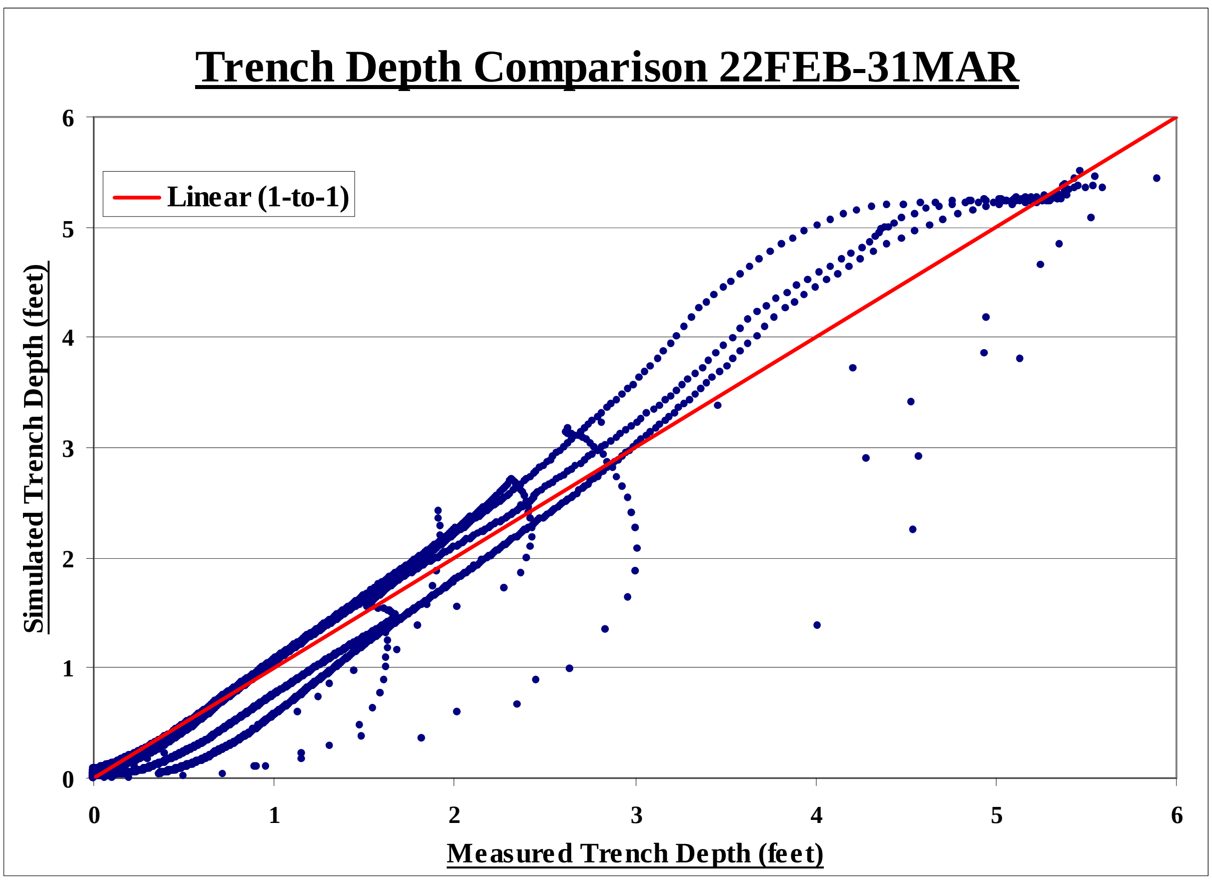

Figure 4-5 a: Simulated versus measured depth of water in the trench.

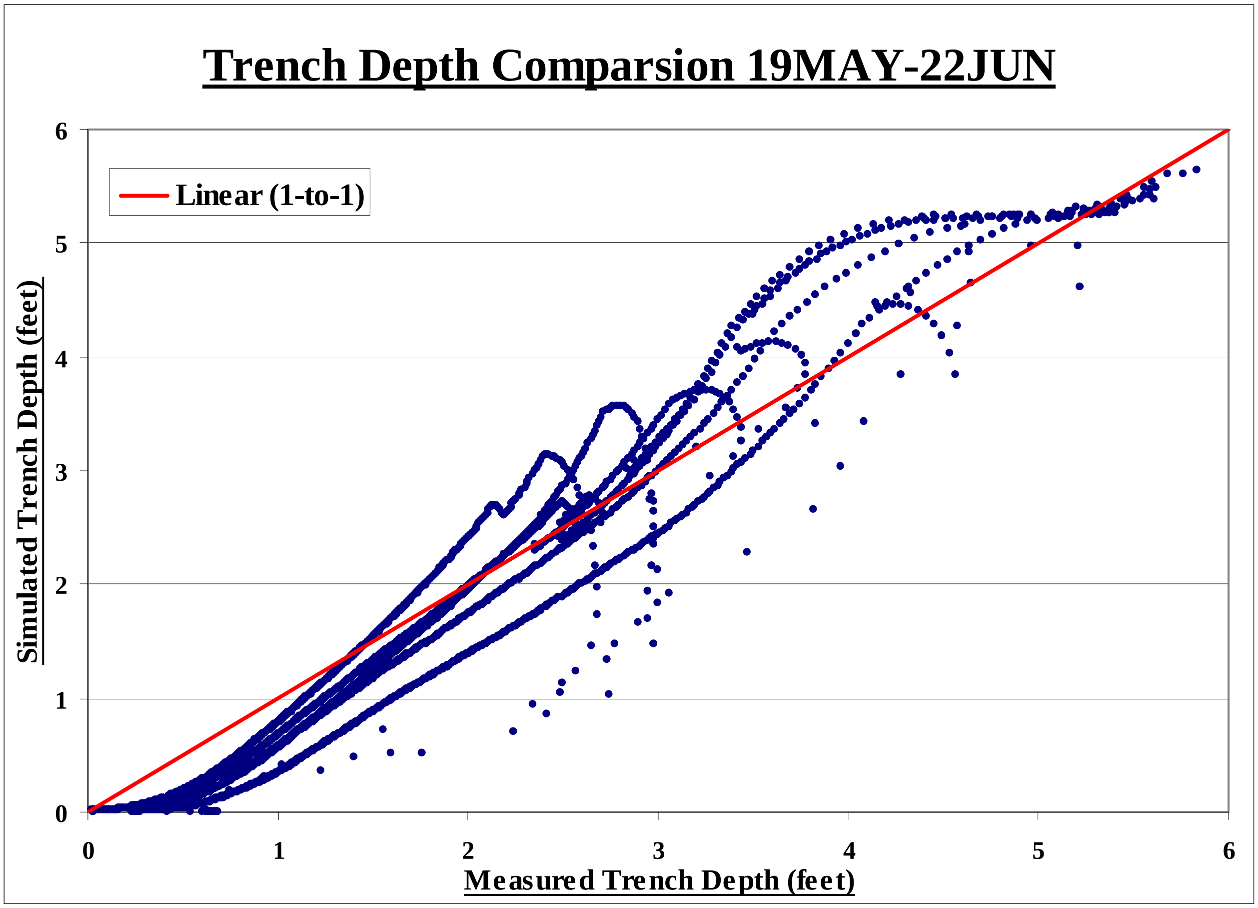

Figure 4-5 b: Simulated versus measured depth of water in the trench.

By choosing the "worst" visually matched data period and the "best" visually matched data period, the full range of performances by the model are examined. The entire year was not examined due to the large quantity of data and periods of missing trench depth data. The periods with missing data combined with the snowmelt events would not be relevant areas to perform a statistical comparison of the model.

The ideal relationship for this model would be a one-to-one correlation with the measured data. This relationship is represented by the straight line running from the origin to the top right corner in each plot. In Figure 4-5 a, the points generally fall closer to the line with only a few points straying further from the line. Figure 4-5 b has fewer points further away from the line, but the majority of the points have a larger range around the ideal line. In both figures, the points far from the ideal line occur while the trench is in the process of filling at the beginning of events. In these instances, the actual depth in the trench increases quickly as flows enter the trench and the timing of the model is slightly off. These points are very few but will have an effect on the overall accuracy of each set of data. The complexity of the trench filling with water was addressed previously in Section 3.7. This is a short period of time during each event, and does not drastically affect the accuracy of the model as a whole, but will be accounted for in the Spearman pair-wise statistical analysis performed in Section 4.3.2.

4.3.2 Spearman Pair-wise Statistical Analysis

A Spearman pair-wise correlation analysis was performed on the two time periods selected. The analysis compares depths produced in the model to the actual depths in the trench at each point in time. In order to prove that the model is capable of accurately modeling the depth of water in the trench, a null hypothesis is developed (H_0). The null hypothesis is tested by comparing the two sets of data on a point by point basis. If the two sets of data have no relation to each other, then the correlation coefficient is zero. If the two sets of data are positively related, then the correlation coefficient approaches one. If the two sets of data are inversely related, then the correlation coefficient approaches negative one.

In this case, the null hypothesis states that the simulated trench depth data has no correlation to measured trench depth data. Assuming that the null hypothesis is true, the correlation coefficient should approach zero. The plausibility (P) that there is no relationship between the two sets of data will approach one (100%). The two sets of data were compared and the results are documented in Table 4-2.

Table 4-2: Statistical analysis of selected time periods

Spearman Pair-wise Correlation		
	19MAY - 22JUN	**22FEB - 31MAR**
Correlation Coefficient	**0.978**	**0.966**
Sig. (2-tailed) *P*	***P*<0.001**	***P*<0.001**
Data Points	**3227**	**3552**

The results of the test show that neither period of time examined produces a correlation coefficient close to zero. Both correlation coefficients approach one, which rejects the null hypothesis that there is no relationship between the simulated and actual data sets. Since the correlation coefficient approaches one in both cases, it is proven that the simulated and measured depths do relate to each other positively. The plausibility (*P*) that there is no relationship between the two sets of data is virtually zero in both cases, which means that there is virtually no chance that the two sets of data are related by coincidence. In other words, less than one in 1,000 simulated depths will not represent the actual depth observed in the trench at that time. The "worse" of the two periods as determined visually turns out to be the stronger relationship statistically. This is explained by the deviance in depths as the trench initially fills. This part of any event is highly variable with multiple factors contributing to the depth observed and can be seen during both time periods.

4.4 Overflow Comparison

Complete verification of the model also includes a comparison of overflow volumes. The first comparison of measured overflows to hydrologically simulated SWMM 5 overflows took place by summing the flow measured by the Palmer-Bowlus flume located in the overflow pipe and comparing that volume to the simulated overflow on a single storm basis. However, this method was a viable option for only one storm in 2006, because the flume was only in operation as a calibrated and verified instrument for a few months of the year. In addition, the method only works if the trench overflows, but does not also overflow through the trench surface. If some of the overflow is exiting through the porous paver surface, then the total flow measured at the overflow pipe is not the only overflow mechanism taking place and is not an accurate measure of the total overflow volume. Only one storm fit these criteria and is shown in Table 4-3.

Table 4-3: Simulated SWMM overflow compared to Measured Flume overflow

Decemeber 25, 2006 Storm					
	Rain	**Measured Flume Over Flow**	**Simulated Overflow**	**Difference**	**% Difference**
Units					
[cubic feet]	1224	662	822	160	19
[inches]	0.72	0.39	0.48	0.09	19

The simulated overflow volume was greater than that which was measured exiting via the overflow pipe by 19%. This could be attributed to several aspects of the site, which have been discussed previously. The most likely reason is the loss of runoff before it reaches the trench, which is known to take place on site but is not accounted for in the model. The second reason is that some of the overflow may have exited the trench through the surface rather than through the pipe, although not likely considering the maximum depths of water observed at the trench were less than the top of the overflow pipe. Since this method of comparison was not very effective at comparing simulated overflow to measured overflow and could only be applied to one event, another method was developed.

The simulated overflow volumes were compared to measured overflow volumes on a storm by storm basis. Overflow volumes were calculated using field measurements and storm-specific developed characteristics. Individual infiltration rating curves were developed based on trench depth readings versus time for each storm. Flow volumes exiting the trench in the SWMM 5 model were taken from the overflow outfall and were summed for the duration of the event. A comparison between these actual calculated overflows and the SWMM 5 simulated overflows is seen in Table 4-4. The storms were again selected so that the majority of the overflow was taking place through the overflow pipe, but overflow through the surface is accounted for in both the model and the calculated actual flows.

Table 4-4: Storm by storm comparison of calculated and simulated overflows.

Storm Date	**Rain**	**Volume**	**Calculated Overflow**	**Simulated Overflow**	**% Difference**	**Volume Difference**
	[in]	[cubic feet]	[cubic feet]	[cubic feet]	[%]	[in]
11-Oct	0.91	1550	1060	1200	13	0.08
27-Oct	2.93	4980	3920	4460	14	0.32
7-Nov	2.69	4570	3760	3940	5	0.11

The calculated overflow volumes were determined by measuring the incoming flow to the trench. The calculated volume infiltrated and change in storage volume over the course of the storm were subtracted from the inflow, in order to obtain the volume that overflowed. The comparison shows that the simulated overflows are similar to those calculated on site with a slight overestimation of the volume of water leaving the trench via the overflow pipe. This slight overestimation is explained by the fact that the model does not include the initial abstractions on site. If the previously discussed losses are subtracted, the error drops significantly. With the focus of the SWMM 5 model being the simulation of the drainage area as designed and not as it is performing in the field, this is an expected difference. The calculated overflow volume depends partially on the measured inflow to the trench, which excludes the volume lost in those initial abstractions. All of the storms examined are larger storms with consistent losses for the duration of the storm. The storm on October 27th has a larger deviation in the volume of overflow, as the storm was a slow, steady rain that allowed runoff more time to leak through the cracks of the deck. These flows never enter the trench and are not measured as inflow since they flow to the old stormwater system, bypassing the trench.

Verification of the hydrologic model was accomplished through the comparison of actual and simulated trench depths, infiltration rates, and overflow volumes. Visual verification revealed the apparent accuracy of the hydrologic model and statistical and mathematical comparisons confirm that the developed model is capable of accurately simulating runoff flowing through the stormwater infiltration trench. Verification of overflow values is less thorough than the verification of infiltration drainage values, because of the lack of available storms with accurately measured outflow. The lack of accurate overflow data is due to the fact that there are multiple overflow mechanisms and the volume flowing over the flume is the only measured overflow.

4.5 Snowmelt Deviation

Although snowmelt events are not included in this model, the majority of snowmelt events can be considered completely infiltrated into the trench for the studied period. As long as a torrential rain does not accelerate the melting process, then the runoff rate will not exceed the infiltration rate and the trench will not overflow. Figure 4-6 is a comparison of the water depth in the trench over the course of a snowmelt event as compared to the simulated depth.

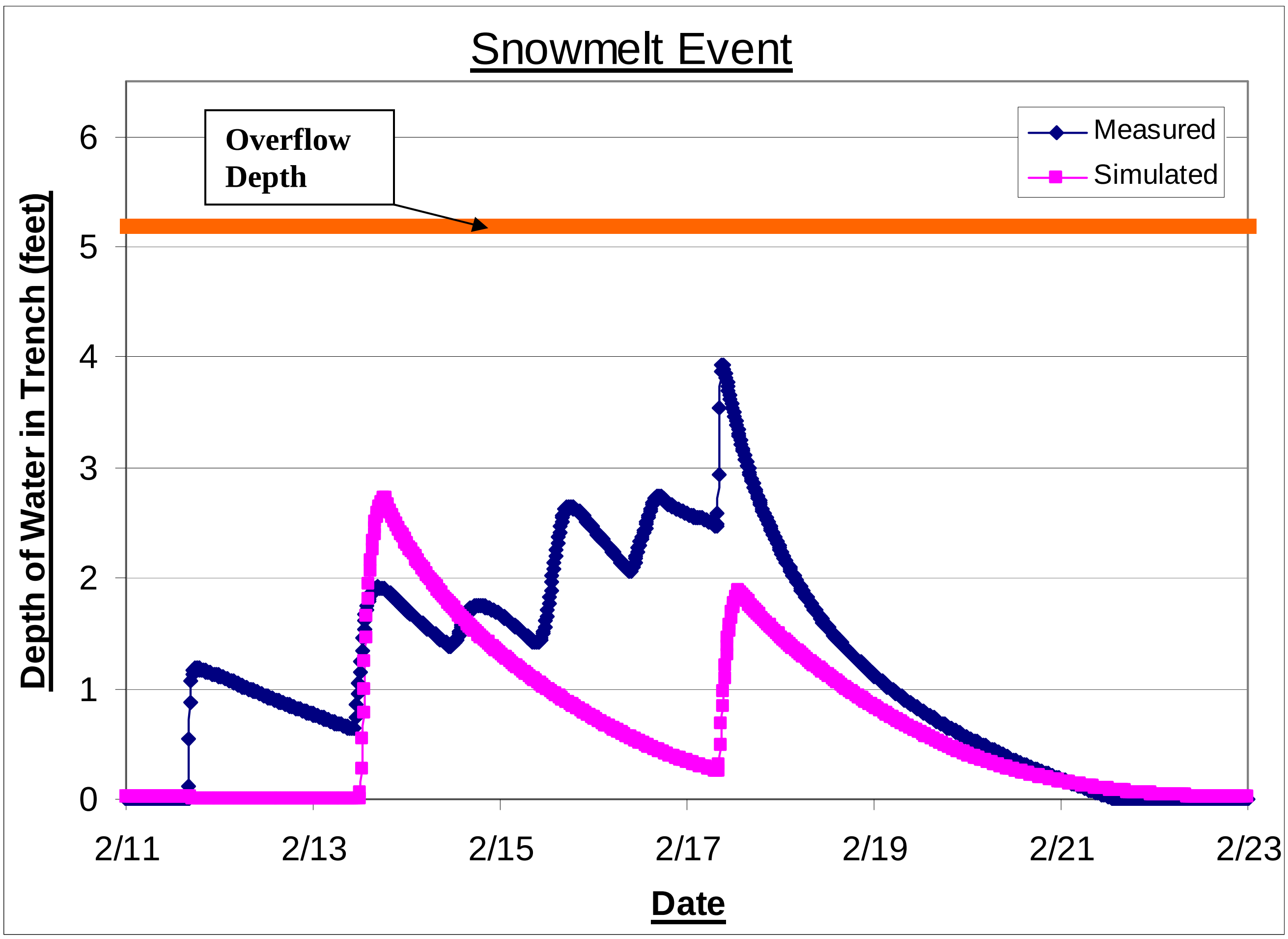

Figure 4-6: Depth of water in the trench during a snowmelt event.

Figure 4-6 illustrates the fact that the simulation does not account for snow melt. There are two peaks in the simulated depth, which were the result of precipitation reaching the tipping bucket rain gauge; this could have been the result of accumulated snow on the gauge which melted as temperatures rose. It appears, in this case, that small amounts of rain did fall since the depth changed abruptly in both the model and in the actual trench data at these two points. The smaller, more gradual changes in depth seen only in the actual data are the result of snowmelt without rain. Even with this rather large snowmelt event, the depth of water in the trench only reaches a maximum of four feet and does not come close to overflowing. It is also important to note that snow falling on this site is typically removed quickly since it is a parking area. Most of the snow is plowed to the opposite end of the lot from the trench and pushed over the edge, which removes it from the drainage area of the trench. Figure 4-7 shows the snow piled below the opposite end of the parking deck.

Figure 4-7: Snow cleared from the upper-level parking deck

A similar snow-clearing procedure would likely be in place at any such public parking area. Snow is commonly piled into a small area, which melts much more slowly than snow spread uniformly over an entire area since the surface area exposed to warming air temperatures and solar radiation is decreased.

Snowmelt events can certainly be significant in some watersheds, but is considered insignificant on this site. Considering the typically small size of areas draining to infiltration trenches and typical snow removal practices, any significant snowmelt runoff event will usually take place slowly enough that a trench will not fill completely, which means that all of the inflow will infiltrate into the ground. For the purpose of this simulation, it is assumed that any significant amount of snow that falls on the drainage area is removed since it is a parking lot. If the snow is not entirely removed, as it was not in February of 2006, then the rate at which it melts will not exceed the rate at which the trench is capable of infiltrating water on any given day.

CHAPTER 5 - TRENCH SIZING AND COMPARISONS

5.1 Introduction

The model developed has been verified to accurately simulate the hydrologic flow of stormwater through the VUSP infiltration trench BMP. Since it is verified, the simulation model is a tool for comparison and forecasting the BMP's expected operational performance. It is important to realize that the model is created for this specific site, and its inherent characteristics. Hydrologic patterns and local climatology for the Philadelphia region as well as soil characteristics surrounding the trench, trench geometric shape, and site construction techniques all affect the performance of the infiltration trench. Changing any of these parameters produces altered annual infiltration estimates. Utilizing this model for a site other than the VUSP infiltration trench would require the input of data specific to that site and will be discussed further in Chapter 6.

This chapter explores the affect of varying the size of the drainage area contributing to the infiltration trench. Infiltration BMPs have proven in many cases to be effective decades after construction (Dechesne et al., 2005). Sustainability remains a concern despite such studies. The concern is warranted considering the complications in excavating and rebuilding these structures, and the associated costs. To reduce the risk of failure due to clogging, the volume of runoff that reaches the BMP is often restricted by restricting the size of the drainage area contributing to the structure. Limiting the water entering the trench limits the volume of fine sediments, which is the primary concern. The most common method of sizing an infiltration structure footprint to the drainage area contributing to it is to create a simple ratio between the two (DA:BMP). There are different recommendations for this ratio and no exact ratio applies to every site but a maximum impervious area to infiltration structure footprint ratio of 5:1 is recommended (PA BMP Manual, 2006). Some jurisdictions will allow higher ratios for “clean runoff” or “green sites”, where the runoff contains low concentrations of fine sediment. These ratios provide an initial size estimate but the exact volume of the trench will vary depending on the depth and subsurface geometry of the structure. The required storage volume is typically determined by a comparison between pre-construction and post-construction runoff volumes. The increased runoff volume from construction needs to be captured when comparing a certain design storm such as the 2-year 24-hour storm (PA BMP Manual, 2006). The ideal ratio of drainage area to infiltration BMP footprint will vary from site to site, with the variation of characteristics specific to each site.

Varying the size of the drainage area contributing to the infiltration trench in the verified model provides further insight pertaining to the ideal ratio to achieve intended goals. A continuous simulation allows the infiltration to be observed over the course of a year, rather than examining the effectiveness for an isolated storm (snap-shot) basis. Ultimately, the best fit DA:BMP will vary from one site to the next, but a continuously simulated approach provides a more comprehensive evaluation of an infiltration structure over an extended period of time.

As discussed previously, the infiltration trench has been intentionally undersized in order to accelerate the aging process of the BMP. Since the trench was originally constructed as large as possible with respect to nearby existing utilities, it is not practical to increase the size of the trench to better fit the drainage area. The size of the watershed could be decreased by diverting part of the contributing area back to the original stormwater system. This would create a drainage area that is closer to the recommended size considering the footprint area of the trench.

5.2 Contributing Area Variations

Different simulations were created with contributing areas of various size, creating different DA:BMPs. In order to determine a more appropriate drainage area, many different size watersheds were input into the model. Areas of 20,400 ft^2, 10,200 ft^2, 1300 ft^2, and 930 ft^2 in Table 5-1 were input into the model to gain a better understanding of what a reasonable drainage area is for this trench. These areas were chosen by considering local stormwater regulations and general rules of infiltration structure design. The different models are referred to by their DA:BMPs for the remainder of this study. The size and BMP footprint of the trench remain constant at 130 ft^2 while the size of the drainage area contributing to the trench varies for each simulation run.

Table 5-1: Model size and description.

DA:BMP	Drainage Area Description	Drainage Area	Trench Capture Volume / Drainage Area
		[Square Feet]	[Inches]
157:1	Existing trench drainage area	20,400	0.09
78:1	Half of the existing area	10,200	0.18
10:1	DA:BMP ratio of 10:1	1,300	1.45
7:1	Capture 2 inches of rain over area	930	2.00

The trench capture volume is divided by the drainage area in these calculations. At a depth of 5.2 feet the trench void space is 155 ft^3. 5.2 feet is the trench depth at which overflow begins. The storage in the trench when it is completely full (approximately 6.0 feet) is 200 ft^3. The simulation with a ratio of 157:1 is the verified model with the drainage area set to the size currently present on site. The simulation with a ratio of 78:1 is the ratio when the original drainage area is halved. The simulation with a DA:BMP of 10:1 is the drainage area sized to have a drainage area of 1,300 ft^2 and is a ratio twice the size of the recommended DA:BMP of 5:1 (PA BMP Manual, 2006). The DA:BMP of 7:1 is the drainage area that would fill the trench to the overflow pipe when exactly two inches of water fell on the drainage area, as can be seen by the capture volume for this model. The area is calculated by using the known storage capacity of the trench which is 155 cubic feet. Since the drainage area is completely impervious, the first two inches of rain multiplied by a specific area yields this volume of water. It should be noted that this volume does not include any infiltration that may occur as the trench is in the process of filling. The capture volumes are calculated as if that volume of water were to instantaneously arrive in the trench void space. Collecting the first two inches of rainfall from every event off an impervious area is expected to remove 95% of the runoff from that area annually (PA BMP Manual, 2006). The following study shows that this goal would be accomplished at the site of study if the drainage area contributing to the infiltration trench was decreased to produce a conservatively estimated ratio of 7:1. The models listed were included in an initial comparison, and provide further evidence that the current trench is severely undersized, and that a much smaller DA:BMP is required for increased performance.

5.3 Varied DA:BMP Infiltration Comparison

These three new models were created and were simulated along with the model of the existing trench for the entire year of 2006. Such large changes in contributing drainage area drastically decrease the volume of water that flows into the trench. A comparison of trench depth over the course of the year is one way to express this difference. Figure 5-1 shows a comparison of the four simulated trench depths for the month of June.

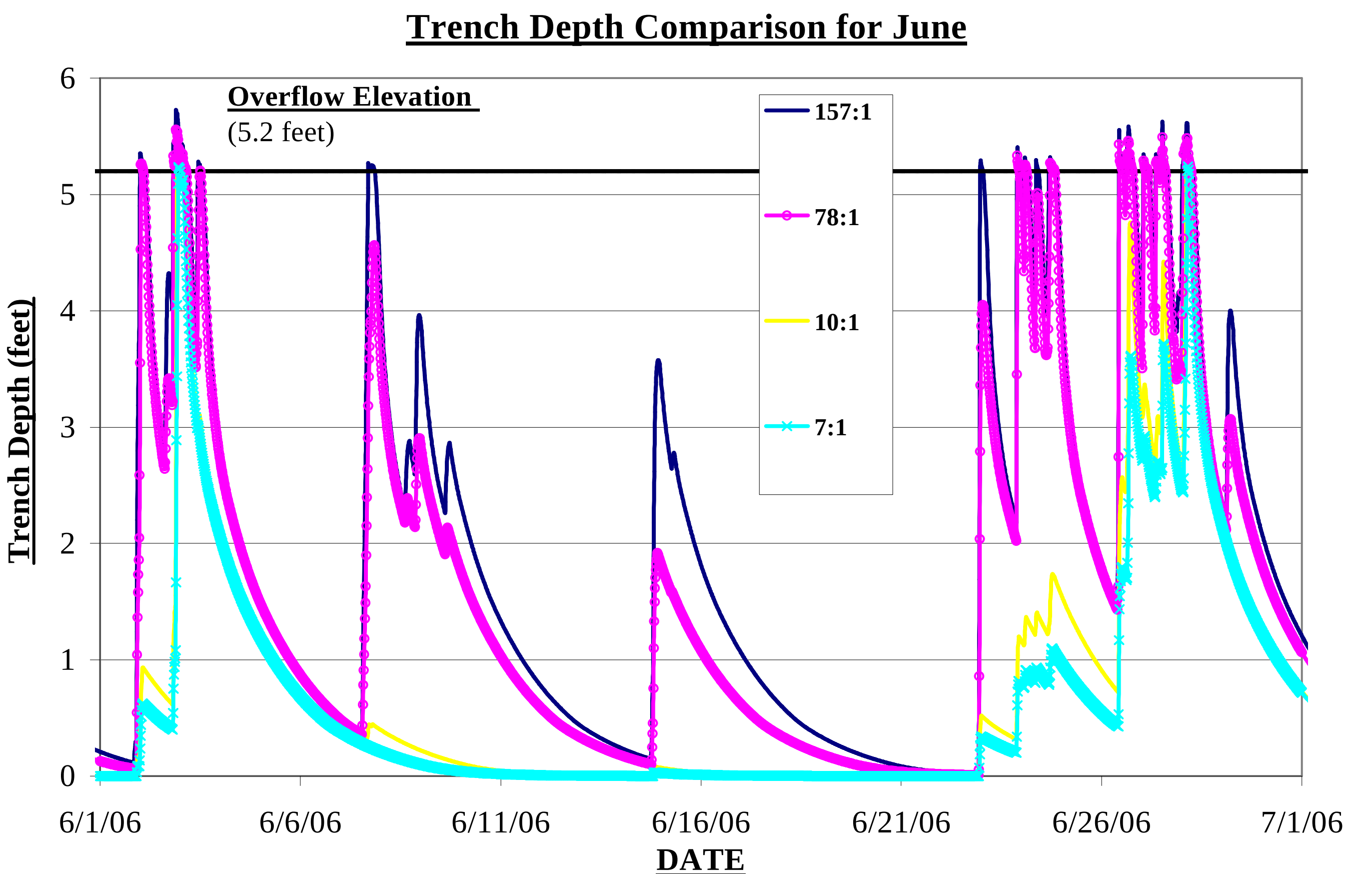

Figure 5-1: Trench depth comparison of varying drainage area models.

Visual examination of the data was performed on smaller time periods, such as Figure 5-1above, so that any differences in the data could be seen. As shorter periods of time are plotted on the x-axis, the resolution between the simulation runs and events becomes much more refined. This is seen when an individual storm such as the June 2^{nd} (Figure 5-2). The full year of data is plotted for these four model simulations and is in Appendix D, but does not reveal much about the differences between the various models. The two storms that filled the trench for all simulations were storms of 3.23 inches and 4.17 inches. When simulations "10:1" and "7:1" filled the trench to the overflow pipe, the trench remained above the overflow depth for only a few minutes. This shows that the volume of water overflowing the trench is minimal even in substantial runoff events for these models. The drainage area that was decreased by 50% produced a similar trench depth curve to the original model. The smaller storms show the trench either not overflowing or taking longer to overflow when compared to the original model. The smaller events were each well below two inches, so they would not be expected to fill a trench that is designed to capture the first two inches of rain from the site. In fact, the volumes of these smaller storms were small enough that they barely even affected the depth of water in the trench for the models with smaller areas. This is visual confirmation that only very small amounts of runoff bypass the trench when it is more appropriately sized.

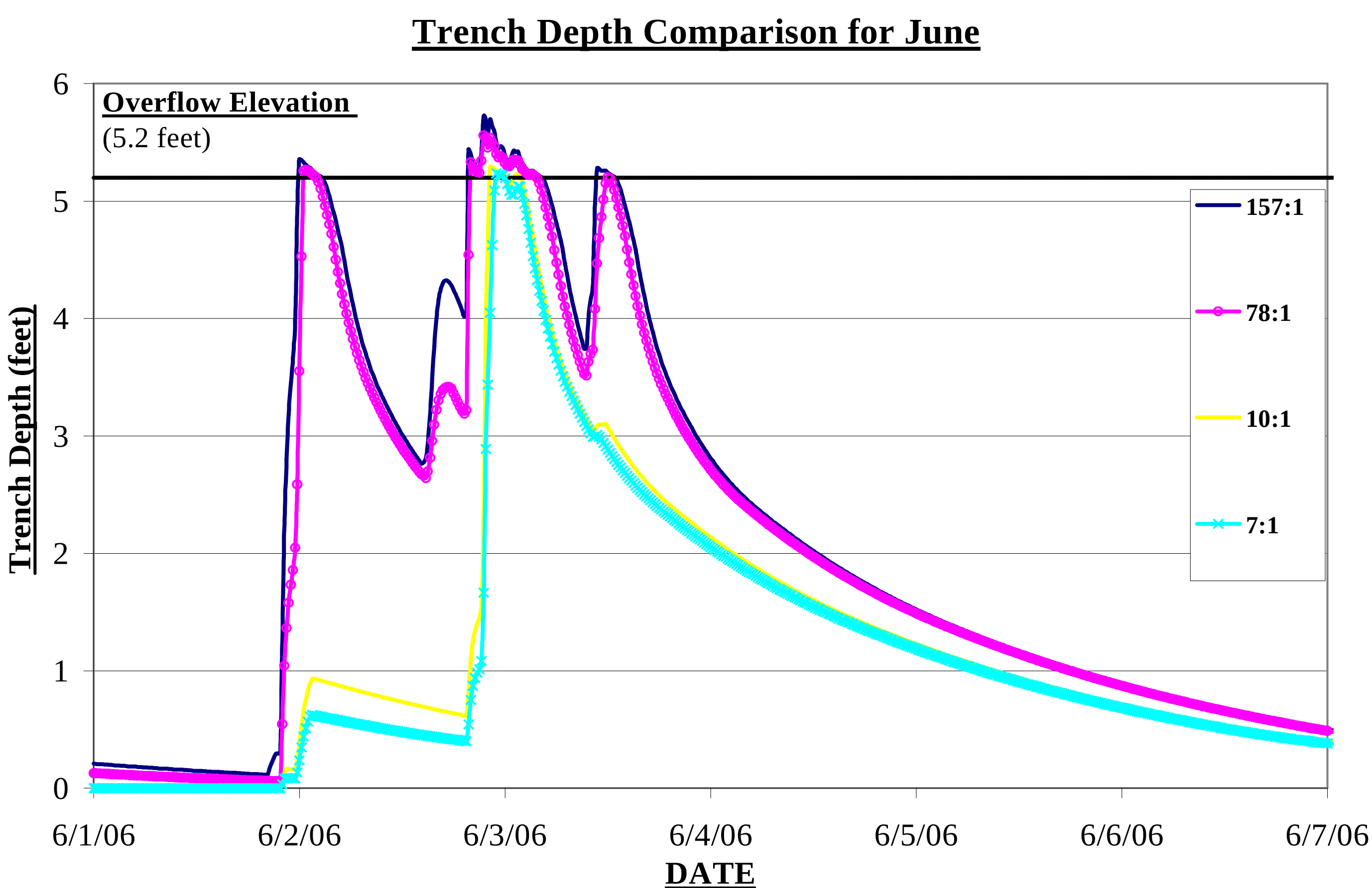

Figure 5-2: June 2nd, 2006 storm for the four model simulations.

Examining trench depths on a single event basis shows that the data that may have looked nearly identical over a longer period of time do differ. The "7:1" and "10:1" simulations did not overflow until the second peak of rain occurred in the June 2nd storm shown above while the two simulations with larger drainage areas overflowed a full day earlier. Some aspects that were not so apparent from the previous plot were the slight differences between the "157:1" and "78:1" simulations and the "10:1" and "7:1" simulations seen in Figure 5-2.

In order to compare the models numerically, the total volume overflowing the trench and total volume infiltrated over the course of the year were summed. The flow rates were recorded in the simulation as inflow, infiltration, and overflow in cubic feet per second. The volumetric flows are much greater in the original model than they are in the model with the smallest drainage area, so each flow volume was expressed as inches of runoff over its respective drainage area for comparison. The total flows entering, infiltrating through, and overflowing the trench for the different models are in Table 5-2. The percent of the total flow infiltrated is also included in the table.

Table 5-2: Flow volumes for various drainage areas for the year 2006.

DA:BMP	Inches over the Watershed			% Infiltrated
	Total Flow	Infiltration	Overflow	(% Total Inflow)
157:1	55.1	13.6	41.5	24.7
78:1	55	20.5	34.5	37.2
10:1	51.8	47.1	4.7	91
7:1	49.4	48.2	1.2	97.6

Analyzing the data in this fashion allows the infiltration to be calculated as a percentage of the total flow entering the trench. It is important to note that the total flow out of the trench decreases as the size of the contributing drainage area decreases. This is because smaller volumes of water are entering the trench. This significantly reduced total volume of runoff makes the model more sensitive to rounding errors. Since the trench experiences much more time with very little water in it, the infiltration rates are very low for long periods of time. This causes very small infiltration rates to be rounded to zero more often. The lost flows due to rounding while the trench is overflowing are not significant since the trench rarely overflows and only overflows for a short amount of time. Therefore, it is assumed that the additional 5.7 inches of flow lost from the simulation “157:1” to the simulation “7:1” could be added to the total infiltration. This study does not include those additional flows in comparison of the various simulations, and will examine the infiltration as a percent of the total flow observed exiting the trench.

The percentage of flow infiltrated varies from approximately 25% for the largest drainage area simulated to 98% for the smallest drainage area simulated. The existing trench still infiltrated nearly 25% of the runoff from the parking deck, despite having a bottom infiltrating surface that is severely clogged. As mentioned previously, the goal of capturing the first two inches of any runoff event is to reduce annual runoff from that site by 95% (PA BMP Manual, 2006). Since 98% of the flow that entered the trench was infiltrated in this simulation for the year 2006, this BMP would have exceeded expectations if the drainage area was sized more appropriately. The amount of rain for the year of 2006 that fell on the site was over 55 inches. That means the year was an above average year of precipitation in comparison to the average annual regional amount of approximately 42 inches. The year also included several large storms so it was an above average year for precipitation. Modeling such design criteria can verify the effectiveness of these regulations.

The developed simulation model proves that if it were designed to meet state BMP design regulations, then the goal of reducing annual runoff from impervious surfaces by 95% would be accomplished. In fact, considering the percent infiltrated and the above average amount of precipitation for the region seen in 2006, such a structure might be considered over-designed. This over-design leads to cost concerns related to wasted space and excessive excavation and fill when constructed. The ideal design would be that which fulfills the requirements of the regulation while minimizing the size of the structure. In order to eliminate the chance that 2006 was an abnormal year of rainfall, another year of simulation would be necessary. Further exploration of different sized trenches is carried out in Section 5.5. Section 5.4 examines the trench sized to capture two inches of runoff in further detail.

5.4 Storage Capacity of a Trench Sized to Appropriate Capture Volume

The greatest advantage of utilizing a continuous flow model in order to simulate the flow of water through a BMP is that antecedent conditions are accounted for in every event. Simulating isolated events at a particular BMP reveals its capacity if every event were to begin while the facility is completely drained. In the case of this infiltration trench, which in its current state takes approximately a week to completely drain, it is rare that an event begins with all of the storage capacity available. A continuous simulation accounts for the volume of water that still occupies storage at the beginning of a new event. When a portion of the storage volume is occupied, the trench reaches the overflow depth more quickly. Isolated event analysis removes the effects of interdependency between events which can be a significant aspect in the overall evaluation of a stormwater BMP's effectiveness.

Examining a double-peaking event that took place over the course of several days in September of 2006 shows the results of three different methods of simulation (Figure 5-3). The first method breaks the event down into two separate events (Isolated Events). Each portion of the storm is individually simulated, and the trench is completely empty. The next method is a continuous simulation of the double peaking event alone (Continuous Event). The trench is assumed empty at the beginning of the simulation, but simulation never stops, and the trench is not assumed empty at the beginning of the second portion of the storm. The third method is a snapshot of the event as it occurred as part of the continuous simulation of the year of 2006 (Continuous 2006). Figure 5-3 shows trench depths for the storm simulated using the three methods described using the same rainfall data from a single storm.

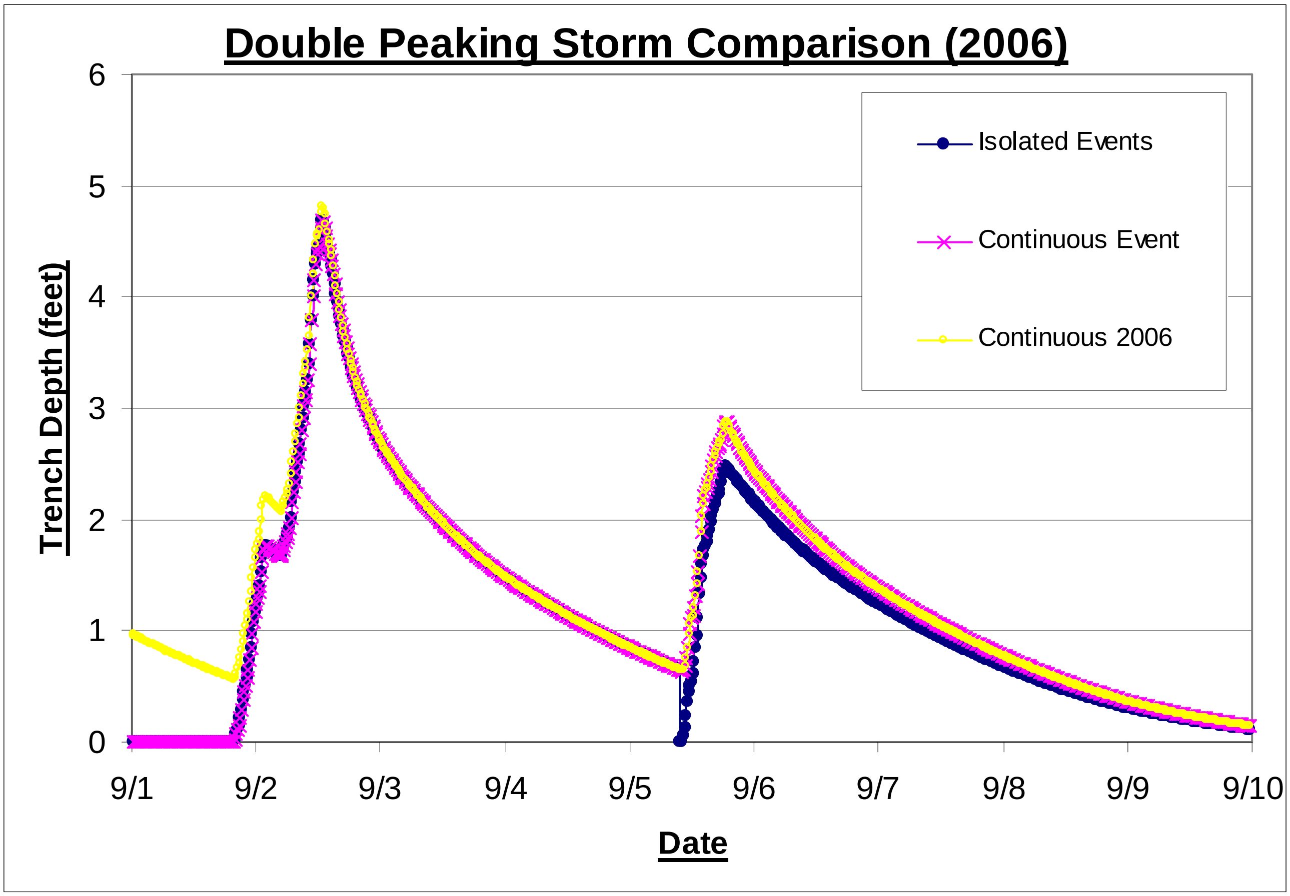

Figure 5-3: Comparison of trench depth for different modeling techniques

For this simulated event, the trench never reaches the overflow pipe for any of the methods used. The "Continuous 2006" simulation represents conditions at the trench for this particular event most accurately, because it accounts for the water still present form the preceding storm at the beginning of the simulation. The "Continuous Event" simulation becomes more accurate as it is further removed from the original assumption that the trench was empty at the beginning of the simulation. The "Isolated Events" simulation treats each peak as a separate event, so accuracy is lost at the beginning of each one, since it is assumed that there is no water occupying the trench for each event. These three variations illustrate the effects of isolating events, rather than modeling them continuously.

An important aspect of this model to note is that the different methods used converge with time. An entire year of data does not have to be modeled in order to obtain accurate data.

Examining the data from the three simulations in Figure 5-3 reveals that continuous modeling and isolated event modeling can produce very different results. To look at the storm more specifically, the total precipitation occurring over the course of the storm is 3.68 inches; 2.67 inches fall in the first peak and 1.01 inches fall in the second peak of the storm. The first peak of the storm is identical between the "Continuous Event" simulation and "Isolated Events" simulation. It is not until the second peak of the storm that the data differs, because the two models began with the same initial trench condition of an empty trench, and were subjected to the same rain data. The divergence occurs when the second peak of the storm begins and the isolated event model has an initial trench condition of zero once again. The continuous model still has a depth of water of approximately 0.70 feet when the second peak begins to enter the trench, which decreases the storage volume available for the second portion of the storm. When analyzed as two separate events it would be assumed that any water left in the trench at the end of the first storm would be infiltrated before the beginning of the next storm and would not occupy any of the trench's volume. This is not what actually happens at the site, since water from a previous storm may not have enough time to completely drain from the trench. Table 5-3 is a tabulation of the total infiltration and maximum depth of water simulated using the three different modeling methods.

Table 5-3: Comparison of infiltration and maximum depth of water in trench

Simulation Method	Infiltration	Max Depth of Trench
	[inches]	[feet]
Isolated Events	3.04	4.69
Continuous Event	3.24	4.69
Continuous 2006	3.55	4.82

Table 5-3 shows the differences between the modeling techniques. The infiltration is a summation of the flow leaving the trench through the "infiltration" node in inches over the watershed. The volume of simulated infiltration is the least when the two peaks area analyzed separately. In this method, the two peaks of the storm are isolated, but are plotted together. Note that the amount of water left in the trench at the end of the first peak is lost, since it is not accounted for as infiltration or stored water. The difference of volume of water infiltrated between the simulation "Continuous Event" and "Isolated Events" can be attributed to the fact that the trench is incorrectly assumed to be completely empty at the beginning of the second peak of the event. Therefore, the "Continuous Event" simulation more accurately depicts the amount of infiltration that took place over the course of the event. The volume of water infiltrated in the "Continuous 2006" simulation is the highest volume at 3.55 inches, because the trench was partially full for the entire simulation. This was because a preceding storm had not completely drained yet. The "Continuous 2006" simulation infiltrated runoff for nearly an entire day before the other two simulations were subjected to runoff. In a larger storm, this simulation will be the first to overflow, and will most accurately simulate the volume of overflow for that event. Simulating double peaking storms using a continuous modeling method most accurately simulates both overflow and infiltration volumes at a detention and infiltration facility, such as the VUSP infiltration trench by accounting for antecedent conditions.

Another important aspect to be observed is that the trench never overflows over the course of a storm that totaled more than three inches of rain. The infiltration trench modeled in this case is designed to capture two inches of runoff from the watershed. The 3.68 inches of rain occurs over a several day period, but the first peak produced nearly 2.5 inches of rain in less than 24 hours and the trench did not overflow. This proves that the volumetric storage capacity of an infiltration BMP exceeds its design as infiltration is always occurring. A storm that produces two inches of rain instantaneously does not exist and even a storm that produces two inches of rain in less than thirty minutes is very rare. Any trench designed to capture a specific volume of runoff will always be able to capture more runoff than the design volume, since infiltration begins as soon as runoff reaches the trench, and it always takes time for the complete volume of runoff to reach the trench. This additional volume is not accounted for in any isolated analysis of a structure, but can be accounted for cumulatively in a continuous simulation, such as the one developed in this study.

5.5 Annual Infiltration with Varying Contributing Area

An examination of the relationship between trench size and percent infiltrated runoff was the next logical step in determining the most efficient BMP design. New drainage areas were calculated as percentages of the current watershed area. Since these percentages are not relevant to anything other than this specific site, they were converted to DA:BMP. This is a more useful format, since it can be used for trench design outside of this model and site. This is not to say that this model will provide the exact DA:BMP at any site, but it provides an estimation of the best BMP footprint area for a site. The efficiency curves and other work that follow are still specific to this site, and could not be utilized at another site without understanding and adjusting the appropriate parameters. The design of any infiltration structure is restricted by conditions specific to the site, such as available area and trench depth. Soil type is an additional concern, but it is assumed an infiltration BMP would only be considered in an area with suitable soil for infiltration.

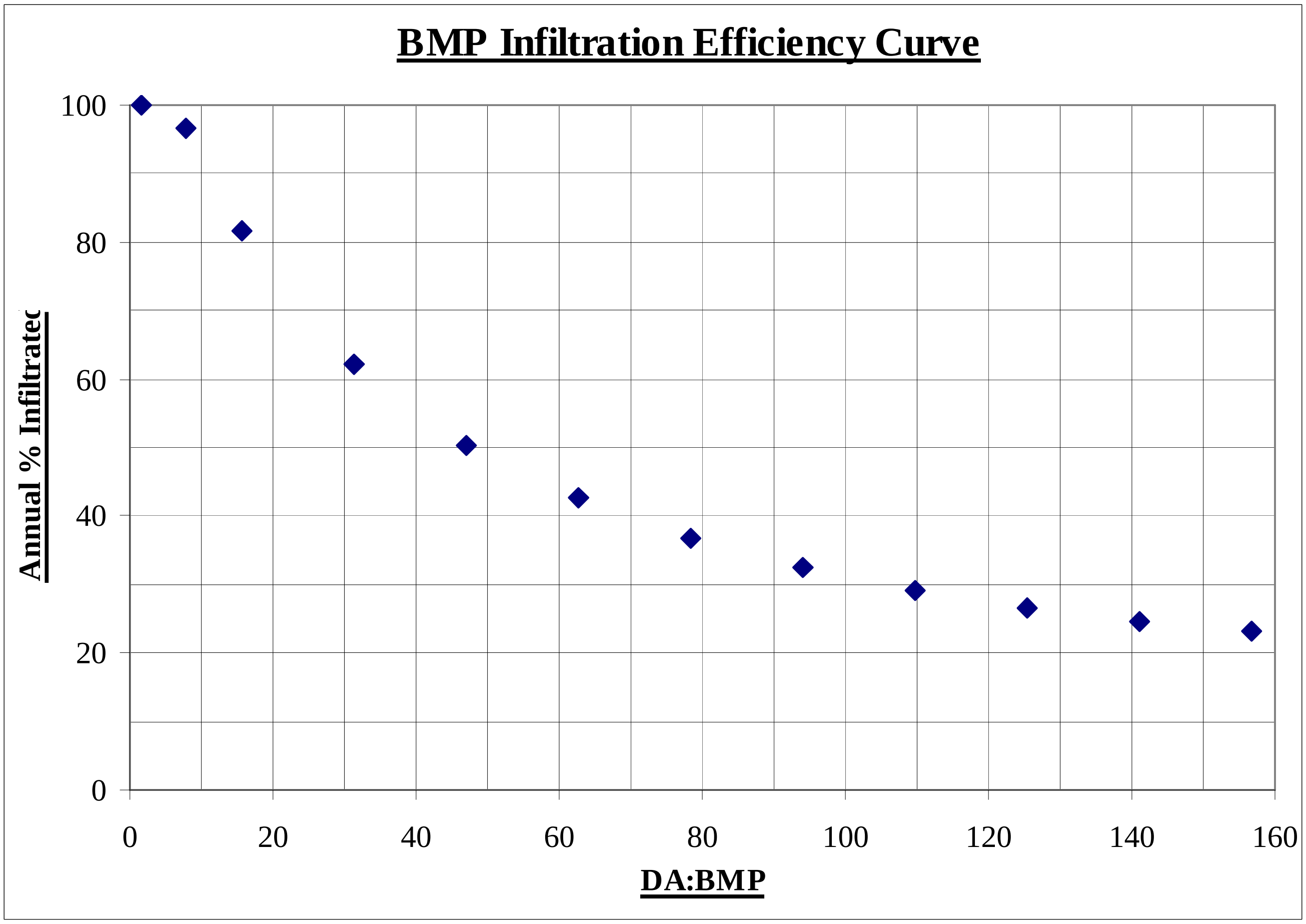

Figure 5-4: Plot of DA:BMP versus % Infiltrated.

The initial plot of DA:BMP seen in Figure 5-4 looks at a broad scale of different areas, and represents trenches from those that are severely overburdened to those that are over-designed (under-burdened). This plot is much more helpful on a smaller scale focused on the point of interest and could be used as a design tool. The point of interest; the inflection point (where the curve turns from concave down to concave up) represents the most efficient DA:BMP for design which is 13.5 for the infiltration trench simulated. Figure 5-4 can also be used by choosing the desired percent of infiltration and identifying the corresponding ratio. Points around the inflection point were simulated for the year of 2006 to produce a more useful plot. The area, DA:BMP, and % Infiltrated are tabulated below in Table 5-4 for different percentages of the current drainage area.

Table 5-4: Percent of drainage area and corresponding percent infiltrated.

% DA	Area [acres]	DA:BMP	% Infiltrated
15	0.070	23.5	71.3
11	0.051	17.2	80.1
10	0.047	15.7	81.5
9	0.042	14.1	84.7
8	0.037	12.5	87.3
7	0.033	11.0	90.0
6	0.028	9.4	93.6
5	0.023	7.8	96.7
4	0.019	6.3	98.7
3	0.014	4.7	100
1	0.005	1.6	100

The table shows that a DA:BMP less than approximately 7:1 would not be a very efficient design because it would infiltrate virtually all of the runoff for the year. When the ratio is less than 7:1, the cost of constructing a larger trench outweighs the minimal increase in the amount of water infiltrated. On the other end of the spectrum, ratios above 20:1 begin to become ineffective in infiltrating a sufficient portion of the total runoff. Figure 5-5 is a plot of DA:BMP versus % Infiltrated, which is created from the data in Table 5-4 to provide a more useful tool.

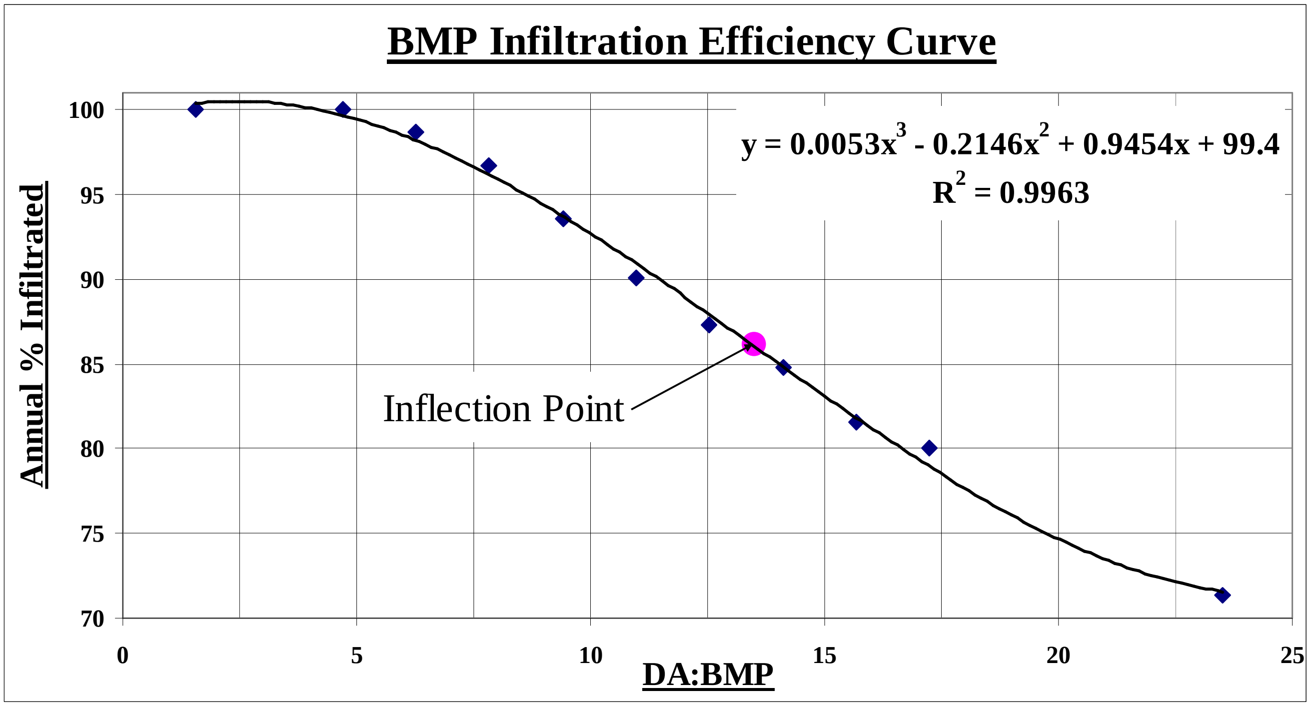

Figure 5-5: Plot of DA:BMP versus % Infiltrated

As illustrated in Figure 5-5, a polynomial equation of the third order was fit to the simulated data. The equation is as follows:

$$\%Infiltrated = 0.0053x^3 - 0.2146x^2 + 0.9454x + 99.4 \qquad \textit{Equation 5-1}$$

Where *x* is the DA:BMP and the line correlates to the data with a correlation coefficient of R^2 equal to 0.9963. The approximate location of the inflection point is between 8.5 and 17, which is helpful in providing a range for the most effective ratio. In order to obtain the true inflection point of the equation, the second derivative was taken. This produced the equation:

$$y = 0.0318x - 0.4292 \qquad \textit{Equation 5-2}$$

Where *y* is the second derivative of *Equation 5-2* and *x* is again the DA:BMP. Solving this equation when $y = 0$ yields the inflection point, which occurs when the DA:BMP = 13.5. It is important to realize that this exact ratio is specific to the site conditions, which include the trench geometry, soil conditions, and hydrologic data. Since this exact ratio is specific to the site and the hydrologic data for 2006, a general range of ratios may be more appropriate than the exact ratio. The straightest portion of the curve spans from a ratio of 8.5 to 14 with infiltration amounts ranging from 85% to 95%. This range may be more helpful than the inflection point for trenches constructed in similar soil and with similar geometric structure at different locations.

The curve can be used in collaboration with regulations to specify the percentage of runoff desired for infiltration. Since the goal of these regulations is to eliminate 95% of the runoff from the impervious area, a line is drawn from 95 on the ordinate until it intersects the curve. A line is drawn down from that point until it intersects the abscissa, which yields a DA:BMP of approximately 8.5. This is the ratio that would have captured exactly 95% of the runoff at this site in 2006.

An additional model was created with a drainage area sized to the calculated “Most Efficient” DA:BMP and was included in Table 5-1 previously as the model “14:1”. This ratio does not represent a trench that fulfills any regulation, but is the ratio that would allow maximum infiltration with regard to the amount of area used for the infiltration trench. This area was calculated to be 0.0404 acres (1760 ft^2) and is included in the following comparisons.

5.6 Flow-Duration Curves

Flow duration curves were developed for the different simulations, because another concern with urban development and the environmental impacts associated with that development are peak flows. Flow duration curves show the magnitude of peak flows and the length of time those flows are reached. Reduced peak flows are the primary goal in peak flow control, but another concern is to keep flows reduced before and after the peak as well. It is not necessarily beneficial to reduce the peak flow at the expense of increasing low flows over an extended period of time. By looking at a flow-duration plot (Figure 5-6), the percentage of time specific flows are exceeded can be seen.

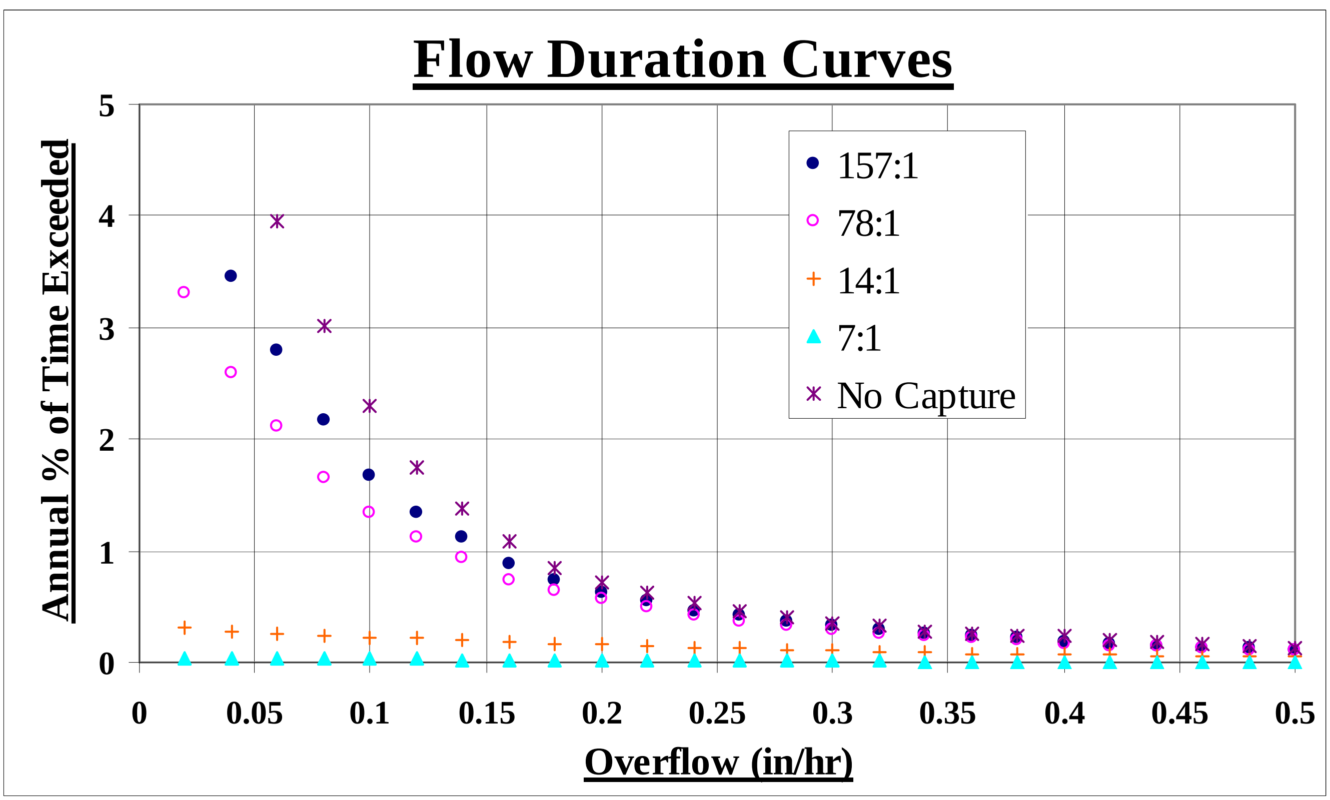

Figure 5-6: Flow-duration plot of models with varying contributing areas.

Two additional models of the site were developed as reference: “No Capture” is a simulation that examines flows leaving the site if the trench did not exist at all, and “14:1” is a simulation with the “most efficient” DA:BMP explained in Section 5.5. Expressing all of the flows as inches over the watershed allows one sized watershed to be compared to another. If it were not expressed in this fashion then only the obvious would be apparent; larger volumes of water would come from larger drainage areas. The curves show that as the drainage area becomes more appropriately sized to the trench, the percentage of time that increased flows are sustained decreases. Table 5-5 looks at a specific flow rate leaving the site (0.1 in/hr), and the amount of time that rate is sustained or exceeded.

Table 5-5: Comparison of time a flow rate is sustained for various models.

				Time exceeded		
Model Name	**Area [acres]**	**Flow [in/hr]**	**% of time exceeded**	**Days**	**Hours**	**Volume [in]**
7:1	0.0213	0.1	0.028	0.1	2.5	0.25
14:1	0.0426	0.1	0.228	0.8	20.0	2.00
78:1	0.234	0.1	1.35	4.9	118.3	11.83
157:1	0.468	0.1	1.67	6.1	146.3	14.63
No Trench	0.468	0.1	2.30	8.4	201.5	20.15

The table shows that a flow rate exceeding 0.1 in/hr exiting the trench overflow occurs 0.028% of the year in “7:1” in comparison to 1.67% of the year in “157:1” (current trench) and 2.3% if there was no trench on site. Each of these differences is appreciable, but to better illustrate the results from each model, the % of time exceeded was converted to days and hours and the total volume of flow leaving at or above a flow rate of 0.1 in/hr was calculated. Flow exiting the trench at a rate higher than 0.1 in/hr only occurs for 2.5 hours when an appropriately sized drainage area is applied to the simulated model, as opposed to the more than 146 hours of flows exceeding that same rate in the current trench. The total volumes leaving at or above these elevated rates are 0.25 inches and 14.63 inches for “7:1” and “157:1” respectively. It is clear that the trench is currently under-sized, but that if the trench were to be sized more appropriately to its watershed, that it would eliminate a very large portion of elevated runoff volumes, and the amount of time that those flows occur. Flows leaving the currently simulated site are still reduced in comparison to the developed site without an infiltration trench BMP.

5.6.1 Pre and Post-Construction Flow-Duration Comparison

Further examination of the site was performed in order to evaluate the effectiveness of a properly sized infiltration trench. The goal of an infiltration BMP is to maintain the runoff conditions of the site as they were before development. The BMP receives the unnatural runoff leaving paved surfaces and stores and infiltrates the water as it would have before construction. The best way to see if the structure is in fact accomplishing this goal is by comparing the runoff leaving the site in its native condition to the runoff leaving the site with the appropriately designed infiltration trench in place. The development of two more simulation models was needed in order to compare the site as it originally existed before the construction of the parking deck. These two models were titled “GA Pre-Dev” and “CN Pre-Dev” which represent the site being simulated using Green and Ampt and the NRCS Curve Number method respectively. These models and a brief description are seen in Table 5-6.

Table 5-6: Model names and descriptions for pre and post construction comparison.

Model Name	**Model Description**
GA Pre-Dev	Green and Ampt Method used on pre-development soil conditions
CN Pre-Dev	Curve Number Method used on pre-development soil conditions

It was assumed that the area was lightly developed before construction of the parking deck, so each model included 10% impervious surface. The soil on site was classified through the excavation of a test pit previous to construction. A mechanical grain size analysis was run on the soil excavated from the test pit and resulted in a composition of 73% sand, 23% silt, and 4% clay (Dean, 2005). This composition of soil is classified as a “loamy sand” according to the US SCS soil texture triangle or a type B soil according to the curve number method. This specific infiltration trench was not designed to reduce post-construction flows to pre-construction levels since the BMP since it is an experimental site and was intentionally undersized. However, with the development of the hydraulic model, and the ability to change the drainage area to a more reasonable size, the comparison became possible.

The parking garage was constructed before the trench, but it is assumed that the soil beneath is the same as the soil that was excavated from the trench itself. Parameters for a “loamy sand” were required in order to simulate the site in its “pre-construction” condition. The soil parameters used for both Green & Ampt and Curve Number infiltration methods are shown in Table 5-7.

Table 5-7: Soil characteristics used in SWMM for different infiltration methods.

GA			CN	
Suction Head [in]	2.4		Curve Number	61
Conductivity [in/hr]	0.74		Conductivity [in/hr]	0.74
Initial Deficit [fraction]	0.105		Drying Time [days]	10

The conductivity was taken as an average between the NRCS recommended rate for a type B soil and the rate recommended for a "loamy sand" (Rawls et al, 1993). Further explanation of the parameters above follows.

5.6.1.1 Curve Number

The existing site before construction is assumed to have been an open space in good condition. The SCS curve number assigned to the area is 61 which accounts for site conditions and the type B soil classification. The saturated hydraulic conductivity for an NRCS type B soil is between 0.15 and 0.30 inches per hour (EPA SWMM 5 Manual). A recommended value of 1.18 inches per hour is recommended (Rawls et al., 1993). The average of the two was taken and a value of 0.74 inches per hour was input into the model as well as a "Drying Time" of ten days for a soil to completely dry. The ten day drying time is a conservative estimate as typical drying times for soils are less than a week.

5.6.1.2 Green & Ampt

The Green & Ampt method was also used as a loss method for simulation of the site pre-construction. Its required parameters include a suction head which is input as 2.4 inches and the initial deficit is 0.105 (Rawls et al., 1993). The saturated hydraulic conductivity of 0.74 inches which was averaged as explained above was used again in this model.

5.6.2 Flow Duration Curve Comparison

The two simulations of the site in its pre-construction state were run, and compared to the simulation with the trench that was designed according to PA BMP Manual (7:1). This verifies that the regulation is achieving the goals that it is intended to fulfill. Figure 5-7 is a plot of flow duration curves.

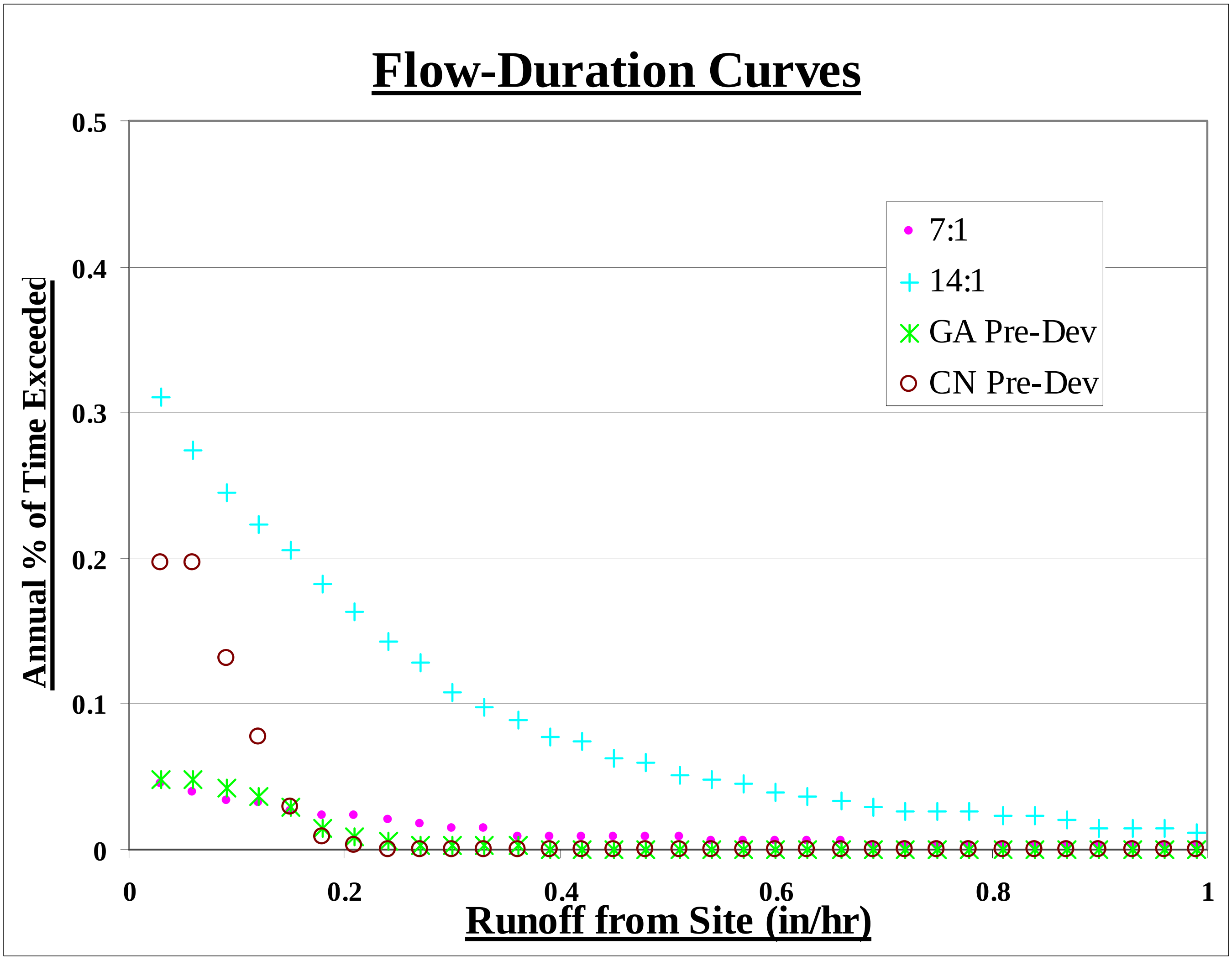

Figure 5-7: Flow duration plot for pre-construction comparison.

As expected, the site as it is currently designed produced elevated flows for longer periods of time when compared to the site pre-construction. The elevated flows are due to the paving of the entire drainage area and the undersized infiltration trench. Also, note that the SCS Curve Number simulation produced slightly higher low flows than the Green & Ampt method. This can be attributed to the fact that the curve number method accounts for pervious runoff and impervious runoff separately, whereas the Green & Ampt method accounts for impervious runoff to flow over pervious surfaces before leaving the site. Therefore, the 10% impervious area included in the simulations is the primary reason for the discrepancy between the two pre-development models. Figure 5-7 shows that the “14:1” simulation has higher volumes of runoff overflowing it than any of the other simulated trenches for the year. The two inch capture design (7:1) produces flows similar to those of the native site, which proves that it does accomplish the goals of state regulations for the year of 2006. While the “14:1” simulation produces heightened flows compared to the other simulations, it does not show signs of being extremely overburdened. Figure 5-6 illustrates the difference between an overburdened trench (157:1) and the “14:1” simulation. The “14:1” simulation was designed to provide the highest percentage of inflow infiltrated with respect to the size of the contributing area. It was not designed to infiltrate a specific amount of water or to restore the native hydrologic conditions.

5.7 Depth-Duration Curves

Depth–duration curves are similar to flow-duration curves except that the depth of water in the trench is monitored rather than the flow leaving the trench. Although they are most commonly used for structures, such as reservoirs, for drought and flood planning, they are also helpful in this situation for determining how quickly the trench is draining and the likelihood of it being full to a certain depth at any given time. When examining a single storm event, the depth of water in the trench at the beginning and end of the storm is needed to evaluate performance. A continuous hydrologic is capable of modeling these depths from one storm to the next. A depth-duration curve can provide the likelihood of the depth being at or below a certain level at any time. Included in the models for the depth duration plot shown in Figure 5-8 is a model which was designed using the “Efficiency Curve” developed earlier. This simulation is called “8.5:1” and was sized so that it would have captured and infiltrated 95% of the flows entering the trench in 2006 (DA:BMP = 8.5).

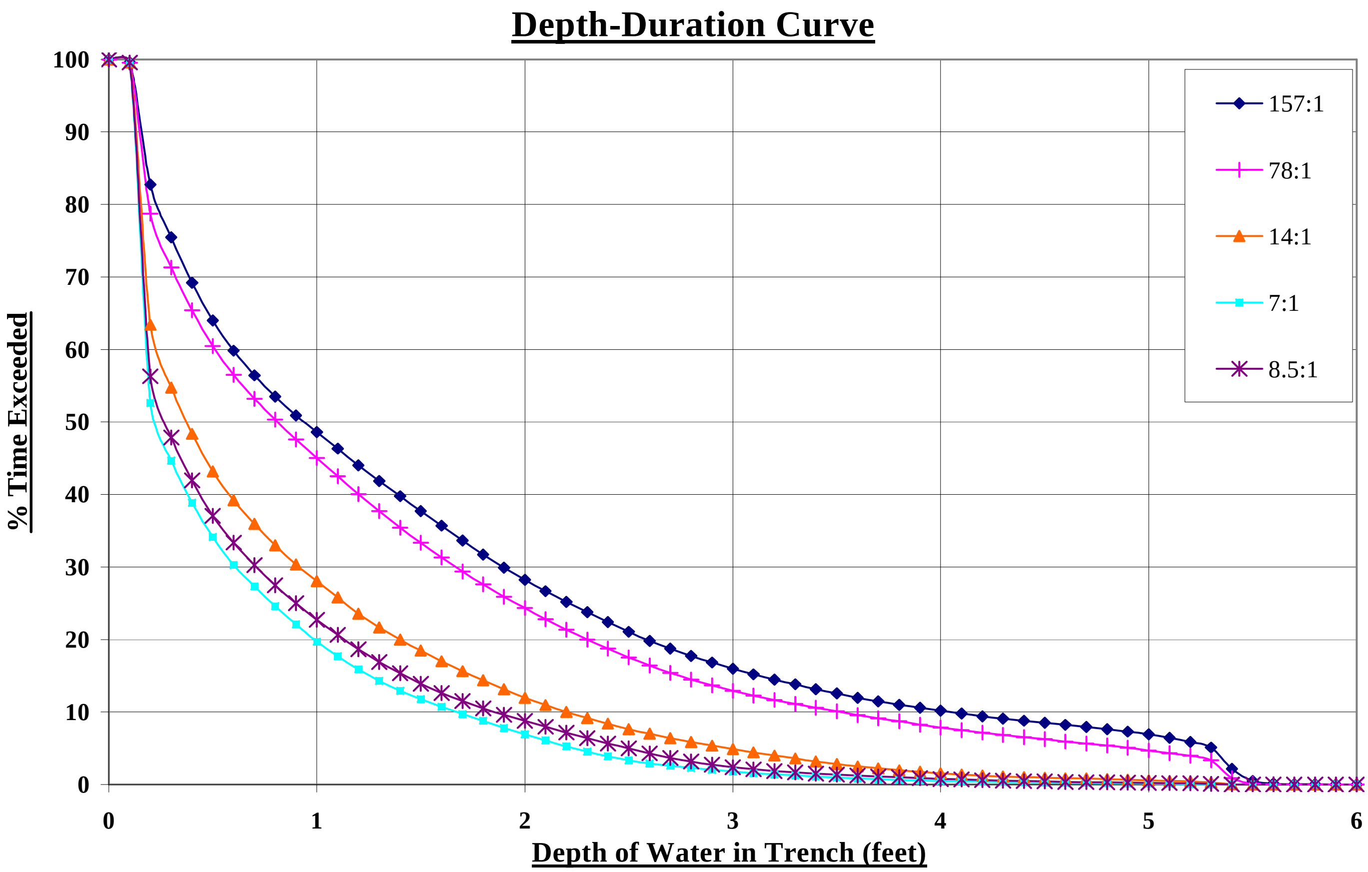

Figure 5-8: Depth duration plot for models with varying drainage areas.

Figure 5-8 shows the "fullness" of the trench as it is sized now, and compares it to several smaller drainage areas. The result of a smaller drainage area is a trench that is less full more often. Looking at the plot shows that the trench as it currently exists had at least two feet of water in it for more than 28% of the year (over 100 days). Compare that to the "7:1" simulation, which was two feet full for less than 7% of the year (less than 26 days). These percentages also represent the likelihood that the trench will be that full at any given time. So there is currently a 28% chance that at the beginning of any runoff event occurring on site, the trench will have two feet of water occupied by residual water, and will not be available for new runoff storage. This number is very high, because the trench is so over-burdened, but it could be more helpful for trenches that are more appropriately sized. For example, the "7:1" simulation has the trench three feet full less than 2% of the year (less than a week). There is less than a 2% chance that it will have three feet of water occupying its storage capacity at any given time.

The verified continuous hydrologic model developed in this study is used as a tool to determine a more appropriate sized contributing area for the VUSP trench. This model is specific to the site and its conditions, but also proves that the trench is capable of achieving stormwater regulations if it were designed to do so. Infiltration efficiency, flow-duration, and depth-duration curves are also developed from this simulation model and provide information pertinent to other infiltration structures.

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions that can be drawn from this study and the continuous simulation model that was developed and verified, and addresses future considerations of continuous modeling and infiltration trench design.

6.1 Trench

The VUSP infiltration trench is a unique BMP intended for use as an analysis tool. This is a critical aspect of this trench that should not be ignored. Some of the unique features of the trench provide an opportunity to investigate characteristics of infiltration structures that are not often addressed. Listed below are the irregularities of this specific infiltration trench with respect to standard design and recommendations of the PA BMP Manual:

- The trench is severely undersized. The trench footprint in comparison to its drainage area (DA:BMP) of 157:1 is far beyond the maximum recommended ratio of 5:1 for such a structure (PA BMP Manual, 2006). Although this trench does not need to have a DA:BMP of 5:1 to achieve state regulations. The constant infiltration that occurs as the trench fills allows more water to be infiltrated over the course of an event.

- The trench is relatively deep. The depth of water above the trench bottom reaches depths in excess of six feet while the recommended maximum depth of water is two feet (PA BMP Manual, 2006).

- The pre-treatment sedimentation device is not proven to remove a sufficient percentage of suspended solids, although the pre-treatment box is cleaned out on a regular basis.

- The site is highly monitored with electronic data-logging instruments. An infiltration trench built in the field will not have all of the instrumentation present at this site. Because the trench is intended for research, there is more instrumentation than would typically be installed at any structure in the field.

These irregularities from typically regulated BMP design provide insight into unique facets of infiltration trench design. Realizing these differences allows the opportunity to understand some of the functions of infiltration trenches that are not often examined and are discussed further in Section 6.3.

6.2 Simulation Model

This hydrologic flow model is derived from site specific rain data, trench geometry, trench depth, and other data collected on site. This model can not simulate another infiltration trench BMP unless information specific to that site is input into the model. The methods used to develop this simulation model can be used in conjunction with instrumentation capable of recording the necessary data at another site. The following instrumentation is required in order to obtain the data necessary to develop a similar hydrologic model.

- Rain Gage (recommended)
- Well with pressure transducer
- Inflow weir and pressure transducer (recommended)
- Overflow weir and pressure transducer (recommended)

In addition to the instrumentation listed, construction information including contributing drainage area, structure geometry, and backfill information would be required. The most basic model could be developed with only the trench geometry and construction details, along with a well and transducer in the BMP and either an inflow or outflow measurement device.

The rain gage is recommended because an existing rain gage in close proximity to the site can be used. If the site is located in a position that is distant from any rain gages, then a rain gage on site becomes more highly recommended. Rainfall can be highly variable from one location to another and can lead to some discrepancy between recordings from a remote gage and rainfall on site. An on site rain gage is especially recommended for smaller drainage areas because it ensures that even the most isolated events will be accurately recorded for the site.

Assuming the rain gage utilized accurately represents the amount of rain falling on the BMP's contributing area, the volume of water reaching the trench is attained. If the structure is completely impervious then the volume is theoretically equal to the volume of rain. This assumes that there is no lost or stored volume of water from leaks in the impervious surface or from ponding. If it is pervious area, then an appropriate loss method is utilized to determine the amount of runoff leaving the site. As was proven in this study, even well maintained impervious structures will have some sort of loss associated with them which is why an inflow measurement device is recommended.

The recommended inflow volume measurement device is an alternative to calculating the amount of runoff reaching the BMP. A calibrated device provides accurate recordings of the volume of water that enters the trench. By utilizing such a device, discrepancy that may be incurred in the process of simulating runoff can be eliminated. Whether the runoff is calculated or measured, the water is then routed to the infiltration trench.

The geometry of the structure and type of backfill are critical in the development of the model. These aspects of the trench are essential to the development of the model because they determine the storage capacity of the structure and can only be measured one time before the trench is backfilled and covered. The depth-storage relationship is developed from this information. The relationship is used in conjunction with the well pressure transducer in order to determine the volume of water stored in the trench at any given time. It is also used to develop the drainage rating curve which is converted to a flow rate and is input as the infiltration rating curve. A plot of decreasing water depth in the trench with respect to time in conjunction with the depth-storage relationship yields variable drainage rates for different depth ranges. Assuming the site is equipped with the appropriate pre-treatment, sedimentation structure, the infiltration rate developed should not decrease over time. Rates should be considered for different seasons because of the variance in rates with respect to temperature change. Averaging these rates will not decrease the accuracy of the model over the course of a year since some rates will be overestimated while others are underestimated.

Flow measurement at the overflow pipe is required but can be achieved by utilizing an outflow control structure rather than measuring the depth of water passing over a weir or through a flume. If the invert of the overflow pipe and the rating curve for that pipe are known, then the well transducer depth reading can be used to determine the overflow volume. This is the method utilized in this model and the method was checked by comparing it to the flow measured in the actual flume. While a direct measurement from the overflow pipe may be more accurate, measurements from the trench well transducer may be suitable.

The above methods are utilized to develop this model and could be implemented on other infiltration trenches in order to accurately model the respective structure. Such a model is capable of simulating the amount of runoff that enters a BMP and the subsequent volume that is stored and infiltrated or bypasses the structure. This information is useful in the determination of the effectiveness of such structures as they are performing in the field.

The simulation model was created to accurately simulate the trench assuming the structure experienced no losses during events. It was proven through existing data and through the model that this is not the case, because the inflow volume measured entering the trench rarely equals the volume of water falling on the parking deck. This resulted in slightly higher volumes of water overflowing the trench than were actually experienced on site. The effect of this overestimation of water entering the trench makes the model more conservative when predicting the percentage of water infiltrated at the trench. These losses did not need to be accounted for after verification of the model since any further modeling was based off of the originally developed model. It is possible that the model could be manipulated to better account for the actual losses experienced at the parking deck. The loss method would have to be studied more thoroughly in order to determine what the factors are that directly effect the amount of runoff lost. This would determine whether an initial loss method or a constant loss method would be more appropriate.

This hydrologic model is better suited for analysis than design since it is derived from on site data. Parameters could be approximated for the estimated runoff and infiltration using traditional methods in order to utilize the model as a design tool. The use of data from the actual site will always be more accurate for that specific site than any pre-construction design parameters.

6.3 Design

Investigation of the trench drainage rating curves shows that as water depths in the trench increase infiltration rates increase. This increase is experienced because of the increased hydraulic head above the bottom of the infiltration bed and because of an increase in wetted infiltration surface due to the sidewalls. The latest literature regarding infiltration BMP guidelines recommends a maximum hydraulic depth of two feet; or a maximum structure depth of two feet (PA BMP Manual, 2006). The trench simulated in this study is approximately six feet deep, which is beyond that maximum recommended depth. The concern is that the bottom of the structure will be too close to groundwater tables, and a deep trench would be much harder to revitalize if it were to become clogged. Groundwater levels on site are estimated at 15 feet below the surface based on a nearby gaining stream which means the bottom of the trench is removed by nine feet of soil. Thus, the two foot maximum trench depth is ridiculous. If groundwater levels can be accurately determined, then the trench depth can be designed according to that depth.

Examination of the drainage rating curves for the trench reveals that most of the infiltration currently taking place at this infiltration BMP is occurring above the recommended maximum depth of two feet. This is the case at this structure because of the sediments that have entered the trench and clogged the bottom infiltrating surface of the structure. While it is ideal for an infiltration BMP to be capable of infiltrating through all possible surfaces, these curves show that infiltration through the side walls of a structure still allow effective drainage. Greater infiltration as depth increases can be partially attributed to the increase in static hydraulic pressure at the bottom of the trench as the water rises. It is attributed more significantly to the sidewall infiltration that takes place as an increase in wetted infiltration surface occurs as determined in earlier studies at the trench (Emerson, 2008). The sidewall infiltration observed at this trench proves that a deep infiltration structure can be effective.

This trench lacks an effective fine sediment removal structure. The fact that this trench lacks such a structure would qualify it as an "abused" structure with respect to the fine sediment load entering. Even with the maligned status of this design, the trench is still capable of infiltrating an ample amount of runoff with respect to the appropriate DA:BMP ratio as demonstrated through simulation. The reason that this structure is still capable of infiltrating large quantities of the total runoff captured is because of the large sidewall area that is not clogged by sediment. The bottom surface of any infiltration trench has the potential to become clogged in any infiltration trench. High sediment loads could be experienced at a trench due to negligent maintenance, local soil disturbance, or other unforeseen and unplanned activity. Infiltration surfaces of an infiltration trench BMP can be broken down into two categories. These two categories are as follows:

- "Potentially Impermeable" – An infiltration surface that has the potential to become impermeable because of fine sediment deposition (bottom).

- "Non-Potentially Impermeable" – An infiltration surface that is not subject to sediment deposition and will not become impermeable (sidewalls).

It is preferable for the sake of infiltration to maximize the amount of "Non-Potentially Impermeable" surface, since these surfaces are not affected by sediment deposition which is the primary concern in infiltration structures. These areas are maximized by constructing deep structures rather than shallow structures. If the VUSP infiltration trench had been constructed with the same storage volume as it currently has but at the recommended maximum depth of 2 feet, it would not infiltrate nearly the volume of runoff that it does. This is because the majority of the infiltration surface for the trench would be "Potentially Impermeable" surface. Since this type of surface is susceptible to sediment loading which is high at this site, the majority of the infiltration surface would be incapable of infiltrating water. Despite concerns of potential failure of deeper infiltration structures, this study has proven that there is potentially less risk of failure with greater sidewall infiltration areas.

Another concern with respect to an infiltration trench that experiences extremely low drainage rates at shallower depths is the fact that the full storage capacity of the trench is rarely available. Depth duration curves in this study show that the current trench experiences a depth of two feet or less nearly 30% of the year. This means that for approximately 100 days out of a year, the potential storage volume below a depth of two feet is occupied. A trench that was simulated with a more appropriate contributing area had that same volume occupied for less than 10% of the year. This reiterates the fact that this specific trench is overburdened, but also provides more information about the potential storage available at any given time. Lack of the appropriate volume of storage capacity at the beginning of an event not only detracts from the volume captured, but will also lead to increased peak flows leaving the site. Peak flows and peak flow duration are a major concern in the hydraulic design of a stormwater BMP, whether it is a volume reduction BMP or a water quality BMP. The peak flows at the current trench are not significantly affected by its slow drainage rate, because it is so severely undersized. A very small volume of rain falling on the watershed will fill the trench whether it is completely empty or if it still has two feet of its depth occupied. This negates any appreciable difference that could be observed between the peak flows of a totally empty trench and a partially empty trench when peak flows are observed.

The effectiveness of deeper infiltration structures and the associated decrease in the possibility of failure should not be ignored. When implemented in the appropriate setting, deeper structures can perform better than shallower structures. This research proves that an infiltration trench deeper than two feet can still be an effective infiltration BMP. The deep trench has a large amount of infiltrating surface available, because of its depth and large sidewall surface area. Sidewall infiltration is effective at the Villanova University infiltration trench, because the bottom of the trench has a very slow infiltration rate (Emerson, 2008). Sidewall infiltration is critical because it is not impeded by fine sediment loading. The recommended PA BMP Manual DA:BMP ratio of 5:1 does not address this due largely to the fact that the trench is six feet deep.

It was determined that a DA:BMP of 7:1 would be appropriate for this site. The current trench configuration which has a DA:BMP of 157:1 is still capable of infiltrating 27% of the yearly precipitation falling on the drainage area, despite the undersized trench surface area footprint. This can be partially attributed to the six foot depth and the additional storage available in comparison to the recommended two feet of depth of a typical infiltration trench. The information produced from this simulation model will be useful in the development of further regulations, as more complex hydrologic events are considered. As the field of hydrologic engineering progresses, the desire to determine the effectiveness of structures subjected to consecutive events will become more prevalent. This continuous hydrologic simulation model is capable of simulating such events, and will provide valuable information with respect to the overall effectiveness of such infiltration structures.

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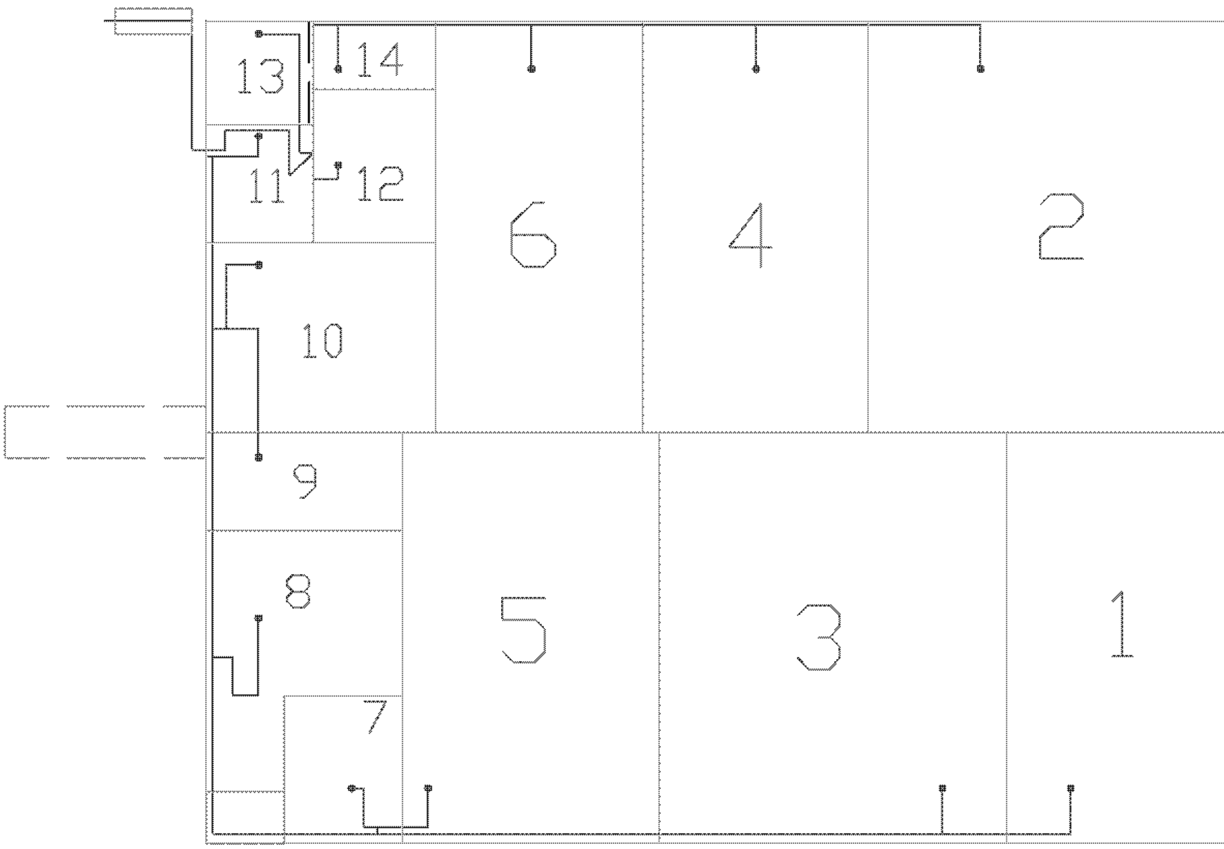
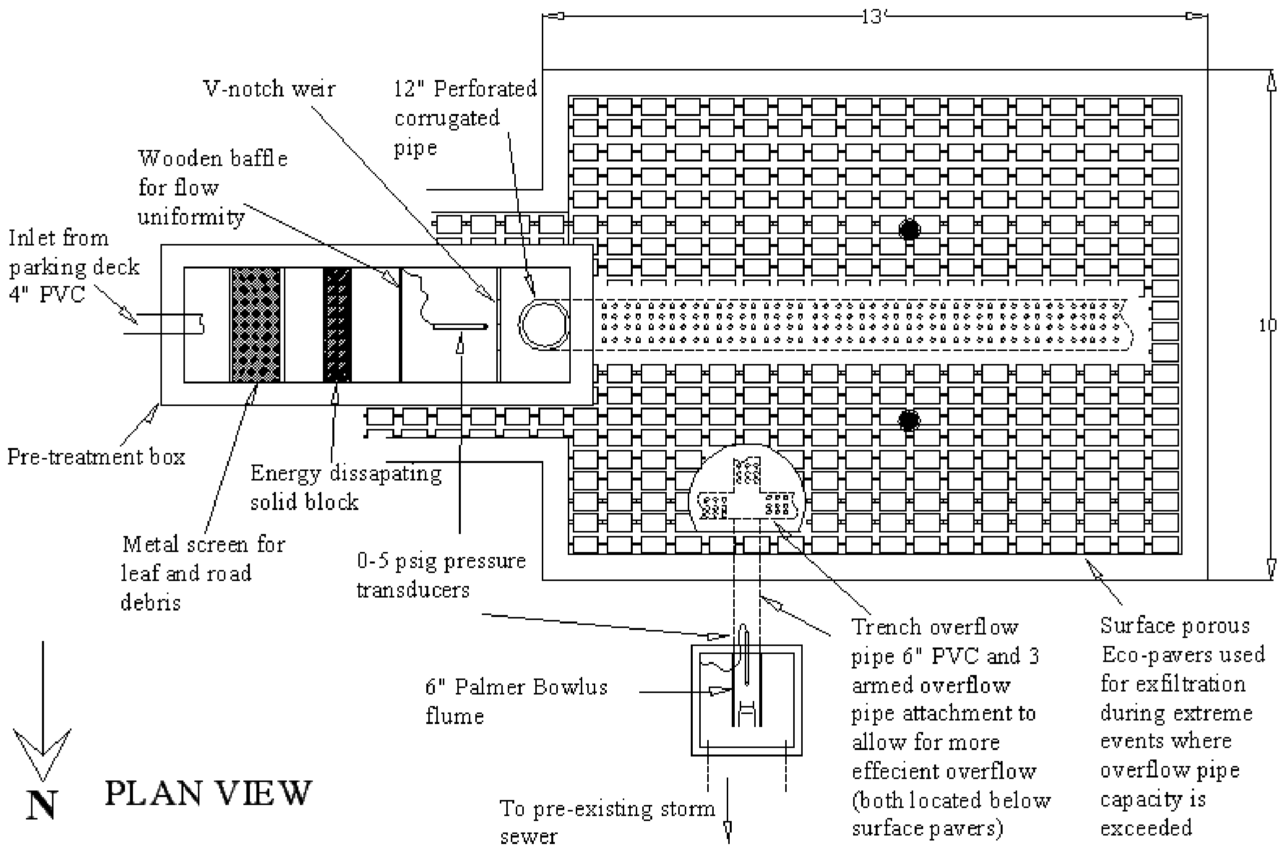
Appendix A: Plan, Profile, and Sketches of the Trench

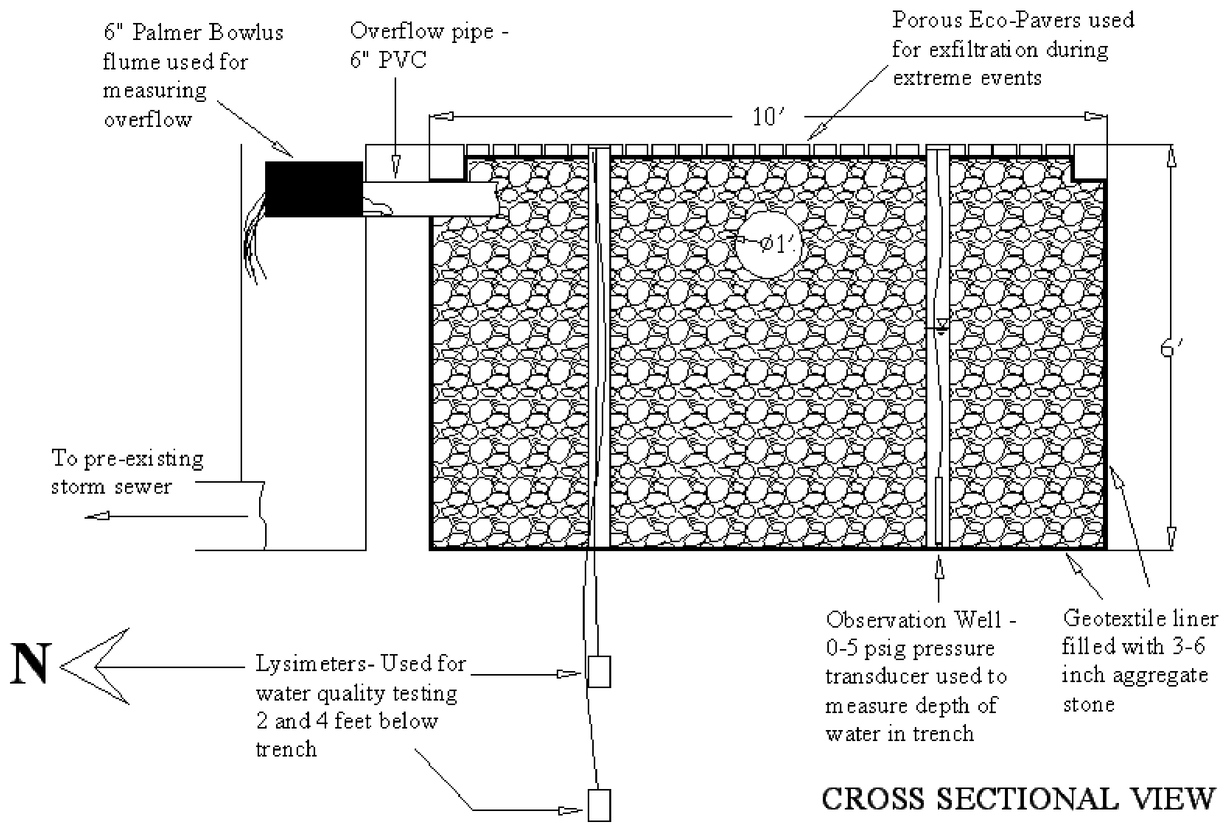
Sketch of Piping Structure at the Trench



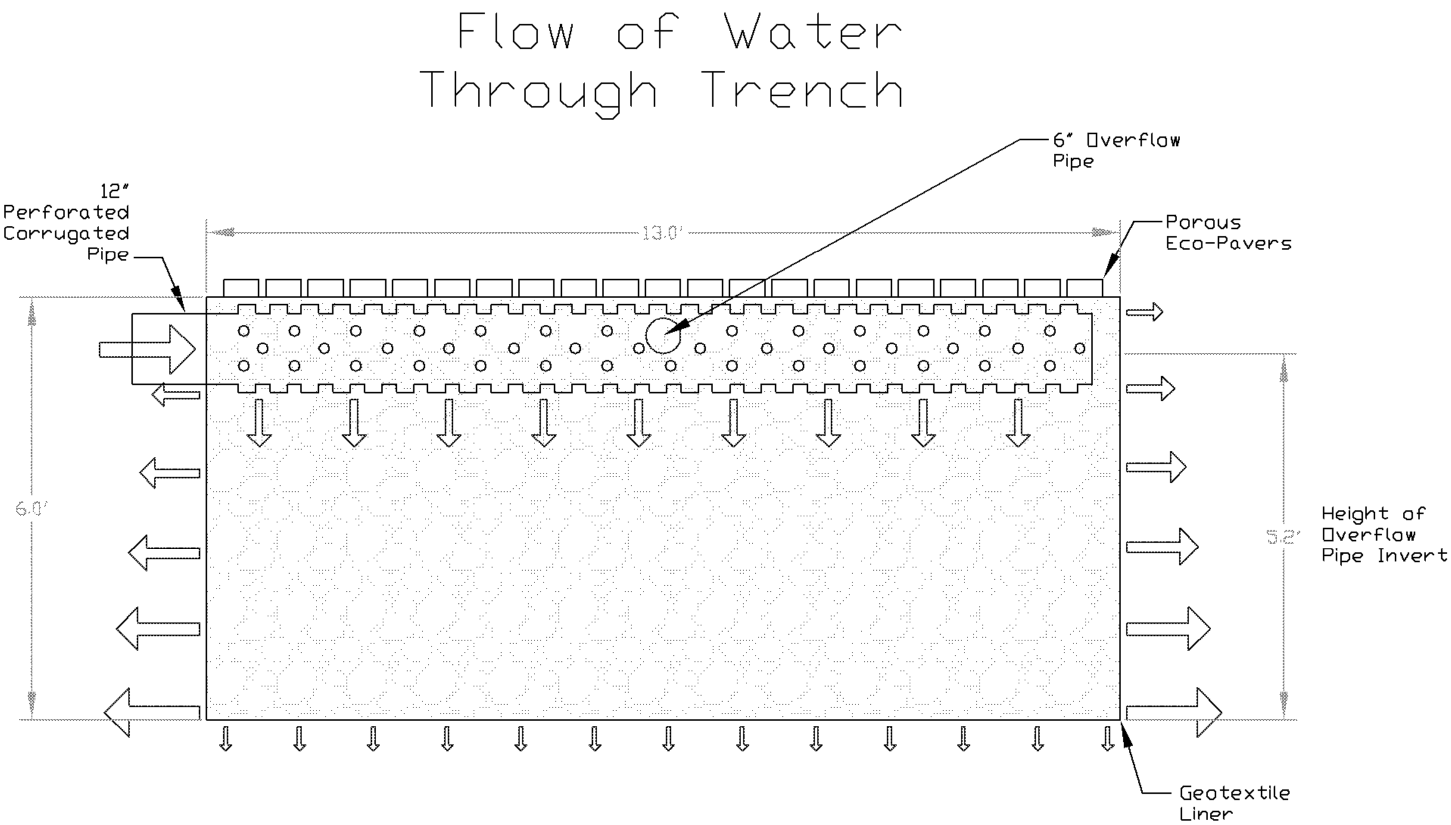
Plan View (Batroney, 2008)



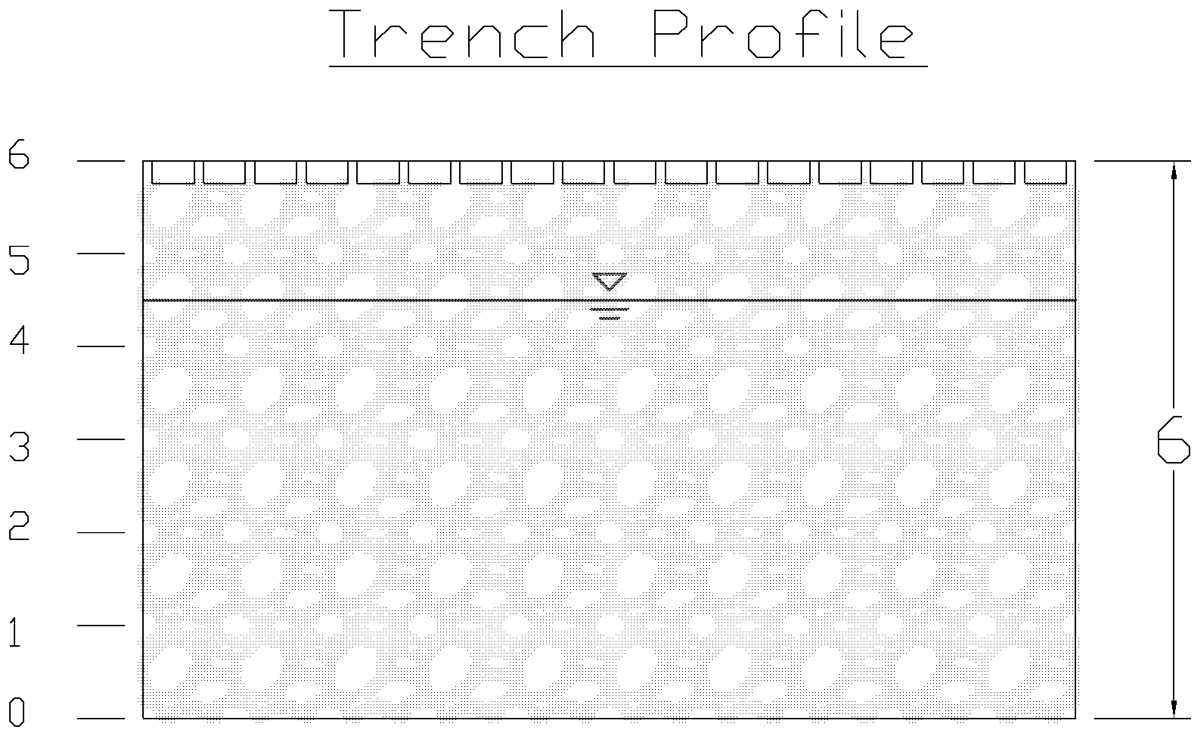
Cross-section Profile View (Batroney, 2008)



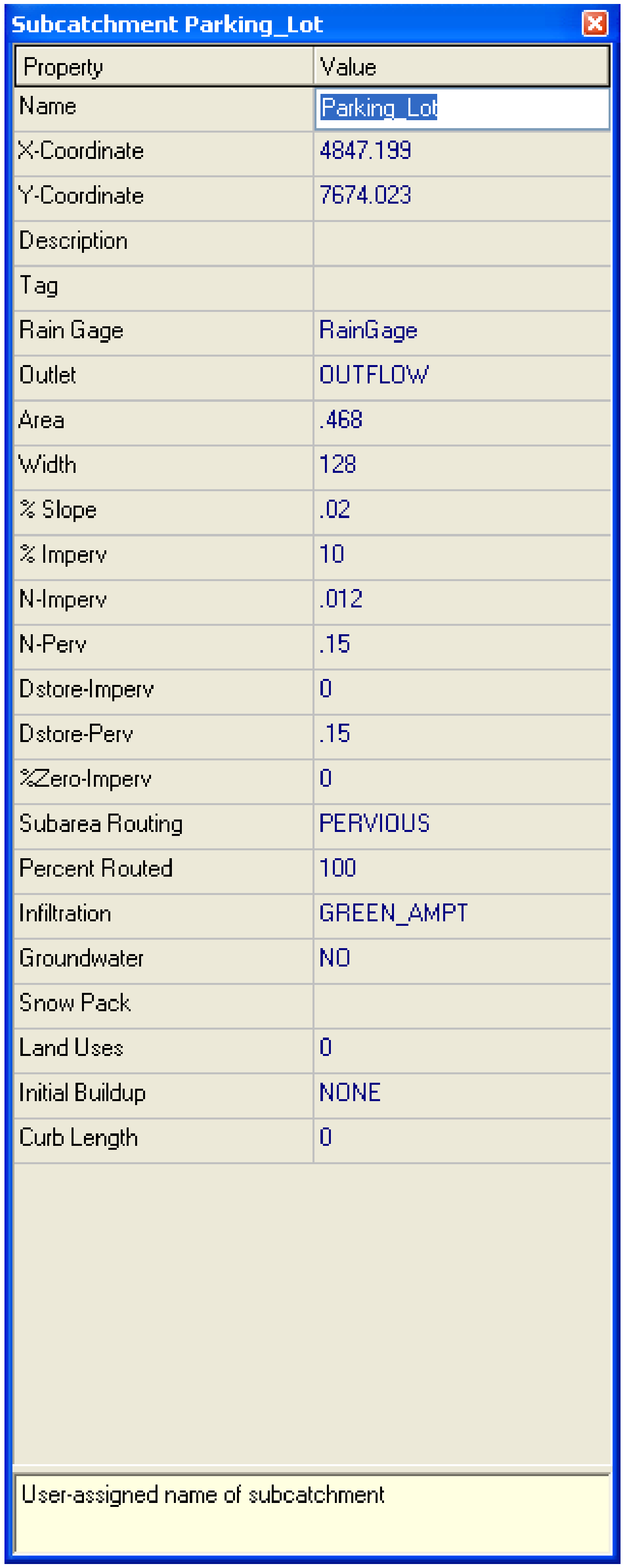
Flow Diagram



Depth Profile



Appendix B: General SWMM Subcatchment Parameters



Subcatchment Parking_Lot

Property	Value
Name	Parking_Lot
X-Coordinate	4847.199
Y-Coordinate	7674.023
Description	
Tag	
Rain Gage	RainGage
Outlet	OUTFLOW
Area	.468
Width	128
% Slope	.02
% Imperv	10
N-Imperv	.012
N-Perv	.15
Dstore-Imperv	0
Dstore-Perv	.15
%Zero-Imperv	0
Subarea Routing	PERVIOUS
Percent Routed	100
Infiltration	GREEN_AMPT
Groundwater	NO
Snow Pack	
Land Uses	0
Initial Buildup	NONE
Curb Length	0

User-assigned name of subcatchment

Appendix C: SWMM Storage, Infiltration, and Overflow Curve Tables

Stage-Storage & Stage-Area Curves for SWMM

Depth (ft)	Storage (cubic feet) n = 0.35	Area (sq ft)
0	0.00	24.30
0.1	2.44	24.42
0.2	4.91	24.53
0.3	7.39	24.64
0.4	9.90	24.75
0.45	11.17	24.82
0.5	12.43	24.87
0.6	14.99	24.98
0.7	17.57	25.10
0.8	20.17	25.21
0.9	22.79	25.32
1	25.44	25.44
1.1	28.11	25.55
1.2	30.80	25.67
1.3	33.52	25.78
1.4	36.26	25.90
1.5	39.02	26.01
1.6	41.81	26.13
1.7	44.62	26.25
1.8	47.45	26.36
1.9	50.31	26.48
2	53.19	26.60
2.1	56.10	26.71
2.2	59.02	26.83
2.3	61.95	26.94
2.4	64.91	27.05
2.5	67.88	27.15
2.6	70.87	27.26
2.7	73.88	27.36
2.8	76.91	27.47
2.9	79.95	27.57
3	83.01	27.67
3.1	86.09	27.77
3.2	89.19	27.87
3.3	92.31	27.97

Depth (ft)	Storage (cubic feet) n = 0.35	Area (sq ft)
3.4	95.44	28.07
3.5	98.59	28.17
3.6	101.76	28.27
3.7	104.95	28.37
3.8	108.16	28.46
3.9	111.39	28.56
4	114.63	28.66
4.1	117.89	28.75
4.2	121.17	28.85
4.3	124.47	28.95
4.4	127.79	29.04
4.5	131.12	29.14
4.6	134.47	29.23
4.7	137.85	29.33
4.8	141.24	29.42
4.9	144.39	29.47
5	147.65	29.53
5.1	151.03	29.61
5.2	154.53	29.72
5.3	158.14	29.84
5.4	161.88	29.98
5.5	165.75	30.14
5.6	169.74	30.31
5.7	173.86	30.50
5.8	173.86	30.50
5.9	173.86	30.50
6	173.86	30.50
6.1	173.86	30.50
6.2	173.86	30.50
6.3	173.86	30.50
6.4	173.86	30.50
6.5	173.86	30.50

Depth-Infiltration Curve for SWMM

Depth (feet)	Infiltration (cfs)
0	0
0.1	0.0000369
0.2	0.0000558
0.3	0.0000751
0.4	0.0000947
0.45	0.0001044
0.5	0.0001152
0.6	0.0001261
0.7	0.0001372
0.8	0.0001484
0.9	0.0001599
1	0.0001715
1.1	0.0001833
1.2	0.0001953
1.3	0.0002075
1.4	0.0002198
1.5	0.0002427
1.6	0.000266
1.7	0.0002897
1.8	0.0003137
1.9	0.000338
2	0.0003624
2.1	0.0003866
2.2	0.0004111
2.3	0.0004359
2.4	0.000461
2.5	0.0005379
2.6	0.0006158
2.7	0.0006946
2.8	0.0007742
2.9	0.0008548
3	0.0009362
3.1	0.0010186
3.2	0.0011018
3.3	0.001186
3.4	0.0012711
3.5	0.0014576
3.6	0.0016462
3.7	0.0018369
3.8	0.0020297

Depth (feet)	**Infiltration (cfs)**
3.9	0.0022245
4	0.0024215
4.1	0.0026205
4.2	0.0028217
4.3	0.003025
4.4	0.0032304
4.5	0.0034379
4.6	0.0036476
5	0.0044194
5.1	0.0047723
5.2	0.0051412
5.3	0.0055262
5.4	0.0059278
5.5	0.0063462
5.6	0.0067818
5.7	0.0072173
5.8	0.0072173
5.9	0.0072173
6	0.0072173
6.1	0.0072173
6.2	0.0072173
6.3	0.0072173
6.4	0.0072173
6.5	0.0072173

Overflow Rating Curve for SWMM

Depth Above Overflow Invert (feet)	Overflow (cfs)
0	0.00000
0.004	0.00027
0.008	0.00061
0.012	0.00103
0.016	0.00153
0.02	0.00209
0.024	0.00274
0.028	0.00345
0.032	0.00424
0.036	0.00510
0.04	0.00604
0.044	0.00705
0.048	0.00814
0.052	0.00929
0.056	0.01052
0.06	0.01182
0.064	0.01320
0.068	0.01465
0.072	0.01616
0.076	0.01776
0.08	0.01942
0.084	0.02115
0.088	0.02296
0.092	0.02484
0.096	0.02679
0.1	0.02881
0.104	0.03090
0.108	0.03306
0.112	0.03530
0.116	0.03760
0.12	0.03997
0.124	0.04242
0.128	0.04493
0.132	0.04752
0.136	0.05017
0.14	0.05289
0.144	0.05569

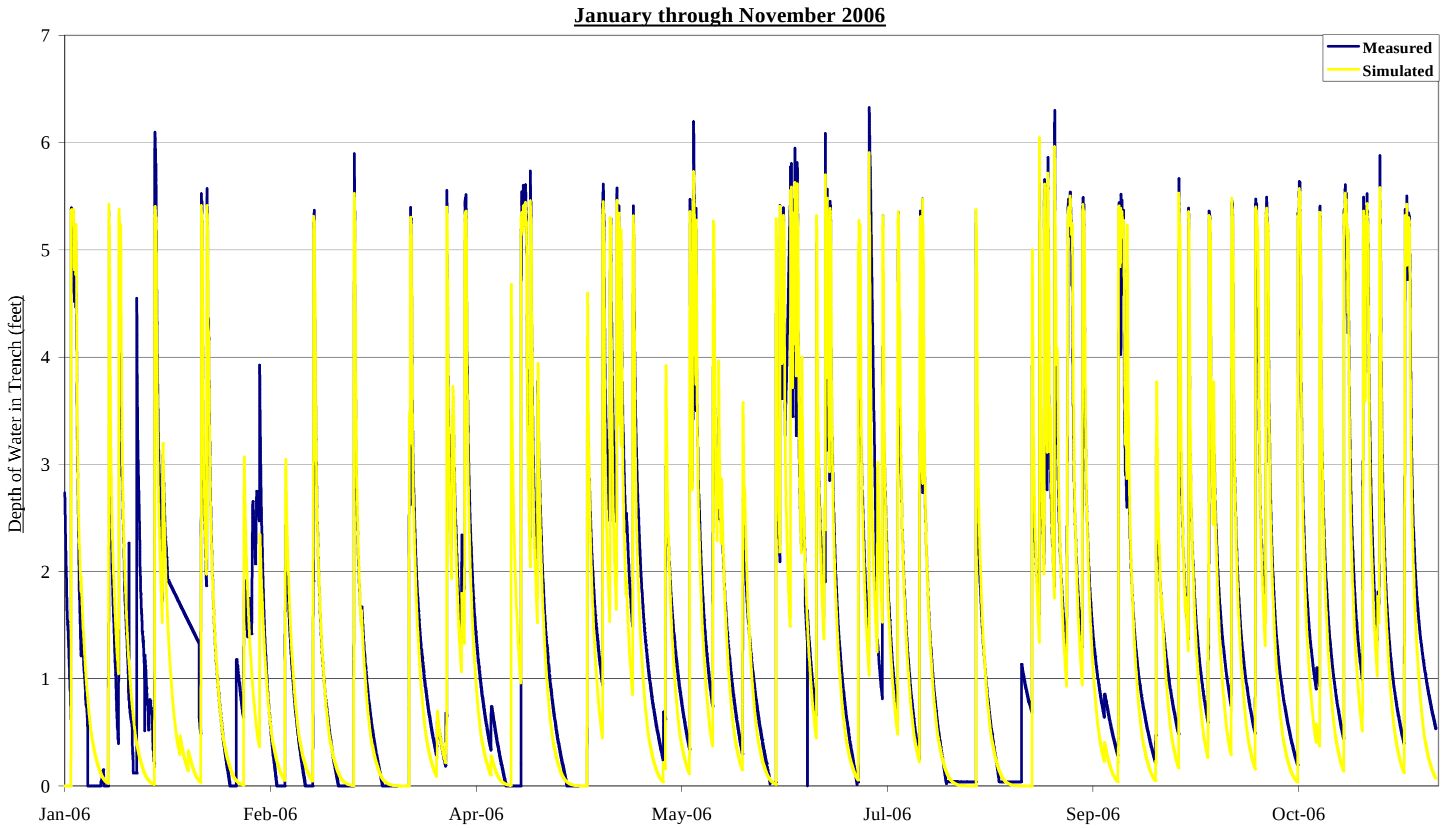
Depth Above Overflow Invert (feet)	**Overflow (cfs)**
0.148	0.05855
0.152	0.06148
0.156	0.06448
0.16	0.06755
0.164	0.07068
0.168	0.07389
0.172	0.07716
0.176	0.08050
0.18	0.08391
0.184	0.08739
0.188	0.09093
0.192	0.09455
0.196	0.09823
0.2	0.10197
0.204	0.10579
0.208	0.10967
0.212	0.11361
0.216	0.11763
0.22	0.12171
0.224	0.12585
0.228	0.13006
0.232	0.13434
0.236	0.13869
0.24	0.14309
0.244	0.14757
0.248	0.15211
0.252	0.15671
0.256	0.16138
0.26	0.16612
0.264	0.17092
0.268	0.17578
0.272	0.18071
0.276	0.18570
0.28	0.19075
0.284	0.19587
0.288	0.20106
0.292	0.20630
0.296	0.21161
0.3	0.21698
0.304	0.22242
0.308	0.22792
0.312	0.23348
0.316	0.23910

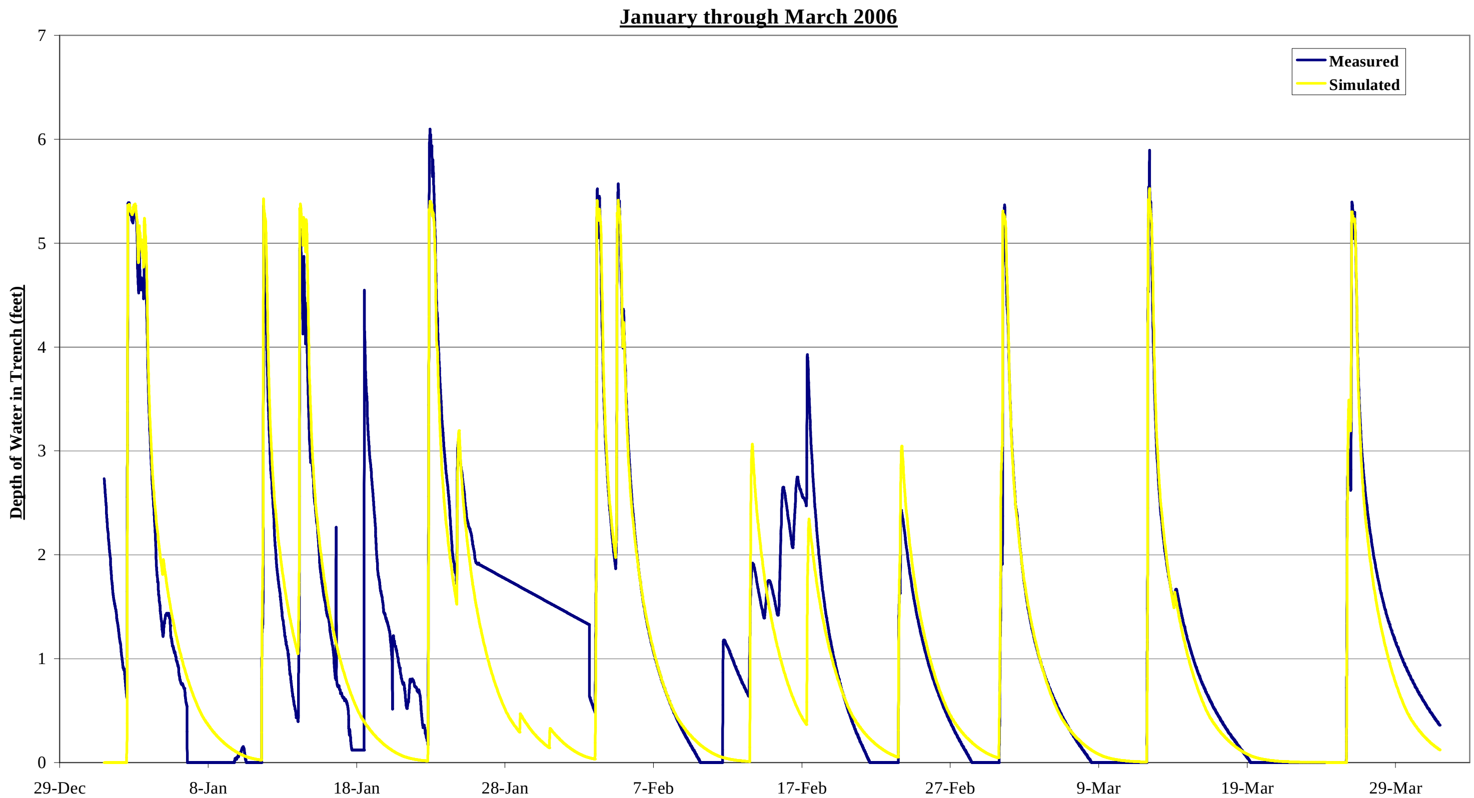
Depth Above Overflow Invert (feet)	**Overflow (cfs)**
0.32	0.24479
0.324	0.25054
0.328	0.25635
0.332	0.26222
0.336	0.26815
0.34	0.27415
0.344	0.28020
0.348	0.28632
0.352	0.29250
0.356	0.29874
0.36	0.30504
0.364	0.31140
0.368	0.31782
0.372	0.32430
0.376	0.33084
0.38	0.33744
0.384	0.34411
0.388	0.35083
0.392	0.35761
0.396	0.36445
0.4	0.37134
0.404	0.37830
0.408	0.38532
0.412	0.39239
0.416	0.39953
0.42	0.40672
0.424	0.41397
0.428	0.42128
0.432	0.42864
0.436	0.43606
0.44	0.44354
0.444	0.45108
0.448	0.45868
0.452	0.46633
0.456	0.47404
0.46	0.48181
0.464	0.48963
0.468	0.49751
0.472	0.50544
0.476	0.51343
0.48	0.52148
0.484	0.52958
0.488	0.53774

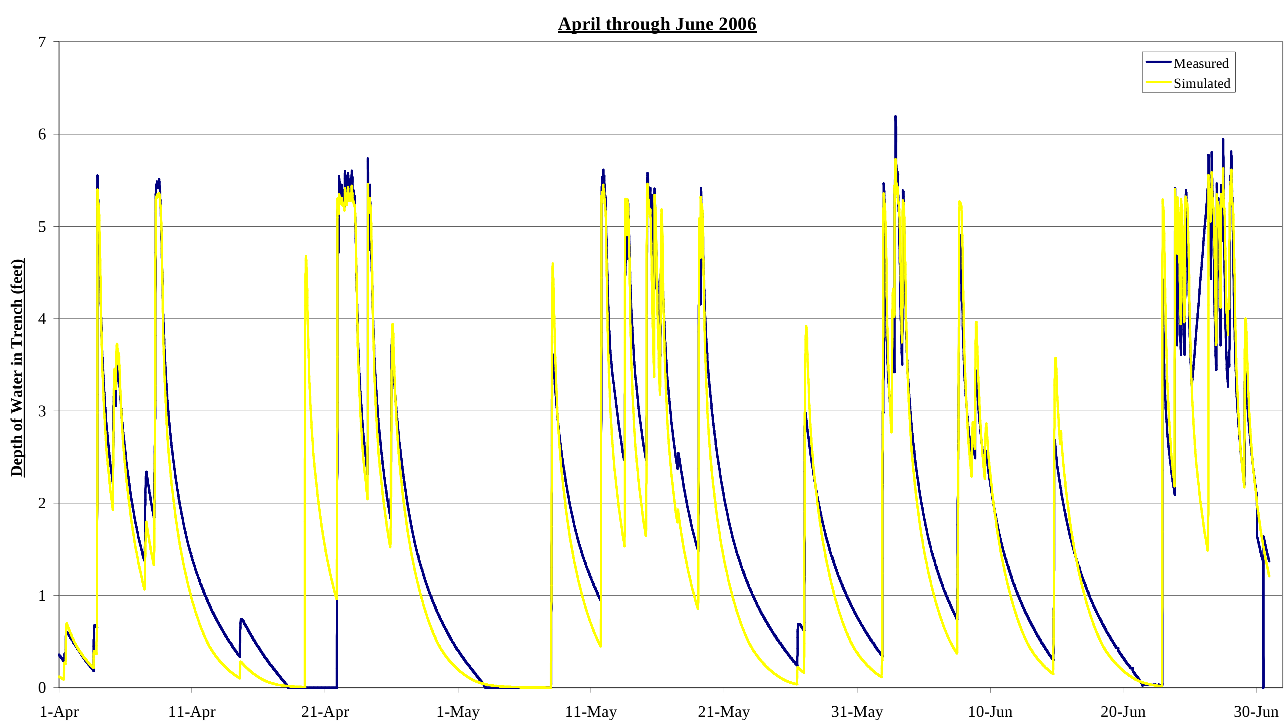
Depth Above Overflow Invert (feet)	Overflow (cfs)
0.492	0.54596
0.496	0.55423
0.5	0.56255
0.504	0.57087
0.508	0.57920
0.512	0.58752
0.516	0.59585
0.52	0.60417
0.524	0.61250
0.528	0.62082
0.532	0.62914
0.536	0.63747
0.54	0.64579
0.544	0.65412
0.548	0.66244
0.552	0.67077
0.556	0.67909
0.56	0.68741
0.564	0.69574
0.568	0.70406
0.572	0.71239
0.576	0.72071
0.58	0.72904
0.584	0.73736
0.588	0.74568
0.592	0.75401
0.596	0.76233
0.6	0.77066
0.604	0.77898
0.608	0.78731
0.612	0.79563
0.616	0.80395
0.62	0.81228
0.624	0.82060
0.628	0.82893
0.632	0.83725
0.636	0.84558
0.64	0.85390
0.644	0.86222
0.648	0.87055
0.652	0.87887
0.656	0.88720
0.66	0.89552

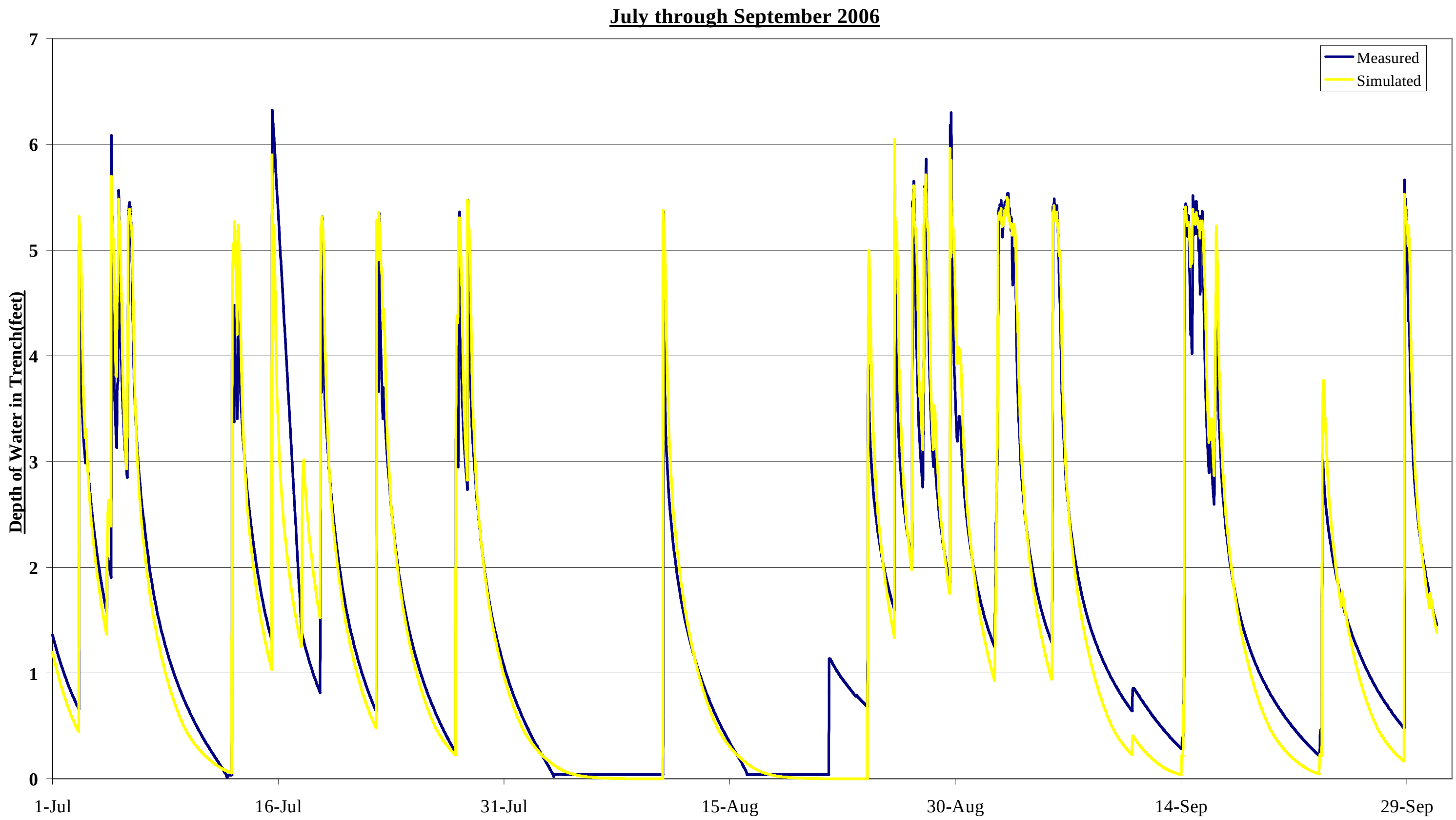
Depth Above Overflow Invert (feet)	Overflow (cfs)
0.664	0.90385
0.668	0.91217
0.672	0.92049
0.676	0.92882
0.68	0.93714
0.684	0.94547
0.688	0.95379
0.692	0.96212
0.696	0.97044
0.7	0.97876
0.704	0.98709
0.708	0.99541
0.712	1.00374
0.716	1.01206
0.72	1.02039
0.724	1.02871
0.728	1.03703
0.732	1.04536
0.736	1.05368
0.74	1.06201
0.744	1.07033
0.748	1.07866
0.752	1.08698
0.756	1.09531
0.76	1.10363
0.764	1.11195
0.768	1.12028
0.772	1.12860
0.776	1.13693
0.78	1.14525
0.784	1.15358
0.788	1.16190
0.792	1.17022
0.796	1.17855
0.8	1.18687
0.804	10.00000
0.808	10.00000
0.812	10.00000
0.816	10.00000
0.82	10.00000

Appendix D: SWMM Results

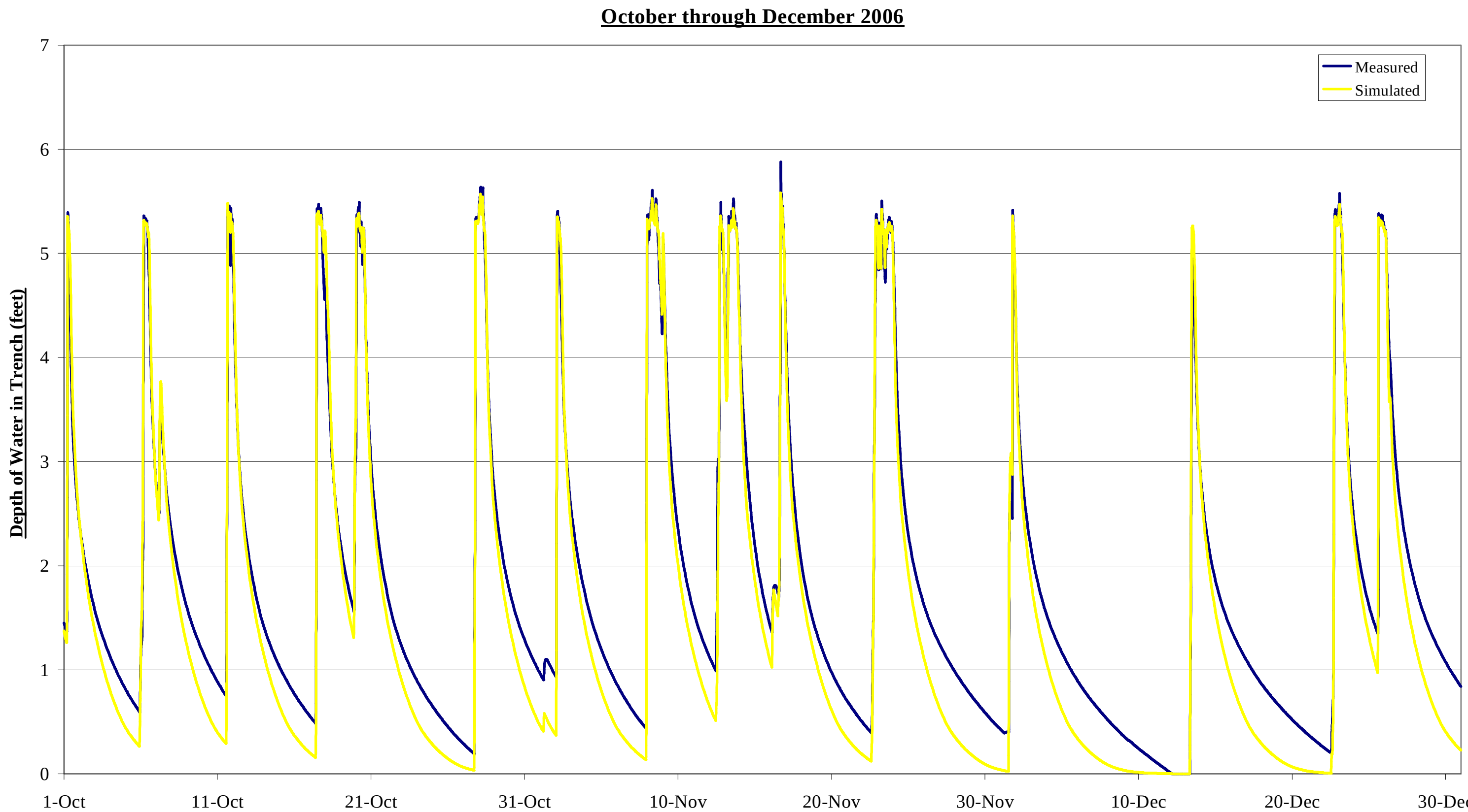



January through March 2006
Depth of Water in Trench (feet)
Measured
Simulated
0
1
2
3
4
5
6
7
29-Dec
8-Jan
18-Jan
28-Jan
7-Feb
17-Feb
27-Feb
9-Mar
19-Mar
29-Mar


April through June 2006
Depth of Water in Trench (feet)
Measured
Simulated
0
1
2
3
4
5
6
7
1-Apr
11-Apr
21-Apr
1-May
11-May
21-May
31-May
10-Jun
20-Jun
30-Jun



July through September 2006
Depth of Water in Trench(feet)
Measured
Simulated
0
1
2
3
4
5
6
7
1-Jul
16-Jul
31-Jul
15-Aug
30-Aug
14-Sep
29-Sep


October through December 2006
Measured
Simulated
Depth of Water in Trench (feet)
0
1
2
3
4
5
6
7
1-Oct
11-Oct
21-Oct
31-Oct
10-Nov
20-Nov
30-Nov
10-Dec
20-Dec
30-Dec