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A HYDROLOGIC ANALYSIS OF AN INFILTRATION TRENCH BEST MANAGEMENT PRACTICE

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Abstract

Widespread use of small, on-site stormwater infiltration structures provide a solution for managing many stormwater runoff problems facing developed and developing areas. A stormwater infiltration trench Best Management Practice (BMP) was constructed as a retrofit on the campus of Villanova University, located in Radnor Township, Pennsylvania. A 10-month rainfall record from the site was used in a mass-balance model to simulate infiltration from the system. The model of the BMP was developed using the hydrologic-routing form of the continuity equation. The predicted depth values were compared to the depth values recorded throughout an event to verify accuracy of the model. It was found that the routing process was accurate at predicting the average infiltration rate that occurred throughout an event but that it under estimated peak infiltration rates. Infiltration from the system was found to be sensitive to both storage capacity and wetted surface area. Results from the study indicate that stormwater infiltration from a relatively small on-site system may be used to manage much of the runoff generated from an impermeable surface during a rainfall event.

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Chapter 1: Introduction

This research is based on field data results collected during monitoring of the Villanova University Stormwater Partnership (VUSP) Infiltration Trench Best Management Practice (BMP) during its initial ten months of operation. The following sections provide research objectives as well as a brief review of the background, current status, and expected new directions in the areas of stormwater management.

1.1 Research Objectives

The goal of this study is to provide a better understanding of hydrologic mitigation using an on-site infiltration system, leading to hydrologic design recommendations for infiltration trench BMPs. The primary objective is the evaluation of stormwater inflow and outflow due to infiltration to provide guidance regarding techniques and specifications for infiltration trench design. The recommendations are based on a mass balance of stormwater runoff entering and depth levels within the trench to determine the outflow due to infiltration.

1.2 Land Development and Urbanization Stormwater Effects

Within the northeastern region of the United States, land development and urbanization is occurring at an extraordinary rate (US EPA, 2003). Many studies have clearly shown the impact that urbanization can have on receiving waterways (Urbonas, et al. 2001). Urbanization removes native vegetation and replaces it with compacted lawn or impervious cover, altering the hydrologic balance through reducing the site's evapotranspiration and infiltration capacity thereby increasing runoff (DeBarry, 2004).

In addition, impervious areas that are connected through gutters, channels, and storm sewers transport runoff more quickly than natural areas. This shortening of the transport time accelerates the rainfall-runoff response of the drainage area, causing flow in downstream waterways to peak faster and higher (Beighley et al. 2002). The increased peak flow rates and volumes can create new and / or aggravate existing downstream flooding, streambank erosion, and sediment deposition. Increases in impervious area decreases opportunities for infiltration through the ground surface; this results in a reduction of groundwater recharge and stream base flow (Lawrence et al. 1996). Reduced base flows can negatively impact the hydrology of adjacent wetlands and the health of biological communities that depend on base flows (Krause, 2002).

In addition to runoff peak and volume increases and loss of groundwater recharge, land development results in the accumulation of pollutants on the land surface that runoff can transport to streams. New impervious areas and cleared surfaces created by development can accumulate a variety of pollutants from fertilizers, animal wastes, and leakage from vehicles (Fischer et al. 2003). Pollutants can also include nutrients, metals, suspended solids, hydrocarbons, and in some cases, pathogens (Lee and Jones, 1998). The directly connected impervious areas bypass the filtration of runoff and the removal of pollutants by surface and channel vegetation. Instead of infiltrating into the soil, runoff enters storm sewers from the directly connected impervious areas and is discharged directly into streams without having any filtration.

Land development can adversely affect water quality and stream biota in more subtle ways than increased pollutant loads. Specifically, the removal of trees along stream banks eliminates shading, decreases bank stabilization, and eliminates the leaf debris that falls into the stream that is used as a food source to the aquatic community (Steiner, 1989). Finally, stormwater falling on impervious surfaces or stored in detention or retention basins can become heated and can contribute to an increase in temperature of the downstream receiving waterway, adversely affecting coldwater species .

1.3 NPS Pollution and Stormwater Legislation

Due to the increase in public awareness of environmental issues in the United States during the 1960s and 1970s, congress passed what would be the first of many laws intended to maintain and protect the countries water resources. The Federal Water Pollution Control Act Amendments of 1972, known as the Federal Clean Water Act (FCWA) addressed the need for the reduction of pollutant loads entering the nation's surface waters (US EPA, 2003). Additionally, an important component of the 1972 Federal Clean Water Act was the National Pollutant Discharge Elimination System (NPDES). The NPDES is a permitting program designed to regulate point source discharge into the nation's surface waters (US EPA, 2003).

The state of Pennsylvania passed the Stormwater Management Act (Act 167) in 1978 in response to problems associated with flooding. Act 167 states that the runoff following the development of a site can be no greater than the runoff that occurred prior to development (Lathia, 2002). The law requires that each county within the state adopt a stormwater management plan for each watershed within that county. Additionally, developers are required to implement stormwater management techniques that meet the criteria as set forth in the appropriate municipal ordinance.

In the past, Act 167 was interpreted to mean the control of peak flow rates for extreme events. However, it has been found that efficient stormwater management must address both volume of stormwater as well as peak flow rate (Guo and Hughes, 2001). Phase II of the previously mentioned NPDES program requires the use of structural and nonstructural Best Management Practices (BMPs) to address both stormwater volume and quality from municipal separate storm sewer systems and construction sites that disturb an area greater than one acre (US EPA, 2003). Amendments to the Federal Clean

Water Act have led to a change in urban stormwater management ideology from flood quantity control to both quantity and quality controls (Guo and Hughes, 2001).

In response to continuing water resource problems associated with both quantity and quality, Pennsylvania Department of Environmental Protection (PA DEP) developed a new stormwater policy and program to improve the way stormwater is managed across the state (PA DEP, 2005). The program integrates the existing Act 167 as well as the NPDES Phase II Permit Program for Municipal Separate Stormwater System (MS4) municipalities, and has stressed focus on volume and quality as well as peak flow rates.

1.4 Stormwater Management Practices

Until recently, traditional stormwater management plans have focused solely on the control of the rate of release of runoff of extreme events (McCuen and Moglen 1988). Historically, developed sites temporarily stored runoff in detention basins that were designed to limit discharges to the pre-development runoff peak rates. These practices did not consider the impact of increased volumes entering the receiving streams and subsequent changes to stream morphology, or the loss of infiltration resulting in decreased groundwater recharge (Lathia, 2002). As a result many state agencies, including Maryland DEP, New Jersey DEP, and Pennsylvania DEP currently require the consideration of and, where feasible, the use of BMPs that are designed to reduce volume through replicating the infiltration characteristics that existed prior to the site development. Changing and improving the way stormwater is managed to include volume mitigation has become a top priority for many states.

1.5 Stormwater Issues in Pennsylvania

On average, the southeastern region of Pennsylvania receives over 45 inches of precipitation a year. A vast majority of the precipitation occurs as a result of small storms (Prokop, 2003). Figure 1 shows a mass curve created by Prokop from daily precipitation records from 1948-2001 for the Chadds Ford, Pennsylvania area.

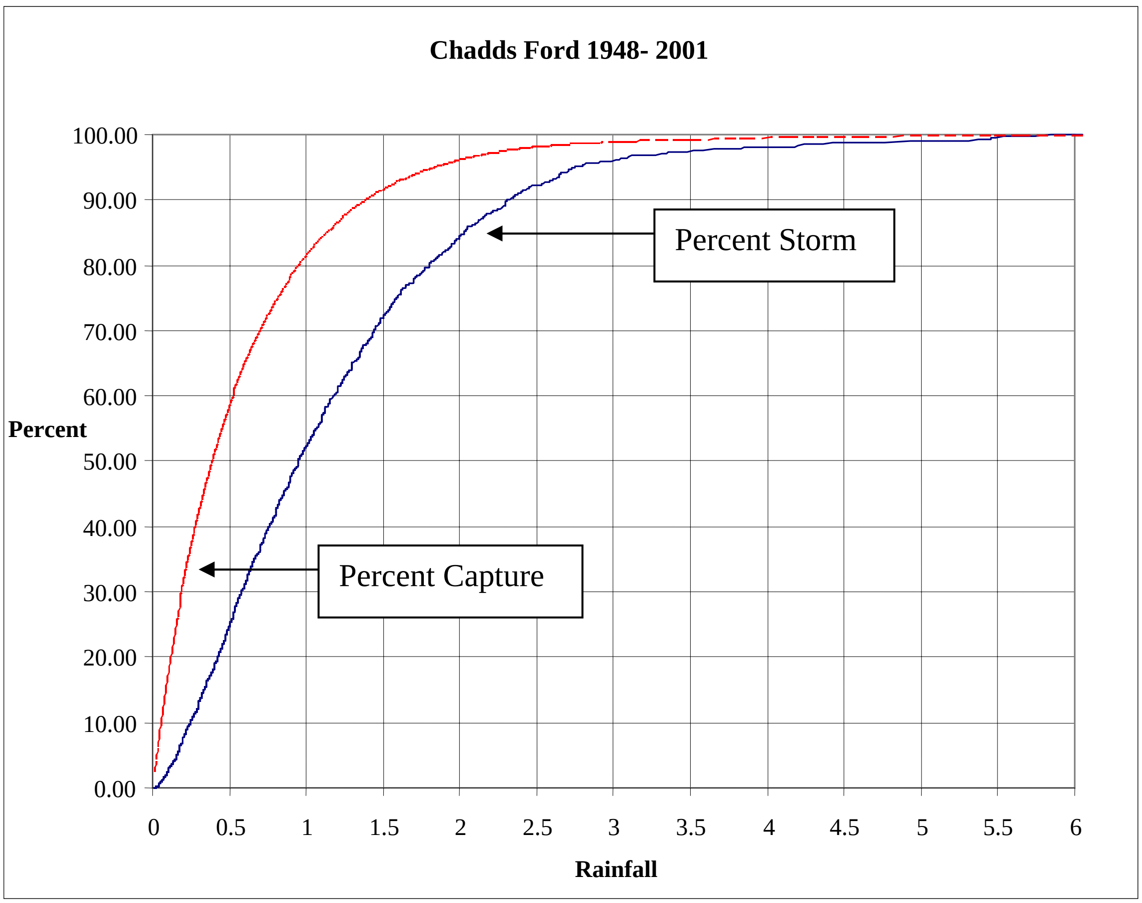

Figure 1: Chadd's Ford Mass Curve

The percent storm, shown in Figure 1 as the dashed line, is defined as the percent of the rainfall volume that falls in storms equal to or less then the rainfall specified. The percent capture, shown on Figure 1 as the solid line, is defined as the percent of the rainfall volume captured when designing for the rainfall specified. For example, for a 1-

inch storm, the percent captured includes all volume in storms less then an inch, and also the first inch of all larger storms. Figure 1 shows that approximately 52% of all precipitation events recorded by the National Weather Service rain gage located in Chadd’s Ford, Pennsylvania were 1-inch or less. In theory, if an infiltration BMP is designed and built to capture 1-inch of rainfall over a given drainage area, then at a minimum, 52% of the annual runoff from the site would be infiltrated (Prokop, 2003).

The removal of this volume of runoff provides a valuable benefit; because of the rapid growth rate and urbanization of the area, runoff generated from storm events has increased floods that result in major expenses for many state townships and municipalities. Major cities, such as Philadelphia, have aging infrastructures and frequently experience surcharging and overflow as a result of inflow and infiltration caused by precipitation events. Other areas in Pennsylvania, such as the historic Washington Crossing area, have suffered millions of dollars in damages to homes and bridges due to flooding. In April 2005 two spring rainfalls combined with snowmelt from the Catskill Mountains of New York State produced record river rises at many stream gages along the Delaware river; thereby causing many townships and municipalities along the river to incur millions of dollars of property damage. In addition to property damages, expenses associated with cleaning up and restoring flooded streams can be significant. In a presentation given by Janet Bowers of the Chester County Water Resources Authority, it was reported that the cost of a stream bank restoration project can be as much as $100.00 to $250.00 per linear foot. The presentation also reported that over the next 5-7 years restoration costs for Chester County are projected to be 169 million dollars (Bowers, 2003).

1.6 Infiltration Trench BMP

As a result of the factors discussed in the preceding sections there continues to be a great necessity to investigate the processes involved in stormwater runoff and the systems that can be used to address runoff volume. A better understanding of these systems is necessary so that stormwater management practices can be customized for more optimal control, and more efficient and cost effective solutions can be devised.

The Villanova Infiltration Trench BMP is specifically designed and built to reduce stormwater runoff volume through infiltration. On-site water quantity instruments record continuous measurements over the drainage area, runoff-flow into the trench, and water level within the trench. Steps in this research involved first verifying the void space within the trench so that accurate storage volumes throughout the event could be obtained. Next, cumulative inflow volumes were compared to depth measurements recorded throughout the storm to verify inflow into the trench. Once inflow and storage measurements were verified a mass balance of the system was performed to calculate the amount of water leaving the trench due to infiltration. Using the recession limbs of storm events a composite equation relating infiltration rate to depth was derived and a discharge rating curve was developed. Once the discharge rating curve was developed it was used in the reservoir routing process to reproduce the outflow hydrograph of an event. After events were modeled an evaluation of the infiltration that occurred throughout a storm event was performed. Design recommendations are based on the infiltration evaluation.

Chapter 2: Literature Review

Stormwater infiltration structures are designed and built to capture runoff that occurs as a result of the increased amount of impervious surface at a developed site (Akan, 2002). Although infiltration systems have been used for many years, few studies on their detailed functioning and long-term performance exist (Warnaars, et al. 1999, Dechesne, et al. 2005). Unlike traditional stormwater management techniques, infiltration structures, such as infiltration trenches, do not have widely accepted design specifications (Chilson, 2004). As a result, land development projects consistently propose traditional techniques such as detention and retention basins to address stormwater runoff. The following sections review findings that suggest the need to evaluate design guidelines for designing and implementing alternative stormwater management options, such as infiltration trenches. Studies that have suggested guidelines for implementing and evaluating infiltration trenches are discussed.

2.1 Volume Control

Studies that model the effectiveness of traditional stormwater management techniques have shown that there must be a stronger emphasis on stormwater volume control that is released and ultimately discharged into receiving water bodies. Traver and Chadderton (1983) used a mathematical model to simulate the effects of an increase in development on stream flow at the furthest downstream point of a watershed. The study varied the amount and location of development to show the downstream accumulation effects of stormwater detention basins in which the design point of reference is the developed site itself. Model results showed that traditional detention basins are only effective in eliminating increased peak flows due to development at the point of design, and the downstream accumulation effects on the receiving water body worsen as development increases in the contributing watershed. Similar results were found by Emerson, et al. (2005) in a study that evaluated the effectiveness of a system of stormwater detention basins at the watershed scale. One component of this particular study evaluated volume-based stormwater management. The study simulated a volume removal from storm flow of water equal to 0.5 inches over the contributing drainage area. Based on this volume there was a resulting decrease in the peak flow rate at the furthest downstream point of the watershed. Both studies have concluded that a volume control approach is warranted and should be emphasized when a stormwater management plan is being developed.

2.2 Groundwater Recharge

In addition to the increased runoff, studies have found that there is a decrease in groundwater recharge caused by the decrease in the amount of infiltration occurring at a developed site (Barbosa and Hvited-Jacobsen, 2001). Infiltration trenches can be used in lieu of a traditional detention basin at a site to allow the runoff to slowly infiltrate into the surrounding soil, thereby reducing the total runoff volume that is released into receiving water bodies and lost from the vadose and groundwater zone. Shaver (1986) describes the benefits provided by the use of infiltration methods in terms of groundwater recharge, low stream flow augmentation, water quality enhancement, and reduction in total runoff volume.

To effectively design an infiltration trench, Shaver (1986) specifies that the following on-site information must be ascertained: the textural character of the soil horizons and/or strata units within the subsurface profile; the location of the seasonal high groundwater table; and the depth to bedrock. Other geotechnical parameters that should be investigated include the topographic character of a site including the slope and proximity of building foundations and water supply wells (Shaver, 1986).

Previous authors have suggested that soil textures with minimum infiltration rates of 0.17 inches per hour or less are not suitable for usage with infiltration practices (Shaver, 1986). These unsuitable soils include those that have at least a 30 percent clay content, making them susceptible to frost heaving, in addition to having a poor capacity to percolate runoff (Shaver, 1986). Additionally, a minimum of 4 feet should exist between the bottom of the infiltration structure and the ground water table, where this buffer prevents the intrusion of groundwater into the infiltration trench rendering the infiltration trench ineffective. A minimum of 10 feet between any structural foundation and infiltration trench, and a minimum of 100 feet horizontally should exist between an infiltration trench and a water supply well (Shaver, 1986).

2.3 Groundwater Quality

Site selection for infiltration systems is also extremely important in protecting groundwater supplies from pollution by stormwater associated constituents (Lee and Jones, 1998). In evaluating an area for the use of an infiltration system, the groundwater hydrology of the area should be well understood. Any compounds of concern potentially present in stormwater runoff should be removed within the region below the land surface and above the groundwater table, known as the vadose zone (Fetter, 2001). Removal of the compounds of concern is important so that they are not introduced into the groundwater. Removal is due partly to the sorption of the compound onto the soil particles within the vadose zone (Fetter, 2001). The greatest sorption capacity for removal of compounds of concern occurs with soils that consist primarily of clays or silts

(Fetter, 2001). These soils, however, have low infiltration rates and would require a large amount of space if being considered for an infiltration system.

In a study done by Fischer, et al. (2003) groundwater samples obtained from beneath stormwater detention basins were collected and analyzed for pesticides, volatile organic compounds (VOCs), major ions, and nutrients. Results were compared to background groundwater samples obtained from the same study area in order to determine the effects of stormwater infiltration on groundwater quality. The study was performed in the southern portion of New Jersey, where a shallow groundwater table and sandy, unconsolidated soils make the area aquifers particularly vulnerable to groundwater contamination. Groundwater samples collected beneath the stormwater detention basins exhibited lower levels of dissolved oxygen, and higher levels of ammonia and organic nitrogen. Greater detection frequency of petroleum hydrocarbons, such as benzene and toluene, as well as pesticides were found to occur in the detention basin samples. Findings from the study stress the importance of careful geotechnical investigation during the consideration phase; an area that displays a shallow groundwater table should not be considered for the use of an infiltration structure unless the design of the structure included a filtration device. The filtration device would serve to remove the constituents contained within the runoff before the runoff infiltrates into the ground.

2.4 Design Storage Volume

Guo and Hughes (2001) suggest a first flush capture volume, also described as a water quality capture volume, lead to a storage volume of approximately 30% of a 2-year 1-hour storm runoff depth. In the southeast region of Pennsylvania for example, a 2-year storm with a duration of 1 hour results in approximately 1.44 inches of rainfall, as obtained from the Region 5 Rainfall Intensity-Duration-Frequency (IDF) curves for

Pennsylvania (Aron, et al. 1988). Therefore, a first flush design runoff volume in depth per drainage area for this storm is equal to 0.43 inches multipled by the area that is draining into the infiltration trench. Shaver (1986) recommends a first flush capture volume of 0.50 inches of runoff per drainage area.

Currently, an infiltration trench’s design storage volume can be calculated as the product of the contributing watershed area and the design runoff volume in depth per watershed area. When considering the fill material used in the trench, an effective trench storage volume can be determined by multiplying the storage volume of the trench by the porosity of the material used to fill the trench.

The problem of sizing stormwater systems can also be approached by comparing the cumulative inflow volumes produced by a time series of rainfall and the cumulative outflow volume that is released from the system (Konrad and Burges, 2001). The largest difference between these two quantities is the trench storage volume needed to prevent overflow from the trench. Konrad and Burges (2001) used a rainfall record from a site in Washington State in a mass-balance model to simulate outflow from on-site detention systems of different storage capacities. It was considered that on site systems, which Konrad and Burges, 2001 define as elementary systems applied at the scale of a single residence, may be able to provide a better representation of the predevelopment spatial distribution of water storage and may more closely approximate the predevelopment temporal distribution of release of stored water (Konrad and Burges 2001; McCuen 1979). The mass balance model of Konrad and Burges calculated runoff from a completely impermeable surface such as a roof or a driveway during a time step as the product of the surface area and rain depth falling during a time step. The impermeable surfaces were assumed to have no depression storage or evaporative losses. No time delay between rainfall and runoff was used, as is consistent with measurements of roof runoff by Hollis and Ovenden (1988). The model allocated total rain volume falling on a surface in each time step to storage, release (controlled outflow), or spill (uncontrolled outflow) by using the conservation of mass. The study did not quantify the volume of water released due to infiltration. However, the study was interesting because it was observed that even at very low outflow rates systems at the scale of a single residence can be effective for replicating hydrologic processes in residential areas, where impervious surfaces no longer support the processes of infiltration and groundwater recharge.

2.5 Infiltration Rate

Infiltration trenches are designed to capture a volume of runoff that will completely drain to the subsurface within some specified time so that the risk of overflow as a result of another storm is minimal. This period of time, specified as the "storage time" is typically given in literature as 72 hours (Shaver, 1986). The maximum rate at which a soil is capable of infiltrating water is affected by many variables, as specified by DeBarry (2004). These variables include antecedent rainfall conditions, antecedent soil moisture conditions, the inwash of fine materials into soil pores, and decreasing temperatures. If a soil is dry, wetting the top of it will create a strong capillary potential, supplementing gravity. As soils become more wet, the infiltration rate decreases toward a minimum value as a function of time since a storm has began, as specified by the Horton equation:

$$f(t) = f_c + (f_0 - f_c)\exp(-kt) \tag{1}$$

In which f(t) = infiltration rate at any time [L/T]; f_0 and f_c = initial and final infiltration rates [L/T], respectively; and k = exponential decay coefficient [1/T]. The Horton equation predicts an exponential decay in the infiltration capacity of a soil towards an equilibrium value as a storm progresses over time (Viessman, 2003).

In addition to the Horton equation, another widely used equation for modeling infiltration is the Green – Ampt method. The Green – Ampt method describes soil infiltration based on physical, measurable properties of the soil and uses the following equation:

$$f_t = K\left[1 + (\phi - \theta_i)\, S_f / F_t\right] \tag{2}$$

Where f_t = loss during period t; K = hydraulic conductivity [L/T]; ϕ-θ_i = volume moisture deficit [L^3]; S_f = wetting front suction [L]; and F_t = cumulative loss at time t. The method is accurate considering that all variables are measurable soil properties. However, accurate measurements may be challenging to obtain, particularly because subsurface soil properties are not homogeneous and values such as hydraulic conductivity may vary along the length of a trench (Steiner and Freeman, 1989).

Warnaars, et al. (1999) conducted a study that evaluated the hydrologic behavior of stormwater infiltration trenches in a central urban area over a period of 2.75 years. Specifically, the study evaluated changes in the infiltration rate as a result of decreasing saturated hydraulic conductivity values of the soil. The aim of the study was to document the feasibility of reducing the volume of stormwater runoff entering the combined sewer system through the use of an infiltration trench. Results from the study indicate that stormwater infiltration in central urban areas with compressed soils and backfill is more feasible than previously anticipated

The study site of Warnaars, et al. (1999) is located in a densely built up area in the City of Copenhagen, Denmark where infiltration structures that are 100 years old are known to exist. Two trenches were constructed after feasibility for infiltration at the site was justified by geotechnical evaluations. A total of 6,458 square feet of roof and pavement area was connected to the infiltration trenches. The trenches were designed based on a storm of 10-minutes duration and a return period of 2-years. As built, each trench is 52 feet in length and 2.6 feet in height and width, corresponding to a total effective storage volume of approximately 285 cubic feet, or 0.33 inches of runoff per drainage area. There is a flow-separator located between the two trenches approximately 1.44 feet above the bottom of the trenches, until the depth in the trenches reaches this point the two trenches operate independently. When the depth in the trenches exceeds 1.44 feet this connection causes the infiltration trenches to function as a single large infiltration structure.

Warnaars, et al. found that over the 2.75 years of measurement, the estimated saturated hydraulic conductivity values decreased in the range of 30 to 70%, which could be an indication of clogging in the trench. However, the authors point out that this determination is based on only a few significant events out of the 89 recorded events that were recorded during the study period, and that further evaluation is pending. Additionally, the storage capacity of the trenches was exceeded only 7 times over the 2.75 years of measuring. Overflow from the trenches, as a result of the exceedance of their storage capacity, caused no damage, because the overflow entered the municipal combined-sewer service system as planned. The use of the infiltration structure did fulfill its aim of reducing the volume of stormwater runoff entering the combined sewer system, and as such reduced the load being conveyed for treatment at the sewer treatment plant.

In another study that focused on the long-term evolution of clogging in an infiltration basin it was found that hydraulic resistance is a good indicator of clogging (Dechesne, 2005). The study monitored storm events that occurred at 4 different infiltration BMPs located in the area of Lyons, France. Ages of the sites ranged from 10 to 21 years of operation, and the sites had been regularly maintained; however, the study did not report the specific maintenance schedule. Clogging of the systems was characterized by the hydraulic resistance value determined at each site. Hydraulic resistance was suggested in the Bouwer model (1969). Bouwer theorized that if the hydraulic conductivity of the interface between soil particles is small enough to maintain the infiltration rate of the underlying soil lower than its hydraulic conductivity, than the underlying soil will stay unsaturated throughout infiltration, as long as the groundwater level is deep enough to prevent contact between the basin bed and the capillary fringe. The study concluded that the BMPs had low hydraulic resistance and good infiltration capacities; this supports the theory that even after an infiltration system is in operation for multiple years, the effectiveness of the system can be sustained.

Chapter 3: Study Site

The Infiltration Trench Best Management Practice (BMP), built in July 2004, is located on the campus of Villanova University, located in Radnor Township, Delaware County, Pennsylvania. The campus is located at the headwaters of Mill Creek within the watershed of the Schuylkill River, located in southeast Pennsylvania. The Infiltration Trench is the newest addition to the existing Villanova Stormwater BMP Research and Demonstration Park, which also includes a Stormwater Wetland, a Bio-Infiltration Traffic Island, and a Porous Concrete Site.

3.1 Site Description

The BMP is a retrofit that exists in a small area between an academic building and a parking garage, as shown in Figure 2.

Figure 2: Study Area

Both existing structures are greater than 8 feet away and up gradient from the BMP, preventing the possibility of flooding subsurface areas. Additionally, there are no potable water supply wells within 100 feet of the BMP, alleviating any chance of intrusion of infiltrated water into a well used for drinking water. The site had previously been providing a picnic area to students and staff for many years, however there was a general lack of landscaping and maintenance and it was considered unsightly. The finished BMP not only fulfills its stormwater management function but also provides a more attractive area for visitors.

3.2 Drainage Area

The drainage area for the BMP is 100% impervious. The area consists of just under one half of a flat, second story 350 feet x 128 feet (44,800 ft^2) concrete parking lot that is used only by Villanova University staff and has an extremely low probability of experiencing any type of hazardous spill. Prior to the construction of the BMP, the entire 44,800 square foot lot was drained by a closed pipe storm sewer system that deposited runoff to the street, where it entered inlets that ultimately discharged to the Constructed Stormwater Wetlands on the west side of campus. The pipes that carry the runoff from the parking lot were re-routed to discharge into the inlet structure of the infiltration trench.

Before any significant analysis of the drainage area could be done, it was necessary to understand its characteristics, much of which was accomplished through observation. Due to the relatively flat nature of the parking lot drainage area it was important to observe the flow patterns during rain events. Delineation of the portion of the parking lot that drains into the BMP was determined through the use of a 'dye tracer method.' During a rain event, red food coloring was dropped along what was assumed to be the border line for the drainage area. Upon observing the flow of the red food coloring during the rain event, the area that enters the infiltration trench was measured with a tape measure as 159.2 feet x 128 feet (20,378 ft^2).

3.3 Subsurface Investigation

Stormwater infiltration design depends highly on properties of the soil that exists at a proposed site. In the initial phases of the design process a site investigation and feasibility test was performed to determine suitability for the installation of an infiltration system. Technical observation was provided by Mr. Bill Heasom of the Villanova Urban Stormwater Partnership for a test pit and percolation test performed in June 2004. The tests were performed along with a review of published geologic data to characterize the subsurface conditions at the site with respect to the types of material, uniformity, depth to bedrock, and depth to groundwater conditions in the vicinity of the anticipated location of the infiltration trench. The field work was performed by excavation subcontractors N. Abbonizio Inc. while under the observation of Mr. Heasom.

3.3.1 Regional Geology

Based upon a review of the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) Soil Survey for Chester and Delaware Counties (1963), the soils in the area of the BMP consist of made land, schist and gneiss materials. These soils are described in the survey as "well drained to moderately well drained, mixed coastal plain materials, 3 to 8 feet thick; underlain by unconsolidated coastal plain deposits of clay, silt, sand and gravel ranging from 4 to 40 feet or more in thickness" (USDA, 1963). These types of soils comprise approximately 13.2 % (15,650 acres) of Delaware County according to the survey.

3.3.2 Test Pit

The test pit was dug to a depth from 4 to 6 feet below existing grade. In general, the test pit encountered a layer of disturbed topsoil, approximately 18 inches thick, followed by an equally thick layer of undisturbed and heavily weathered schist. The bottom 36 inches of the soil profile was dominated by a tan, silty sand layer. Laboratory testing was performed on selected soil samples obtained from the subsurface exploration to assess the grain size characteristics of encountered soils and verify field soil classifications. A mechanical grain size (sieve analysis) analysis determined that the soil at the site consists of 73% sand, 23% silt, and 4% clay. This type of soil is classified as a loamy sand according to the US SCS Soil Texture Triangle, and a type 'B' soil according to the curve number method. A summary of the lab results, including calculations, are presented in Appendix A.

The depth to bedrock in the original test pit was noted as approximately 6 feet. No signs of mottling were encountered while digging the test pit. Due to the small distance to bedrock in the original test pit, as well as the presence of an existing underground conduit, the location of the BMP was changed slightly. Upon digging to a total depth of 10 feet (6 feet to the bottom of the trench plus an additional 4 feet that was hand augered) at the new location, no bedrock was encountered. The depth to groundwater at the site of the BMP was estimated at approximately 15 feet. This estimation is based on the difference between the location and known elevation of a nearby gaining stream and the location and known elevation of the BMP.

3.3.3 Percolation Test

The percolation test was performed using a constant-head infiltrometer. The infiltrometer consists of a 6-inch diameter metal ring that is hammered into the soil to a depth of 3 inches. A graduated water supply tube stands on top of the ring and maintains a constant six inches of head on the soil surface. The flow rate was calculated directly using the graduations and a stop watch. The percolation results showed that the soil absorbs 8.1 inches per hour. However, it should be noted that this rate is not due to one-dimensional vertical flow only, but also lateral flow.

3.4 Site Design

Stormwater infiltration is the primary design objective of the infiltration trench BMP. However, there were design components specific to the site's monitoring and demonstration purposes. For the purposes of describing the design of the system, the infiltration trench BMP will be divided into 3 main entities; the inflow conveyance system, the inlet structure, and the trench itself.

3.4.1 Inflow Conveyance System

Inflow to the trench is carried via a system of interconnecting 4 inch diameter polyvinyl chloride plastic (PVC) pipes. The existing pipes were part of the parking garage's former stormwater collection system and were re-routed to carry flow under the second story parking lot, through the inlet structure, and into the trench.

3.4.2 Inlet Structure

The inlet structure serves as an intersecting point for the pipes coming from the parking lot. The structure is a rectangular box that is 9.33 feet long by 3 feet wide and constructed of pressure treated 6-inch by 6-inch pine garden ties. The top of the inlet structure consists of nine "Trex" brand decking boards fastened together to form a lid. There are 2 locks on the inlet structure to prevent tampering of any type. The inside of the inlet structure consists of a wire screen to separate out large particles that enter along with the inflow, a baffle to create a more uniform flow, and a V-notch weir. More specific information on the V- notch weir can be found in Chapter 5 of this paper.

3.4.3 Trench

The trench, as constructed, provides an effective storage capacity of 200 ft^3, equivalent to approximately 0.12 inches of rainfall over the drainage area; this volume accounts for the aggregate that was used to fill the trench. The storage capacity of the trench was determined by an analysis of the stage-storage relationship between the depth of water and the storage volume. The volume was calculated by using simple geometric formulas expressed as a function of depth. The process for creating the storage-rating curve will be described in detail in section 5.3.2 of this paper.

The initial design of the BMP was based upon the capture of the first flush of runoff from the contributing drainage area, which is recommended by Shaver (1986) to be 0.50 inches over the drainage area. The capacity necessary to provide a storage volume equal to 0.50 inches of runoff from the drainage area is determined by the product of the drainage area and amount of runoff. Note that this storage volume however, does not include the aggregate backfill.

The effective storage capacity of the trench is acceptable due to both the observed subsurface conditions at the site as well as the nature of the inflow conveyance system. For example, the area contributing runoff to the trench can be decreased. This can be done by re-routing the PVC pipes carrying runoff to the street stormwater inlets, instead of the trench. In addition, the subsurface conditions at the site are such that runoff entering the trench infiltrates into the surrounding soils at a very high rate. Due to this rapid infiltration rate overflow from the trench is generally not observed from storms that are less than 0.85 inches.

Chapter 4: Construction

4.1 Site Plans

In addition to the feasibility study (discussed in Chapter 3) that was performed, preliminary construction tasks included the collection and analysis of existing University site plans. These plans were reviewed in an effort to determine the locations of various utility lines that were known to exist at the proposed site. Plans were found to be available for both the parking garage and the academic building, but no plans were found that were specific to the common area between the two structures, at the proposed BMP site. Therefore, an onsite investigation was relied upon.

The onsite investigation found that the area contained three large electrical conduits which were encased in concrete, one single telephone line, two stormwater conduits, and an existing stormwater inlet; this amount of infrastructure is dense for an area only approximately 45 feet wide. The locations of these utilities, along with the shallow depth to bedrock that had been observed in the original test pit, ultimately determined the exact size and orientation of the trench. Based on the findings of the utility investigation, the final location of the trench is approximately 10 feet away from the test pit that was initially dug. This new location is directly downhill along what was likely the original slope of the site. Therefore, it was assumed that the depth to bedrock at this particular location would be larger. Ultimately there was no contact with bedrock during the excavation of the trench or during the installation of the monitoring instruments.

4.2 Retaining Wall

Construction on the site took place during the months of May and June of 2004. The first phase of the process was not directly part of the BMP project and funding, but was necessary to ensure that the project would be successful. This part of the process involved building a retaining wall prior to the excavation of the trench to prevent potential compaction and the migration of sediment into the newly constructed trench. Additionally, the retaining wall was built to alleviate the erosion of the steep slope that existed adjacent to the location of the future trench. The eroding slope that existed prior to the construction of the retaining wall is shown as Figure 3.

Figure 3: Pre-Existing Conditions

4.3 Trench Excavation:

The second phase of the construction process involved marking out the boundaries of the infiltration trench to the required depth and dimensions, and digging the trench. The trench was excavated to a final depth of approximately 6 feet. No bedrock was encountered by hand augering to an additional depth of 4 feet within the base of the trench, to a depth of 10 feet total. The final length of the trench is approximately 13 feet, and the final width at the surface is approximately 10 feet. The excavation process was performed so that no heavy equipment came in contact with the undisturbed soil, causing compaction, therefore preserving its infiltration capacity.

After trench excavation, a 4-inch overflow pipe was installed between the south sidewall of the trench and the existing storm sewer inlet, located approximately 2-feet away. The invert of the overflow pipe is at an elevation of 4.9-feet from the bottom of the trench. The overflow pipe was intended to carry flow from the trench once the water surface elevation within the trench met the invert elevation of the outflow pipe.

Two 4-inch diameter PVC monitoring wells were installed in the base of the trench. Each well was installed with a pair of soil lysimeters, one at 2 feet and one at 4 feet beneath the bottom of the trench in the undisturbed subsoil. The soil lysimeters allow for the sampling and analysis of infiltrated runoff with respect to water quality parameters such as nutrient concentrations, metals, pH, conductivity, and total dissolved solids. One of the monitoring wells was instrumented with an INW PS9800 pressure transducer, enabling the depth in the trench to be monitored. The excavated trench, along with the installed geotextile liner and monitoring wells are shown as Figure 4.

Figure 4: Trench Liner

The geotextile shown in Figure 4 was used to line the base and sides of the entire trench, with enough fabric used to allow for the top of the trench to be wrapped as well. The geotextile liner was used for controlling sediment transport into the trench, which otherwise may clog and cause a decrease in the effective storage. The side walls of the trench are lined to help direct the water flow downward and to reduce lateral flows. Upon the geotextile liner was laid a bed of large, clean, washed stone aggregate, approximately 3 to 6 inches in diameter to a depth of approximately 2 feet above the bottom of the trench. A 12-inch diameter corrugated 'L' shaped distribution pipe was then positioned in the center of the stone bed and the remaining trench area was filled with stone. The geotextile liner was then wrapped around the top. Figure 5 shows the excavated trench filled with aggregate along with the monitoring wells and the distribution pipe.

Figure 5: Trench Excavation

Not shown in Figure 5 is the 6-inch outflow pipe placed between an existing storm sewer inlet and the infiltration trench. The invert of the overflow pipe is at an elevation of 4.9 feet from the trench bottom. It was included in the construction of the trench to carry flow from the trench into the storm sewer, located 2 feet away from the trench, when depths within the trench exceed 4.9 feet.

4.4 Porous Pavers Installation

To complete the trench a 2-inch layer of choker stone was placed at the top of the bed above the geotextile liner and was overlain with EP Henry brand ‘Eco-Pavers’. The porous pavers have nubs that evenly space them apart and provided approximately 17.4% open space according to the manufacturer’s specification sheet. The open space between the porous pavers was then filled with small choker stone to complete the porous paver installation. Finally, 6-inch by 6-inch timbers were used to outline the porous pavers, and to create a more attractive presentation. The pavers used in the project not only provide a durable and attractive surface to the trench but they permit overflow in periods of intense rainfall when the trench fills with runoff and the capacity of the overflow pipe is exceeded. This overflow comes through the top of the trench, through the pavers, and over a 2-foot wide grass area into the existing storm inlet. The completed trench is shown as Figure 6.

Figure 6: Completed Trench

Chapter 5: Methods

This section describes, in detail, the methods involved in the collection, analysis, calibration and verification of data obtained from the Villanova University Stormwater Infiltration Trench during the study period of July 2004 through April 2005. On-site water quantity instruments were installed during the month of June 2004 to record continuous measurements of rainfall over the drainage area, runoff into the trench, and water level within the BMP. The purpose behind the measurement system is to track the runoff from where it fell on the parking lot drainage area to the trench. Outflow throughout the storm event was then found indirectly for each storm from a mass balance based on the inflow and water level measurements. This data was used to create a hydrologic model of the Infiltration Trench BMP utilizing the reservoir-routing method. Finally, an evaluation of the factors affecting the infiltration rate through out the event was performed.

5.1 Data Collection

The data used for this particular study spans the period from 26 June 2004 to 30 April 2005. Data from the study site was downloaded on a weekly basis from an American Sigma 980 flow meter. All measurements were recorded at one-minute intervals. Throughout the data collection time frame there were 2 periods during which data was not obtained; the week of 16 August 2004 through 24 August 2004, in which data was accidentally overwritten, and the period of 25 April 2005 through 30 April 2005, in which the data logger had to be removed from the site for servicing.

5.1.1 Rainfall Data

Rainfall is measured through the use of a tipping-bucket rain gage located directly in the drainage area of the infiltration trench, as shown in Figure 7.

Figure 7: Rain Gauge

Care was taken during the installation of the rain gage to ensure that the location of the gage was such that the rain gage accurately reflects the rainfall over the drainage area. Specifically, the gage is located on top of one of the parking lot support columns and is not near any existing trees or tall structures that might contribute to errors in rainfall measurements.

5.1.2 Inflow Data

Flow that enters the infiltration trench through the parking garage piping system is measured using a pressure transducer in conjunction with a V-notch weir, located within the inlet structure, as shown in Figure 8.

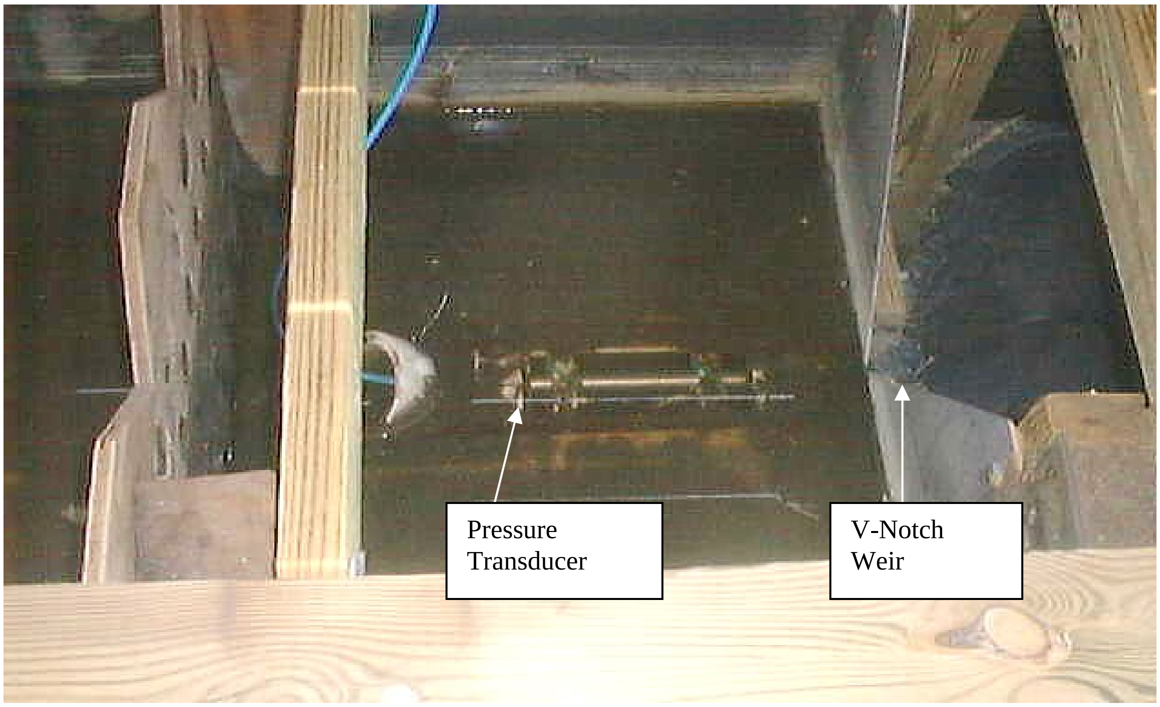

Figure 8: Pressure Transducer and V-Notch Weir

The pressure transducer measures the height of water before the weir. The flow rate was calculated using the measured vertical distance from the crest of the weir to the water surface elevation along with the v-notch weir equation, as given by Munson (1994) in Equation 3:

$$Q = \frac{8}{15} C_d (2g)^{1/2} \tan\frac{\theta}{2} H^{5/2} \quad (3)$$

In which θ = 45 Degrees; Q = Flow Rate [L^3T^{-1}]; C_d = Discharge coefficient (0.58); and H = Height of water over the weir [L].

5.1.3 Depth Data

A pressure transducer was used to measure the depth within the infiltration trench. The pressure transducer is located at the bottom of the trench within a 4-inch diameter PVC monitoring well. Increases in depth occur as the result of runoff from the drainage area entering the trench. Additionally, a small amount of inflow into the trench also occurs through the porous pavers on the surface of the trench itself which is considered insignificant for this study.

5.2 Initial Model Development

This section describes, in detail, the methods involved in the analysis of storm data obtained from individual storm events, prior to the modeling of the individual events. A summary spreadsheet was created for each of the events in order to evaluate the observed storm characteristics. Prior to developing the model for each of the events, depth and rainfall versus time was plotted, inflow volumes were verified, and inflow and outflow hydrographs were created. Procedures followed for these pre-modeling steps are described in the following sections.

5.2.1 Summary List

A spreadsheet of rainfall information was created to maintain a record of storm events that occurred at the site. For this study, a storm event is defined as periods of rainfall that caused an associated inflow and rise in depth of water within the trench. Specifically, event duration is defined as the time period from when rainfall began to fall to the time that the depth in the trench fell back to zero. The date and time of the beginning and end of the rainfall is noted along with the total amount of precipitation (in), the event duration (hrs), and the antecedent dry time since the last storm event (hrs). Additional characteristics of each event are also noted in the spreadsheet, as shown in

Figure 9 for the 9 Sept 2004 storm event. The number of recorded events at the infiltration trench during the study period is 38, of which 23 did not produce depths within the trench greater than 5.7 feet, which would produce overflow from the trench. The complete event list is included as Appendix B.

Notes:	
Date:	20040909
Rainfall Start Time (Event Start):	9/9/04 10:43 AM
Trench Starts Filling Time:	9/9/04 10:56 AM
Rainfall End Time:	9/9/04 4:02 PM
Trench Empty Time (Event End):	9/9/04 7:59 PM
Total Rainfall (in.):	0.14
Storm Duration (hr.):	5.32
Storm Intensity (in/hr):	0.03
Event Duration (hrs):	9.27
Max Trench Depth (ft.):	3.05
Max Trench Depth time:	11:43 AM
Time From Rainfall End to Trench Empty (hrs):	3.95
Time of Last Rainfall:	9/9/04 4:02 PM
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.02
Time Between Event and Last Trench Depth of 0 (hrs):	13.22

Figure 9: Event Summary (09 Sept 2004)

5.2.2 Depth and Rainfall Versus Time Curves

To observe the relationship between rainfall and the corresponding depth within the trench, rainfall and depth versus time was graphed as shown in Figure 10 for the 8 September 2004 storm event. The depth and rainfall versus time graphs for each modeled event are included as Appendix C.

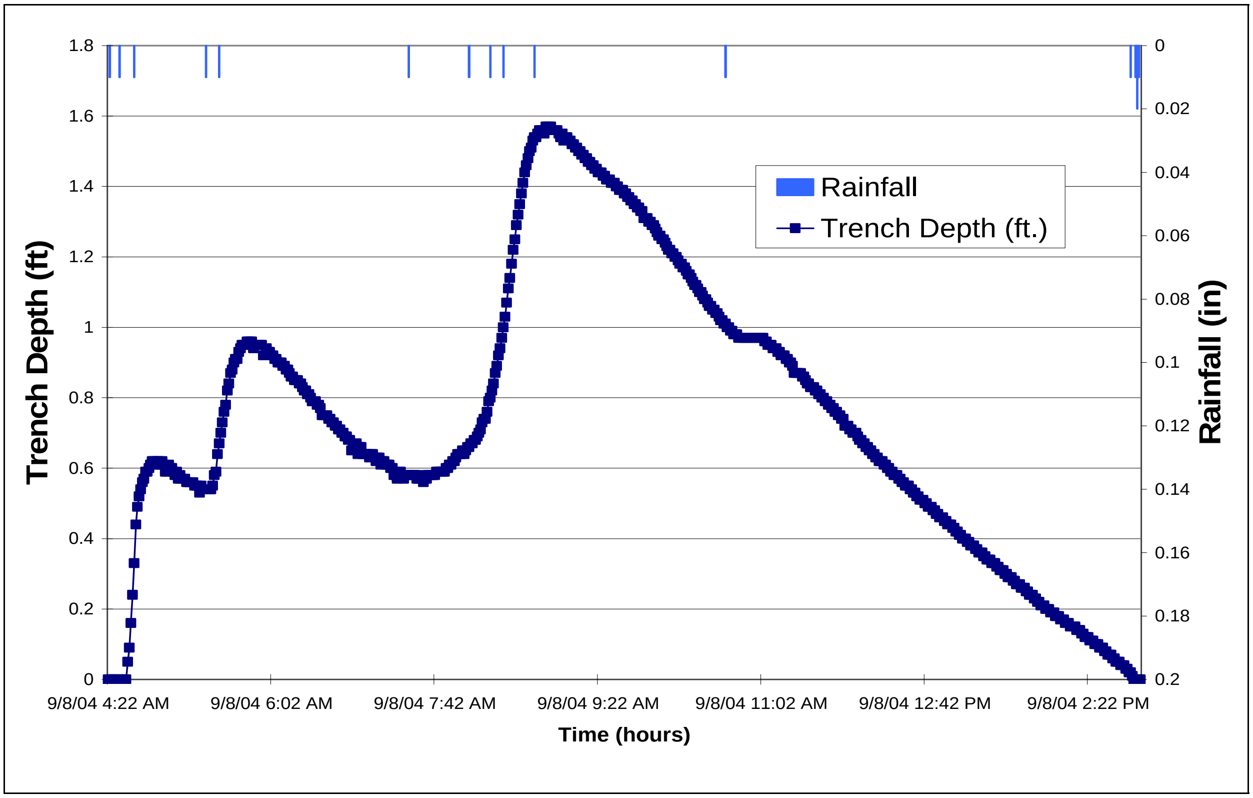

Figure 10: Depth and Rainfall Versus Time (8 Sept 2004)

As seen from Figure 10, the rainfall on the drainage area (secondary abscissa), causes an increase in trench depth to occur. When there is a lag in rainfall, the depth in the trench decreases showing the infiltration effects.

5.2.3 Inflow Verification

To verify the amount of inflow entering the trench from the drainage area, the depth in the trench was converted into volume within the trench based on the regression equation obtained from the storage-rating curve. The procedure to develop the storage-rating curve will be described in section 5.3.2. The volume within the trench throughout the storm was compared with the cumulative trench inflow volume, as shown in Figure 11 for the 8 September 2004 storm event. The inflow verification graphs for each modeled event are included as Appendix D.

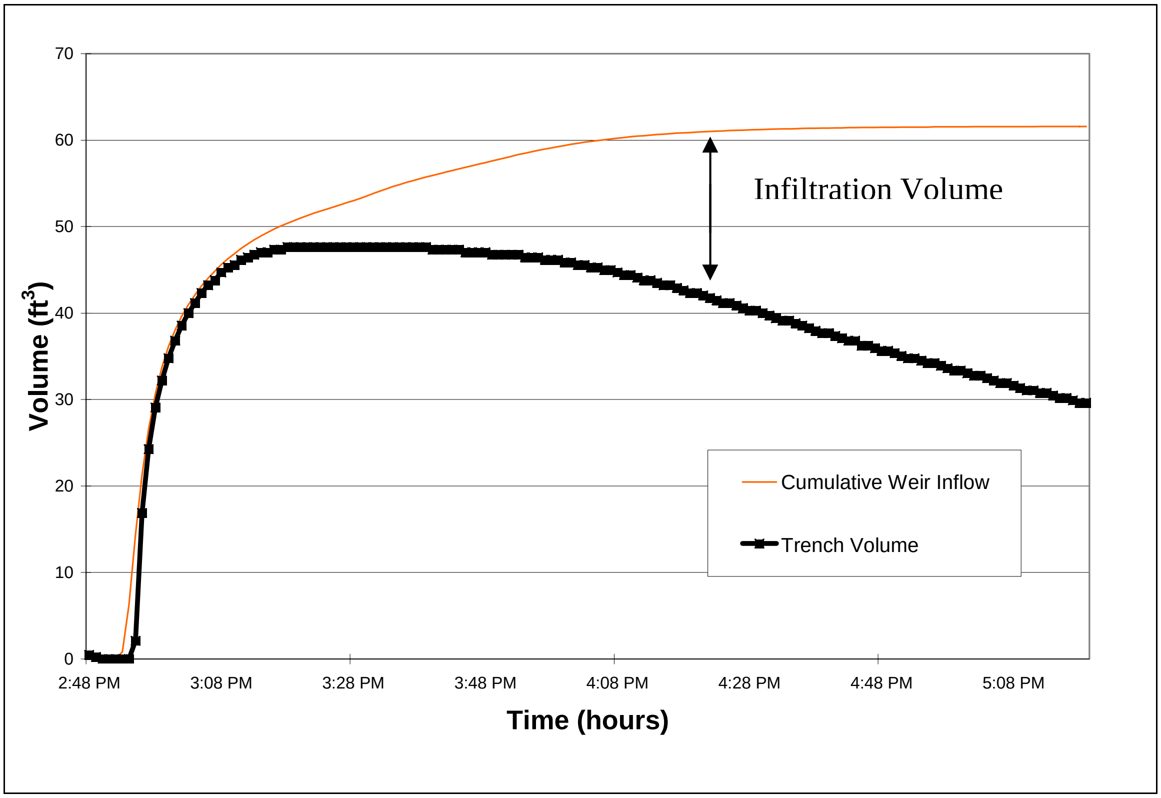

Figure 11: Inflow Verification Graph (8 Sept 2004 Event 2)

As can be seen from Figure 11, the dark, thick line represents the volume within the trench over time, and the thin line represents the cumulative inflow volume throughout the storm. At the start of the storm the two lines exactly match, showing the fact that the amount of water within the trench is equal to the amount of water that flowed over the weir. Within ten minutes of the trench starting to fill infiltration starts and the two lines begin to separate from each other, the difference between the two being the volume of water that has infiltrated.

This was also the method used to verify the amount of void space within the trench. Originally, based on values obtained from literature, a void space of 40% was used to calculate the effective trench volume. This value resulted in a greater volume within the trench in the beginning of the storm then the cumulative amount of inflow that had entered the trench over the weir. The values for void space were altered through trial and error until a value of 36% yielded a reasonable representation of trench conditions as determined by the volume in the trench matching the cumulative inflow volume at the very start of the storm.

5.2.4 Inflow and Outflow Hydrographs

Once the volume entering the trench was verified for each storm an inflow hydrograph was generated. A mass balance was used to evaluate the attenuation that the runoff underwent as it entered the infiltration trench. By knowing the inflow entering the trench, and the storage volume within the trench at all times, the volume of outflow due to infiltration was solved for using the continuity equation. The continuity equation states that the change in storage over time is equal to the inflow minus the outflow, as given by Viessman (2003) in Equation 4 shown below:

$$I - O = \frac{\Delta S}{\Delta T} \tag{4}$$

In which I = inflow rate [L^3T^{-1}]; O = outflow rate [L^3T^{-1}]; S = storage [L^3]; and T = time [T]. In order to smooth the recorded data points, Simpson’s rule was applied to the inflow rates throughout the event using 5 data points for each segment (Chapra and Canale, 2002). An inflow and outflow hydrograph for the infiltration trench is shown in Figure 12 for the 7 July 2004 storm event. The inflow and outflow hydrographs for each modeled event are included as Appendix E.

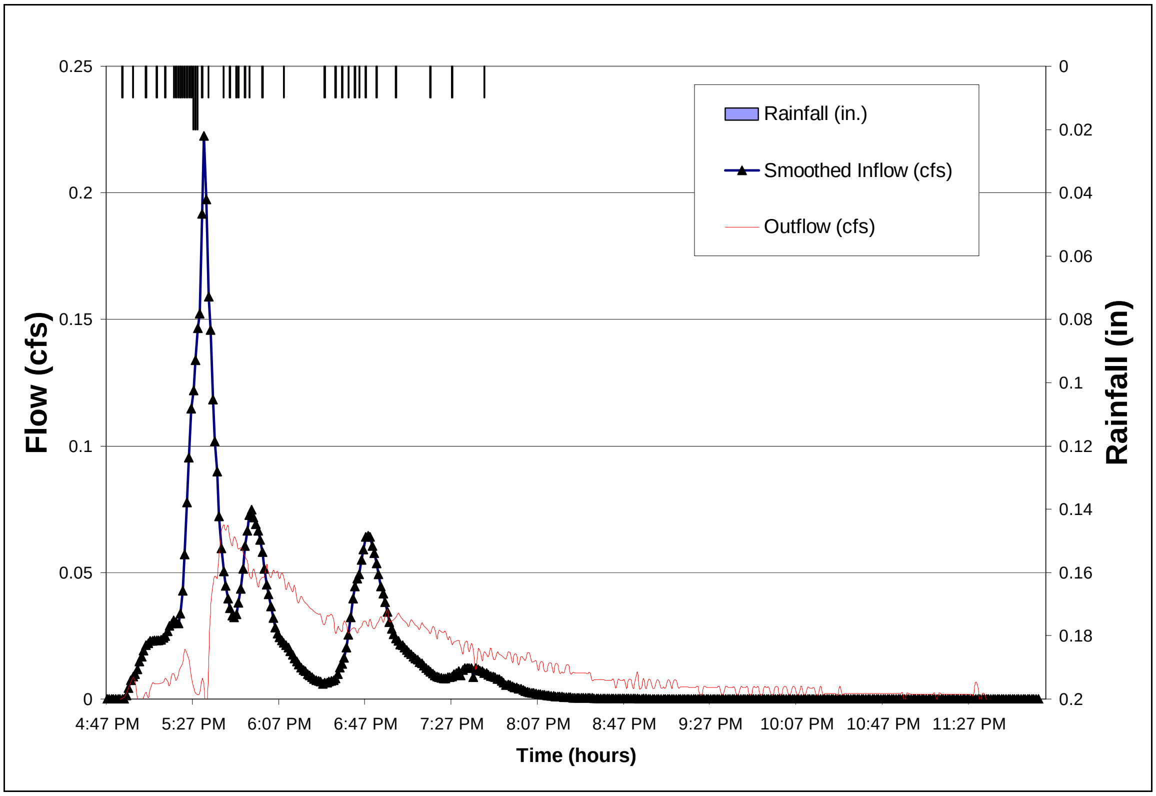

Figure 12: Inflow and Outflow Hydrograph (7 July 2004)

As can be seen from Figure 12 the peaks in inflow correspond to rainfall over the drainage area entering the trench. Up until the point when the outflow peaks along the recession curve of the inflow peaks, storage within the trench is increasing. This corresponds to increasing outflows. The maximum storage within the trench occurs when the outflow rate first exceeds the inflow rate, which is the point on the recession curve where the inflow hydrograph becomes less than the outflow hydrograph. When inflow into the trench decreases, storage within the trench decreases as the trench is emptying out. This is shown when the outflow values are higher than the inflow values, because rainfall has stopped and runoff is no longer entering the trench, and the only change in storage taking place is due to infiltration.

5.3 Model Development

Once individual storm characteristics were analyzed, a model of the Infiltration Trench BMP was developed using basic equations for reservoir routing. A total of four storms were used to calibrate the model and nine storms were used to verify the accuracy of the model. After the required relationships were developed the hydrologic-routing form of the continuity equation was used to derive the outflow hydrograph. Modeled outflow values were converted to depth values and compared to recorded depth values. It was through a comparison of the depth values that the model was evaluated to see if it accurately modeled the infiltration trench. The following sections describe the data requirements necessary and the procedures used in creating the model.

5.3.1 Data Requirements

There are 5 data requirements that are necessary to obtain the modeled output:

- The inflow hydrograph
- The storage rating curve
- The discharge rating curve
- Initial values of storage and outflow rate
- The routing (Δt) increment

The process used to obtain the inflow hydrograph for each event was described previously in section 5.2.2. Initial values of storage and the outflow rate were both zero and a one minute routing increment was used. The following sections are intended to provide information about the mechanics of the routing process. Additionally, development of the curves used in the routing process are described.

5.3.2 Storage-Rating Curve

In order to convert the recorded depth data to storage volume within the trench a storage-rating curve was developed. Based on the survey elevations obtained during the construction of the trench, storage capacities for different trench depths were able to be determined. The known information was the area of the bottom of the trench, the area at a distance of 2 feet from the bottom, 4.81 feet from the bottom, and the area at the ground surface, or top of the trench. The trench was divided into slices, starting at the bottom and increasing 0.1 feet until the top of the bed, at 5.71 feet from the bottom, was reached. The known areas of the bottom, 2 foot, 4.81 foot, and top slice provided a relationship that approximated the area of each slice as the elevation increased. The areas between two slices were averaged to produce an incremental volume. The incremental volume, when added to the volume of the previous two slices, gives the volume of the trench to that point.

Once the volume-depth relationship was found, the volume of pore space available for water storage was estimated. This estimation of void space was initially based on the assumption that the stone aggregate filling the trench has a void space of 40%, thus 40% of the total trench volume is available for water storage. The actual void space within the trench was later verified in the study to be 36% (as described in section 2.3 of Chapter 5) and the storage-rating curve was adjusted. Plotting volume versus trench depth, the points fit along a relatively smooth curve and fits well to a fourth order polynomial function. The plot of the data is shown in Figure 13, along with the regression equation relating volume to depth of the trench. The spreadsheet used to create the storage-rating curve is included as Appendix F.

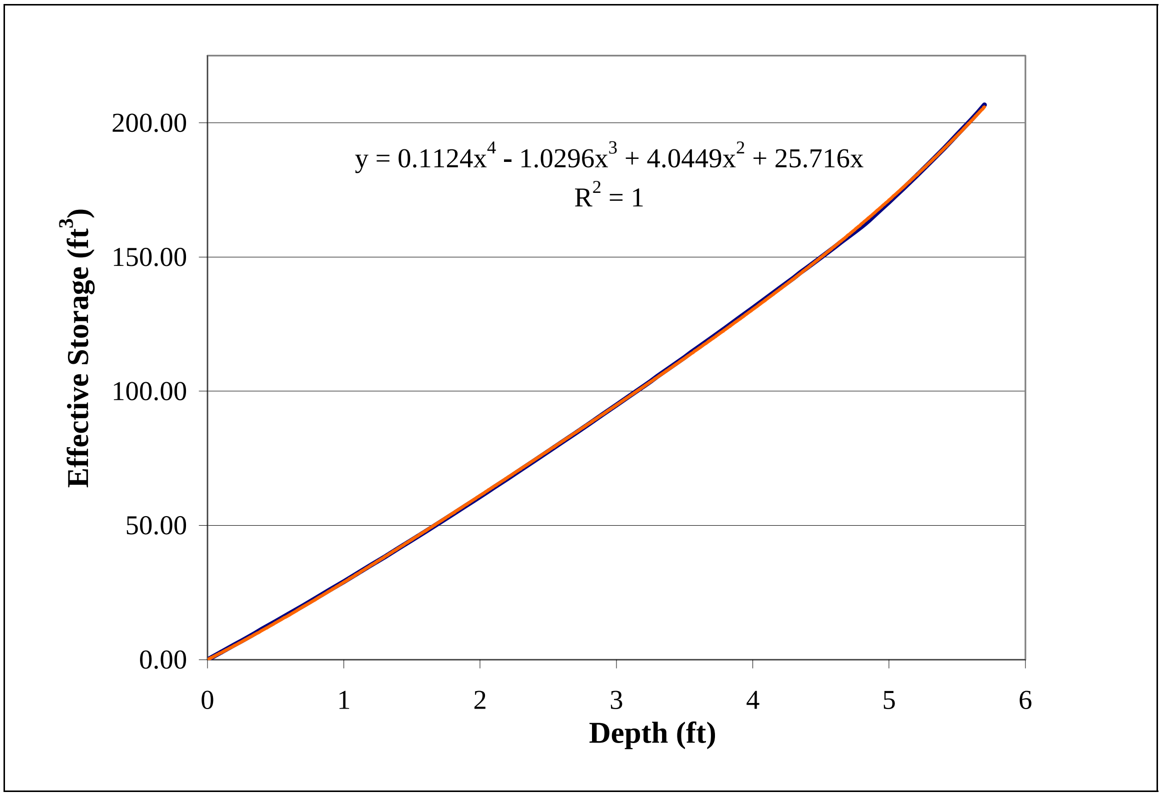

Figure 13: Storage-Rating Curve

5.3.3 Discharge-Rating curve

The discharge-rating curve was developed from the outflow hydrograph created in section 5.2.4. The first step was creating a graph of discharge versus depth for the discharge occurring during the recession limb of the event. A second order polynomial function was fit to the data and the y-intercept of the line was set to zero, as shown in Figure 14 for the 7 July 2004 storm event.

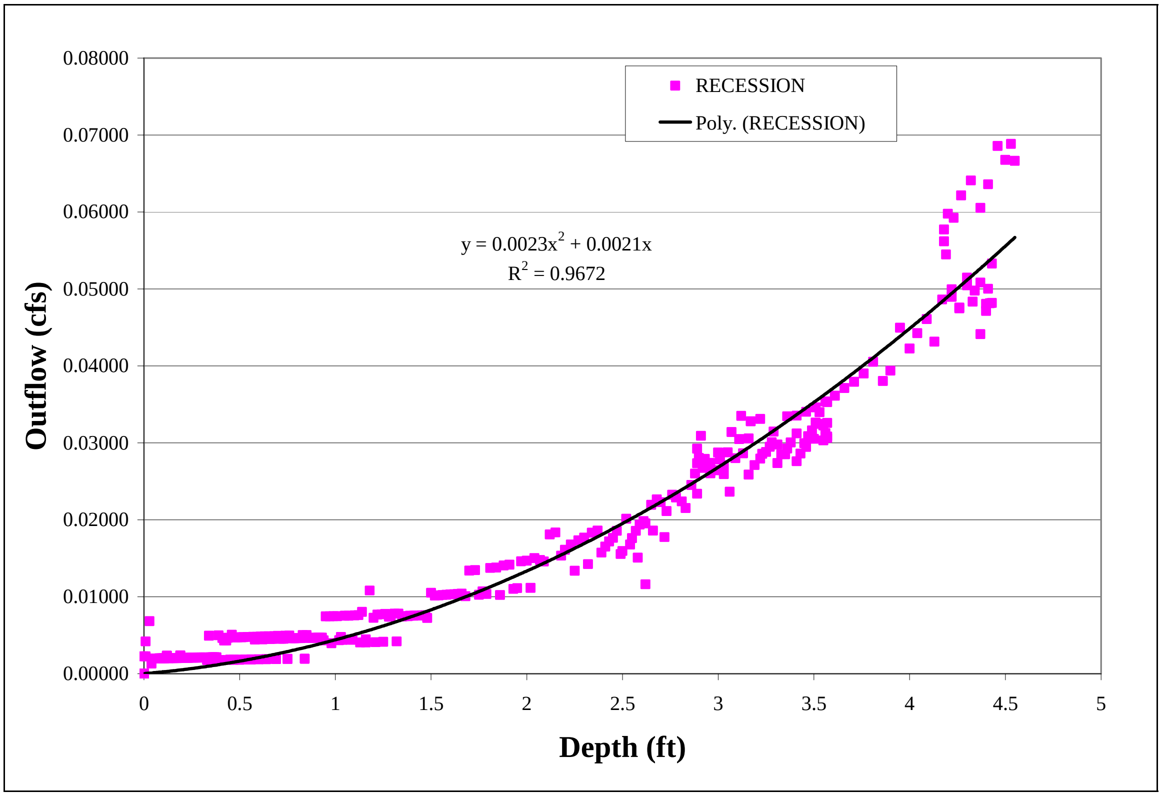

Figure 14: Recession Infiltration Graph (7 July 2004)

The R^2 value for the curve in Figure 14 is 0.97, indicating a very good fit of data to the curve. Note that the data points are collected at one-minute intervals, and as such scatter of the data points is inherently existent based on noise associated with the instruments used to collect the data. According to the manufacturers specification sheet, the INW PS9800 pressure transducer used during the study has a static accuracy value of +/-0.1 percent.

The second step in creating the discharge-rating curve involved deriving a composite equation based on the results obtained from four of the events. The individual event regression equations obtained from the trend lines of the four events were compared, as shown in Figure 15.

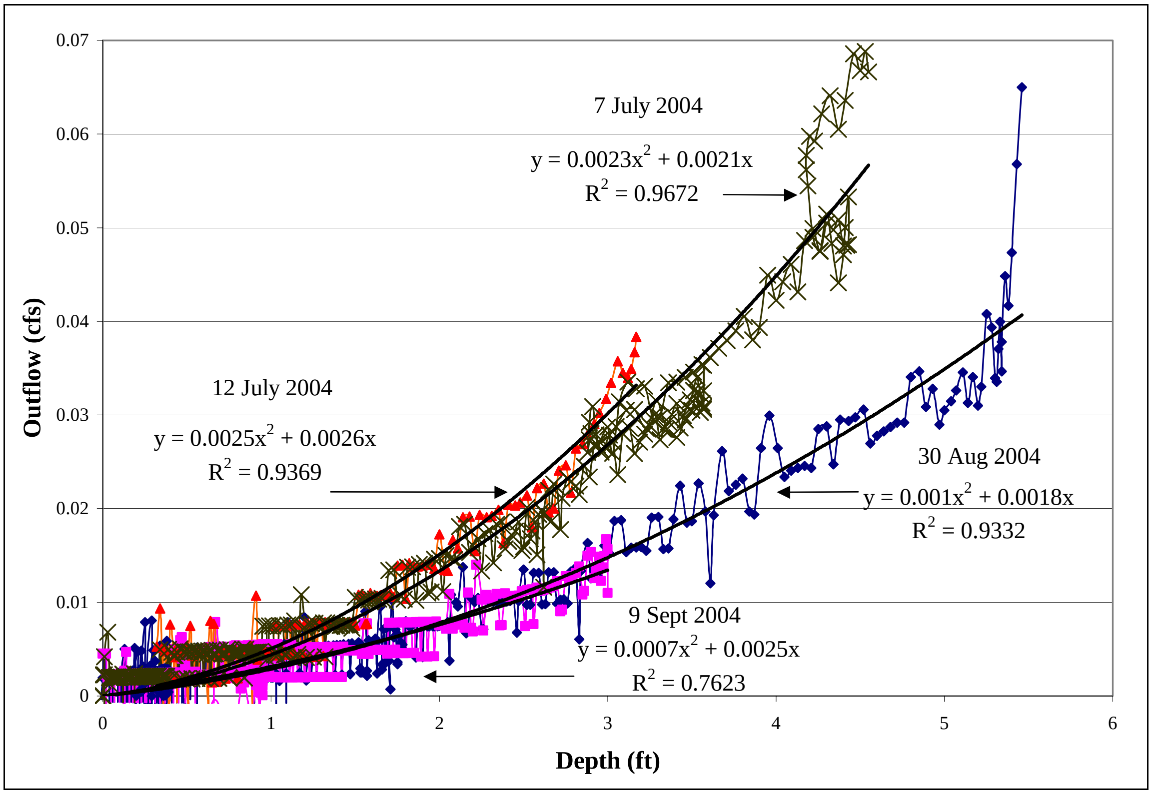

Figure 15: Multiple Event Recession Infiltration Graph

From the events shown in Figure 15 the composite polynomial equation was derived using the averaged ‘a’, ‘b’, and ‘c’ values to obtain representative values, as given in Equation 5:

$$Y = 0.001625x^2 + 0.00225x \quad (5)$$

The equations used to derive Equation 5 and the events from which they were based are further shown in Table 1.

Event Date	Rainfall (in.)	Equation $y = ax^2 + bx + c$			R^2 Value
		a	b	c	
07/07/2004	0.43	0.0023	0.0021	0	0.97
07/12/2004	4.30	0.0025	0.0026	0	0.94
08/30/2004	0.34	0.001	0.0018	0	0.93
09/09/2004	0.14	0.0007	0.0025	0	0.76

Table 1: Calibration Events and Composite Polynomial Derivation

Using Equation 5, the discharge occurring at each recorded depth within the trench was calculated, and the discharge-rating curve was created, as shown in Figure 16.

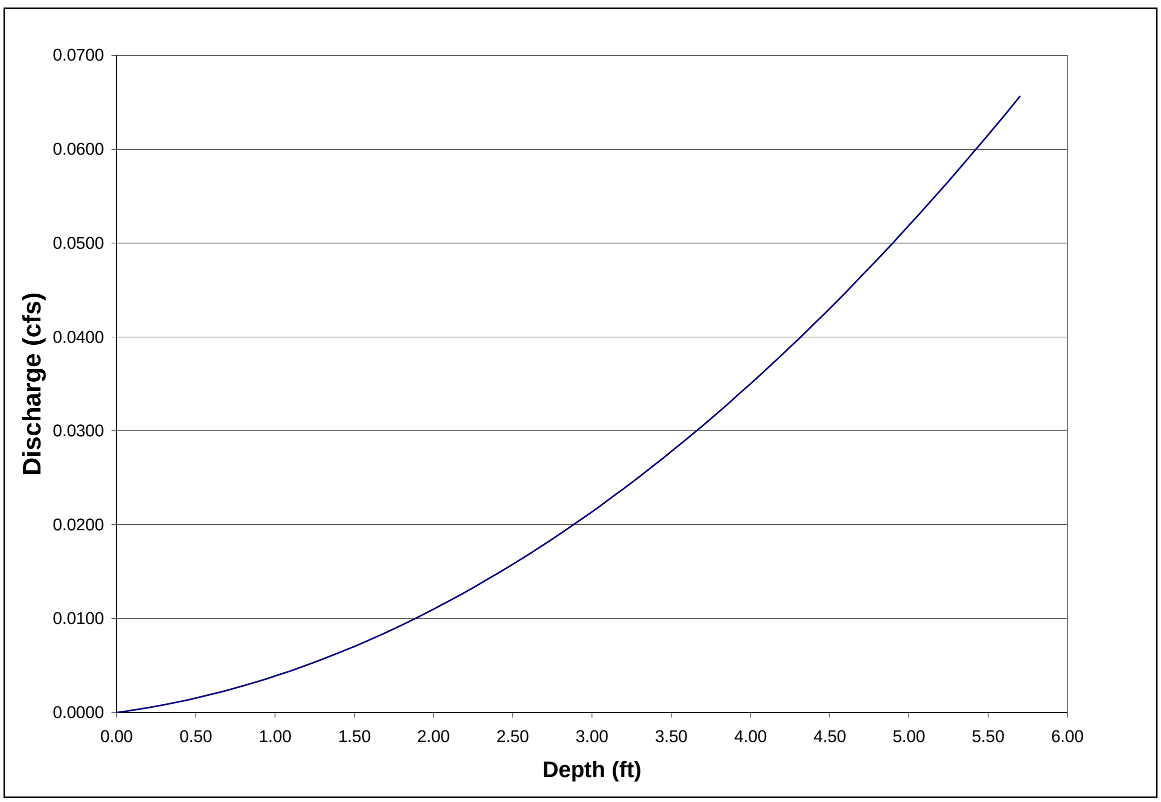

Figure 16: Discharge-Rating Curve

5.3.4 Elevation-Storage-Discharge Table

Upon development of the stage-storage and the stage-discharge curves, an elevation-storage-discharge table for every depth within the infiltration trench was produced. An outflow, due entirely to infiltration, was calculated based on the composite polynomial equation given in Equation 5 for every change of depth within the trench. This information was entered into a corresponding elevation-storage-discharge table and a graph of the Elevation-Storage-Outflow information for the trench was generated, as shown in Figure 17.

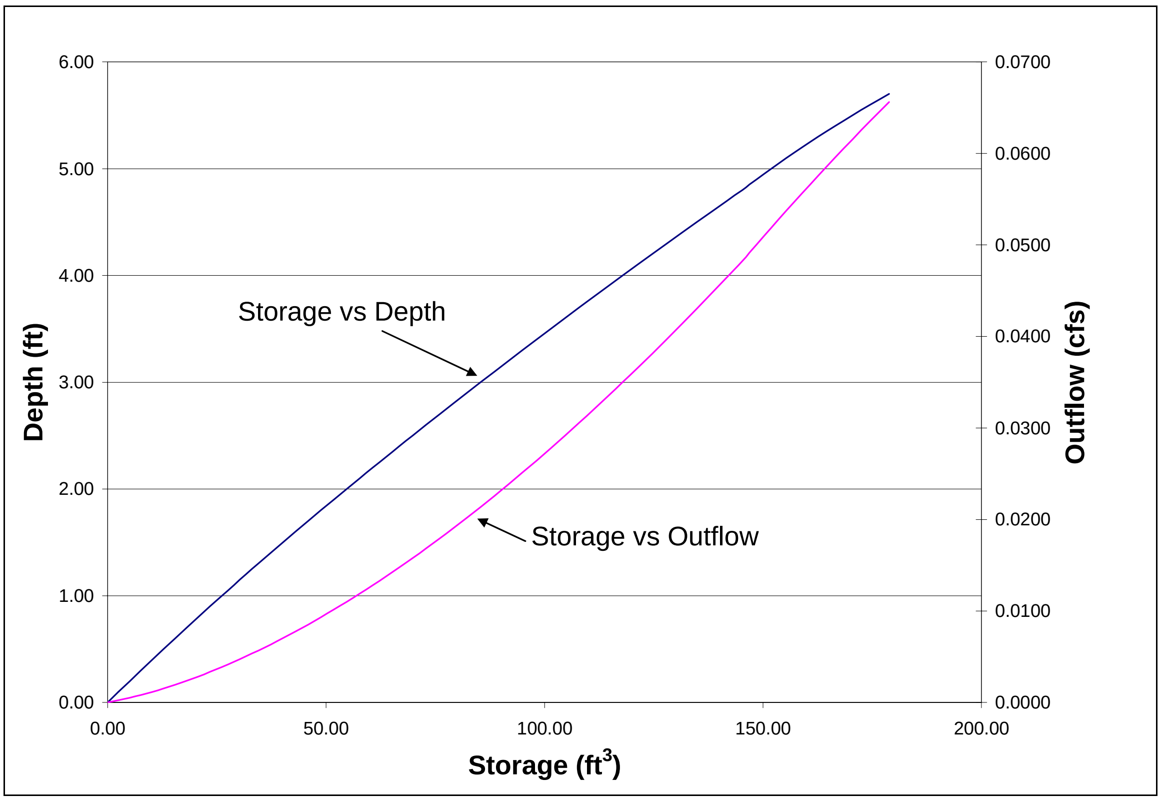

Figure 17: Elevation-Storage-Outflow Graph

The outflow curve in Figure 17 is solely the infiltration taking place within the trench. For this study flow thru the pipe was considered negligible. This was because the inlet to the overflow pipe is flush against the sidewall of the trench. As such, both the aggregate as well as the filter fabric liner restrict flow from entering the overflow pipe. Since the pipe is restricted, water takes the path of least resistance and instead of leaving through the overflow pipe, depths within the trench exceed the crown of the pipe and exit through the porous pavers at the top of the trench. Based on observation both during actual storm events as well as observation of measured data, the overflow pipe does not experience submerged flow conditions.

5.3.5 Storage Indication Curve

After the necessary relationships between storage within the trench and outflow from the trench were developed, storm events could be verified. The following sections describe the development of the storage indication curve and the steps followed to route an inflow hydrograph through the infiltration trench.

Using the hydrologic-routing form of the continuity equation, given as Equation 6, the continuity equation becomes:

$$\frac{I_1 + I_2}{2}\Delta t - \frac{O_1 + O_2}{2}\Delta t = S_2 - S_1 \qquad (6)$$

Where subscript 1 is the value at the start of the time step; subscript 2 is the value at the end of the time step, and Δt is the chosen time step. Rearranging Equation 6 and putting known values on the left, the equation becomes:

$$(I_1 + I_2) + \left(\frac{2S_1}{\Delta t} - O_1\right) = \left(\frac{2S_2}{\Delta t} + O_2\right) \qquad (7)$$

Equation 7 represents one equation with two unknowns (S_2 and O_2); to determine their values a second equation between storage (S) and outflow (O) is needed. The second necessary relationship is the equation based on the storage-discharge relationship. Once the storage-discharge relationship was developed it was then used to derive the storage-indication curve, which is a relationship between O and ($2S_2/\Delta T + O_2$). Using the storage-discharge curve, (Figure 17), the following procedure as outlined by McCuen (1989) was followed to develop the storage-indication curve (Figure 18):

1. Select a value of O.
2. Determine the corresponding value of S from the storage-discharge curve.
3. Use the values of S and O to compute ($2S_2/dT + O_2$).

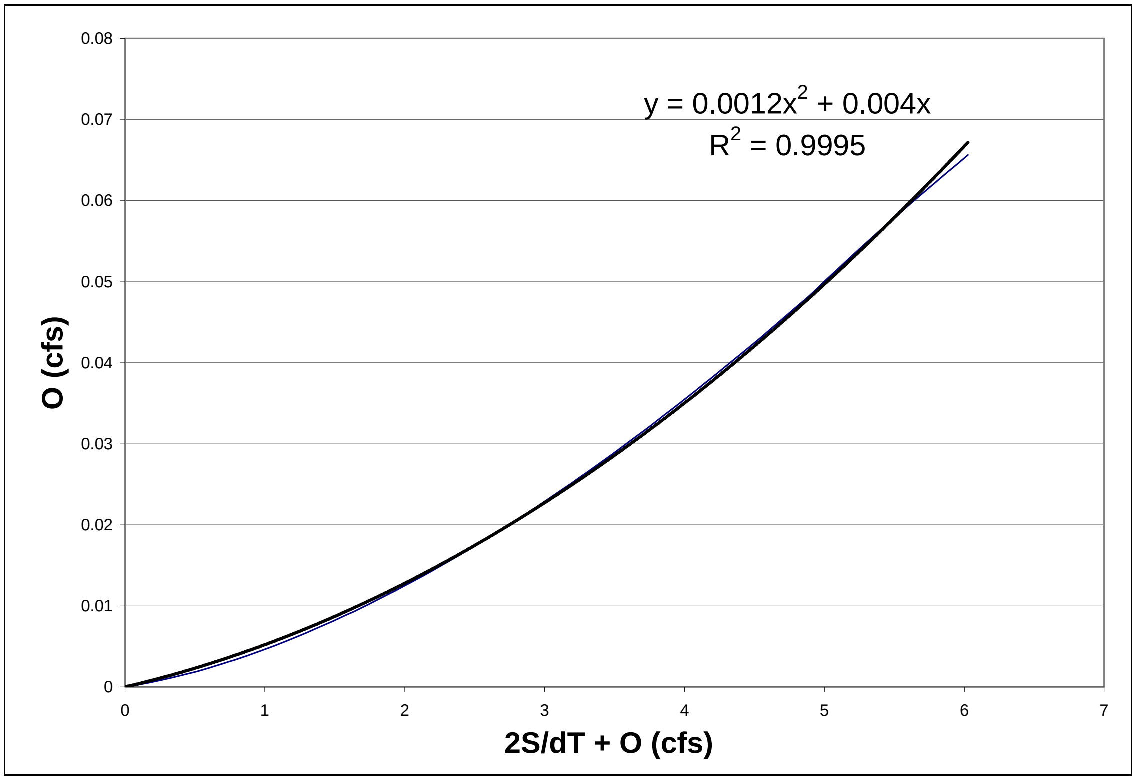

Figure 18: Storage Indication Curve

Using the storage indication curve shown in Figure 18, along with the calculated value of ($2S_2/dT + O_2$), the outflow value occurring at the next time interval was obtained and the process was repeated for the duration of the storm event. The modeled output values were obtained and compared to observed values. Results are discussed in Chapter 6.

6.0 Results and Discussion

This chapter discusses verification and subsequent analysis of the model developed in Chapter 5. Model verification involved first checking that the methods utilized conserved mass. A total of nine events were used to verify the model through a comparison of predicted to recorded trench depths. Of the nine verification events, one was modeled using the storm specific infiltration curve and the remaining eight were modeled using the composite infiltration curve as described in Chapter 5. Results of verification using the storm specific infiltration and composite infiltration curve are presented in the first two sections of this chapter. After model verification, the average and peak infiltration rates that occurred throughout the storm events were compared, and the relationship between trench geometry and infiltration is presented. Finally, changes in infiltration rates that occurred over the period of this study were evaluated and results are presented in the final section.

6.1 Mass Conservation Check

The routing methodology was verified to ensure mass conservation; that is the total outflow volume must equal the inflow volume. Minor differences in inflow and outflow are attributed to errors in representation of the discharge-rating and the storage-indication curve, or roundoff error. For all modeled events, measured inflow volumes and modeled outflow volumes along with the relative errors are shown in Table 2, along with the relative error between the measured and modeled outflow. The relative error is calculated using Equation (8).

$$\frac{Differnce\ Between\ Values}{Actual\ Value} \times 100\% \qquad (8)$$

Event Date	Measured Inflow (ft^3)	Modeled Outflow (ft^3)	Relative Error (%)
07 July 2004	373.31	366.69	1.77
18 July 2004	975.05	971.82	0.33
13 August 2004	65.92	63.81	3.20
8 Sept 2004 (1)	75.82	80.01	-5.52
8 Sept 2004 (2)	61.59	59.71	3.05
12 Nov 2004	2214.44	2214.20	0.01
20 Nov 2004	344.82	339.10	1.65
7 Dec 2004	1293.00	1286.44	0.50
10 Dec 2004	2191.45	2184.20	0.33
Totals	9137.24	9104.76	0.35

Table 2: Mass Conservation Check

The range of relative error between the measured inflow volume and modeled outflow volume is -5.52 to 3.20 percent. On 8 September 2004 there were two different periods of rainfall; where the lag time between the two periods allowed the trench to completely empty; therefore, 8 September 2004 is defined as two separate events. Figure 19 further illustrates conservation of mass verification.

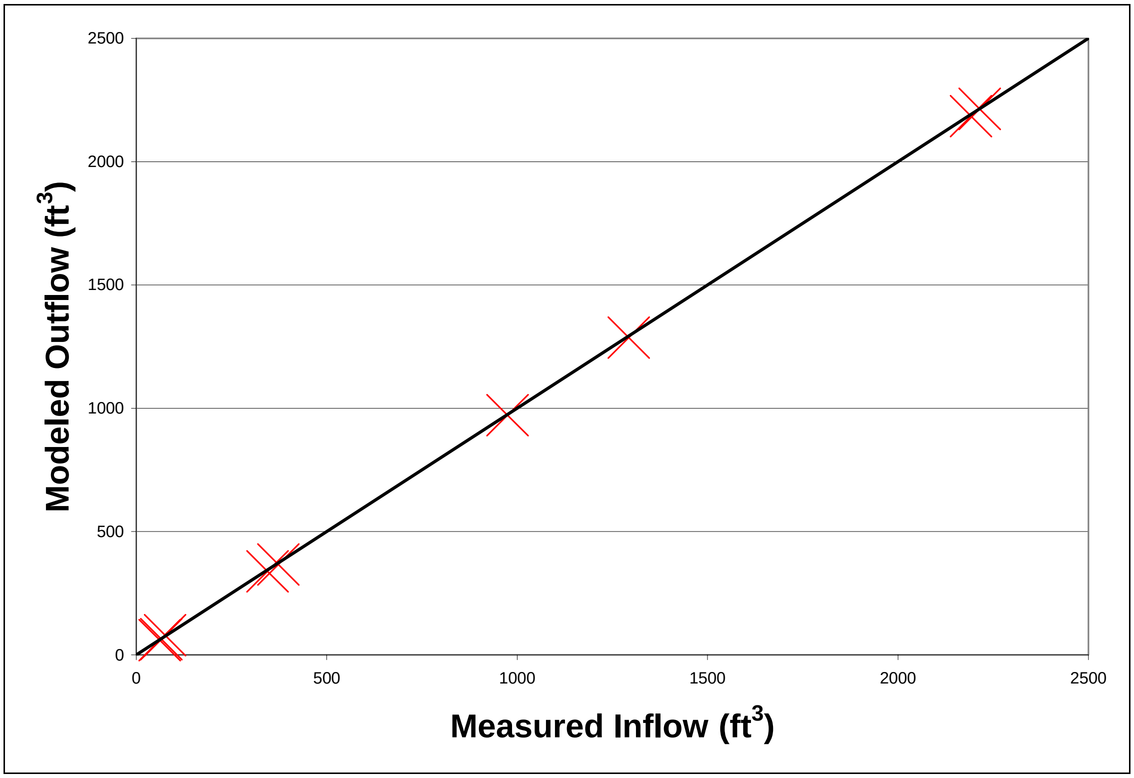

Figure 19: Mass Conservation Check

Figure 19 shows measured inflow volumes as the abscissa and modeled outflow volumes as the ordinate. A line that makes a 45-degree angle between itself and the abscissa was drawn and the data points from Table 2 were plotted against the line. All of the data points fall almost directly on the line, with only a small positive bias. This shows that there is a direct relationship between the inflow and outflow values and verifyies that conservation of mass is upheld by the routing procedures used.

6.2 Model Verification

Model verification further required examination of the routing results when using the storm specific and composite infiltration curves. The performance of the model was checked against recorded depth data for a specific storm. Next, to complete the verification process the composite infiltration curve was used to model five large events and three small events that were not used in the curve development.

6.2.1 Storm Specific Infiltration Curve

Verification using the storm specific infiltration curve was validated by routing the 7 July 2004 event through the infiltration trench. The storm specific infiltration curve provided an accurate approximation of the trench water surface elevation throughout the storm, as shown in Figure 20.

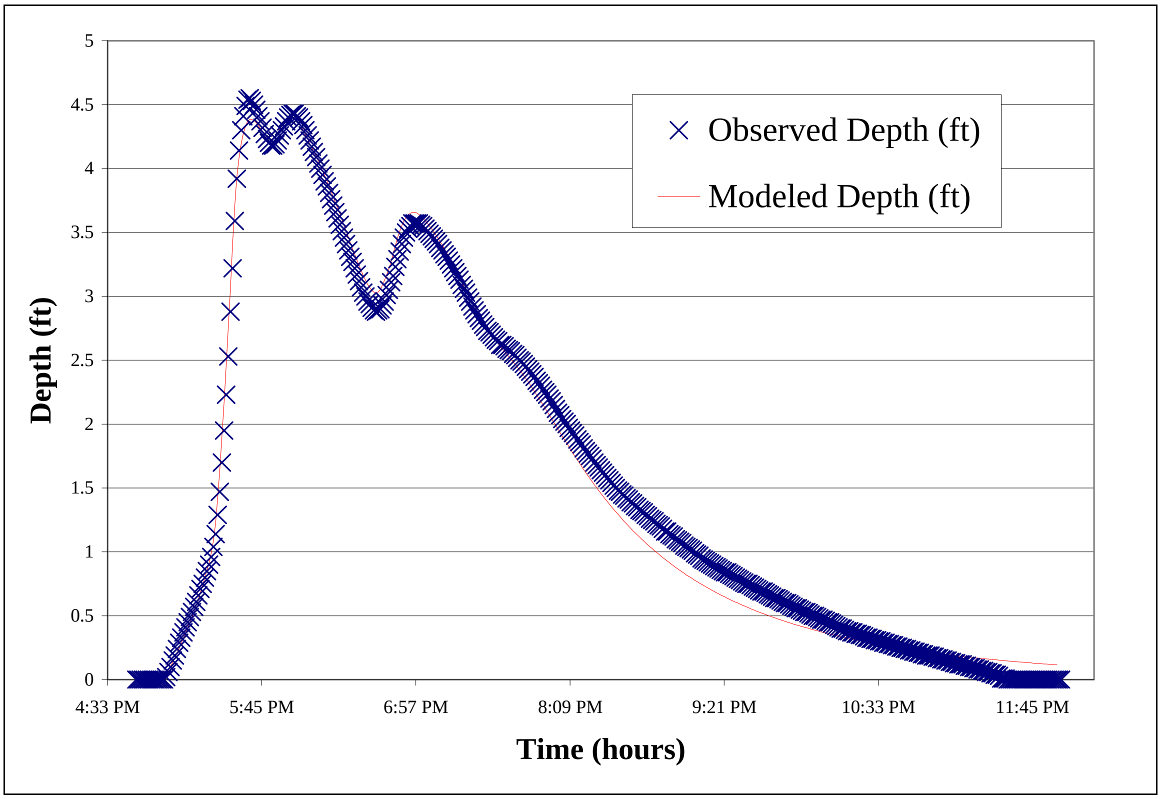

Figure 20: Depth Versus Time (7 July 2004)

For the 7 July 2004 event shown in Figure 20, the model closely simulates the observed depth points throughout the storm. This is an expected result since the equation used to predict infiltration was obtained from the modeled event itself.

The Mean Square Error (MSE) was used to quantify the skill of the model. The MSE is a measure of control and quantity and equals the mean of the squares of the deviations from the target value as shown below in Equation (9):

$$MSE = \frac{1}{m}\sum_{i=1}^{m}(x_i - T)^2 \qquad (9)$$

In which x_i = ith value of a group of m values (model value); T = target or intended value for the product variable of interest, which is the observed value (Battaglia, 1996). The MSE was calculated for the data set for the 7 July 2004 event using observed and modeled depth values. A zero error is an exact fit and the MSE for the 7 July 2004 event is 0.02 as shown in Table 3.

Event Date	Rainfall (in.)	Mean Square Error (in^2)
7/7/2004	0.43	0.02

Table 3: Mean Square Error (Storm Specific Infiltration Curve)

To further evaluate model accuracy when using the storm specific infiltration curve, model depth values were compared to recorded depth values for the 7 July 2004 event. Table 4 presents the maximum depth recorded during the event and predicted by the model, along with the relative error between the two values.

Date	Maximum Depth (ft)		Relative Error (%)
	Recorded	Modeled	
7 July 2004	4.55	4.39	-3.51

Table 4: Event Maximum Depth (Storm Specific Infiltration Curve)

The model accurately predicted the timing of the multiple peaks in depth, as well as reproduced the depths within the trench throughout the event when using the storm specific infiltration curve; this verifies that the routing method is valid for individual storms.

6.2.2 Composite Infiltration Curve

Once the model was verified using the storm specific infiltration curve, the next step was to verify the composite infiltration curve using eight storms not used in the development of the composite infiltration curve (as described in Section 5.3.3). Events modeled included both large (equal to or greater than 0.14-inches) and small (less than 0.14-inches), and only included events that did not produce depths within the trench above 5.7 feet, so that all outflow from the trench was due to infiltration. For each of the eight events modeled using the composite infiltration curve, the MSE was calculated using observed and modeled depth values. Characteristics of the modeled events along with MSE values are shown in Table 5.

Event Date	Rainfall (in.)	Event Size	Mean Square Error (in^2)
13 Aug 2004	0.08	Small	0.09
8 Sept 2004 (1)	0.11	Small	0.15
8 Sept 2004 (2)	0.06	Small	0.18
18 July 2004	0.85	Large	0.53
12 Nov 2004	1.48	Large	2.26
20 Nov 2004	0.14	Large	0.19
07 Dec 2004	0.71	Large	0.90
10 Dec 2004	1.04	Large	1.10

Table 5: Mean Square Error (Composite Infiltration Curve)

Comparing model depth values from the composite infiltration curve to recorded depth values shows that, for both large and small events, the model accurately predicted the timing of the multiple peaks of an event. However, the model was not as accurate in reproducing the peak depths within the trench, particularly for small events showing a negative bias possibly due to smoothing of the inflow data (Table 6). For all events modeled using the composite infiltration curve depth versus time graphs are included as Appendix G.

Date & Event Size	Maximum Depth (ft)		Relative Error (%)
	Recorded	Modeled	
13 Aug 2004 (Small)	1.66	1.35	-18.60
8 Sept 2004 (1) (Small)	1.57	0.98	-37.60
8 Sept 2004 (2) (Small)	1.75	1.16	-33.70
18 July 2004 (Large)	5.02	5.91	17.8
12 Nov 2004 (Large)	5.47	5.28	-3.6
20 Nov 2004 (Large)	4.55	4.40	-3.3
07 Dec 2004 (Large)	5.56	6.11	9.8
10 Dec 2004 (Large)	5.49	4.97	-9.5

Table 6: Event Maximum Depths (Composite Infiltration Curve)

Table 6 shows that for six of the eight events modeled using the composite infiltration curve the maximum depth was under predicted, particularly for the three small modeled events, as shown by the high relative error values. This observation indicates that for small events the model over predicted infiltration from the trench, which is further illustrated in the depth versus time graph for one of the small events, shown in Figure 21.

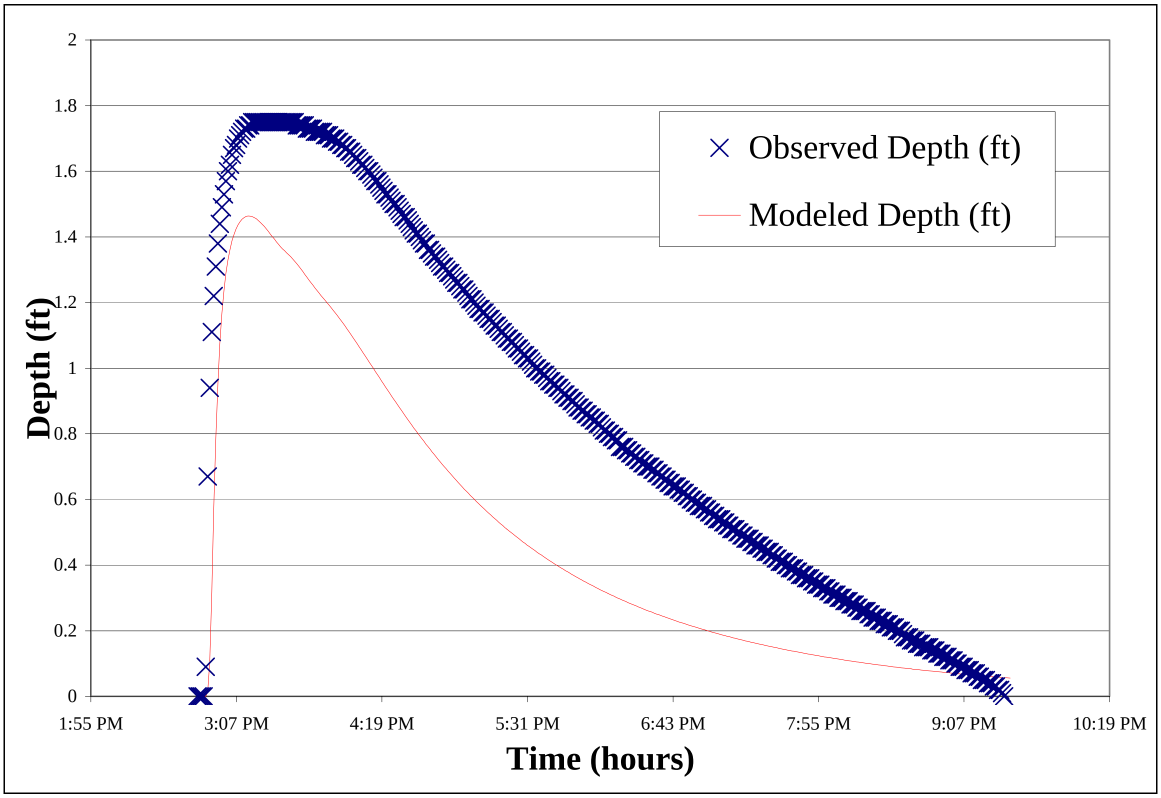

Figure 21: Depth Versus Time (8 Sept 2004 (2))

The modeled depth values, as shown by the line in Figure 21, match the recorded depth values in the first twenty minutes. However, after this point the model under predicted trench depth values. Also shown in Figure 21 is the fact that the model under predicted the maximum trench depth that occurred during the event.

For the large events that were modeled using the composite infiltration curve, the model was more accurate at predicting maximum trench depths than it was for small events. For the 18 July 2004 event and the 7 December 2004 events the model over predicted the maximum trench depth. The largest relative error (17.8 %) was the 18 July 2004 event. The model predicted a maximum depth of 5.91 feet when the max depth recorded during the event was 5.02 feet. This is further illustrated in the depth versus time graph for the 18 July 2004, shown as Figure 22.

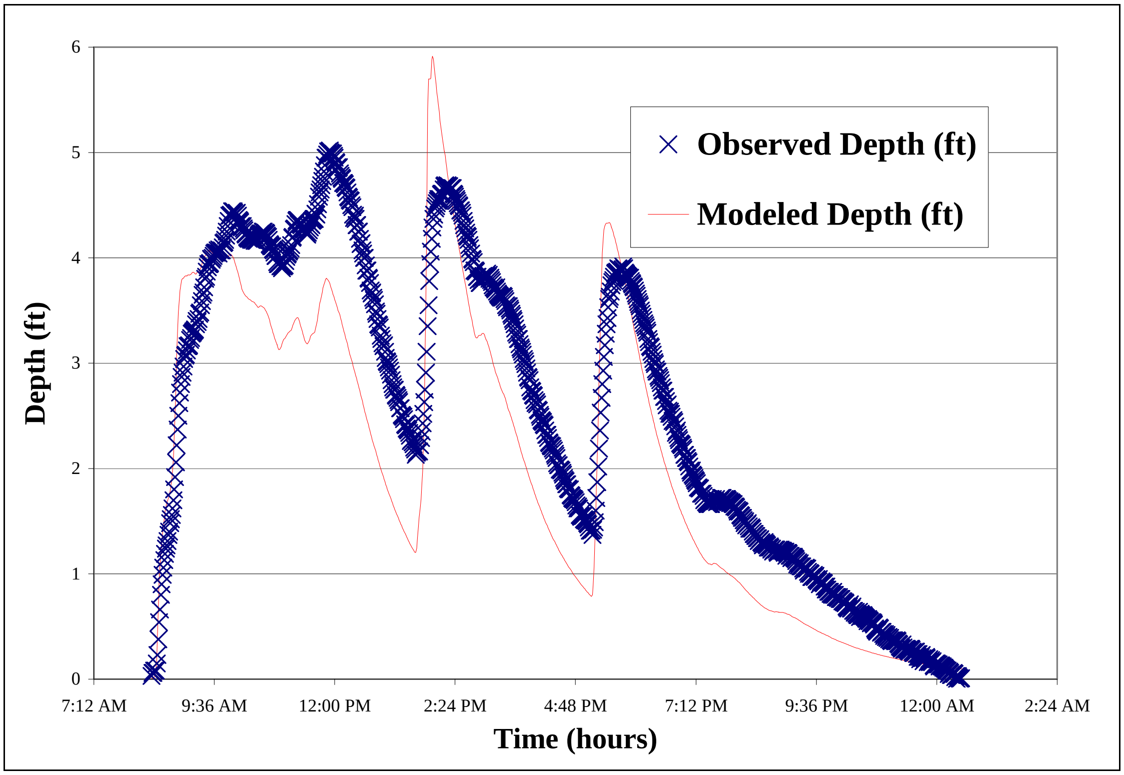

Figure 22: Depth Versus Time (18 July 2004)

Figure 22 illustrates that the model over predicted the peaks in trench depths that occurred later in the event. Specifically, the peak in trench depth that occurred at 2:17 pm was recorded to be 4.68 feet, however the model predicted a peak depth of 5.89 feet. For this peak in trench depth, flow is modeled as lost through overflow through the porous pavers when in fact no such overflow occurred. The peak in trench depth that occurred at 5:44 pm was recorded to be 3.95 feet, while the model predicted a peak depth of 4.29 feet. Other than these peaks that occurred later in the event, the model generally over predicted infiltration from the trench, resulting in modeled depth values lower than recorded depths.

Overflow from the trench was also predicted by the model for the 7 Dec 2004 event, with a maximum depth of 6.11 feet, while the maximum depth recorded during the event was 5.56 feet. This is further illustrated in the depth versus time graph for the 7 Dec 2004 event, shown as Figure 23.

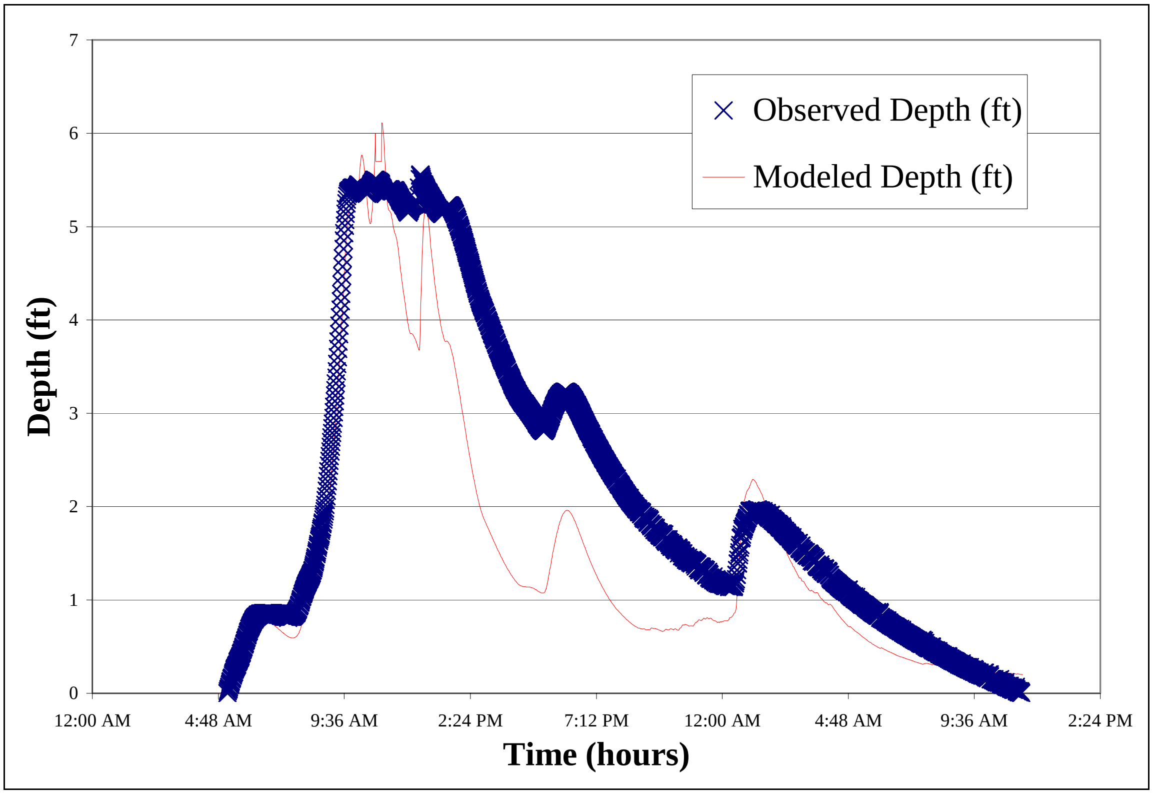

Figure 23: Depth Versus Time (7 Dec 2004)

The model over estimation of the maximum trench depth for the 18 July 2004 and 7 Dec 2004 events may be due to when the depth within the trench is at a peak, the surface area that the water is infiltrating through is at a maximum value also. Therefore, water within the trench is exposed to a larger amount of surface area. This provides more contact for the water to infiltrate through and as a result the actual volume of water that is infiltrating is greater than what the model predicts during that time period. Another factor that may have contributed to errors in predicted trench depths is the value that was used for void space within the trench. The model used a constant value when in fact the void space may not be the same at all depths within the trench.

6.3 Infiltration Rates

The average and peak infiltration rates were calculated for each storm using the outflow data from the storm specific routing and the composite curve routing data. The average infiltration rate was determined by taking the arithmetic average of all outflow values throughout the event. The peak infiltration rate is the peak rate over the event. The storm specific outflow values (Section 5.2.4) were found using the recorded inflow and storage to determine the outflows through conservation of mass, so they are considered to be an accurate representation of actual values.

6.3.1 Large Storm Events

Characteristics of the large events modeled are given in Table 7, along with the storm specific and modeled average infiltration rate throughout the event. Modeled outflow hydrographs for large events are included as Appendix E.

Date	Precipitation (in.)	Average Infiltration Rate (cfs)		Relative Error (%)
		Storm Specific	Composite	
18 July 2004	0.85	0.0162	0.0166	2.46
12 Nov 2004	1.48	0.01872	0.01873	0.05
20 Nov 2004	0.14	0.0072	0.0071	-1.39
07 Dec 2004	0.71	0.0117	0.0116	-0.85
10 Dec 2004	1.04	0.01513	0.01508	-0.33

Table 7: Large Event Average Infiltration Rates

The average infiltration rate modeled using the composite infiltration rate curve is referred to as the 'Composite' average infiltration rate. For large events, the range of values for the composite average infiltration rates is from 0.0071 cfs to 0.01873 cfs. When the lowest rainfall event is removed this range is reduced to 0.0117 to 0.01873. The higher rainfall depths had the higher average infiltration rates. The range of values for relative error between modeled average infiltration rates and storm specific infiltration rates is from –1.39 to 2.46. Based on these small values, the model was considered accurate in predicting the average outflow rate that occurred throughout an event. However, overall, the model under predicted peak infiltration rates for all but one of the large events, as shown in Table 8.

Date	Peak Infiltration Rate (cfs)		Relative Error (%)
	Storm Specific	Composite	
18 July 2004	0.490	1.00	104
12 Nov 2004	0.0823	0.0583	-29.16
20 Nov 2004	0.0813	0.0423	-47.97
07 Dec 2004	0.1611	0.1200	-25.50
10 Dec 2004	0.1110	0.0533	-51.98

Table 8: Large Event Peak Infiltration Rates

The outflow hydrograph for the event with the largest relative error in Table 8 (18 July 2004) is shown in Figure 24.

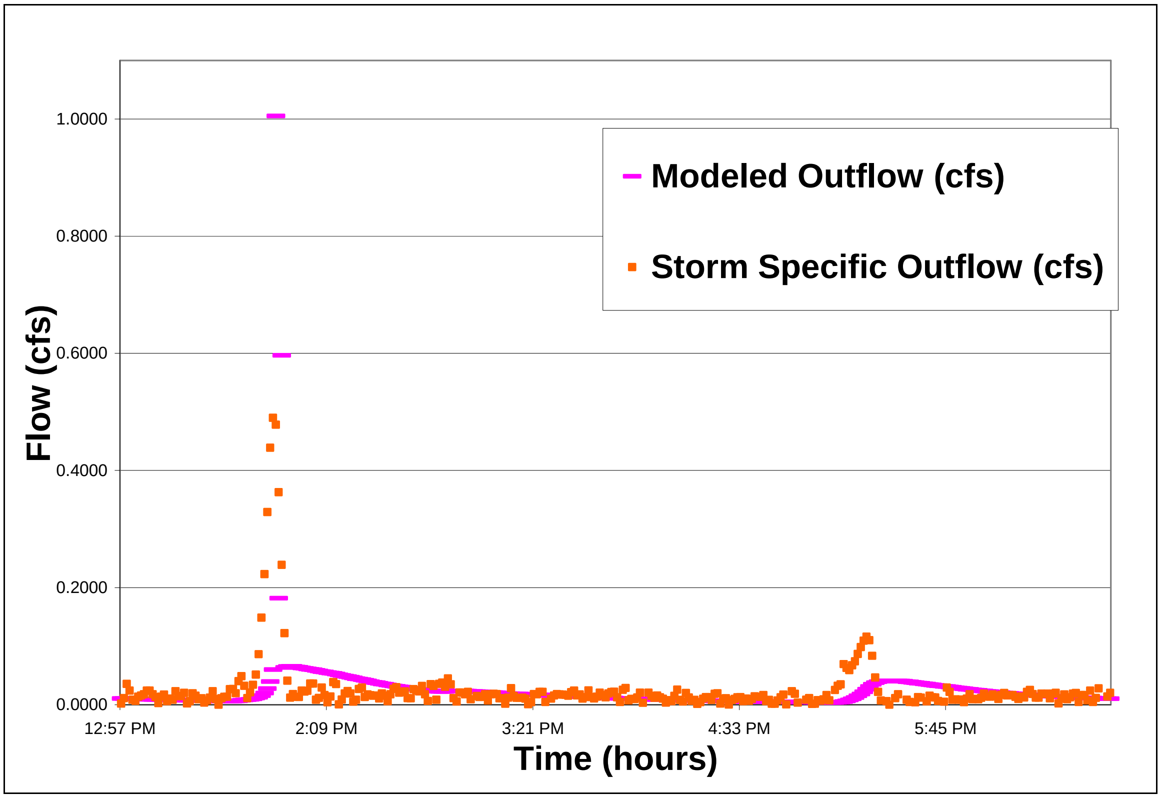

Figure 24: Outflow Hydrograph (18 July 2004)

The period of time shown in Figure 24 includes the two peaks in outflows. The model under predicted the peak infiltration rates for this event for every minute with the exception of three minutes, leading to a large relative error between the initial and the modeled outflow. If those three data points are excluded, the peak infiltration rate is under predicted for the 18 July 2004 event just like each of the other large event peak infiltration rates are under predicted.

The outflow hydrograph for the 12 Nov 2004 event, which was the largest of the storms (1.48 inches of rainfall) used for verification, is shown in Figure 25.

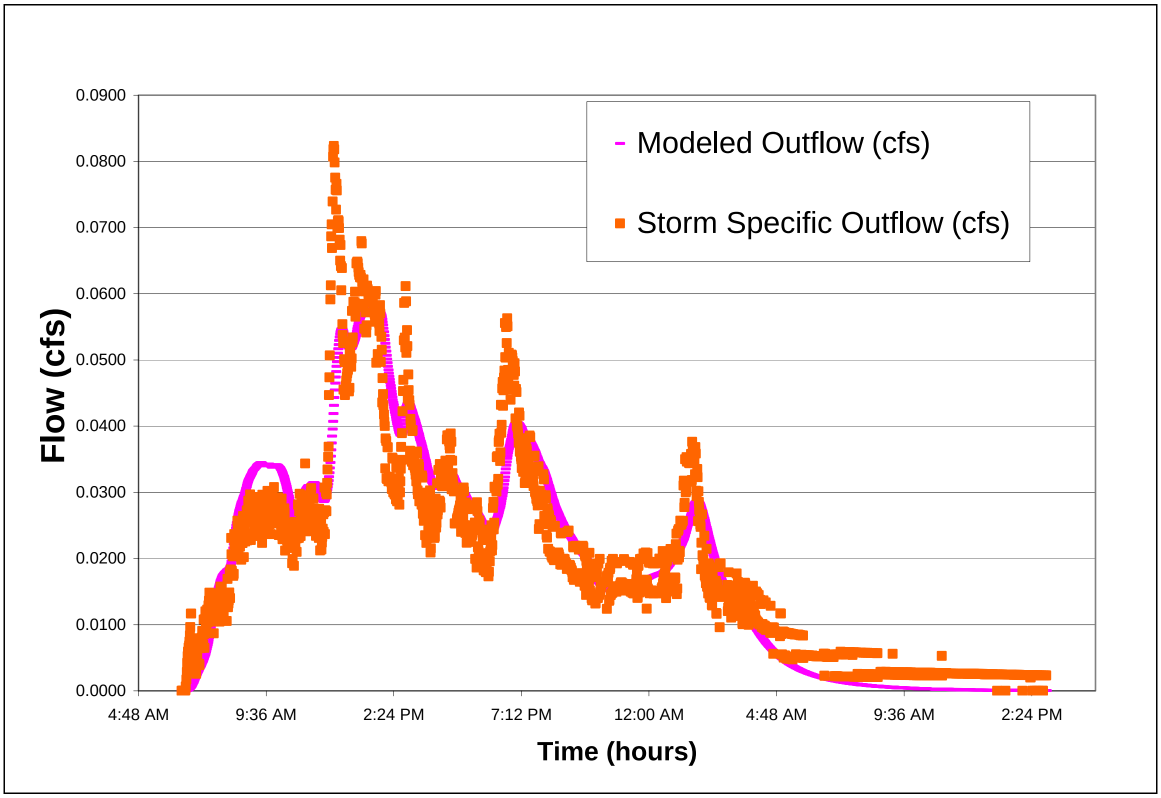

Figure 25: Outflow Hydrograph (12 Nov 2004)

Figure 25 shows that the model accurately reproduced the shape of the outflow hydrograph. Additionally, infiltration rates throughout the event were closely predicted. However, peak infiltration rates for all of the peaks except the initial peak were under estimated by the model.

6.3.2 Small Storm Events

With respect to the outflow hydrographs obtained from the routing procedure, storm events in which the amount of rainfall was less than 0.14 inches were not accurately modeled. Characteristics of the small events modeled are given below in Table 9, along with the storm specific and modeled average infiltration rate throughout the event.

Date	Precipitation (in.)	Average Infiltration Rate (cfs)		Relative Error (%)
		Storm Specific	Composite	
13 Aug 2004	0.08	0.0029	.0026	-10.34
8 Sept 2004 (1)	0.11	0.00206	.0021	1.94
8 Sept 2004 (2)	0.06	0.0026	.0025	-3.85

Table 9: Small Event Average Infiltration Rates

The range of values for modeled average infiltration rates is from 0.0021 cfs to 0.0026 cfs, with a similar range of values for storm specific average infiltration rate. The range of values for relative error between modeled average infiltration rates and storm specific infiltration rates is from -10.34 to 1.94. Similar to large events, the model was accurate in predicting the average infiltration rate that occurred throughout smaller events. However, the model under predicted peak infiltration rates for small events (Table 10).

Date	Peak Infiltration Rate (cfs)		Relative Error (%)
	Storm Specific	Composite	
13 Aug 2004	0.0493	0.0071	-85.59
8 Sept 2004 (1)	0.0220	0.0033	-85.00
8 Sept 2004 (2)	0.0744	0.0078	-89.51

Table 10: Small Event Peak Infiltration Rates

The calibration method may be responsible for under prediction of the infiltration. Model calibration was described in section 5.3.3. Each of the recession limbs of the calibration events were fitted to a polynomial trend line. In fact, for small events the infiltration rate is linear, as observed from recorded trench depths. Therefore, a polynomial representation is not accurate for small events. Smaller storms do not produce as much runoff as larger storms, so the resulting volume of water that enters the trench is less than larger events and the trench depths are lower. These lower trench depths translate to an infiltration rate that is constant instead of an infiltration rate that is variable with depth. To predict infiltration rates from smaller storms, a constant rate may have to be used, instead of a rate that is a function of depth.

The observation that the model predicted lower depths for both large and small events may also be attributable to the routing method itself. The method consists of the repetitive solutions of the continuity equation and is based on the assumption that the trench water surface remains horizontal and that outflow from the trench is a unique function of storage. In reality, the maximum rate at which a soil is capable of infiltrating water is affected by many variables, including antecedent rainfall conditions, antecedent soil moisture conditions, the inwash of fine materials into soil pores, and changing temperatures. The method does allow the option to examine the effect of trench geometry on the infiltration process; this can be accomplished by varying the storage rating curve to reflect different options for sizing and volume. Once the outflow hydrograph is computed, the volume of discharge can be compared to a target volume upon which decisions can be made regarding the storage capacity of the system.

6.4 Role of Trench Surface Geometry

The relationship between infiltration and infiltration per unit surface area was evaluated to further evaluate differences in infiltration rates between events and the effect of wetted surface area. It was considered that infiltration may not only be affected by trench depth, but also by the surface area to which water enters the soil. By dividing the storm specific curve by the representative area for a given depth, unit infiltration rates as a function of depth were developed. These values were graphed as a scatter plot and a trend line was fit to the data as shown in Figures 26 and 27 for the 7 Sept 2004 event and the 30 Aug 2004 event, respectively.

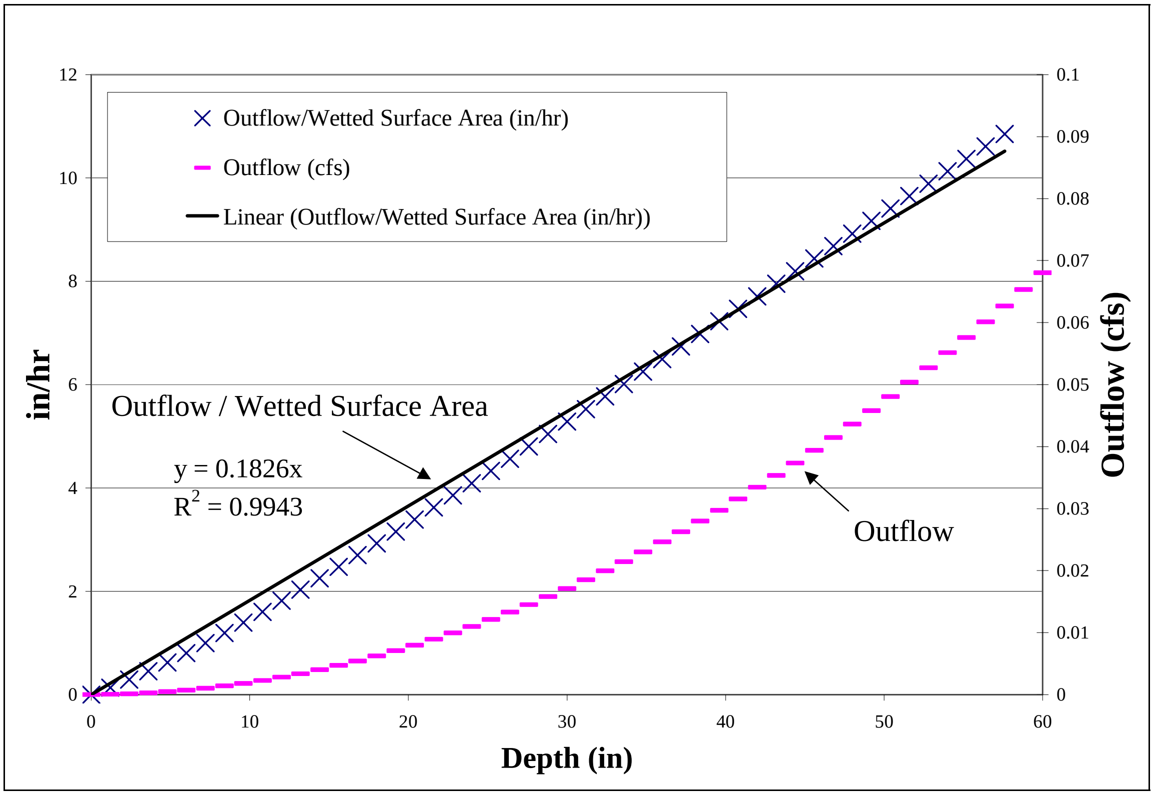

Figure 26: Unit Infiltration (7 July 2004)

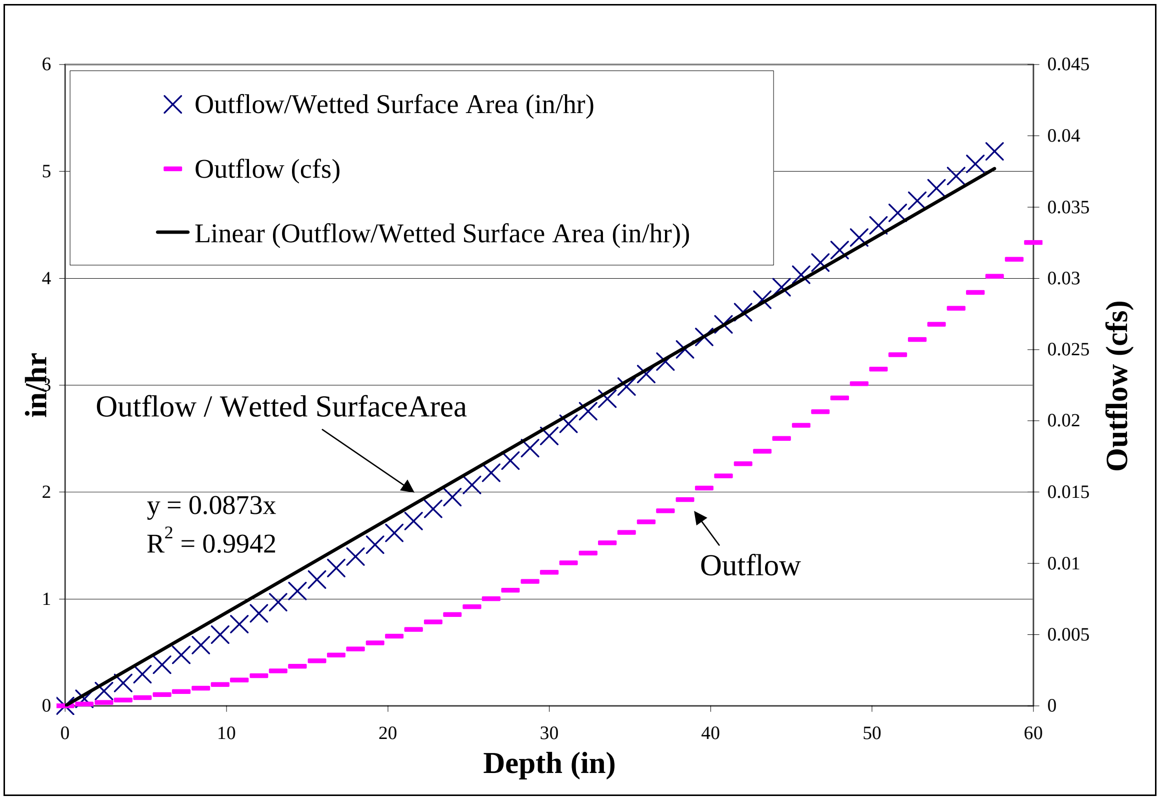

Figure 27: Unit Infiltration (30 Aug 2004)

For the events shown in Figures 26 and 27, depth (inches) is plotted on the abscissa. Infiltration per unit area (in/hr) is plotted on the primary ordinate, and infiltration (cfs) is plotted on the secondary ordinate. The process of dividing outflow values by the wetted surface area at a given depth changed the curve from a polynomial to a linear representation, indicating that infiltration rates may be just as sensitive to wetted surface area as depth values. This is critical when considering the design of an infiltration system and is further discussed in the design recommendations section of the conclusions chapter.

6.5 Long Term Changes in Infiltration Rate

To evaluate changes in infiltration rate occurring over time, the final receeding limb of a storm event was graphed as a scatter plot and a trend line was fit to the data as shown in Figure 28 for the 9 Sept 2004 event.

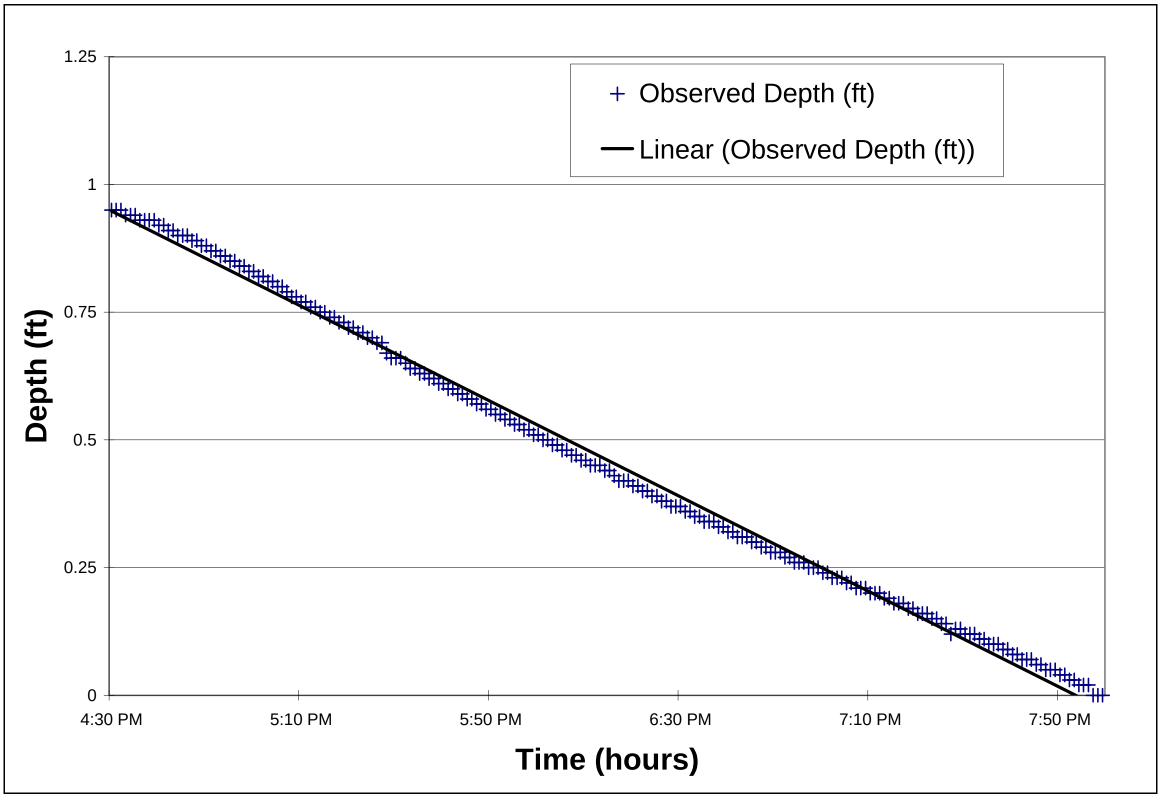

Figure 28: Final Recession Depth Versus Time (9 Sept 2004)

For the 9 Sept 2004 event shown in Figure 28 data was converted into cubic feet per second for each value of depth using the change in storage at that depth. A graph was generated of the infiltration occurring at each depth within the trench during the final receeding limb, as shown in Figure 29.

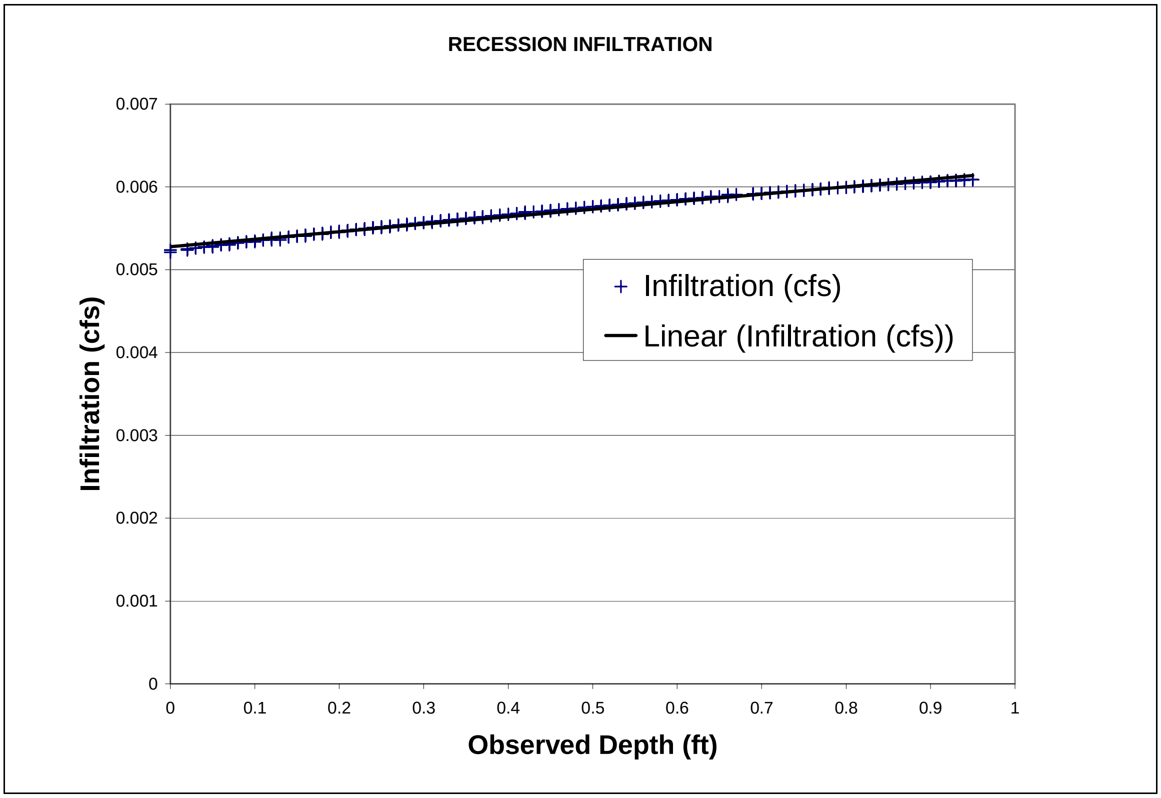

Figure 29: Recession Depth Versus Infiltration (9 Sept 2004)

Estimating the rate of infiltration through the floor of the trench and through the walls of the trench is difficult because the rate varies throughout the trench. Based on Figure 29 it is speculated the y-axis reflects the infiltration rate through the bottom area of the trench and the slope of the line may represent the infiltration values for the side walls of the trench. This process was repeated and a graph showing multiple storm events was created, as shown in Figure 30.

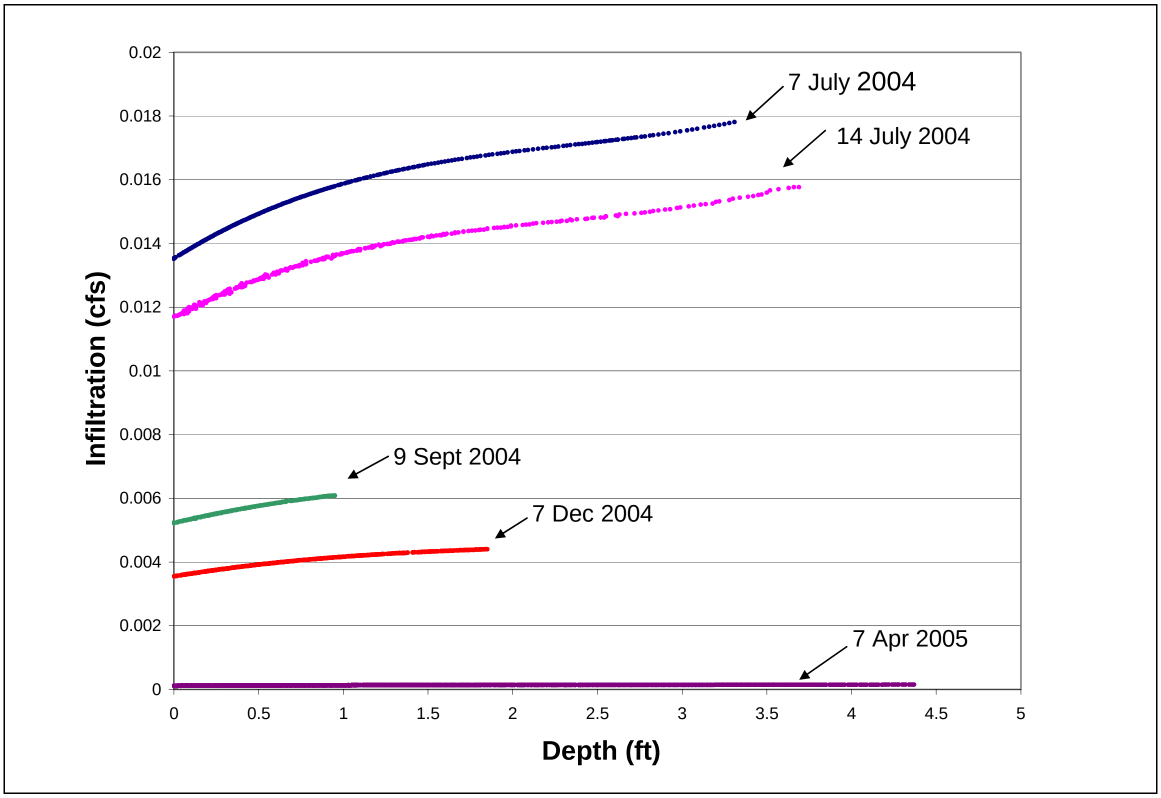

Figure 30: Multiple Series Depth Versus Infiltration

It appears, from Figure 30, that over ten months of data evaluation the infiltration rates through the bottom of the trench are decreasing, as indicated by the y-intercept of each line. This is further shown in Table 11.

Event Date	Rainfall (in.)	Y-intercept	Slope
7 July 2004	0.43	0.0141	0.0013
14 July 2004	0.47	0.0123	0.0011
9 Sept 2004	0.14	0.0053	0.0009
7 Dec 2004	0.71	0.0037	0.0005
7 April 2005	0.67	0.0001	0.00001

Table 11: Bottom and Side Wall Infiltration

Table 11 shows that for the five storms analyzed, there was a decrease in the y-intercept value for each of the events. This decrease may be an indication that the trench bottom is slowly clogging. Clogging of the trench could be caused by the inflow of fine sediments, suspended in the runoff, that eventually settle and cause a decrease in the ability of the trench to infiltrate water. Decreased infiltration from the trench may also be attributed to the filter fabric liner impeding the infiltration rate of the soil medium. Figure 29 and Table 11 were produced by the evaluation of a limited number of events, and after the period of time that this study took place it has been noted that there has been some recovery. Specifically, it was observed that the time it took for the trench to empty as a result of a storm event that occurred in July 2005 was much faster then the April storm depicted above, but still reduced from the July 2004 events.

7.0 Conclusions and Recommendations

The following sections summarize conclusions and offer recommendations based on the findings of this study.

7.1 Conclusions:

The following is a list of observations and conclusions from the present study:

- The rate at which water infiltrated into the subsurface of the infiltration trench was found to vary throughout the study. Based on the collected data it is clear that the infiltration rate from the trench is influenced by trench storage volume and the wetted surface area of the soil.
- The highest average infiltration rate of a modeled event was found to be 0.019 cfs. The lowest average infiltration rate of a modeled event was found to be 0.002 cfs. These are similar to infiltration rates observed at the Porous Concrete Infiltration Basin BMP also located at Villanova University. Ladd (2004) observed infiltration rates at the porous concrete site between 0.002 cfs and 0.005 cfs. Further, the lowest value observed during the study falls within the range of hydraulic conductivity values given by Fetter (2001) for loamy sand soils, which is the soil type at the infiltration trench. The highest value is above the range.
- Overflow from the trench was defined by a maximum trench depth recorded during an event of 5.7 feet or greater. The largest event modeled was a 1.48 inch storm that produced a maximum trench depth of 5.47 feet. Due to the high infiltration rates at the trench overflow was generally not observed from storms less than 0.85 inches. This is significant considering that the effective storage capacity of the trench is equal to 0.12 inches of rainfall over the drainage area.

Therefore, the system is effective in removing much of the runoff generated from the parking lot drainage area.

- The routing method used to model infiltration produced accurate results when the storm specific infiltration curve was used. When the composite infiltration curve was used, the model produced accurate results for large storm events, however the model was not skillful for small events. Depths within the trench during small storm events were under predicted. This is not a primary concern, however, as small events do not cause overflow from the trench. Part of the reason small events were modeled less accurately is due to the process used to calibrate the model. The model was calibrated using large storm events, in which the receeding limb of the water surface elevation curve decreased non-linearly. In order to model small storm events more accurately, a linear relationship is required.
- The model produced accurate results for both small and large events with respect to the average infiltration rates that occurred throughout storm events. However, peak infiltration rates were under predicted.
- Outflow versus depth curves varied between storm events. When the storm specific curves were divided by the wetted surface area at a given depth, a linear relationship developed, with different slopes for each storm.
- Infiltration rates from the trench have decreased since monitoring of the trench began in July of 2004. In the beginning of this study, when the trench was first constructed, conditions were such that the trench only took approximately 12 hours to empty from storms that filled the trench with water. By the end of the study, after approximately 11 months of operation the amount of time it took for the trench to empty increased to approximately 72 hours for a storm that filled the

trench. This may be a result of the trench's bottom area becoming clogged. Note that in a recent storm event some recovery in infiltration was shown, therefore it is important that research at the infiltration trench continues.

7.2 Design Recommendations:

The following is a list of design recommendations taken from the present study's observations.

- In the feasibility stage of an infiltration system's design, determining the rate of infiltration through the bottom and through the sides of a proposed system is difficult. It is important to consider the spatial variability of field measured soil physical parameters. Multiple soil samples should be collected in order to appropriately characterize infiltration rates of the soil at the proposed location. Measurements should be made at many specific spots within the proposed location of the trench. The trench should be divided into several sections of equal area, and the infiltration rate measured at each intersection on the grid, to obtain multiple testing results. In order to obtain rates that are conservative, and therefore have some factor of safety built in, infiltration tests should be done after a period of wet weather. As such, infiltration rates will be lower than rates that would be obtained under dry soil conditions.
- The maximization of the outer surface area within an infiltration system should be done to accommodate runoff from large drainage areas. If conditions at a site being considered for an infiltration system are such that there is enough distance between the bottom of the trench and the groundwater zone, along with the appropriate soil conditions, the trench should be built so that the area of soil in contact with water is at a maximum. Also, by maximizing the surface area within

an infiltration trench not only is contact area gained for infiltration but storage capacities are increased which decreases the risk of overflow. When possible, depths within an infiltration system should be maximized. Trenches that are deep and narrow instead of shallow and wide may be more effective over time. This is because of the possibility of trench bottoms becoming clogged with litter and particles. Maximizing the side wall areas should be done so that water can still infiltrate through the side walls of a trench in the event that the bottom area eventually experiences decreased infiltration capacity.

- The use of a geotextile to line an infiltration system should be carefully reviewed. Specifically, careful investigation into the technical specifications of a geotextile is warranted. Not using a liner at the bottom of the system should be considered. This is because over time, infiltration through the bottom area of a system lined with a geotextile may decrease due to particles contained in the runoff clogging the geotextile.

7.3 Future Research Recommendations:

The following are several recommendations for future avenues of research on infiltration trench BMPs:

- Factors that were not evaluated during this study that might be affecting the infiltration rates at the trench should be studied. These factors include an evaluation of dissolved and suspended solids that are contained within the runoff that enters the trench. Dissolved and suspended solids entering the trench may be causing a decrease in the infiltration capacity of the bottom of the trench, and an additional silt separator with finer openings should be considered for use.

- Temperature effects and seasonal variations in infiltration rates should be evaluated. Infiltration rates from storm events over multiple seasons should be compared with temperature data to examine the relationship between infiltration rate and temperature, and whether or not temperature plays a role in infiltration at the site.
- Samples of water entering the trench should be collected and analyzed for hydrocarbon data. In conjunction with analyzing water quality samples obtained from the drainage area, a groundwater monitoring well should be installed down gradient from the infiltration trench and a groundwater monitoring program should be implemented to verify that infiltrated water is not contributing any sort of hydrocarbon contamination to the local groundwater aquifer.

In summary, an introductory examination of infiltration rates within a newly built infiltration trench BMP was presented. A model based upon the reservoir-routing process was created and was used to analyze the infiltration occurring at the BMP. The requirement for each event analyzed was that there was no overflow from the trench. Infiltration was characterized as a distribution of rates as opposed to a single mean value. Study findings indicate that the BMP is fulfilling its stormwater function, and that much of the runoff generated from the parking lot drainage area can be infiltrated from the relatively small system.

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Appendix A: Sieve Analysis Results

Grain Size Analysis - Sieve Sheet					
Tare		Moisture content:	Tare +wet	Dry Soil	
195.42 g		0.0205	832.5 g	624.28 g	
Sieve No.	Cumulative Retained	Diameter	Cummulative Weight	Percent Retained	Percent Finer
Tare	195.6				
1/2'	207.74	12.7	12.14	1.9	98.1
3/8"	216.62	9.525	21.02	3.4	96.6
1/4"	245.36	6.35	49.76	8.0	92.0
4	259.35	4.75	63.75	10.2	89.8
10	373.78	2	178.18	28.5	71.5
20	507.81	0.85	312.21	50.0	50.0
40	587.13	0.425	391.53	62.7	37.3
100	691.85	0.15	496.25	79.5	20.5
200	747.26	0.075	551.66	88.4	11.6
Pan	756.48				

Grain Size Analysis - Hydrometer Analysis									
Moist Soil	Hydroscopic Moisture	Dry Soil	Zero Correction	Meniscus Correction	Temp. Correction	Assumed Gs:	a	Constant Temp (deg. C)	A
77.71	0.0205	76.15	5	-1	0.4	2.6	1.01	21	0.0137

Time (min)	Reading	Corr. Reading	Percent Finer	Rcl	L	D (mm)
1	18	13.40	27.07	19.00	13.2	0.050
2	13	8.40	16.97	14.00	14	0.036
5	11	6.40	12.93	12.00	14.3	0.023
15	9	4.40	8.89	10.00	14.7	0.014
30	8	3.40	6.87	9.00	14.8	0.010
60	8	3.40	6.87	9.00	14.8	0.007
120	7	2.40	4.85	8.00	15	0.005
240	7	2.40	4.85	8.00	15	0.003
1440	6.5	1.90	3.84	7.50	15.1	0.001

Grain Size Analysis - Results				
Type	Sieve Size (mm)	High (%)	Avg (%)	Low (%)
gravel	>2	28.5	28.5	28.5
sand	2-0.05	44.5	57.5	65.5
silt	.05-.002	23	10	2
clay	<0.002	4	4	4
Total (%)		100	100	100
Classification		Sand	Loamy Sand	Loamy Sand

Appendix B: Event List

	July-04			
Notes:				
Date:	20040707	20040712	20040714	20040718
Rainfall Start Time (Event Start):	7/7/04 4:47 PM	7/12/04 1:58 AM	7/14/04 4:14 PM	7/18/04 5:34 AM
Trench Starts Filling Time:	7/7/04 5:01 PM	7/12/04 2:04 AM	7/14/04 4:28 PM	7/18/04 8:22 AM
Rainfall End Time:	7/7/04 7:44 PM	7/12/04 6:09 PM	7/14/04 8:51 PM	7/18/04 7:41 PM
Trench Empty Time (Event End):	7/7/04 11:31 PM	7/12/04 11:19 PM	7/15/04 2:00 AM	7/19/04 12:31 AM
Total Rainfall (in.):	0.43	4.30	0.47	0.85
Storm Duration (hr.):	2.95	16.18	4.62	14.12
Storm Intensity (in/hr):	0.15	0.27	0.10	0.06
Event Duration (hrs):	6.73	21.35	9.77	18.95
Max Trench Depth (ft.):	4.55	6.46	5.69	5.02
Max Trench Depth time:	5:43 PM	11:23 AM	7:53 PM	11:54 AM
Time From Rainfall End to Trench Empty (hrs):	3.78	5.17	5.15	4.83
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.03	0.03	0.02	0.01
Time Between Event and Last Trench Depth of 0 (hrs):	NA	98.45	40.92	75.57

Notes:
NA: Not Available
PT: Pressure Transducer

	August-04		
Notes:		20040816-20040814 data overwritten	
Date:	20040801	20040813	20040830
Rainfall Start Time (Event Start):	8/1/04 4:14 AM	8/13/04 2:52 AM	8/30/04 5:54 PM
Trench Starts Filling Time:	8/1/04 4:27 AM	8/13/04 3:00 AM	8/30/04 5:58 PM
Rainfall End Time:	8/1/04 8:49 AM	8/13/04 5:07 AM	8/31/04 1:11 AM
Trench Empty Time (Event End):	8/1/04 5:30 PM	8/13/04 9:38 AM	8/31/04 3:51 AM
Total Rainfall (in.):	2.41	0.08	0.34
Storm Duration (hr.):	4.58	2.25	7.28
Storm Intensity (in/hr):	0.53	0.04	0.05
Event Duration (hrs):	13.27	6.77	9.95
Max Trench Depth (ft.):	6.63	1.66	5.78
Max Trench Depth time:	7:17 AM	4:10 AM	6:05PM
Time From Rainfall End to Trench Empty (hrs):	8.68	4.52	2.67
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.02	0.03	0.12
Time Between Event and Last Trench Depth of 0 (hrs):	315.72	273.37	416.27

Notes:
NA: Not Available
PT: Pressure Transducer

	September-04				
Notes:					
Date:	20040908 (1)	20040908 (2)	20040909	20040918	20040928
Rainfall Start Time (Event Start):	9/8/04 4:23 AM	9/8/04 2:48 PM	9/9/04 10:43 AM	9/18/04 12:49 AM	9/27/04 10:58 PM
Trench Starts Filling Time:	9/8/04 4:34 AM	9/8/04 2:54 PM	9/9/04 10:56 AM	9/18/04 1:03 AM	9/28/04 11:17 PM
Rainfall End Time:	9/8/04 8:43 AM	9/8/04 3:47 PM	9/9/04 4:02 PM	9/18/04 3:17 PM	9/29/04 5:07 AM
Trench Empty Time (Event End):	9/8/04 2:47 PM	9/8/04 9:30 PM	9/9/04 7:59 PM	9/18/04 10:08 PM	9/29/04 9:35 AM
Total Rainfall (in.):	0.11	0.06	0.14	2.82	7.07
Storm Duration (hr.):	4.33	0.98	5.32	14.47	30.15
Storm Intensity (in/hr):	0.03	0.06	0.03	0.19	0.23
Event Duration (hrs):	10.40	6.70	9.27	21.32	34.62
Max Trench Depth (ft.):	1.57	1.75	3.00	6.05	6.38
Max Trench Depth time:	8:50 AM	3:18 PM	11:43 AM	3:17AM	4:37PM
Time From Rainfall End to Trench Empty (hrs):	6.07	5.72	3.95	6.85	4.47
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.02	0.05	0.02	0.02	0.01
Time Between Event and Last Trench Depth of 0 (hrs):	192.53	0.02	13.22	196.83	216.83

Notes:
NA: Not Available
PT: Pressure Transducer

October-04	
Notes:	
Date:	20041030
Rainfall Start Time (Event Start):	10/30/04 1:51 AM
Trench Starts Filling Time:	10/30/04 2:01 AM
Rainfall End Time:	10/30/04 5:45 AM
Trench Empty Time (Event End):	10/30/04 2:59 PM
Total Rainfall (in.):	0.64
Storm Duration (hr.):	3.90
Storm Intensity (in/hr):	0.16
Event Duration (hrs):	13.13
Max Trench Depth (ft.):	5.76
Max Trench Depth time:	2:14AM
Time From Rainfall End to Trench Empty (hrs):	9.23
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.09
Time Between Event and Last Trench Depth of 0 (hrs):	736.27

Notes:
NA: Not Available
PT: Pressure Transducer

	November-04				
Notes:					
Date:	20041104	20041112	20041120	20041128	20041130
Rainfall Start Time (Event Start):	11/4/04 10:38 AM	11/12/04 6:26 AM	11/20/04 7:40 PM	11/27/04 8:08 PM	11/30/04 9:40 PM
Trench Starts Filling Time:	11/4/04 10:52 AM	11/12/04 6:45 AM	11/20/04 7:53 PM	11/28/04 8:26 PM	11/30/04 10:12 PM
Rainfall End Time:	11/4/04 7:50 PM	11/13/04 3:37 AM	11/20/04 9:34 PM	11/28/04 10:50 AM	12/1/04 10:57 AM
Trench Empty Time (Event End):	11/5/04 8:17 AM	11/13/04 3:38 PM	11/21/04 8:53 AM	11/28/04 9:55 PM	12/1/04 11:14 PM
Total Rainfall (in.):	1.44	1.48	0.14	2.43	0.92
Storm Duration (hr.):	9.20	21.18	1.90	14.70	13.28
Storm Intensity (in/hr):	0.16	0.07	0.07	0.17	0.07
Event Duration (hrs):	21.65	33.20	13.22	25.78	25.57
Max Trench Depth (ft.):	5.83	5.47	4.55	6.19	5.88
Max Trench Depth time:	5:43PM	12:06AM	8:56PM	7:09AM	10:09AM
Time From Rainfall End to Trench Empty (hrs):	12.45	12.02	11.32	11.08	12.28
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.02	0.01	0.02	0.01	0.02
Time Between Event and Last Trench Depth of 0 (hrs):	115.65	166.15	172.03	155.25	47.75

Notes:
NA: Not Available
PT: Pressure Transducer

	December-04		
Notes:			
Date:	20041207	20041210	20041219
Rainfall Start Time (Event Start):	12/7/04 4:44 AM	12/9/04 3:17 PM	12/19/04 2:53 PM
Trench Starts Filling Time:	12/7/04 5:09 AM	12/10/04 3:28 PM	12/19/04 2:58 PM
Rainfall End Time:	12/8/04 1:20 AM	12/11/04 1:50 AM	12/19/04 6:40 PM
Trench Empty Time (Event End):	12/8/04 11:26 AM	12/11/04 7:29 AM	12/20/04 5:53 AM
Total Rainfall (in.):	0.71	1.04	0.07
Storm Duration (hr.):	20.60	34.55	3.78
Storm Intensity (in/hr):	0.03	0.03	0.02
Event Duration (hrs):	30.70	40.20	15.00
Max Trench Depth (ft.):	5.56	5.49	1.86
Max Trench Depth time:	12:33PM	8:26PM (Dec 9)	4:56PM
Time From Rainfall End to Trench Empty (hrs):	10.10	5.65	11.22
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.02	0.04	0.01
Time Between Event and Last Trench Depth of 0 (hrs):	125.50	27.85	199.40
Notes:			
NA: Not Available			
PT: Pressure Transducer			

	Jan-05			
Notes:	No PT at weir	No PT at weir	No PT at weir	No PT at weir
Date:	20050105	20050107	20050113	20050125
Rainfall Start Time (Event Start):	1/5/05 1:19 AM	1/7/05 9:25 PM	1/13/05 10:43 PM	1/25/05 11:20 AM
Trench Starts Filling Time:	1/5/05 2:14 AM	1/7/05 9:38 PM	1/13/05 10:51 PM	1/25/05 9:58 AM
Rainfall End Time:	1/6/05 5:17 PM	1/8/05 12:26 PM	1/14/05 11:26 AM	1/25/05 1:30 PM
Trench Empty Time (Event End):	1/7/05 10:50 PM	1/9/05 7:56 AM	1/15/05 5:00 AM	1/27/05 10:50 AM
Total Rainfall (in.):	1.03	0.49	1.96	0.09
Storm Duration (hr.):	39.97	15.02	12.72	2.17
Storm Intensity (in/hr):	0.03	0.03	0.15	0.04
Event Duration (hrs):	69.52	34.52	30.28	47.50
Max Trench Depth (ft.):	5.50	5.62	5.97	1.60
Max Trench Depth time:	1/5/05 8:14 AM	10:49AM	01/14/2005 4:57AM	01/25/05 3:44PM
Time From Rainfall End to Trench Empty (hrs):	29.55	19.50	17.57	45.33
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.02	0.02	0.01	0.02
Time Between Event and Last Trench Depth of 0 (hrs):	379.43	68.10	110.78	246.33
Notes:				**SNOW MELT**
NA: Not Available				
PT: Pressure Transducer				

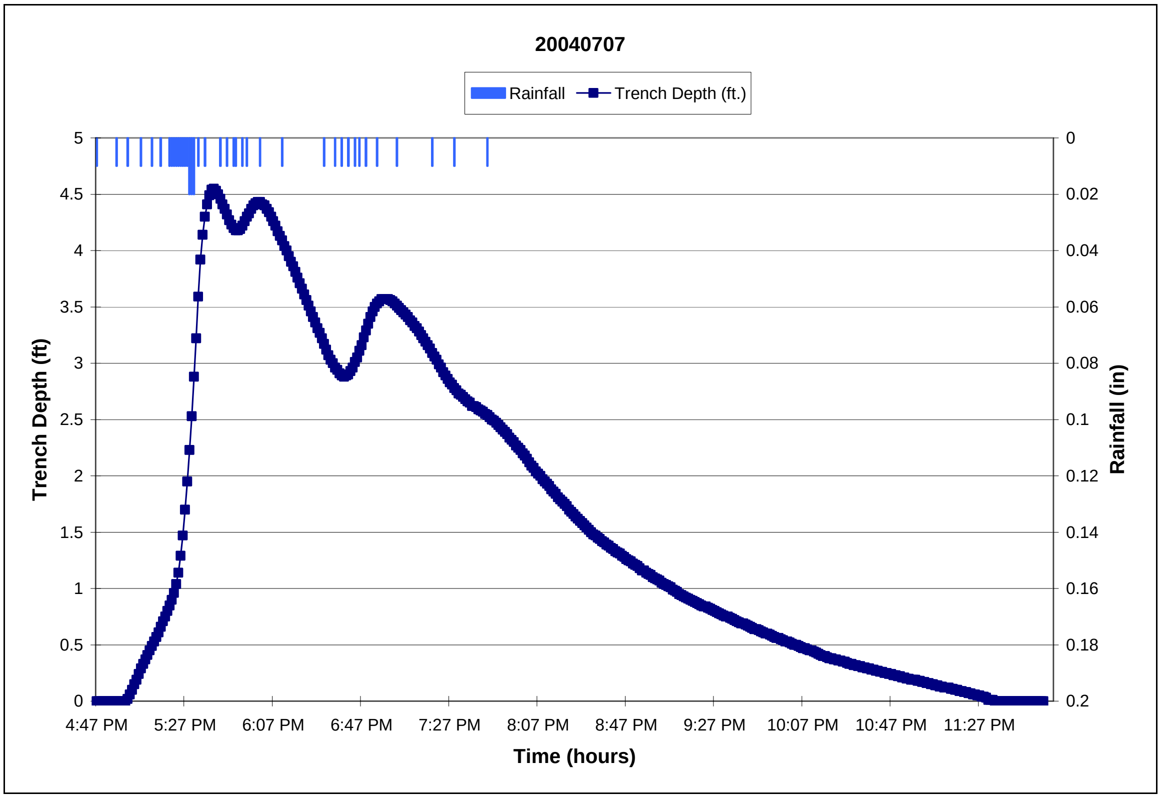
Feb-05				
Notes:	No PT at weir	No PT at weir	No PT at weir	No PT at weir
Date:	20050210	20050214	20050221	20050225
Rainfall Start Time (Event Start):	2/10/05 2:57 AM	2/14/05 9:21 AM	2/21/05 10:17 AM	2/25/05 12:21 PM
Trench Starts Filling Time:	2/10/05 3:13 AM	2/14/05 9:27 AM	2/21/05 9:43 AM	2/25/05 11:00 AM
Rainfall End Time:	2/10/05 7:10 AM	2/14/05 10:50 PM	2/22/05 12:08 AM	2/25/05 1:33 PM
Trench Empty Time (Event End):	2/11/05 5:04 AM	2/16/05 6:54 AM	2/24/05 7:12 AM	2/27/05 11:26 AM
Total Rainfall (in.):	0.14	1.30	0.44	0.19
Storm Duration (hr.):	4.22	13.48	13.85	1.20
Storm Intensity (in/hr):	0.03	0.10	0.03	0.16
Event Duration (hrs):	26.12	45.55	68.92	47.08
Max Trench Depth (ft.):	3.56	5.82	2.31	3.20
Max Trench Depth time:	2/10/05 6:12 AM	2/14/05 6:47 PM	2/21/05 4:11 PM	2/25/05 1:06 PM
Time From Rainfall End to Trench Empty (hrs):	21.90	32.07	55.07	45.88
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.03	0.02	NA	NA
Time Between Event and Last Trench Depth of 0 (hrs):	328.12	76.28	123.38	29.15
Notes:			**SNOW MELT**	**SNOW MELT**
NA: Not Available				
PT: Pressure Transducer				

Mar-05						
Notes:	No PT at weir	No PT at weir	No PT at weir	No PT at weir	No PT at weir	No PT at weir
Date:	20050301	20050308	20050311	20050320	20050323	20050327
Rainfall Start Time (Event Start):	3/1/05 12:47 AM	3/8/05 5:29 AM	3/11/05 8:47 PM	3/20/05 3:06 AM	3/23/05 4:48 AM	3/27/05 5:47 PM
Trench Starts Filling Time:	2/28/05 12:17 PM	3/6/05 2:22 PM	3/11/05 8:57 PM	3/20/05 3:07 AM	3/23/05 5:19 AM	3/27/05 6:07 PM
Rainfall End Time:	3/1/05 2:33 AM	3/9/05 12:58 PM	3/12/05 10:09 AM	3/20/05 8:29 PM	3/23/05 10:18 PM	3/29/05 2:57 AM
Trench Empty Time (Event End):	3/2/05 12:37 PM	3/10/05 7:56 PM	3/13/05 11:48 AM	3/22/05 12:12 PM	3/26/05 5:15 AM	3/31/05 8:48 AM
Total Rainfall (in.):	0.37	0.30	0.09	0.27	1.13	1.78
Storm Duration (hr.):	1.77	31.48	13.37	17.38	17.50	33.17
Storm Intensity (in/hr):	0.21	0.01	0.01	0.02	0.06	0.05
Event Duration (hrs):	35.83	62.45	39.02	57.10	72.45	87.02
Max Trench Depth (ft.):	2.46	5.44	3.80	4.50	5.34	5.77
Max Trench Depth time:	3/1/05 12:47 AM	3/8/05 9:25 AM	3/12/05 12:43 AM	3/20/05 8:40 PM	3/23/05 10:20 PM	3/28/05 2:11 PM
Time From Rainfall End to Trench Empty (hrs):	34.07	30.97	25.65	39.72	54.95	53.85
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	NA	NA	0.01	0.01	0.03	0.02
Time Between Event and Last Trench Depth of 0 (hrs):	37.35	136.87	24.85	159.30	16.60	36.53
Notes:	**SNOW MELT**	**SNOW MELT**	**SNOW MELT**			
NA: Not Available						
PT: Pressure Transducer						

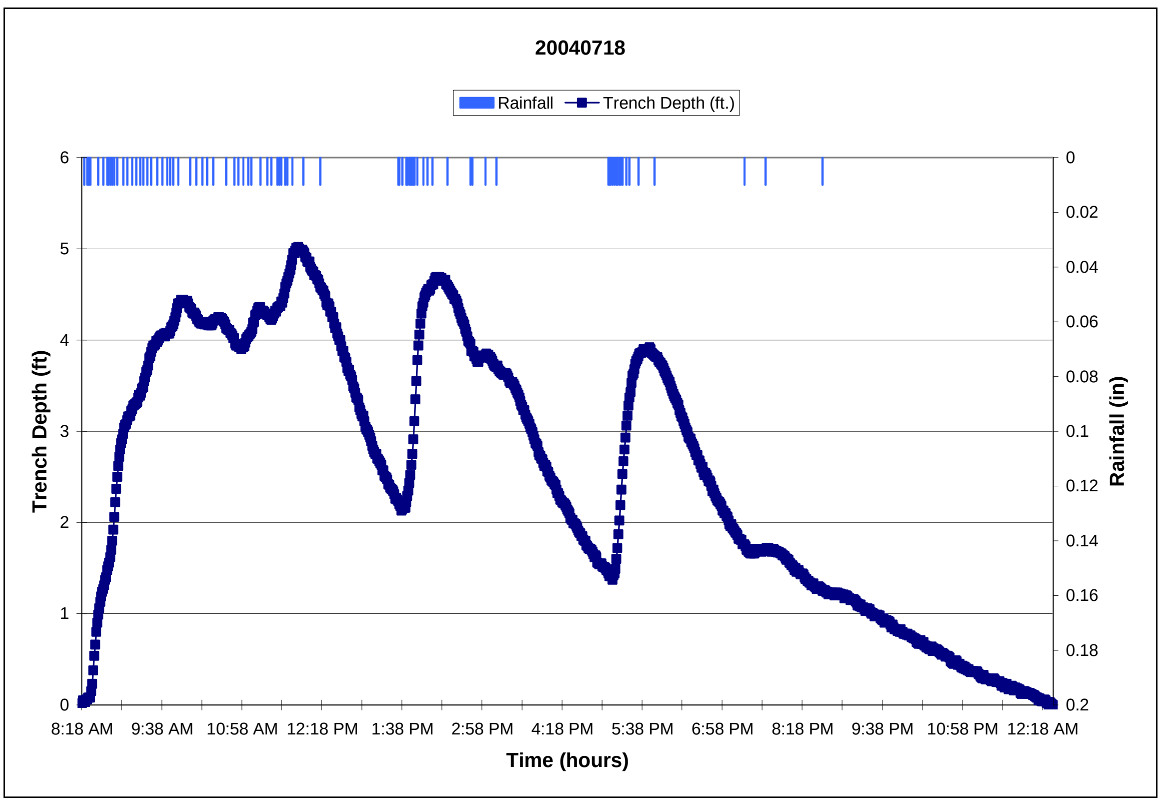
Apr-05			
Notes:	No PT at weir	No PT at weir	No PT at weir
Date:	20050401	20050407	20050423
Rainfall Start Time (Event Start):	4/1/05 10:32 PM	4/7/05 8:33 PM	4/23/05 5:06 AM
Trench Starts Filling Time:	4/1/05 11:02 PM	4/7/05 8:47 PM	4/23/05 5:21 AM
Rainfall End Time:	4/3/05 2:26 PM	4/8/05 5:45 AM	4/24/05 3:43 AM
Trench Empty Time (Event End):	4/5/05 9:49 PM	4/10/05 8:25 AM	NA
Total Rainfall (in.):	4.33	0.67	0.64
Storm Duration (hr.):	39.90	9.20	22.62
Storm Intensity (in/hr):	0.11	0.07	0.03
Event Duration (hrs):	95.28	59.87	NA
Max Trench Depth (ft.):	6.36	5.59	5.95
Max Trench Depth time:	4/2/05 4:12 PM	4/8/05 1:20 AM	4/23/05 1:51 PM
Time From Rainfall End to Trench Empty (hrs):	55.38	50.67	NA
Amount of Rainfall Fallen Before Increase in Trench Depth is Observed (in.)	0.02	0.02	0.02
Time Between Event and Last Trench Depth of 0 (hrs):	37.73	46.73	308.68

Notes:
NA: Not Available
PT: Pressure Transducer

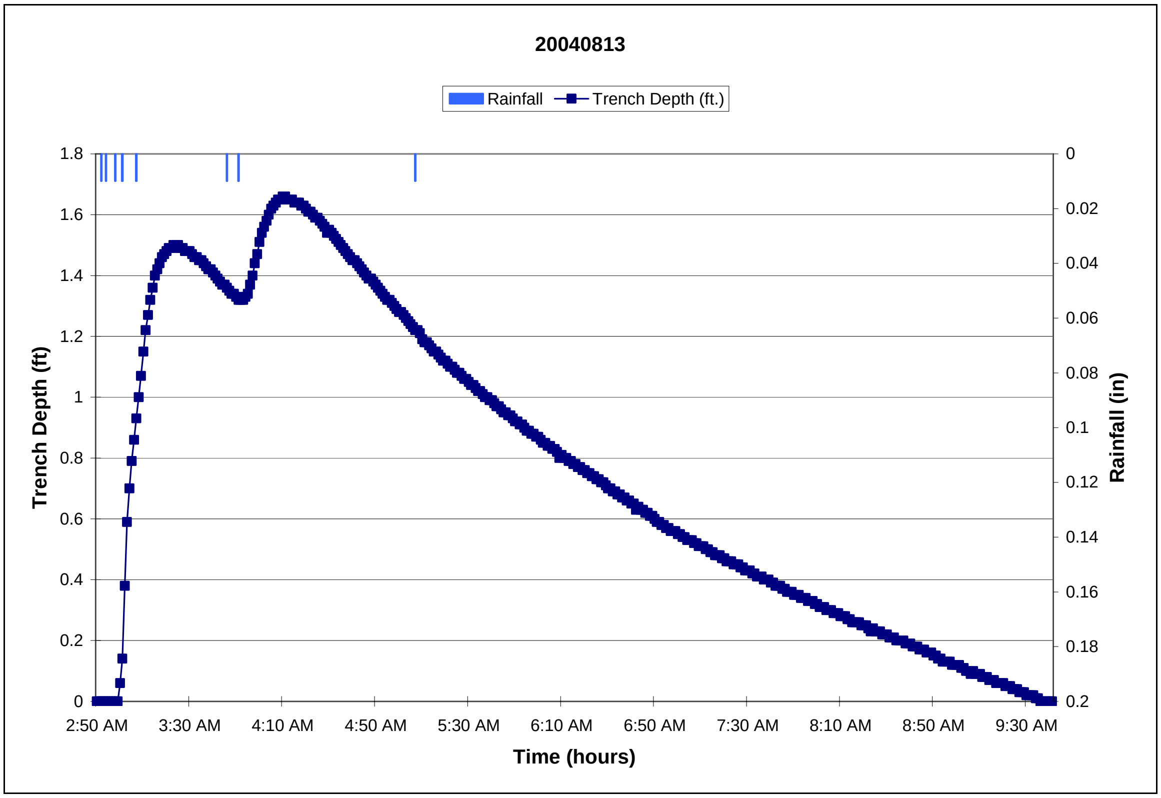
Appendix C: Depth and Rainfall Versus Time Graphs

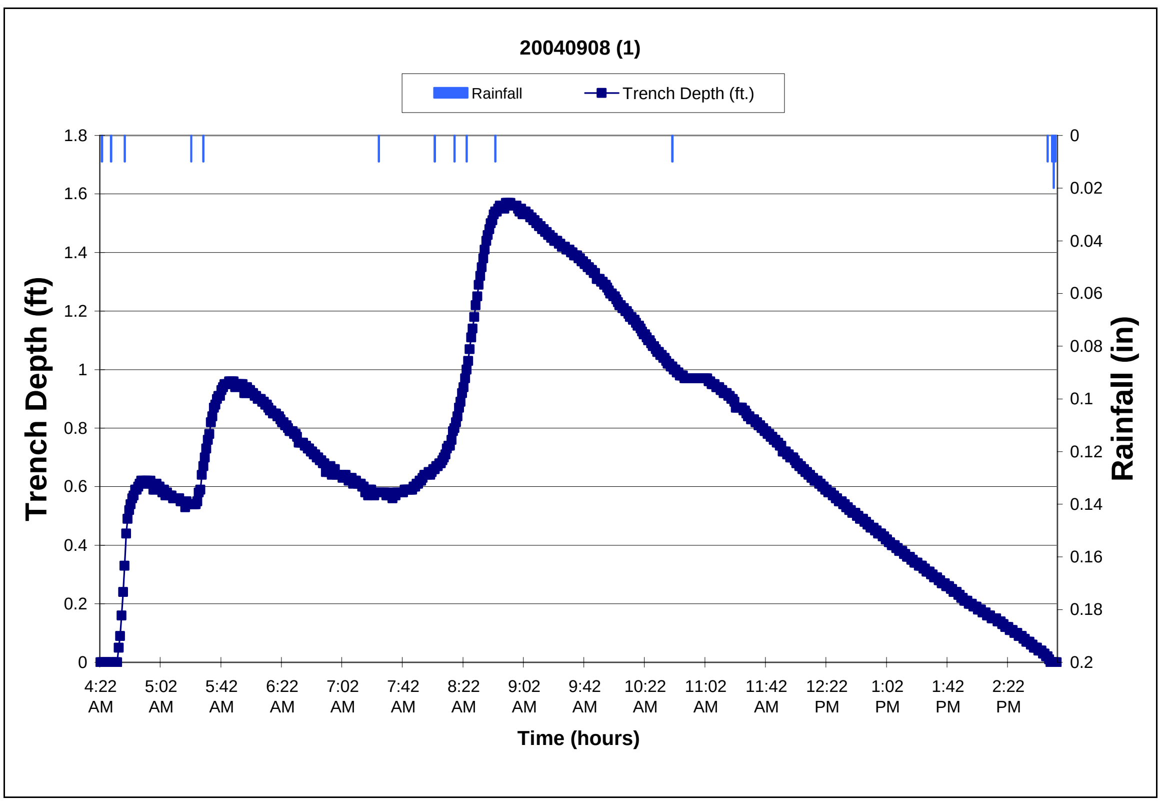


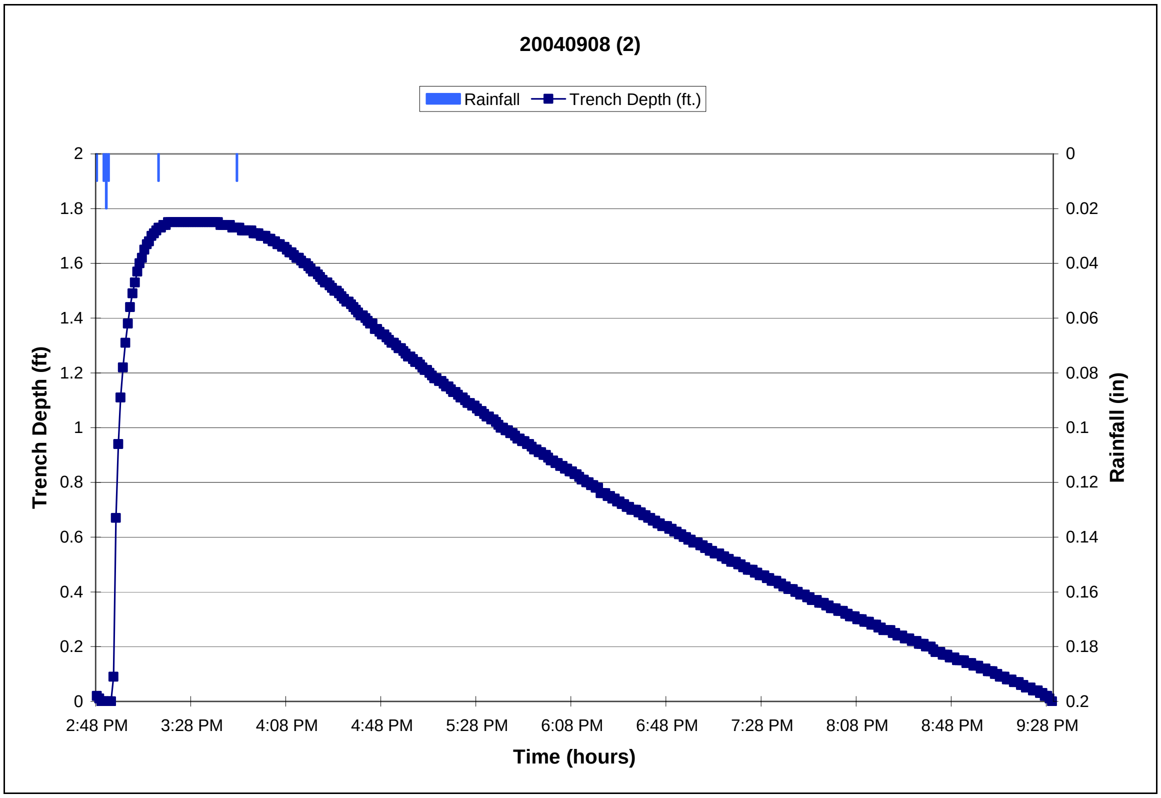
20040707
Rainfall
Trench Depth (ft.)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Trench Depth (ft)
Rainfall (in)
4:47 PM
5:27 PM
6:07 PM
6:47 PM
7:27 PM
8:07 PM
8:47 PM
9:27 PM
10:07 PM
10:47 PM
11:27 PM
Time (hours)

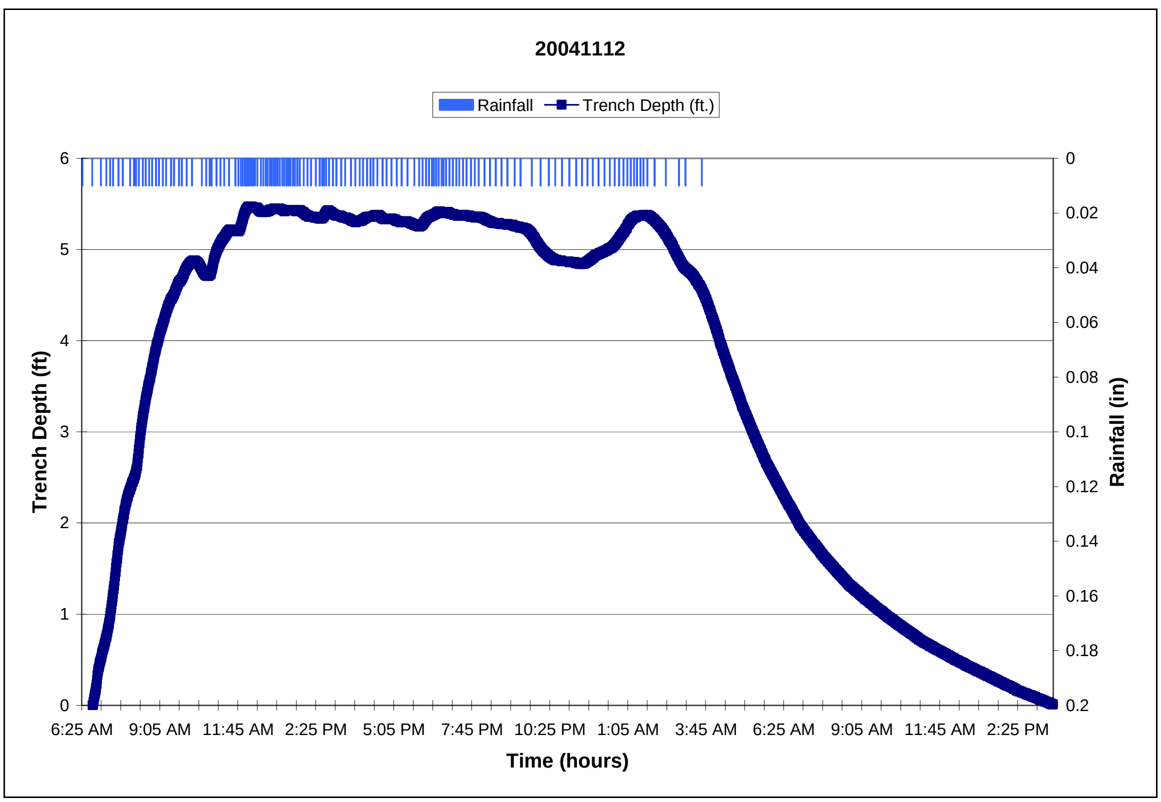


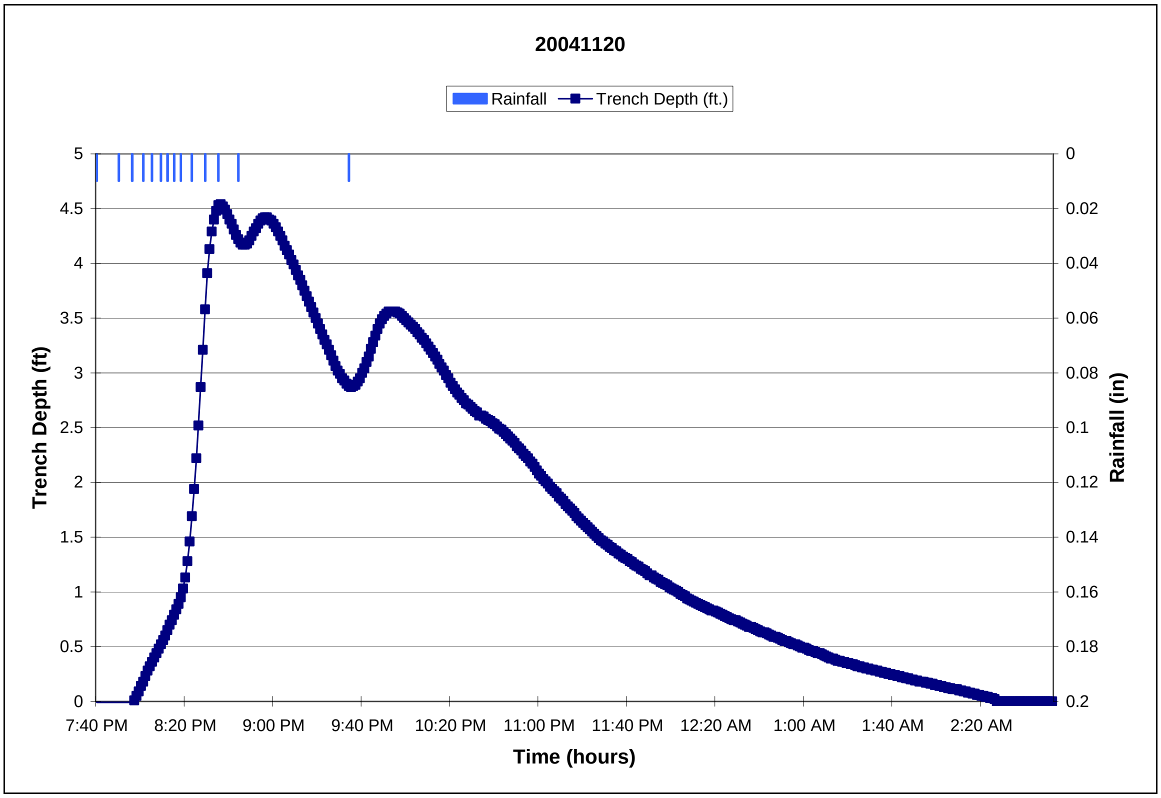
20040718
Rainfall
Trench Depth (ft.)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Trench Depth (ft)
Rainfall (in)
8:18 AM
9:38 AM
10:58 AM
12:18 PM
1:38 PM
2:58 PM
4:18 PM
5:38 PM
6:58 PM
8:18 PM
9:38 PM
10:58 PM
12:18 AM
Time (hours)


20040813
Rainfall
Trench Depth (ft.)
Trench Depth (ft)
Rainfall (in)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
2:50 AM
3:30 AM
4:10 AM
4:50 AM
5:30 AM
6:10 AM
6:50 AM
7:30 AM
8:10 AM
8:50 AM
9:30 AM
Time (hours)

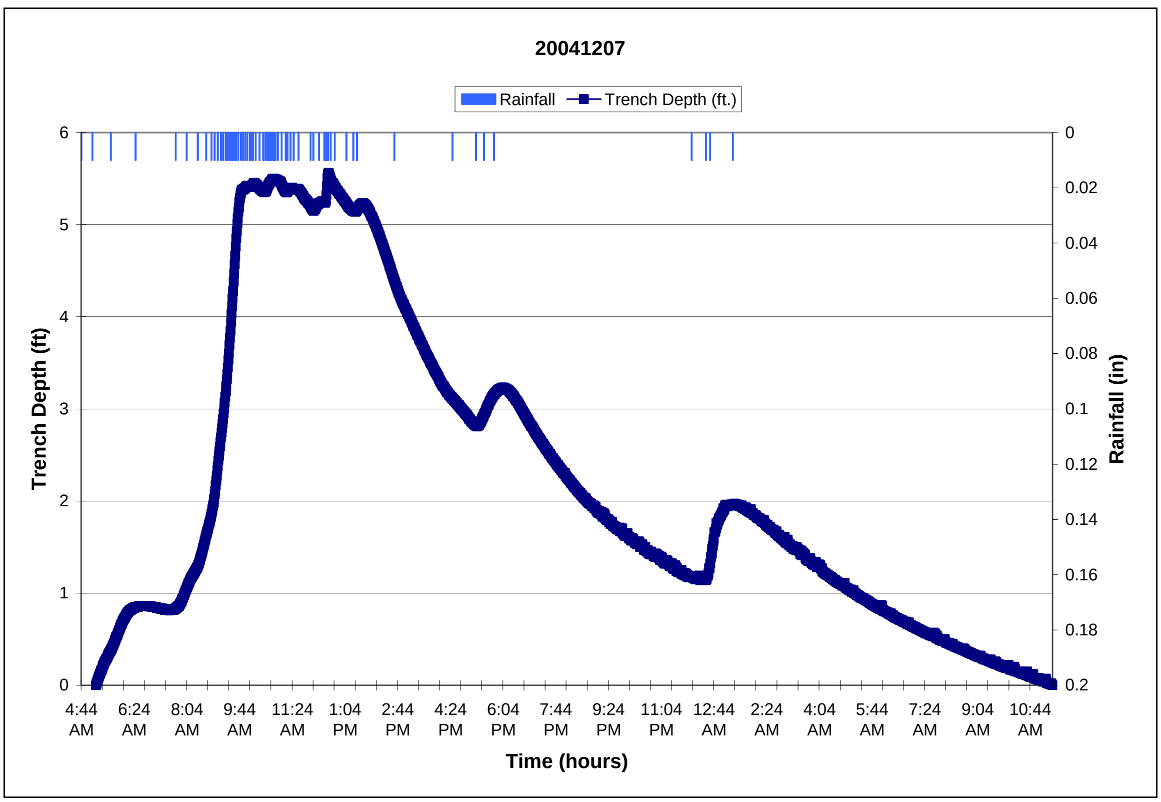

20040908 (1)
Rainfall
Trench Depth (ft.)
Trench Depth (ft)
Rainfall (in)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
4:22 AM
5:02 AM
5:42 AM
6:22 AM
7:02 AM
7:42 AM
8:22 AM
9:02 AM
9:42 AM
10:22 AM
11:02 AM
11:42 AM
12:22 PM
1:02 PM
1:42 PM
2:22 PM
Time (hours)


20040908 (2)
Rainfall
Trench Depth (ft.)
Trench Depth (ft)
Rainfall (in)
Time (hours)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
2:48 PM
3:28 PM
4:08 PM
4:48 PM
5:28 PM
6:08 PM
6:48 PM
7:28 PM
8:08 PM
8:48 PM
9:28 PM

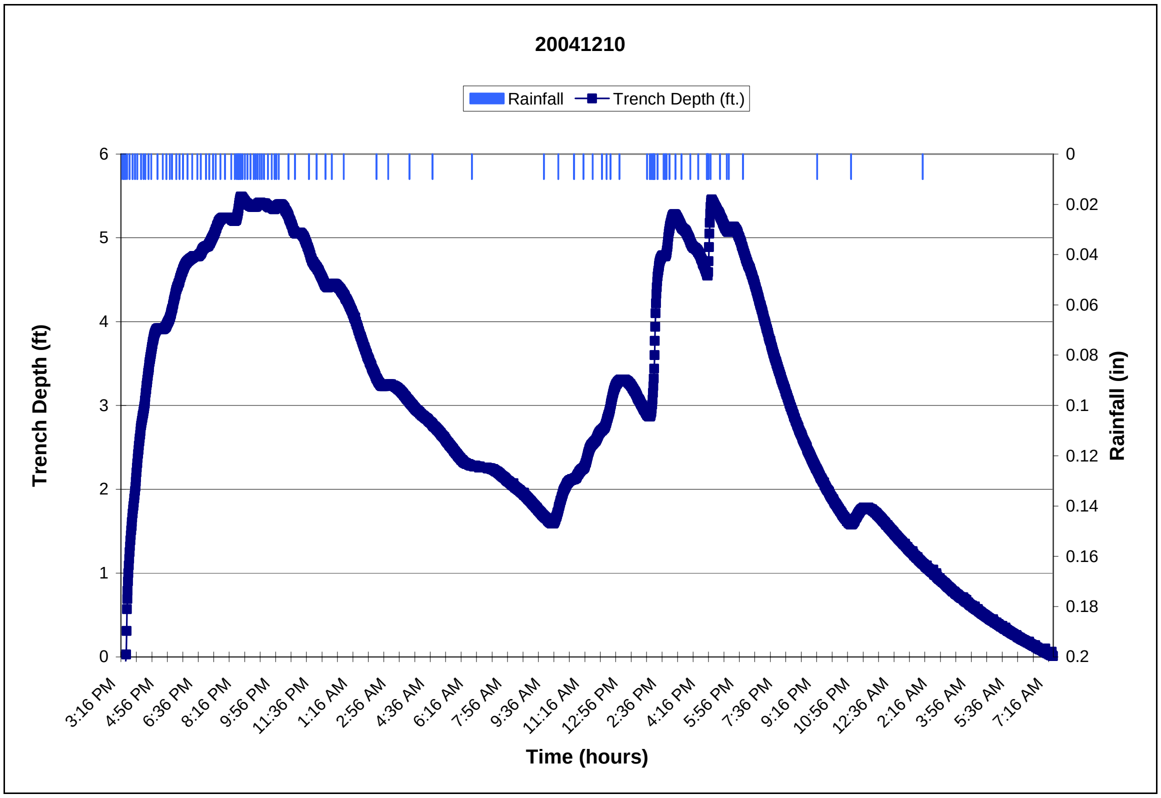

20041112
Rainfall
Trench Depth (ft.)
Trench Depth (ft)
Rainfall (in)
Time (hours)
6
5
4
3
2
1
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
6:25 AM
9:05 AM
11:45 AM
2:25 PM
5:05 PM
7:45 PM
10:25 PM
1:05 AM
3:45 AM
6:25 AM
9:05 AM
11:45 AM
2:25 PM



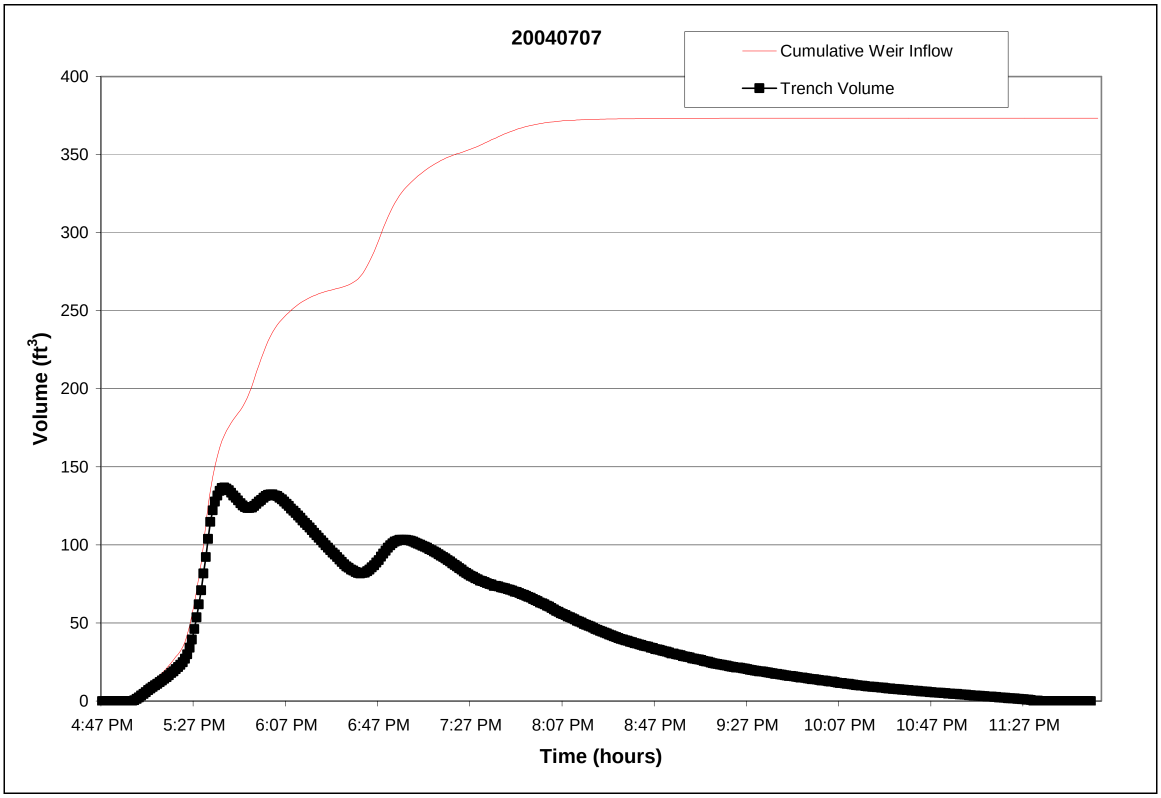
20041120
Rainfall
Trench Depth (ft.)
Trench Depth (ft)
Rainfall (in)
Time (hours)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
7:40 PM
8:20 PM
9:00 PM
9:40 PM
10:20 PM
11:00 PM
11:40 PM
12:20 AM
1:00 AM
1:40 AM
2:20 AM

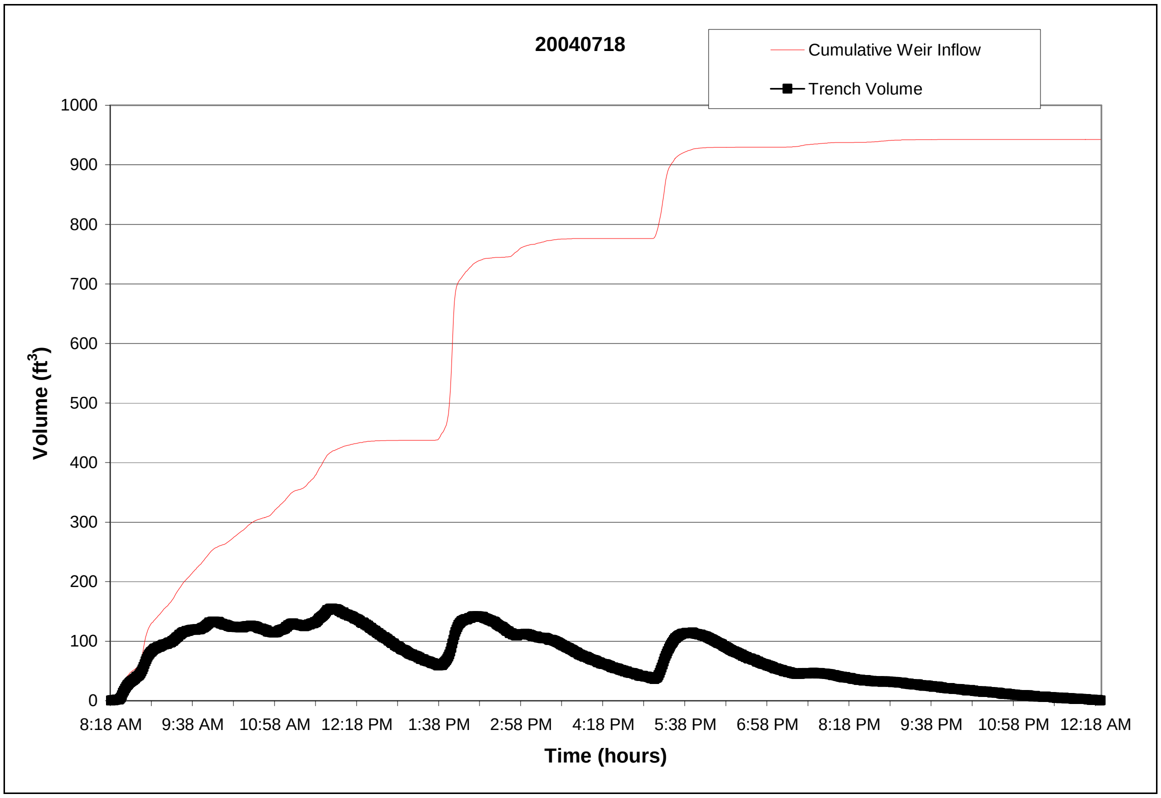


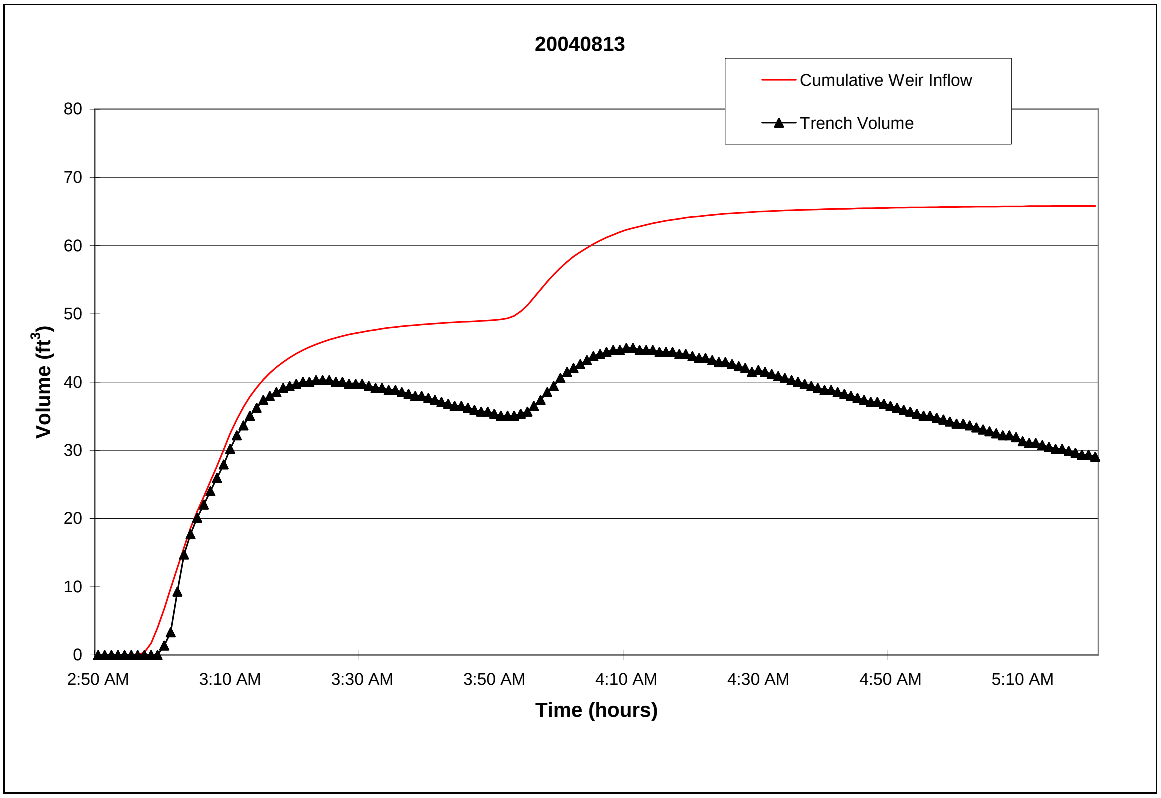
20041207
Rainfall
Trench Depth (ft.)
Trench Depth (ft)
Rainfall (in)
Time (hours)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
4:44 AM
6:24 AM
8:04 AM
9:44 AM
11:24 AM
1:04 PM
2:44 PM
4:24 PM
6:04 PM
7:44 PM
9:24 PM
11:04 PM
12:44 AM
2:24 AM
4:04 AM
5:44 AM
7:24 AM
9:04 AM
10:44 AM

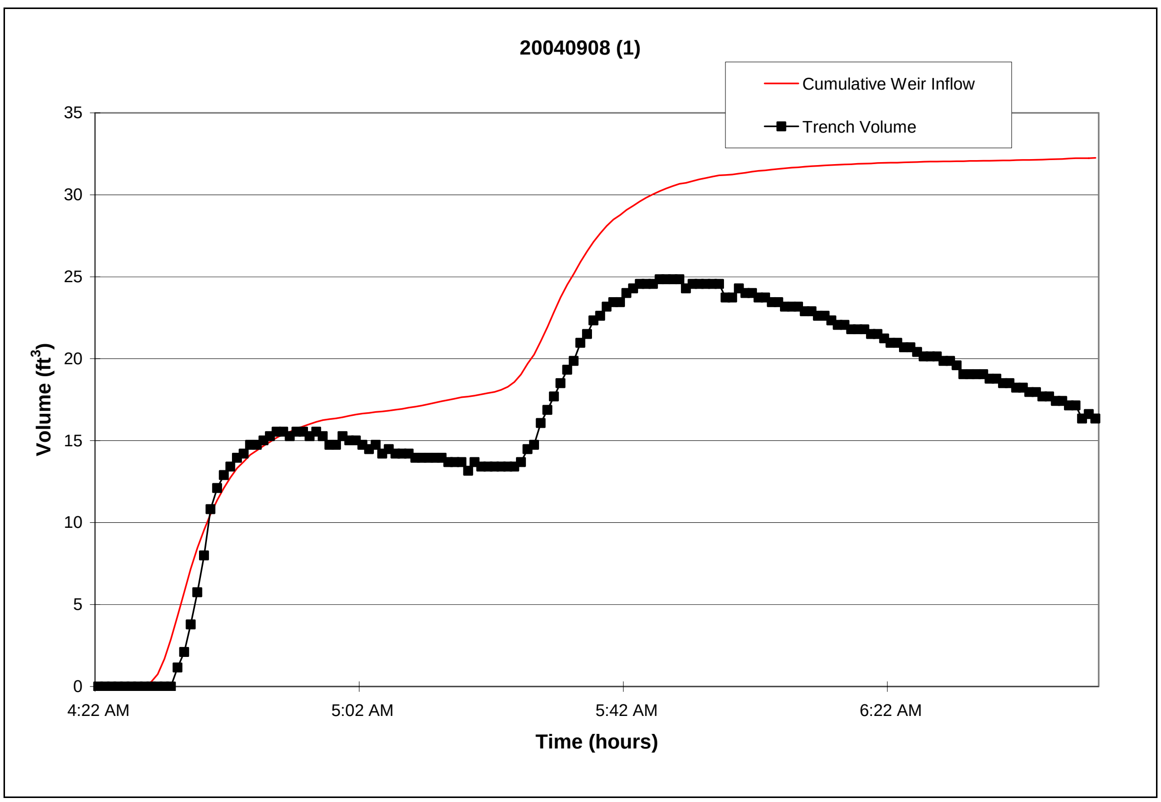

20041210
Rainfall
Trench Depth (ft.)
Trench Depth (ft)
Rainfall (in)
Time (hours)
6
5
4
3
2
1
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
3:16 PM
4:56 PM
6:36 PM
8:16 PM
9:56 PM
11:36 PM
1:16 AM
2:56 AM
4:36 AM
6:16 AM
7:56 AM
9:36 AM
11:16 AM
12:56 PM
2:36 PM
4:16 PM
5:56 PM
7:36 PM
9:16 PM
10:56 PM
12:36 AM
2:16 AM
3:56 AM
5:36 AM
7:16 AM

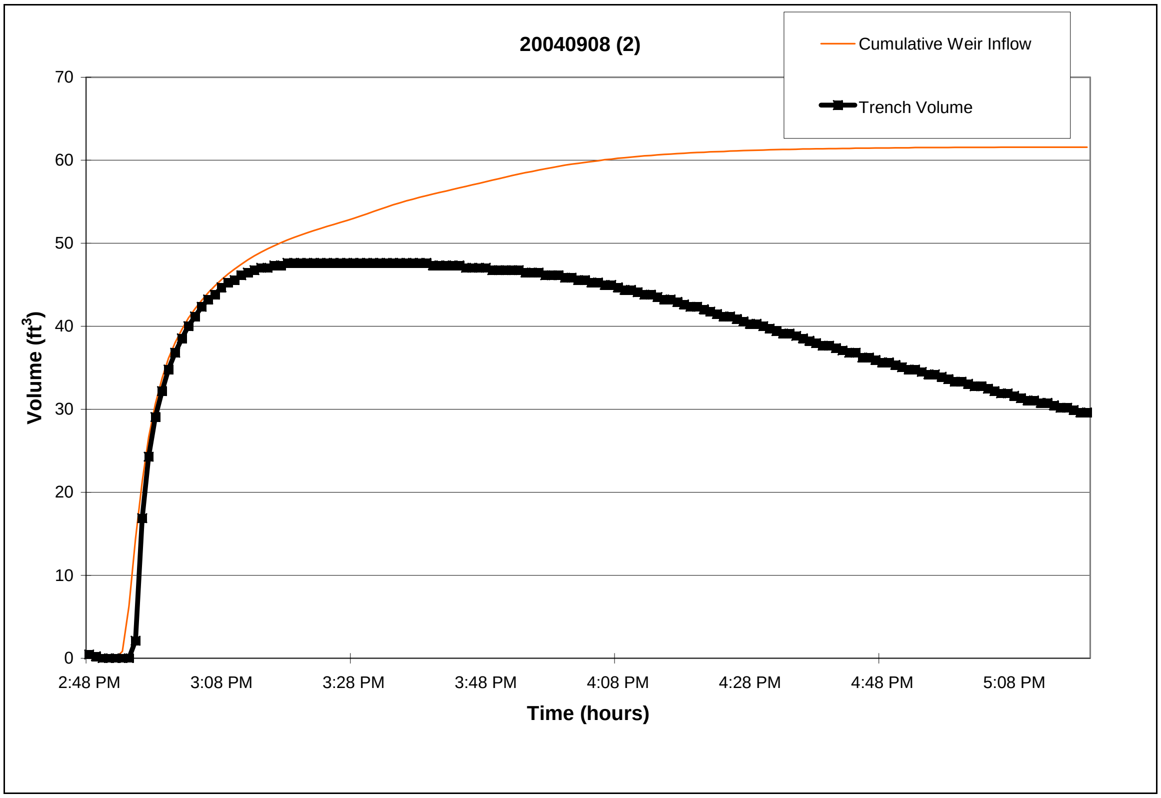
Appendix D: Inflow Verification Graphs



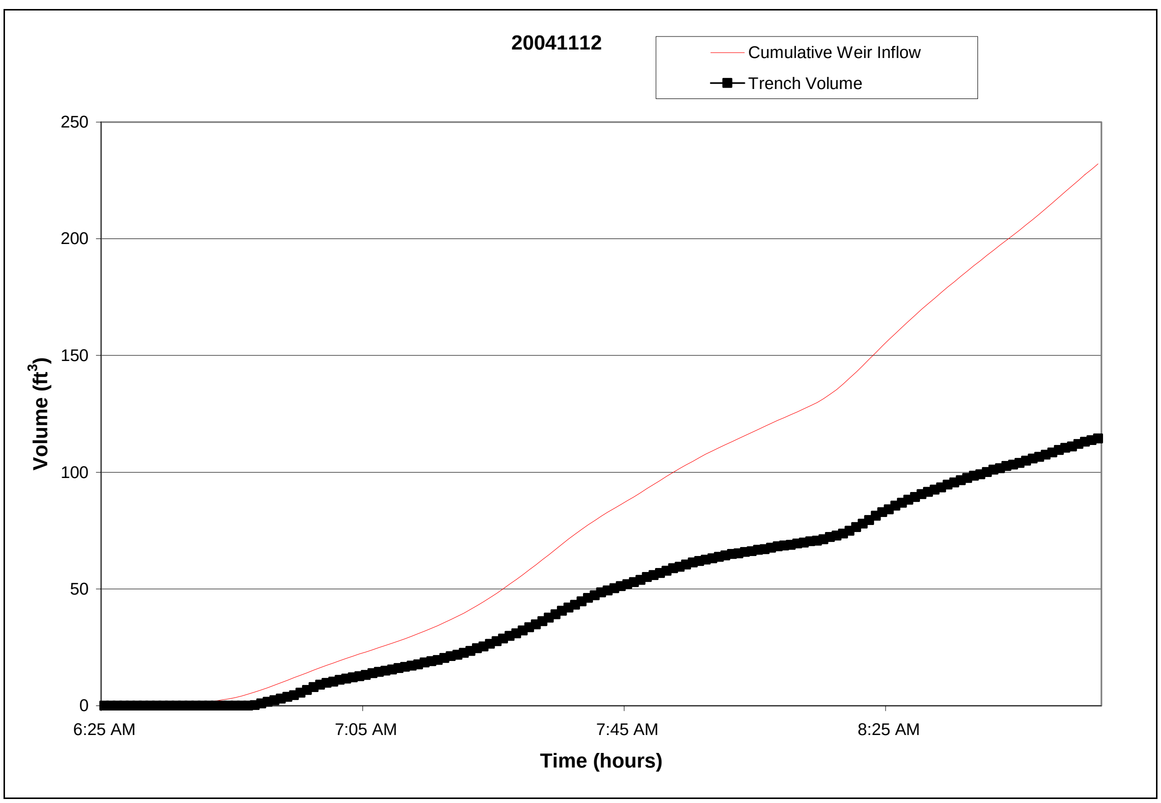



20040813
Cumulative Weir Inflow
Trench Volume
Volume (ft3)
80
70
60
50
40
30
20
10
0
2:50 AM
3:10 AM
3:30 AM
3:50 AM
4:10 AM
4:30 AM
4:50 AM
5:10 AM
Time (hours)

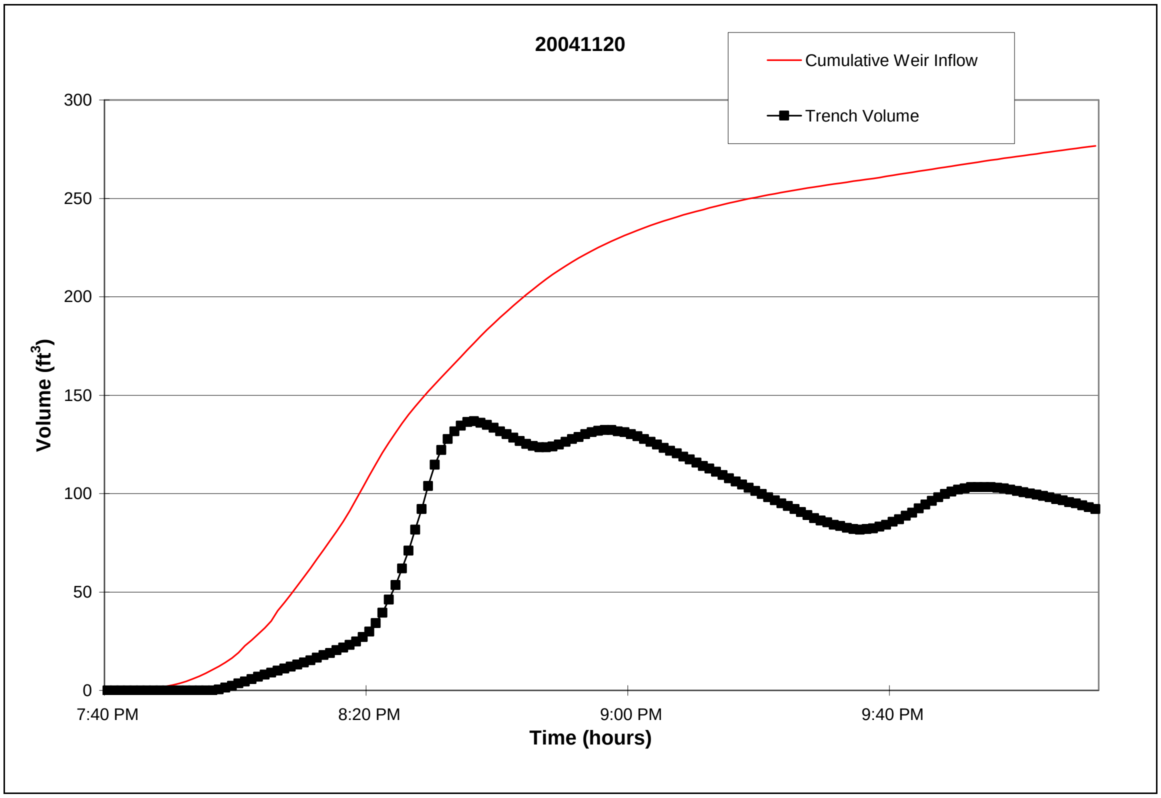

20040908 (1)
Cumulative Weir Inflow
Trench Volume
Volume (ft3)
35
30
25
20
15
10
5
0
4:22 AM
5:02 AM
5:42 AM
6:22 AM
Time (hours)

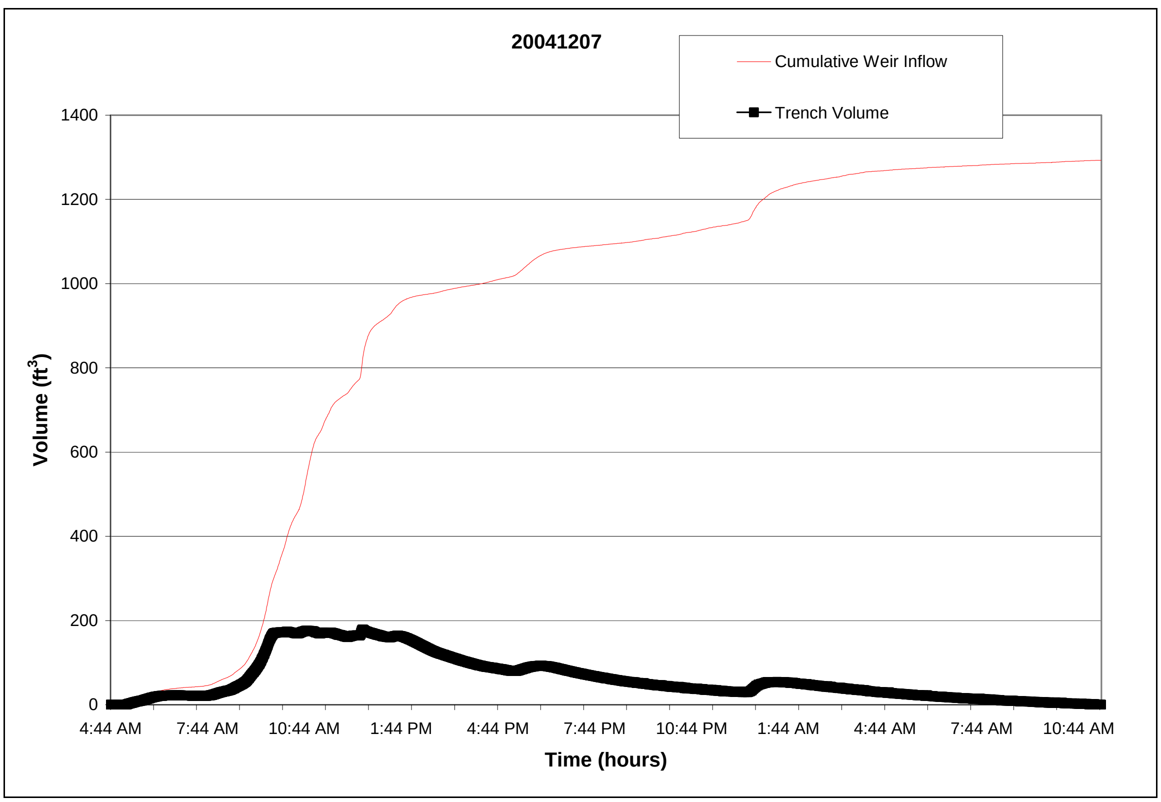


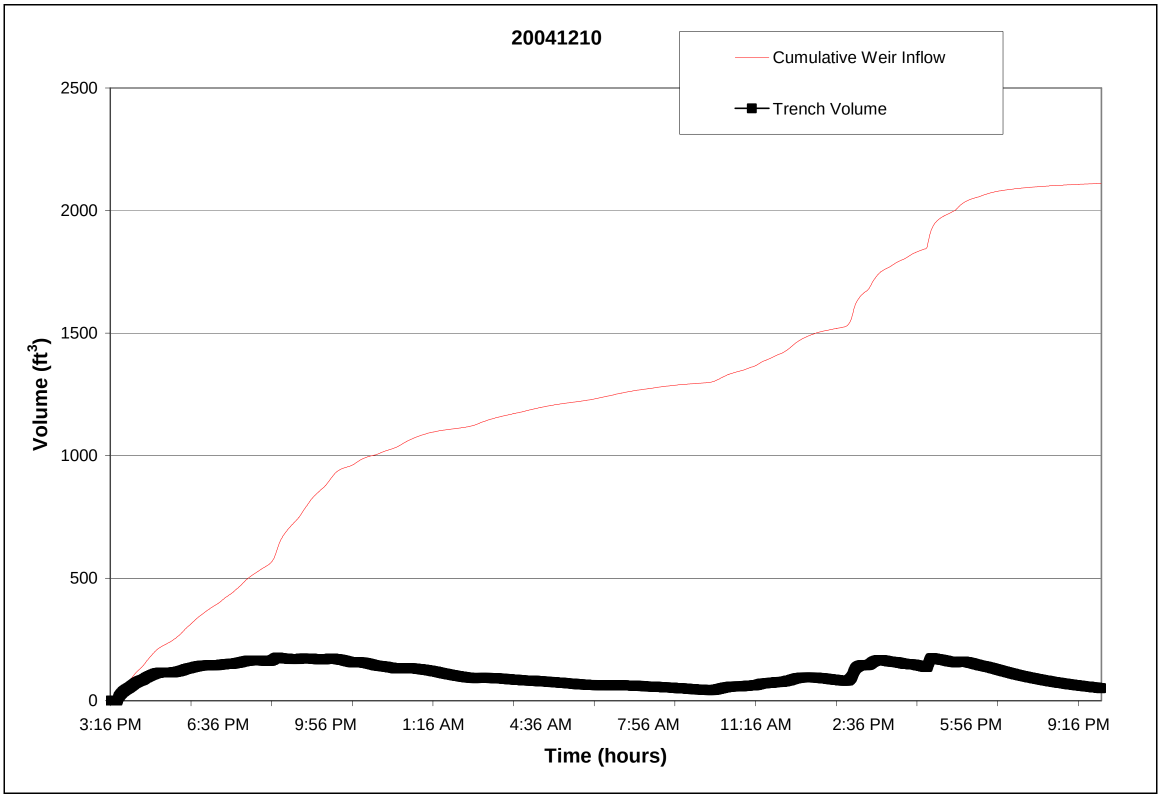
20040908 (2)
Cumulative Weir Inflow
Trench Volume
Volume (ft3)
70
60
50
40
30
20
10
0
2:48 PM
3:08 PM
3:28 PM
3:48 PM
4:08 PM
4:28 PM
4:48 PM
5:08 PM
Time (hours)



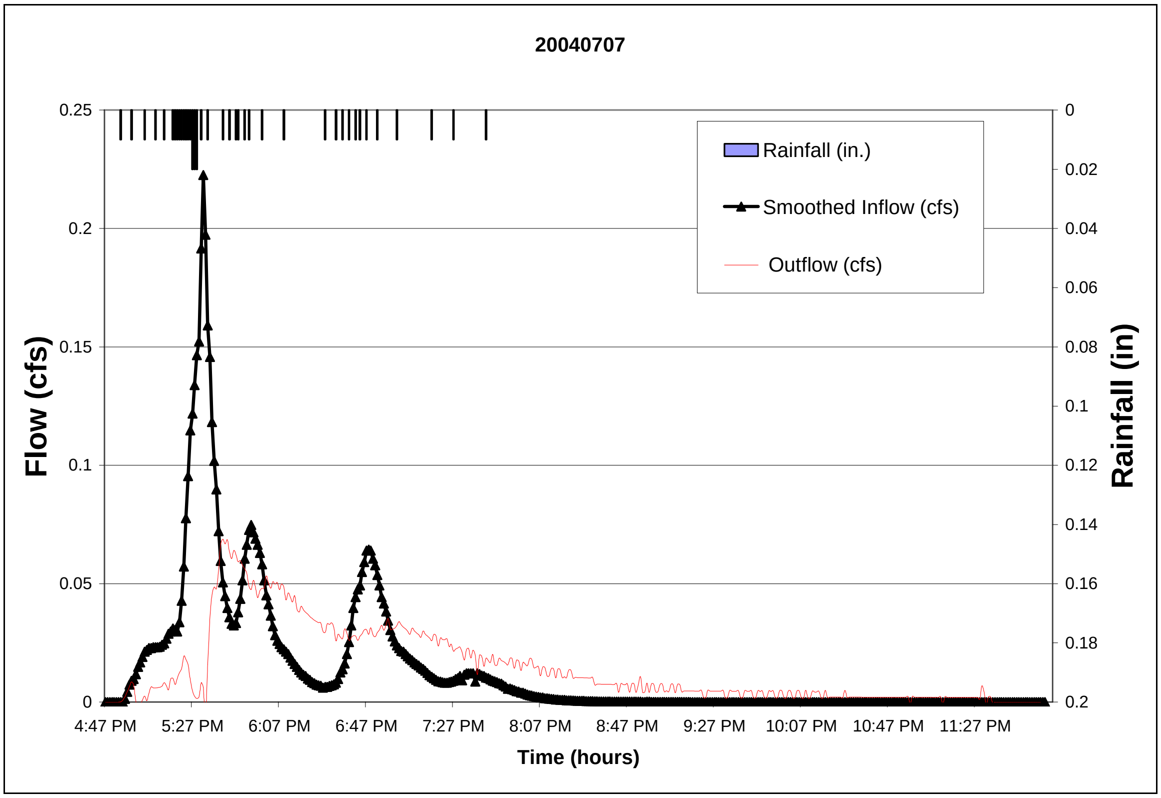
20041112
Cumulative Weir Inflow
Trench Volume
Volume (ft3)
250
200
150
100
50
0
6:25 AM
7:05 AM
7:45 AM
8:25 AM
Time (hours)

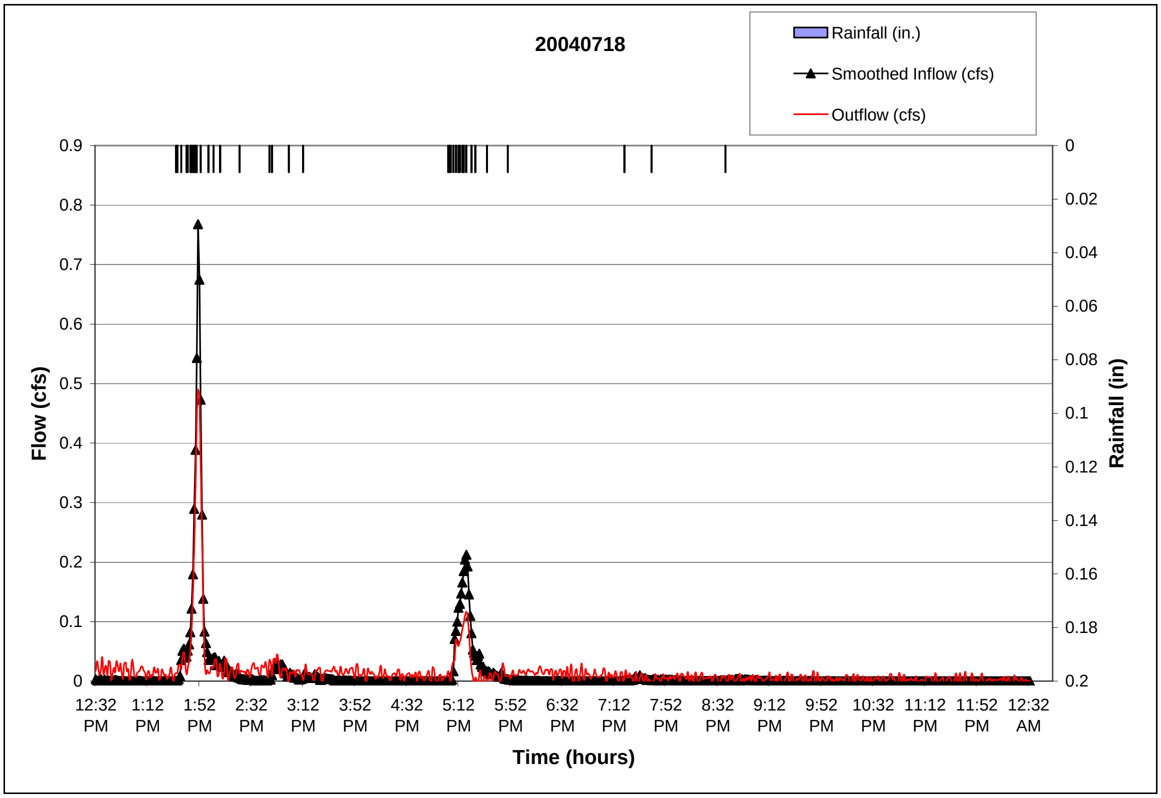

20041120
Cumulative Weir Inflow
Trench Volume
Volume (ft^3)
300
250
200
150
100
50
0
7:40 PM
8:20 PM
9:00 PM
9:40 PM
Time (hours)

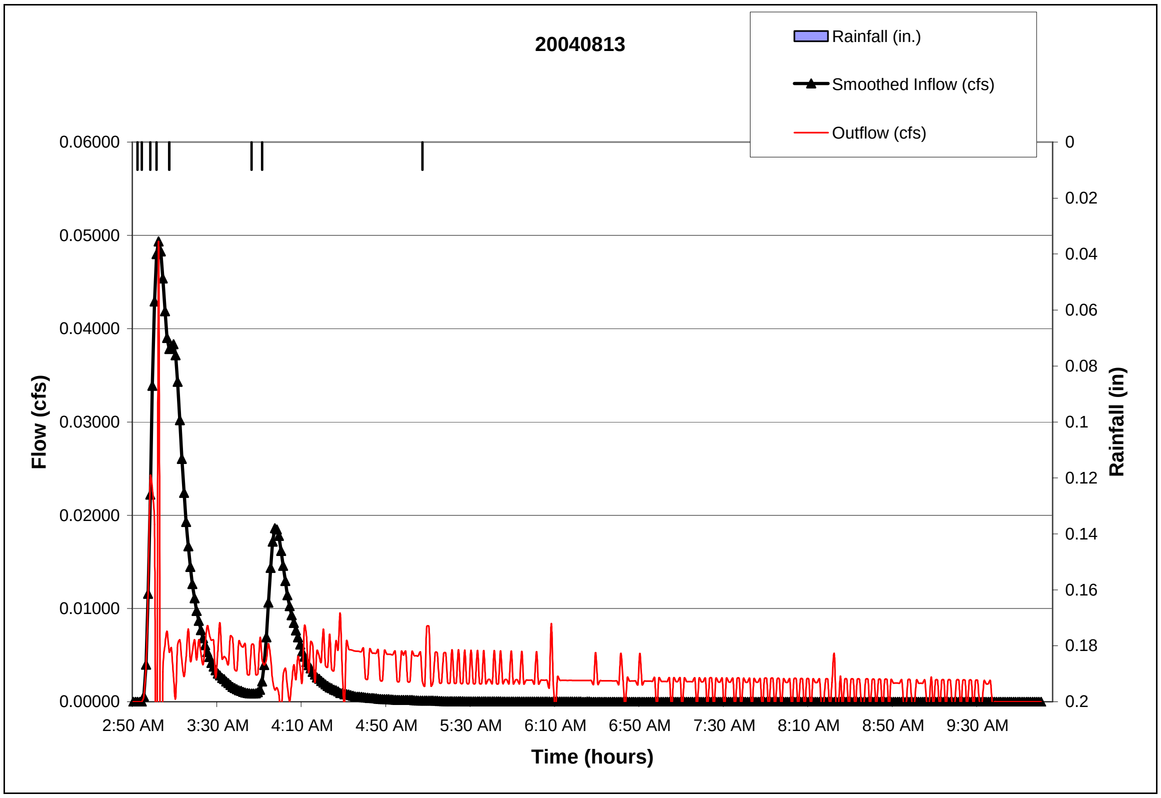

20041207
Cumulative Weir Inflow
Trench Volume
Volume (ft^3)
1400
1200
1000
800
600
400
200
0
4:44 AM
7:44 AM
10:44 AM
1:44 PM
4:44 PM
7:44 PM
10:44 PM
1:44 AM
4:44 AM
7:44 AM
10:44 AM
Time (hours)

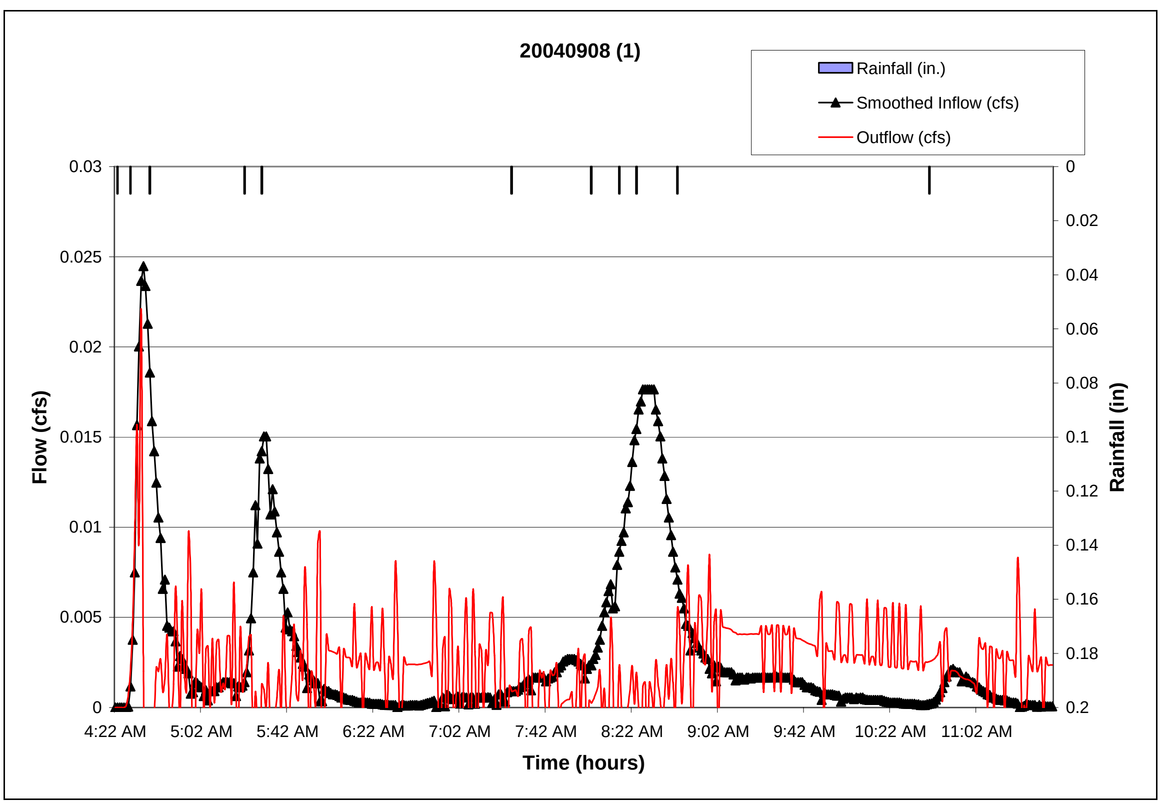

20041210
Cumulative Weir Inflow
Trench Volume
2500
2000
1500
1000
500
0
Volume (ft3)
3:16 PM
6:36 PM
9:56 PM
1:16 AM
4:36 AM
7:56 AM
11:16 AM
2:36 PM
5:56 PM
9:16 PM
Time (hours)

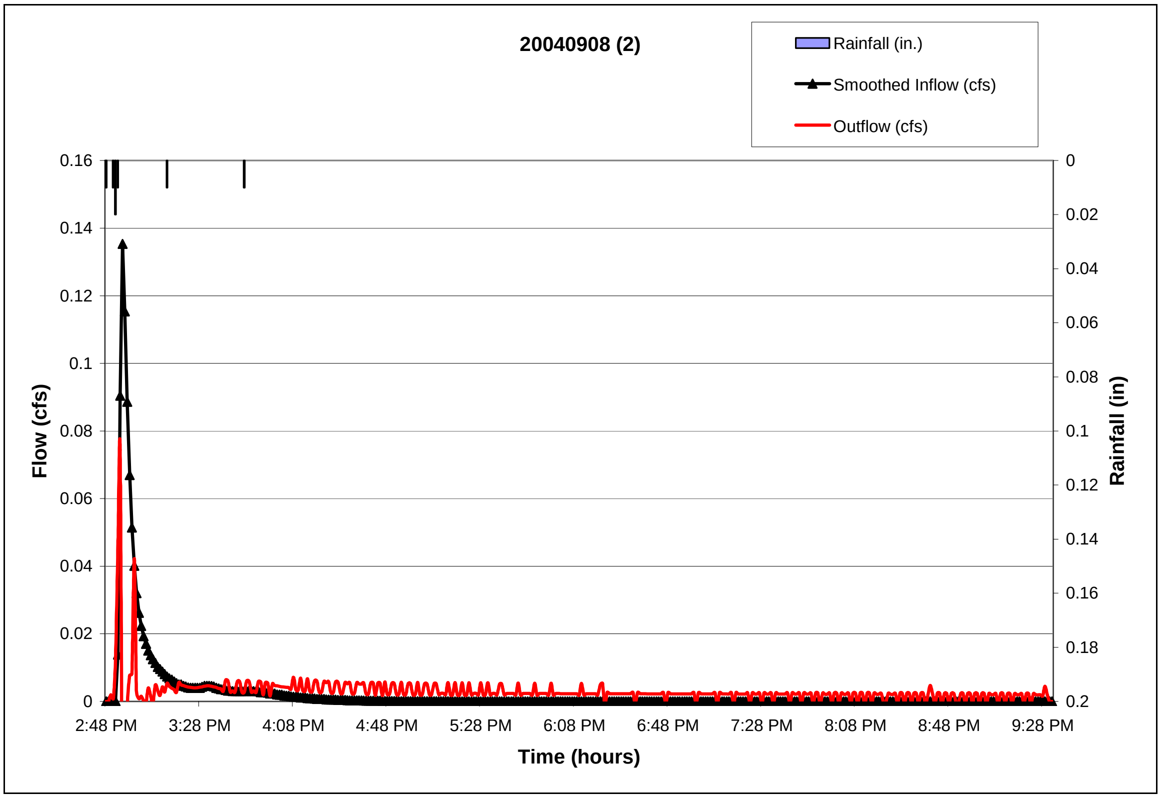
Appendix E: Inflow and Outflow Hydrographs

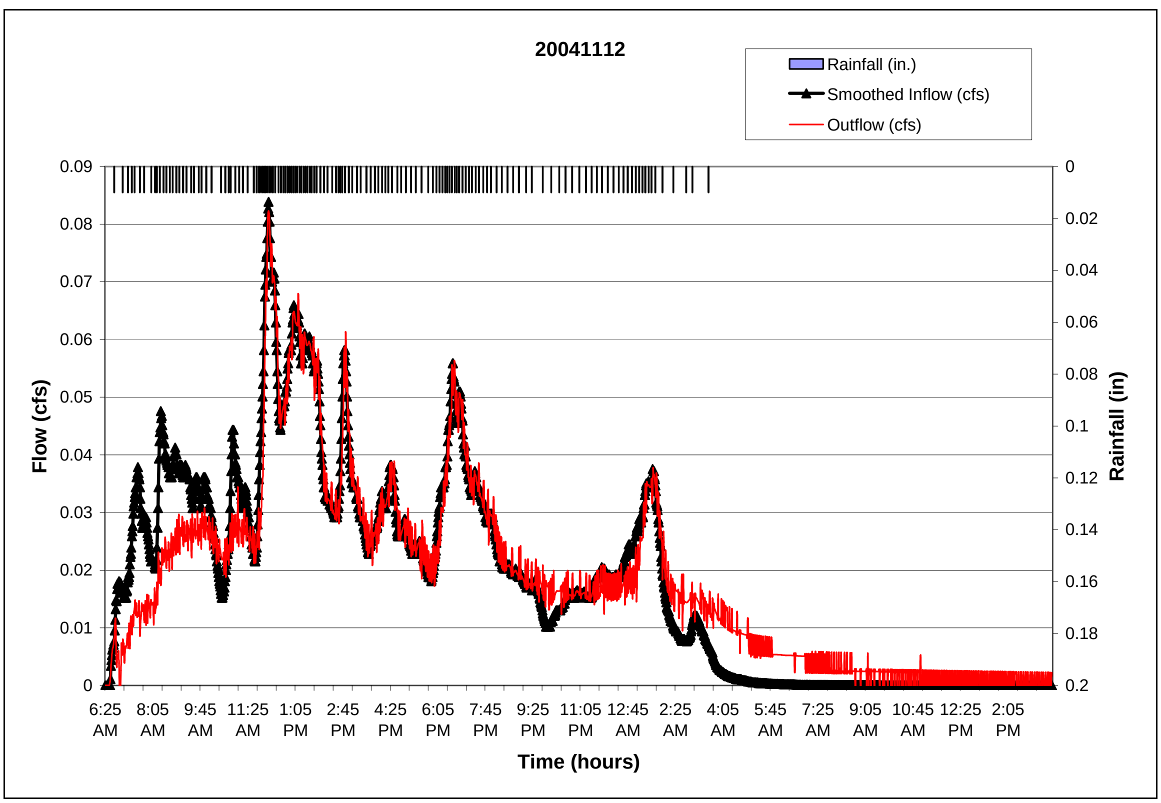


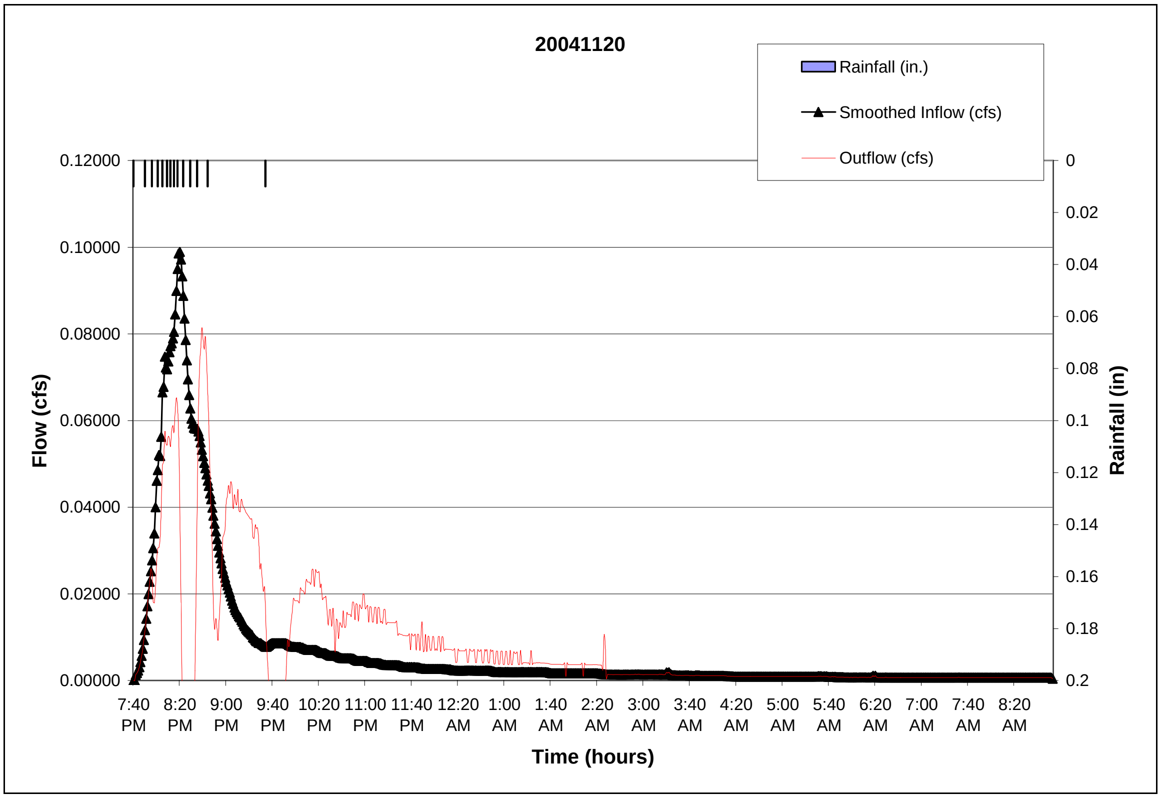


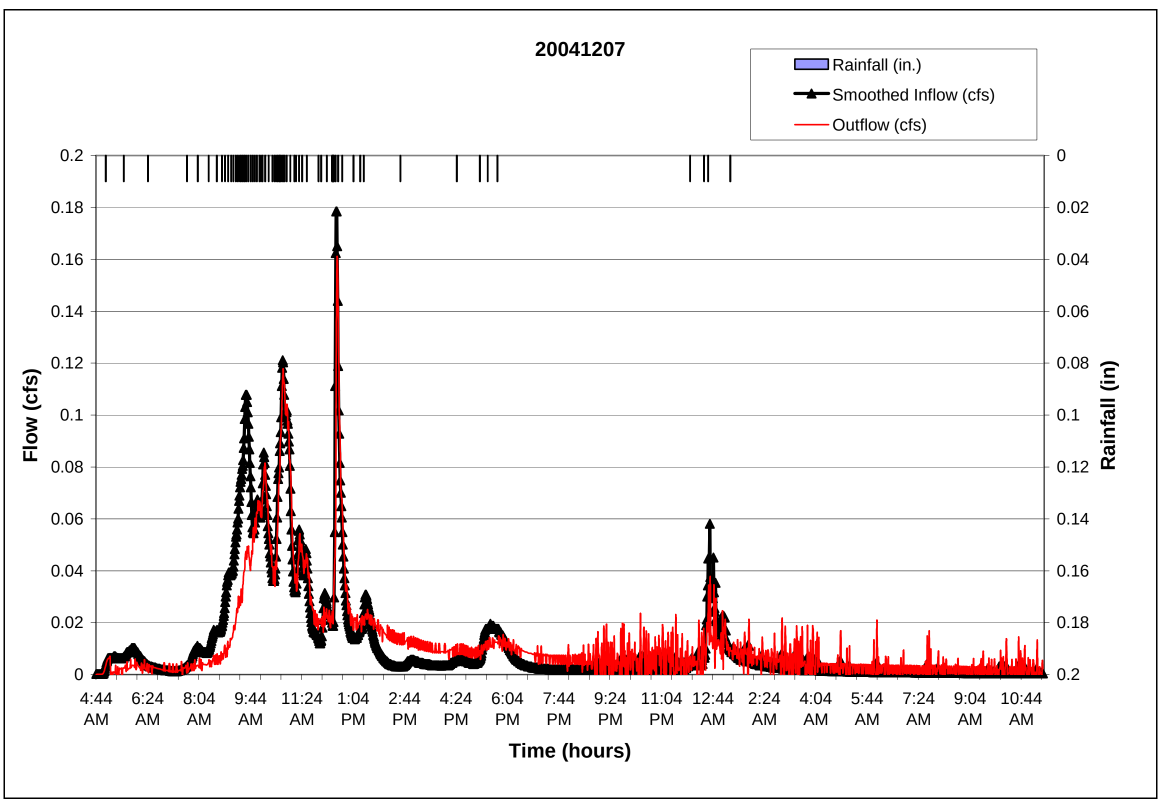

20040813
Rainfall (in.)
Smoothed Inflow (cfs)
Outflow (cfs)
0.06000
0.05000
0.04000
0.03000
0.02000
0.01000
0.00000
Flow (cfs)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Rainfall (in)
2:50 AM
3:30 AM
4:10 AM
4:50 AM
5:30 AM
6:10 AM
6:50 AM
7:30 AM
8:10 AM
8:50 AM
9:30 AM
Time (hours)

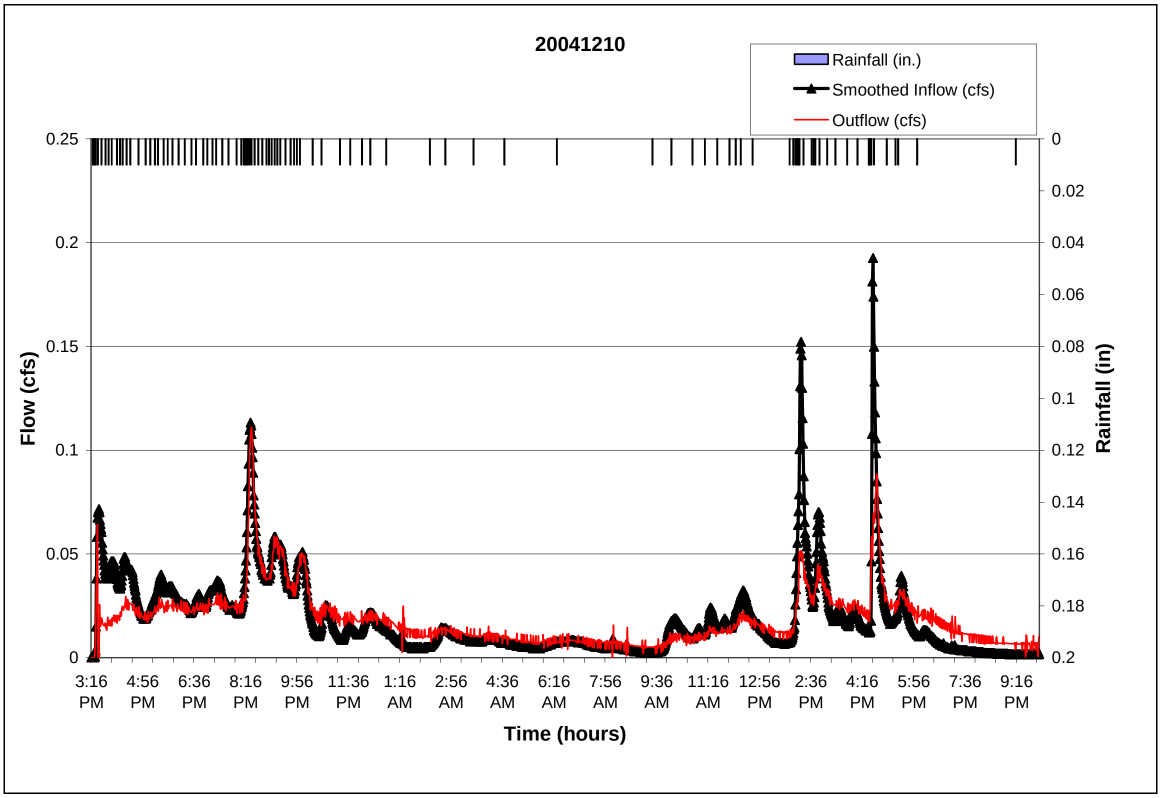

20040908 (1)
Rainfall (in.)
Smoothed Inflow (cfs)
Outflow (cfs)
0.03
0.025
0.02
0.015
0.01
0.005
0
Flow (cfs)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Rainfall (in)
4:22 AM
5:02 AM
5:42 AM
6:22 AM
7:02 AM
7:42 AM
8:22 AM
9:02 AM
9:42 AM
10:22 AM
11:02 AM
Time (hours)


20040908 (2)
Rainfall (in.)
Smoothed Inflow (cfs)
Outflow (cfs)
Flow (cfs)
Rainfall (in)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
2:48 PM
3:28 PM
4:08 PM
4:48 PM
5:28 PM
6:08 PM
6:48 PM
7:28 PM
8:08 PM
8:48 PM
9:28 PM
Time (hours)


20041112
Rainfall (in.)
Smoothed Inflow (cfs)
Outflow (cfs)
Flow (cfs)
Rainfall (in)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
6:25 AM
8:05 AM
9:45 AM
11:25 AM
1:05 PM
2:45 PM
4:25 PM
6:05 PM
7:45 PM
9:25 PM
11:05 PM
12:45 AM
2:25 AM
4:05 AM
5:45 AM
7:25 AM
9:05 AM
10:45 AM
12:25 PM
2:05 PM
Time (hours)


20041120
Rainfall (in.)
Smoothed Inflow (cfs)
Outflow (cfs)
Flow (cfs)
Rainfall (in)
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
7:40 PM
8:20 PM
9:00 PM
9:40 PM
10:20 PM
11:00 PM
11:40 PM
12:20 AM
1:00 AM
1:40 AM
2:20 AM
3:00 AM
3:40 AM
4:20 AM
5:00 AM
5:40 AM
6:20 AM
7:00 AM
7:40 AM
8:20 AM
Time (hours)


20041207
Rainfall (in.)
Smoothed Inflow (cfs)
Outflow (cfs)
Flow (cfs)
Rainfall (in)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
4:44 AM
6:24 AM
8:04 AM
9:44 AM
11:24 AM
1:04 PM
2:44 PM
4:24 PM
6:04 PM
7:44 PM
9:24 PM
11:04 PM
12:44 AM
2:24 AM
4:04 AM
5:44 AM
7:24 AM
9:04 AM
10:44 AM
Time (hours)

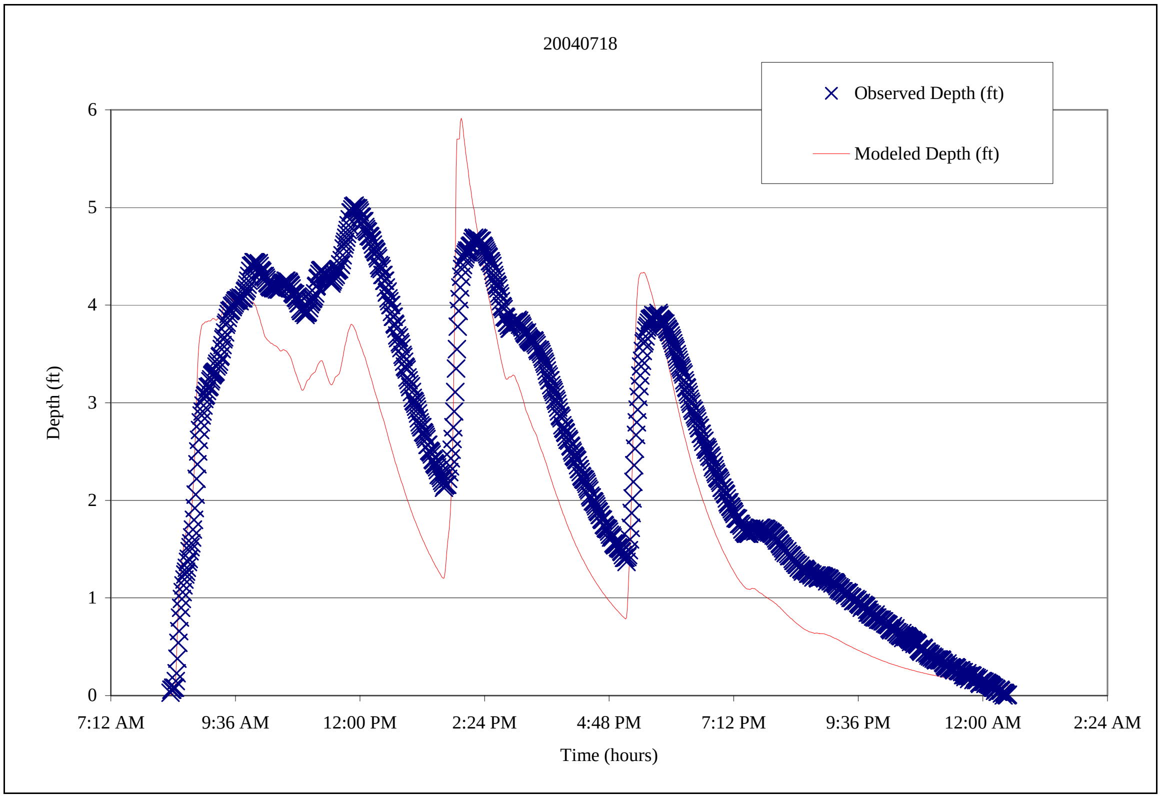

20041210
Rainfall (in.)
Smoothed Inflow (cfs)
Outflow (cfs)
Flow (cfs)
0.25
0.2
0.15
0.1
0.05
0
Rainfall (in)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
3:16 PM
4:56 PM
6:36 PM
8:16 PM
9:56 PM
11:36 PM
1:16 AM
2:56 AM
4:36 AM
6:16 AM
7:56 AM
9:36 AM
11:16 AM
12:56 PM
2:36 PM
4:16 PM
5:56 PM
7:36 PM
9:16 PM
Time (hours)

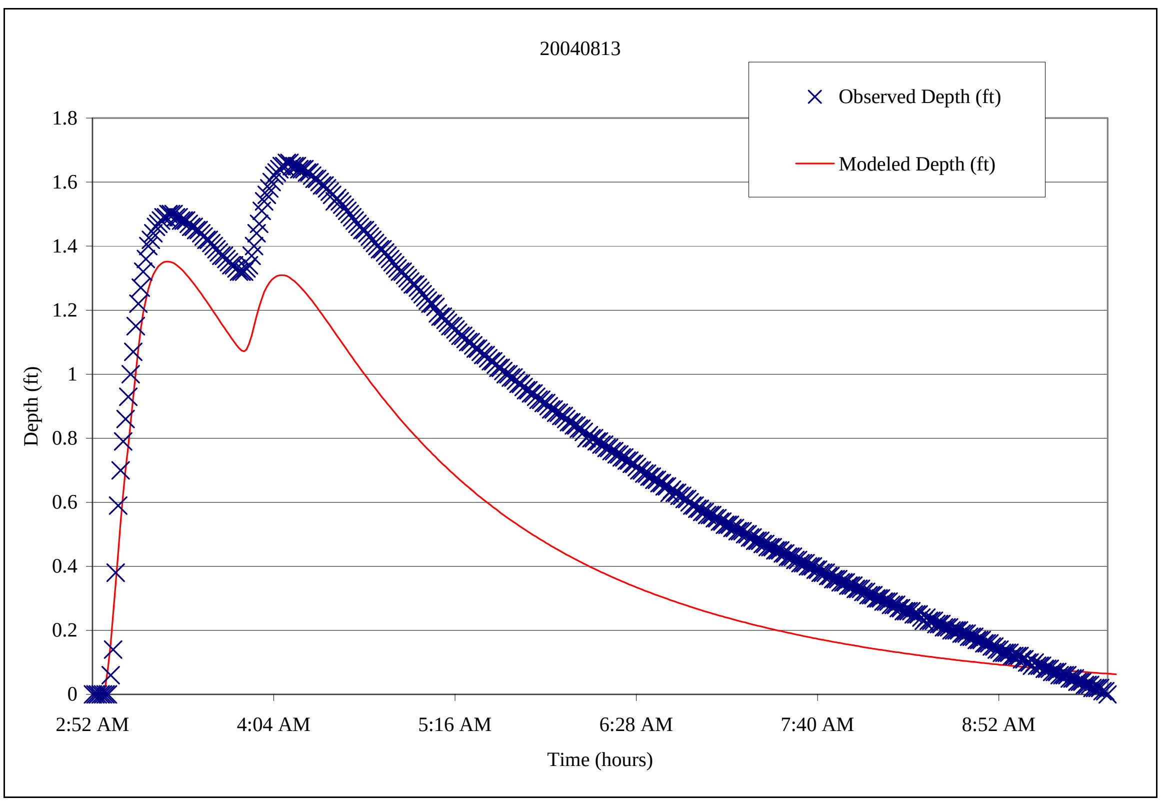
Appendix F: Storage-Rating Curve Development Sheet

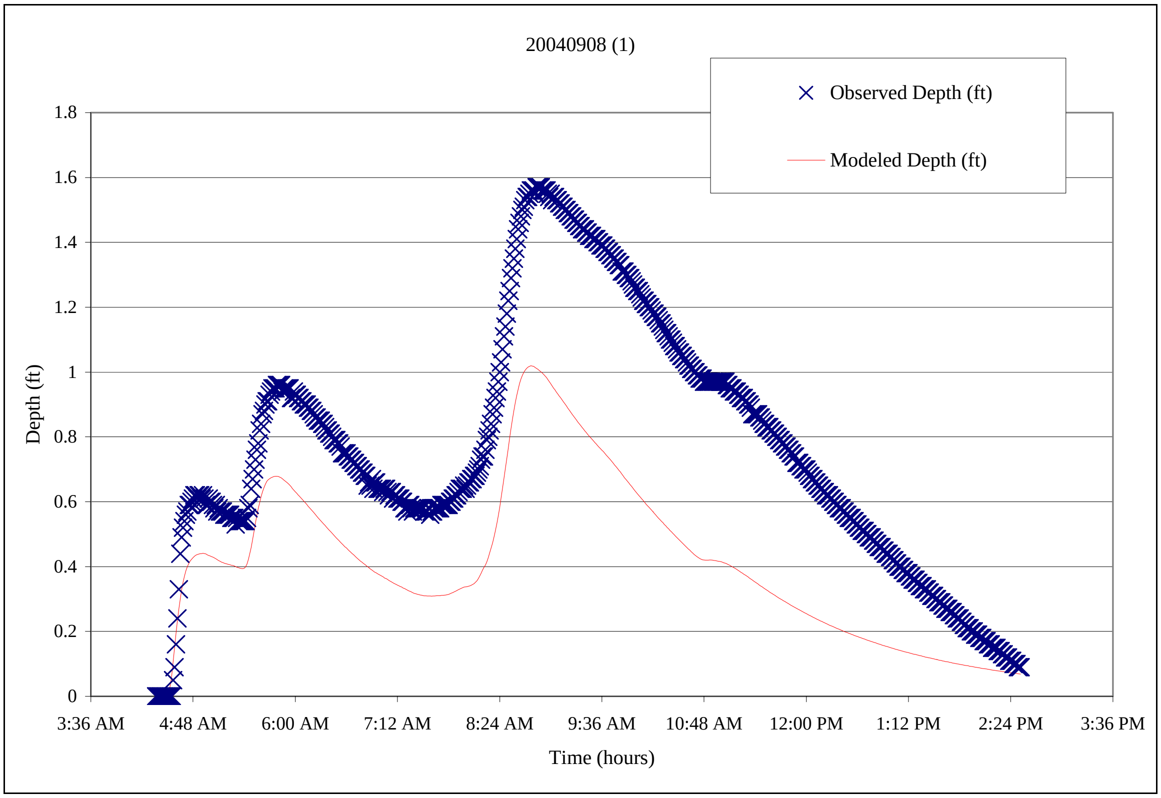
Depth from bottom (ft)	width (ft)	length, long side (ft)	length, short side (ft)	Difference (ft)	Area, rectangle (ft^2)	Area, triangle (ft^2)	Total Area (ft^2)	Incremental Volume (ft^3)	Cumulative Volume (ft^3)
0.00	7.00	11.42	8.42	3.00	58.94	10.50	69.44	0.00	0.00
0.10	7.05	11.46	8.42	3.04	59.36	10.72	70.08	6.98	6.98
0.20	7.10	11.50	8.42	3.08	59.78	10.94	70.73	7.04	14.02
0.30	7.15	11.54	8.42	3.12	60.20	11.17	71.37	7.10	21.12
0.40	7.20	11.59	8.42	3.17	60.62	11.40	72.02	7.17	28.29
0.50	7.25	11.63	8.42	3.21	61.05	11.63	72.67	7.23	35.53
0.60	7.30	11.67	8.42	3.25	61.47	11.86	73.32	7.30	42.83
0.70	7.35	11.71	8.42	3.29	61.89	12.09	73.98	7.37	50.19
0.80	7.40	11.75	8.42	3.33	62.31	12.33	74.64	7.43	57.62
0.90	7.45	11.79	8.42	3.37	62.73	12.57	75.30	7.50	65.12
1.00	7.50	11.84	8.42	3.41	63.15	12.81	75.96	7.56	72.68
1.10	7.55	11.88	8.42	3.46	63.57	13.05	76.62	7.63	80.31
1.20	7.60	11.92	8.42	3.50	63.99	13.29	77.28	7.70	88.00
1.30	7.65	11.96	8.42	3.54	64.41	13.54	77.95	7.76	95.77
1.40	7.70	12.00	8.42	3.58	64.83	13.79	78.62	7.83	103.60
1.50	7.75	12.04	8.42	3.62	65.26	14.04	79.29	7.90	111.49
1.60	7.80	12.08	8.42	3.66	65.68	14.29	79.97	7.96	119.45
1.70	7.85	12.13	8.42	3.71	66.10	14.54	80.64	8.03	127.48
1.80	7.90	12.17	8.42	3.75	66.52	14.80	81.32	8.10	135.58
1.90	7.95	12.21	8.42	3.79	66.94	15.06	82.00	8.17	143.75
2.00	8.00	12.25	8.42	3.83	67.36	15.32	82.68	8.23	151.98
2.10	8.04	12.28	8.42	3.86	67.66	15.52	83.18	8.29	160.28
2.20	8.07	12.32	8.42	3.90	67.96	15.72	83.68	8.34	168.62
2.30	8.11	12.35	8.42	3.93	68.26	15.92	84.19	8.39	177.01
2.40	8.14	12.38	8.42	3.96	68.56	16.13	84.69	8.44	185.46
2.50	8.18	12.41	8.42	3.99	68.86	16.33	85.20	8.49	193.95
2.60	8.21	12.45	8.42	4.03	69.16	16.54	85.70	8.55	202.50
2.70	8.25	12.48	8.42	4.06	69.47	16.75	86.21	8.60	211.09
2.80	8.29	12.51	8.42	4.09	69.77	16.96	86.72	8.65	219.74
2.90	8.32	12.55	8.42	4.13	70.07	17.17	87.23	8.70	228.44
3.00	8.36	12.58	8.42	4.16	70.37	17.38	87.74	8.75	237.18
3.10	8.39	12.61	8.42	4.19	70.67	17.59	88.26	8.80	245.98
3.20	8.43	12.64	8.42	4.22	70.97	17.80	88.77	8.85	254.84
3.30	8.46	12.68	8.42	4.26	71.27	18.02	89.29	8.90	263.74
3.40	8.50	12.71	8.42	4.29	71.57	18.23	89.80	8.95	272.69
3.50	8.54	12.74	8.42	4.32	71.87	18.45	90.32	9.01	281.70
3.60	8.57	12.78	8.42	4.36	72.17	18.67	90.84	9.06	290.76
3.70	8.61	12.81	8.42	4.39	72.47	18.89	91.36	9.11	299.87
3.80	8.64	12.84	8.42	4.42	72.77	19.11	91.88	9.16	309.03
3.90	8.68	12.87	8.42	4.45	73.07	19.33	92.40	9.21	318.24
4.00	8.71	12.91	8.42	4.49	73.37	19.55	92.93	9.27	327.51
4.10	8.75	12.94	8.42	4.52	73.68	19.78	93.45	9.32	336.83
4.20	8.79	12.97	8.42	4.55	73.98	20.00	93.98	9.37	346.20
4.30	8.82	13.01	8.42	4.59	74.28	20.23	94.50	9.42	355.62
4.40	8.86	13.04	8.42	4.62	74.58	20.45	95.03	9.48	365.10
4.50	8.89	13.07	8.42	4.65	74.88	20.68	95.56	9.53	374.63
4.60	8.93	13.10	8.42	4.68	75.18	20.91	96.09	9.58	384.21
4.70	8.96	13.14	8.42	4.72	75.48	21.14	96.62	9.64	393.85
4.80	9.00	13.17	8.42	4.75	75.78	21.38	97.16	9.69	403.54
4.90	9.11	13.37	8.67	4.70	78.99	21.43	100.42	9.88	413.42
5.00	9.22	13.58	8.92	4.66	82.26	21.47	103.73	10.21	423.62
5.10	9.33	13.78	9.17	4.61	85.59	21.51	107.10	10.54	434.16
5.20	9.44	13.98	9.42	4.56	88.97	21.55	110.52	10.88	445.05
5.30	9.56	14.19	9.67	4.52	92.40	21.58	113.98	11.22	456.27
5.40	9.67	14.39	9.92	4.47	95.89	21.61	117.50	11.57	467.84
5.50	9.78	14.59	10.17	4.42	99.44	21.63	121.07	11.93	479.77
5.60	9.89	14.80	10.42	4.38	103.04	21.64	124.68	12.29	492.06
5.70	10.00	15.00	10.67	4.33	106.70	21.65	128.35	12.65	504.71

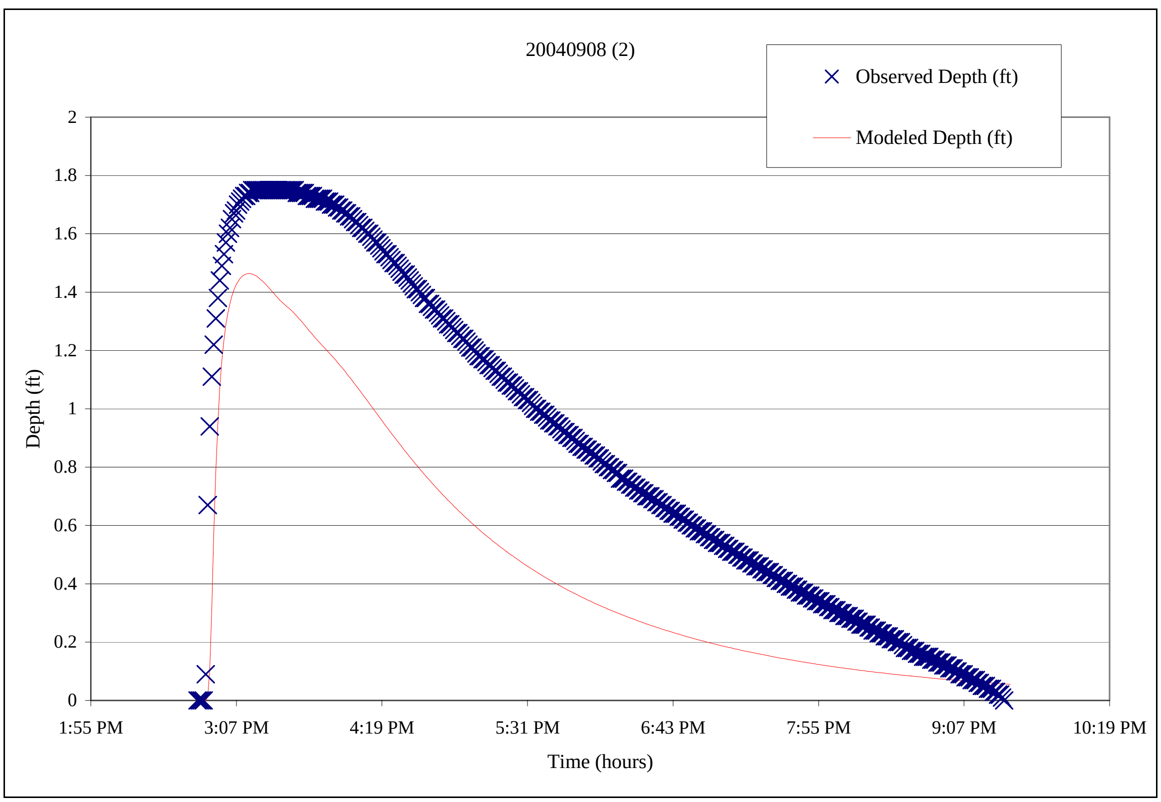
Distribution Pipe width (ft)	Distribution Pipe length (ft)	Distribution Pipe Area (ft²)	Incremental PipeVolume (ft³)	Cumulative Pipe Volume (ft³)	vol in trench - pipe vol	stor. In stone bed (ft³) (n=0.40)	eff stor (ft³) (n=0.40)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	6.98	2.79	2.79
0.00	0.00	0.00	0.00	0.00	14.02	5.61	5.61
0.00	0.00	0.00	0.00	0.00	21.12	8.45	8.45
0.00	0.00	0.00	0.00	0.00	28.29	11.32	11.32
0.00	0.00	0.00	0.00	0.00	35.53	14.21	14.21
0.00	0.00	0.00	0.00	0.00	42.83	17.13	17.13
0.00	0.00	0.00	0.00	0.00	50.19	20.08	20.08
0.00	0.00	0.00	0.00	0.00	57.62	23.05	23.05
0.00	0.00	0.00	0.00	0.00	65.12	26.05	26.05
0.00	0.00	0.00	0.00	0.00	72.68	29.07	29.07
0.00	0.00	0.00	0.00	0.00	80.31	32.12	32.12
0.00	0.00	0.00	0.00	0.00	88.00	35.20	35.20
0.00	0.00	0.00	0.00	0.00	95.77	38.31	38.31
0.00	0.00	0.00	0.00	0.00	103.60	41.44	41.44
0.00	0.00	0.00	0.00	0.00	111.49	44.60	44.60
0.00	0.00	0.00	0.00	0.00	119.45	47.78	47.78
0.00	0.00	0.00	0.00	0.00	127.48	50.99	50.99
0.00	0.00	0.00	0.00	0.00	135.58	54.23	54.23
0.00	0.00	0.00	0.00	0.00	143.75	57.50	57.50
0.00	0.00	0.00	0.00	0.00	151.98	60.79	60.79
0.00	0.00	0.00	0.00	0.00	160.28	64.11	64.11
0.00	0.00	0.00	0.00	0.00	168.62	67.45	67.45
0.00	0.00	0.00	0.00	0.00	177.01	70.80	70.80
0.00	0.00	0.00	0.00	0.00	185.46	74.18	74.18
0.00	0.00	0.00	0.00	0.00	193.95	77.58	77.58
0.00	0.00	0.00	0.00	0.00	202.50	81.00	81.00
0.00	0.00	0.00	0.00	0.00	211.09	84.44	84.44
0.00	0.00	0.00	0.00	0.00	219.74	87.90	87.90
0.00	0.00	0.00	0.00	0.00	228.44	91.37	91.37
0.00	0.00	0.00	0.00	0.00	237.18	94.87	94.87
0.00	0.00	0.00	0.00	0.00	245.98	98.39	98.39
0.00	0.00	0.00	0.00	0.00	254.84	101.93	101.93
0.00	0.00	0.00	0.00	0.00	263.74	105.50	105.50
0.00	0.00	0.00	0.00	0.00	272.69	109.08	109.08
0.00	0.00	0.00	0.00	0.00	281.70	112.68	112.68
0.00	0.00	0.00	0.00	0.00	290.76	116.30	116.30
0.00	0.00	0.00	0.00	0.00	299.87	119.95	119.95
0.00	0.00	0.00	0.00	0.00	309.03	123.61	123.61
0.00	0.00	0.00	0.00	0.00	318.24	127.30	127.30
0.00	0.00	0.00	0.00	0.00	327.51	131.00	131.00
0.00	0.00	0.00	0.00	0.00	336.83	134.73	134.73
0.00	0.00	0.00	0.00	0.00	346.20	138.48	138.48
0.00	0.00	0.00	0.00	0.00	355.62	142.25	142.25
0.00	0.00	0.00	0.00	0.00	365.10	146.04	146.04
0.00	0.00	0.00	0.00	0.00	374.63	149.85	149.85
0.00	0.00	0.00	0.00	0.00	384.21	153.68	153.68
0.00	0.00	0.00	0.00	0.00	393.85	157.54	157.54
0.89	10.00	8.86	0.00	0.00	403.54	161.41	161.41
0.89	10.00	8.86	0.89	0.89	412.53	165.01	165.90
0.89	10.00	8.86	0.89	1.77	421.85	168.74	170.51
0.89	10.00	8.86	0.89	2.66	431.51	172.60	175.26
0.89	10.00	8.86	0.89	3.54	441.50	176.60	180.14
0.89	10.00	8.86	0.89	4.43	451.84	180.74	185.17
0.89	10.00	8.86	0.89	5.32	462.53	185.01	190.33
0.89	10.00	8.86	0.89	6.20	473.57	189.43	195.63
0.89	10.00	8.86	0.89	7.09	484.97	193.99	201.08
0.89	10.00	8.86	0.89	7.97	496.74	198.70	206.67

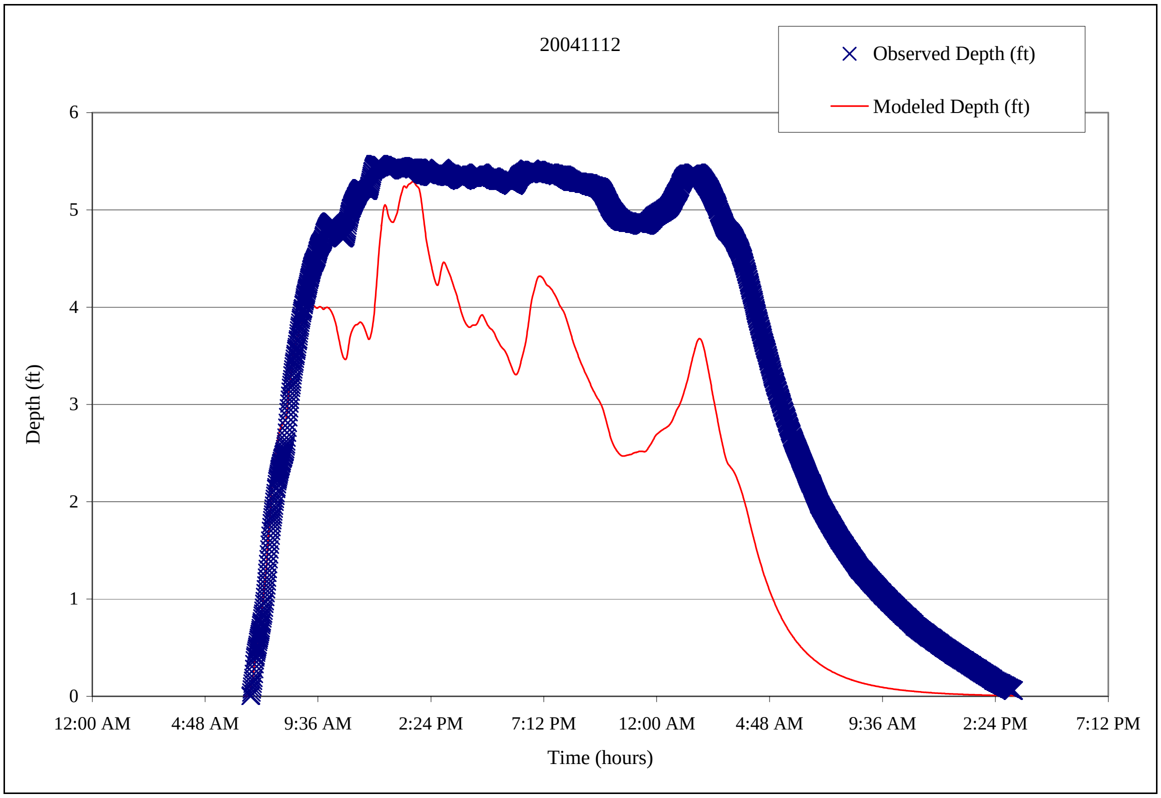
Appendix G: Depth Versus Time Graphs

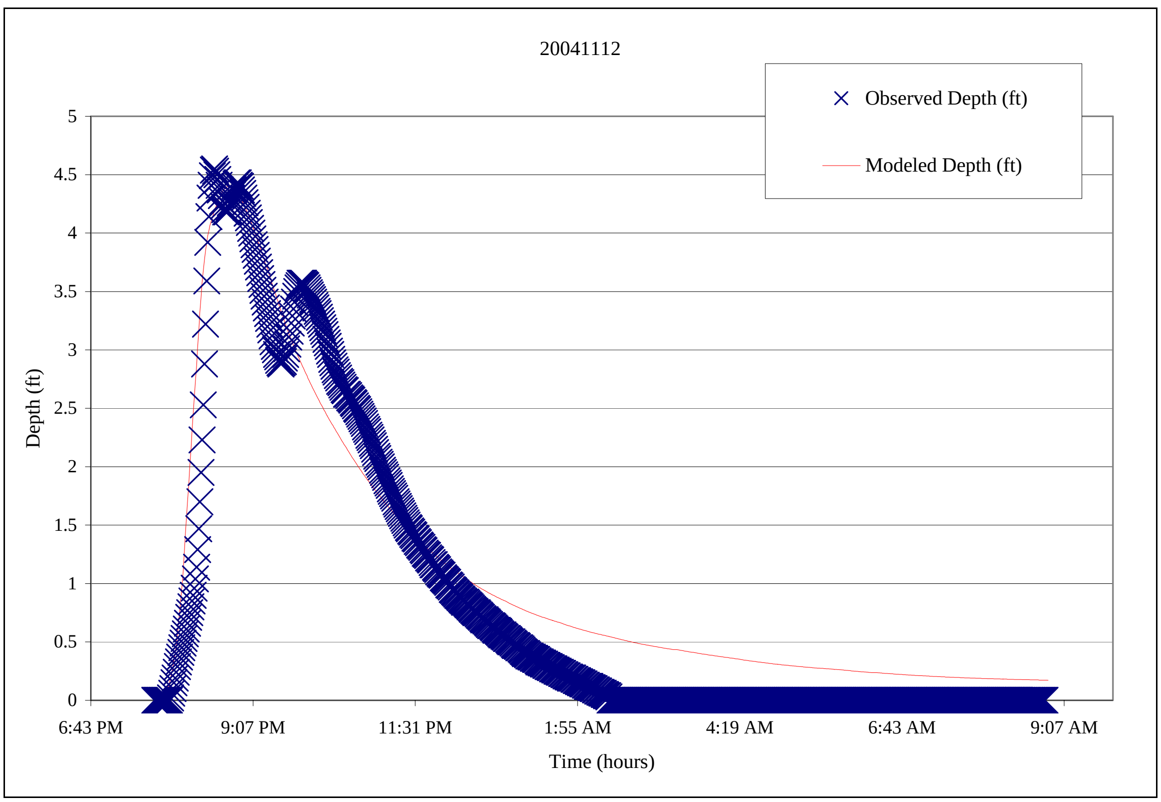


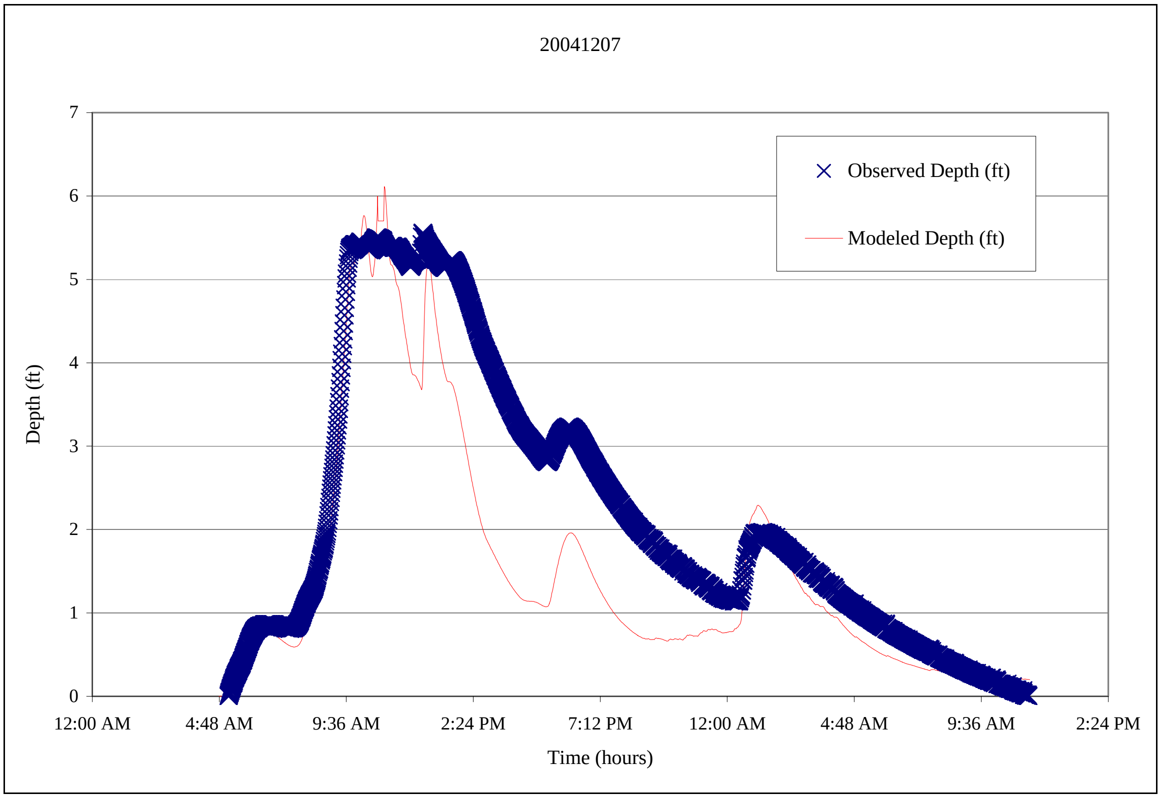



20040908 (1)
Observed Depth (ft)
Modeled Depth (ft)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Depth (ft)
3:36 AM
4:48 AM
6:00 AM
7:12 AM
8:24 AM
9:36 AM
10:48 AM
12:00 PM
1:12 PM
2:24 PM
3:36 PM
Time (hours)

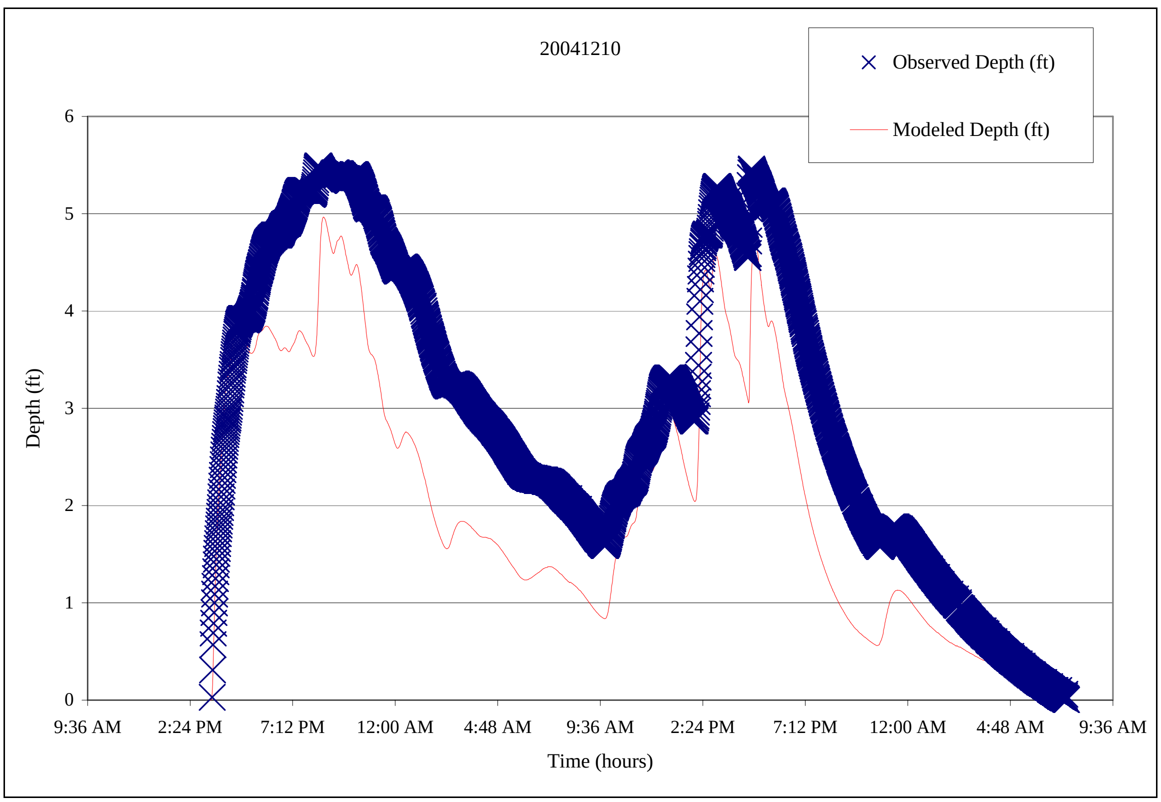

20040908 (2)
Observed Depth (ft)
Modeled Depth (ft)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Depth (ft)
1:55 PM
3:07 PM
4:19 PM
5:31 PM
6:43 PM
7:55 PM
9:07 PM
10:19 PM
Time (hours)


20041112
Observed Depth (ft)
Modeled Depth (ft)
Depth (ft)
6
5
4
3
2
1
0
12:00 AM
4:48 AM
9:36 AM
2:24 PM
7:12 PM
12:00 AM
4:48 AM
9:36 AM
2:24 PM
7:12 PM
Time (hours)


20041112
Observed Depth (ft)
Modeled Depth (ft)
Depth (ft)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
6:43 PM
9:07 PM
11:31 PM
1:55 AM
4:19 AM
6:43 AM
9:07 AM
Time (hours)



20041207
Observed Depth (ft)
Modeled Depth (ft)
Depth (ft)
7
6
5
4
3
2
1
0
12:00 AM
4:48 AM
9:36 AM
2:24 PM
7:12 PM
12:00 AM
4:48 AM
9:36 AM
2:24 PM
Time (hours)



20041210
Observed Depth (ft)
Modeled Depth (ft)
Depth (ft)
6
5
4
3
2
1
0
9:36 AM
2:24 PM
7:12 PM
12:00 AM
4:48 AM
9:36 AM
2:24 PM
7:12 PM
12:00 AM
4:48 AM
9:36 AM
Time (hours)