HYDRAULIC CHARACTERIZATION OF PERMEABLE INTERLOCKING CONCRETE PAVEMENTS

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AMANDA RENE LEIPARD

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HYDRAULIC CHARACTERIZATION OF INTERLOCKING CONCRETE PERMEABLE PAVEMENTS

Amanda Rene Leipard, Candidate for the Master of Science Degree

University of Missouri at Kansas City, 2015

ABSTRACT

The environmental benefits of permeable pavements are vast and include stormwater quantity reduction, stormwater quality improvement, urban heat island mitigation, and groundwater recharge, among others. Permeable Interlocking Concrete Pavements, PICP explicitly infiltrate water, a new concept to engineering practice for pavements. This technology as a load-carrying surface has not yet been fully characterized nor has the decades of design and performance experience of conventional pavements.

This research project developed a hydraulic design methodology for PICPs. Test sections were evaluated in a two layer hydraulic flume to determine horizontal infiltration rates, and overflow rates for various block spacing, patterns, and across a broad range of pavement cross slopes. Results demonstrated the infiltration rate of the PICPs exposed to horizontal sheet flow was significantly lower than the measured vertical infiltration rate which is currently used in field verification. The results also showed that the infiltration rates are inversely related to the cross slope of the pavement. Additional research included permeable concrete pavement as an alternative sub-base and clogging tests which included the creation of synthetic stormwater for PICP was completed and analyzed.

APPROVAL PAGE

The following faculty listed as appointed by the Dean of the School of Computing and Engineering, have examined a thesis entitled "Hydraulic Characterization of Interlocking Concrete Permeable Pavement," present by Amanda R. Leipard, a candidate for the Master of Science Degree, and certify in their opinion it is worth acceptance.

Supervisory Committee

John T. Kevern, Ph.D., Committee Chair
Department of Civil Engineering

Jerry Richardson, Ph.D.
Department of Civil Engineering

Megan Hart, Ph.D.
Department of Civil Engineering

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CHAPTER 1

OVERVIEW

The environmental impacts of increasing surface runoff produced by urbanization are extensive. Increased impervious spaces decrease the available infiltrating greenspace resulting in an overall increase of stormwater quantity, urban heat island effects, and decreasing groundwater, among others. Likewise, an increased runoff volume leads to an increase in urban stream flow creating additional stream erosion and flooding events (Booth, 1991). The amount of increased surface runoff due to urbanization can be as much as 10% of the water cycle with natural ground cover to as much as 55% of the water cycle when ground cover becomes 75-100% impervious surface (EPA, 2004 b). Impervious pavements also increase contaminant loading (USEPA, 1983) while permeable surfaces combat such loading.

Permeable surfaces are high porous (gaped) surfaces that allow stormwater to be captured and stored allowing for infiltration. Permeable surfaces such as Permeable Interlocking Concrete Pavements, PICPs combat the effects of urbanization by explicitly infiltrating water, a new concept to engineering practice for pavements.

The most common permeable surfaces include porous asphalt, pervious concrete, and PICPs. Proficient design criteria of pavements require four areas:

1) Structural Load Capacity, strength
2) Material Selection, durability and cost
3) Hydrologic Design, retention, detention
4) Hydraulic Design, flow rates, and depths

Design for durability or detention sizing have a large amount of supportive research while the hydraulic behavior of these surfaces lacks research. The misconception that a permeable surface has an infinite capacity to receive run-off from adjacent area are common and the field testing method currently does not account for such run-on flow. The test method for permeable pavement's hydraulic performance is the ASTM C1781 (ASTM, 2013). The C1781 method measures the vertical surface infiltration of a permeable surface and does not describe the horizontal sheet flow capacity of the pavement. Additionally, field experience display decreasing infiltration rates due to aging surfaces that have acquired sedimentation clogging. Horizontal sheet flow with sediment clogging research has also been limited.

From a design perspective, horizontal flow should be considered in permeable pavements. The following research concentrates upon the horizontal hydraulic behavior of PICPS. Multiple test sections at various patterns were evaluated in a two layer hydraulic flume. The research targeted the determination for allowable contributing run-off area for a variety of design storms. Horizontal hydraulic flow such as the capture discharges, infiltration rates, and overflow flow rates for various block spacing across a broad range of pavement cross slopes was examined and analyzed.

Additionally, synthetic stormwater was created and the system was analyzed for hydraulic behavior. Clogging analysis included before, during, and after clogging (recapture) hydraulic behavior. In addition to the clogging and unclogging experiments the research included a pervious platform section for comparison and for a suggested alternative sub-base material in place of some of the aggregate base. A pervious concrete section would increase the structural load capacity for a PICPs.

To adequately present all of the information the thesis has been divided into eight chapters. Each chapter was separated based upon the different criteria examined for example clogged vs. unclogged. The chapters are then further subdivided for ease of explanation and informational purposes.

Chapters one and two present an overview and literature review of significant articles and other research used within the experiment. An overview of the EPA, the driving force in urbanization consequences and controls, and local best management practices, BMPs, was also included.

Chapter three describes the experimental design, methods and procedure. The two layer hydraulic flume design and calibration of the flume was included within the chapter section. An in depth description of the PICP experimental test sections which includes drawings and the materials was included within chapter three.

Chapters four and five encompass the results and discussion of the unclogged experimental analysis. Such analysis includes the horizontal and vertical hydraulic testing of the PICP test sections. The statistical analyses of the various experiments was included in chapter five and included individual t-test comparison between groups and ANOVA comparison between all experimental groups.

Chapter six provides the explanation for the clogged experiments including the results. Statistical analyses were also completed for the clogged data. Chapter seven describes the impervious concrete platform experimental results and discussion. Chapter eight concludes the thesis with discussion, summary and a dialog on possible future research.

CHAPTER 2

LITERATURE REVIEW

Introduction of Clean Water Acts

Environmental policies have existed within the US federal government as far back as the establishment of Yellowstone, the first national park, at the beginning of the 20th century (Fiksel, 2009). However, it was not until 1960's that the US experienced significant environmental disasters calling for more stringent federal environmental regulation (Barry, 1970). Disasters such as the LA fog crisis and the Cuyahoga River Fire led to the presidential initiative by Richard Nixon to establish the Environmental Protection Agency, EPA, and sign the National Environmental Policy Act, NEPA, all within the year of 1970 (Barry, 1970) creating the foundation for current US environmental policies. The Federal Water Control Act of 1948 also helped establish the framework for the Clean Water Act, CWA, of 1972 which essentially gave the federal government clear goals and authority to regulate and control the Nation's waters (Adler, 1993). The CWA outlined three main objectives that included by 1985 eliminating pollutant discharge in navigable waters, provide water quality for the protection and propagation of fish and wildlife by 1983, and to prohibit discharge of toxic amounts of toxic pollutants (Adler, 1993). To satisfy these goals, the CWA established the National Pollutant Discharge Elimination System, NPDES, creating requirements for communities and municipalities to develop programs that reduce water pollutants (Gaba, 2007) and mitigate runoff volumes.

In 1990, the NPDES was expanded into the Storm Water Program (Phase I) focusing on stormwater runoff of (1) "medium and 'large municipal separate storm sewer systems (MS4) generally serving populations of 100,000 or greater (2) construction activity

disturbing 5 acres or greater and (3) five categories of industrial activity" (EPA, 2000). In 1999, the NPDES expanded into Phase II which included regulation of nonpoint source pollution. The EPA defined point source pollution as "any discernible, confined, and discrete conveyance… from which pollutants may be discharged. This term does not include return flows from irrigated agriculture or agriculture stormwater runoff" (EPA, 2000). Phase II also included permitting areas of investigation that affect small MS4s in "urbanized areas" as defined by the Bureau of Census and construction areas between one to five acres (EPA, 2000) this change extended the amount of municipalities affected by NPDES. With phase II the EPA proposed the achievement goal of improving water quality to the Maximum Extent Practicable (MEP), a standard many municipalities already implement for their Best Management Practices (BMP) (EPA 2000).

Through the Phase II of the NPDES six minimum control measures, stated below, were defined to be the basis of a management plan for measurable goals of reducing the amount of water pollution (EPA, 2000):

I. Public education/outreach
II. Public participation/involvement
III. Illicit discharge detection elimination
IV. Construction site stormwater runoff control
V. Post construction stormwater management
VI. Pollution prevention/good maintenance

Urbanization in the Hydrologic Cycle

Urbanization has a great affect upon the environment such as an increase in urban heat island effects, increase in surface runoff due to increased impervious area, and loss of overall greenspace. Surface runoff is defined as the amount of water that does not infiltrate the ground. The amount of increased surface runoff due to urbanization can be as much as 10% of the water cycle with natural ground cover to as much as 55% of the water cycle when ground cover becomes 75-100% impervious surfaces. Figure 1 displays the hydrological cycle with the effects of urbanization upon the cycle.

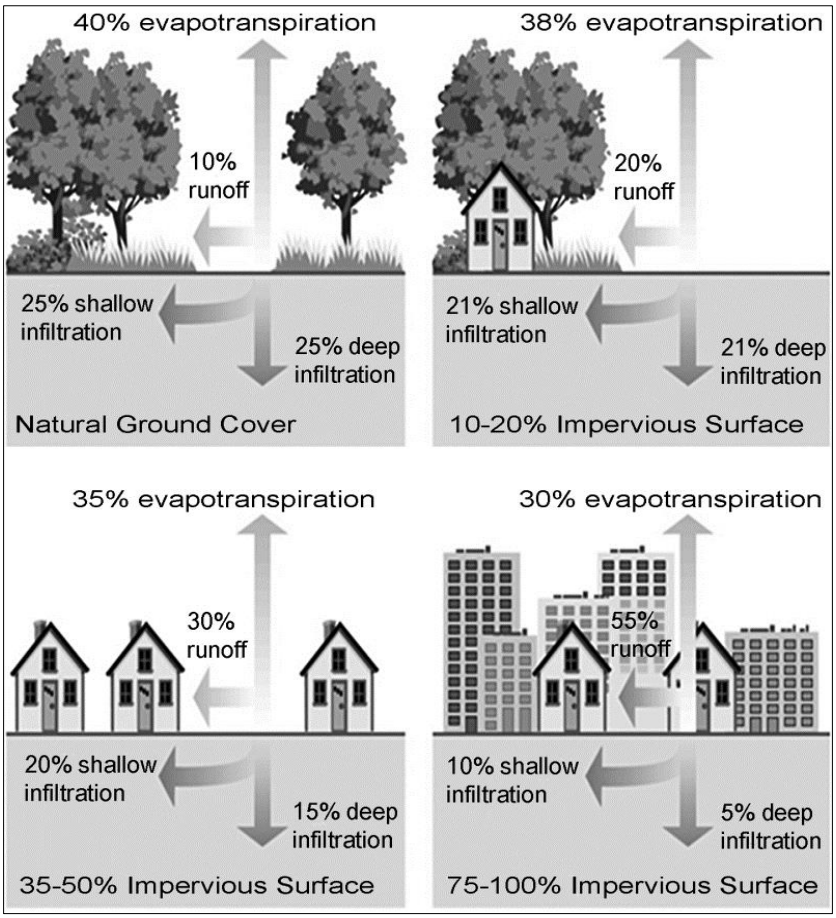


Figure 1- Effect of Impervious Surface on Hydrologic Cycle from NRCS (NEH-653, 1998)

Urbanization suppresses evapotranspiration due to the removal of green space with trees and plants which also suppresses infiltration due to shallow or lack of root systems. Impervious surfaces such as increased parking lot areas and building areas further decreases green space preventing groundwater recharge through infiltration (EPA, 2004 a). All modifications to the urban landscape that decrease in evapotranspiration, decrease in infiltration, and increase in impervious surfaces lead to increase in surface runoff and thus discharge (stormwater) pollution.

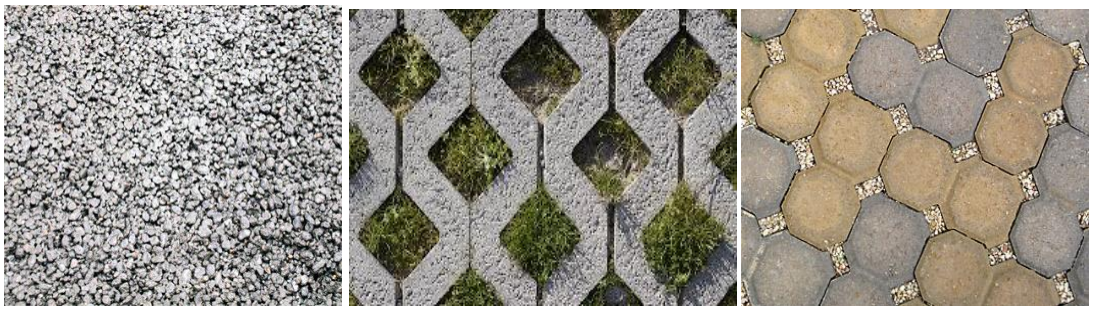
Best Management Practices

Best management practices are methods that originally referred to water pollution control but currently are practices used that are determined to be the most effective and applicable in achieving a specific objective (EPA, 2010). Designing procedures and systems that intercept and infiltrate stormwater runoff back into the groundwater system are suggested by the EPA (EPA, 2004 a). Such systems have been shown to not only attenuate peak flows from design storms (reduce captured runoff) but have been shown to reduce particulate pollution (Brown, 2014). The most common water pollutant carrier within the US is sediment (Ostercamp, 1998). Eroded transported sediment creates a non-point source pollutant that carries chemicals from regional land use such as fertilizer in agricultural areas or manufacturing chemical wastes from industrial areas (Terrence, 2002) or even oil from cars on roadways. As such, PICP systems are adequate for the use of best management practices to reduce water pollutants, reduce stormwater and mitigate peak flows.

Permeable Pavements Designed as Best Management Practice

Permeable pavements are defined as porous structures that are used to infiltrate urban runoff and increase water quality (Young, 2008). PICPs are defined by the use of solid

concrete pavers placed over highly permeable aggregate bedding material with aggregate filler material of various gradations used to fill joints (ICPI, 2014). Figure 2 displays typical porous pavements. The bottom two are the PICP patterns used within the experiment of this thesis.



Permeable Concrete Concrete Grid Pavers PICP

Straight Herringbone PICP Herringbone Pattern

Figure 2 -Types of Permeable Pavement (ICPI, 2015; Grahl, 2012)

Designs of permeable pavements include multiple system analysis such as structural, hydrological, and hydraulic similar to an impermeable pavement design. Common applications of PICP and other porous systems include parking lots, driveways, pedestrian access and bike lanes, as well as used for slope stabilization and erosion control (Schotzl, 2006). Design decisions of PICP include both structural and hydrological analysis just as in

impermeable pavement design. Structural analyses for design include intended use of the PICP system, adequate strength and thickness of the base layer that accomplishes such use. Hydrologic factors that should be considered for design purposes include the volume of water that needs to be mitigated, the depth of the aggregate base and how much water via infiltration can be held. Figure 3 displays one example of a design flow chart for permeable pavement systems.

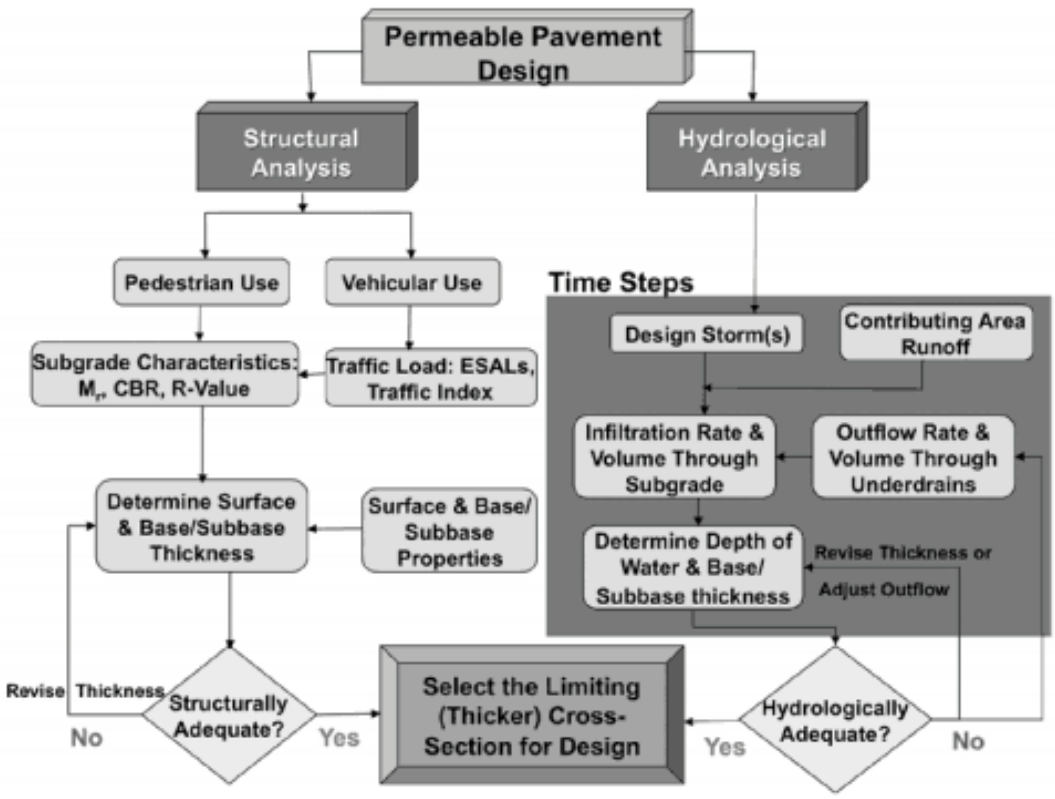


Figure 3 - Permeable Pavement Design Flow Chart (ICPI, 2015)

Design of permeable pavements, such as PICP, for BMP's would include analysis of experimental testing for pollutant reduction, infiltration rates to predict the stormwater runoff reduction, and proper design including life cycle costs including installation and

maintenance. Several studies have shown that porous pavements have been shown to adequately reduce pollutants from stormwater runoff (Roseen, 2012). For the purpose of the following research, particular interest was placed upon infiltration and overflow flow rates. Infiltration rates from porous pavements have been shown to adequately infiltrate direct storm and runoff from adjacent areas for the most extreme storm events (Brown, 2014).

Previous research, such as the Brown, 2014 study, has concentrated on vertical infiltration hydraulic anaylsis of PICP field test sections. The hydraulic analysis has been conducted using the current test method for permeable pavement's hydraulic performance, the ASTM C1781 (ASTM, 2013). The ASTM C1781 method measures the vertical surface infiltration of a permeable surface and does not describe the horizontal sheet flow capacity of the pavement. Additionally, field sections display decreasing infiltration rates due to aging surfaces that have acquired sedimentation clogging. Horizontal sheet flow with sediment clogging research has not been conducted. Figure 4 represents a typical PICP cross section and displays the example of the experimental test section used in the following research.

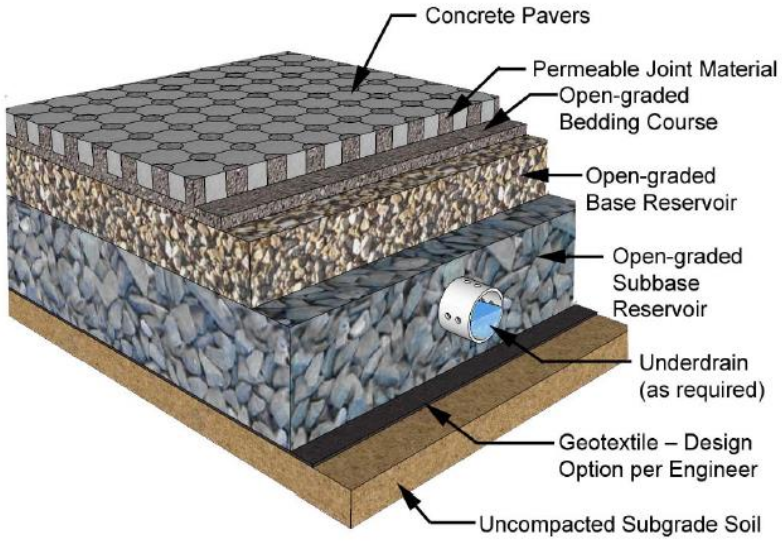


Figure 4 - PICP Cross Section (ICPI, 2015)

Figure 5 displays the hydraulic behavior of a system displaying surface infiltration and overflow (surface runoff). For research purposes a subsurface drain was also used within the experiment to adequately model the typical systems matching both figures 4 and 5.

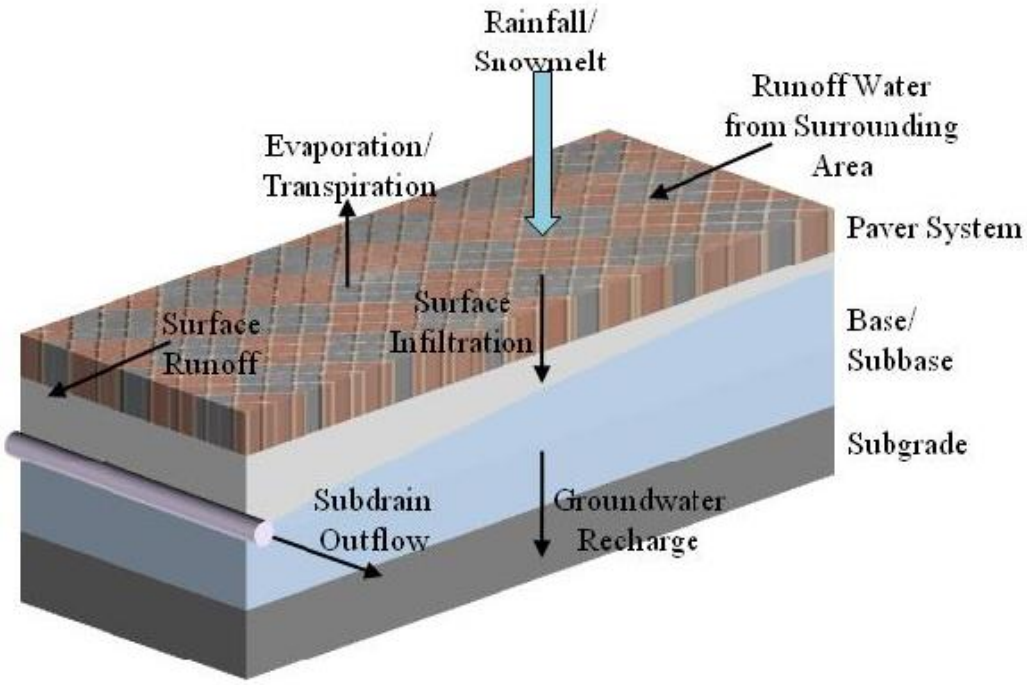


Figure 5 - Water Inflow and Outflow on Permeable Pavement (ICPI, 2015)

While these permeable pavement systems have been shown to provide adequate infiltration, life cycle, and maintenance has been shown to be a concern (Young, 2012). Life cycles of porous pavements have been related directly to hydraulic performance and the decrease of that performance (Young, 2012). Decrease of hydraulic performance can be caused by the clogging or collapsing of pavement pores. Clogging is a physical component or process of decreasing porosity from the accumulation of particulates (sediment) that occurs over time with permeable pavements (Young, 2008), thus pavement clogging would then adversely affect life cycle costs.

PICP Benefits and Concerns

Most cities install pipe stormwater systems which capture and divert water either into a separate system or into sewer systems (Schotzl, 2006). These systems not only negativity effect the groundwater recharge and pollutant mitigation but are often expensive and inefficient (Schotzl, 2006) and in the event of diverting runoff into sewer systems violate the NPDES Storm Water Program (Phase I). As such, PICP systems would satisfy the Storm Water Program for the NPDES. Other benefits, as previously stated, include groundwater recharge, runoff mitigation, as well other recycled water benefits (Schotzl, 2006).

Permeable pavements have also been shown to decrease harmful pollutants such as heavy metals, particulates such as suspended solids (sediment) and ammonia levels without the significant maintenance that is typically required for highway gullies (Roseen, 2012; Schotzl, 2006). The increased water quality from PICP systems provides the desirable benefit for fulfillment of Phase II NPDES Storm Water Programs.

Permeable pavements have also been shown to mitigate urban island heat effects (Kevern, 2012). Many pavements contribute to urban heat due to causing a decrease in evapotranspiration, heat absorption and bulk mass properties (Kevern, 2012) while permeable pavements have been shown to store less heat (Kevern, 2012). PICP systems alone have been shown to have lower surface temperatures however, cooling properties were related directly to available surface water (wetting) (Li, 2013). Regardless, PICP as a permeable pavement system can thus be used to mitigate urban island heat effects providing a much needed benefit.

Issues with permeable pavement systems include structural loading issues such as displacement due to wheel loading and decreased performance over the life of the system

primarily due to clogging (Schotzl, 2006). Main causes of clogging are traffic sediment ground into pavement prior to being washed off, stormwater suspended sediment, and shear stress from vehicles (wheel loading issue) collapsing pores (Schotzl, 2006). However, several studies have found PICP and other permeable pavement systems to not suffer from significant clogging issues. According to Booth et. Al (2003), after 6 years of permeable pavement use, which included a concrete block with lattice pattern, clogging issues were not found to be an issue. Similarly, Lucke (2011) found PICP system's infiltration was satisfactory after 8 years of continuous service with no maintenance performed on the pavers suggesting that clogging probably should not be as much of a concern.

Other non-hydrologic issues with permeable pavements include displacement due to tree roots. Trees lining such permeable pavements cause an increase in root structures in search of water (Lucke, 2011) that is not found with impermeable pavements.

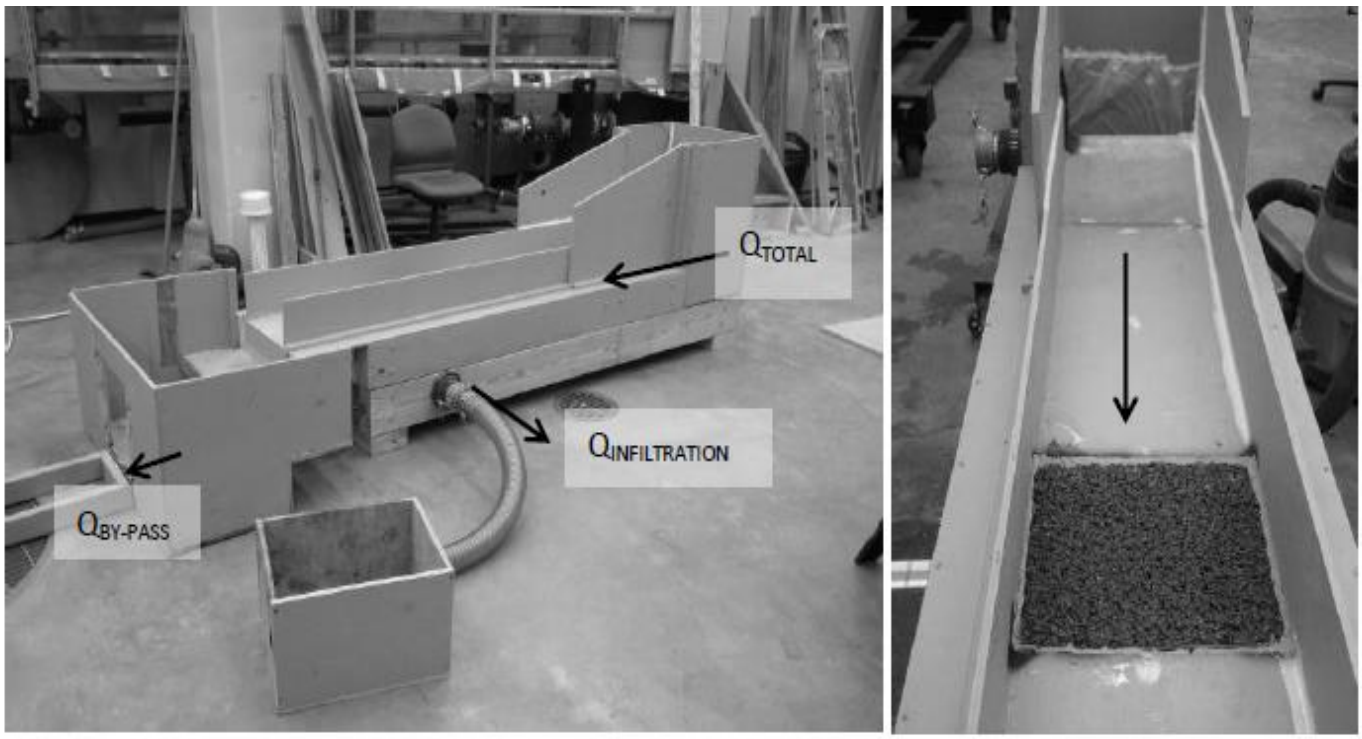
Since the EPA and the NPDES require infiltration and water quality improvement, systems such as PICP are becoming more widely used within urban environments. The benefits of PICP include groundwater recharge, increased over all stormwater quality such as peak flow mitigation and pollution reduction conceivably outweigh any issues such as possible clogging system issues.

Previous Research Design Considerations

The initial laboratory deign was based on the thesis research performed from Nathan Grahl, (2012), "Hydraulic Design of Pervious Concrete Highway Shoulders." The Grahl thesis research was similar in structure as a flume was constructed to allow for infiltration and overflow discharge to be measured individually. The Grahl research indicated that vertical infiltration was greater than measured horizontal infiltration for Portland Cement Pervious test

sections. The difference between the vertical and horizontal infiltration values led to the following research on PICP test sections. PICP systems have, to date, been studied only via vertical infiltration and have not been studied for horizontal hydraulic sheet flow. As pavements receive discharge in the form of horizontal sheet flow the hydraulic performance of PICP systems under such conditions may provide important information such as infiltration and overflow rates. Figure 6 shows the designed Flume for the Grahl research and was similar to the designed two layer flume for the following PICP research.

Figure 6 – Flume for Grahl Research, (Grahl, 2015)



CHAPTER 3

EXPERIMENTAL DESIGN

Flume Design

A two layer hydraulic flume was designed to split the flow vertically and horizontally for infiltration experimentation. The flume was manufactured locally with each piece individually drawn in the 3D program of Solidworks. The Figures 7 through 10 were the produced CAD drawings used in the design. Figure 11 displays the whole laboratory set up as water flows through the pumping system. The initial laboratory deign was based on the thesis research performed from Nathan Grahl, (2012). “Hydraulic Design of Pervious Concrete Highway Shoulders.”

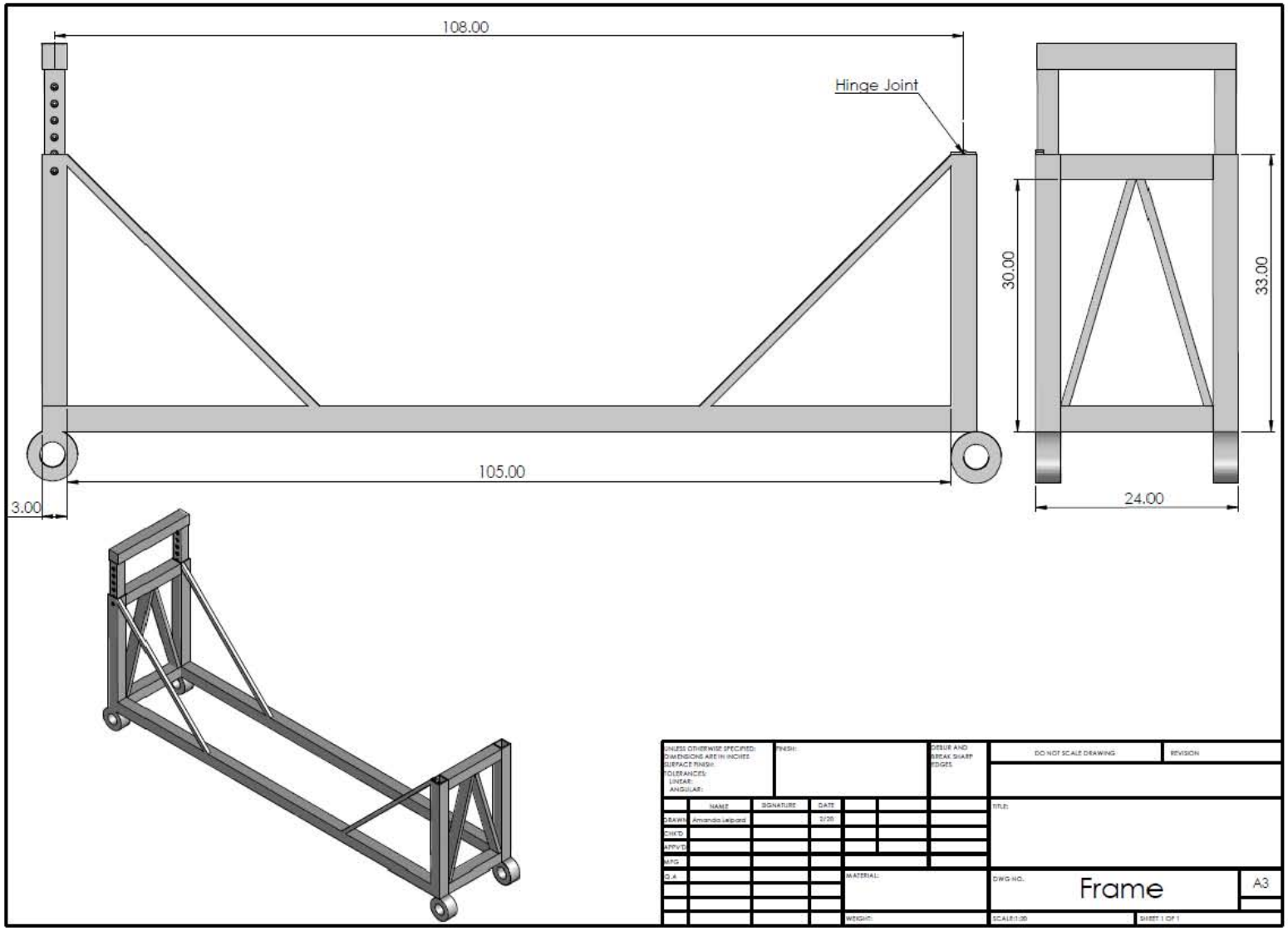


Figure 7 – Bottom Support Frame Assembly Drawing

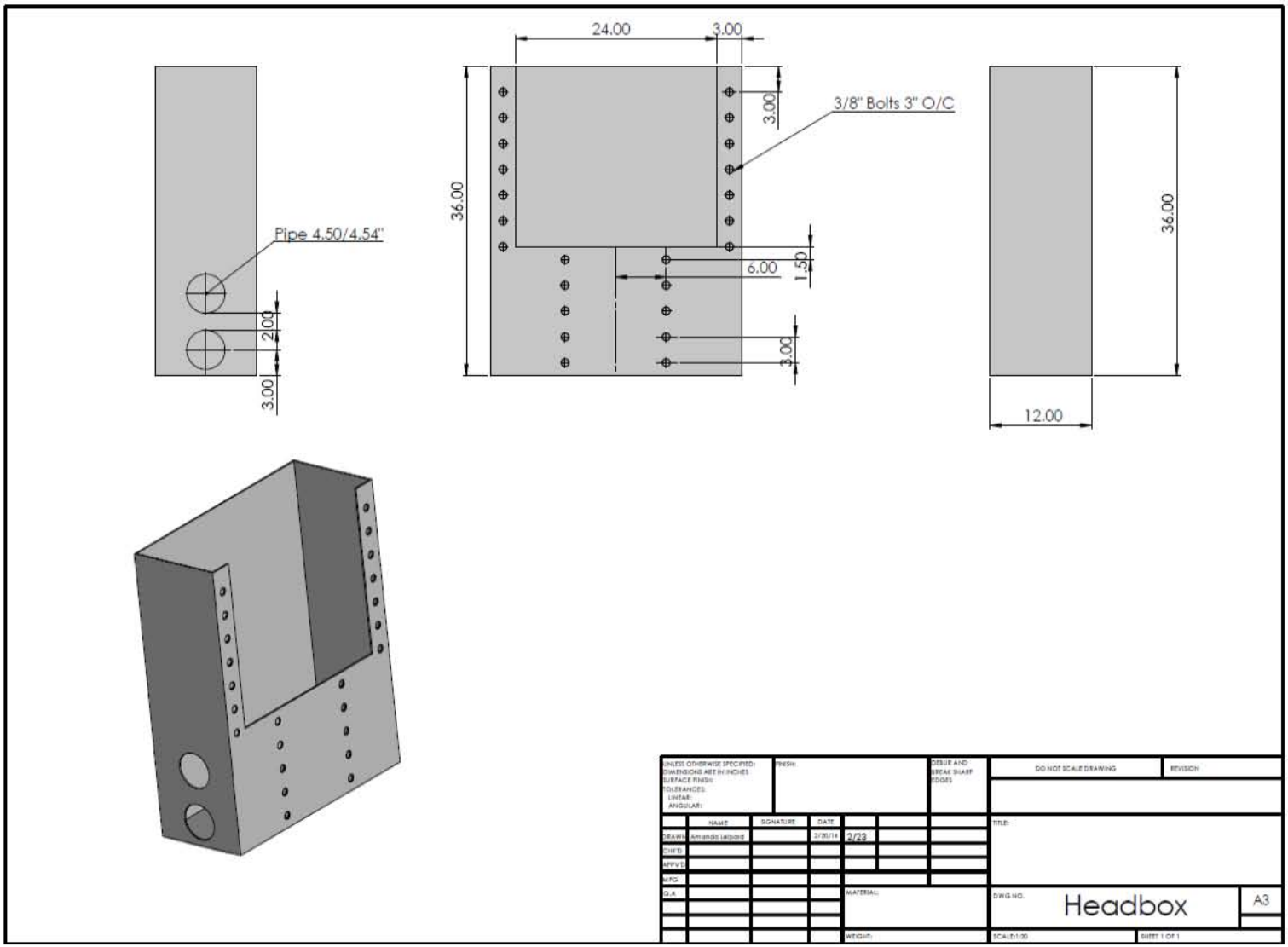


Figure 8 – Bent Sheet Metal Headbox Drawing

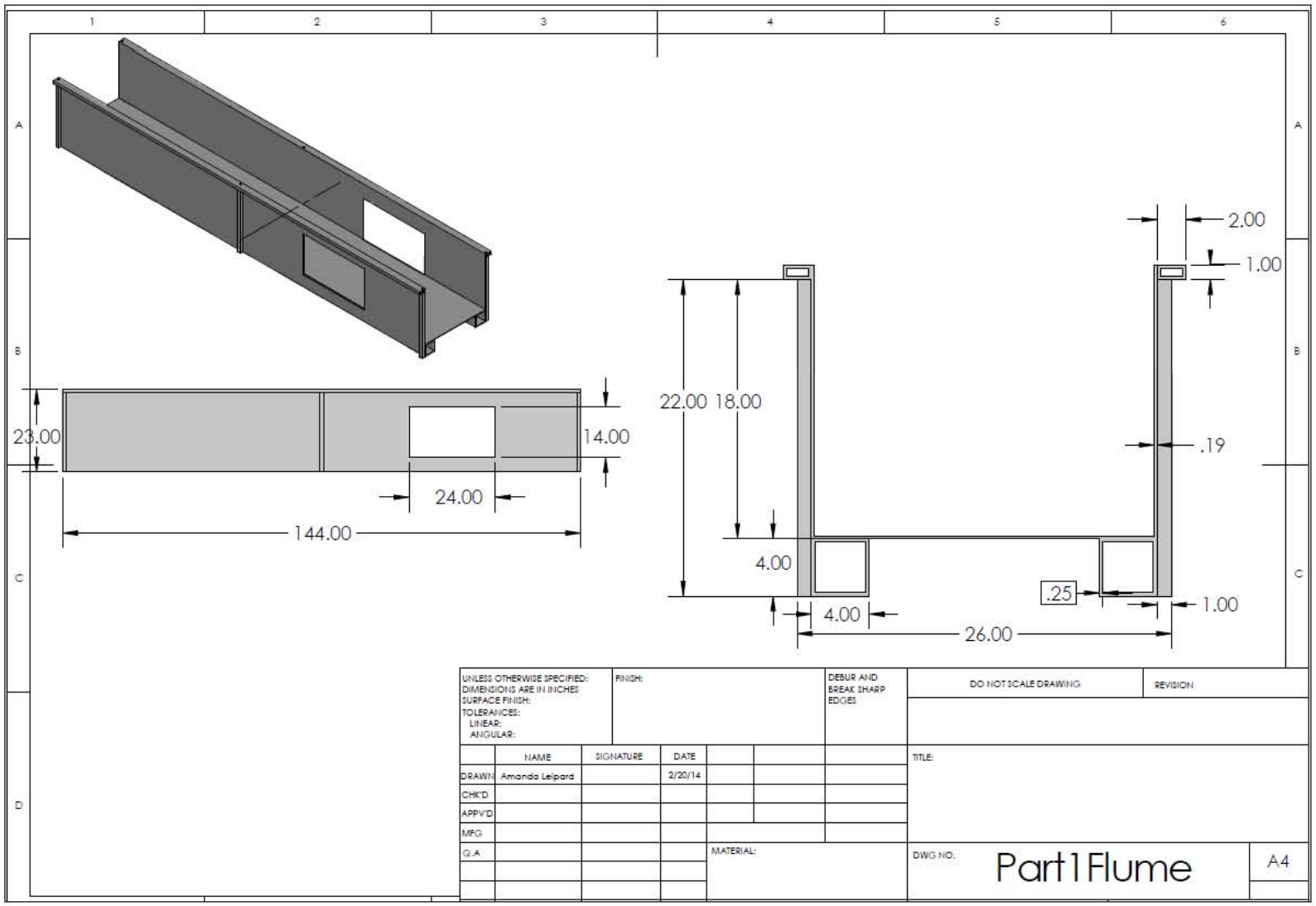


Figure 9 – Base Layer Part 1 Flume Drawing

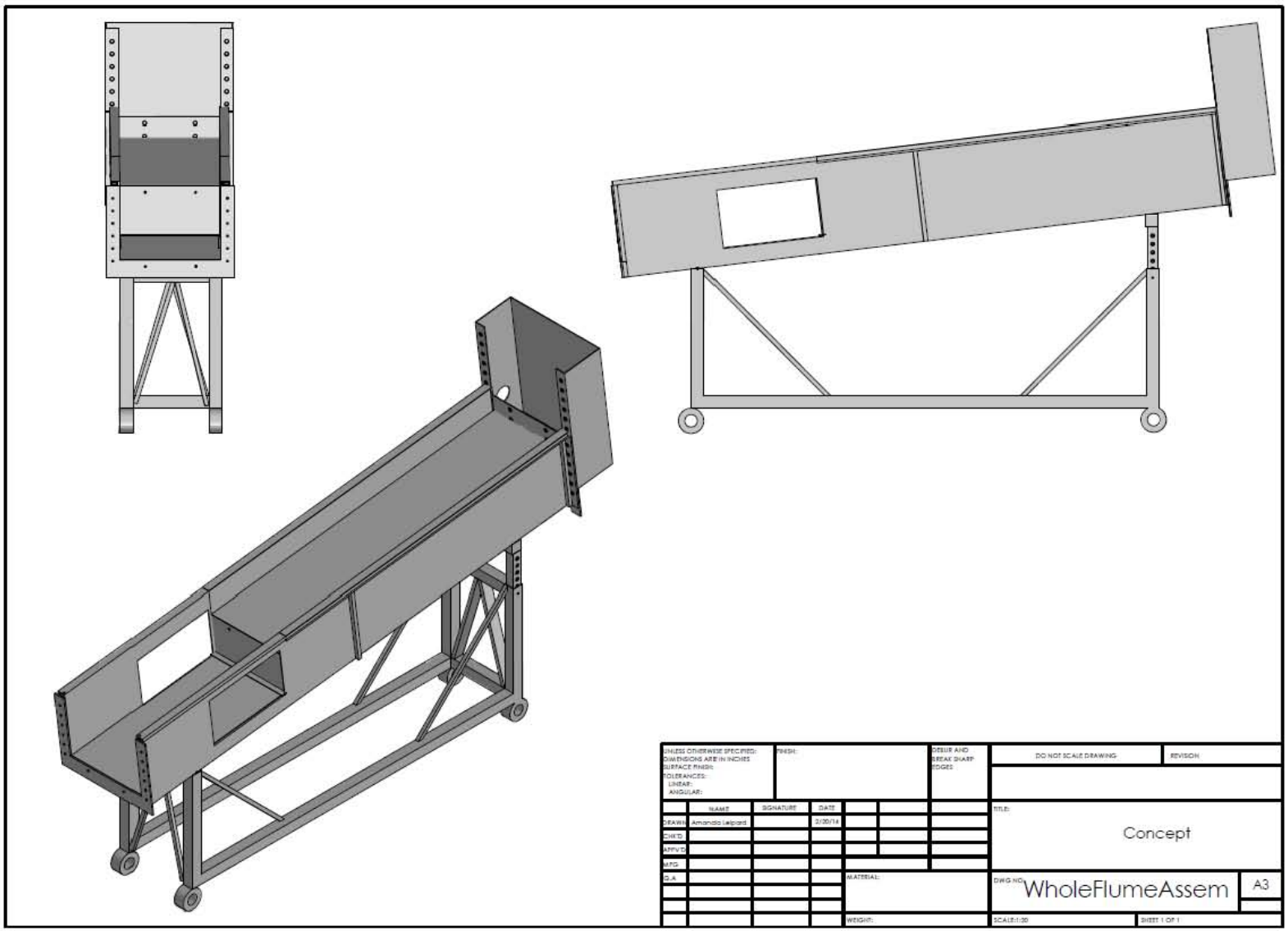


Figure 10 – Whole Flume Assembly Drawing Including Top Layer Insert

Figure 11 displays the directional flow of water through the pumping circulatory system. The tank was filled and holds an initial amount of water that was pumped through the Venturi meter where the initial total discharge (Qin) was measured. The discharge then flows through the head box of the flume to the upper level of the flume. The discharge flow than moves across the pavement section where the vertical discharge split occurs allowing for the water to either infiltrate or overflow across the test section. The end boxes are then used to retain and split horizontally the discharge flow. The V notch weirs were used to measure the infiltration (Q infiltration) and overflow rates (Q overflow). The infiltration and overflow flow rates when added together calculate the total flow out of the system (Q out).

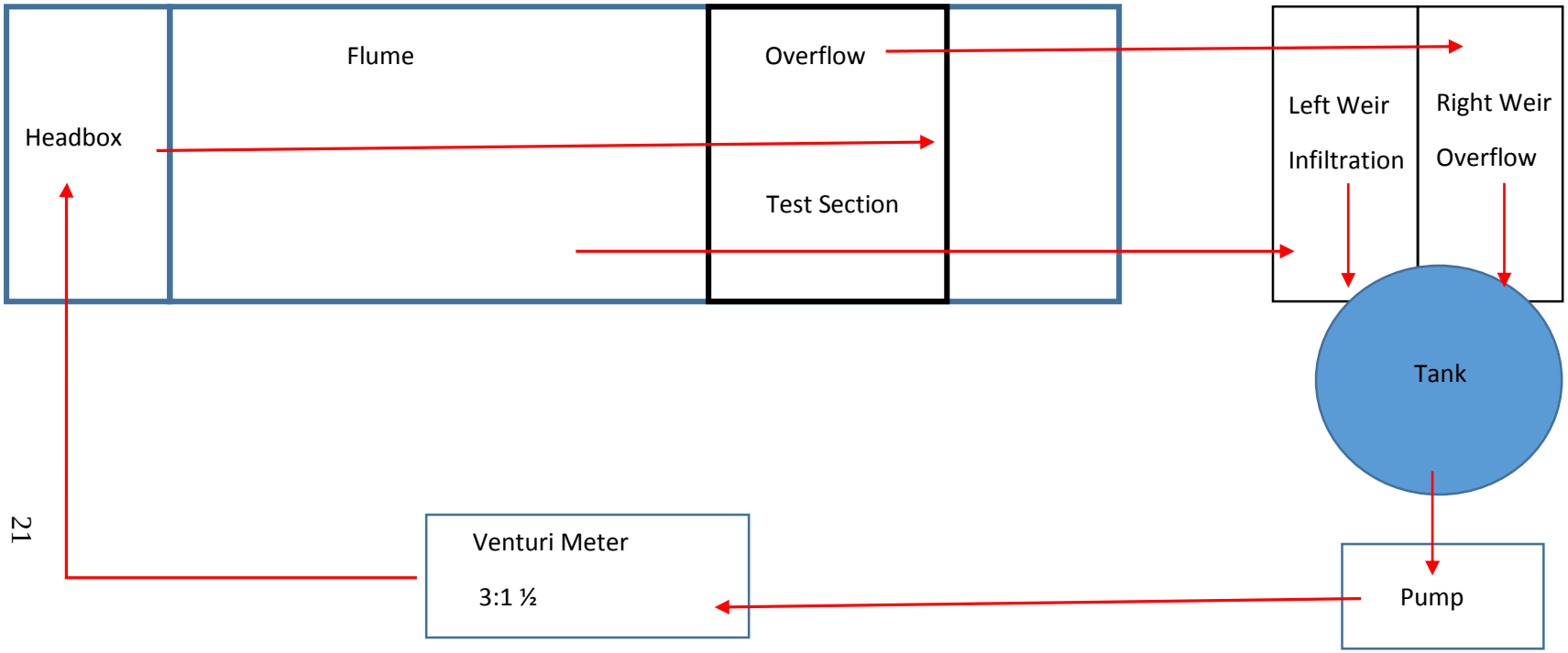


Figure 11 – Whole Laboratory Setup and Circulatory Pumping System

The two layer hydraulic Flume was used to analyze hydraulic flow across the test sections at different slopes and flow rates. The flow into the system ($Q_{total\ in}$) was measured via a Venturi meter and flow was measured out of the system by horizontally split V notch weirs. Figure 12 below displays the actual laboratory setup with the separated vertical and horizontal flow.

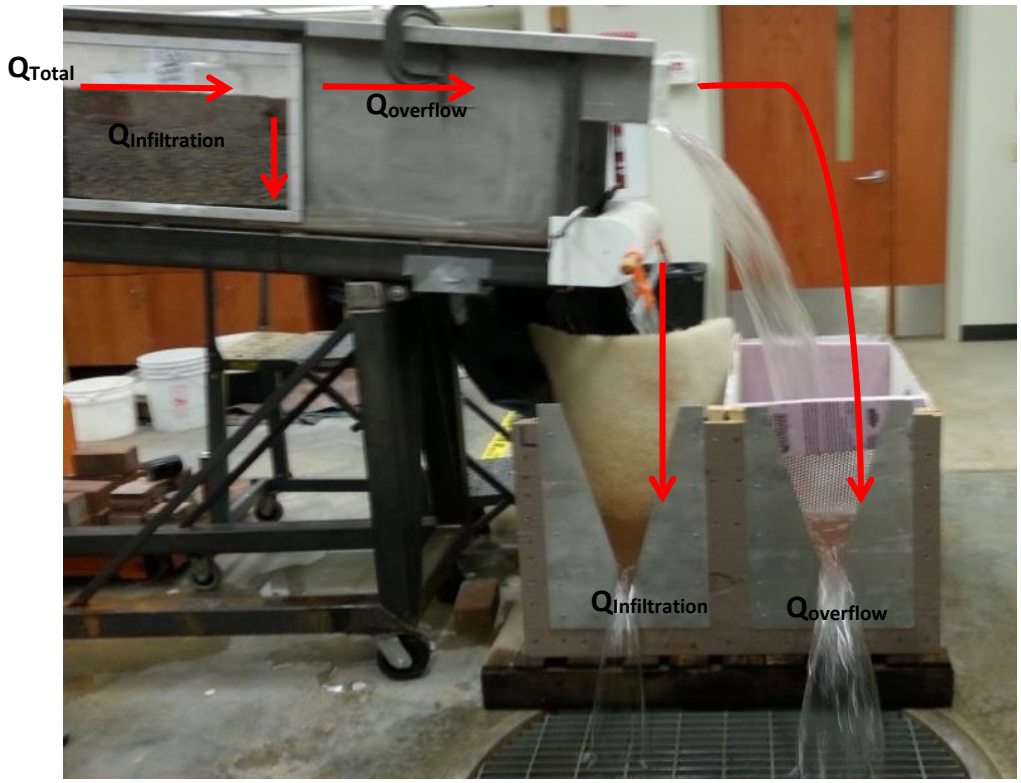


Figure 12 – Completed two layer Hydraulic Flume.

The PICP system was hand placed within the flume. The two layer flume allowed for a changeable section length allowing for experimental variability if necessary. Figure 13 displays the set experimental set up with discharge shown overflowing the test section. Sides were sealed with standard plumbers putty or other sealant materials. For proper hydraulic measurements and horizontal discharge over the test sections upstream supercritical sheet

flow was necessary. The flume was designed for 8 feet of stabilized sheet flow. Figure 14 displays the supercritical sheet flow.

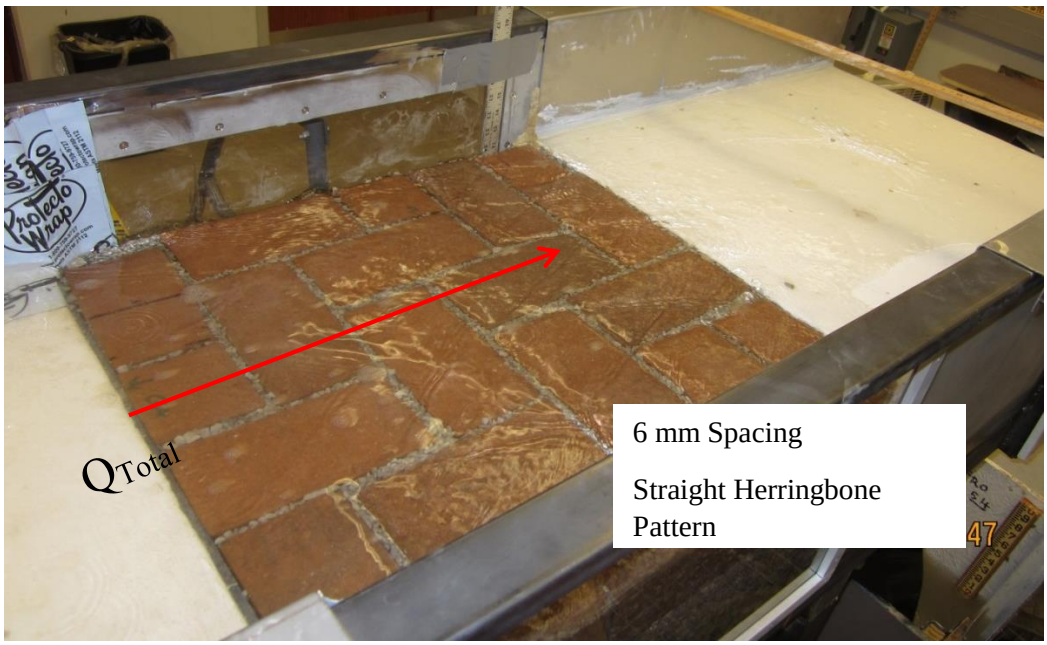


Figure 13 – Experiment Testing Section

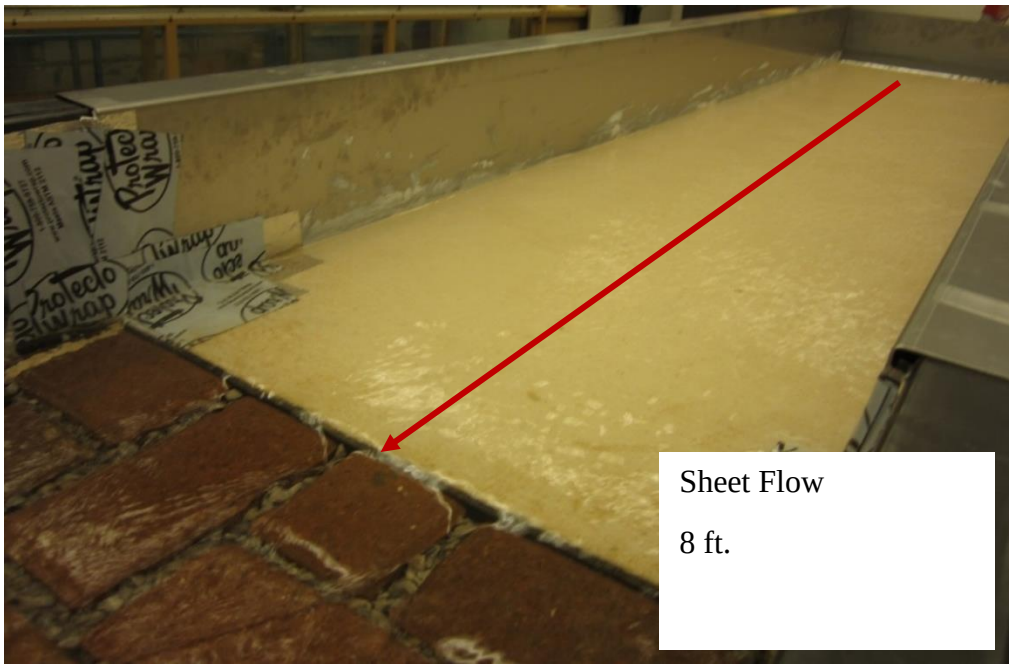


Figure 14 – 8 feet of Horizontal Sheet Flow

A hydraulic jack was used to alter the slope of each experimental section. Each set up was tested at five different slopes 0%, 1%, 2%, 5% and 10%. As previously stated, the flume was designed to maintain 8 feet of horizontal supercritical sheet flow over each of the tests slopes. Figure 15 displays the jacking system used.

Figure 15 – Flume with variable slope and Jacking System

Calibration and Discharge Calculations

The Venturi meter determined the total flow into the system. Figure 16 and 17 displays the Venturi meter. The calculated flow rate for the Venturi was determined by:

Venturi Equation:

$$Q = C_d\sqrt{2gH}$$

Where:

C_d = Calibrated Weir Coefficient

g = gravity, 32.2 ft/s^2

H = Height difference in meter, ft.

Where $H_{in} = H\Delta\ (SG_{merrium} - 1)$ and H_Δ is the height difference of dye in Venturi meter.

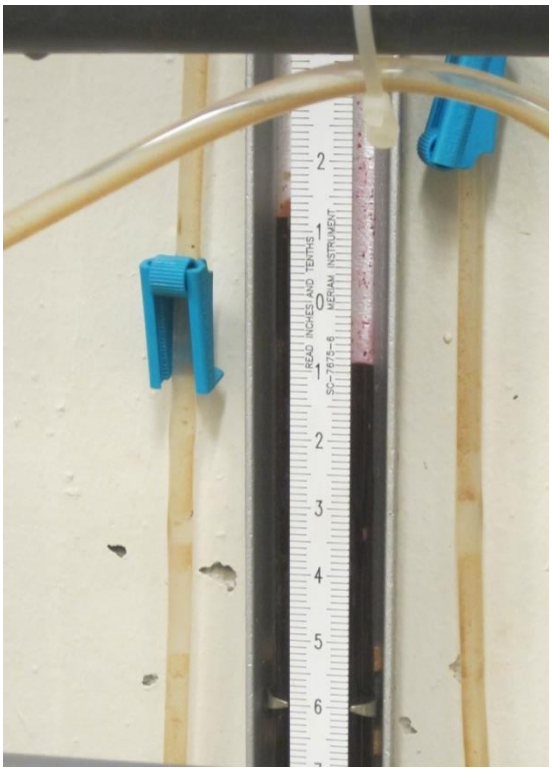


Figure 16 - Venturi Meter Used to Determine Total Flow Rate into the System

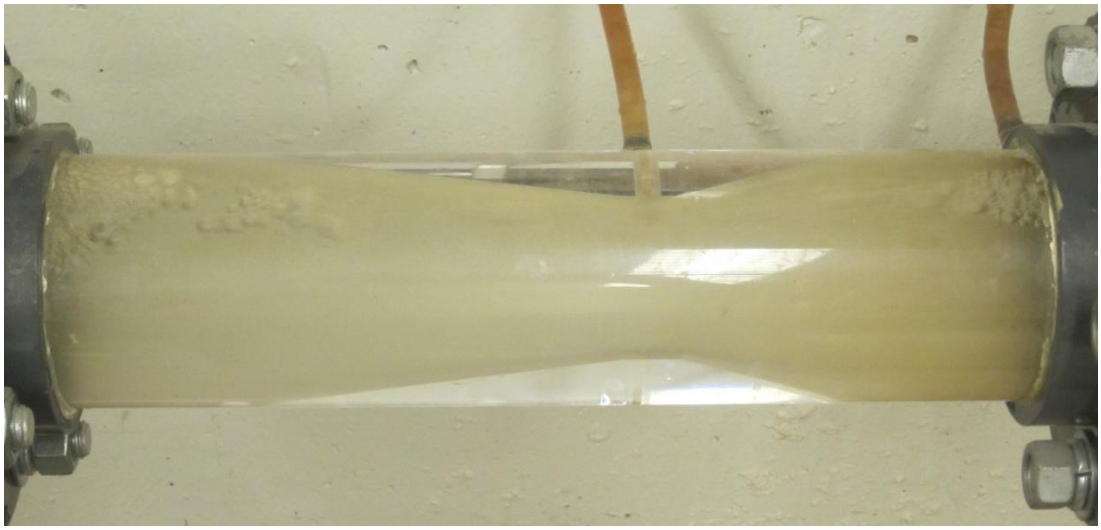


Figure 17 - Venturi Meter

The V notch weirs were constructed from a cut piece of eighth inch thick aluminum metal at 30° degree angle as shown in Figure 18. The use of the V notch weirs were used to determine the infiltration and overflow rate of the experimental sections. The following weir equation was used in determining the required discharge flow rates with a required measured depth of the water upstream of the weirs (H). The individual weir coefficient was a calibrated value for each side of the tail box. For calibration of the weirs a known value of water (Q total in) was ran through the system timed and then weighed. The coefficient of discharge, Cd, was then back calculated with the infiltration coefficient found to be 0.844 and Overflow coefficient at 0.799.

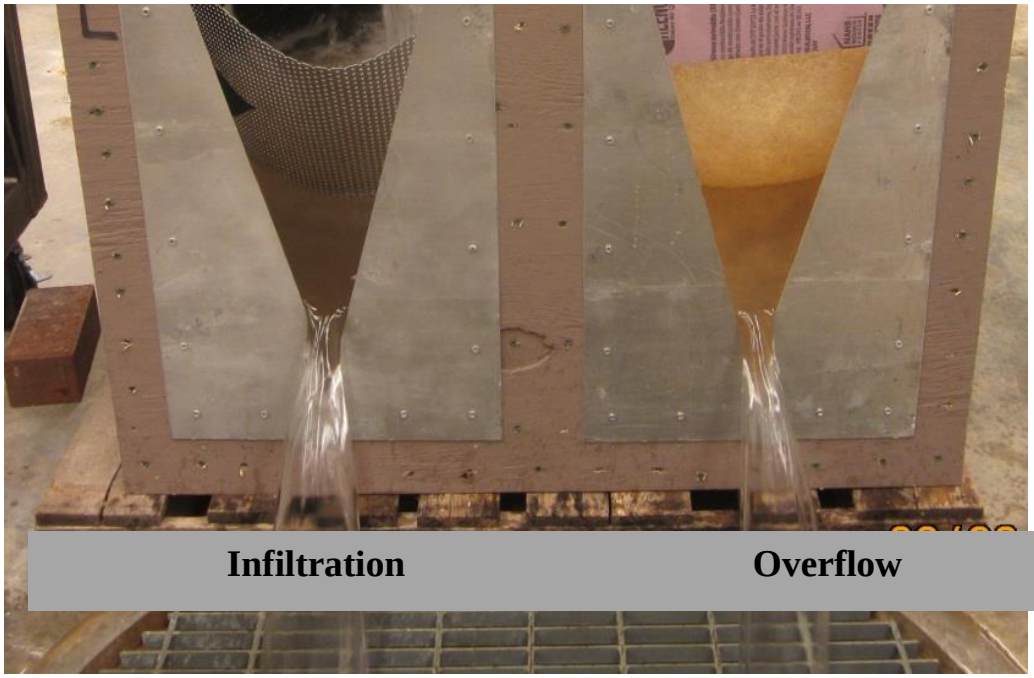


Figure 18 - V Notch Weirs in Tail box

Weir Equation:

$$Q = C_d\sqrt{2gH^{5/2}}$$

Where:

C_d = Calibrated Weir Coefficient

g = gravity, 32.2 ft/s^2

H = water depth prior to weir

The flume was initially calibrated to determine the coefficients of both the Venturi and v-notch weirs. Using the weir and venture meter equations, known area and weir geometry the weirs and meter were calibrated with a known volume. Essentially, as water flowed through the system a known volume was filled and timed providing the measured discharge value, Q in ft^3/s. This value as well as the set known area of the meter and geometry of the weirs the coefficient of discharge was calculated. Thirty tests with readings

for each weirs and the venture meter was completed. The resulting coefficients are seen in Table 1 and Calibration calculations are found in the appendix.

Table 1 - Calibrated Coefficients

Weir	Calibrated Weir Coefficient
Venturi	1.035
Left V-Notch	0.844
Right V-Notch	0.799

Test Section Placement

The 2 ft. by 12 ft. long two layer flume was installed with the various PICP patterns. Each spacing and pattern was cut to fit the 2 foot wide section. The base fill aggregate materials included 7 inches of number 57 rock gradation, 2 inches of number 8 aggregate gradation, followed by the pavers at different spacing with either number 8 or number 9 filler materials. Figure 19 shows the finished flume with the system set up and Figure 20 displays the base materials set within the flume.

Figure 19 – Two Layer Hydraulic Flume

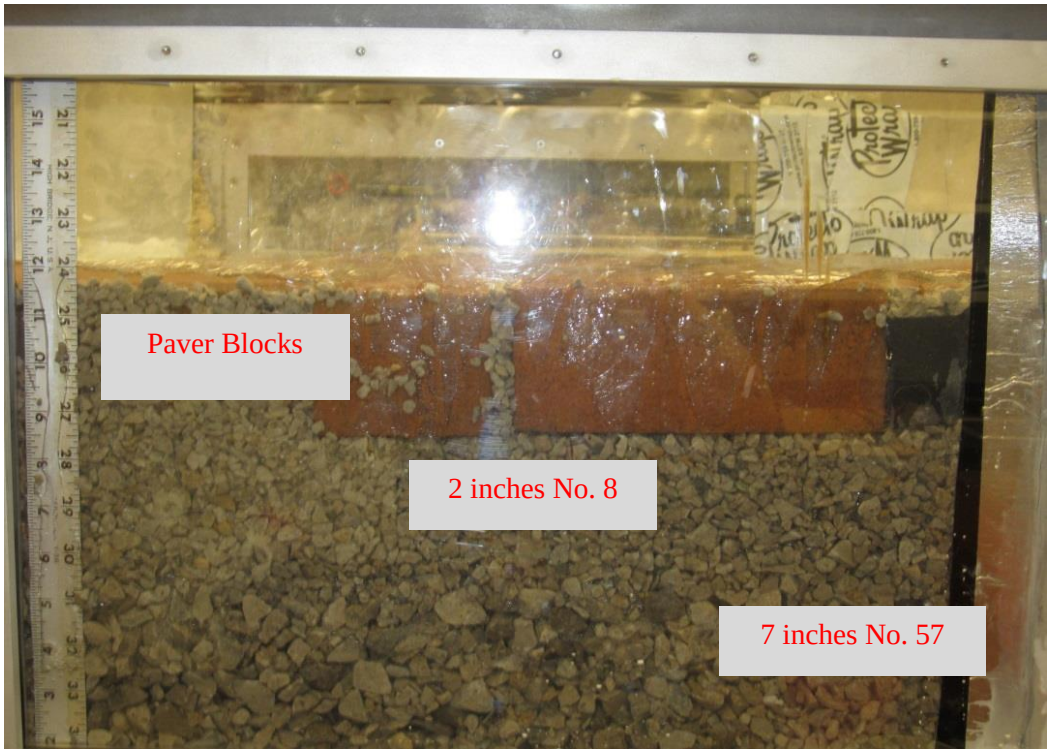


Figure 20 - Aggregate Gradation Set in Flume

Number 8 ASTM Gradation was used as the base layer under the PICP pavers as well as the filler stone material for the 10 mm and 12.5 mm spacing straight herringbone pattern. The number 9 gradation was used as the filler material for the 6 mm straight herringbone pattern and the 6 mm 45 degree herringbone pattern. Generally the gradations were found to be on the lower range for the percent passing and thus had a greater diameter sizing. Each test was had sieved aggregate to ensure the proper range of gradation. An example of batch gradation of each of the filler materials are shown in Figures 21 and 22.

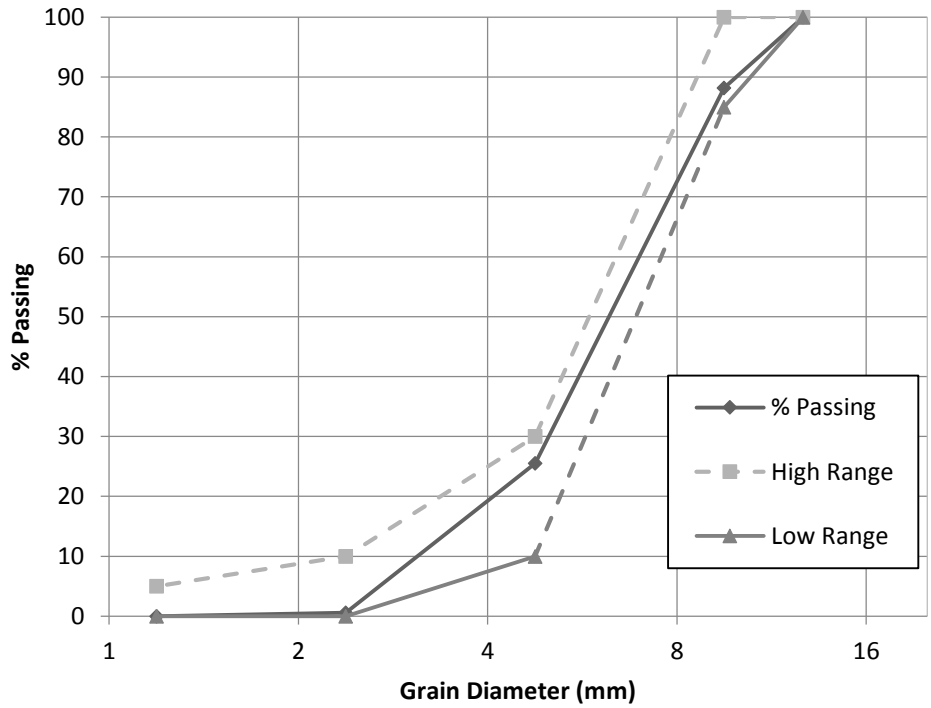


Figure 21 – No. 8 Gradation for Base and 10 mm/12.5 mm Spacing Filler Material

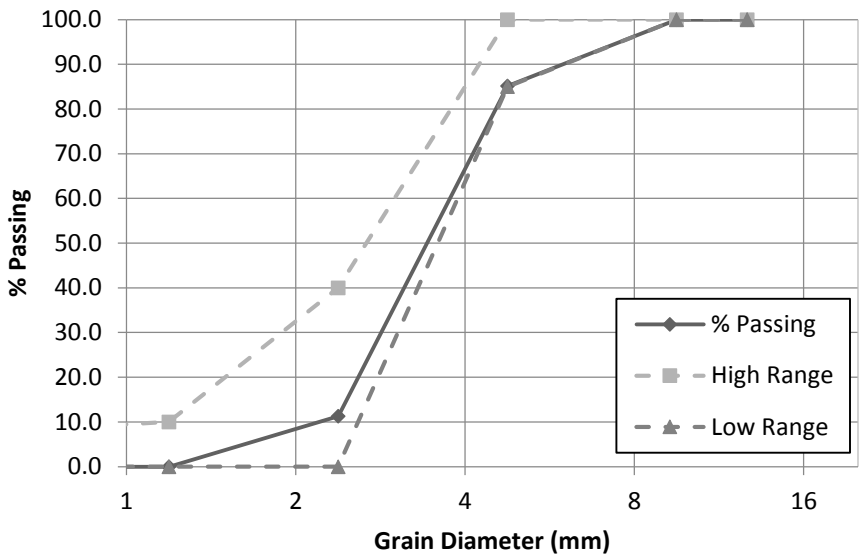


Figure 22 – No. 9 Gradation for 6 mm Spacing Filler Material

Two different patterns were used within experimental testing. Figure 23 displays the straight herringbone pattern and Figure 24 displays the 45 degree herringbone pattern.

Figure 23 – Straight Herringbone Pattern with Horizontal Flow

.

Figure 24 – 45 Degree Herringbone Pattern without Horizontal Flow

The independent variables were the varying degree of spacing or pattern styles between the pavers across various discharge flow measurements. The measured dependent variables were the separated infiltration and over flow rates within the test section at differing degrees of pavement slope. Figure 25 below shows the test section measured dependent variables. Each experiment was completed within 120 minutes with thirty total initial minutes to ensure hydraulic stabilization of the flume.

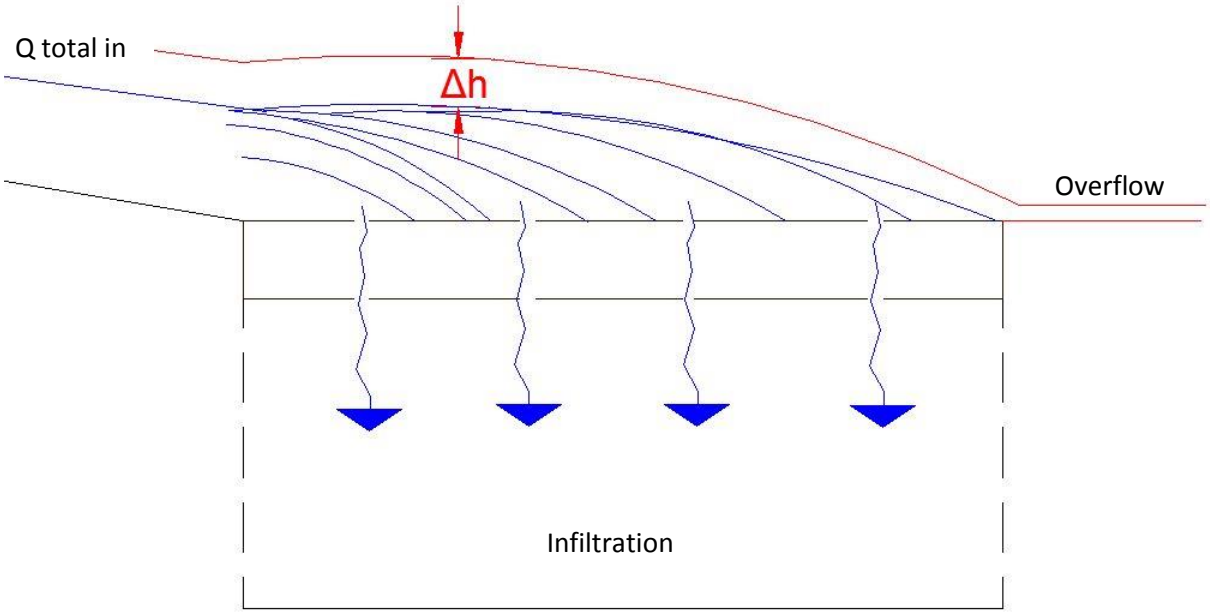


Figure 25 – Test Section Infiltration and Overflow Draw

Test Section Field Calibration

As a result of the literary review local field verification was completed to complete the Flume calibration. In, "Investigation of Hydraulic Capacity and Water Quality Modification of Stormwater by Permeable Interlocking Concrete Pavement (PICP) System," Kim examined field PICP systems (Kim, 2013). The PICP systems in the field are constructed with base conditions that include mechanical compaction of the base layer aggregate, filter fabric as shown in Figure 26, and mechanical compaction of the concrete pavers after installation with additional filler material added. The Kim study reported infiltration rates for no 8 and no 9 filler materials at 398.5 in/hr., 271.4 in/hr. with an approximately 9.0% open area as compared to the experimental open areas of 7%, 11.1%, and 14 % for this study. The water services new parking lot infiltration ranged from 350-408 in/hr.

Figure 26 –Water Services Field Construction

CHAPTER 4

RESULTS AND DISCUSSION UNCLOGGED TESTING

Flow Rate Performance Curves Development

The results presented within this chapter are for the hydraulic response for unclogged permeable interlocking concrete pavements (PICP) for the straight herringbone pattern. Three sections at filler spacings 6 mm, 10 mm, and 12.5 mm were tested at five different cross slopes. Figure 27 displays a typical performance curve. Results indicate that as the flow rate increase infiltration increases until overflow occurs. A small increase in the infiltration was observed as the flow depth increases as well as the overflow flow rate was shown to steadily increase.

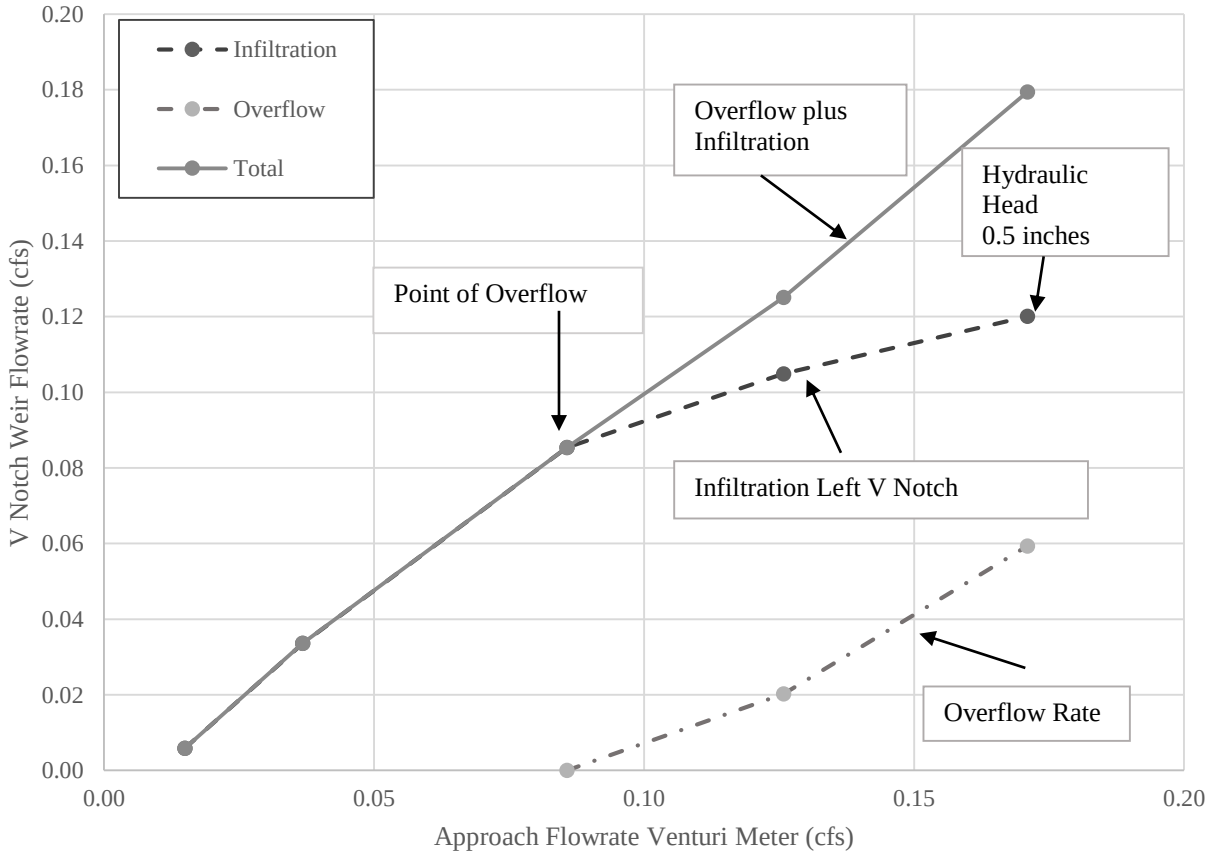


Figure 27 – Typical Performance Curve Explanation

A performance curve was plotted for each block spacing, slope, and average for a total of eighty performance curves. Each spacing across all of the pavement slopes had at least 3 individual experiments were completed for 55 total experiments. Performance curves were similar and Figures 28-30 represent the average curves for three PICP spacings at the 0 % cross slope. The point of overflow shown in figure 27 displays the value determined to be the incipient overflow value. The overflow point was defined at the maximum amount of flow that will infiltrate the section prior to water overflowing the test section.

The performance curves shown in Figures 28-30 indicate that as the block spacings were increased (void rate increased) the infiltration increases as expected. Results also indicate that at the higher block spacings the infiltration increases and obtains a much greater over flow point.

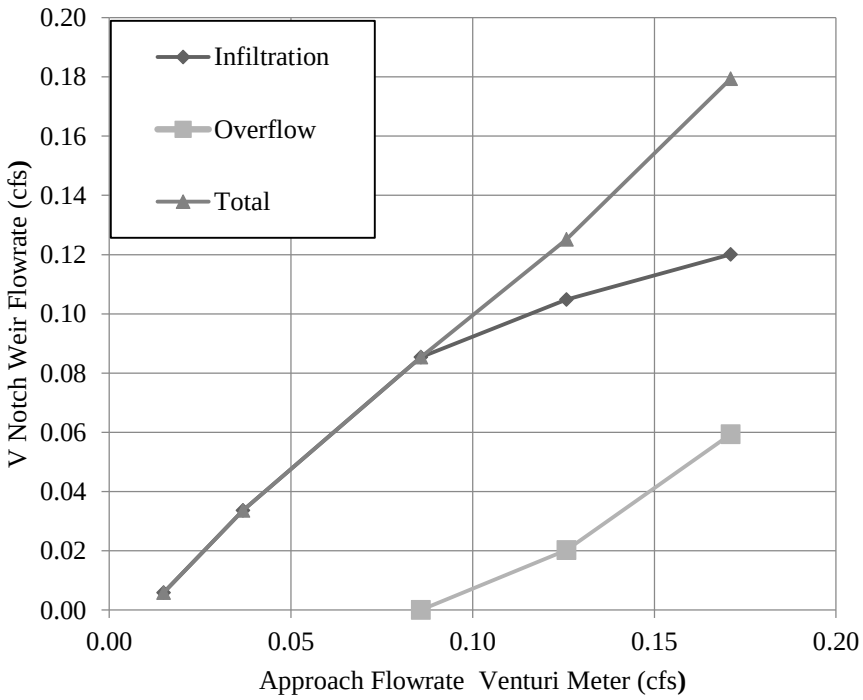


Figure 28 – Performance Curve 6 mm Spacing 0 % Slope

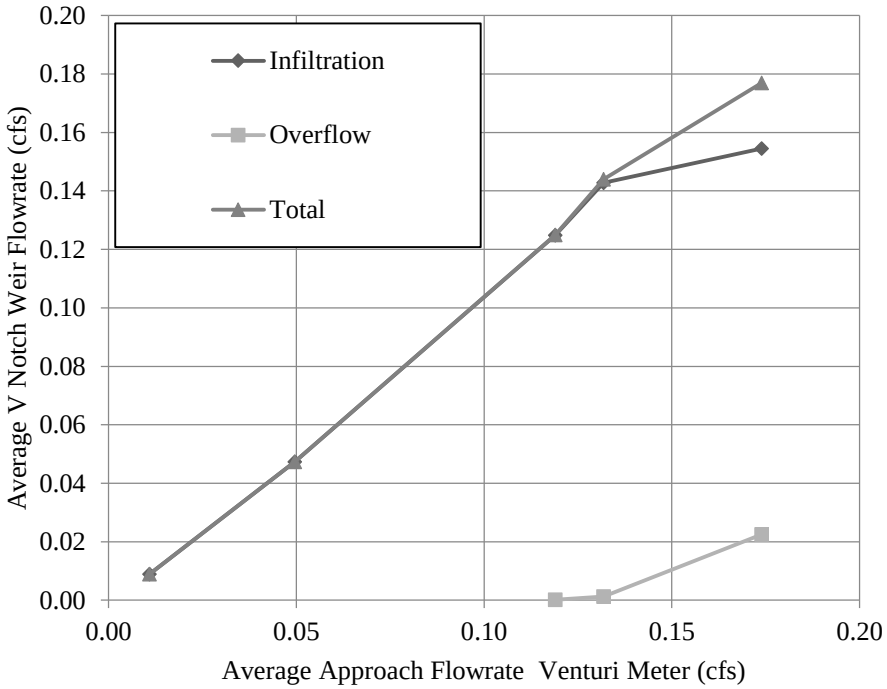


Figure 29 – Performance Curve 10 mm Spacing 0 % Slope

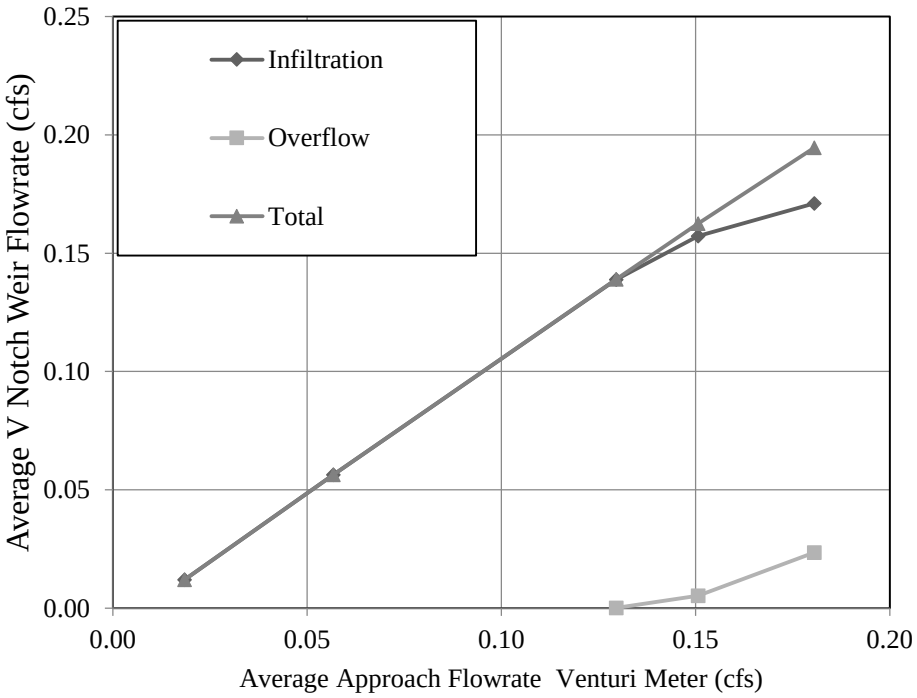


Figure 30 – Performance Curve 12.5 mm Spacing 0 % Slope

The average maximum over flow discharge rates per pavement slope for each of the PICP spacing are shown in Table 2 and Figure 31.

Table 2 –Average Max Overflow Rates per Pavement Cross Slope

Spacing	Pavement Cross Slope				
	0 %	1%	2%	5%	10 %
	Overflow Rates, cfs				
6 mm	0.090	0.079	0.074	0.067	0.061
10 mm	0.125	0.133	0.135	0.135	0.138
12.5 mm	0.139	0.140	0.140	0.139	0.138

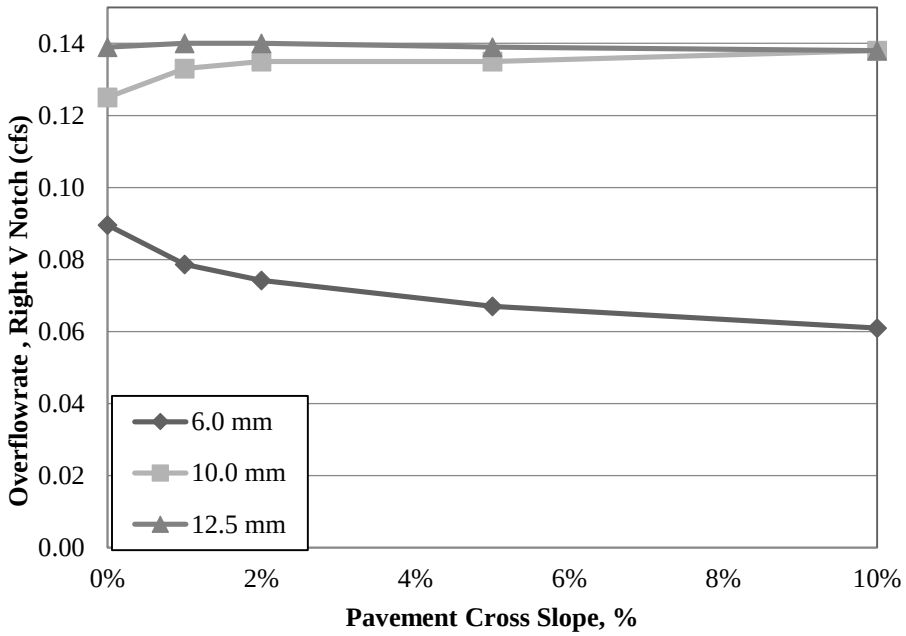


Figure 31 – Average Max Overflow Rates per Pavement Slope

The maximum infiltration rates displayed show an increase from 0 % to 1 % cross slope with the greatest increase shown for the 6 mm spacing. The infiltration rates also either flatten out or decrease as pavement slope increases suggesting that an optimum pavement slope might occur around the 1-2% slope range.

Incipient Overflow Rate

Performance curves were also used to determine the maximum overflow rate by a linear regression of the overflow data as shown in Figure 32. The equation from the overflow trend line was used to calculate the point where overflow initially began (x-axis intercept). The calculated maximum overflow rates are shown in Table 3. The data indicates that as spacing size was increased the maximum infiltration rate at overflow increased, as expected.

Table 3 –Calculated Maximum Overflow Rates per Pavement Cross Slope

Slope	Block Spacing		
	6 mm	10 mm	12.5 mm
	In/hr.		
0%	937	1331	1353
1%	823	1286	1298
2%	777	1315	1327
5%	722	1301	1250
10%	670	1350	1210

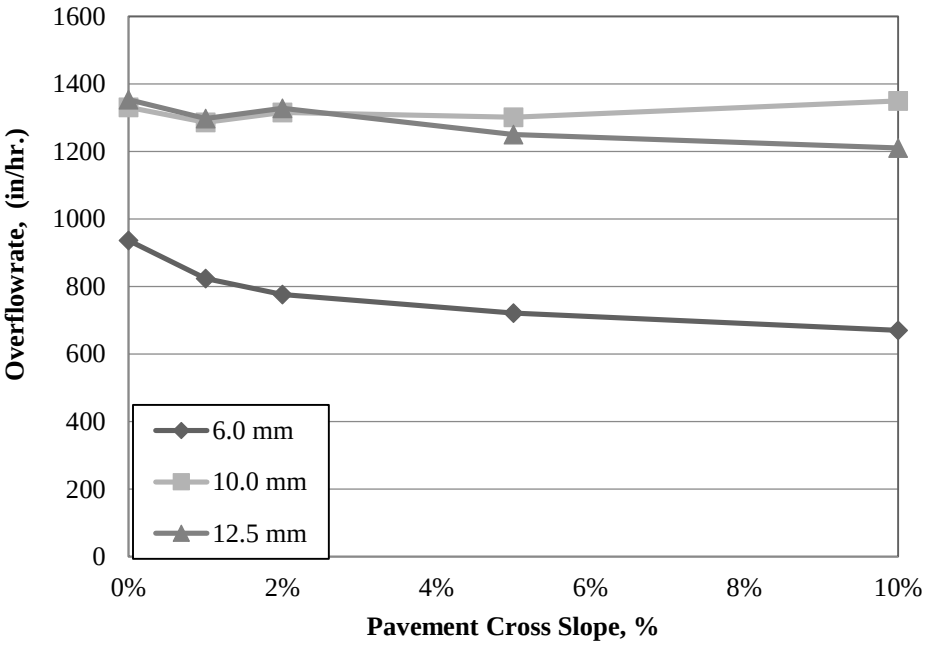


Figure 32 – Average Incipient Overflow Rates per Pavement Slope

Infiltration

The current standard to measure pavement infiltration flow rates does not include supercritical horizontal sheet flow. The current standard utilizes the vertical infiltration test defined by the ASTM C 1781 standard (ASTM, 2013). ASTM C 1781 is completed by using a set specified amount of water and determining the time the water takes to infiltrate through the section (ASTM, 2013). The procedure utilizes a constant head method where five gallons of water is poured at a constant rate into a specified set area (ring). This infiltration equation per ASTM C1781 was given as follows:

$$I = \frac{KM}{D^2 t}$$

Where:

I = infiltration rate in/hr

K = dimensional constant, in-Ibs.

M= mass of water, Ibs.

D= diameter of infiltration ring, in.

T= time measured, seconds.

Figure 33 displays the predefined area and Table 4 displays the results at each of the patterns and spacings.

Figure 33 – Vertical Infiltration C 1781 Test

Table 4 – C 1781 Average Vertical Infiltration, in/hr., Before Horizontal Test

Pavement Slope	6 mm, in/hr.	10 mm, in/hr.	12.5 mm, in/hr.
0 %	1077	1505	2012
1%	1088	1558	2345
2%	1226	1628	2532
5%	1140	1514	2505
10%	1115	1495	2439

Figure 34 displays the results of the vertical infiltration vs. pavement slope. The results indicate that as the PICP block spacing decreases the vertical infiltration increases.

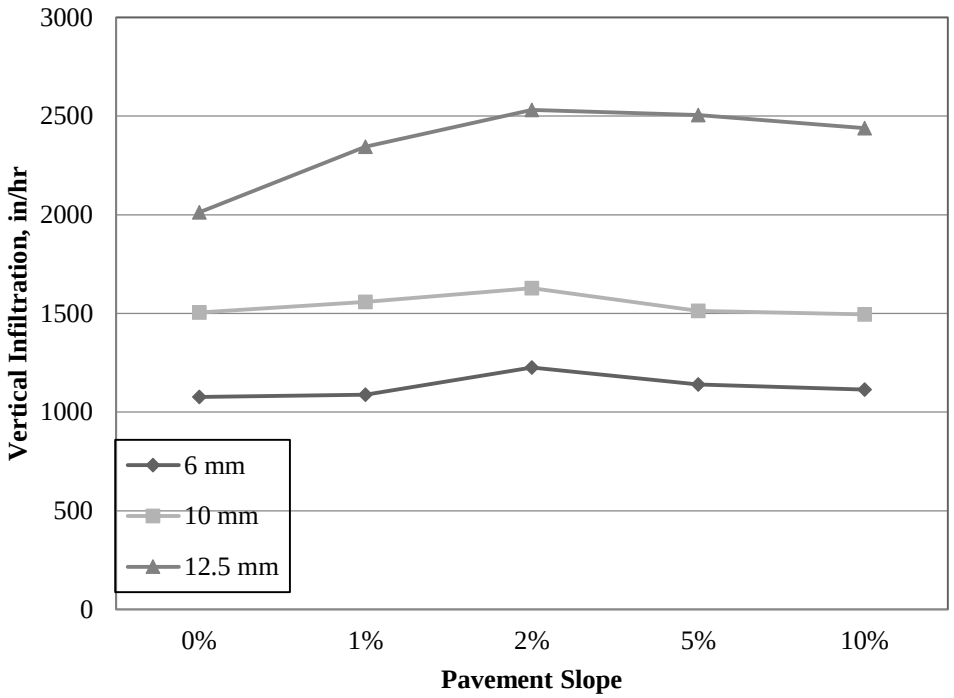


Figure 34 – Vertical Infiltration C 1781 vs. Pavement Slope for Each PICP Spacing

Horizontal infiltration rates were converted from the effective intensity values by a unit transformation by multiplying the intensity values from 43,200(3600 seconds per 1 hour multiplied by 12 inches per foot).The infiltration rates at the incipient overflow point for each of the spaces are displayed in Table 5 below. Figure 35 displays the horizontal infiltration values across each of the studied PICP spacing plotted against the vertical infiltration C 1781 values for each pavement cross slope. The results indicate that as slope increases the infiltration decreases additional statistical analyses of infiltration verses the pavement slope is included in Chapter 5.

Table 5 – Horizontal Infiltration (Regression) for Each PICP Spacings

Spacing	Horizontal Infiltration Per Pavement Slope (In. /hr.)				
	0 %	1%	2%	5%	10 %
6	893	832	748	704	643
10	1348	1434	1460	1460	1487
12.5	1412	1424	1412	1399	1399

Figure 35 also indicates that as the spacing sizes increase infiltration either within the vertical or horizontal increase. The displacement between the 6 mm and the 12.5 mm spacing was shown to be approximately 1000 in/hr. different regardless of pavement slope. The values of the infiltration also slightly decrease and level off as the pavement slope increases suggesting that the PICP system is perhaps more efficient at a lower pavement slope and perhaps most efficient at a 1-2% pavement slope, in particular for the 6 mm spacing. A less affect was shown for the 12.5 mm spacing on the pavement slope and block spacing sizes.

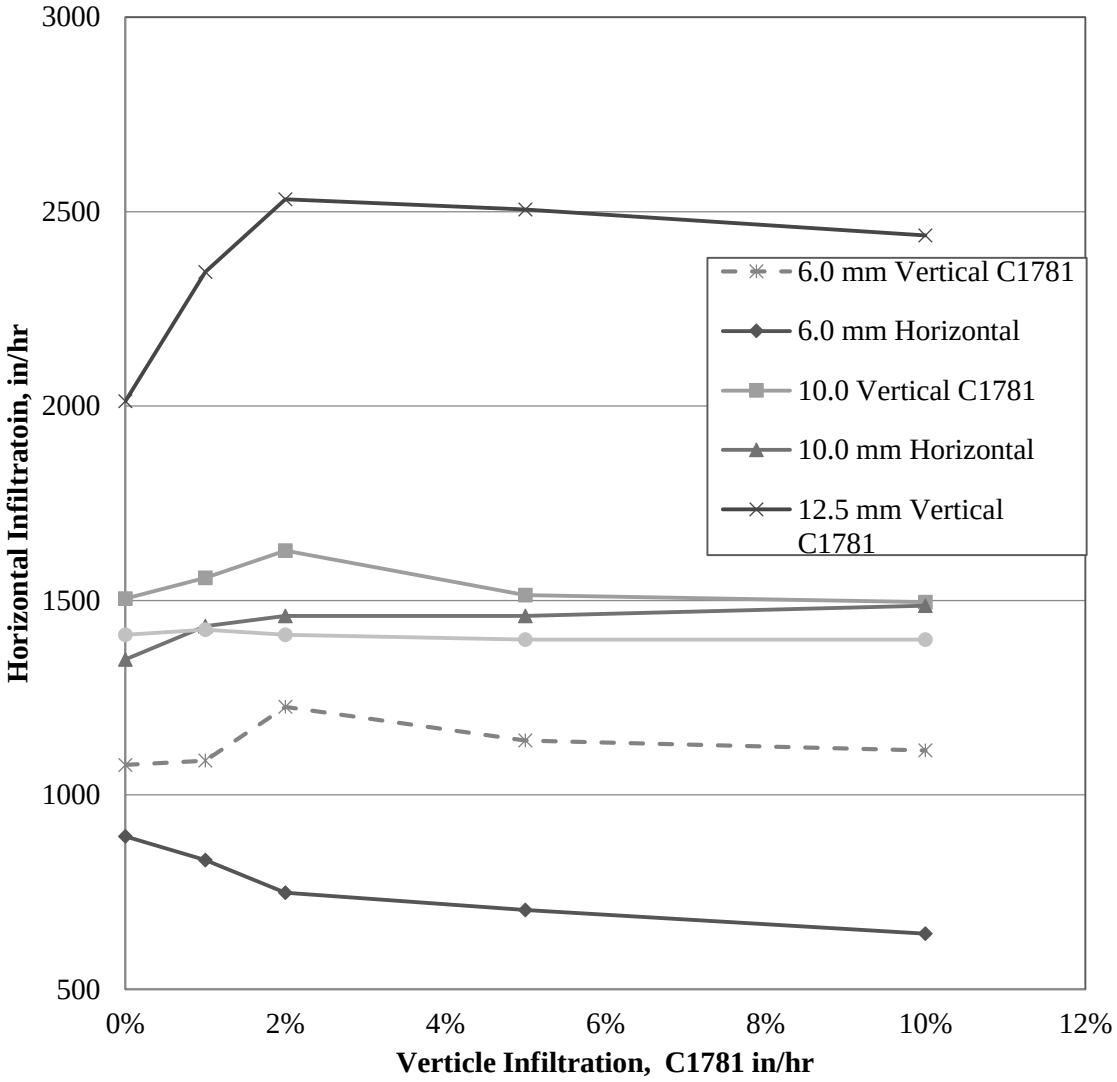


Figure 35 – Vertical Infiltration and Horizontal Infiltration across Pavement Slopes

Figure 36 displays the averaged linear regressed horizontal infiltration rates per pavement slope. Results indicate that as spacings increase infiltration increased and that as pavement slope increases past 2% infiltration rates decreased. It should be noted that both of the C 1781 vertical infiltration and horizontal infiltration rates indicate the same pavement slope and spacing trend. It was also found that horizontal infiltration was lower than the C1781 infiltration rates.

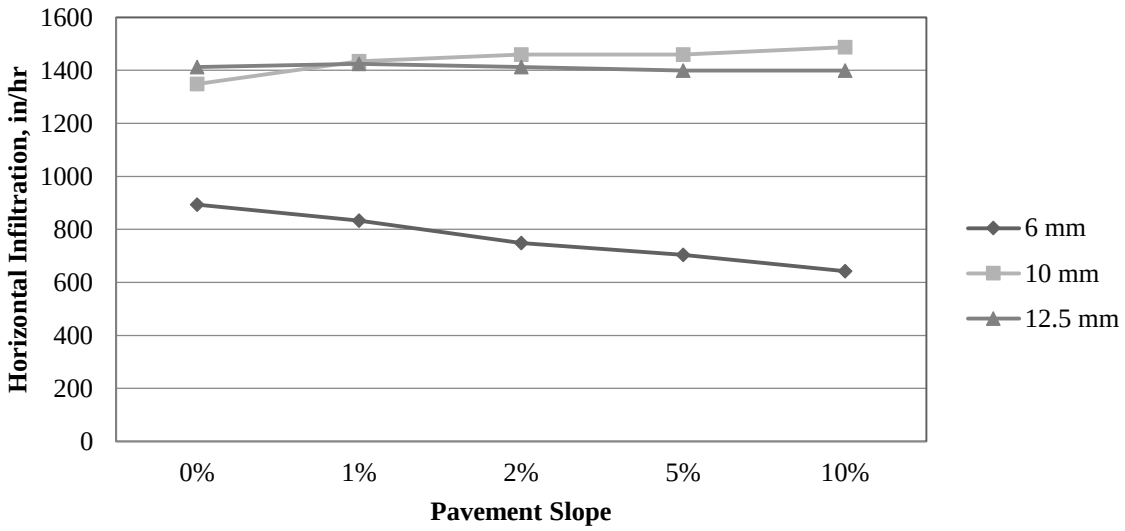


Figure 36 –Horizontal Infiltration across Pavement Slopes

The water services field observation (field calibration see the end of Chapter 3) was conducted on a 6 mm straight herringbone pattern in a parking lot section of the new development and the values were found to be 369 in/hr. The construction differences from the experimental study and field are cited as the probable cause for the differing data. Previous research indicates that field conditions, which include mechanical compaction, display a decrease in hydraulic conductivity of porous pavements (McCain, 2010) compared to laboratory testing. The calibrated experimental vertical data is shown in Table 6.

Table 6 – C 1781 Experimental and Calibrated Vertical Infiltration

	Infiltration Values per PICP Spacing, in/hr.					
Pavement Slope	6 mm	6 mm Calibrated	10 mm	10 mm Calibrated	12.5 mm	12.5 mm Calibrated
0 %	1077	359	1505	502	2012	671
1%	1088	363	1558	519	2345	782
2%	1226	409	1628	543	2532	844
5%	1140	380	1514	505	2505	835
10%	1115	372	1495	498	2439	813

Figures 37 shows the Kansas City Missouri Water Services Departments' new parking lot and construction of the parking lot. The site includes the herringbone pattern at the 6 mm spacing as shown if Figure 38.

Figure 37 –Water Services Field Construction

Figure 38 –Water Services Vertical Test and Pavement 6 mm Straight herringbone

Pattern and Validation Testing

A validation test was performed to determine test variation after a new pump was installed and after an inactive testing period of several months occurred. The validation test was completed on the 6 mm spacing regular pattern as this pattern appeared to be the most sensitive within the research experiments. In addition to the validation experiment a 6 mm 45 degree herringbone pattern experiment was completed and analyzed. Figures 39 and 40 display the difference between the patterns.

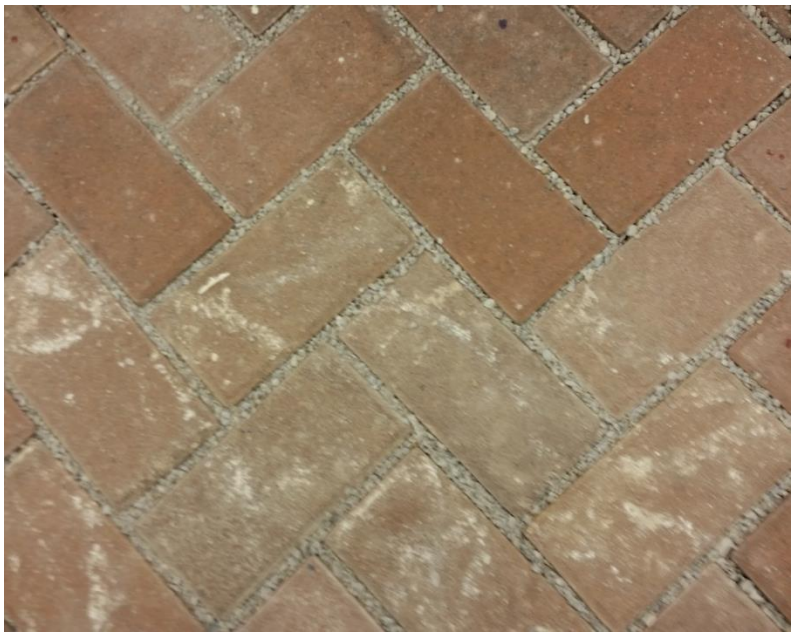


Figure 39 – 45 Degree Herringbone Pattern 6 mm Spacing

Figure 40 –Straight herringbone Pattern 6 mm Spacing

Infiltration Rate at Overflow Point Comparison

Table 7 and Figure 41 displays the infiltration rates at overflow per section area for each of the three experimental groups. These values are the values also used in statistical comparison.

Table 7 – Infiltration Rate at Overflow per Section Area per Group, cfs/section area.

Slope	Herringbone Pattern	Validation	Average Straight herringbone
		Flow Rate, cfs	
0.00%	0.016	0.018	0.021
1.00%	0.015	0.016	0.022
2.00%	0.015	0.016	0.017
5.00%	0.014	0.015	0.016
10.00%	0.014	0.016	0.015

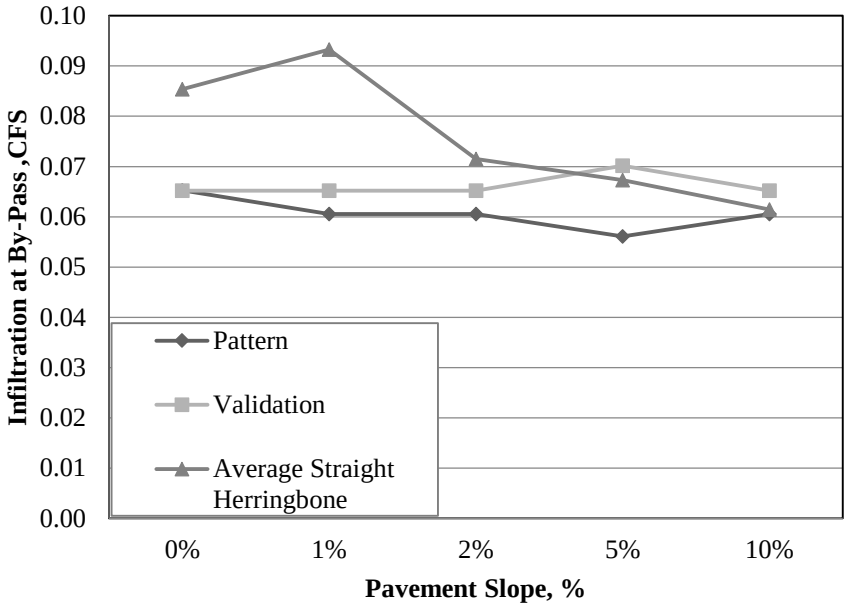


Figure 41 –Comparison of Infiltration at Overflow, cfs/area

The graphed results above indicate that the 45 degree herringbone pattern appears to be lower than the straight herringbone tests while the validation test appears to be inconclusive. As such, statistical analysis was completed on the values to determine differences between the groups. For such analyses the raw data values as well as the effective intensity values for the experiments were used. Table 8 displays an example of the raw data for the 0 % slope for the 45 degree herringbone pattern. Each slope was included within the analysis.

Table 8 –Example of Raw Data Values Used in Statistical Analysis

45 degree Herringbone Pattern				
Slope	Q in Total	Overflow	Infiltration	Q Out Total
		Discharge Rates, cfs		
0%	0.013	0	0.0133	0.013
	0.034	0	0.0334	0.033
	0.064	0.00001	0.0652	0.065
	0.081	0.00558	0.0753	0.081

CHAPTER 5

STATISTICAL ANALYSIS OF UNCLOGGED RESULTS

The main objective of the statistical analysis was to determine similarity of the means within the five experimental groups. Statistical analysis included a One-Way ANOVA to compare the unknown variance (unknown means) of the five experimental group's capture discharge flow rates. The assumed null hypothesis was that all of the means were equal with the alternative hypothesis assumed to be that at least one group mean was different. The statistical significance level used was 0.05 or 5%. A One-Way ANOVA is based on the assumption that the sample populations are normally distributed and as such a comparison to the normal population was included. Each group contained five values of a calculated effective intensity capture discharge flow rate at each of the five pavement slopes: 0%, 1%, 2%, 5% and 10%.

Analyzed Data and Normality Test

The incipient overflow rates (point at which water just begins to overflow the test section) was used as the most sensitive experimental value as described in chapter 5 and was based upon the linearly regressed equation found from the averages. Table 9 displays the incipient overflow rates per group spacing.

Table 9 –Incipient Overflow Rates per Group Spacing, Slope

Spacing	Pavement Cross Slope				
	0 %	1%	2%	5%	10 %
	Overflow Rates, cfs				
6 mm	0.088	0.099	0.074	0.069	0.064
10 mm	0.123	0.119	0.122	0.120	0.123
12.5 mm	0.130	0.129	0.130	0.123	0.118
45 degree Herringbone	0.065	0.061	0.061	0.056	0.061

As the ANOVA and t-tests are based on the assumption of normal distribution an initial normal distribution check was ran on the data sets. Figure 42 displays the results. The data sets appeared to be normally distributed based a p value greater than 0.05 for all groups.

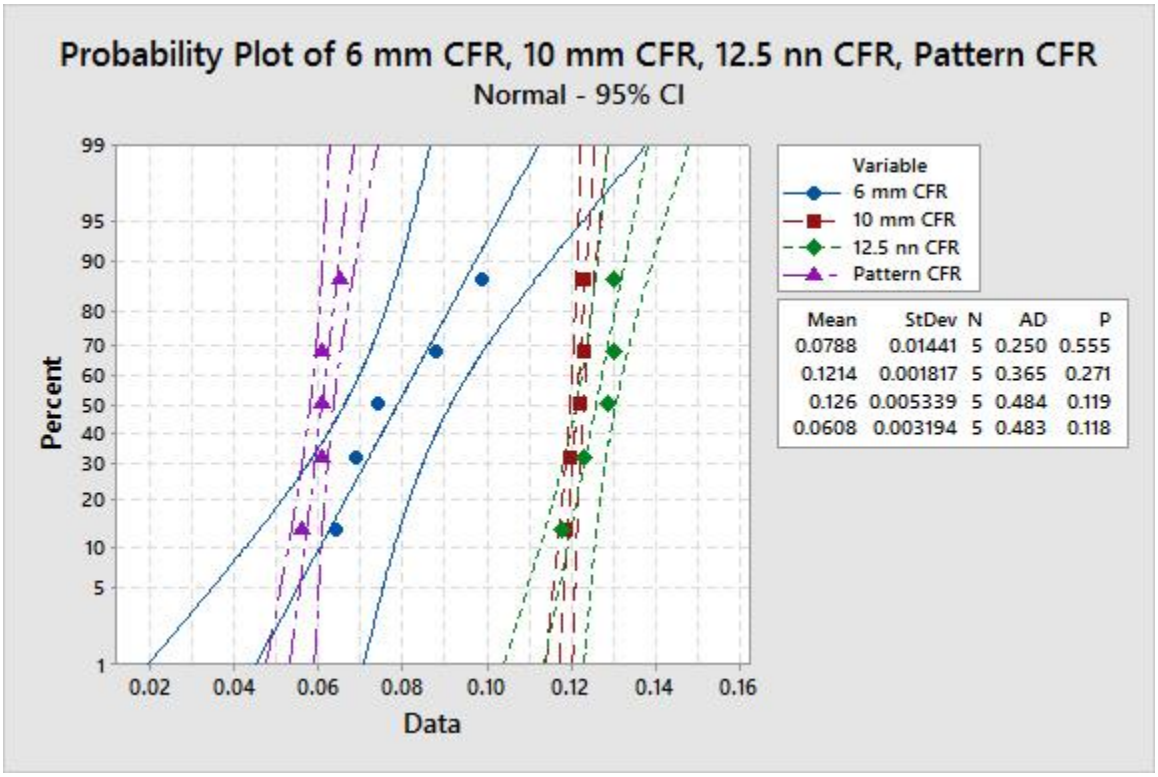


Figure 42 –Normal Probability Check

One-Way ANOVA Results

A One-Way ANOVA to compare the unknown variance (unknown means) of the four experimental groups' effective intensity capture discharge flow rates. The null hypothesis was that all of the means were equal with the alternative hypothesis that at least one group mean was different with a significance level of 0.05 or 5%. Each group contained five values of a calculated capture discharge flow rate at each of the five pavement slopes: 0%, 1%, 2%, 5% and 10%. The interval plot appears to display differences in the means of some of the

groups, particularly the pattern and 6 mm group with the rates from the 10 mm and 12.5 mm groups.

The p-value of 0.000 indicates that the null hypothesis that the means are equal should be rejected and that at least one mean within the group is not equal but is different. The R^2 value of 93.91%, is defined as the fraction of the overall variance resulting from the differences among the group means. A large value indicates that a large fraction of the variation was due to the treatment that defines the groups, in this case the type of spacing between the paver blocks or pattern. Another way of describing the R value is as a descriptive statistic that quantifies the strength of the relationship between groups (6 mm, 10 mm, 12.5 mm, etc.) and the variable measured (effective intensity capture discharge flow rate at overflow). The One-way ANOVA was also run with and without the assumption of equal variances and produced similar results. Tables 10 and 11 summarize the results of the ANOVA analysis.

Table 10 –One Way ANOVA Summary

Standard Deviation	R^2	F –Value	P-Value
0.654	93.91	82.71	0.000

Table 11 –Individual Factor Summary and Confidence Intervals

Group (Factor)	Mean	Standard Deviation	99 % Confidence Interval	
45 degree Herringbone	0.061	0.0039	0.0533	0.06829
6 mm	0.079	0.01441	0.0713	0.08269
10 mm	0.0121	0.00181	0.1139	0.12889
12.5 mm	0.126	0.00543	0.1185	0.13349

Figure 43 displays the box plot of the ANOVA test and indicates that a large difference occurs between the 6 mm spacing and the other spacing sizes. To investigate the differences between the groups individual t tests were conducted.

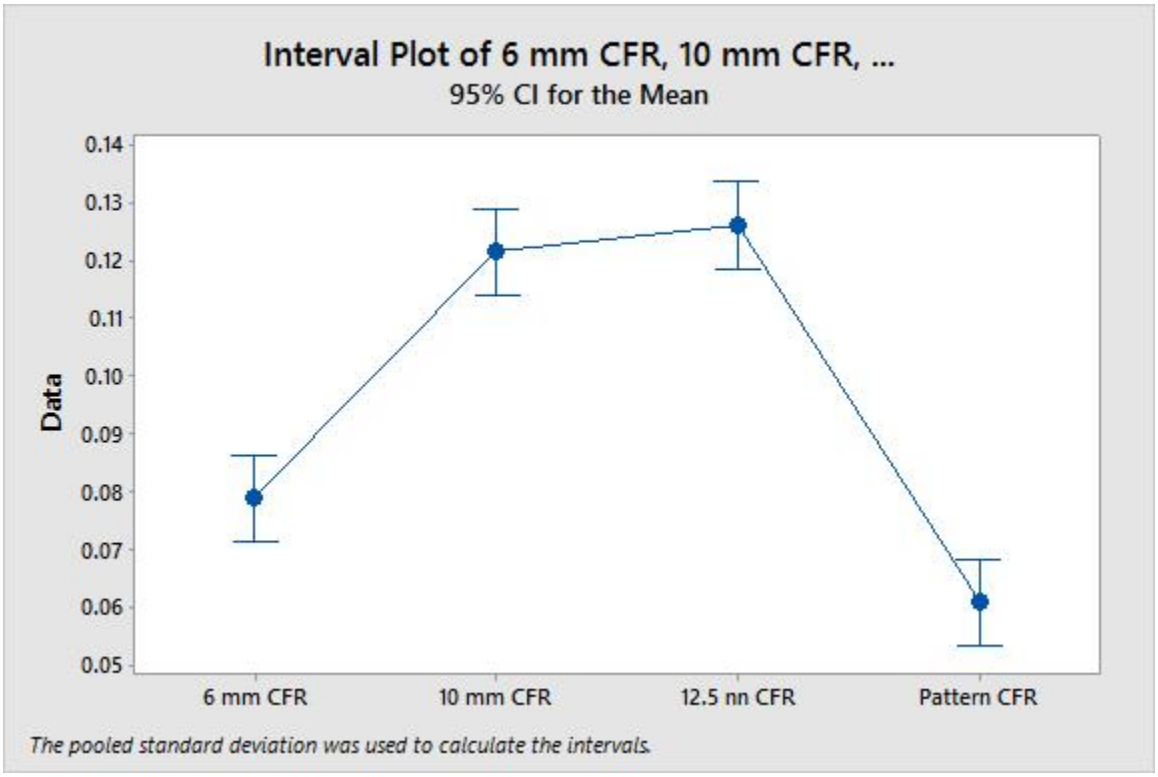


Figure 43 – Interval Plot of ANOVA Groups

T-Test Comparisons

An additional analysis included individual two sample t-tests between the 6 mm spacing group and the 10 mm spacing groups. Infiltration, incipient overflow rate, and values at overflow were all compared. The null hypothesis was assumed to be that the means were equal with zero difference with the alternative hypothesis indicated as the means were not equal with a significance level, alpha of 0.05 or 5%.

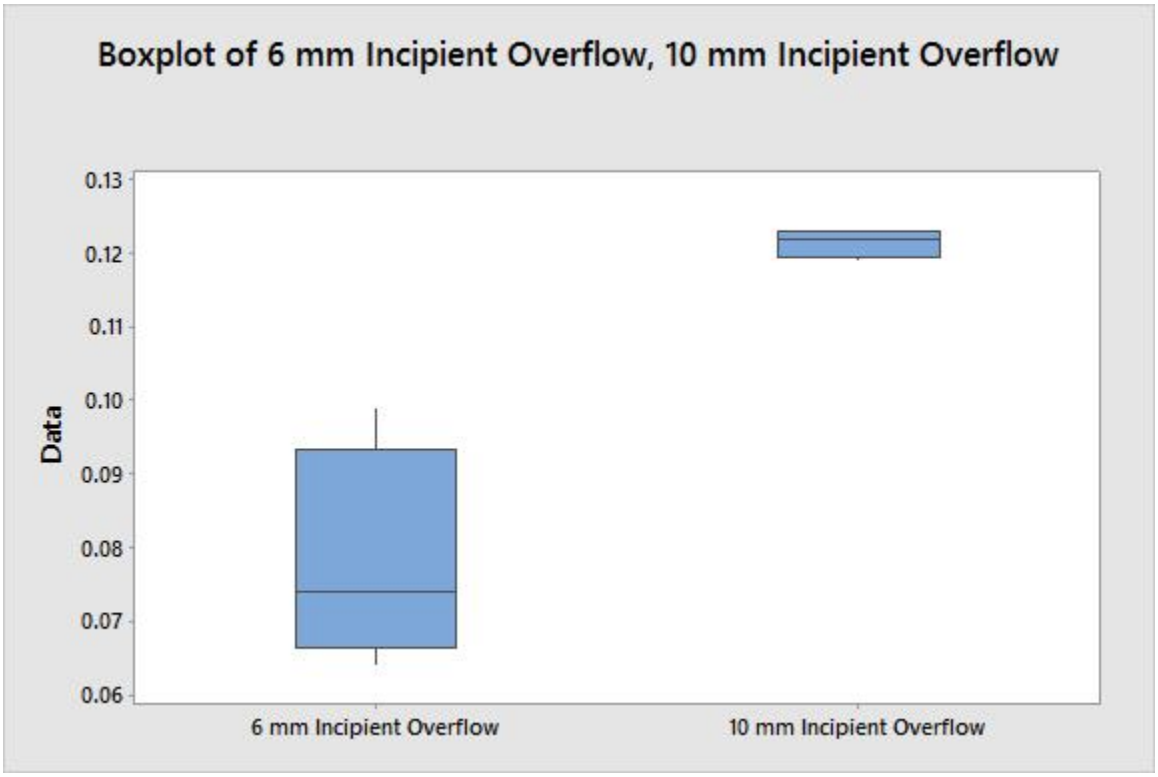


Figure 44 - Boxplot Incipient Overflow Rate between 6 mm and 10 mm.

Table 12 – t-test Summary Comparison between 6 mm and 10 mm

Experimental Group Value Test	P-Value	Indication
6 mm and 10 mm Incipient Overflow Rates	0.003	Reject Null Hypothesis
6 mm and 10 mm Infiltration Values	0.049	Reject Null Hypothesis
6 mm and 10 mm Overflow Values	0.042	Reject Null Hypothesis

The p values of ≤ 0.05 indicate a rejection of the null hypothesis suggesting that there is some indication that the 6 mm spacing separation differs from the 10 mm.

An additional analysis included individual two sample t-tests between the 10 mm spacing group and the 12.5 mm spacing groups. Infiltration, Incipient Overflow rate, and values at Overflow were all compared. The null hypothesis was assumed to be that the means

were equal with zero difference with the alternative hypothesis indicated as the means were not equal with a significance level, alpha of 0.05 or 5%. Figure 45 and Table 13 display the results.

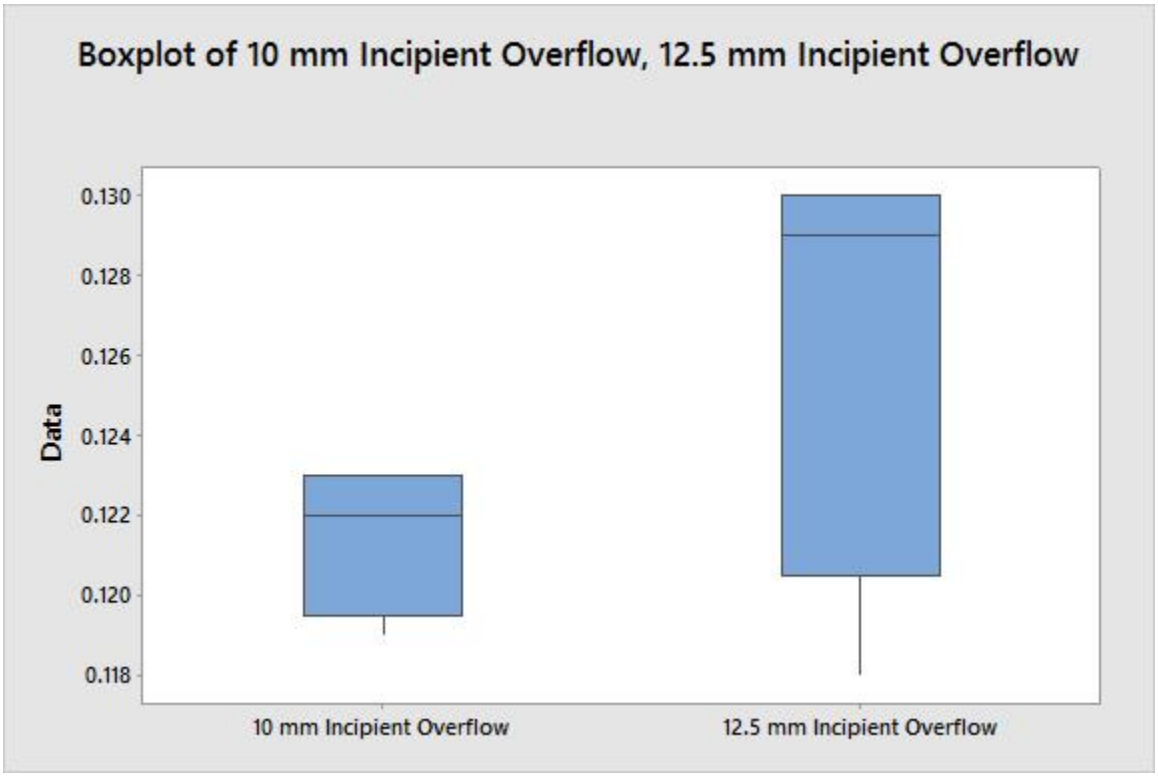


Figure 45 – Boxplot Incipient Overflow Rate between 10 mm and 12.5 mm.

Table 13 – t-test Summary Comparison between 10 mm and 12.5 mm

Experimental Group Value Test	P-Value	Indication
10 mm and 12.5 mm Incipient Overflow Rate	0.142	Fail Reject Null Hypothesis
10 mm and 12.5 mm Infiltration Values	0.487	Fail Reject Null Hypothesis
10 mm and 12.5 mm Overflow Values	0.455	Fail Reject Null Hypothesis

The p values of greater than 0.05 indicate that there is not statistical difference between the means of the 10 and 12.5 mm groups.

Individual two sample t-tests between the validation 6 mm spacing group and the summer 6 mm spacing groups. Additionally, the 45 degree herringbone pattern was compared to the straight herringbone pattern data points. As stated previously, infiltration, Infiltration at overflow per section area, and overflow values were all compared. The null hypothesis was that the means were equal with zero difference with the alternative hypothesis indicated as the means were not equal with a significance level, alpha of 0.01 or 1%. The smaller the value of alpha, the less likely it is that a rejection or a true null hypothesis will occur. The variances were not assumed to be equivalent. Full Minitab results are displayed within the appendix of this report. Figures 46 and 47 display the box plot values for the infiltration at overflow per section area found in Table 14.

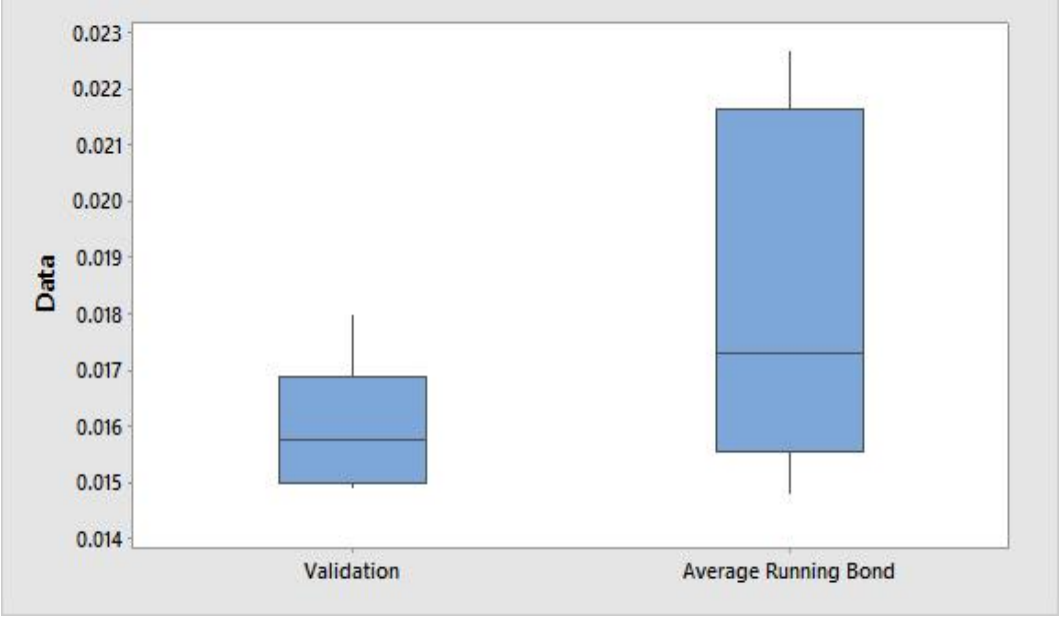


Figure 46 – Boxplot Average 6 mm Straight Herringbone 6 mm vs. Validation Values

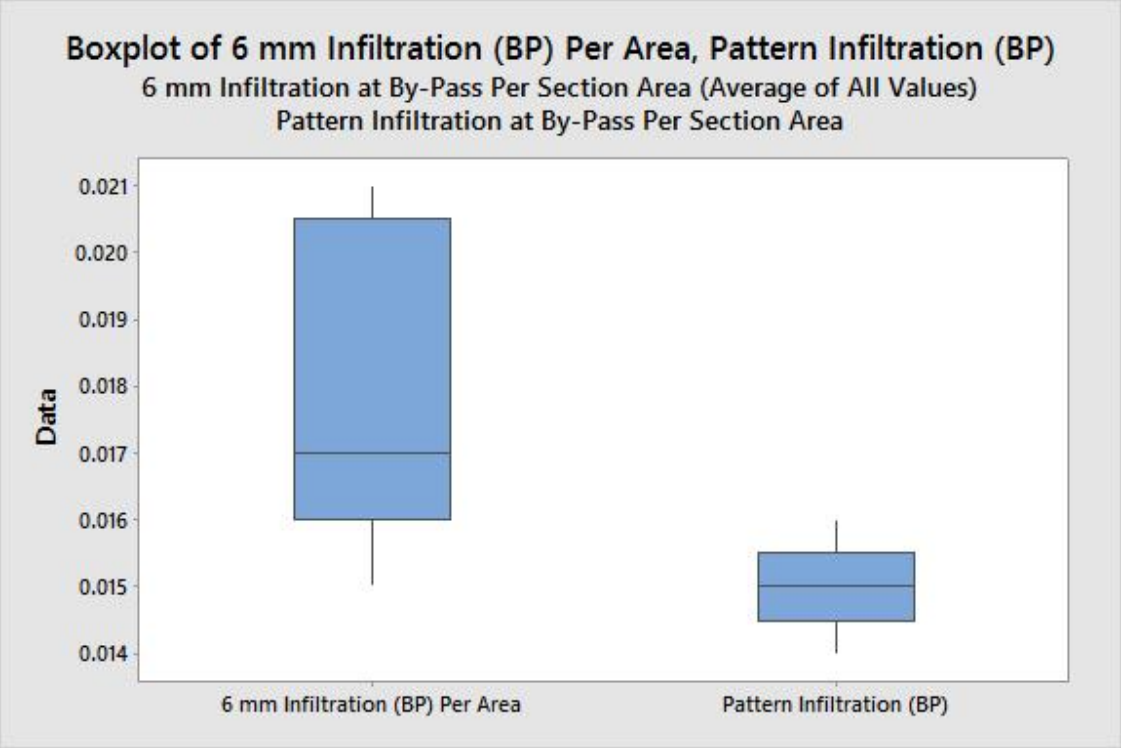


Figure 47 – Boxplot Average 6 mm vs. Herringbone Pattern Infiltration per Section Area (cfs/ft^2)

Table 14 displays the statistical results for the validation compared to the summer values. The failure to reject the null hypotheses indicates that the assumption that the means of the 6 mm and the validation test are equivalent is probable. This indicates that the pump or time difference did not affect the experiment.

Table 14 –t-test Summary Comparison between 6 mm and Validation Group

Experimental Group Value Test	P-Value	Indication
6 mm and validation infiltration at overflow	0.153	Fail to Reject Null Hypothesis
6 mm and validation infiltration values	0.311	Fail to Reject Null Hypothesis
6 mm and validation overflow values	0.747	Fail to Reject Null Hypothesis

The t-tests between the 45 degree herringbone pattern and the 6 mm spacing group was completed with both a significant level of 0.05 (5%) and 0.01 or 1 % significance. This analysis was completed upon the infiltration, Infiltration at overflow per section area and values at Overflow. The null hypothesis was assumed to be that the means were equal with zero difference with the alternative hypothesis indicated as the means were not equal. The p value of 0.030 indicates a failure to reject of the null hypothesis value for an alpha of 0.01. However this p value for an alpha of 0.05 indicates a rejection of the null hypothesis indicating that the pattern data differs slightly from the regular 6 mm pattern. Table 15 displays the results. Further experiments and at alternate spacing would be suggested for additional research to explore pattern differences.

Table 15 –t-t Summary All 6 mm data values and Pattern Comparison

Experimental Group Value Test	P-Value	Indication
6 mm Average vs. 45 degree pattern: Infiltration at Overflow per section Area	0.030	Reject Null Hypothesis at 5%
6 mm Infiltration vs. Pattern Infiltration Values	0.270	Fail to Reject Null Hypothesis
6 mm vs. Pattern Overflow Values	0.822	Fail to Reject Null Hypothesis

Pavement Slope Analysis

Correlation Analysis was completed between pavement slope and different spacing capture discharge rates. The strength of the correlation was determined if the absolute value was closer to 1. The sign indicates the direction of the relationship. All negative values indicate an inverse relationship meaning that as the slope of the pavement increases the capture flow rate decreases. The Spearman Rho and Pearson correlation tests were used. Pearson is used in a linear relationship while Spearman Rho is used as the tests were not necessarily linearly based. The analysis was performed on the 6 mm spacing as this was the most sensitive experiment to the pavement slope. The results are shown in Table 16 and indicate that a strong inverse correlation between the overflow rates and pavement slope.

Table 16 - Correlation Summary between Pavement Slopes & Overflow Rate

Experiment	Spearman Rho	Pearson
6 mm	-0.901	-0.801

CHAPTER 6

RESULTS AND DISCUSSION CLOGGED

Infiltration systems such as PICPs are widely used in urban environments as a deterrent to water pollution and to control urban runoff volumes. One aspect that impacts the functionality of infiltration systems is the ability of the systems to become clogged. The most common water pollutant within the US is sediment (Ostercamp, 1998) which is a large component to stormwater (Sansalone, 1998).

For PICPs clogging synthetic storm water was formulated to closely fit the gradation from the New Jersey Corporation for Advanced Technology, NJCAT. This gradation was determined to be a sandy silt soil classification according to the United Soil Classification System (USCS) Standard. The material, common to the area, was collected from the North Kansas City location shown in Figure 48.

Synthetic Stormwater Properties

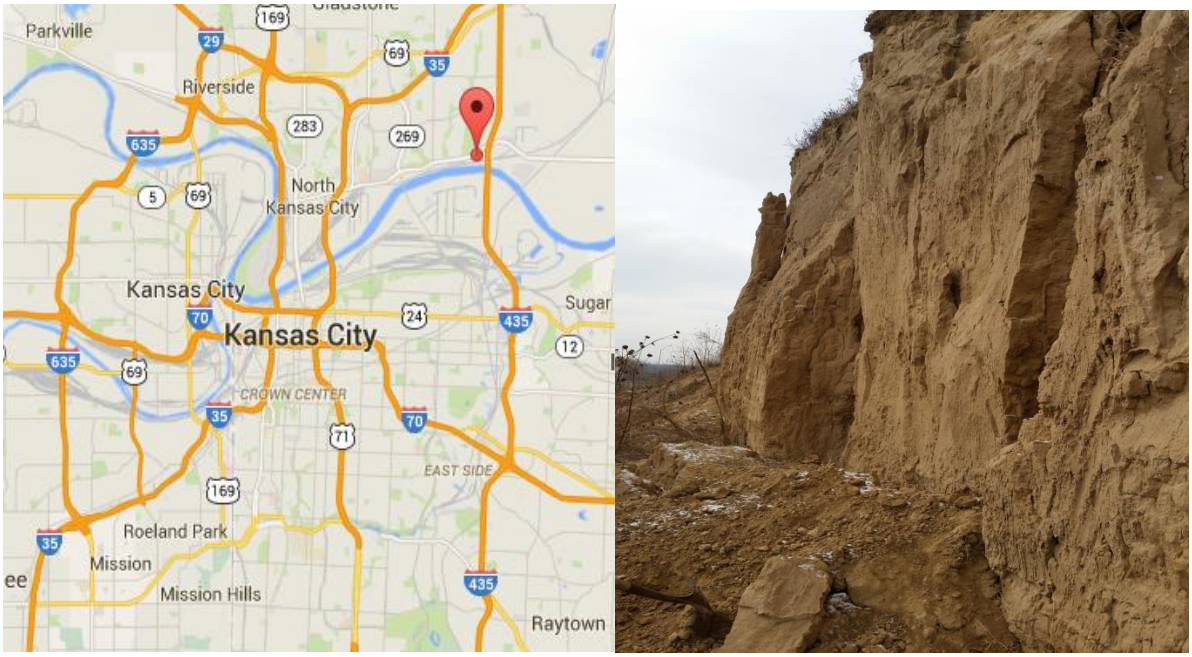


Figure 48 – Location and Picture of Synthetic Stormwater Soil Location

A sieve analysis was used to create the required diameter sizes. The created synthetic stormwater contained 45% of finer materials of silt and clay mixture. Hydrometer testing was completed to determine the grain size of the finer materials. The following Table 17 displays the required specification. Figure 49 displays the percent passing for the larger particles in the sieve analysis.

Table 17 – Synthetic Stormwater Soil Particle Size and Percent by Mass

Particle Size (microns, μm)	Percent By Mass
500-1000 (Coarse Sand)	5%
250-500 (Medium Sand)	5%
100-250 (Find Sand)	30%
50-100 (Very Fine Sand)	15%
1-50 (Silt and Clay)	45%

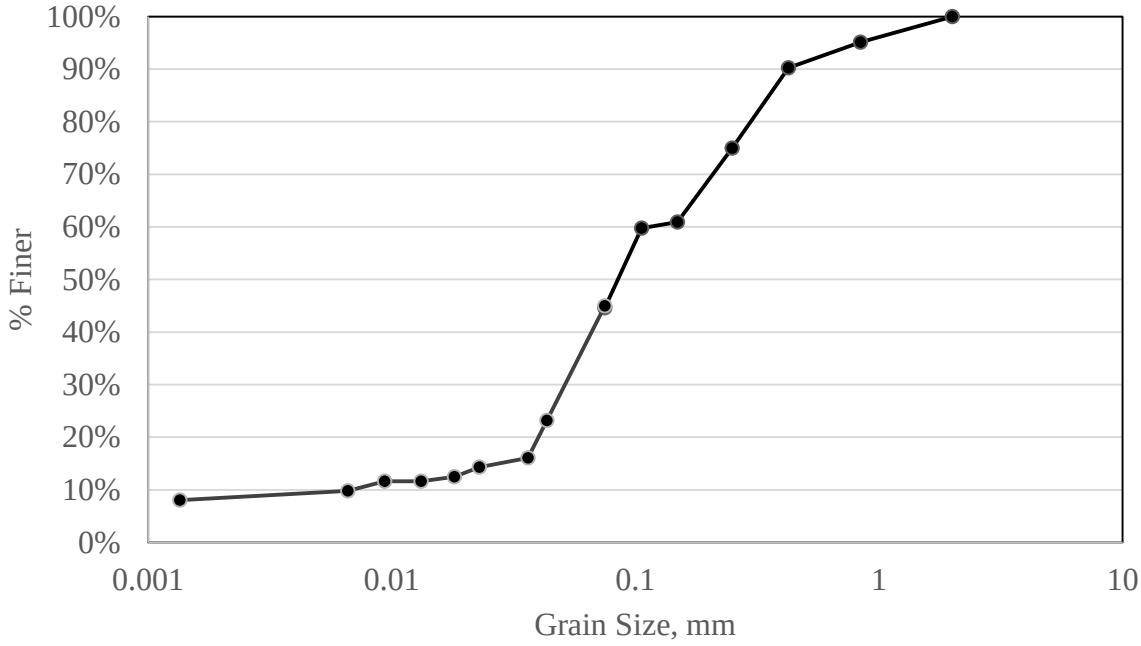


Figure 49 – Synthetic Storm Water Percent Finer, % vs. Grain Size in millimeters, mm

Figure 50 displays the synthetic stormwater loading compared to other more common loading values. The loading rate was much greater than previous studies such as the Kim, J. Y. et al. study (2013), "Investigation of Hydraulic Capacity and Water Quality Modification of Stormwater by Permeable Interlocking Concrete Pavement (PICP) System" that used vertical applications at 300 mg/l (Kim, 2013). Without using a greater loading rate, due to the greater infiltration of the testing set-up, the experimental tests would not have been able to be completed in a reasonable amount of time. Each application included this amount of loading applied upstream of the experimental sections. Table 18 displays the loadings used for each of the three test sections. Figures 51 and 52 displays the stormwater dissipation prior to and across the PICP test section for the 6 mm experiment.

Table 18 – Clogging Test Horizontal Loading Summary

6 mm, mg/l	10 mm, mg/l	12 mm, mg/l
14,014	16,349	16,424

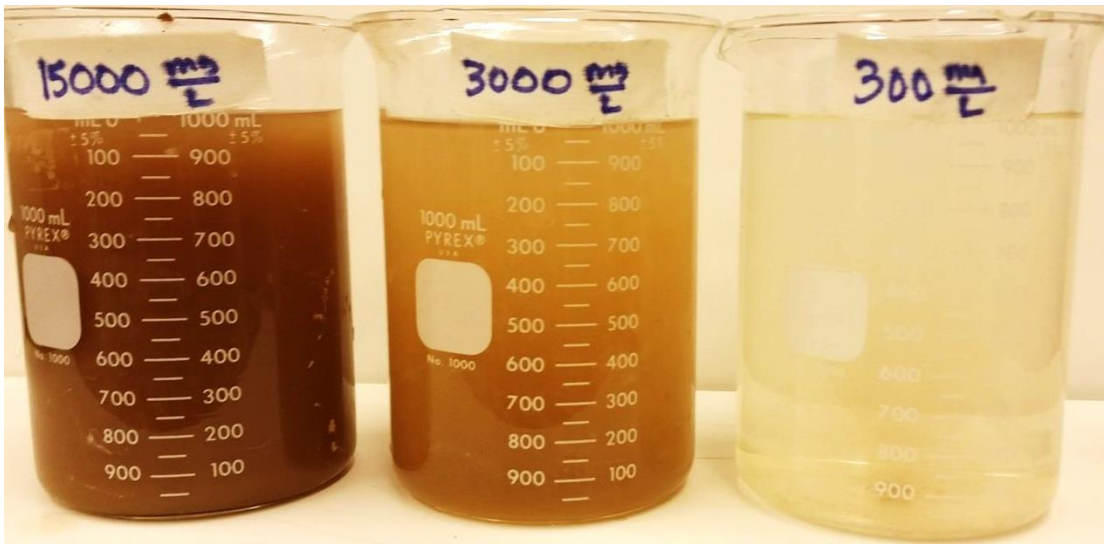


Figure 50 – Synthetic Stormwater Mixture Loading Comparison

Figure 51 – Synthetic Stormwater Dispensed Upstream of the Test Section

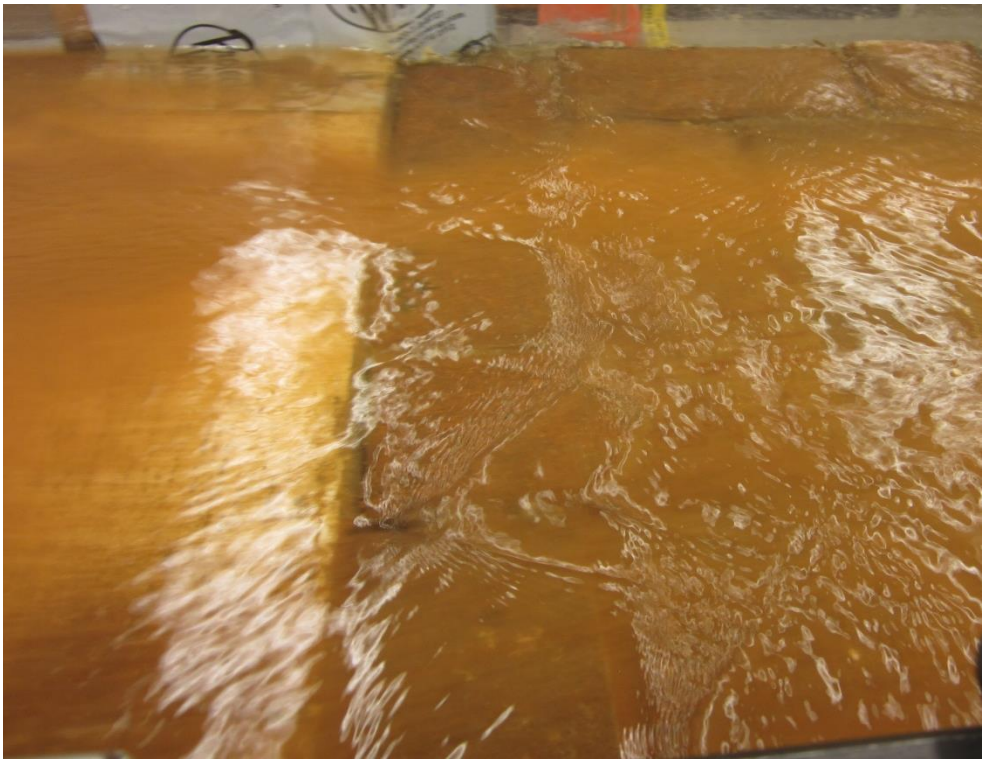


Figure 52 – Synthetic Stormwater Passing over the Test Section

Infiltration Flowrate (Left V Notch Weir) vs. Application Results

Clogging tests were performed on the straight herringbone pattern at 6 mm, 10 mm and 12.5 mm spacing. The results show the 6 mm spacing was clogged at a much higher rate (fewer applications) than either the 10 mm or 12.5 mm spacing. The 12.5 mm spacing proved to require the greater number of applications of synthetic stormwater. Figure 53-55 displays the results for the different spacing clogging test including two post clogging test values after the filler material was vacuumed and replaced. It should be noted that the 12.5 mm spacing test required nearly 5 times the number of applications that the 6 mm spacing test required.

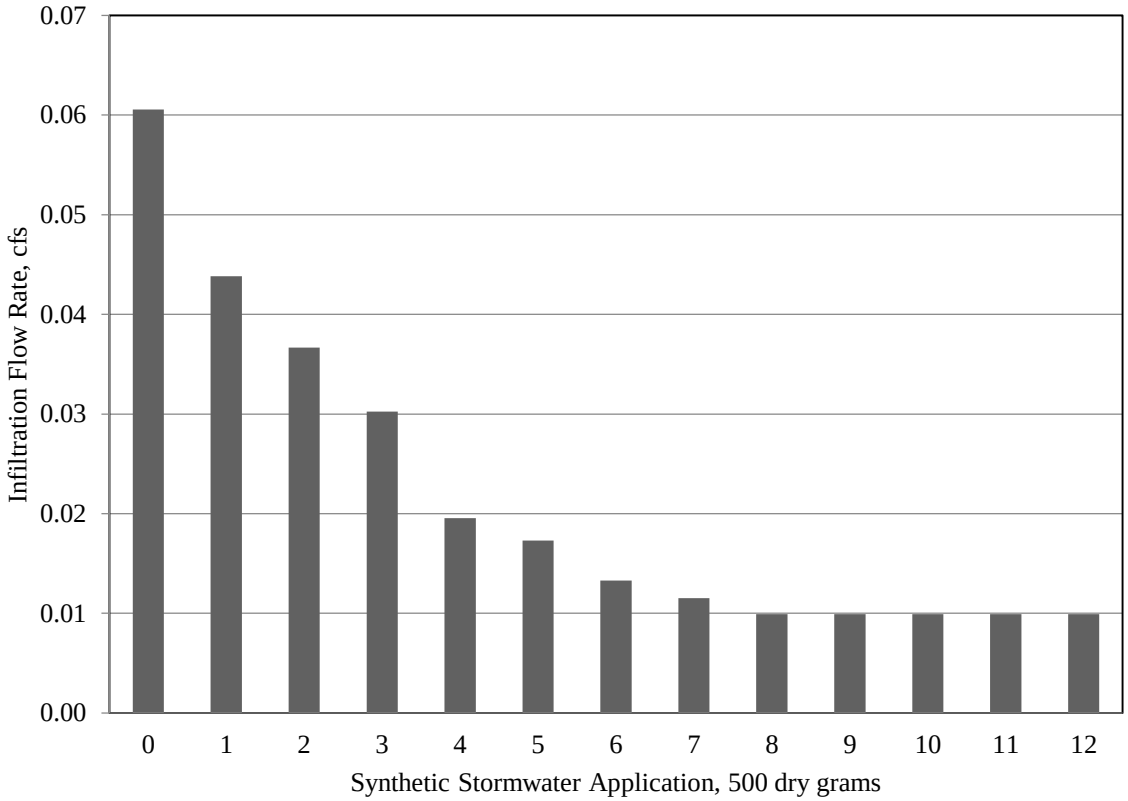


Figure 53 – 6 mm Spacing Flow Rate vs. Application Result

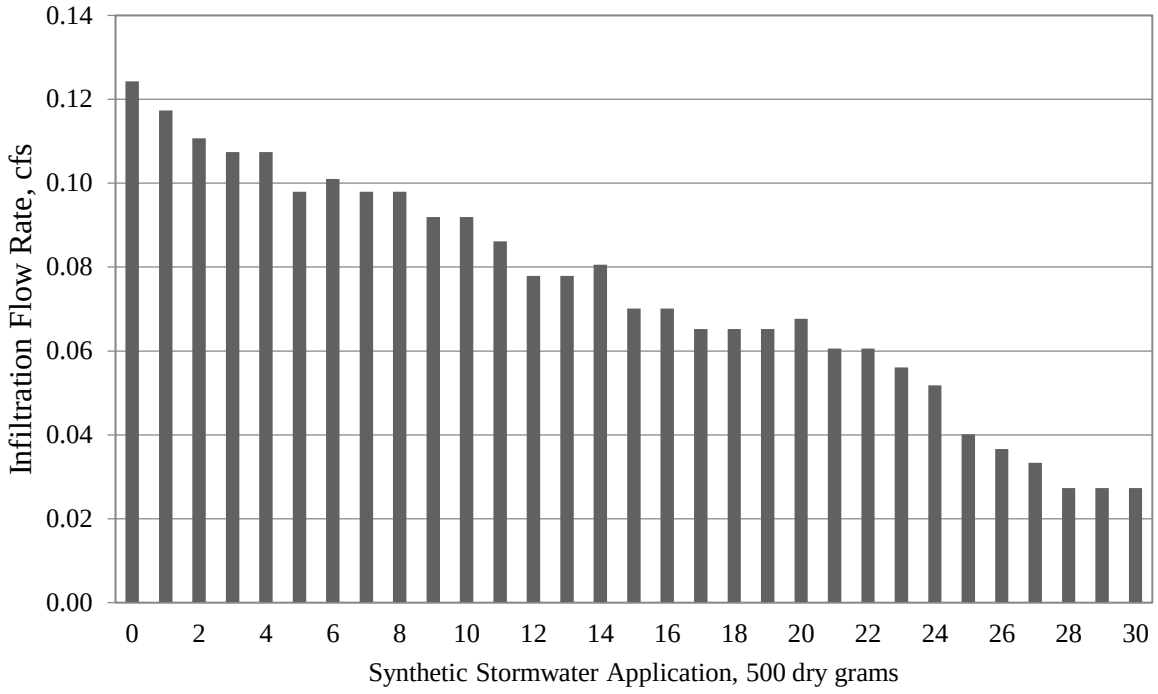


Figure 54 – 10 mm Spacing Flow Rate vs. Application Result

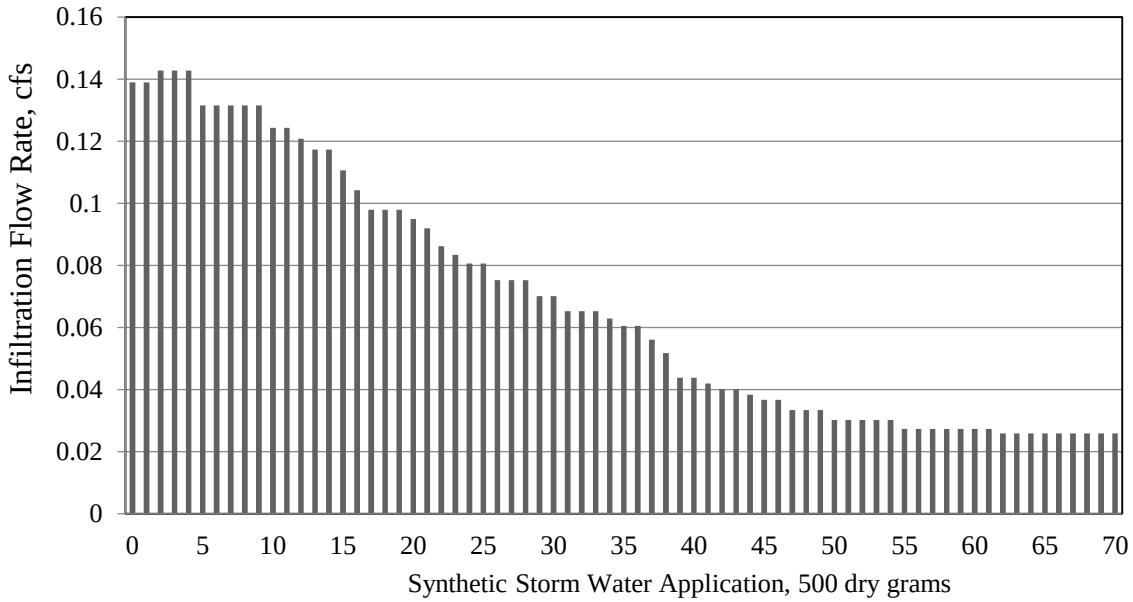


Figure 55 – 12.5 mm Spacing Flow Rate vs. Application Result

Linear Fitted Line Regression Results

Each of the three tests was analyzed within Minitab 17.0 for linear best fit equations and plots. The linear equations with the larges R values, a predictor of test strength, were chosen and each of the tests had a cubic equation as the best fit. Figures 56-58 display each of the three test fitted line plots.

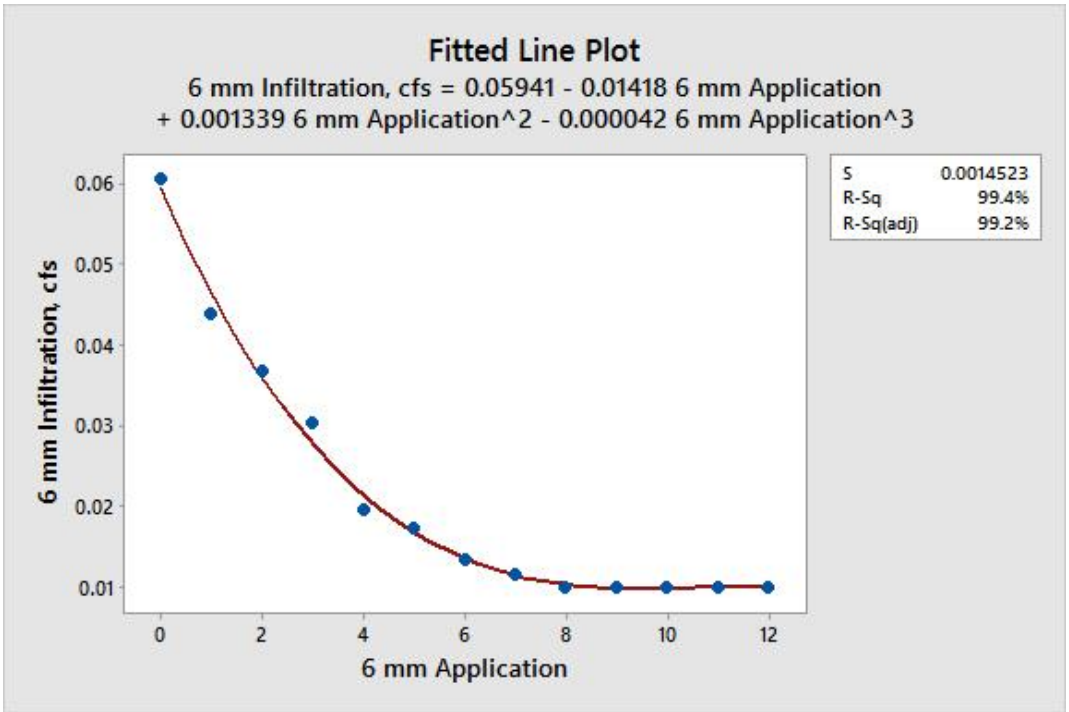


Figure 56 – 12.5 mm Spacing Flow Rate vs. Application Result

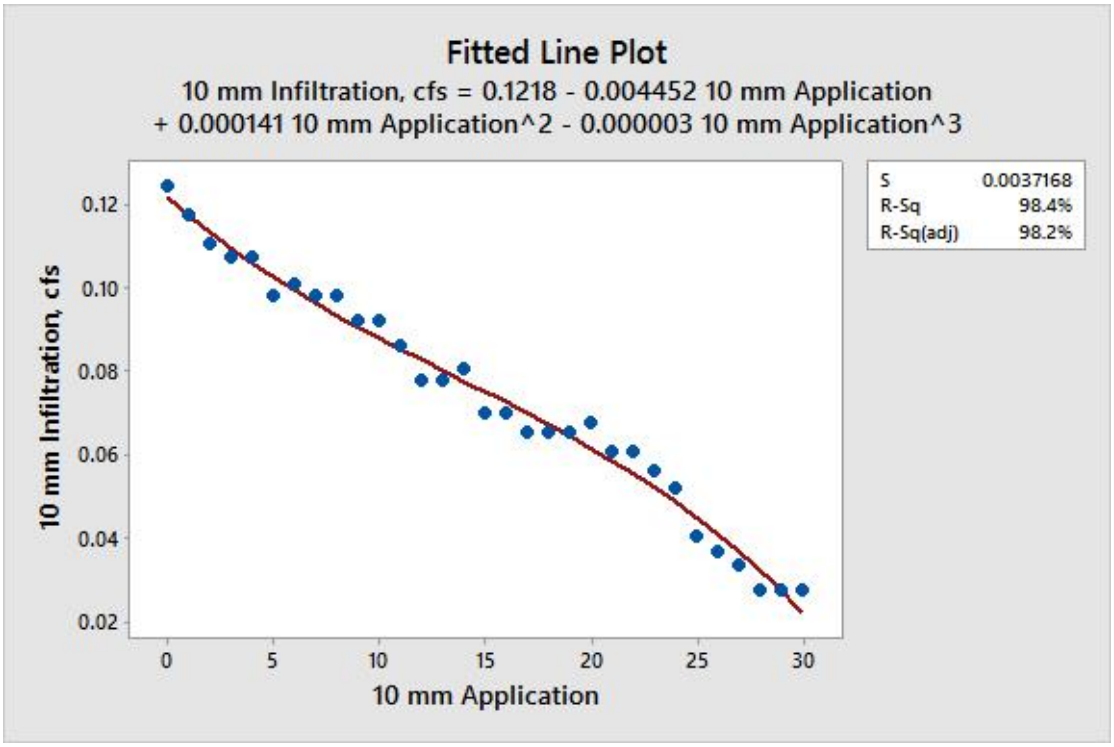


Figure 57 – 10 mm Spacing Flow Rate vs. Application Result

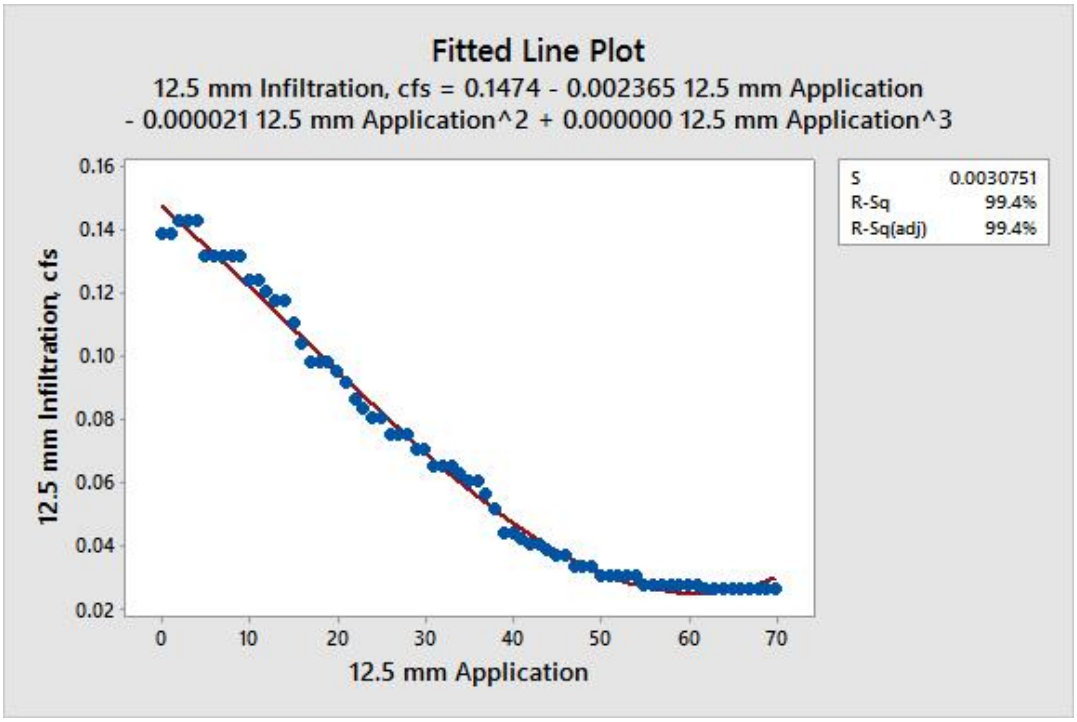


Figure 58 – 12.5 mm Spacing Flow Rate vs. Application Result

Infiltration and Overflow Rate Results and Comparisons

The calculated infiltration values pre, and post verses application values are shown below in Tables 19-21. These values display the pretest, end of the clogging value, and posttest after filler material replacement.

Table 19 – 6 mm Clogging Test Infiltration and Application Summary

Test Description	Application	Infiltration, in/hr
Pretest: No Clogging	0	2511
After Clogging	12	411
Posttest: After Filler Replacement	5	718

Table 20 – 10 mm Clogging Test Infiltration and Application Summary

Test Description	Application	Infiltration, in/hr
Pretest: No Clogging	0	5155
After Clogging	30	1133
Posttest: After Filler Replacement	10	3813

Table 21 – 12.5 mm Clogging Test Infiltration and Application Summary

Test Description	Application	Infiltration, in/hr
Pretest: No Clogging	0	5648
After Clogging	70	1054
Posttest: After Filler Replacement		

Results also indicated that the infiltration discharge rate at the overflow point decreases with increased stormwater applications. Results also indicate an increase in the overflow rate as experimental testing continued. The 6 mm summary is shown in Table 22.

Table 22 – 6 mm Summary Incipient Overflow Rate, Infiltration Rate per Section Area

Stormwater Applications	Overflow, cfs	Infiltration Rate, cfs
0	0.0003	0.0438
5	0.0286	0.0173
12	0.0380	0.00991

Results also show that as the infiltrate rates decrease the overflow rate increases. Figure 59 displays the set entrance flow rate, the infiltration rate and overflow. During testing the overflow rate increased to the point where the majority of the stormwater would be carried across the top of the test section preventing complete clogging to zero infiltration. Table 23 and Figure 60 display the results for the 10 mm test

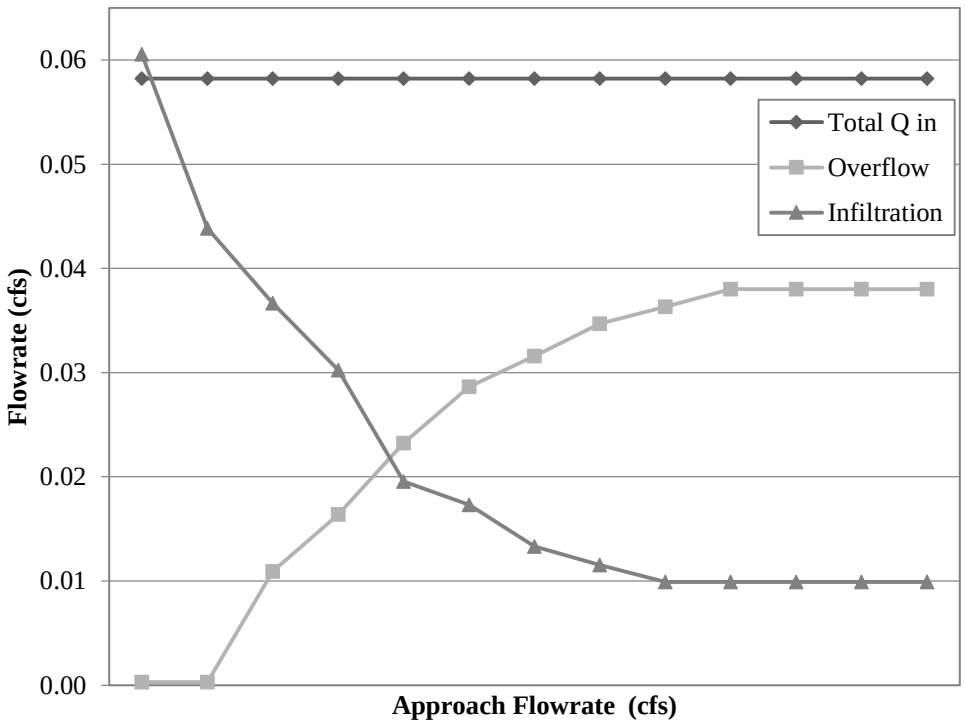


Figure 59 – 6 mm Total Discharge, Overflow, Infiltration Rates

Table 23 – 10 mm Summary of Infiltration discharge per Stormwater Applications

Stormwater Applications	Infiltration, cfs
0	0.124
5	0.098
10	0.092
20	0.068
30	0.027

The straight line indicates the set flow rate of the clogging experiments. This value is the flowrate at which overflow first occurs and this flow is not changed during the test. The infiltration measured values were observed to display a slight increase at the beginning of the experiment. The initial application of stormwater to the flow was observed to increase the viscosity (thickness) of the stormwater which may account for this phenomenon. Table 24 and Figure 61 display the results for the 12.5 mm test.

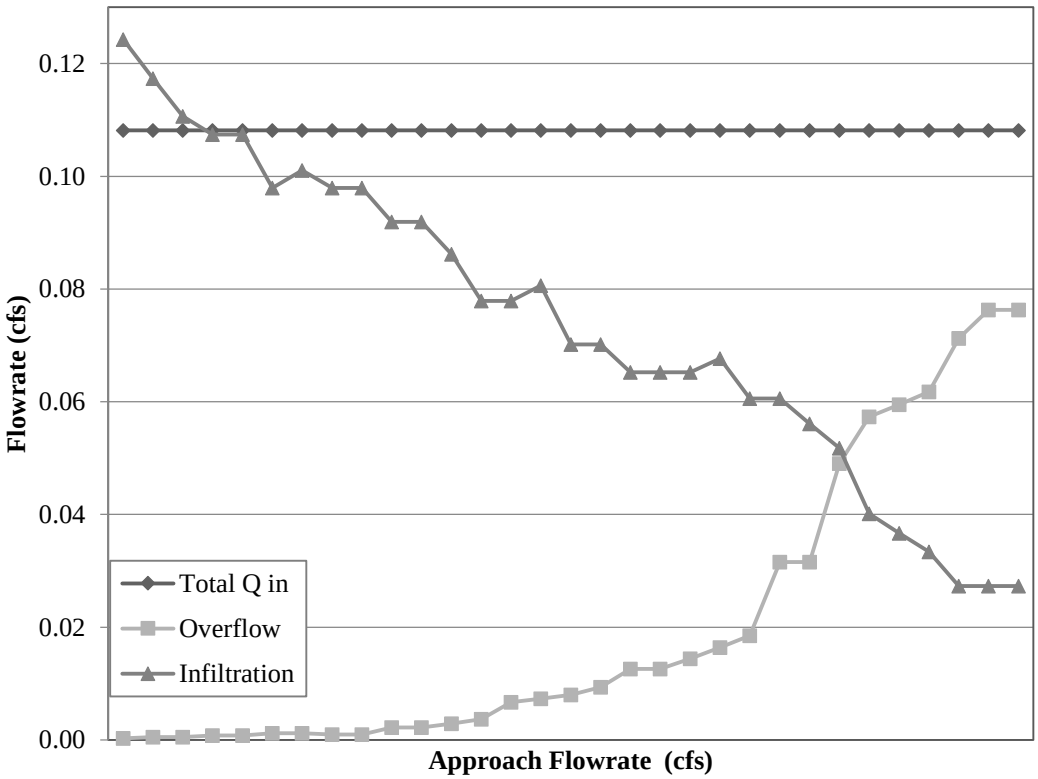


Figure 60 – 10 mm Total Discharge, Overflow, Infiltration Rate

Table 24 – 12.5 mm Summary of Infiltration discharge per Stormwater Applications

Stormwater Applications	Infiltration, cfs
0	0.139
5	0.131
10	0.124
30	0.070
50	0.030
70	0.026

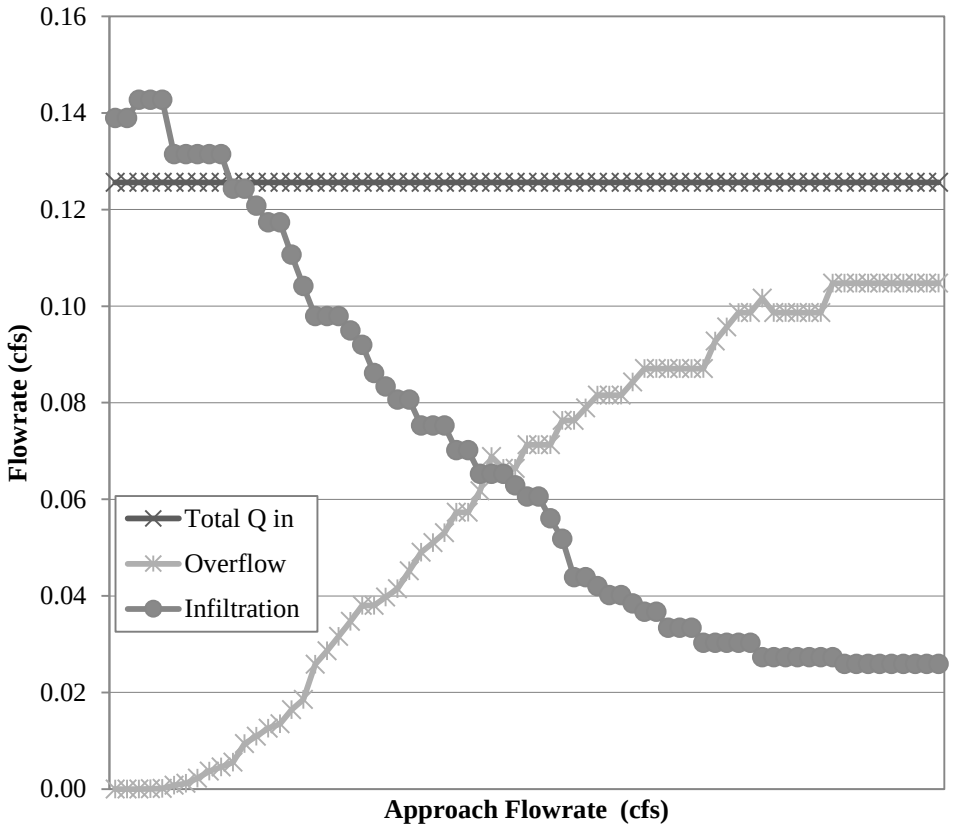


Figure 61 – 12.5 mm Total Discharge, Overflow, and Infiltration Rate

After clogging tests were completed the sections were vacuumed, the filler material was replaced and a five point test was then completed. The recaptured rates at the entrance flow rate (After Unclogging value) and the test overflow rate were determined (After Unclogging Full Test) and displayed in Figure 62-64 below.

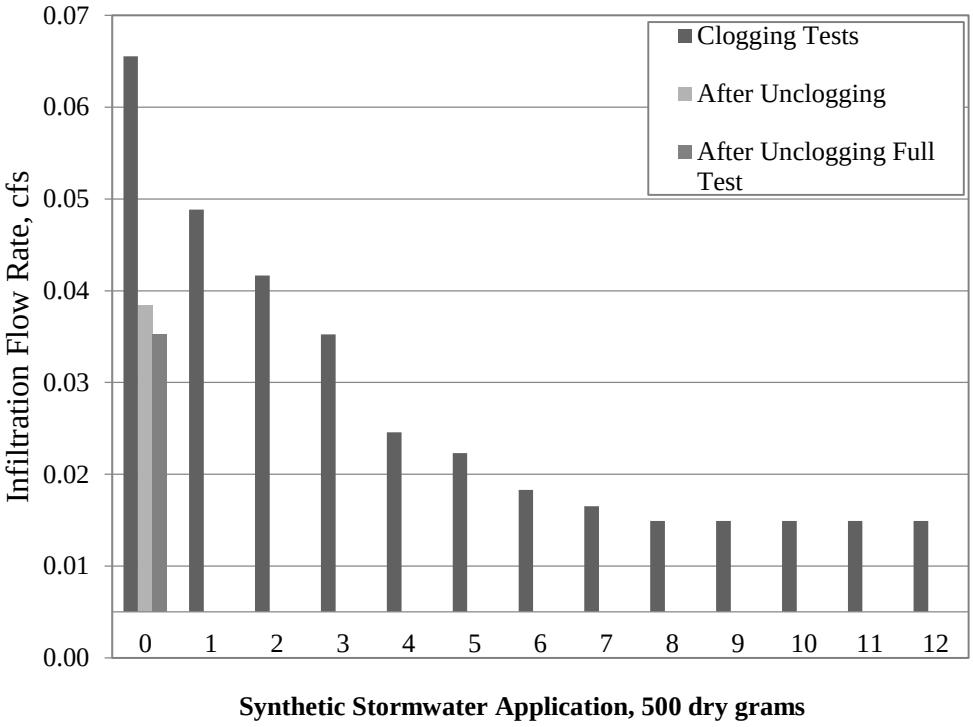


Figure 62 – 6 mm After Clogging Recapture Rate vs. Application Result

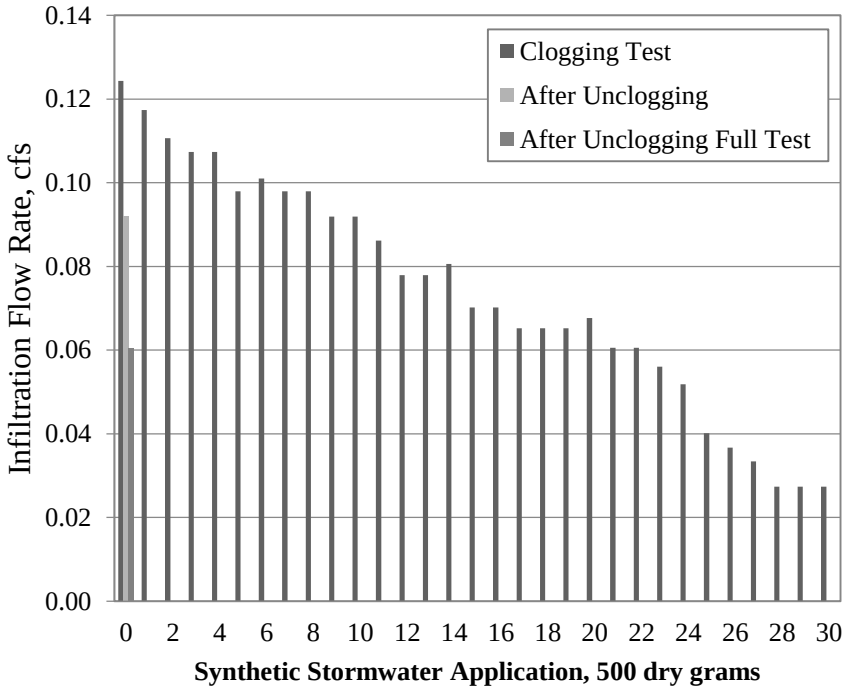


Figure 63 – 10 mm After Clogging Recapture Rate vs. Application Result

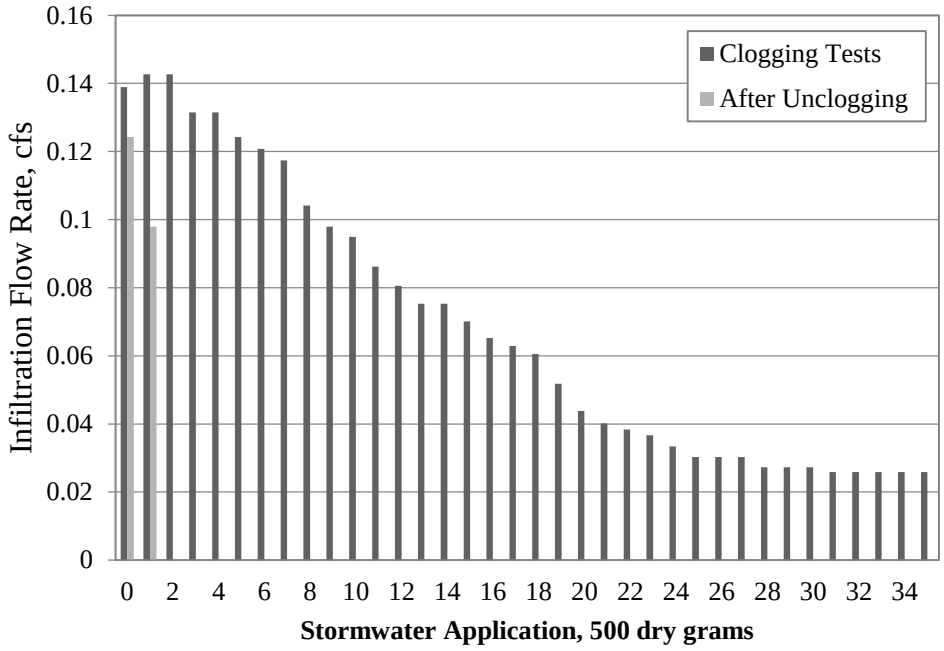


Figure 64 – 12.5 mm After Clogging Recapture Rate vs. Application Result

The recaptured infiltration rates at the clogging entrance flow rate value are displaced in Table 25 below. The recaptured rate fell between 55-89% of the initial flowrate value indicating that maintenance of the PICP system by replacing the filler material recaptures a large value of the initial infiltration. Table 26 expresses the values in infiltration, in. /hr. and percentage of recapture rates.

Table 25 –Summary of Infiltration Flowrate, Recaptured Rates, and Percentage Recaptured

Spacing	Initial Infiltration Value, cfs	End Infiltration Value, cfs	Recapture Infiltration, cfs	Percentage of Initial Value, %
6 mm	0.061	0.009	0.033	46%
10 mm	0.124	0.027	0.092	26%
12.5 mm	0.139	0.026	0.124	11%

Table 26 –Summary of Infiltration and Percentage Recaptured

Spacing	Initial Infiltration, (in/hr.)	End Infiltration, (in/hr.)	Recapture Infiltration (in/hr.)	Recapture Percentage
6 mm	628	103	538	85.7%
10 mm	1289	283	953	74.0%
12.5 mm	1412	263	1263	89.5%

Performance curves pre and post clogging (maintenance) tests were completed for comparison. Figures 65-67 display these curves. The overflows rates before are much lower than the maintenance overflow values. Infiltration rates prior to clogging are much greater than the maintenance values.

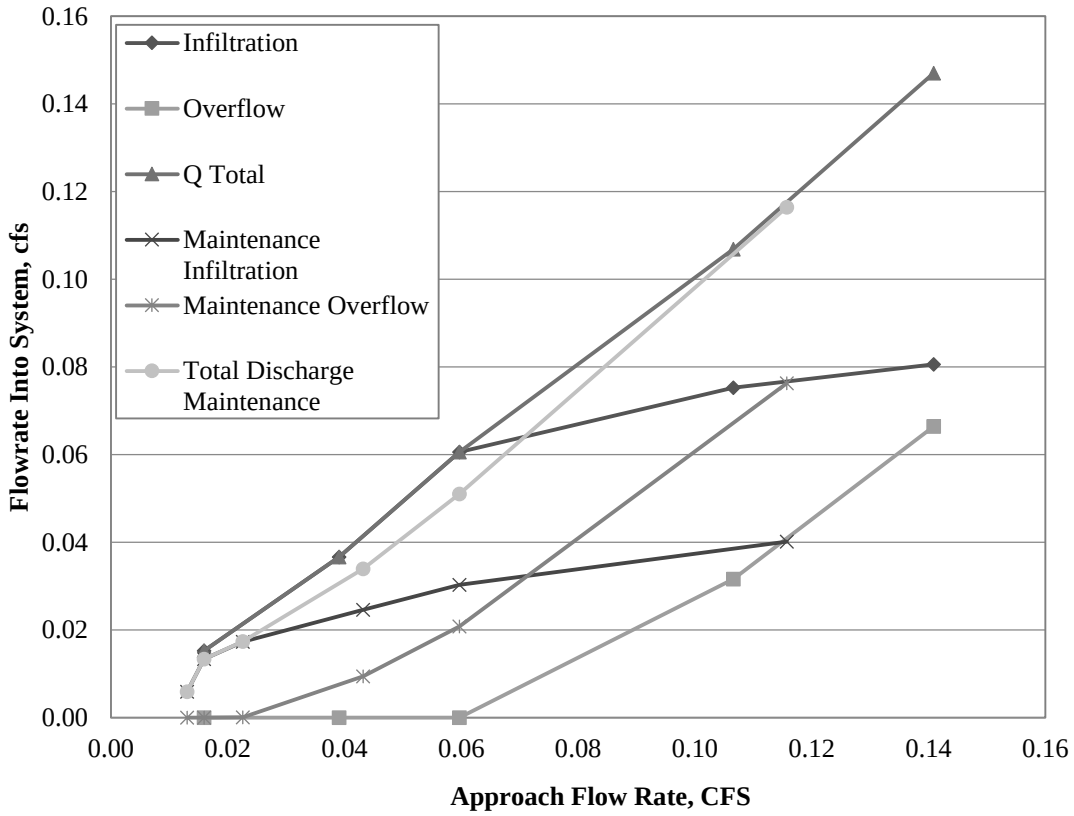


Figure 65 – 6 mm Before and After Clogging Performance Curve

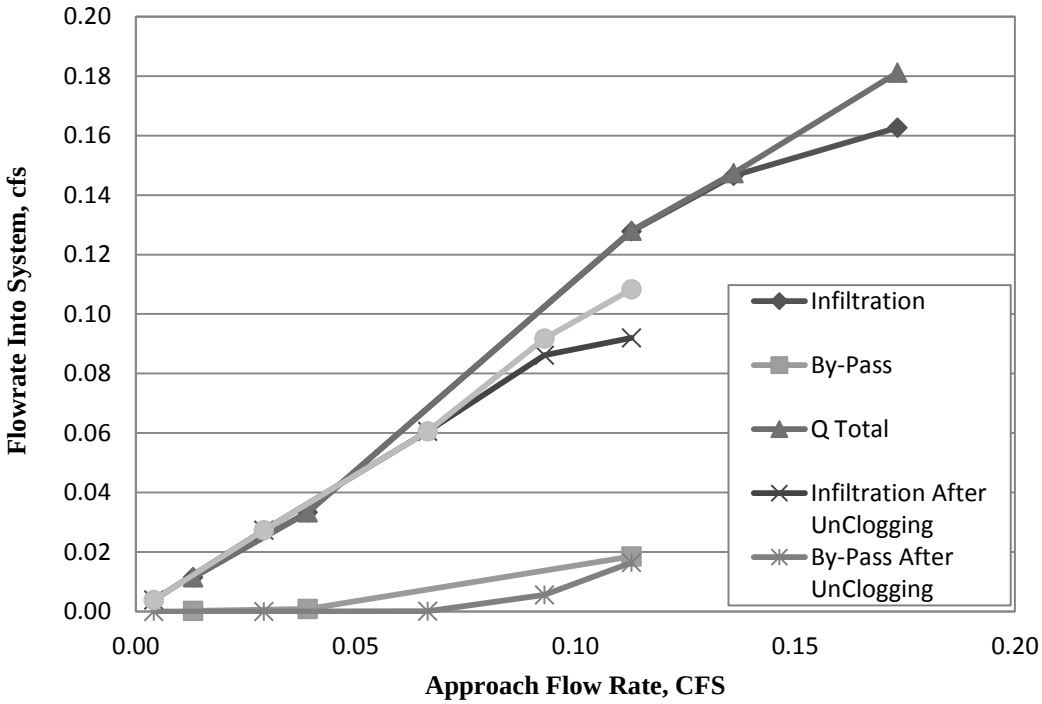


Figure 66 – 10 mm Before and After Clogging Performance Curve

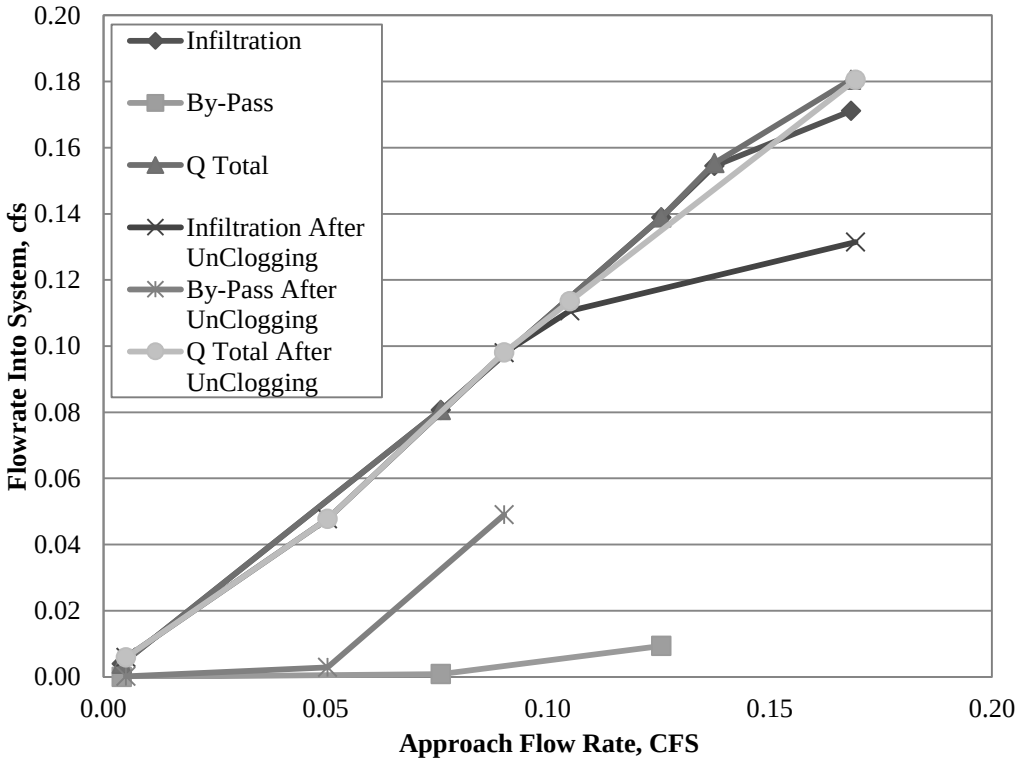


Figure 67 – 12.5 mm before and After Clogging Performance Curve

In summary, as the applications of synthetic stormwater increase the infiltration decrease and the overflow rate increases, as expected. The results also indicate a linear relationship between applications and decreased infiltration and that as the spacing size increases the number of required applications of stormwater necessary to clog the system increases. After maintenance was completed the sections were retested and the system recovered anywhere from 55-89 %of the initial infiltration values.

Infiltration per Previous Field Research

As stated earlier, the synthetic stormwater loading was greater compared to other field experimental studies stormwater loading values but the trend of the data was found to be similar. A greater synthetic loading rate was required for experimental completion to occur in a reasonable amount of time. For comparison purposes the linear regressed equation found from the clogging experiments were used to translate (decrease) to the field data found in the study, "Investigation of Hydraulic Capacity and Water Quality Modification of Stormwater by Permeable Interlocking Concrete Pavement (PICP) System," by J. Y. Kim (2013). Table 27 states the beginning and ending infiltration values for 300 mg/l loading from the Kim study (2013). These values were used to find a translated lower multiplier to use with the linear regression equations as shown in Figures 68 to 70.

Table 27 –Kim Infiltration Values per Aggregate Filler Spacing (Kim, 2013)

	Kim Data 300 mg/l Loading	
Filler Aggregate	Start Infiltration in/hr.	Ending Infiltration in/hr.
No. 9 Gradation	275.5	7.9
No. 8 Gradation	405.5	26.9

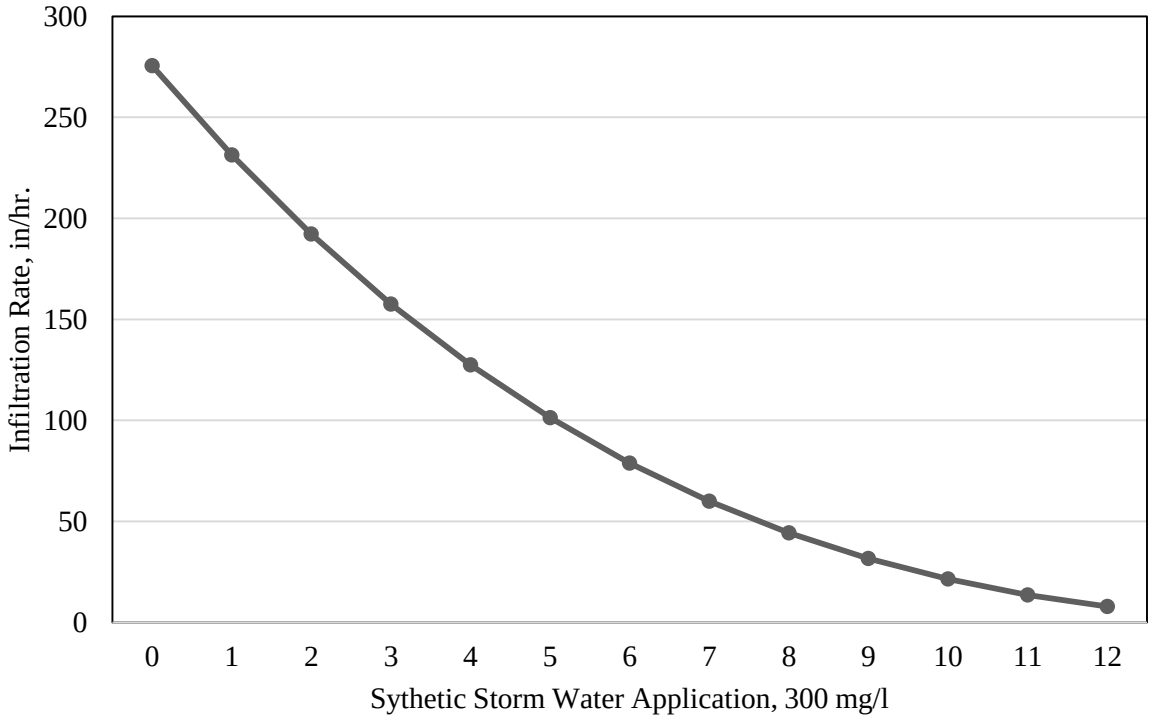


Figure 68 – 6 mm Calibrated Infiltration Rate per Stormwater Application Curve

Two assumptions were made for the 12.5 mm and 10 mm clogging calibrated analysis. Figures 69 and 70 display the calibrated 10 mm and 12.5 mm experimental infiltration values per stormwater application with the assumption that the data for the No. 8 aggregate filler material at the 300 mg/l loading would closely match both. In addition to both using the same initial and ending values, both used the linear regression equation found from the 12.5 mm spacing experiment. The 12.5 mm experiment had a greater amount of data to find a fitted equation the calibrated data resembles previous research (Kim, 2013).

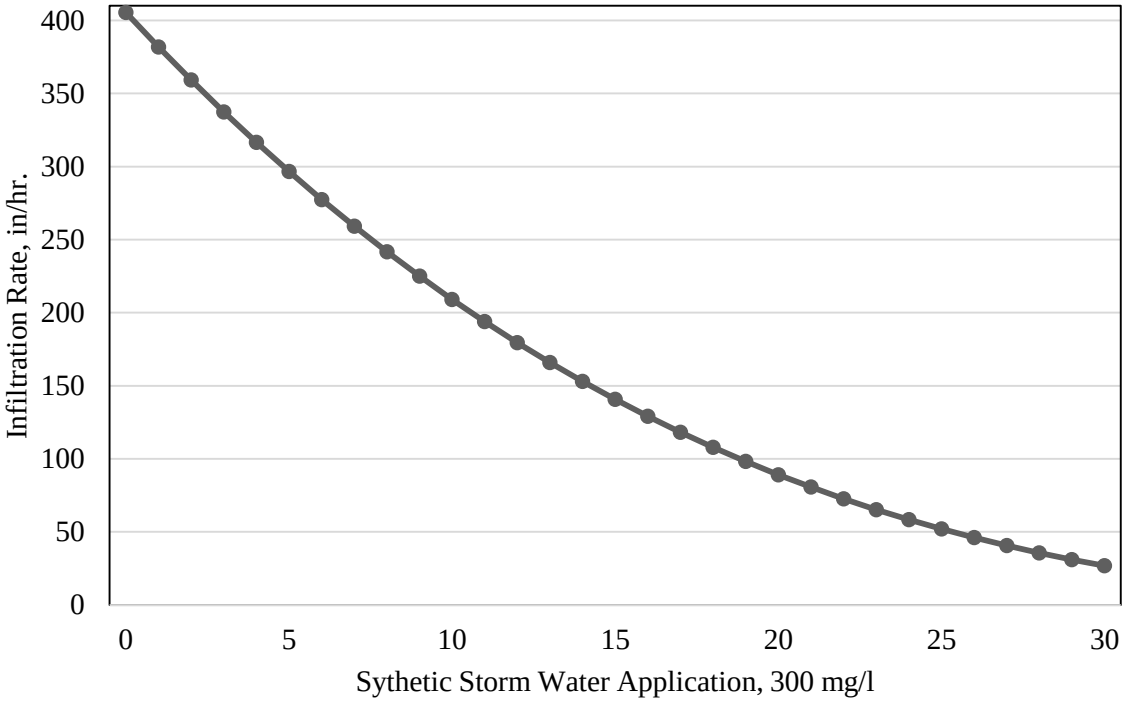


Figure 69 – 10 mm Calibrated Infiltration Rate per Stormwater Application Curve

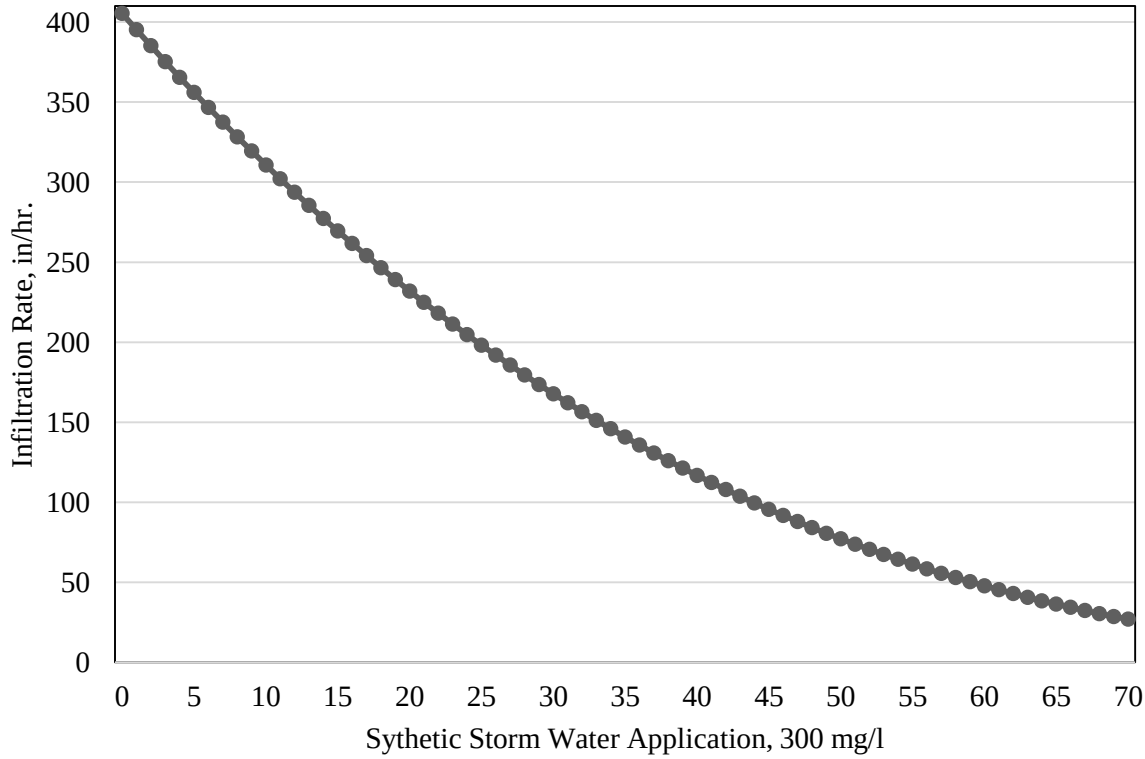


Figure 70 – 12.5 mm Calibrated Infiltration Rate per Stormwater Application Curve

CHAPTER 7

RESULTS AND DISCUSSION PLATFORM TESTING

Portland Cement Pervious Concrete (PCPC), like PICP, is a permeable structure that are used to infiltrate urban runoff and increase water quality. PCPC are generally set in place sections that have been shown to infiltrate at a higher rate than PICP and exhibit higher loading strength. As such a system that would include PCPC under a paver block system would be attractive to increase pavement strength while not jeopardizing infiltration rates.

Material Properties

For the purpose of this experimentation a light-weight PCPC platform was constructed. For a light-weight concrete, coarse aggregate was replaced with a light-weight aggregate mixture. The fine aggregate was also replaced with a medium absorption material from Hydraulic Press Brick Company from Brooklyn, Indiana. The sample was mixed according to ASTM C192 standard. Table 28 displays the summary of the concrete mixture including the water to cement ratio (w/c). Figure 71 displays the PCPC platform set in place within the flume.

Table 28 – Summary of Concrete Mixture

Cement (PCY)	Coarse Aggregate SSD (pcy)	Fine Aggregate SSD (pcy)	Water (pcy)	W/C
573	1127 (WSD)	145 (WSD)	195	0.34

Figure 71 – PCPC Lightweight Platform

According to the 2013 report, "Reducing the Curing Requirements of Pervious Concrete Using Prewetted Lightweight Aggregate for Internal Curing" the following hardened concrete test results and strength testing results for the mixture are shown in Tables 29 and 30.

Table 29 – Hardened Concrete Results

Fresh Unit Weight ASTM C1688	Hardened Unit Weight ASTM C1754		Voids ASTM C1754		Permeability ASTM C1754	
Avg. (pcy)	Avg. (pcf)	COV (%)	Avg. (%)	COV (%)	Avg.(in/hr)	COV (%)
76.4	63.3	0.3	42.8	0.9	4600	5.5

Table 30 – Strength Testing Results

Compressive Strength 7 Day ASTM C39		Compressive Strength 28-day C39		Tensile Strength 28-day ASTM C497	
Avg. (psi)	COV (%)	Avg. (psi)	COV (%)	Avg. (psi)	COV (%)
817	39.2	897	4.0	213	4.7

Platform Infiltration

A regular five point experiment, with the same testing procedure was completed on the lightweight PCPC platform. An example overflow curve for the platform is shown in Figure 72.

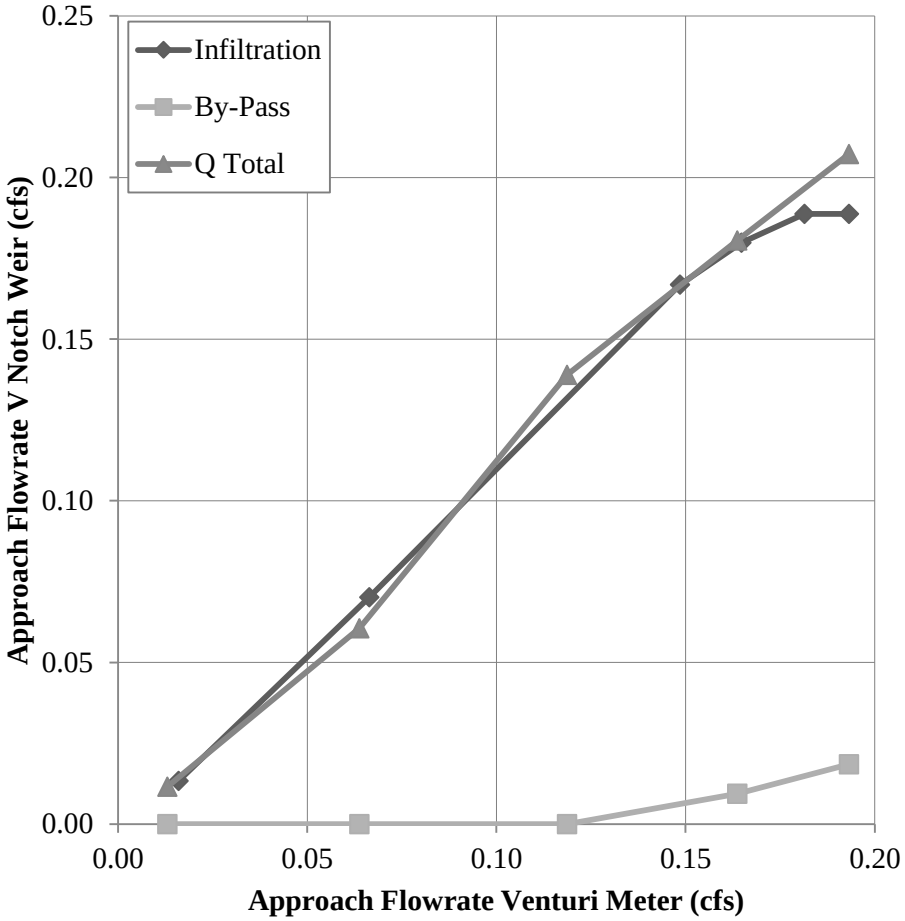


Figure 72 – PCPC Platform Performance Curve

The PCPC platform was also tested for vertical infiltration according to the C1701 standard (ASTM, 2007). The average infiltration was found to be 2201.9 in/hr. for the section which was considerably higher than the PICP vertical infiltration test as expected.

Horizontal infiltration was calculated for the PCPC platform without the PICP system to assess the functionality of the platform as a base layer to the PICP system. The platform was expected to have a higher horizontal infiltration than the greatest space sizing in the PICP system (12.5 mm). Table 31 below displays the comparison between the platform and the average horizontal infiltration values per pavement slope for each type of spacing. The results indicate the experimental values matched the expect result.

Table 31 – Horizontal Infiltration Averages per Pavement Slope

Slope	Platform	12.5 mm	10 mm	6 mm
		Infiltration, in/hr.		
0%	1827.50	1411.97	1348.25	893.37
1%	1739.23	1424.87	1433.71	992.80
2%	1696.07	1411.97	1460.01	748.15
5%	1411.97	1399.29	1460.01	704.15
10%	1489.96	1399.29	1486.74	642.75

PICP and Platform System

The PICP were then placed on top of the PCPC platform for an additional test. The 12.5 mm with the number 8 gradation joint filler material was used. As expected the infiltration was similar to the infiltration found without the lower platform base. This finding indicates that the infiltration rate for the experimental test sections is governed by the filler spacings and the top layer of the system. Figure 73 displays an example of the performance curve for the system. Figure 74 displays the horizontal infiltration at the overflow point comparison for the platform PCPC, PICP and PCPC system, and the average 12.5 mm spacing tests.

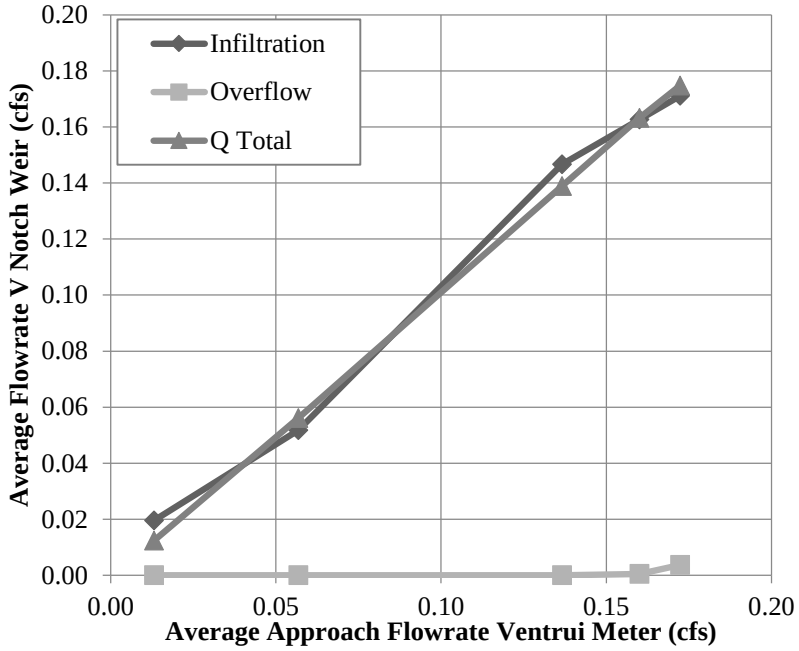


Figure 73 – PICP and PCPC Platform System Performance Curve

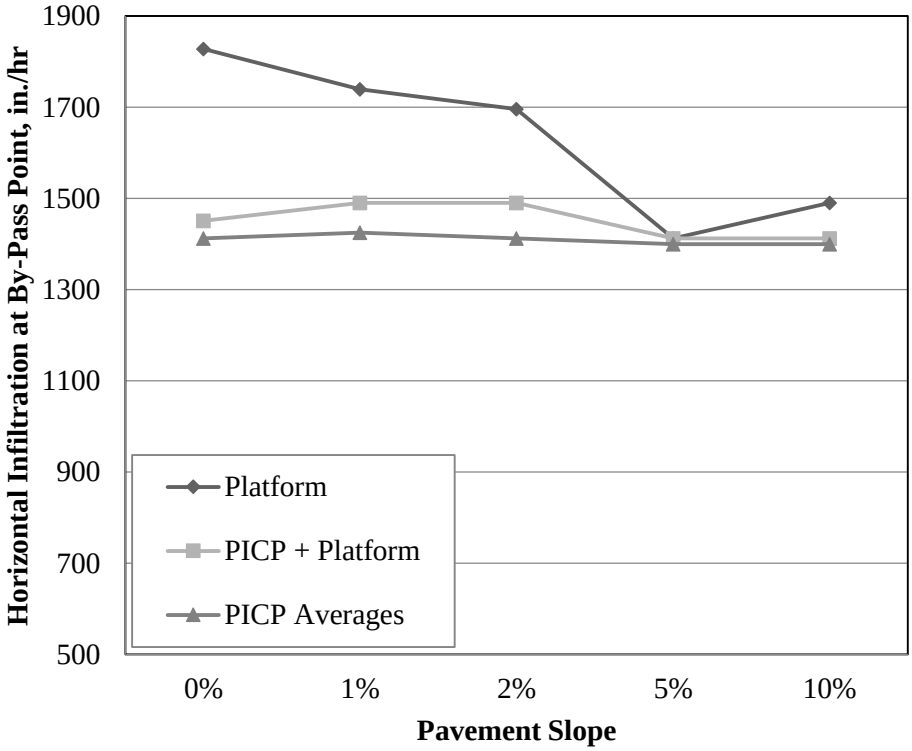


Figure 74 –PICP, PCPC Platform, and 12.5 mm Averages per Payment Slope

The results of the horizontal combined system experiment displays that the infiltration was controlled by the top layer within the experiment. However, as noted in Chapter 5 this may not be the case within the field. It should also be noted that the platform and the pavers and platform system at the higher slopes, 10-5%, displayed cavitation during experimentation as shown in Figure 75. Cavitation across a pavement will display a lower infiltration as indicated in the results. Table 32 displays the horizontal infiltration comparison values.

Table 32 – Horizontal Infiltration at Overflow Point per Pavement Slope

Slope	Platform	Pavers +Platform System Infiltration, in/hr.	Average 12.5 mm Pavers
0%	1827.50	1450.65	1411.97
1%	1739.23	1489.96	1424.87
2%	1696.07	1489.96	1411.97
5%	1411.97	1411.97	1399.29
10%	1489.96	1411.97	1399.29

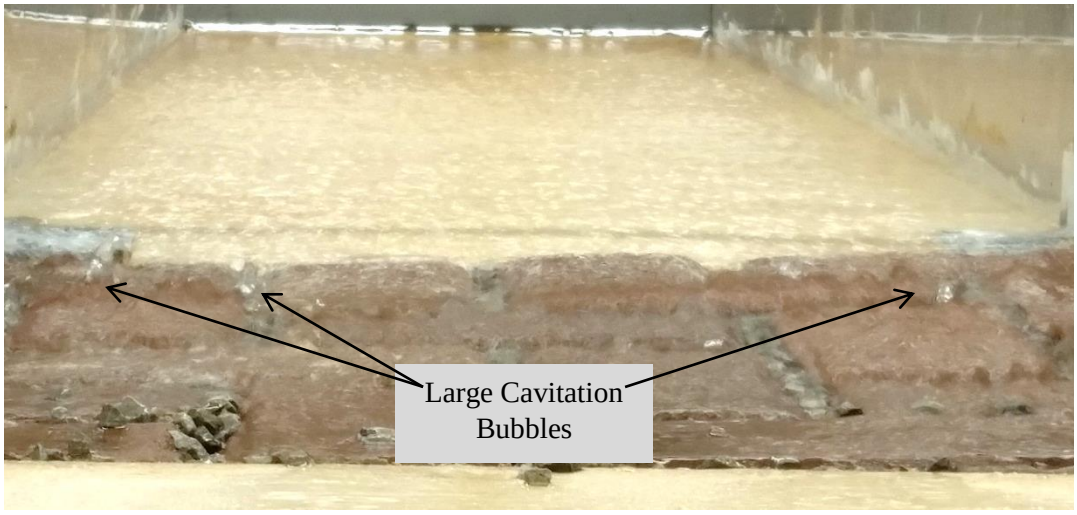


Figure 75 –Cavitation Example 10 % Slope

CHAPTER 8

CONCLUSION AND FUTURE RESEARCH

The environmental benefits of permeable pavements are vast and include stormwater quantity reduction, stormwater quality improvement, urban heat island mitigation, and groundwater recharge, among others. Permeable Interlocking Concrete Pavements explicitly infiltrate water, a new concept to engineering practice for pavements. This technology as a load-carrying surface has not yet been fully characterized nor has the decades of design and performance experience of conventional pavements. This research project developed a hydraulic design methodology for PICPs. Test sections were evaluated in a two layer hydraulic flume to determine infiltration rates, and overflow rates for various block spacing, patterns, and across a broad range of pavement cross slopes. The research results included the following:

- Horizontal infiltration lower than field by about 11-35% (0° slope).
- Development of horizontal infiltration at different hydraulic heads.
- Incipient overflow infiltration identification per gap spacing.
- Infiltration inversely related to cross slope: As slope increases infiltration decreases with a Spearman Rho of -0.91.
- Infiltration reduces significantly per synthetic stormwater application.
- After synthetic stormwater application maintenance the PICP system recaptured about 45% for the 6 mm spacing.
- Research led to the development of a usable Design Tool.

Results showed the infiltration rate of the PICPs exposed to horizontal sheet flow is lower than the measured vertical infiltration rate by 35%-11% which is currently used in field verification. The results also demonstrate that the infiltration discharge rates are inversely related to the cross slope of the pavement with a Spearman Rho of -0.91. The horizontal and vertical infiltration rates were higher than field observations by a factor of three, the data was translated and compared to vertical field observation tests completed in the local Water Services Department of Kansas City Missouri's newly constructed parking lot.

Clogging tests which included the creation of synthetic stormwater for PICP was completed and analyzed. The experimental tests included setting the initial testing discharge to a set flowrate, the rate at which overflow occurs for each of the PICP spacings. The synthetic stormwater was applied at a fixed dry mass amount that was dissipated as the flow was running across each of the three test sections; 6 mm, 10 mm, 12.5 mm straight herringbone pattern. The results indicate an inverse relationship between the amount of stormwater applications and infiltration as expected. Results also indicate that as the applications of stormwater increase the overflow rate increases. Similar to the vertical infiltration tests the clogging loading rates (14,014 mg/l, 16,349 mg/l, and 16,424 mg/l) were higher than previous research (300 mg/l) which is used field data. However, the overall trend of the clogging research matched previous research and as such linear trend line regressions were created and can be used to predict system clogging patterns. After maintenance the PICP system recaptured approximately 45 % of initial infiltration for the 6 mm filler spacing pattern.

Additional research included permeable concrete pavement as an alternative sub-base which displayed infiltration and overflow rates similar to previous 12.5 mm straight

herringbone patter data. This result indicates that for the experimental set up the infiltration and overflow rates are controlled by the surface aggregate and open area. Since Infiltration and overflow rates of the permeable concrete pavement are greater than the controlling PICP, a system which includes the pavement as a sub base layer would be a viable option and would provide greater strength. Experimental results indicated a possible cavitation at the higher pavements slopes indicating that infiltration may possibly be reduced. Future research to further examine these affects and a combination PCPC and PICP system would perhaps expand the use of PICP providing broader applications including perhaps where greater pavement loading is required.

The above described thesis research lead to the creation of the Design Tool, more information provided in the thesis, Hydraulic Design of Interlocking Concrete Pavements by Monica Stochl (Stochl, 2015). Future research that would improve and expand the application of the Tool would include additional spacing, pattern analysis, and additional life cycle analysis such as the experimentation on pollutant reduction. Pattern analysis should include more herringbone 45 degree testing and subway tile patterns which are common in field applications similar to the experimental straight herringbone pattern. Along with pollutant reduction analysis, further horizontal synthetic stormwater flow would expand the life cycle analysis which could aid in the Design Tool as well as overall knowledge of PICP performance.

APPENDIX

Procedures: Unclogged and Clogged

The step by step unclogged experimental procedure was as follows:

Start Up:

1) Make sure head box valve is closed.
2) Turn on Power to pump.
3) Turn on pump.
4) Open pump valve.
5) Open/Unclamp Venturi Tubes.

Record RPM of pump.

Run water through flume for 30 minutes before taking measurements.

Testing:

0% Slope

1) Turn Valve the approximate number of turns required. Record Valve Turns.
2) Wait 2 minutes for flow to stabilize.
3) Read and Record Venturi measurements.
4) Read and Record V notch Weir measurements.
5) Open Valve more and Repeat until desired amount of flow and data points are collected.
6) Clamp and close Venturi Tubes.
7) Close Valve completely.

8) Turn off pump.

1% Slope

1) Jack up flume to hole position number 2.
2) Turn pump back on.
3) Turn Valve the approximate number of turns required. Record Valve Turns.
4) Wait 2 minutes for flow to stabilize.
5) Read and Record Venturi measurements.
6) Read and Record V notch Weir measurements.
7) Open Valve more and Repeat.
8) Clamp and close Venturi Tubes to maintain pressurization.
9) Close Valve completely.
10) Turn off pump.

Repeat Procedure for 2, 5 and 10% slope (Use white separator for 2% Slope).

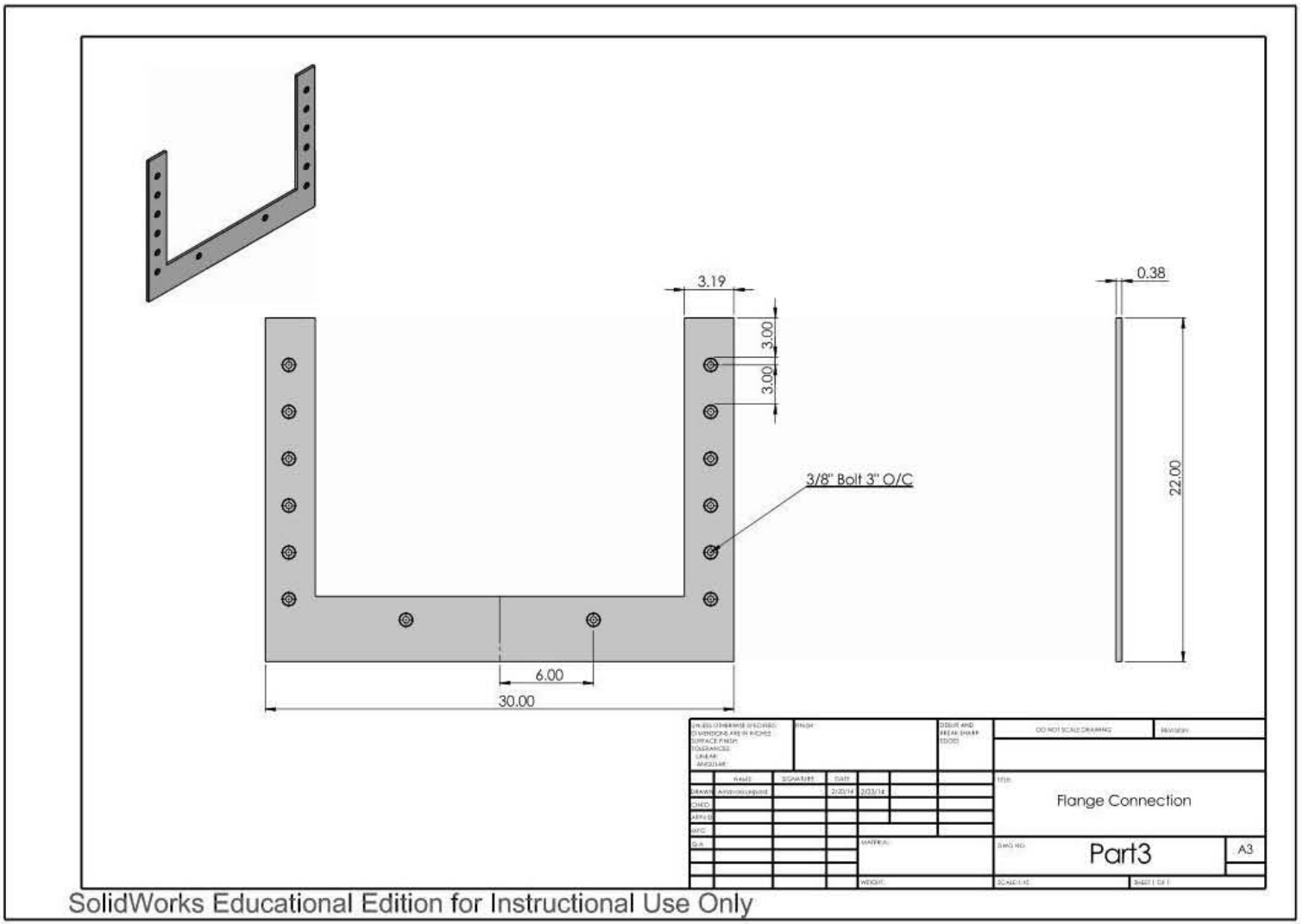
The step by step clogged experimental procedure was as follows:

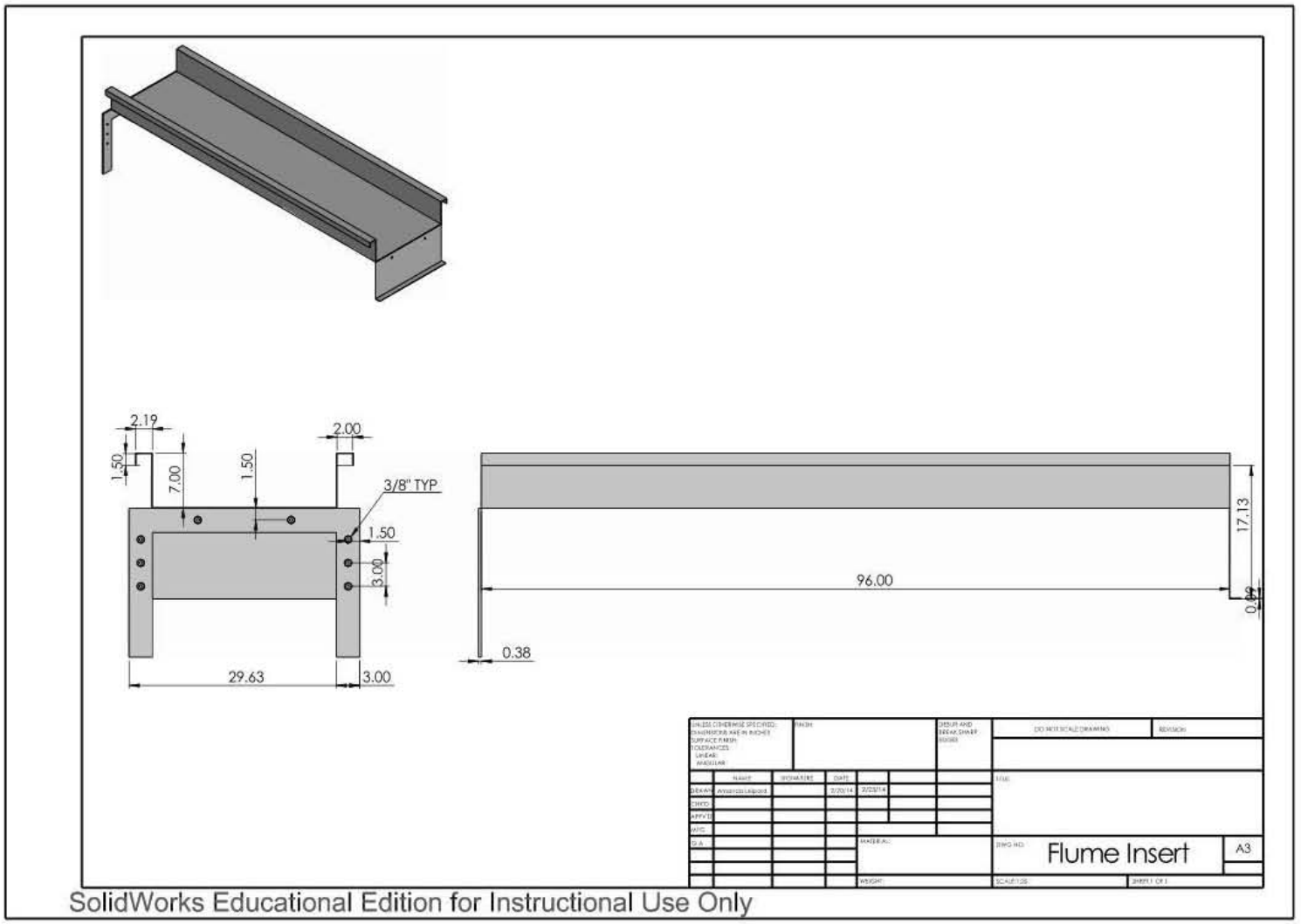
Testing Requirements

1) A regular 5 point (low flow, 50% across section, Overflow, ¼" head, ½" head) Pretest of the section was completed.
2) Testing at each of the three spacing regular pattern set ups at a fixed 1 % pavement slope will be completed till an asymptote upon the infiltration flow rate, cfs, was reached.

3) A set concentration of 500 grams of dry synthetic stormwater will be applied 1-3 feet upstream at a stabilized bypass discharge flow rate. Time between applications will be 2 minutes.

After a test was completed the test will be allowed to dry and a shop vac will be used to remove the top layer of the spacing rock. Additional rock will be replaced and a second test will be completed to determine the effectiveness of this maintenance technique. A 5 point after test of the section was completed.


3.19
3.00
3.00
3/8" Bolt 3" O/C
6.00
30.00
0.38
22.00
Flange Connection
Part3
A3
SolidWorks Educational Edition for Instructional Use Only



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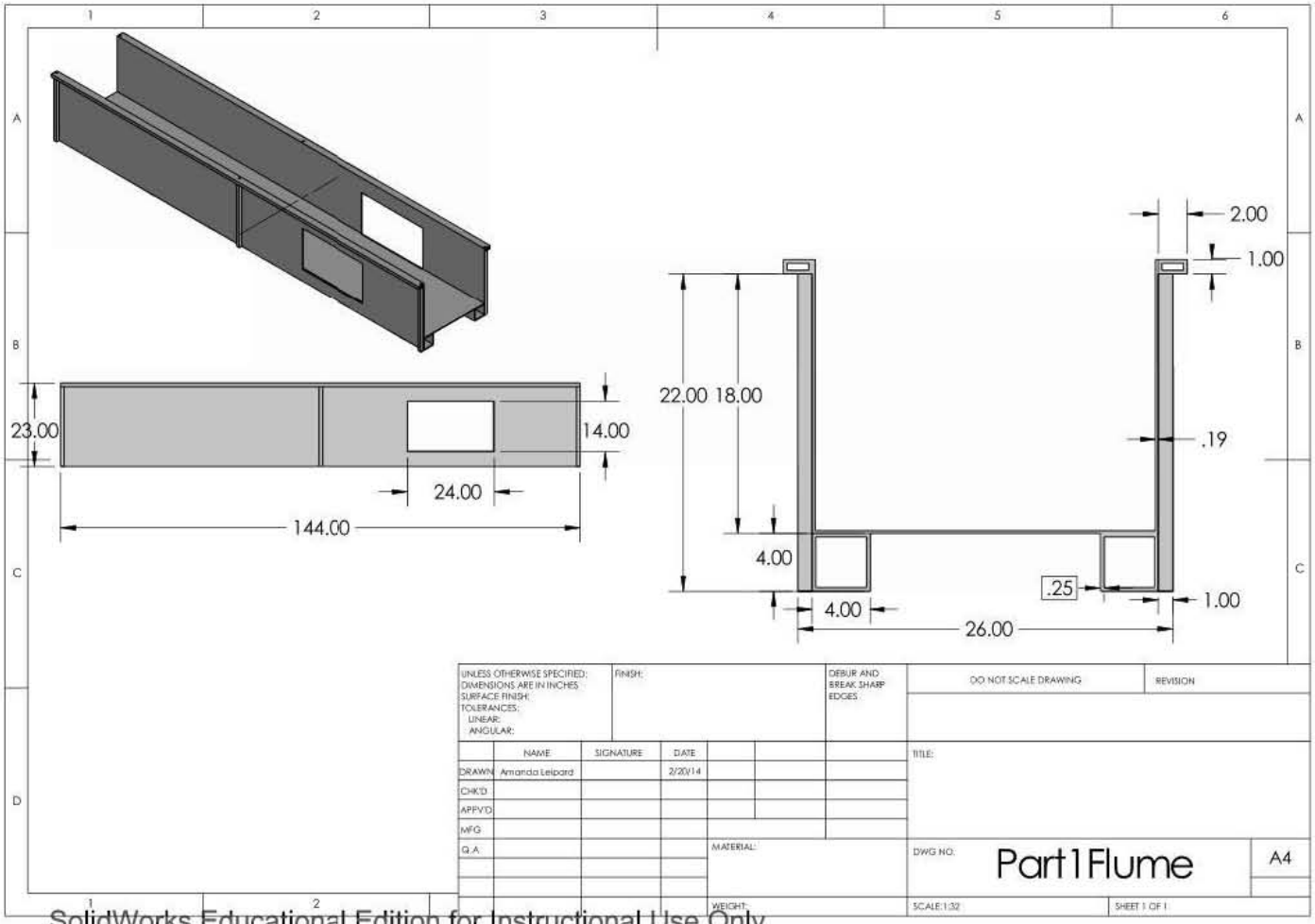

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Appendix B1	
Project	Flume Calibration
Task	Venturi Meter Results
Date	6/10/2014
By	MS

Calibration Bin Dimensions		
Gross WT	lb	90.25
Net WT	lb	86
Volume	ft^3	1.378

		Venturi Calibration		**V-Notch Calibration**				
Run	**Pump @ 42.3 rpm**	**h_1 (in) Left**	**h_2 (in) Right**	**Left /Right**	**Weir (ft)**	**Trial**	**Time (sec)**	**Flow Rate (cfs)**
		0.9	1.2	Left	6.865	1	23.38	
						2	22.78	
						3	23.78	
1	1 turn					Avg	23.31	0.0591
		0.35	0.1	Left	6.765	1	50.65	
						2	49.5	
						3	48.81	
2	1/2 turn					Avg	49.65	0.0278
		0.18	0.1	Left	6.66	1	174.61	
						2	175.66	
						3	174.71	
3	1/4 turn					Avg	174.99	0.0079
		7.15	7.1	Left	7.4	1	11.79	
						2	11.59	
						3	11.35	
						Avg	11.58	0.1191
		7.15	7.1	Right	8.63	1	39.35	
						2	39.02	
						3	38.72	
4	3 turns					Avg	39.03	0.0353
		9.1	9.2	Left	7	1	11.16	
						2	11.61	
						3	11.3	
						Avg	11.36	0.1214
		9.1	9.2	Right	8.65	1	25.2	
						2	26	
						3	26.45	
5	3 1/2 turns					Avg	25.88	0.0532
		1.1	0.9	Left	6.86	1	23.36	
						2	23.76	
						3	23.91	
6	1/2 turn					Avg	23.68	0.0582
		0.3	0.1	Left	6.76	1	52.51	

		Venturi Calibration		V-Notch Calibration				
Run	Pump @ 42.3 rpm	h_1 (in) Left	h_2 (in) Right	Left /Right	Weir (ft)	Trial	Time (sec)	Flow Rate (cfs)
						2	53	
						3	53.76	
7	1/3 turn					Avg	53.09	0.0260
		0.2	0	Left	6.69	1	101.26	
						2	100.98	
						3	100.01	
8	1/4 turn					Avg	100.75	0.0137
		3.15	3	Left	6.92	1	16.9	
						2	16.46	
						3	15.96	
						Avg	16.44	0.0838
		3.15	3	Right	8.53	1	80.03	
						2	80.45	
						3	78.51	
9	1 turns					Avg	79.66	0.0173
		10.2	10	Left	6.94	1	14.3	
						2	14.2	
						3	14.08	
						Avg	14.19	0.0971
		10.2	10	Right	8.72	1	15.68	
						2	15.6	
						3	15.65	
10	2 turns					Avg	15.64	0.0881
		10.5	10.35	Left	6.935	1	14.75	
						2	14.93	
						3	14.85	
						Avg	14.84	0.0929
		10.5	10.35	Right	8.75	1	14.55	
						2	14.55	
	2 1/2					3	14.51	
11	turns					Avg	14.54	0.0948
		10.7	10.55	Left	6.935	1	15.33	
						2	15.11	
						3	15.1	
						Avg	15.18	0.0908
		10.7	10.55	Right	8.77	1	13.58	
						2	13.48	
	3 1/2					3	13.76	
12	turns					Avg	13.61	0.1013
		0.7	0.5	Left	6.83	1	31.71	
						2	31.55	
						3	32.5	
13	1/2 turn					Avg	31.92	0.0432
		0.6	0.4	Left	6.865	1	22.7	

		Venturi Calibration		V-Notch Calibration				
Run	Pump @ 42.3 rpm	h_1 (in) Left	h_2 (in) Right	Left /Right	Weir (ft)	Trial	Time (sec)	Flow Rate (cfs)
						2	22.93	
						3	22.96	
						Avg	22.86	0.0603
		0.6	0.4	Right	8.495	1	130.35	
						2	129.55	
						3	126.73	
14	3/4 turn					Avg	128.88	0.0107
		2.85	2.65	Left	6.885	1	21.29	
						2	20.9	
						3	21.13	
						Avg	21.11	0.0653
		2.85	2.65	Right	8.59	1	46.13	
						2	45.98	
						3	45.78	
15	1 turns					Avg	45.96	0.0300
		4.25	4.05	Left	6.895	1	19.91	
						2	19.78	
						3	19.91	
						Avg	19.87	0.0694
		4.25	4.05	Right	8.645	1	29.01	
						2	28.56	
	1 1/4					3	29.31	
16	turns					Avg	28.96	0.0476
		8.1	7.9	Left	6.9	1	18.91	
						2	18.96	
						3	18.9	
						Avg	18.92	0.0728
		8.1	7.9	Right	8.745	1	15.18	
						2	15	
	1 1/2					3	14.85	
17	turns					Avg	15.01	0.0918
		9.3	9	Left	6.91	1	18.18	
						2	18.81	
						3	18.53	
						Avg	18.51	0.0745
		9.3	9	Right	8.765	1	13.15	
						2	13.28	
	1 3/4					3	13.23	
18	turns					Avg	13.22	0.1043
		9.6	9.4	Left	6.905	1	18.83	
						2	19.05	
						3	19.01	
						Avg	18.96	0.0727
		9.6	9.4	Right	8.775	1	12.86	

		Venturi Calibration		V-Notch Calibration				
Run	Pump @ 42.3 rpm	h_1 (in) Left	h_2 (in) Right	Left /Right	Weir (ft)	Trial	Time (sec)	Flow Rate (cfs)
						2	12.85	
						3	13.05	
19	2 turn					Avg	12.92	0.1067
		10.1	9.8	Left	6.9	1	18.75	
						2	18.53	
						3	18.63	
						Avg	18.64	0.0740
		10.1	9.8	Right	8.775	1	12.36	
						2	12.15	
	2 1/2					3	12	
20	turns					Avg	12.17	0.1132
		10.35	10.15	Left	6.9	1	19.46	
						2	19.33	
						3	19.28	
						Avg	19.36	0.0712
		10.35	10.15	Right	8.8	1	11.88	
						2	12.03	
						3	11.66	
21	3 turns					Avg	11.86	0.1162
		0.6	0.4	Left	6.82	1	34.76	
						2	34.91	
						3	35.3	
22	1/4 turn					Avg	34.99	0.0394
		0.55	0.35	Left	6.805	1	35.48	
						2	35.25	
						3	35.7	
23	1/4 turn					Avg	35.48	0.0388
		0.3	0.1	Left	6.765	1	49.51	
						2	50.03	
						3	50.06	
24	1/8 turn					Avg	49.87	0.0276
		1.2	1.5	Left	6.845	1	25.7	
						2	25.71	
						3	25.75	
						Avg	25.72	0.0536
		1.2	1.5	Right	8.545	1	67.03	
						2	67.12	
						3	66.66	
25	1/2 turn					Avg	66.94	0.0206
		2.7	2.5	Left	6.85	1	24.5	
						2	24.36	
						3	24.28	
						Avg	24.38	0.0565
		2.7	2.5	Right	8.61	1	38.9	

		Venturi Calibration		V-Notch Calibration				
Run	Pump @ 42.3 rpm	h_1 (in) Left	h_2 (in) Right	Left /Right	Weir (ft)	Trial	Time (sec)	Flow Rate (cfs)
						2	38.18	
						3	38.06	
26	3/4 turns					Avg	38.38	0.0359
		4.05	3.9	Left	6.865	1	22.58	
						2	22.88	
						3	23.01	
						Avg	22.82	0.0604
		4.05	3.9	Right	8.66	1	25.63	
						2	25.8	
						3	25.8	
27	1 turns					Avg	25.74	0.0535
		6.8	6.55	Left	6.87	1	22.01	
						2	21.96	
						3	21.71	
						Avg	21.89	0.0630
		6.8	6.55	Right	8.73	1	15.9	
						2	16.46	
	1 1/4					3	16.33	
28	turns					Avg	16.23	0.0849
		7.95	7.8	Left	6.875	1	21.63	
						2	21.76	
						3	21.9	
						Avg	21.76	0.0633
		7.95	7.8	Right	8.765	1	13.71	
						2	14.08	
	1 1/2					3	13.98	
29	turns					Avg	13.92	0.0990
		8.75	8.5	Left	6.88	1	21.56	
						2	21.63	
						3	22.35	
						Avg	21.85	0.0631
		8.75	8.5	Right	8.77	1	12.48	
						2	12.48	
						3	12.38	
30	1 3/4 turn					Avg	12.45	0.1107

Appendix B2	
Project	Flume Calibration
Task	Venturi Meter Check
Date	6/10/2014
By	MS

Removed as outlier

Run	Q (cfs)	Δh_{merium} (ft)	$\Delta h_{FT,H20}$ (ft)	$C_D A_O$ (ft^2)	C_D
1	0.0591	2.1	0.341	0.0126	1.025
2	0.0278	0.45	0.073	0.0128	1.040
3	0.0079	0.28	0.046	0.0046	0.374
4	0.1544	14.25	2.316	0.0126	1.028
5	0.1746	18.3	2.974	0.0126	1.026
6	0.0582	2	0.325	0.0127	1.034
7	0.0260	0.4	0.065	0.0127	1.032
8	0.0137	0.2	0.033	0.0095	0.769
9	0.1011	6.15	0.999	0.0126	1.025
10	0.1852	20.2	3.283	0.0127	1.036
11	0.1877	20.85	3.388	0.0127	1.033
12	0.1921	21.25	3.453	0.0129	1.047
13	0.0432	1.2	0.195	0.0122	0.991
14	0.0710	1	0.163	0.0219	1.784
15	0.0953	5.5	0.894	0.0126	1.021
16	0.1170	8.3	1.349	0.0125	1.020
17	0.1647	16	2.600	0.0127	1.034
18	0.1787	18.3	2.974	0.0129	1.050
19	0.1793	19	3.088	0.0127	1.034
20	0.1872	19.9	3.234	0.0130	1.055
21	0.1874	20.5	3.331	0.0128	1.040
22	0.0394	1	0.163	0.0122	0.990
23	0.0388	0.9	0.146	0.0127	1.029
24	0.0276	0.4	0.065	0.0135	1.098
25	0.0742	2.7	0.439	0.0140	1.134
26	0.0924	5.2	0.845	0.0125	1.019
27	0.1139	7.95	1.292	0.0125	1.015
28	0.1479	13.35	2.169	0.0125	1.017
29	0.1623	15.75	2.559	0.0126	1.028
30	0.1738	17.25	2.803	0.0129	1.052
Average	0.1094	-	-	0.0127	1.029

Appendix B2	
Project	Flume Calibration
Task	Left V-Notch Check
Date	6/10/2014
By	MS

Removed as outlier

Run	Q (cfs)	ΔH (ft)	ΔH^2.5	Q/ΔH^2.5	C_D
1	0.0591	0.325	0.185	0.319	0.278
2	0.0278	0.225	0.024	1.156	1.008
3	0.0079	0.12	0.005	1.579	1.377
4	0.1191	0.86	0.686	0.174	0.151
5	0.1214	0.46	0.144	0.846	0.737
6	0.0582	0.32	0.058	1.005	0.876
7	0.0260	0.22	0.023	1.144	0.997
8	0.0137	0.15	0.009	1.570	1.369
9	0.0838	0.38	0.089	0.942	0.821
10	0.0971	0.4	0.101	0.960	0.837
11	0.0929	0.395	0.098	0.947	0.826
12	0.0908	0.395	0.098	0.926	0.807
13	0.0432	0.29	0.045	0.953	0.831
14	0.0603	0.325	0.060	1.001	0.873
15	0.0653	0.345	0.070	0.934	0.814
16	0.0694	0.355	0.075	0.924	0.806
17	0.0728	0.36	0.078	0.937	0.817
18	0.0745	0.37	0.083	0.894	0.780
19	0.0727	0.365	0.080	0.903	0.787
20	0.0740	0.36	0.078	0.951	0.829
21	0.0712	0.36	0.078	0.916	0.798
22	0.0394	0.28	0.041	0.949	0.828
23	0.0388	0.265	0.036	1.075	0.937
24	0.0276	0.225	0.024	1.151	1.004
25	0.0536	0.305	0.051	1.043	0.909
26	0.0565	0.31	0.054	1.057	0.921
27	0.0604	0.325	0.060	1.003	0.874
28	0.0630	0.33	0.063	1.006	0.877
29	0.0633	0.335	0.065	0.975	0.850
30	0.0631	0.34	0.067	0.936	0.816
Average	0.0622	-	-	0.9724	0.848

Appendix B2	
Project	Flume Calibration
Task	Left V-Notch Check
Date	6/10/2014
By	MS

Removed as outlier

Run	Q (cfs)	ΔH (ft)	ΔH^2.5	Q/ΔH^2.5	C_D
4	0.0353	0.29	0.045	0.780	0.680
5	0.0532	0.31	0.054	0.995	0.868
9	0.0173	0.19	0.016	1.099	0.959
10	0.0881	0.38	0.089	0.990	0.863
11	0.0948	0.41	0.108	0.881	0.768
12	0.1013	0.43	0.121	0.835	0.728
14	0.0107	0.155	0.009	1.131	0.986
15	0.0300	0.25	0.031	0.960	0.837
16	0.0476	0.305	0.051	0.926	0.808
17	0.0918	0.405	0.104	0.880	0.767
18	0.1043	0.425	0.118	0.885	0.772
19	0.1067	0.435	0.125	0.855	0.745
20	0.1132	0.435	0.125	0.907	0.791
21	0.1162	0.46	0.144	0.810	0.706
25	0.0206	0.205	0.019	1.082	0.944
26	0.0359	0.27	0.038	0.948	0.827
27	0.0535	0.32	0.058	0.924	0.806
28	0.0849	0.39	0.095	0.894	0.780
29	0.0990	0.425	0.118	0.841	0.733
30	0.1107	0.43	0.121	0.913	0.796
Average	0.0708	-	-	0.9268	0.808

Block - Single	
Width (in)	4
Length (in)	8
Total Area (sqin	32

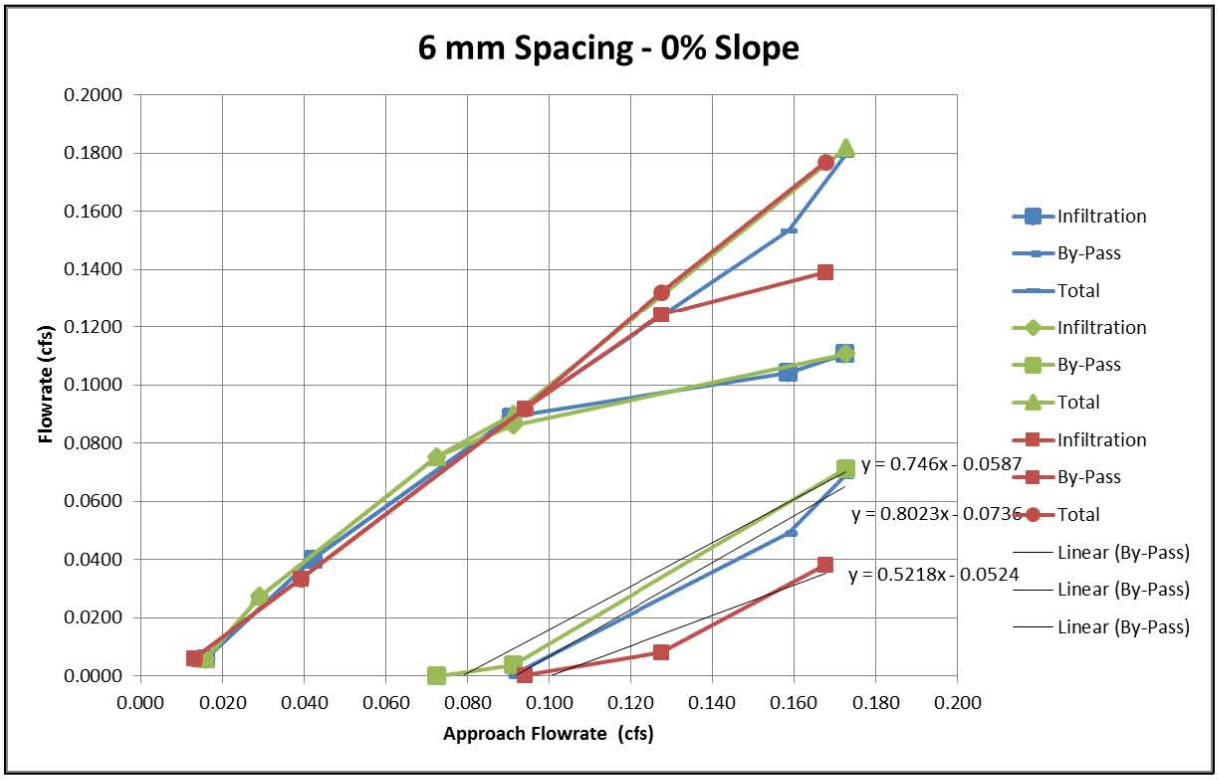
Spacer			
Width (mm)	6	10	12.5
Width (in)	0.24	0.39	0.49

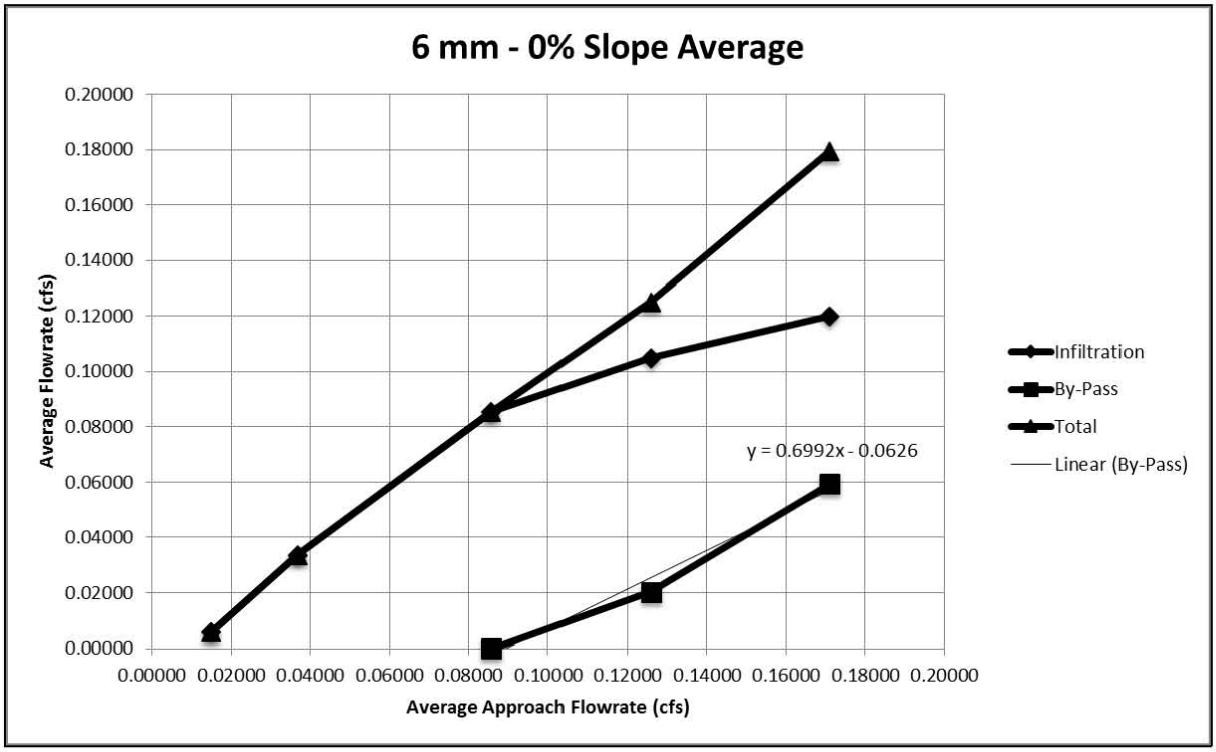
Total Area			
Width (in)	24	24	24
Length (in)	24.75	25	25.5
Total Area (sqin	594	600	612

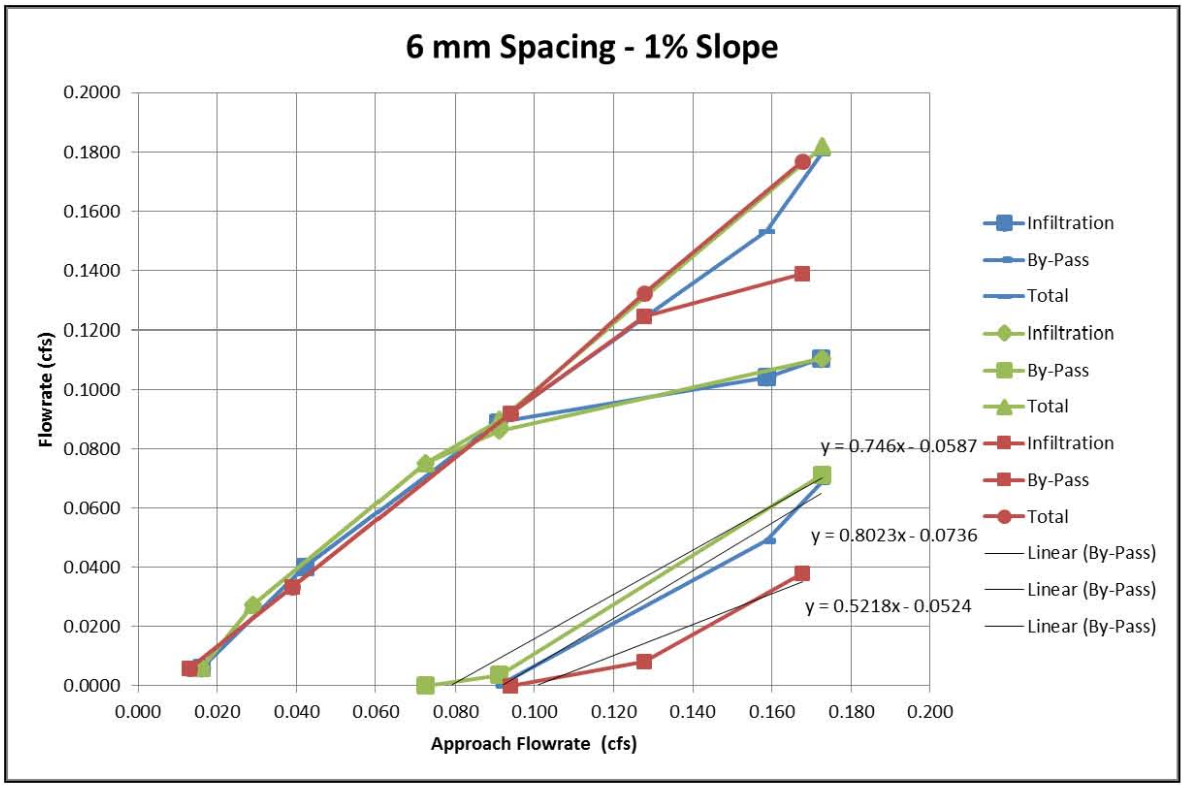
Block Area			
No Full	13	12	12
Full Area	416	384	384
N, S, W			
N Length	3.81	3.43	3.53
S Length	0.00	3.43	3.53
W Length	0.00	4.00	4.00
N Area	15.22	13.70	14.13
S Area	0.00	13.70	14.13
W Area	0.00	16.00	16.00
East			
E 1/2/5 Length	7.06	6.43	6.03
E 3/4 Length	3.06	2.43	2.03
E 1 Area	28.22	25.70	24.13
E 2 Area	28.22	25.70	24.13
E 3 Area	24.44	19.40	16.25
E 4 Area	12.22	9.70	8.13
E 5 Area	28.22	25.70	24.13

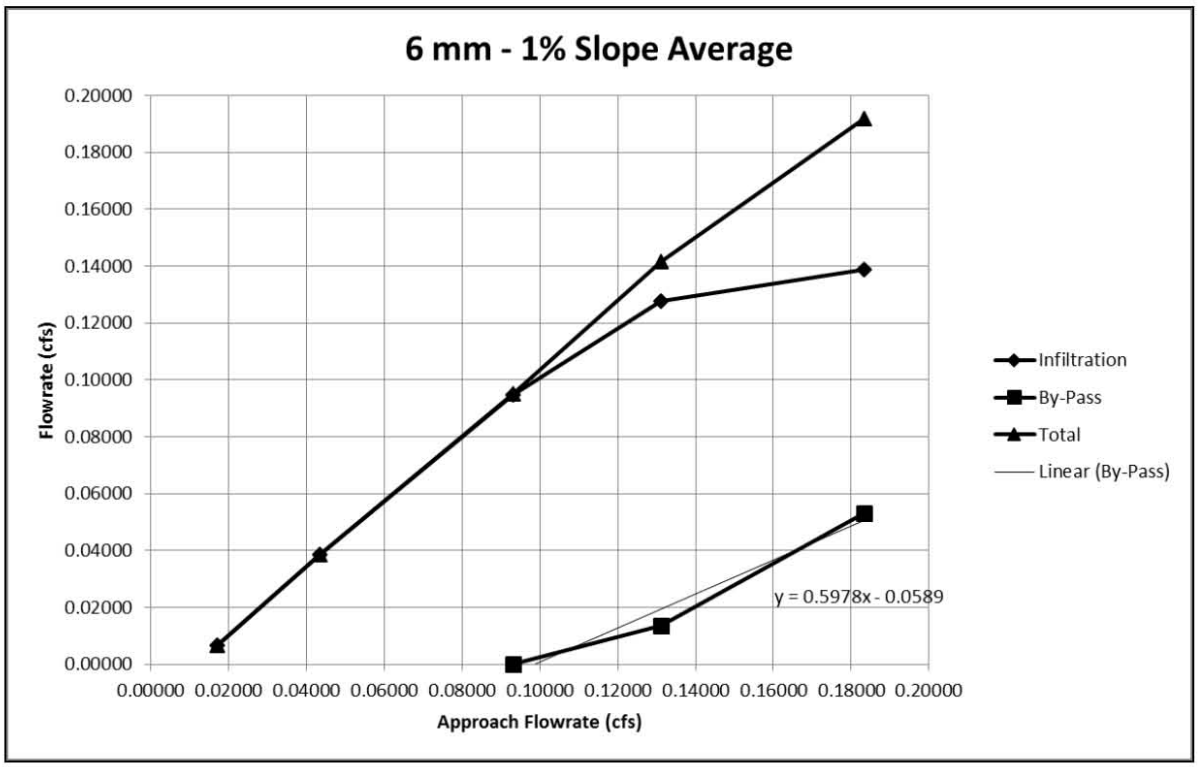
Pervious Area	552.54	533.61	525.01
Imperious Area	41.46	66.39	86.99
% Pervious	93.0	88.9	85.8
% Impervious	7.0	11.1	14.2

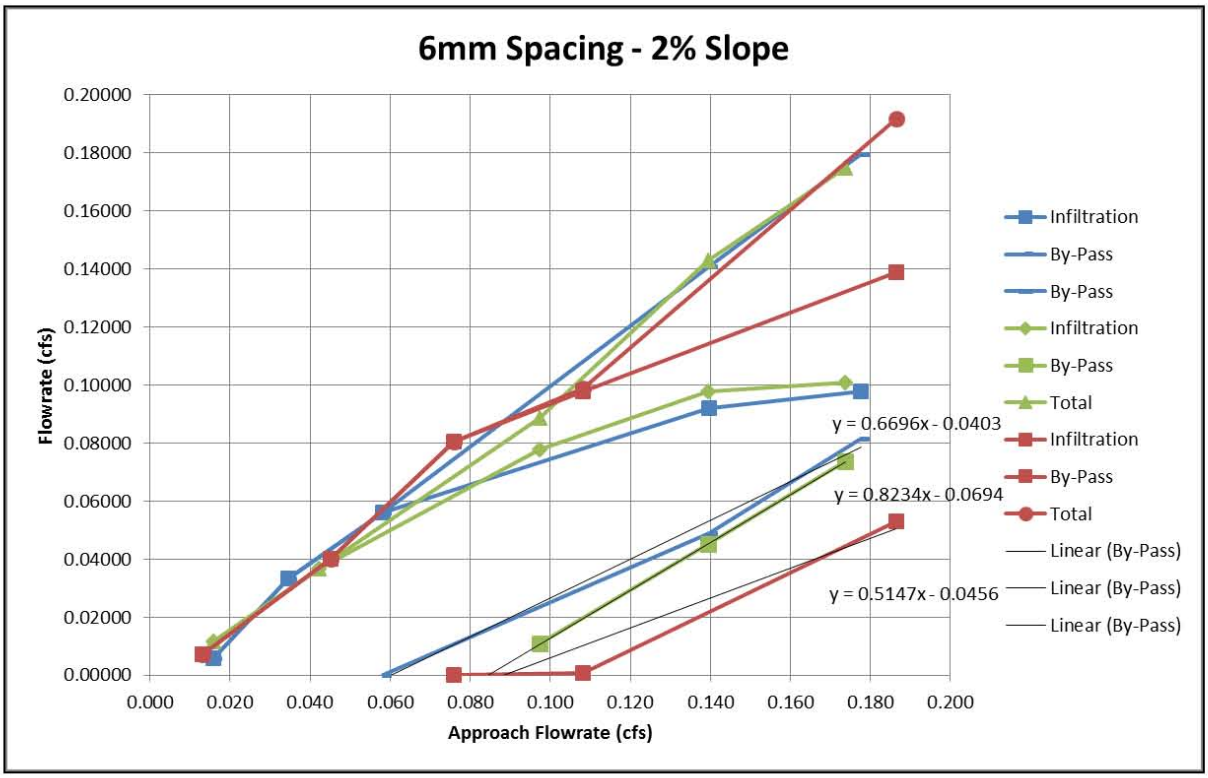
Input
Calculated
Constant
Title
Output

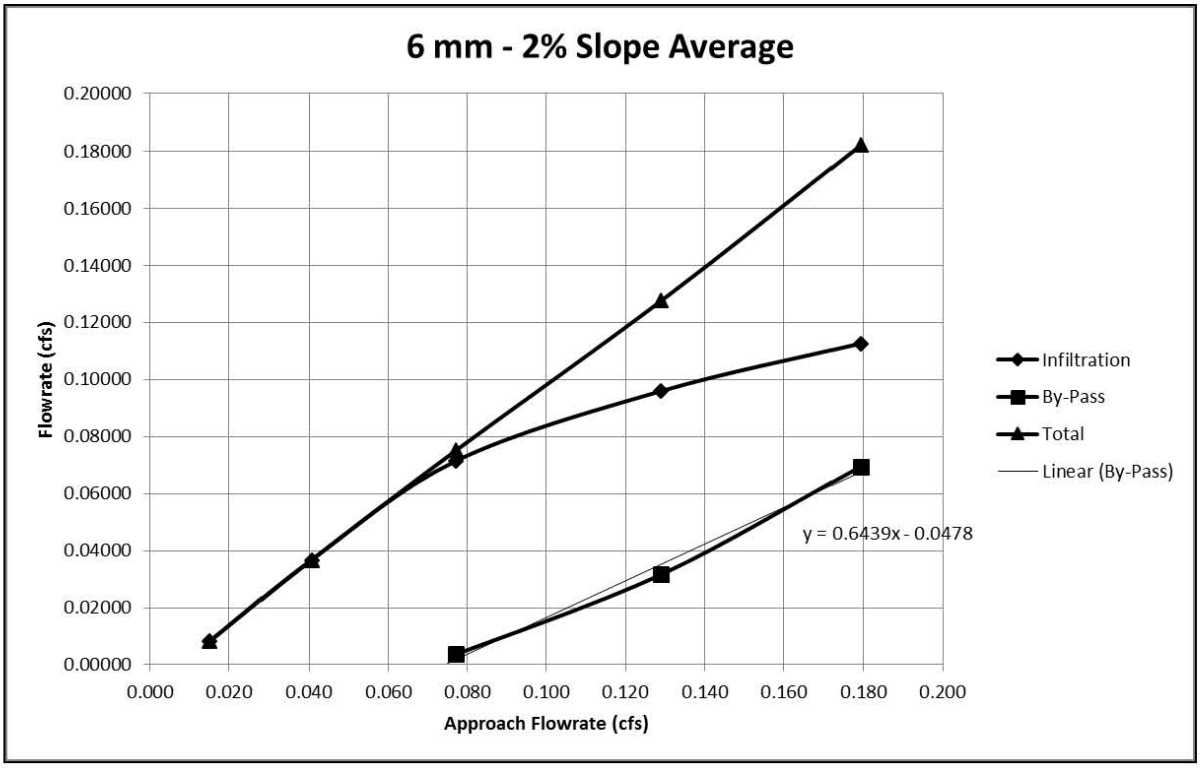

6 mm Spacing - 0% Slope
Flowrate (cfs)
0.2000
0.1800
0.1600
0.1400
0.1200
0.1000
0.0800
0.0600
0.0400
0.0200
0.0000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
Approach Flowrate (cfs)
y = 0.746x - 0.0587
y = 0.8023x - 0.0736
y = 0.5218x - 0.0524
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

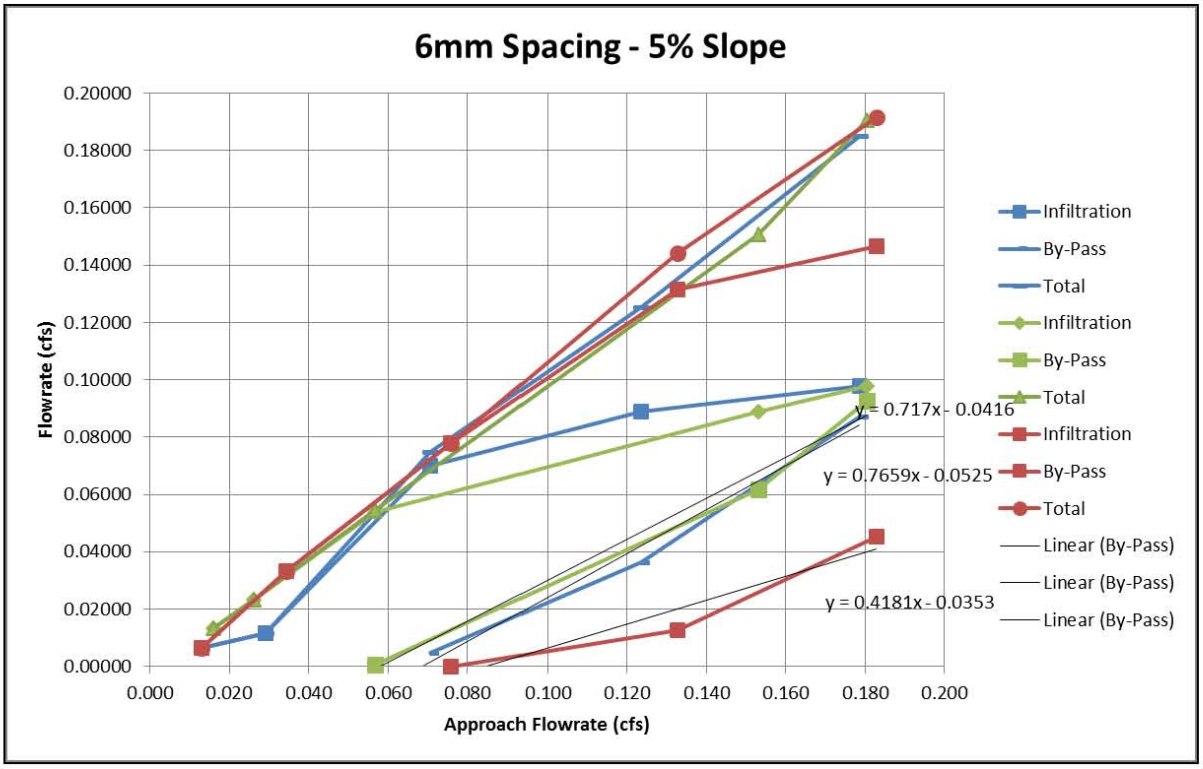

6 mm - 0% Slope Average
Average Flowrate (cfs)
0.20000
0.18000
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
0.00000
0.02000
0.04000
0.06000
0.08000
0.10000
0.12000
0.14000
0.16000
0.18000
0.20000
Average Approach Flowrate (cfs)
y = 0.6992x - 0.0626
Infiltration
By-Pass
Total
Linear (By-Pass)

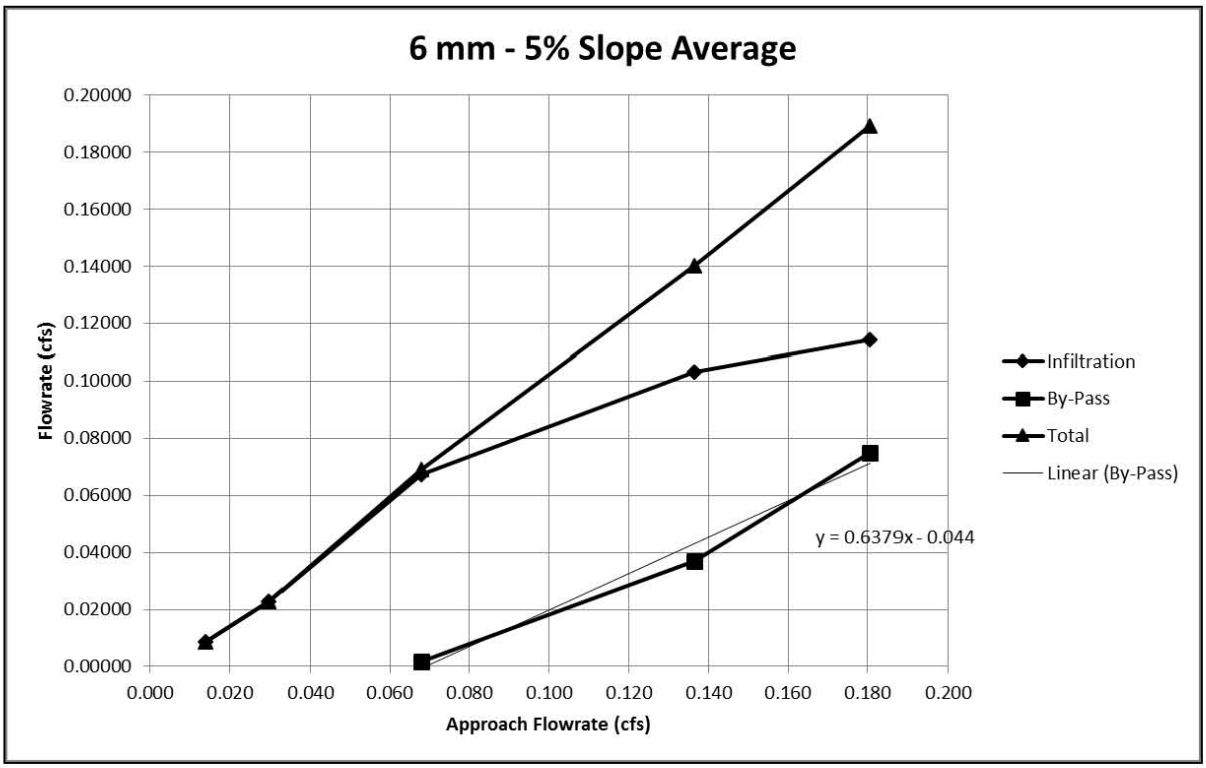

6 mm Spacing - 1% Slope
Flowrate (cfs)
0.2000
0.1800
0.1600
0.1400
0.1200
0.1000
0.0800
0.0600
0.0400
0.0200
0.0000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
Approach Flowrate (cfs)
y = 0.746x - 0.0587
y = 0.8023x - 0.0736
y = 0.5218x - 0.0524
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

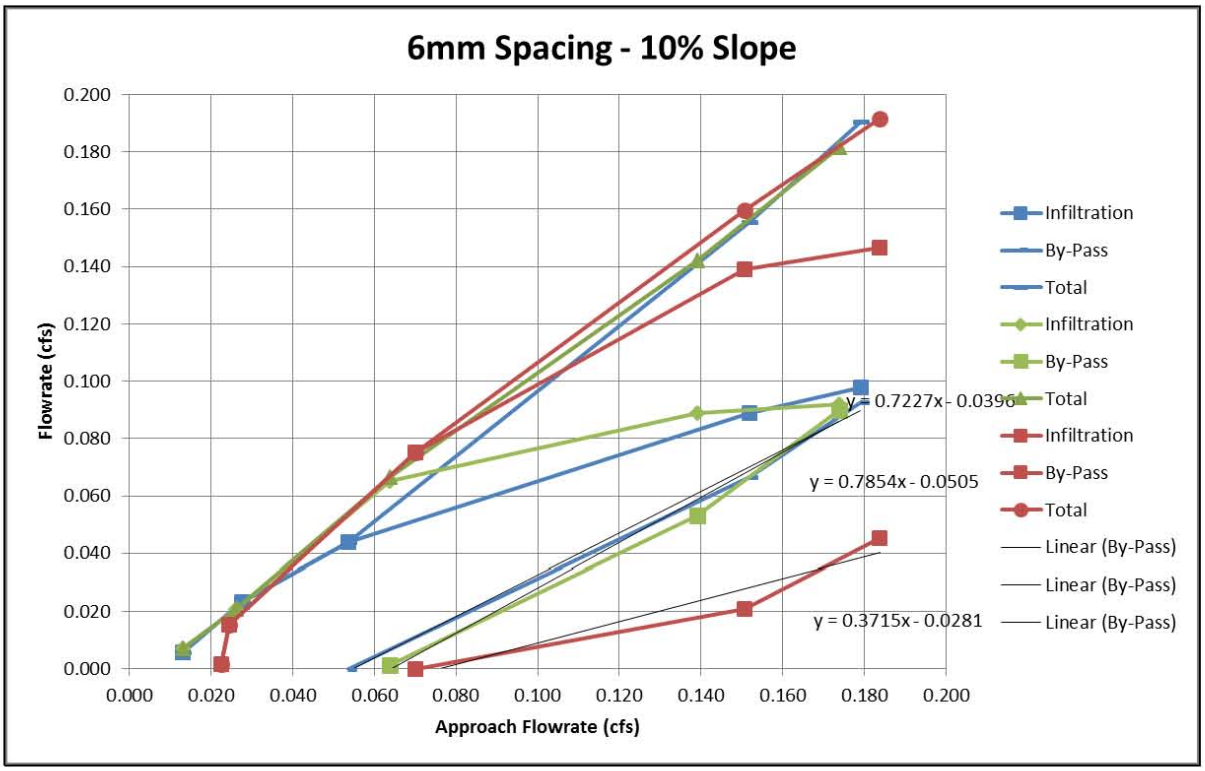

6 mm - 1% Slope Average
Flowrate (cfs)
0.20000
0.18000
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
0.00000
0.02000
0.04000
0.06000
0.08000
0.10000
0.12000
0.14000
0.16000
0.18000
0.20000
Approach Flowrate (cfs)
y = 0.5978x - 0.0589
Infiltration
By-Pass
Total
Linear (By-Pass)

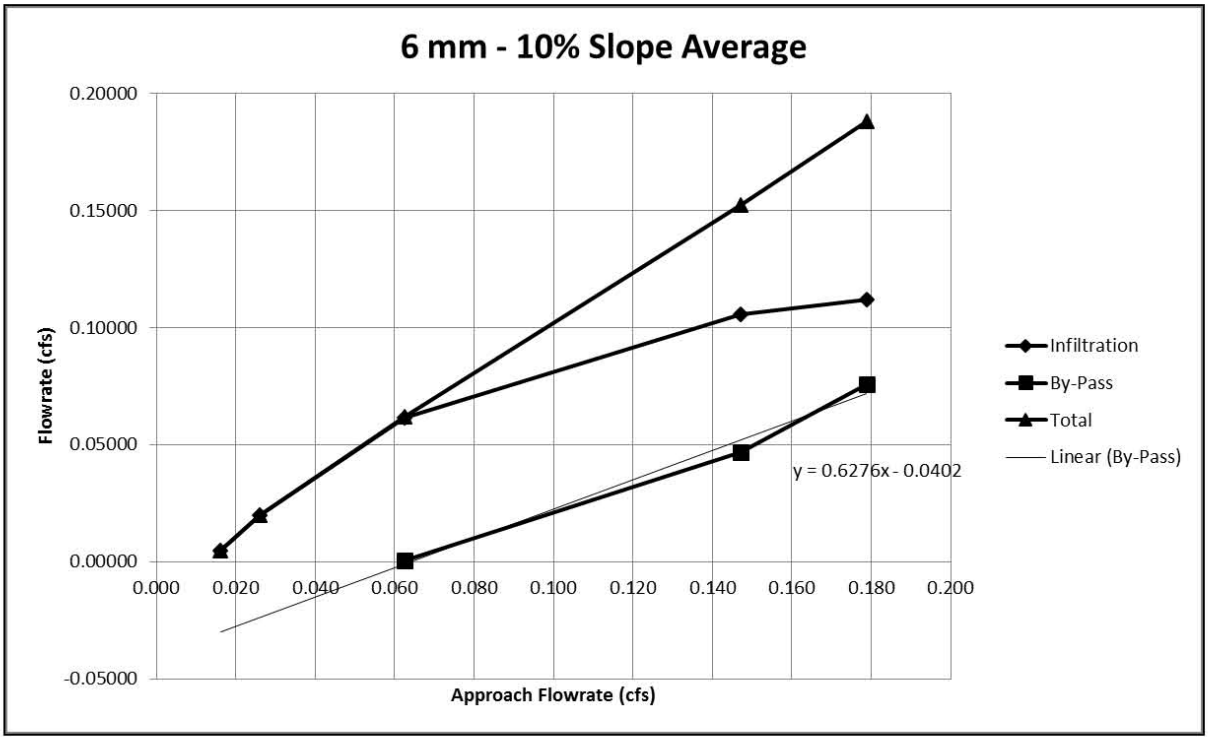

6mm Spacing - 2% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.20000
0.18000
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.6696x - 0.0403
y = 0.8234x - 0.0694
y = 0.5147x - 0.0456
Infiltration
By-Pass
By-Pass
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

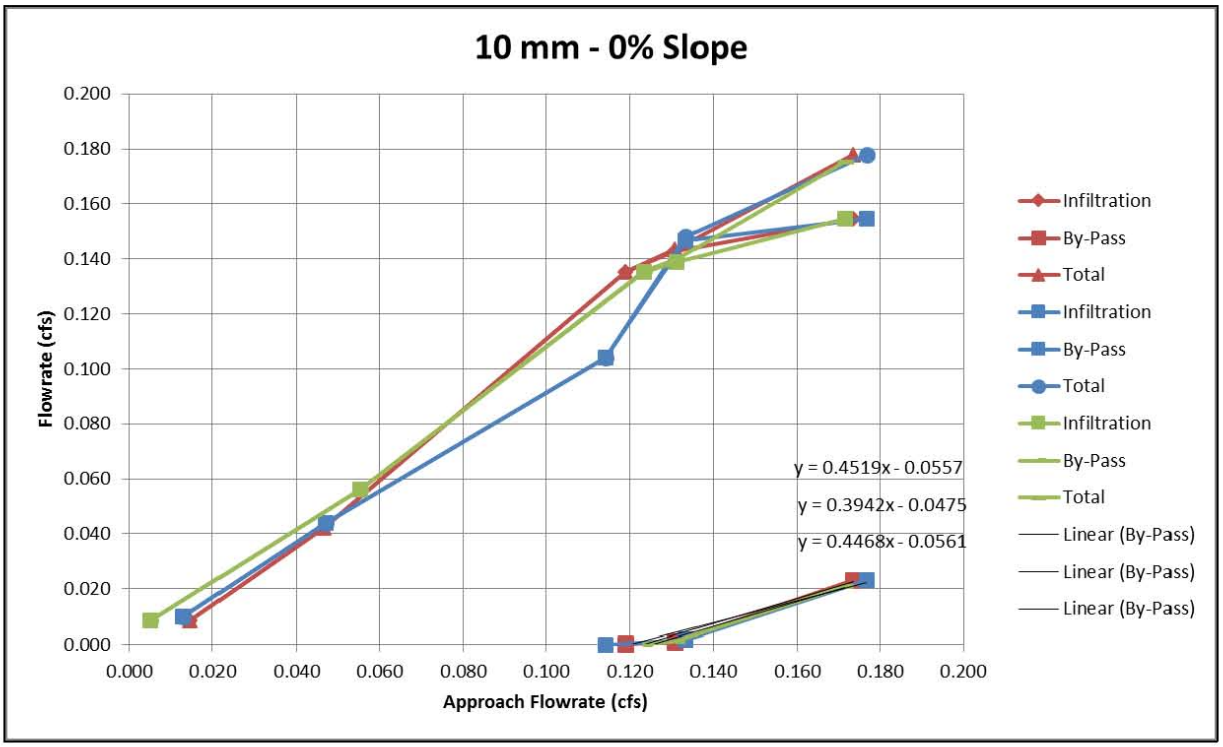

6 mm - 2% Slope Average
Flowrate (cfs)
Approach Flowrate (cfs)
0.20000
0.18000
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.6439x - 0.0478
Infiltration
By-Pass
Total
Linear (By-Pass)

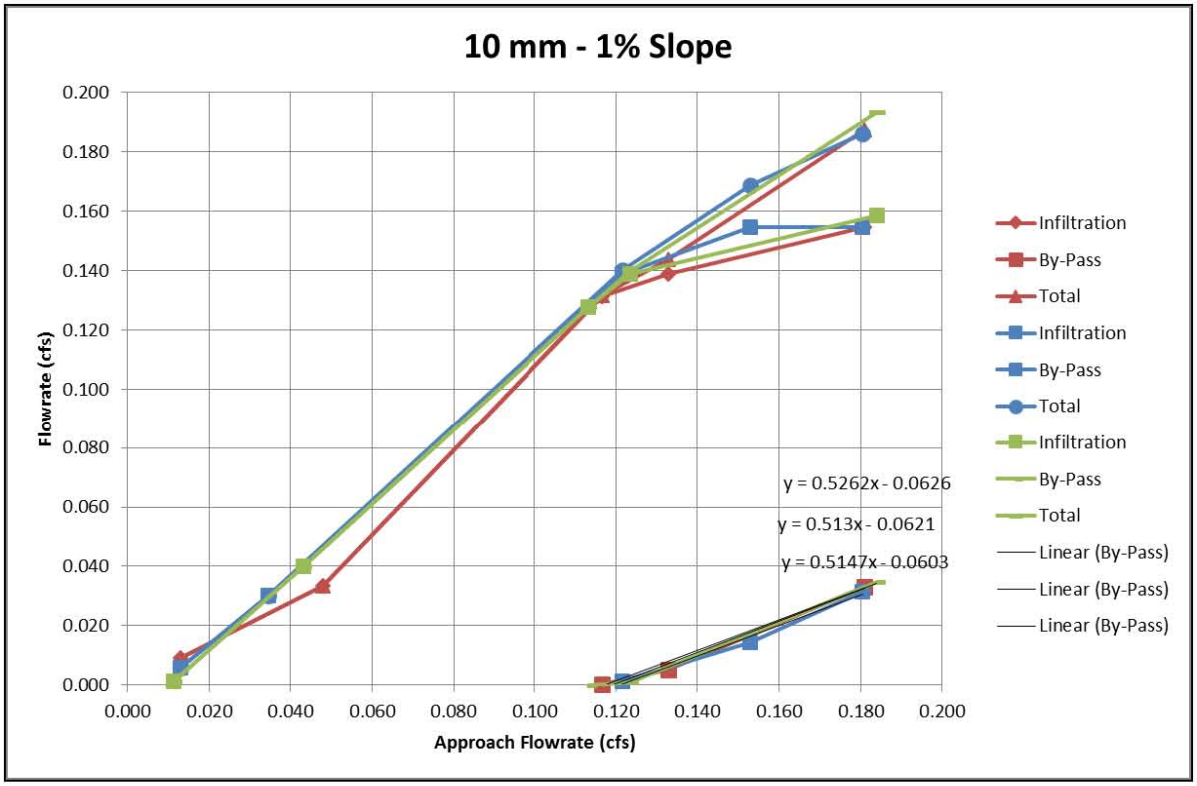

6mm Spacing - 5% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.20000
0.18000
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.717x - 0.0416
y = 0.7659x - 0.0525
y = 0.4181x - 0.0353
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

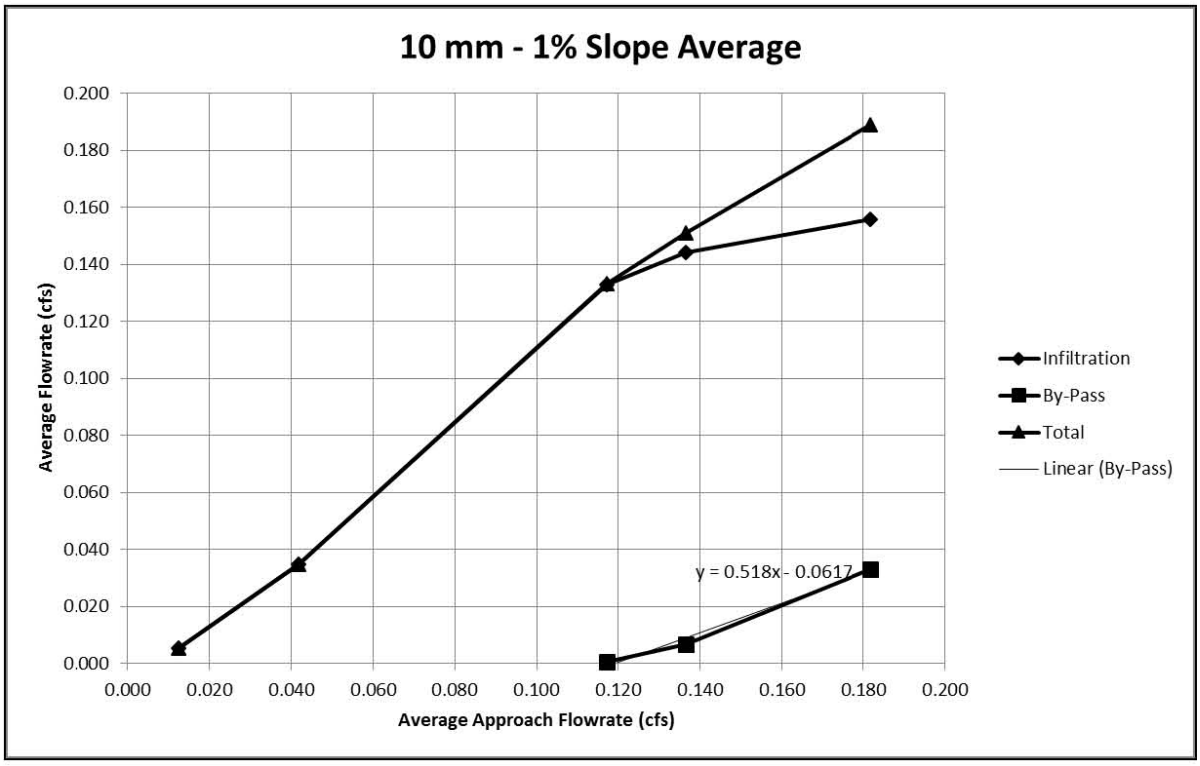

6 mm - 5% Slope Average
Flowrate (cfs)
Approach Flowrate (cfs)
0.20000
0.18000
0.16000
0.14000
0.12000
0.10000
0.08000
0.06000
0.04000
0.02000
0.00000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.6379x - 0.044
Infiltration
By-Pass
Total
Linear (By-Pass)

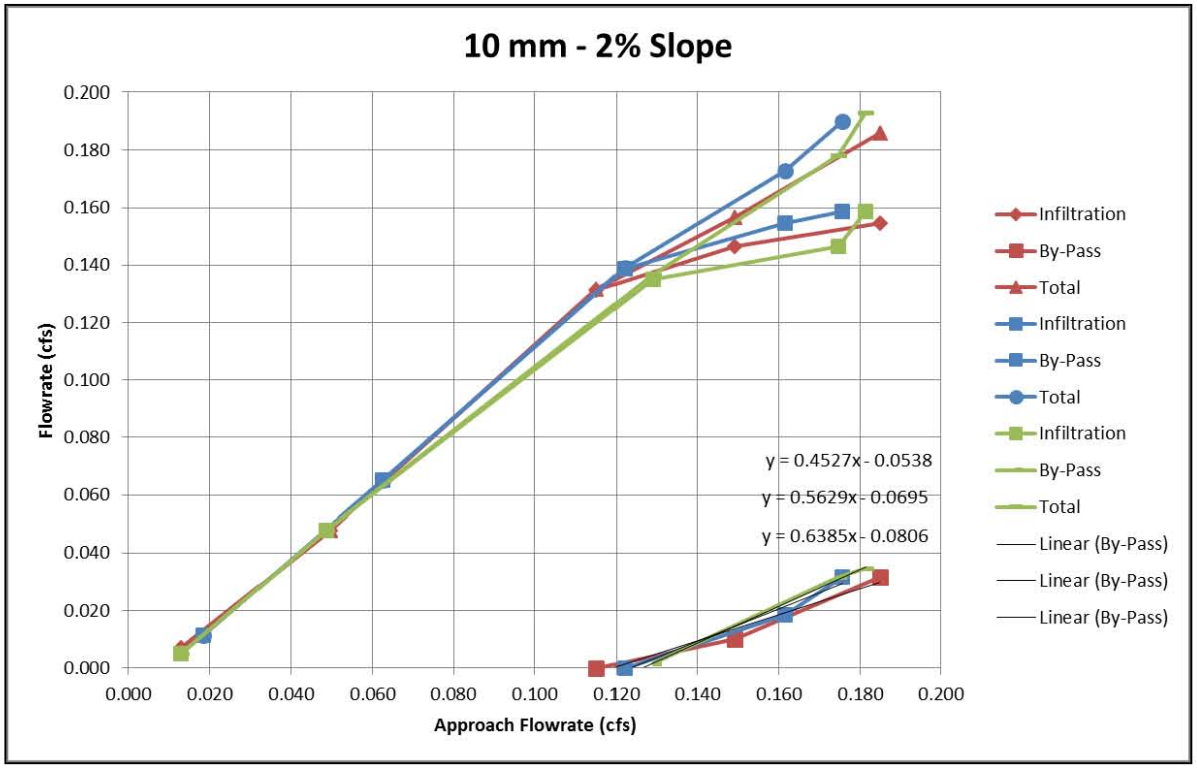

6mm Spacing - 10% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.7227x - 0.0396
y = 0.7854x - 0.0505
y = 0.3715x - 0.0281
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

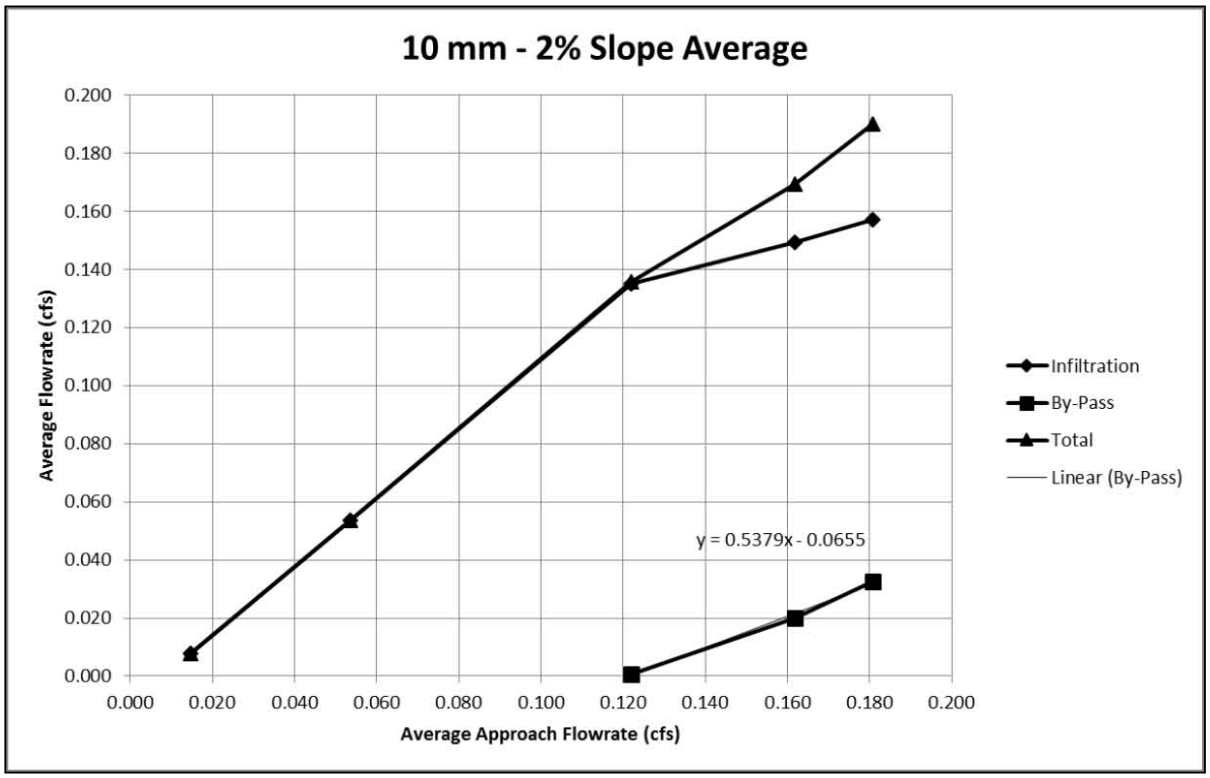

6 mm - 10% Slope Average
Flowrate (cfs)
Approach Flowrate (cfs)
0.20000
0.15000
0.10000
0.05000
0.00000
-0.05000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.6276x - 0.0402
Infiltration
By-Pass
Total
Linear (By-Pass)

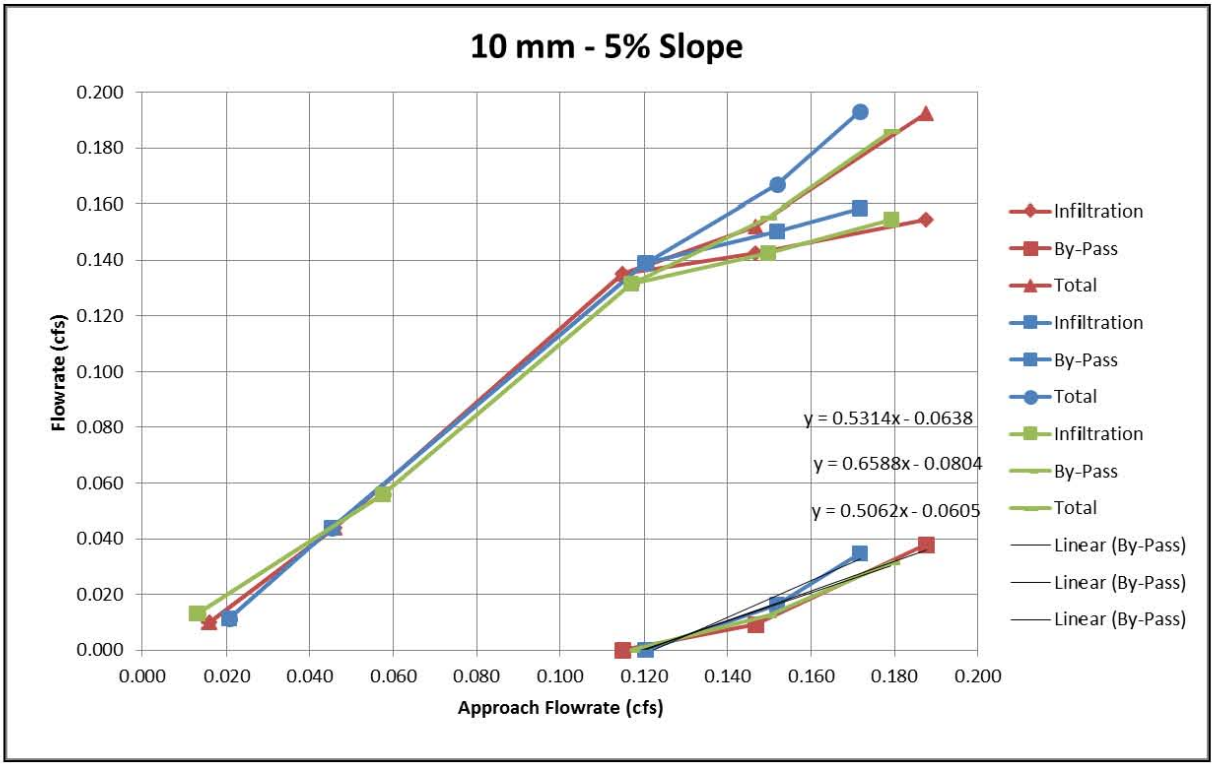

10 mm - 0% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.4519x - 0.0557
y = 0.3942x - 0.0475
y = 0.4468x - 0.0561
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

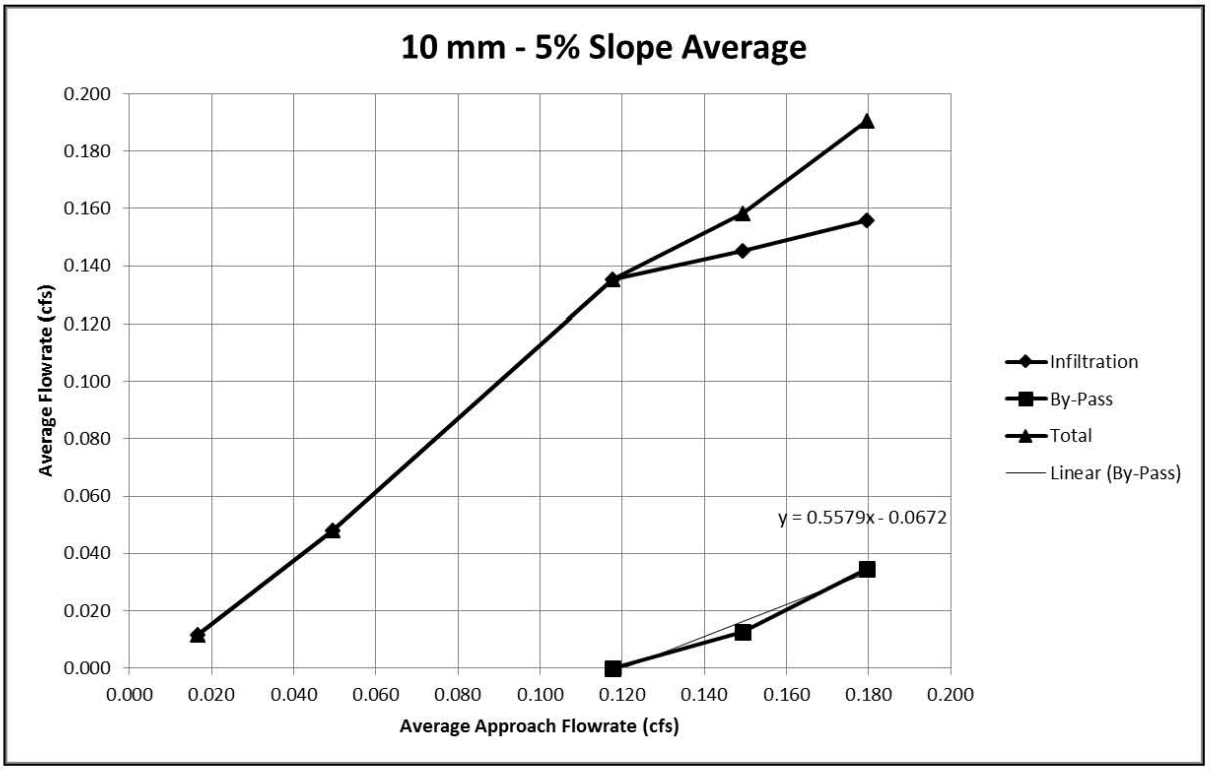

10 mm - 1% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.5262x - 0.0626
y = 0.513x - 0.0621
y = 0.5147x - 0.0603
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

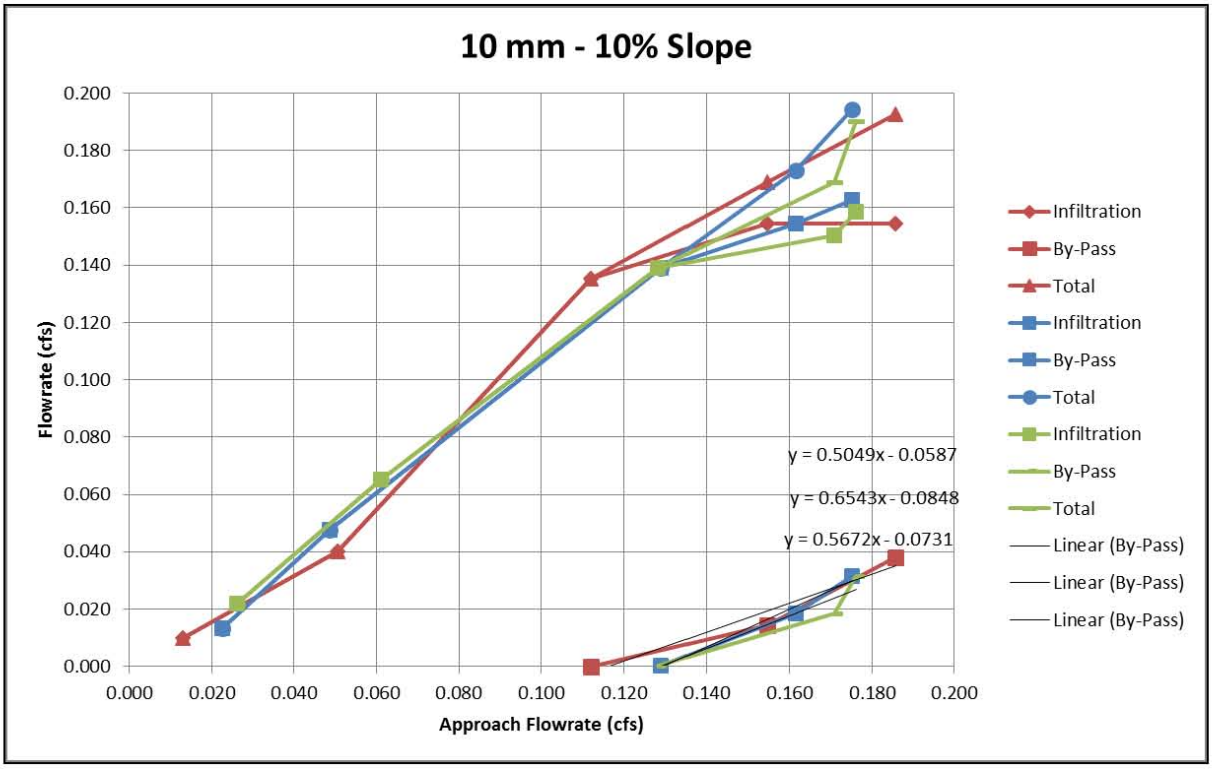

10 mm - 1% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.518x - 0.0617
Infiltration
By-Pass
Total
Linear (By-Pass)

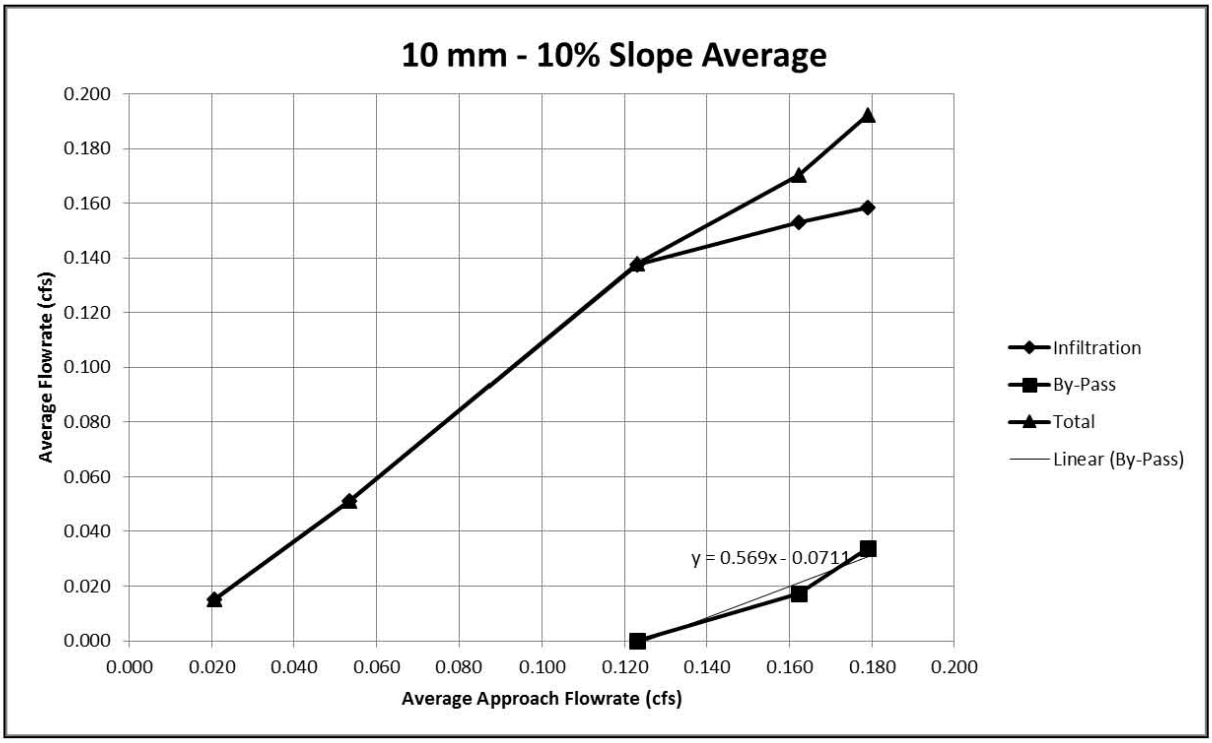

10 mm - 2% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.4527x - 0.0538
y = 0.5629x - 0.0695
y = 0.6385x - 0.0806
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

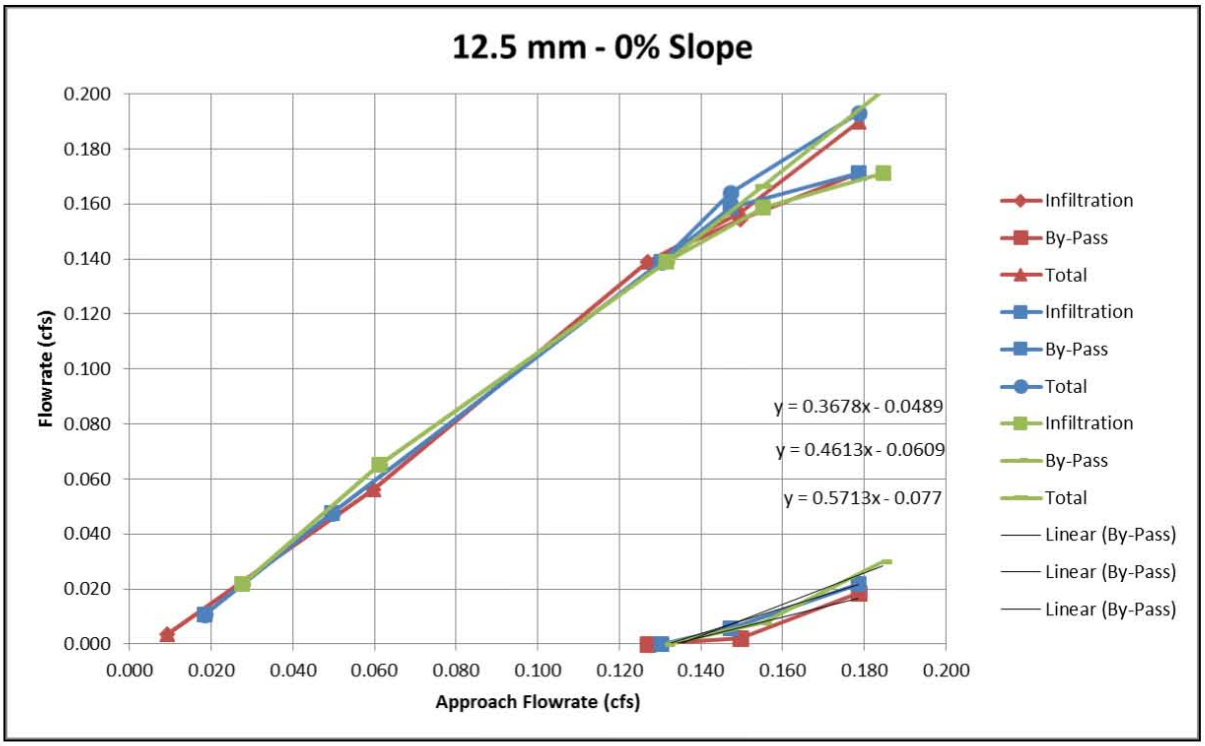

10 mm - 2% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.5379x - 0.0655
Infiltration
By-Pass
Total
Linear (By-Pass)

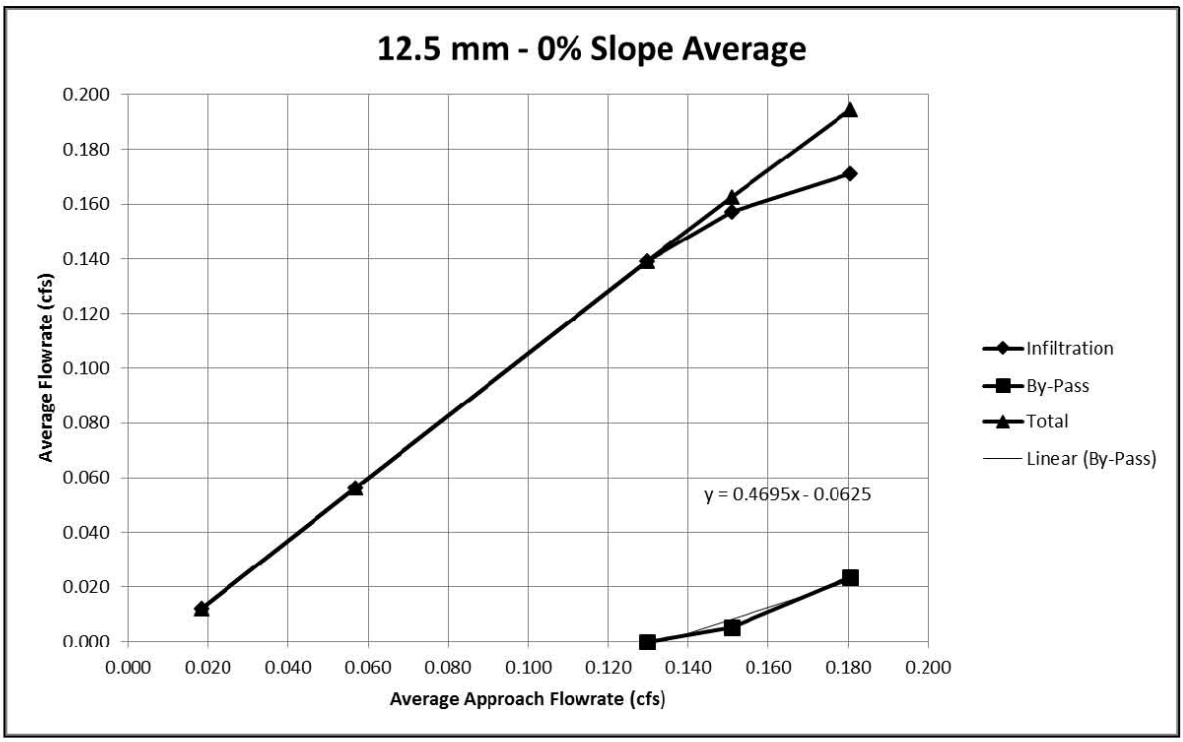

10 mm - 5% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.5314x - 0.0638
y = 0.6588x - 0.0804
y = 0.5062x - 0.0605
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

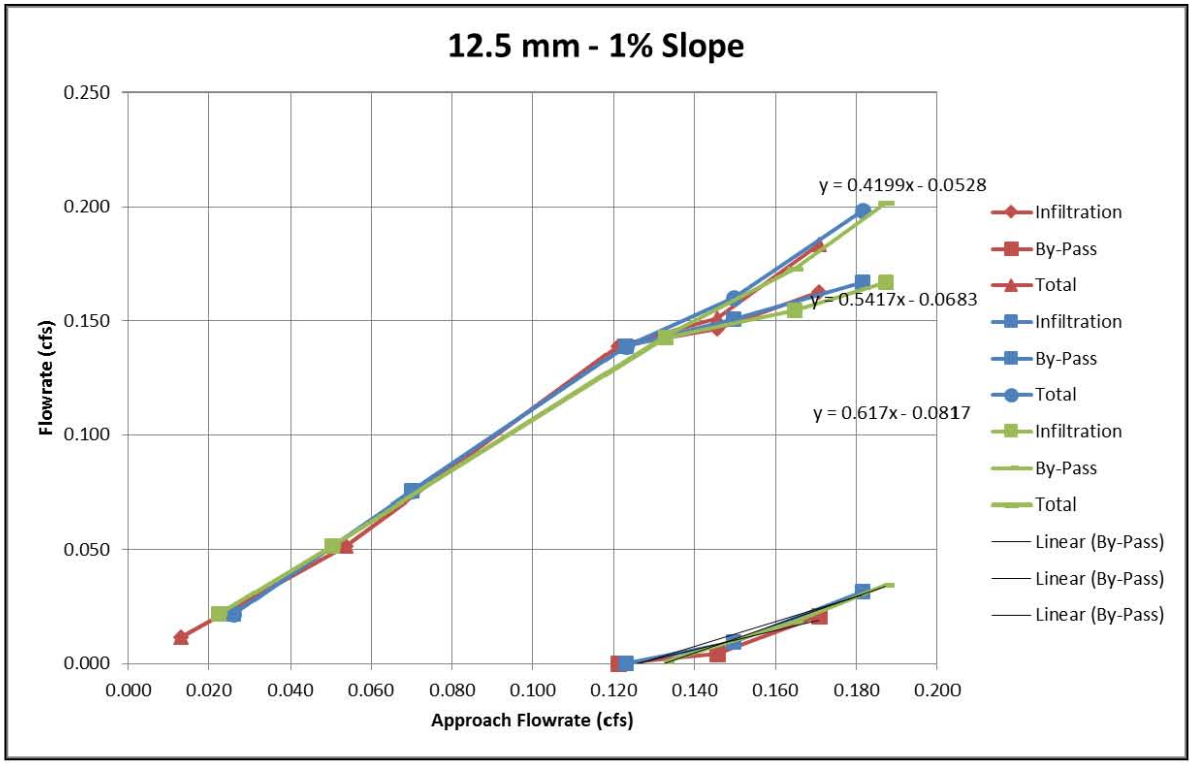

10 mm - 5% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.5579x - 0.0672
Infiltration
By-Pass
Total
Linear (By-Pass)

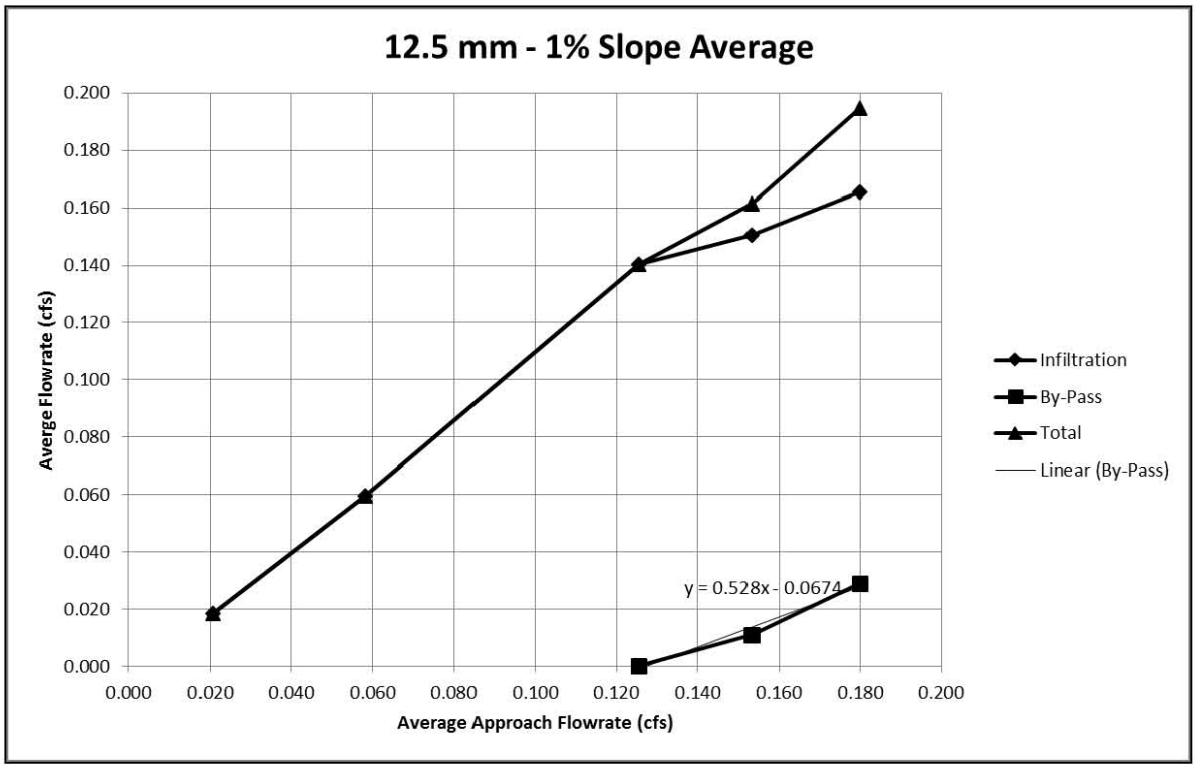

10 mm - 10% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.5049x - 0.0587
y = 0.6543x - 0.0848
y = 0.5672x - 0.0731
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

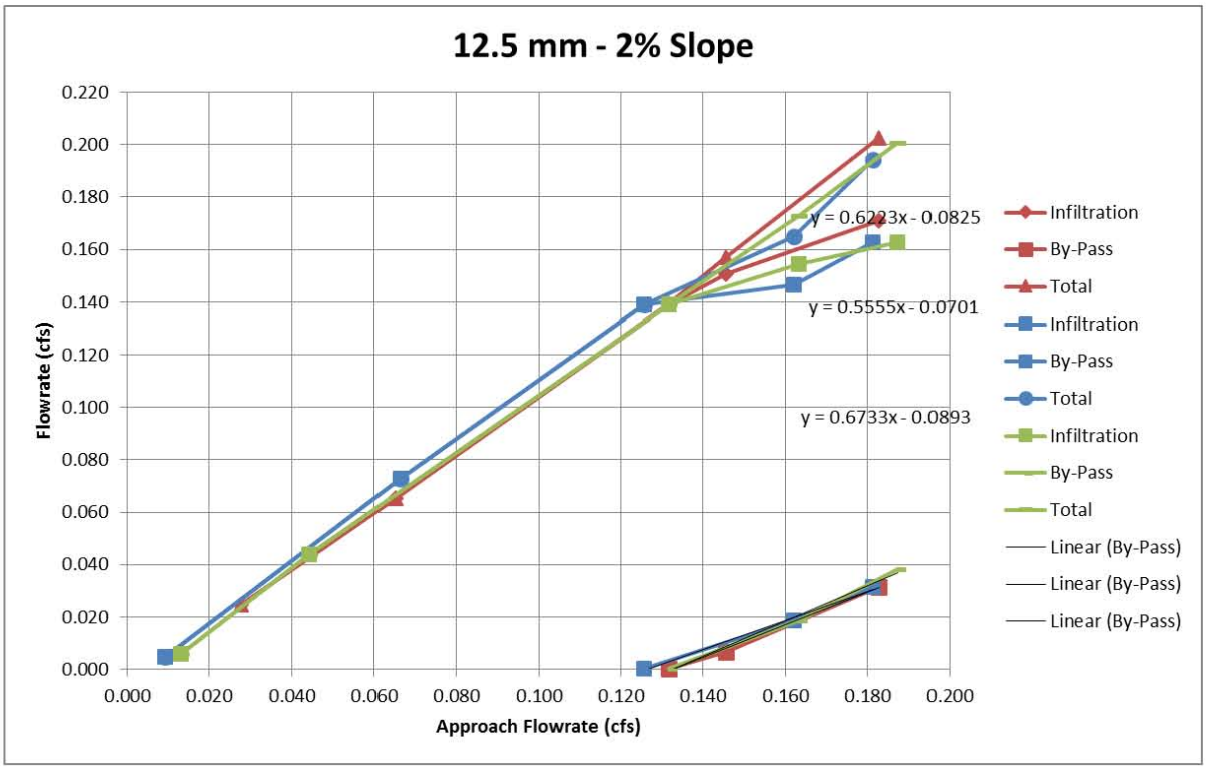

10 mm - 10% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.569x - 0.0711
Infiltration
By-Pass
Total
Linear (By-Pass)

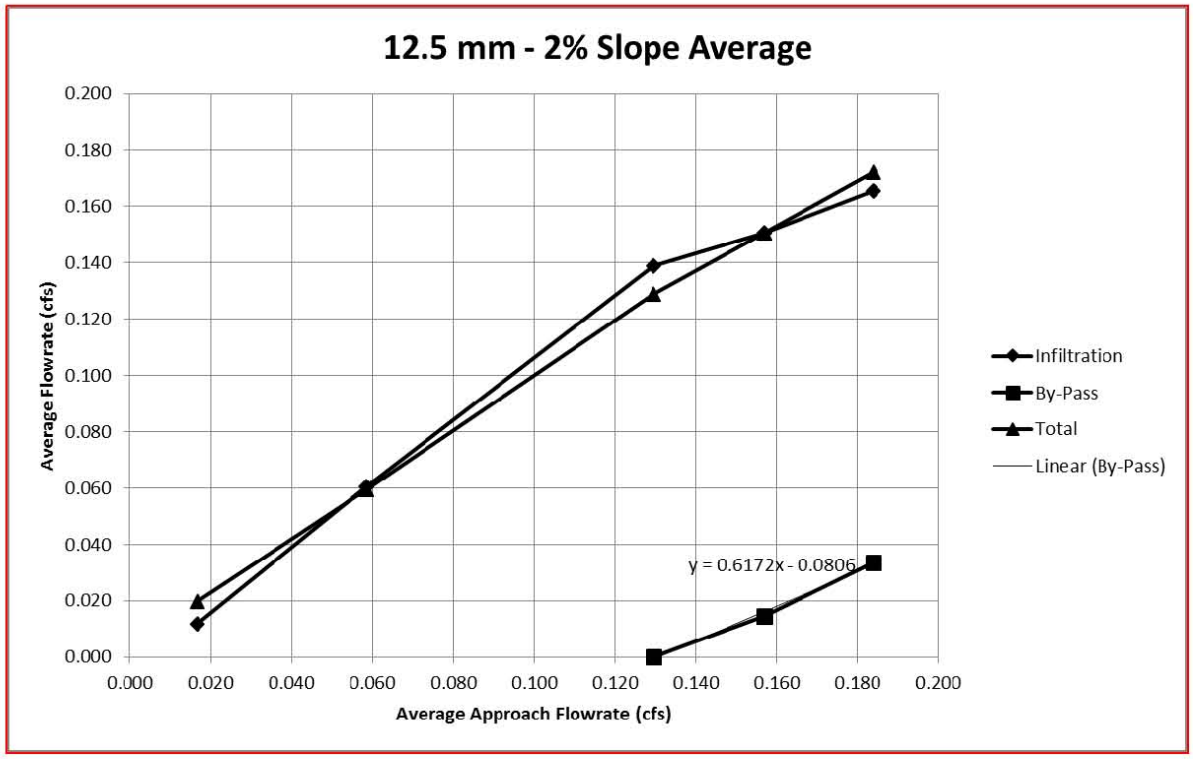

12.5 mm - 0% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.3678x - 0.0489
y = 0.4613x - 0.0609
y = 0.5713x - 0.077
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

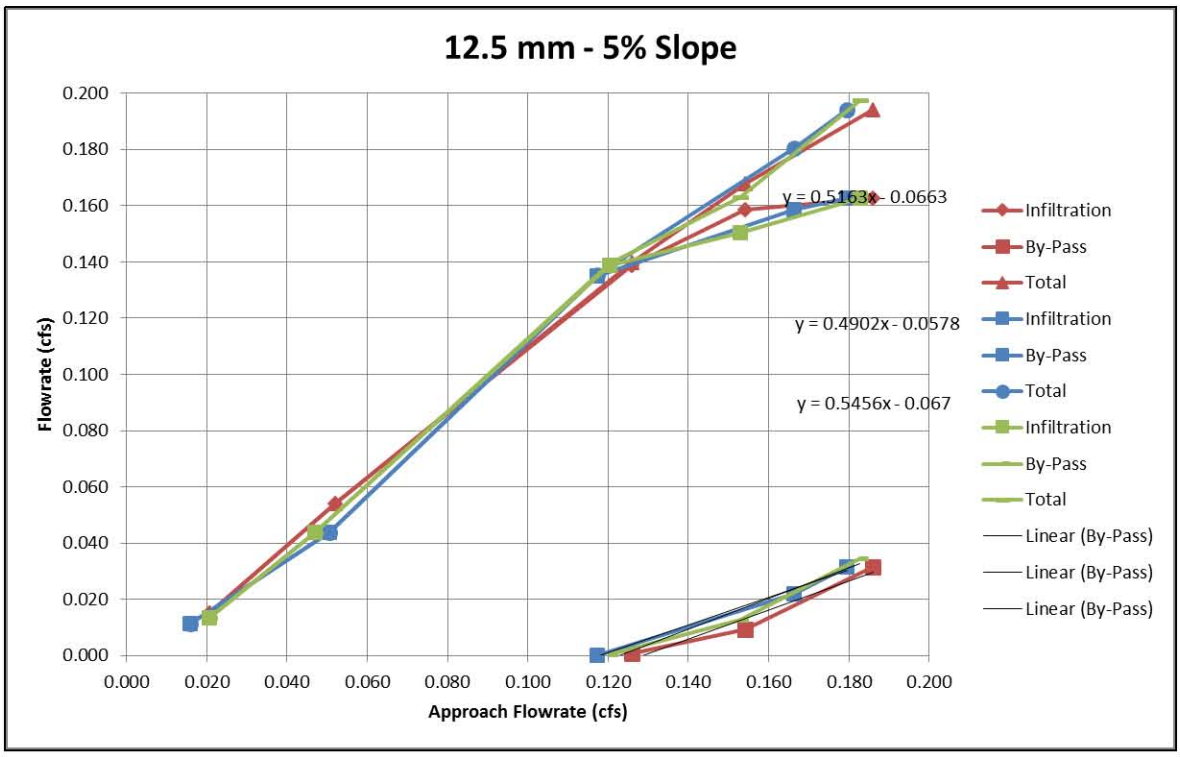

12.5 mm - 0% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.4695x - 0.0625
Infiltration
By-Pass
Total
Linear (By-Pass)

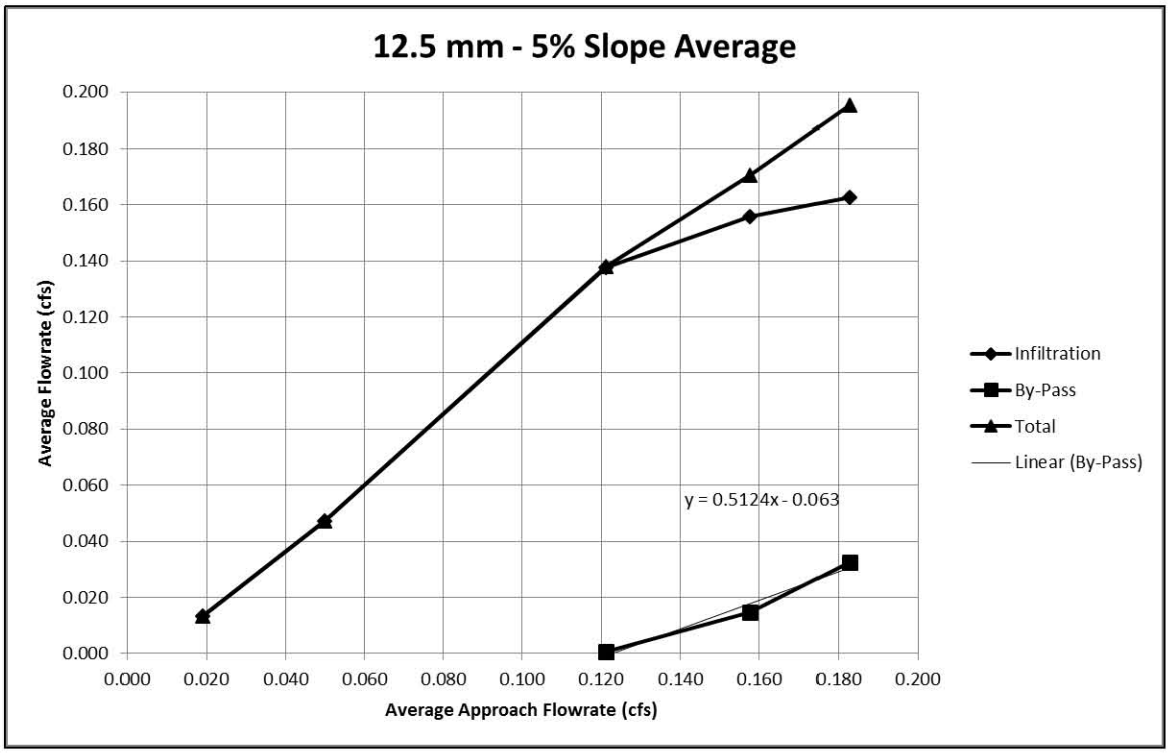

12.5 mm - 1% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.250
0.200
0.150
0.100
0.050
0.000
0.000 0.020 0.040 0.060 0.080 0.100 0.120 0.140 0.160 0.180 0.200
y = 0.4199x - 0.0528
y = 0.5417x - 0.0683
y = 0.617x - 0.0817
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)

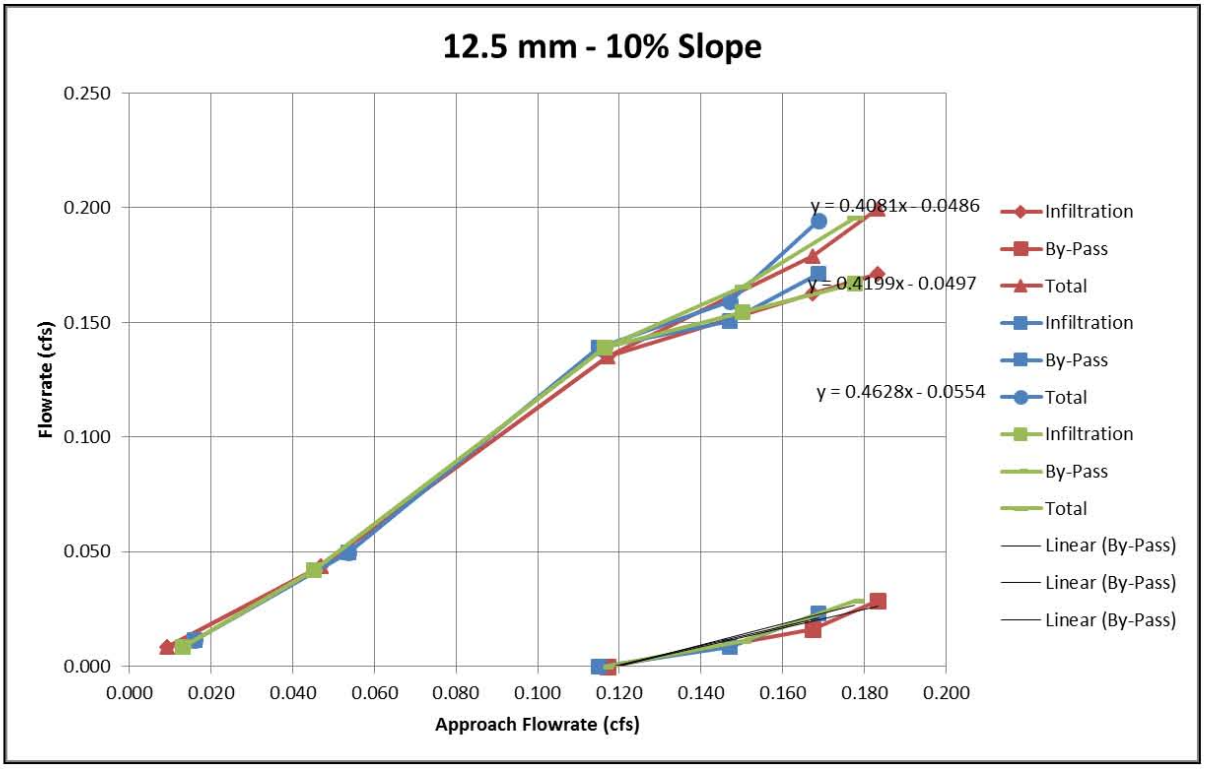

12.5 mm - 1% Slope Average
Averge Flowrate (cfs)
Average Approach Flowrate (cfs)
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0.000 0.020 0.040 0.060 0.080 0.100 0.120 0.140 0.160 0.180 0.200
y = 0.528x - 0.0674
Infiltration
By-Pass
Total
Linear (By-Pass)

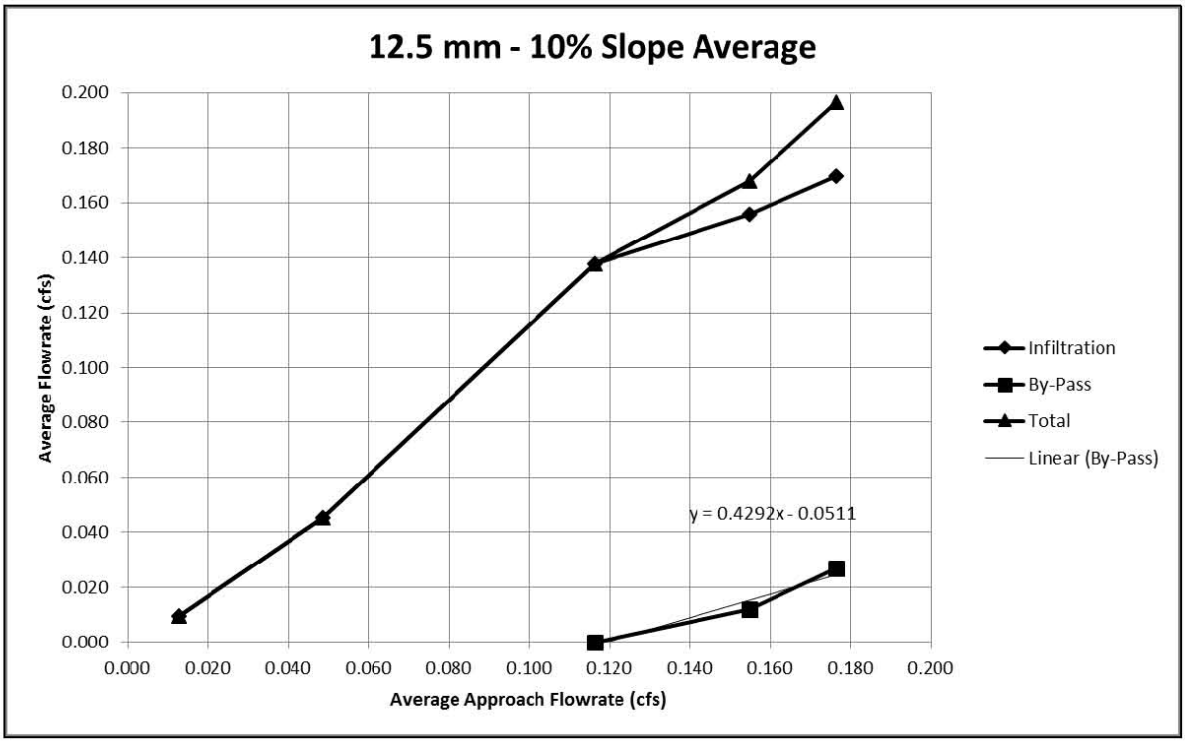

12.5 mm - 2% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
0.220
y = 0.6223x - 0.0825
y = 0.5555x - 0.0701
y = 0.6733x - 0.0893
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)


12.5 mm - 2% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.6172x - 0.0806
Infiltration
By-Pass
Total
Linear (By-Pass)


12.5 mm - 5% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.5163x - 0.0663
y = 0.4902x - 0.0578
y = 0.5456x - 0.067
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)


12.5 mm - 5% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
y = 0.5124x - 0.063
Infiltration
By-Pass
Total
Linear (By-Pass)


12.5 mm - 10% Slope
Flowrate (cfs)
Approach Flowrate (cfs)
0.250
0.200
0.150
0.100
0.050
0.000
0.000 0.020 0.040 0.060 0.080 0.100 0.120 0.140 0.160 0.180 0.200
y = 0.4081x - 0.0486
y = 0.4199x - 0.0497
y = 0.4628x - 0.0554
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Infiltration
By-Pass
Total
Linear (By-Pass)
Linear (By-Pass)
Linear (By-Pass)


12.5 mm - 10% Slope Average
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0.000 0.020 0.040 0.060 0.080 0.100 0.120 0.140 0.160 0.180 0.200
y = 0.4292x - 0.0511
Infiltration
By-Pass
Total
Linear (By-Pass)

Data:

C64	C65
6 mm Infiltration (BP) Per Area	Pattern Infiltration (BP)
0.020	0.016
0.021	0.015
0.017	0.015
0.017	0.014
0.015	0.015

Result:

Two-Sample T-Test and CI: 6 mm Infiltration (BP) Per Area, Pattern Infiltration (BP)

```
Two-sample T for 6 mm Infiltration (BP) Per Area vs Pattern Infiltration (BP)

                          N      Mean     StDev  SE Mean
6 mm Infiltration (BP) P  5   0.01800   0.00245   0.0011
Pattern Infiltration (BP  5  0.015000  0.000707  0.00032


Difference = μ (6 mm Infiltration (BP) Per Area) - μ (Pattern Infiltration (BP))
Estimate for difference:  0.00300
99% CI for difference:  (-0.00083, 0.00683)
T-Test of difference = 0 (vs ≠): T-Value = 2.63  P-Value = 0.030  DF = 8
Both use Pooled StDev = 0.0018
```

Data:

In Minitab Worksheet. Average of all 6 mm test compared to pattern (1 test) data

Two-Sample T-Test and CI: 6 mm Overflow (all), Pattern Bypass

```
Two-sample T for 6 mm Overflow (all) vs Pattern Bypass

                      N    Mean   StDev  SE Mean
6 mm Overflow (all)  15  0.0316  0.0293   0.0076
Pattern Bypass       15  0.0290  0.0321   0.0083


Difference = μ (6 mm Overflow (all)) - μ (Pattern Bypass)
Estimate for difference:  0.0026
99% CI for difference:  (-0.0285, 0.0337)
T-Test of difference = 0 (vs ≠): T-Value = 0.23  P-Value = 0.822  DF = 27
```

Two-Sample T-Test and CI: 6 mm Infiltration (all), Pattern Infiltration (Q1)

```
Two-sample T for 6 mm Infiltration (all) vs Pattern Infiltration (Q1)

                          N    Mean   StDev  SE Mean
6 mm Infiltration (all)   25  0.0637  0.0425   0.0085
Pattern Infiltration (Q1  25  0.0526  0.0252   0.0050


Difference = μ (6 mm Infiltration (all)) - μ (Pattern Infiltration (Q1))
Estimate for difference:  0.01105
99% CI for difference:  (-0.01572, 0.03782)
T-Test of difference = 0 (vs ≠): T-Value = 1.12  P-Value = 0.270  DF = 38
```

Two-Sample T-Test and CI: Average Running Bond, Validation

```
Two-sample T for Average Running Bond vs Validation

                      N     Mean    StDev  SE Mean
Average Running Bond  5  0.01834  0.00324   0.0014
Validation            5  0.01589  0.00124  0.00055


Difference = μ (Average Running Bond) - μ (Validation)
Estimate for difference:  0.00245
99% CI for difference:  (-0.00275, 0.00765)
T-Test of difference = 0 (vs ≠): T-Value = 1.58  P-Value = 0.153  DF = 8
Both use Pooled StDev = 0.0025
```

Two-Sample T-Test and CI: Validation Average Infiltration, Average 6 mm Infiltration

```
Two-sample T for Validation Average Infiltration vs Average 6 mm Infiltration

                          N    Mean   StDev  SE Mean
Validation Average Infil  25  0.0569  0.0303   0.0061
Average 6 mm Infiltratio  25  0.0681  0.0454   0.0091


Difference = μ (Validation Average Infiltration) - μ (Average 6 mm Infiltration)
Estimate for difference:  -0.0112
99% CI for difference:  (-0.0405, 0.0181)
T-Test of difference = 0 (vs ≠): T-Value = -1.03  P-Value = 0.310  DF = 48
Both use Pooled StDev = 0.0386
```

Two-Sample T-Test and CI: Validation Bypass, Average 6 mm Overflow

```
Two-sample T for Validation Bypass vs Average 6 mm Overflow

                       N    Mean   StDev  SE Mean
Validation Bypass      15  0.0288  0.0329   0.0085
Average 6 mm Overflow  15  0.0325  0.0291   0.0075


Difference = μ (Validation Bypass) - μ (Average 6 mm Overflow)
Estimate for difference:  -0.0037
99% CI for difference:  (-0.0350, 0.0276)
T-Test of difference = 0 (vs ≠): T-Value = -0.33  P-Value = 0.747  DF = 28
Both use Pooled StDev = 0.0310
```

Two-Sample T-Test and CI: 6 mm CFR, 10 mm CFR

```
Two-sample T for 6 mm CFR vs 10 mm CFR

           N     Mean    StDev  SE Mean
6 mm CFR   5   0.0788   0.0144   0.0064
10 mm CFR  5  0.12140  0.00182  0.00081


Difference = μ (6 mm CFR) - μ (10 mm CFR)
Estimate for difference:  -0.04260
99% CI for difference:  (-0.07251, -0.01269)
T-Test of difference = 0 (vs ≠): T-Value = -6.56  P-Value = 0.003  DF = 4
```

Two-Sample T-Test and CI: Summer Average Infiltation, Summer Average Infiltation_10mm

```
Two-sample T for Summer Average Infiltation vs Summer Average Infiltation_10mm

                          N    Mean   StDev  SE Mean
Summer Average Infiltati  25  0.0681  0.0454   0.0091
Summer Average Infiltati  25  0.0986  0.0604    0.012


Difference = μ (Summer Average Infiltation) - μ (Summer Average Infiltation_10mm)
Estimate for difference:  -0.0305
99% CI for difference:  (-0.0712, 0.0101)
T-Test of difference = 0 (vs ≠): T-Value = -2.02  P-Value = 0.049  DF = 44
```

Two-Sample T-Test and CI: Summer Average Bypass, Summer Average Bypass_10 mm

```
Two-sample T for Summer Average Bypass vs Summer Average Bypass_10 mm

                          N    Mean   StDev  SE Mean
Summer Average Bypass     15  0.0325  0.0291   0.0075
Summer Average Bypass_10  15  0.0144  0.0142   0.0037


Difference = μ (Summer Average Bypass) - μ (Summer Average Bypass_10 mm)
Estimate for difference:  0.01811
99% CI for difference:  (-0.00565, 0.04188)
T-Test of difference = 0 (vs ≠): T-Value = 2.17  P-Value = 0.042  DF = 20
```

One-way ANOVA: 6 mm CFR, 10 mm CFR, 12.5 nn CFR, Pattern CFR

Method

Null hypothesis All means are equal
Alternative hypothesis At least one mean is different
Significance level $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor Levels Values
Factor 4 6 mm CFR, 10 mm CFR, 12.5 nn CFR, Pattern CFR

Analysis of Variance

Source DF Adj SS Adj MS F-Value P-Value
Factor 3 0.015389 0.005130 82.17 0.000
Error 16 0.000999 0.000062
Total 19 0.016388

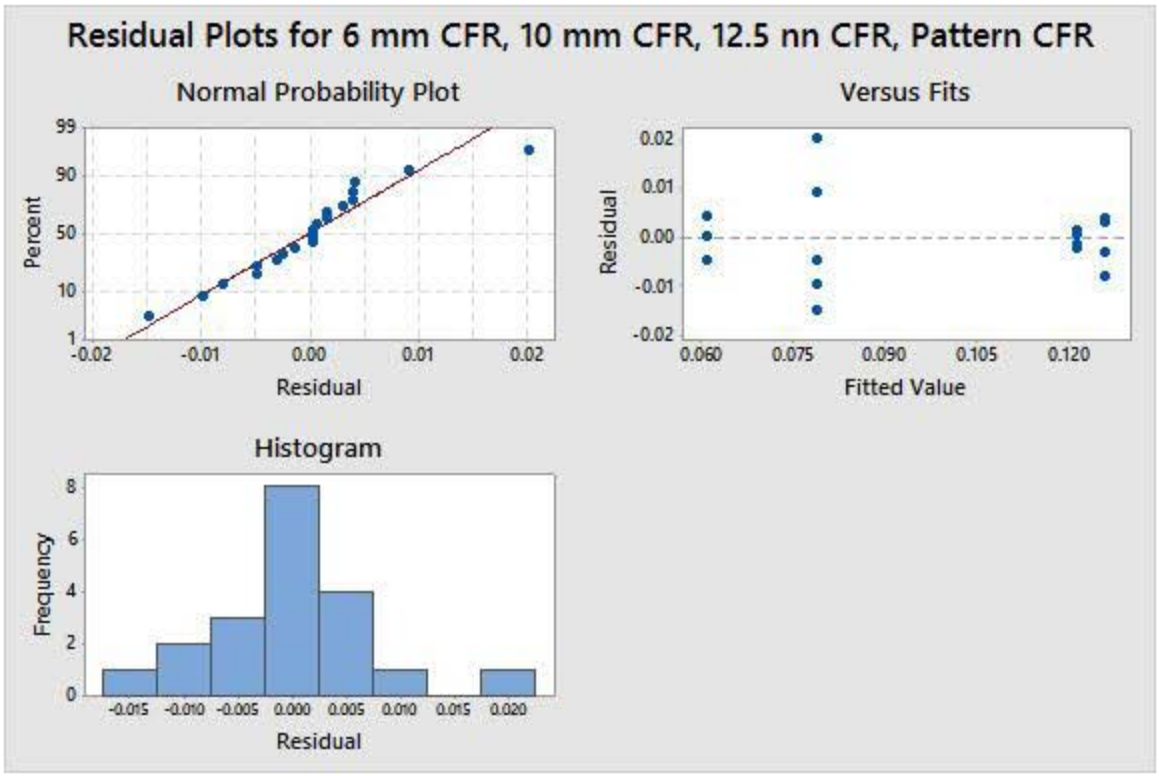
Model Summary

S R-sq R-sq(adj) R-sq(pred)
0.0079009 93.91% 92.76% 90.48%

Means

Factor N Mean StDev 95% CI
6 mm CFR 5 0.07880 0.01441 (0.07131, 0.08629)
10 mm CFR 5 0.121400 0.001817 (0.113910, 0.128890)
12.5 nn CFR 5 0.12600 0.00534 (0.11851, 0.13349)
Pattern CFR 5 0.06080 0.00319 (0.05331, 0.06829)

Pooled StDev = 0.00790095


Residual Plots for 6 mm CFR, 10 mm CFR, 12.5 nn CFR, Pattern CFR
Normal Probability Plot
Percent
99
90
50
10
1
-0.02
-0.01
0.00
0.01
0.02
Residual
Versus Fits
Residual
0.02
0.01
0.00
-0.01
-0.02
0.060
0.075
0.090
0.105
0.120
Fitted Value
Histogram
Frequency
8
6
4
2
0
-0.015
-0.010
-0.005
0.000
0.005
0.010
0.015
0.020
Residual

Two-Sample T-Test and CI: 12.5 mm CFR, 10 mm CFR

```
Two-sample T for 12.5 nn CFR vs 10 mm CFR

             N     Mean    StDev  SE Mean
12.5 nn CFR  5  0.12600  0.00534   0.0024
10 mm CFR    5  0.12140  0.00182  0.00081


Difference = μ (12.5 nn CFR) - μ (10 mm CFR)
Estimate for difference:  0.00460
99% CI for difference:  (-0.00701, 0.01621)
T-Test of difference = 0 (vs ≠): T-Value = 1.82  P-Value = 0.142  DF = 4
```

Two-Sample T-Test and CI: Summer Average Bypass_10 mm, Summer Average Bypass_12.5mm

Two-sample T for Summer Average Bypass_10 mm vs Summer Average Bypass_12.5mm

	N	Mean	StDev	SE Mean
Summer Average Bypass_10	15	0.0144	0.0142	0.0037
Summer Average Bypass_12	15	0.0112	0.0104	0.0027

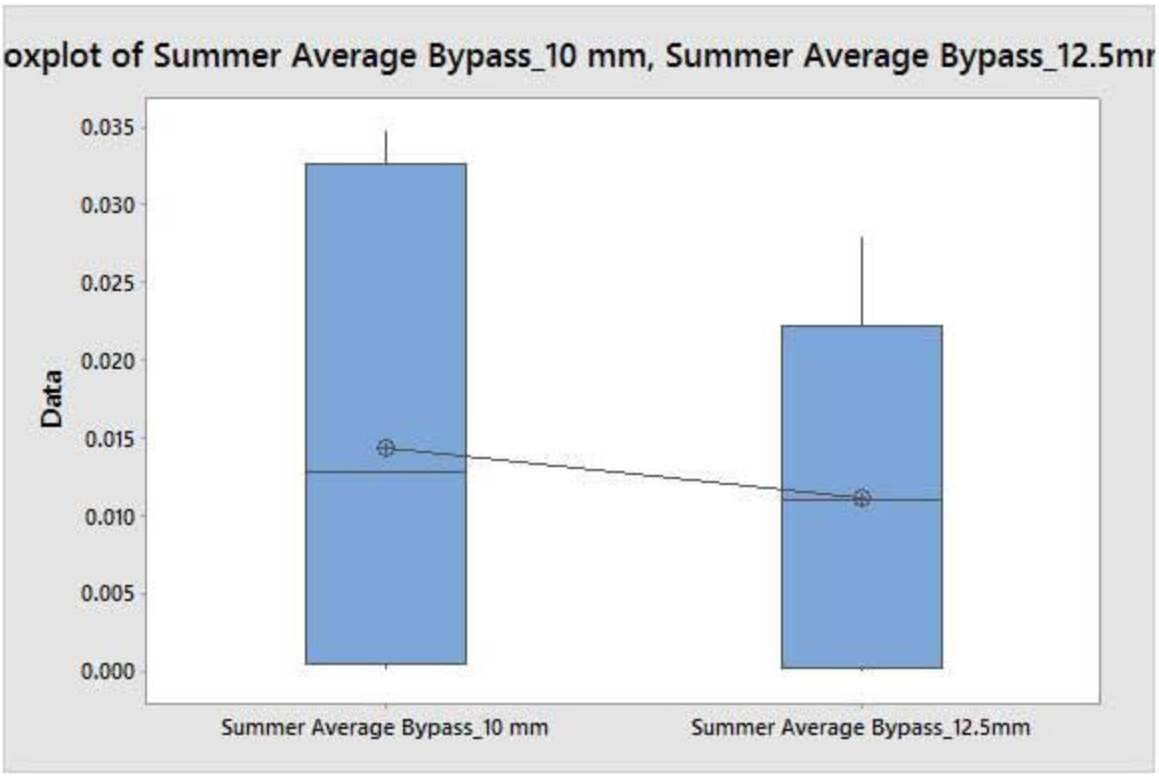
Difference = μ (Summer Average Bypass_10 mm) - μ (Summer Average Bypass_12.5mm)
Estimate for difference: 0.00320
95% CI for difference: (-0.00614, 0.01255)
T-Test of difference = 0 (vs ≠): T-Value = 0.71 P-Value = 0.487 DF = 25

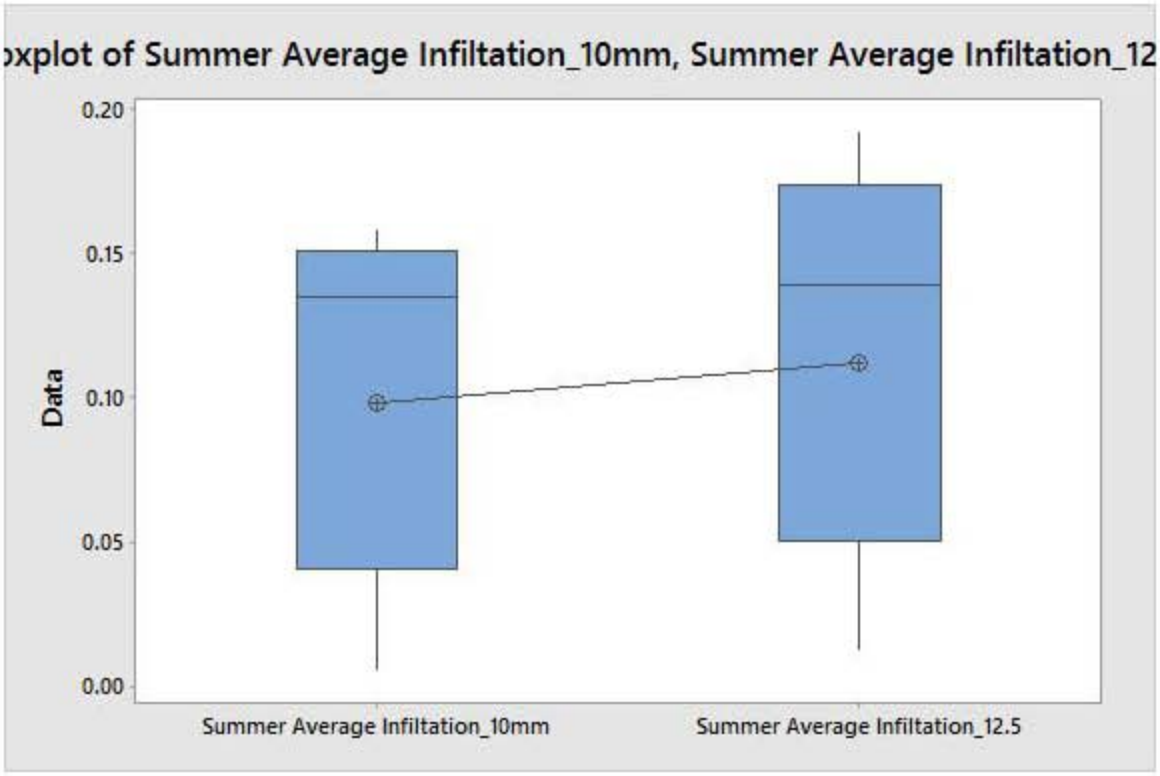
Two-Sample T-Test and CI: Summer Average Infiltation_10mm, Summer Average Infiltation_12.5

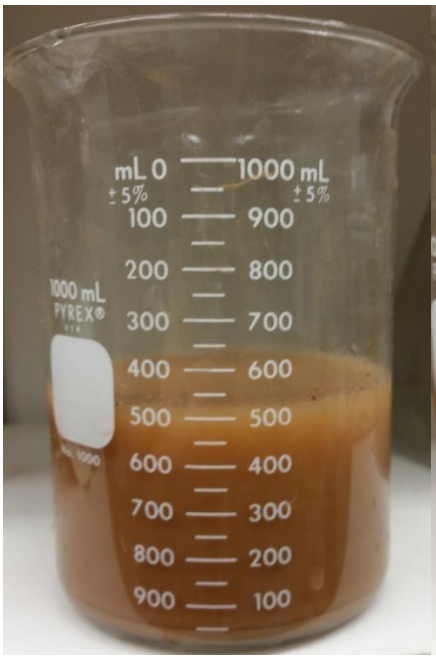
Two-sample T for Summer Average Infiltation_10mm vs Summer Average Infiltation_12.5

	N	Mean	StDev	SE Mean
Summer Average Infiltati	25	0.0986	0.0604	0.012
Summer Average Infiltati	25	0.1122	0.0671	0.013

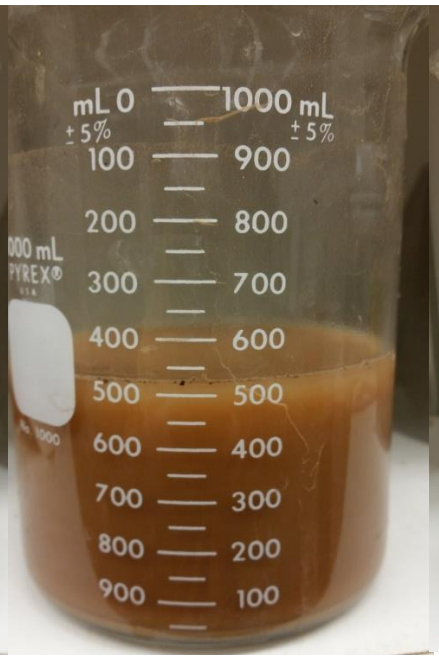
Difference = μ (Summer Average Infiltation_10mm) - μ (Summer Average Infiltation_12.5)
Estimate for difference: -0.0136
95% CI for difference: (-0.0499, 0.0227)
T-Test of difference = 0 (vs ≠): T-Value = -0.75 P-Value = 0.455 DF = 47


oxplot of Summer Average Bypass_10 mm, Summer Average Bypass_12.5mr
Data
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Summer Average Bypass_10 mm
Summer Average Bypass_12.5mm

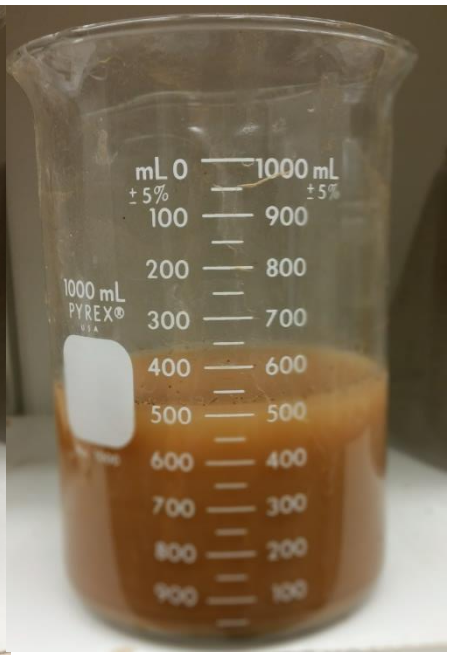

oxplot of Summer Average Infiltation_10mm, Summer Average Infiltation_12
Data
0.20
0.15
0.10
0.05
0.00
Summer Average Infiltation_10mm
Summer Average Infiltation_12.5



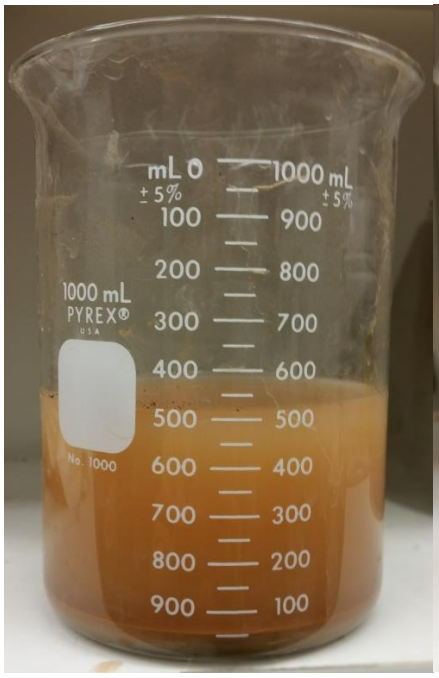
0 minutes



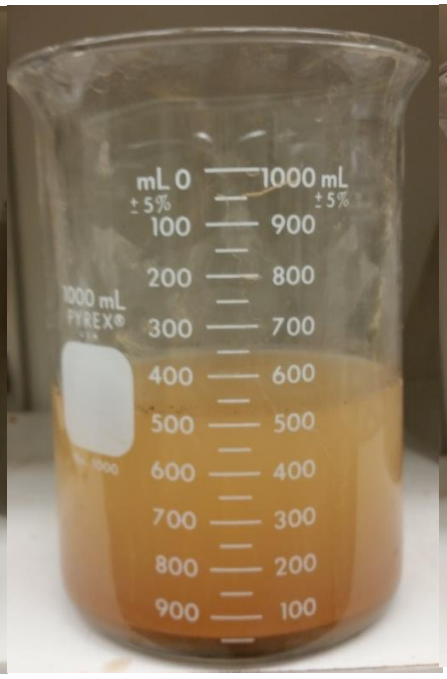
1 minute



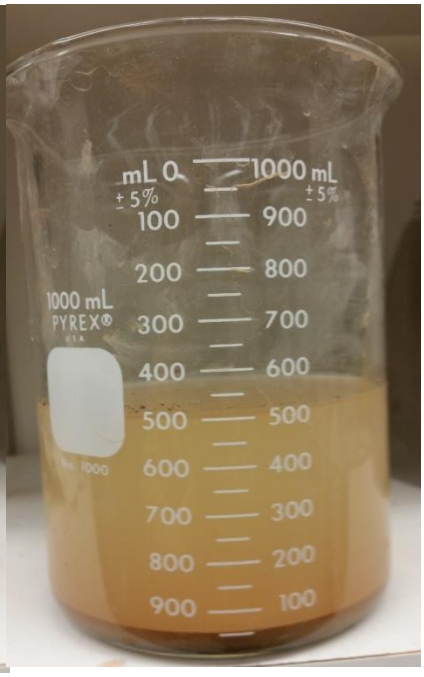
4 minutes



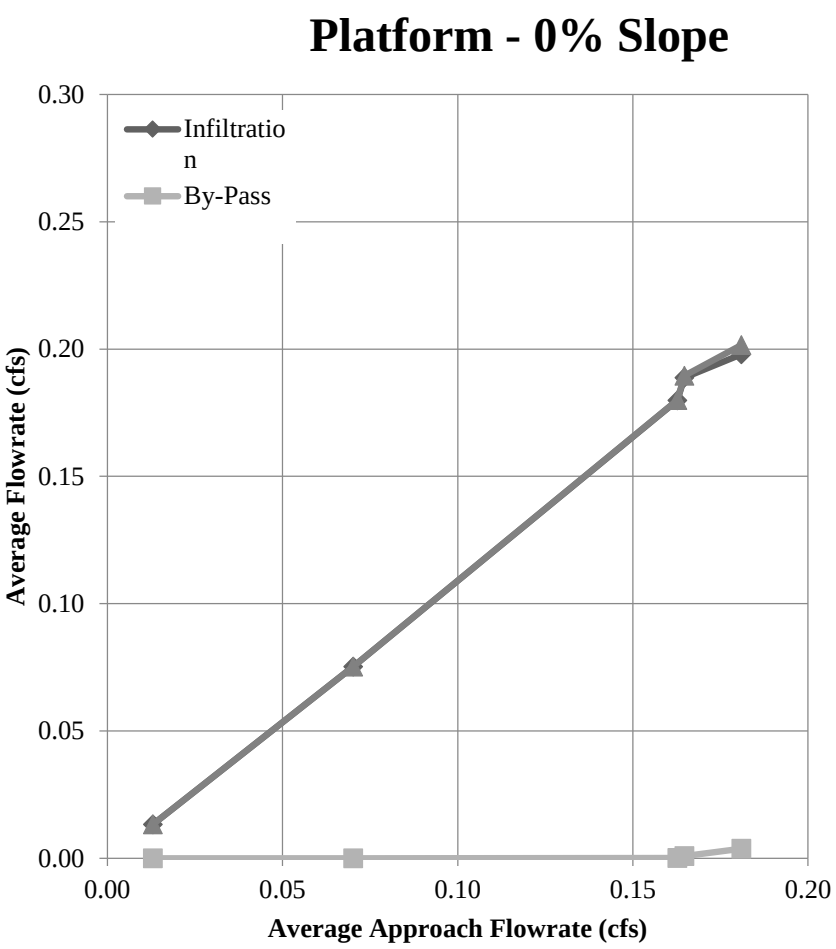
6 minutes

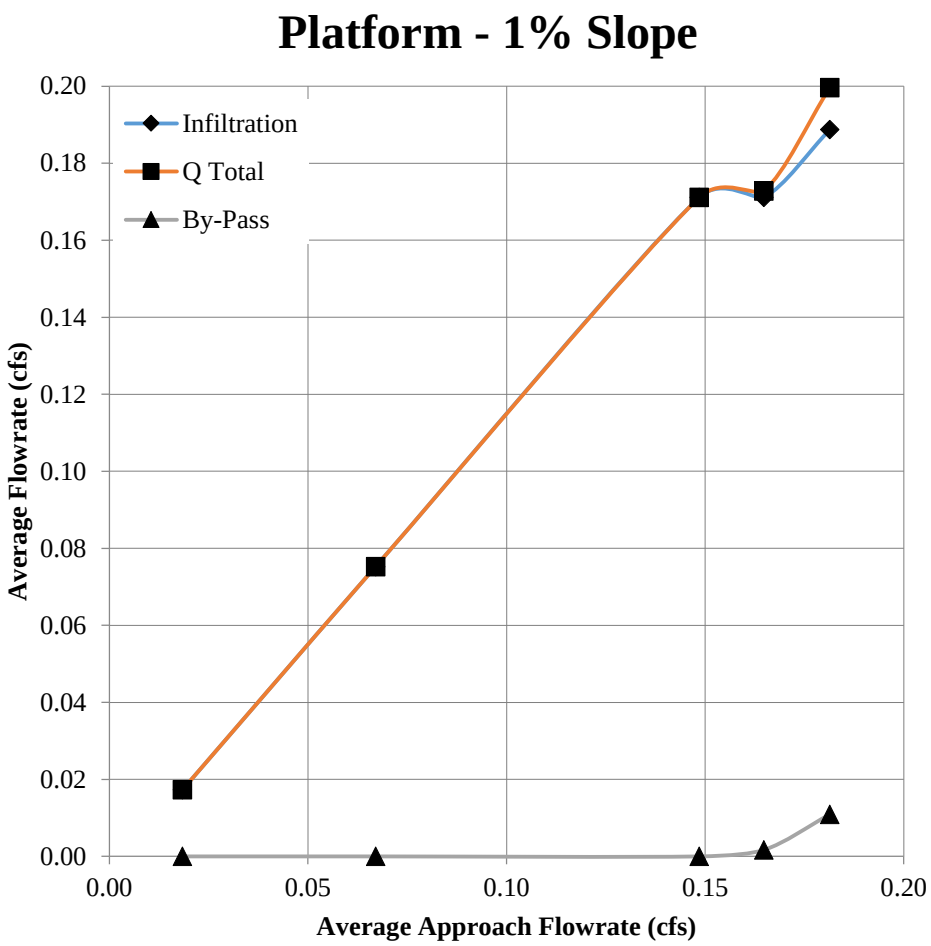


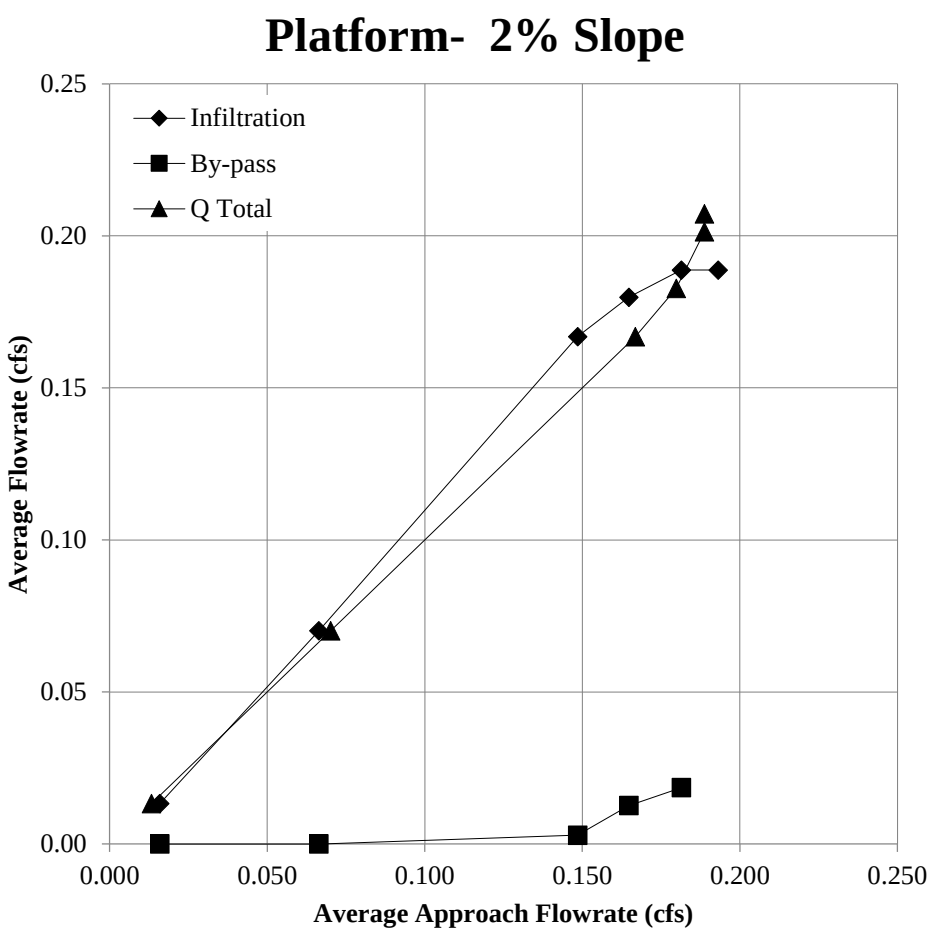
34 minutes

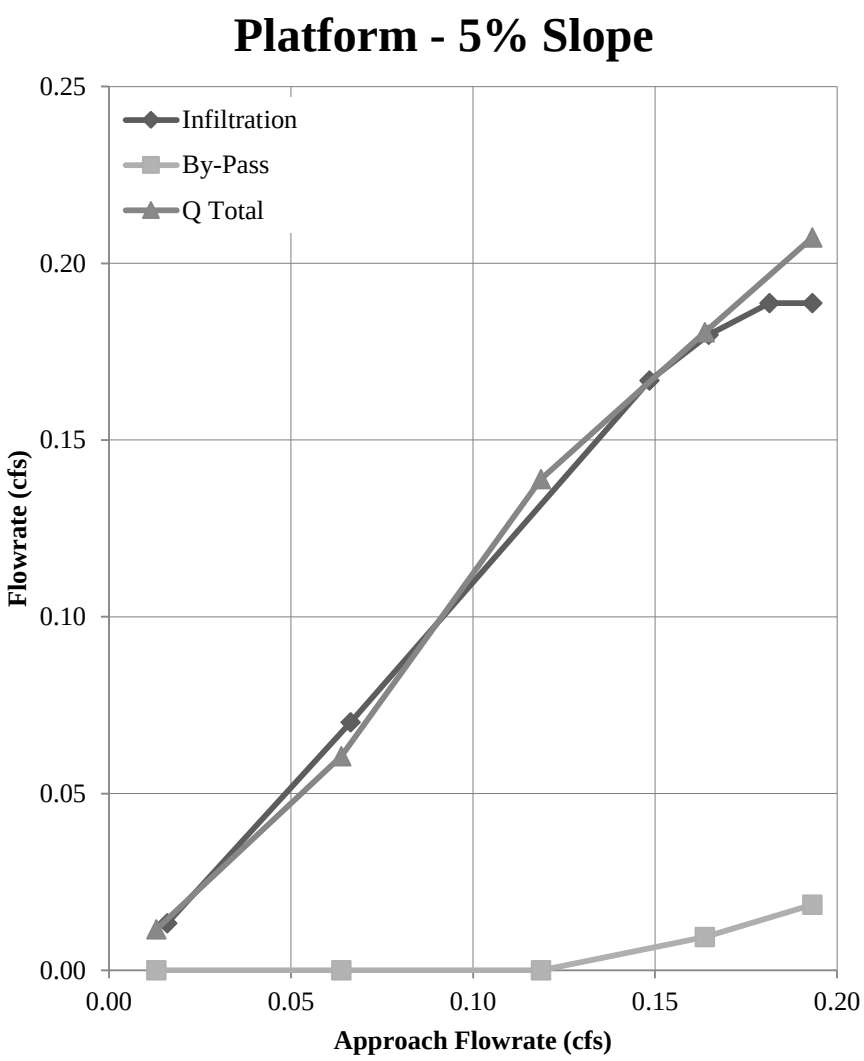


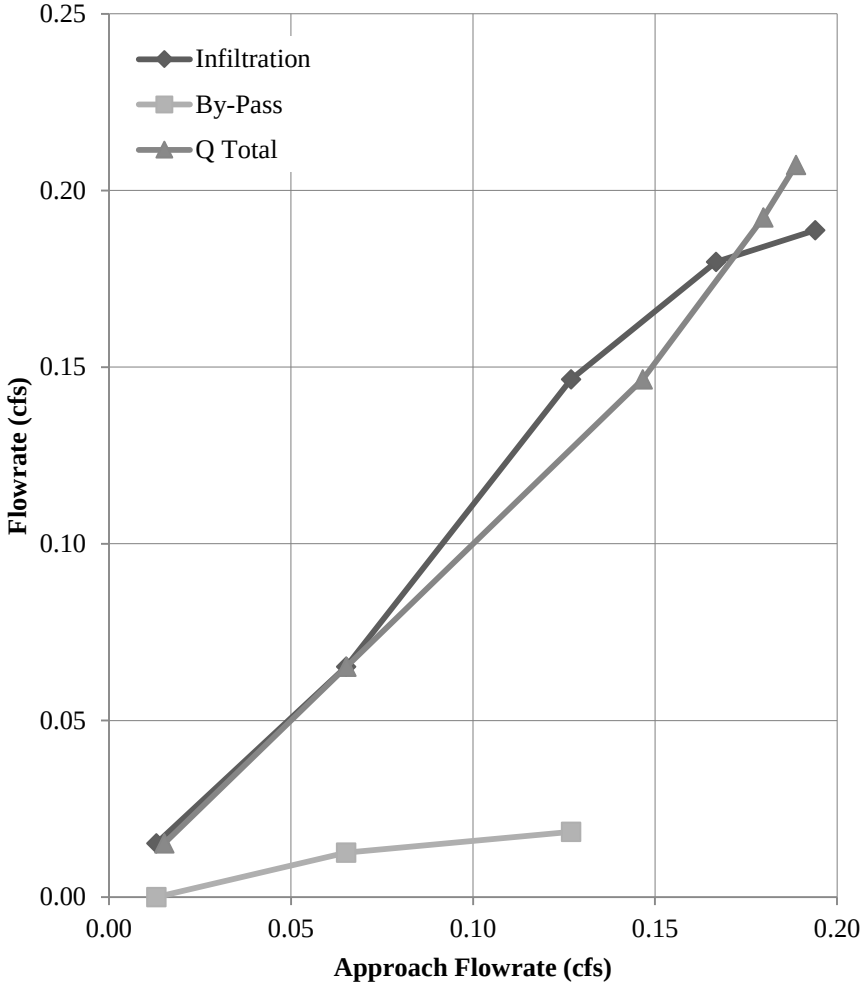
60 minutes

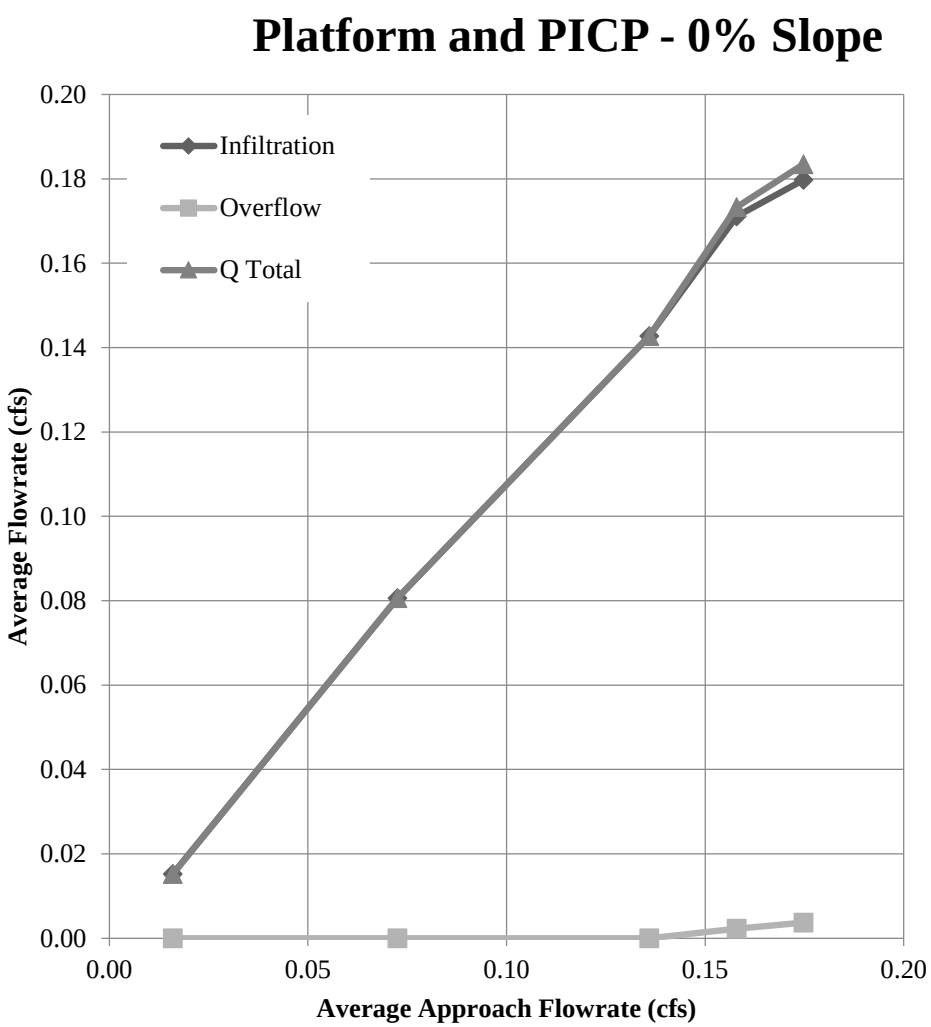

Platform - 0% Slope
Infiltration
By-Pass
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.05
0.10
0.15
0.20

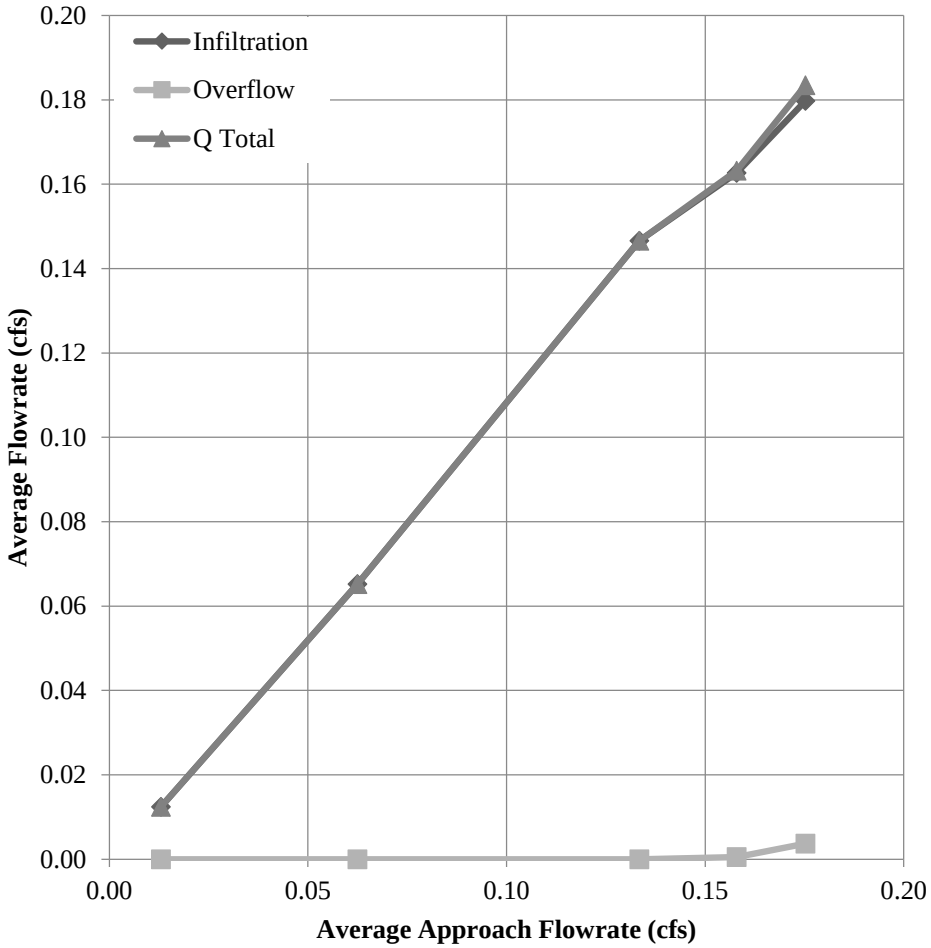

Platform - 1% Slope
Infiltration
Q Total
By-Pass
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.00
0.05
0.10
0.15
0.20

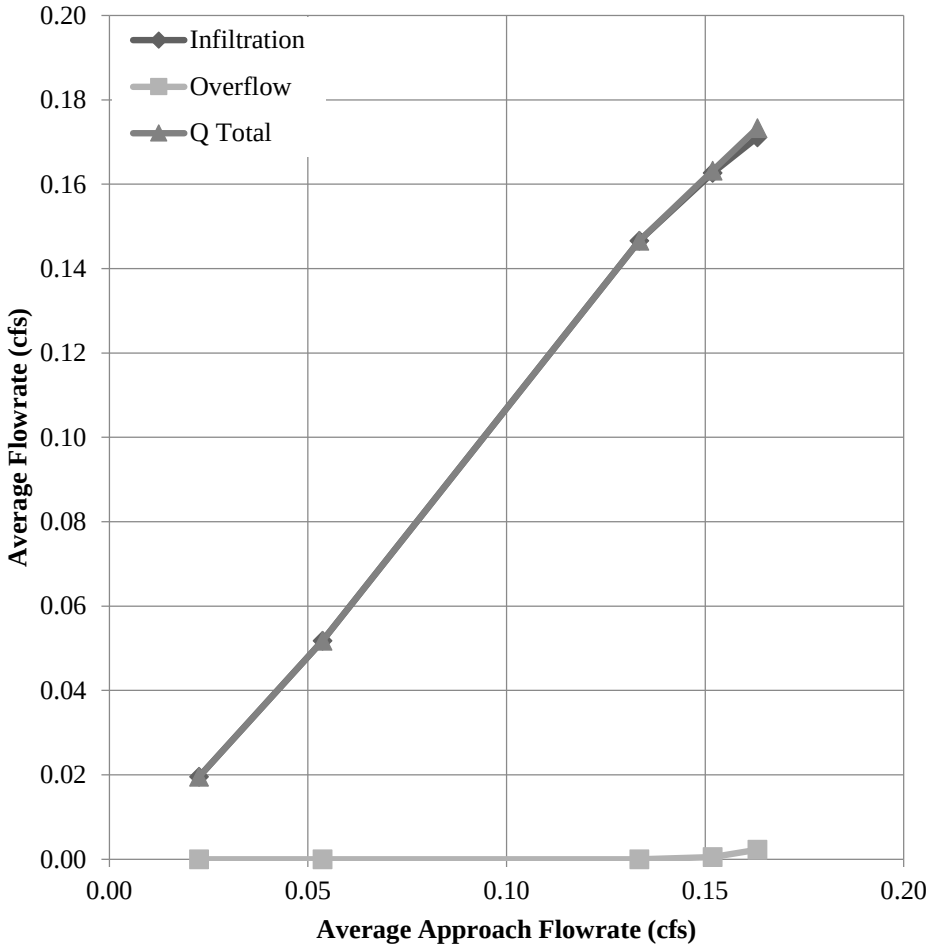

Platform- 2% Slope
Infiltration
By-pass
Q Total
Average Flowrate (cfs)
0.25
0.20
0.15
0.10
0.05
0.00
0.000
0.050
0.100
0.150
0.200
0.250
Average Approach Flowrate (cfs)

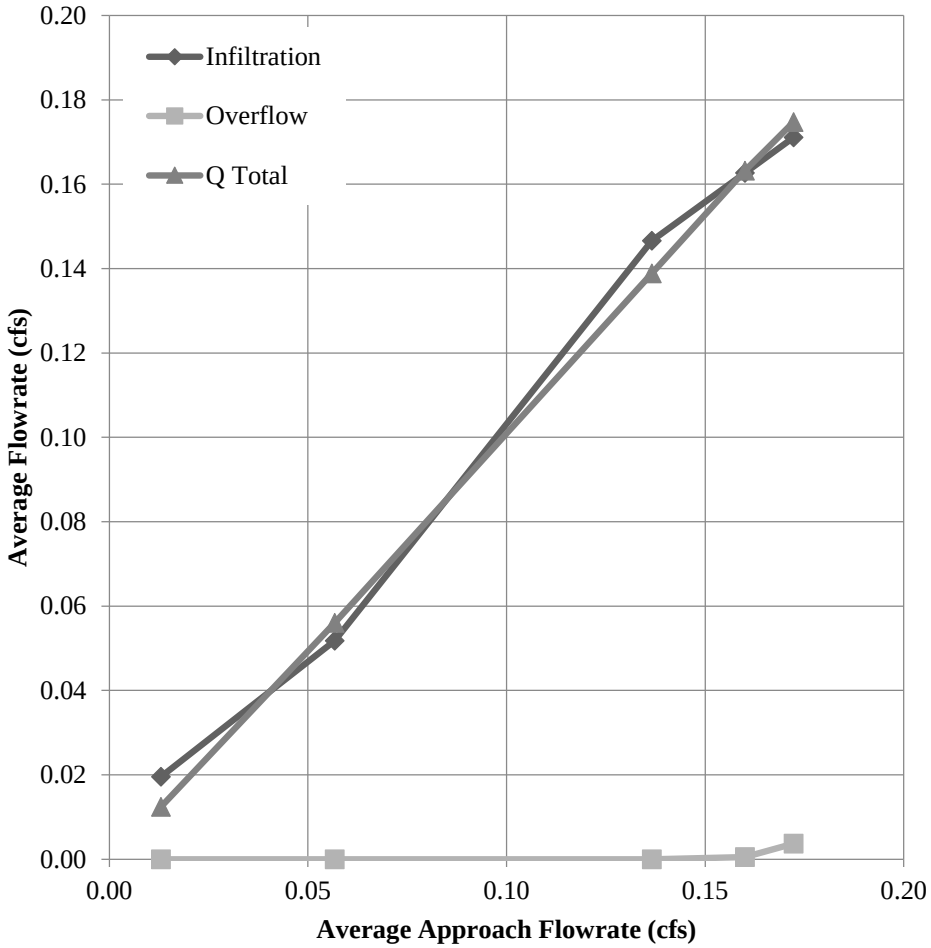

Platform - 5% Slope
Infiltration
By-Pass
Q Total
Flowrate (cfs)
Approach Flowrate (cfs)
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.05
0.10
0.15
0.20


Platform - 10% Slope
Infiltration
By-Pass
Q Total
Flowrate (cfs)
Approach Flowrate (cfs)
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.05
0.10
0.15
0.20

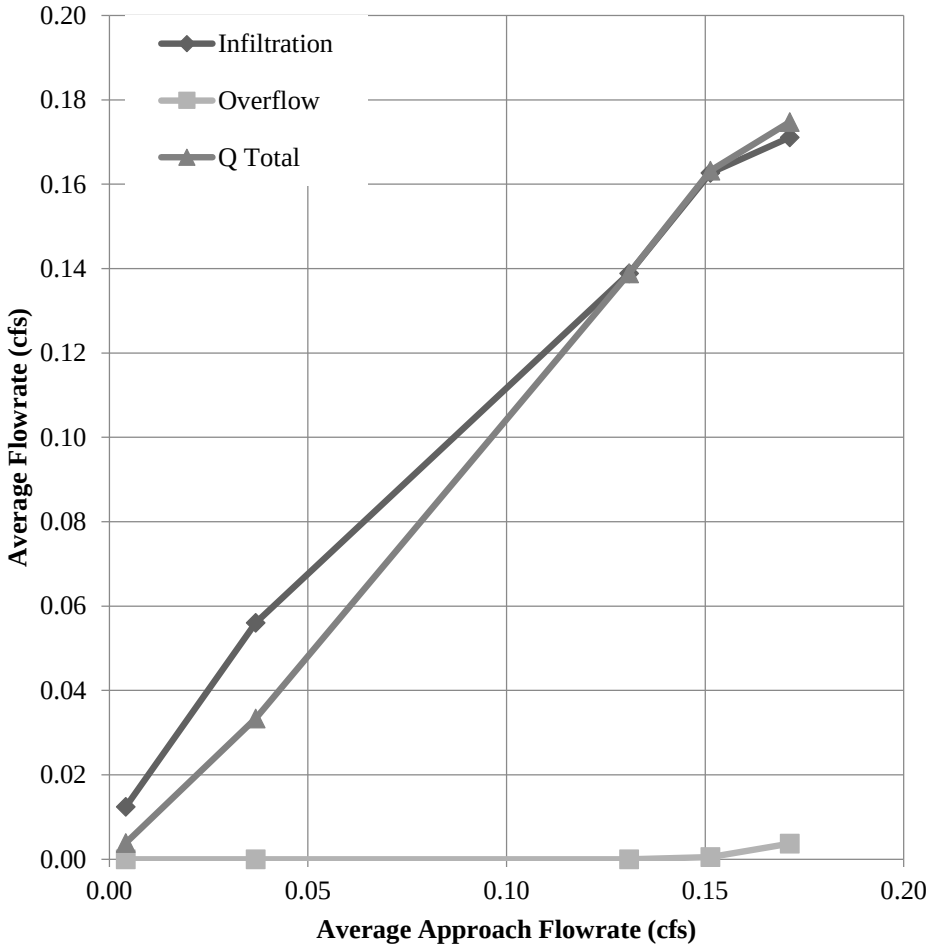

Platform and PICP - 0% Slope
Infiltration
Overflow
Q Total
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.00
0.05
0.10
0.15
0.20


Platform and PICP - 1% Slope
Infiltration
Overflow
Q Total
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.00
0.05
0.10
0.15
0.20


Platform and PICP - 2% Slope
Infiltration
Overflow
Q Total
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.00
0.05
0.10
0.15
0.20


Platform and PICP - 5% Slope
Infiltration
Overflow
Q Total
Average Flowrate (cfs)
Average Approach Flowrate (cfs)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.00
0.05
0.10
0.15
0.20

Platform and PICP -10% Slope



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VITA

Amanda Rene Leipard was born on May 5th 1983 in Boone County Missouri. She attended David H. Hickman High School in Columbia Missouri. She then studied Psychology at the University of Missouri-Columbia. After a brief break to her educational career Amanda moved to Kansas City and completed a degree in Civil Engineering at the University of Missouri-Kansas City school of Computing and Engineering. While in school Amanda has worked as the hydraulic laboratory assistant where she acquired the knowledge and had the opportunity to build a physical model of Brush Creek in Mission Hills. She currently is working at an Engineering Intern with Water Resource Engineering. After graduation has accepted a position with HDR Engineering, Inc. as a Water Resources EIT where she intends to pursue her career in water resource management