Effect of Rainfalls

on Permeable Pavement Induced Volume Reduction in Combined Sewers

by Muhammed Mustafa, Bachelor of Science

A Thesis Submitted in Partial
Fulfillment of the Requirements
for the Degree of
Master of Science
in the field of Civil Engineering

Advisory Committee:

Jianpeng Zhou, Chair

Susan Morgan

Laurent Ahiablame

Graduate School
Southern Illinois University Edwardsville
May, 2014

ABSTRACT

EFFECT OF RAINFALLS
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by

MUHAMMED MUSTAFA

Chairperson: Professor Jianpeng Zhou

Permeable pavements are considered as an effective technique for reducing stormwater runoffs and pollutants. Studies showed that permeable pavements can reduce stormwater runoffs up to 100%. There are many factors affecting the efficiency of permeable pavements to reduce stormwater runoff volume, which may include, but are not limited to the following: type of the permeable pavements, design, installation, site slope and rainfalls. Being studied in this research were the effects of rainfalls on the stormwater volume reduction of three types of permeable pavements: permeable concrete, permeable asphalt and permeable interlocking concrete blocks.

The City of St. Louis started a pilot study in 2008 to evaluate the effectiveness of permeable pavements on runoff volume reduction and quality improvement. For the purpose of the study, three sites were selected in the St Louis metropolitan area, and their surface covers were replaced with permeable pavements. Then, data were collected for these sites under the conditions existing in 2008 and also after the installation of the permeable pavements in 2011. The collected data, which included rainfalls and flow rates in the combined sewers during the period of the pilot study, were used in this research.

After detailed calculations and analysis of the collected data and comparison of the results, it was found that rainfall intensity affected the volume of stormwater runoff generated from the three sites. When rainfall intensity increased, the volume of the runoff generated per each inch of rainfall increased as well. The results showed that the reduction rates in the volume of the runoff generated due to the use of permeable pavements decreased with the increase in rainfall intensity. All storms that occurred during the study period were divided into four groups based on their rainfall intensities. For group 1, which included all storms whose rainfall intensities were between 0.01-0.25 in/hr, the reductions were 60%, 36% and 69% for permeable concrete, permeable asphalt and permeable interlocking concrete blocks, respectively. For group 2, which included all storms whose rainfall intensities were between 0.25-0.50 in/hr, the reductions were decreased to 28%, 24% and 53%, respectively. For group 3, which included all storms whose rainfall intensities were between 0.50-0.75 in/hr, the reductions were decreased to 21%, 15% and 27%, respectively. For group 4, which included all storms whose rainfall intensities were between 0.75-1.00 in/hr, the reductions were decreased to 10%, 9% and 22%, respectively.

ACKNOWLEDGMENTS

"In the name of Allah, the Most Gracious, the Most Merciful"

I would like to acknowledge the valuable support of my advisor Dr. Jianpeng Zhou, Associate Professor of Civil Engineering at SIUE. Without his assistance, guidance, and continual encouragement, this thesis would not have been possible. I also graciously thank Dr. Susan Morgan and Dr. Laurent Ahiablame for serving on my thesis committee and their constructive comments.

In addition, I would like to thank my beloved parents and siblings. They have been a source of encouragement and inspiration to me throughout my life. It is their unconditional love that motivates me to set higher goals in my life. Furthermore, I extend special thanks to my beloved wife, who has taken the responsibilities of taking care of our children during my study.

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CHAPTER 1

INTRODUCTION AND STATEMENT OF PROBLEM

1.1 Introduction

1.1.1 Combined sewer system

The evolution of personal lifestyles throughout time has caused a considerable increase in the volume of wastewater. In the middle of 19th century, the volume of wastewater exceeded the capacity of the existing cesspools in some European cities. Thus, these cities started to discharge their wastes into sewers originally designed for transferring surface runoff (Burian 1999). Discharging sewage to the storm sewer systems caused the generation of combined sewer systems (CSS), which are sewer systems that collect and convey sanitary sewage with surface runoff in the same piping system.

In the meantime, a rapid urbanization occurred in the United States. Urban area populations more than doubled between 1840 and 1880 (U.S. Census Bureau 2014). Therefore, Americans began to study European systems to decide whether to combine or separate the two systems. By the end of the 19th century, the decision was made to combine the two systems in highly populated urban areas by transmitting the wastewater to the receiving water bodies through existing sewer systems. Those who made the decision thought that there was enough dilution from the receiving water bodies to reduce the harm of the sewage. Thus, the practice of combining sanitary wastewater with surface runoff in one pipe was adopted (Moffa 1997). There were approximately 1,100 CSSs in the United States serving 43 million people (Meyland et al., 1998). In the combined sewers, the wastewater is conveyed to wastewater treatment plants. Sometimes, during heavy storms, combined sewers receive higher than usual flows, but due to the limited capacity of the treatment facilities, these facilities are unable to handle more than their designed capacity. In such cases, the excess stormwater and untreated wastewater bypass the treatment facility, discharging directly into a water body. This flow is known as combined sewer overflows (CSOs). Figure 1 illustrates the general scheme of CSOs.

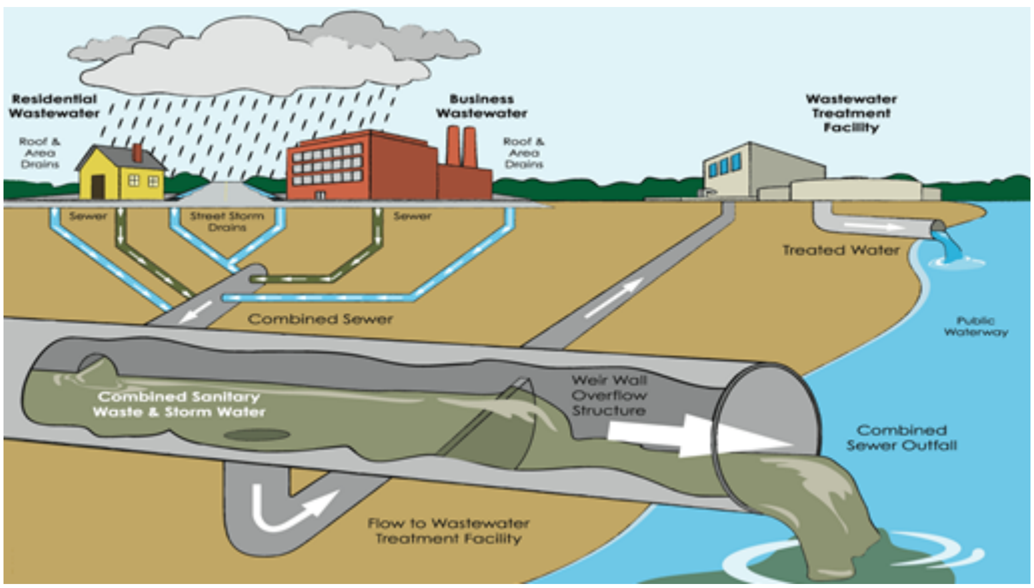


Figure 1. Combined Sewer Overflows (Bullock, 2011)

The main concern about CSOs is their effect on water quality and recreational uses. By the middle of the 20th Century, sanitary experts began to understand the hazards present in wastewater and the serious water pollution threat posed by overflows. Scientific researchers had shown the significant health and environmental hazards of untreated overflows of raw sanitary wastewater and stormwater. Their studies prompted the US Congress to address the concern by passing the Federal Water Pollution Control Act in 1965. This Act acknowledged the need to regulate CSOs output by authorizing funding for research, development, and demonstration of techniques to control them. By 1994, the US EPA had reported that CSSs discharged their overflows 50 to 80 times per year on average nationwide. This resulted in the delivering of about 1.2 trillion gallons of untreated wastewater and stormwater runoff into receiving waters each year (USEPA 1994).

The impacts of CSOs on the receiving waters include (but are not limited to) adverse human health effects, beach closures, endangerment of fish, shellfish bed closures, and aquatic life toxicity in general. In addition, CSOs can seriously damage the aesthetic quality of receiving waters, such as taste, odor, and color, which have significant socio-economic impacts on the affected area.

There are three ways to solve the CSOs problem:

1- Rebuild the sewer system in such a way that both the storm flow and the sanitary flow has its own sewer network.

2- Enlarge the treatment facilities so that they will be able to handle and treat high flows during wet weather days.

3- Reduce stormwater runoffs by implementing best management practices (e.g. permeable pavements, green roofs, bioretention cells, etc.)

Total sewer separation or the building of high capacity treatment plants could solve the CSOs problem; these solutions, however, are economically costly. Therefore, the focus for solving combined sewer overflows is switched from treating the flow to reducing it. Reducing the CSOs can be resolved through a reduction in the volume of stormwater runoff during the heavy rainfall events.

1.1.2 Permeable pavements

Parallel to the rapid increase in the urbanization nationwide, more permeable vegetated areas were replaced with impermeable roofs and paved surfaces, and this replacement caused a notable decrease in the natural infiltration process. When less rainfall infiltrates, the surface runoff will increase. Runoffs carry different types of contaminants to the receiving water body and cause damages to natural ecosystems. Figure 2 shows that in case of natural ground cover the runoff rate is 10%, while in case of 75-100% impermeable cover the rate of runoff increases to 55%.

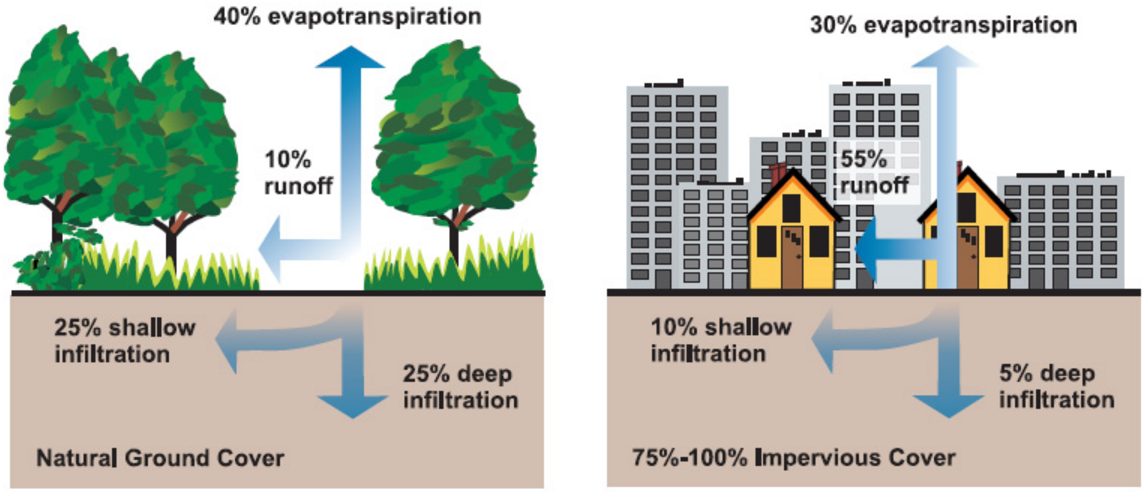


Figure 2. Infiltration Rates for Permeable vs. Impermeable Surfaces (USEPA, 2003).

To circumvent this problem, runoffs should be decreased. One of the effective ways for reducing stormwater runoffs is the use of permeable pavements instead of impermeable pavements. Permeable pavement, which is also known as pervious or porous pavement, is a surface material that allows penetration of water to the underlying reservoir. The water from reservoir, depending on the soil conditions, either naturally infiltrates to underlying soils or transfers by a subsurface drain to the sewer system. Figure 3 shows an example design of permeable pavements.

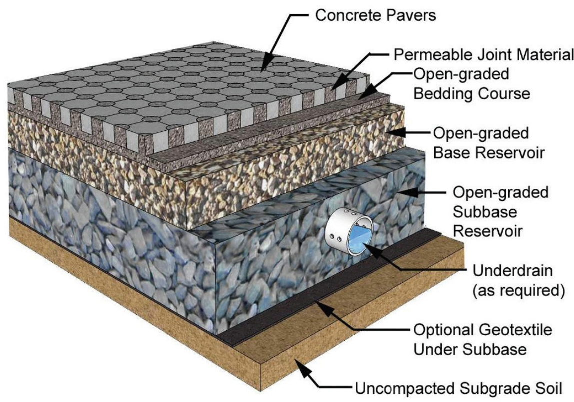


Figure 3. Profile of an Example of Permeable Pavement (Smith, 2006).

In impermeable pavements, rainwater runs across the surface to stormwater inlets that collect and direct it into pipes. The runoff and the pollutants associated with it are conveyed to the wastewater treatment plants or, in case of combined sewer overflows, directly into streams and rivers causing a lot of health and environmental problems.

In contrast, the sub-base aggregate of the permeable pavements are designed to store water during storm events and release it later either to the underlying soil or passes into the drain system. At the same time, within the infiltration process many pollutants such as total suspended solids, total nitrogen and total phosphorus are captured and removed from the discharged water (Pratt et al., 1995; James and Shahin, 1998). Surface runoff from permeable pavements showed lower pollutant concentrations compared to impermeable pavement surface runoff (Gilbert and Clausen, 2006). Long-term research studies conducted on permeable pavements showed their effectiveness in removing different pollutants such as total suspended solids, total nitrogen, total phosphorous, chemical oxygen demand, zinc and cooper. Permeable pavements may reduce both total nitrogen and total phosphorus by approximately 60% on a mass load basis. For further advanced designs where permeable pavements have adequate filtration layers underneath, which provide longer residence time, the reduction of total nitrogen and total phosphorus increases to 80% on a mass load basis (Sample, 2007).

There are several types of permeable pavements: permeable asphalt, permeable concrete, permeable pavers and others. The main differences among them are in the total pore space, their underlying permeable layers and their structural strength. Permeable concrete is a mixture of portland cement, fly ash, washed gravel and water (NRMCA, 2004). Unlike impermeable concrete, permeable concrete contains 12-25% void spaces to allow water to infiltrate to the underlying layers. Typical thicknesses for the permeable concrete range from 4" to 12", depending on the traffic load and other requirements (MSD, 2010). Permeable asphalt consists of fine and course stone aggregate bound by bituminous based binder. Its void spaces are typicaly between 15-20% (Ferguson, 2005). Permeable pavers are available in many different shapes and sizes. Generally, water infiltrates through the openings between the blocks, these openings are creating 8-20% of the total area (ICPI, 2004).

Permeable pavements can be used for an extensive range of applications including residential, commercial, municipal and industrial applications. They are particularly suited for constructing parking lots, walkways, driveways, emergency lanes, low-load roads, boat ramps, and storage facilities (Center for Watershed Protection, 1998). However, it should be noted that there are some limitations for using permeable pavements, and in certain circumstances permeable pavements should be avoided. These circumstances may include lots used for maintenance and cleaning, and lots used by industrial facilities for storing or generating hazardous materials. In addition, permeable pavements may not be practical when the slope of the land exceeds 5% (Massachusetts LID Toolkit, Fact sheet #6, 2014). Figure 4 shows different types of permeable pavements.

a) Permeable concrete b) Permeable asphalt c) Permeable interlocking concrete blocks

Figure 4. Types of Permeable Pavements

The functioning of permeable pavements depends on the underlying base soil and maintenance. For poor draining soils, where the percolation of the soil is less than 0.5 inches per hour, an underdrain system is required (City of San Francisco, 2009). Maintenance is a required and essential element to ensure the long-term performance of permeable pavement. It consists mainly of preventing the void structure from clogging. Vacuuming annually or more often is required to remove debris from the surface of the pavements (Tennis et al., 2004).

In a study conducted in North Carolina, Maryland and Delaware, when concrete grid pavers and permeable interlocking concrete pavers were tested, results showed that after performing maintenance, the permeability improved at a confidence level of 99.8% on 13 out of 14 sites (Bean et al., 2004). The surrounding soil stabilization is also important. According to a survey conducted in North Carolina and other Mid-Atlantic states of 48 permeable pavement lots, the result showed that permeable pavement lots which were built adjacent to active construction zones were more likely to clog (Hunt et al., 2006).

1.2 Problem Statement

There is a reasonable shift in managing and controlling stormwater runoff. Previously, stormwater was collected, then either diverted to treatment facilities or discharged directly to the receiving water body. Recently, efforts are being made to control stormwater at or close to its source, both in terms of quantity and quality, by reducing its volume and capturing and reducing its contaminant compounds, such as suspended solids. Theoretically, if site materials and design can eliminate or reduce the volume of stormwater runoff in the first place where it is generated, then significant progress is made towards protecting the receiving water body. This type of approach is known as low impact development (LID). One of the important tools in LID practice is permeable pavements.

Many researchers have shown the effectiveness of permeable pavements in reducing the volume of stormwater runoff that eventually reduce combined sewer overflows. In fact, stormwater runoff is mainly influenced by two different types of factors: physiographic factors and climatic factors. Physiographic factors are mainly associated with watershed characteristics, such as shape, size, slope, and soil type. The climatic factors of the watershed are mainly associated with the precipitation's characteristics, such as type of precipitation (rain, snow, hail, etc.), rainfall depth, rainfall intensity, duration, and rainfall distribution.

The impact of precipitation's characteristics on the reduction of stormwater runoff volume in combined sewers, in case of having permeable pavements, are poorly understood.

There are a limited number of studies conducted in this regard especially when different types of permeable pavements are considered.

Researchers (Zhou and Alyaseri, 2013) at Southern Illinois University Edwardsville (SIUE), in cooperation with the City of St. Louis, conducted a pilot study in 2008 through 2011 to find the percentage of stormwater runoff reduction due to the use of permeable pavements. In their study, they concentrated on the runoff volume reduction due to the installation of the permeable pavements without distinguishing between different rainfall intensities associated with the storms and their effects on the reduction rates. In this study, the flow and rainfall data from the pilot study were used in order to find the effects of rainfall intensity on the stormwater runoff reduction by each type of permeable pavements used in the pilot study. Knowing the effects of rainfall intensity on the volume of runoff generated after rainstorms helps the project designers to incorporate this factor into their consideration when they design sewer systems in different areas with different rainfall intensities.

1.3 Objective of the research

The objective of this research was to evaluate the effects of rainfall intensity on the effectiveness of three different types of permeable pavements (permeable asphalt, permeable concrete and permeable interlocking concrete blocks) in regard to stormwater volume reduction in combined sewer systems.

CHAPTER 2

LITERATURE REVIEW

2.1 <u>Stormwater Runoff Volume Reduction</u>

Several monitoring studies have shown the benefits of permeable pavements in reducing stormwater runoff. Because of their high surface infiltration rates, permeable pavements can reduce surface runoff quantity and peak runoff rates, and delay peak flows (Pratt et al., 1989; Hunt et al., 2002; Bean et al., 2007b, Kwiatkowski et al., 2007; Collins et al., 2008). Depending on the design, rainfall, soil type and paving material, permeable pavement can infiltrate as much as 70% to 80% of annual rainfall (Massachusetts LID Toolkit, Fact sheet #6, 2014). A study result from the University of Washington conducted in King County, Washington, showed that the amount of pavement's permeability is positively correlated with the reduction of runoff volume (USEPA, 2000).

In a study conducted on planted (i.e. Turfstone) and unplanted concrete block pavements in a parking lot in Renton, Washington, results showed no surface runoff. During the study period, which lasted for 18 months, 15 observed storms were recorded. Due to the geographical location of the study, the rainfall intensities of the observed storms were very low. The highest rainfall intensity observed during the study was 0.29 in/hr. (Booth and Leavitt, 1999). In a follow up investigation to the same site after four years, it showed similar results (Brattebo and Booth, 2003).

Researchers at the University of Guelph, Canada, conducted several experimental and field tests on permeable pavements to find their effectiveness on the quantity reduction and quality improvement of surface runoff. They found that permeable interlocking concrete paver showed a 90% reduction in surface runoff volume compared to impermeable asphalt even in relatively high intensity storms up to 1.3 in/hr (James, 2002).

In Virginia Piedmont area, where the average annual rainfall was 42.7 inches, several types of best management practices (BMPs) were tested in regard to the effectiveness for stormwater volume reduction. According to Table 1, stormwater runoff reduction for permeable pavements in general was from 45% to 75% (Battiata et al., 2010).

Table 1
Runoff Reduction for Various BMPs in the Virginia Piedmont Area (Battiata et al., 2010)

	BMPs Type	**Runoff Reduction (%)**
1	Infiltration	50-90
2	Soil Amendments	50-75
3	Sheet flow to Open Space	50-75
4	Permeable Pavements	45-75
5	Green Roof	45-60
6	Bioretention	40-80
7	Dry Swale	40-60
8	Rain tanks and cisterns	40
9	Rooftop Disconnection	22-50
10	Grass channel	10-20
11	ED Pond	0-15
12	Wet Swale	0
13	Filtering Practice	0
14	Constructed Wetland	0

In a comparison study of permeable concrete (PC), two types of permeable interlocking concrete pavers (PICP) and concrete grid pavers (CGP) conducted in Kinston, North Carolina, results showed no considerable difference in the amount of surface runoff generated from each type (Table 2; Collins et al., 2008). Data were collected in 2006 and 2007, more than 40 storms were included.

Table 2
Percent Reduction of Runoff in Kinston, North Carolina (Collins et al., 2008)

Pavement Type	Mean (%)	Medium (%)	Minimum (%)
Permeable Concrete	99.9	99.9	99.0
PICP – Type 1	99.3	99.4	97.8
PICP – Type 2	99.5	99.7	96.9
Concrete Grid Pavement	98.2	98.7	91.1
Standard Asphalt	34.6	29.4	0.0

In another study, researchers at North Carolina State University tested several permeable lots in eastern North Carolina where the rainfall intensity for a 1 year, 24 hour event was 3.24 in/hr. They found that each lot reduced annual runoff volume by at least 60% (Hunt, 2006).

Finally, between 2008 and 2011, a pilot study was conducted by the City of St Louis to evaluate the effectiveness of permeable pavement on volume reduction in combined sewers at three alleys in St. Louis, MO. The study reported that a reduction rate of 46%, 35.6% and 12.7% were found in the stormwater runoff volume due to installation of permeable interlocking concrete blocks, permeable concrete and permeable asphalt, respectively (Table 3; Zhou and Alyaseri, 2013).

Table 3
Percentage Reduction in Runoff in the Three Locations of the Study
(Zhou and Alyaseri, 2013)

Site	Type	Pre-construction Phase		Post-construction Phase		Reduction Rate in Stormwater Runoff Volume
		No. of Rainfall Storms	Stormwater Runoff Volume per Inch of Rain (gal/inch)	No. of Rainfall Storms	Stormwater Runoff Volume per Inch of Rain (gal/inch)	
Eads	Permeable concrete	23	21372	25	13774	36%
Cardinal	Permeable asphalt	39	4426	32	3865	13%
Geyer	Permeable pavers	22	4915	23	2652	46%

2.2 Rainfall Intensity

Rainfall intensity is the ratio of the total amount of rain falling during a storm event to the duration of the storm. It is expressed in depth of rainfall per unit time, usually as mm per hour (mm/hr) or inch per hour (in/hr). Rainfall intensity is considered a major factor in generating runoffs. When rainfall intensity is greater than infiltration rate of the surface, runoff takes place (Wen et al., 1991; Zhu and Jin, 1991). In case of low intensity rainfall, runoff takes place after saturating the underlying layers, which takes a specific time depending on characteristics such as porosity, storage space and others.

Rainfall intensity is considered one of the dominant factors in generating runoff (Wen et al., 1991). When rainfall intensity increases, the kinetic energy of the raindrops increases as well, which consequently increases the scouring force on the ground surface as well as increases the runoff on permeable pavements (Hou et al., 2008).

In a study conducted in Mentougou experimental station of Beijing Hydraulic Research Institute in 2004, the result showed 100% reduction of runoff from one of the permeable pavement designs compared to impermeable pavement, even when the rainfall intensity was 2.3 in/hr. The permeable pavement design consisted of permeable concrete blocks with a subbase of 4″ thick concrete without sand and 6″ thick aggregate base (Hou et al., 2008).

In an experimental parking lot at Melbourne, Australia, two types of permeable pavements, C&M Ecotrihex pavers and Atlantis turf cells, were tested. Due to the lack of significant rainfall events at the time of the study in Melbourne, sprinklers were used to simulate storm events. The flow rate from the sprinklers was adjusted to simulate rainfall intensities between 0.5 in/hr to 0.8 in/hr. Results showed that the C&M Ecotrihex pavers and Atlantis turf cells reduced surface runoff up to 55% and 60%, respectively, when compared to the impermeable asphalt pavement (Jayasuriya et al., 2008).

In another laboratory study conducted in South Carolina, permeable concrete slabs, which were 7″ thick with 6″ thick sand bedding layer, were tested under simulated rainfall events. Results showed that only under high intensity events (i.e., 0.8-1.8 in/hr) were runoffs observed from the slabs (Valavala et al., 2006).

Furthermore, researchers have conducted a field study on the effectiveness of permeable pavements in the reduction of peak flow and runoff volume in Charles City, Iowa and they found that it reduced stormwater peak flows by at least 75% for 10-year storm events and 40% for 100-year storm events. Also, it reduced the surface runoff volume by over 60% up to the 10-year storm event, and over 30% for the 100-year storm event (Yang et al. 2012).

Rainfall intensity is considered a very important parameter when rainfall-runoff relationships is demonstrated especially in areas where infiltration-excess runoff (i.e., when rainfall intensity is higher than the infiltration rate of the surface) is expected (Beven, 2004; Amore et al., 2004). Research showed that the amount of surface runoff generated from permeable surfaces depends more on rainfall intensity than rainfall depth (Day et al., 1981; Hunt et al., 2002; Valavala et al., 2006; Collins et al., 2008). Therefore, storms of low intensity that have a long duration would produce much less runoff than high intensity, short duration storms that might have a lower total rainfall. This means, in case of high rainfall intensity, the runoff is more likely due to the exceeding of rainfall intensity over the infiltration ability of the permeable pavement rather than saturation in the underlying layers of the permeable pavement.

The underdrain flow, in those systems of permeable pavements which include under drains, depends on rainfall depth and rainfall intensity (Dempsey and Swisher, 2003; Gilbert and Clause, 2006). The effects of rainfall depth on the underdrain flow becomes less significant as rainfall intensity increases. As intensity increases, the porous spacing of the permeable pavement may limit the amount of the precipitation passes through and the rate at which it passes to the base course. Therefore, in case of high intensity storms, pavement surface infiltration rate is a limiting hydrologic design factor rather than the storage capacity of the system (ASCE, 2007).

CHAPTER 3

METHODOLOGY

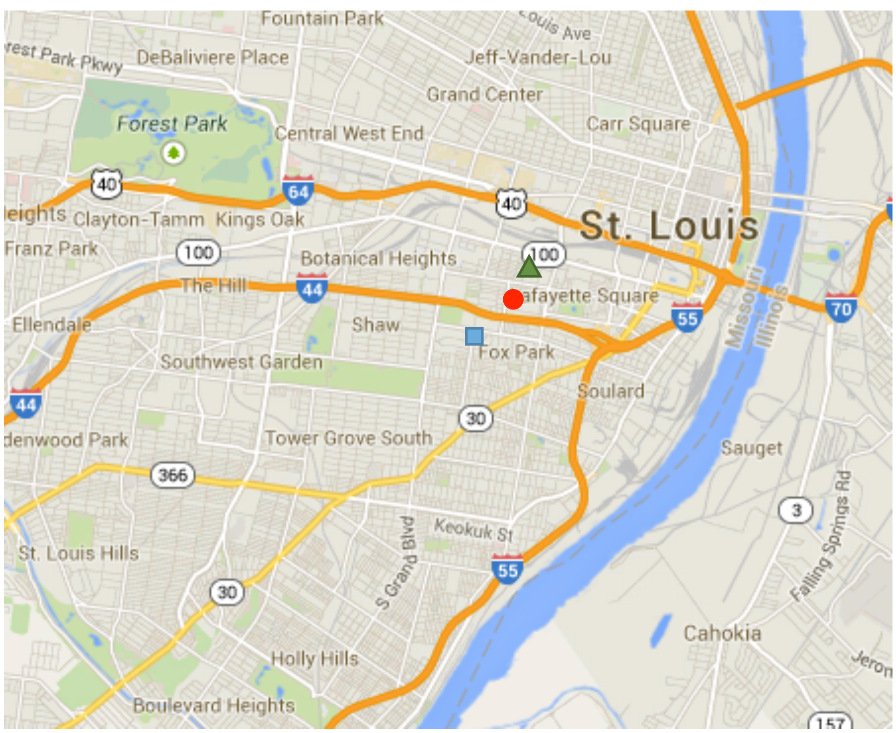
In 2008, the City of St Louis, Missouri started a pilot study to evaluate the effectiveness of permeable pavements on volume reduction and water quality improvement in combined sewers at three alleys in the City of St. Louis. The pilot study was planned for three phases: Phase-I was to measure the flows and monitor water quality in combined sewers in the period between 3/26/2008 to 7/17/2008 under the existing conditions (i.e. pre-installation of the permeable pavements); Phase-II was to design and install permeable pavements at the three alleys. Phase-II was conducted and completed in 2009; Phase-III was to re-measure the flows in order to evaluate the effectiveness of volume reduction under the new conditions (i.e. post-installation of the permeable pavements). Phase III was carried out in 2011 to 2012.

Metropolitan St Louis Sewer District (MSD) installed and maintained the flowmeters during the monitoring periods, and downloaded the data. The flows were measured by using Teledyne ISCO type of flowmeter, which recorded liquid level and average flow velocity in the sewers. The nearest rain gauge station to each site was chosen to obtain rainfall data for analysis. Then, MSD calculated the flow rates and provided the data to SIUE for analysis. Researchers at SIUE analyzed the data to obtain the reduction rate in the runoff volume generated from each site due to the installation of the permeable pavements. SIUE researchers' analyses were limited to the runoff volume reduction without distinguishing between different rainfall intensities associated with the rain storms and their effects on the reduction rates. As it was discussed in chapter 2, rainfall intensity may affect the effectiveness of permeable pavements. So, it is important to understand the weight of this effect.

In this research, further analysis was done using the same data from the pilot study in order to quantify and evaluate the effects of rainfall intensity on the performance of the permeable pavements.

3.1 Study Sites

Three alleys at Eads, Geyer and Cardinal Avenues were selected as the study sites. These avenues are located in the City of St. Louis within one mile from each other. Figure 5 shows the location of the alleys.



▲ Alley at Cardinal Ave. ● Alley at Eads Ave. ■ Alley at Geyer Ave.

Figure 5. Locations of the Alleys in the Pilot Study (Google Map, 2014).

All precipitation events before and after the installation of permeable pavements were in the form of rainfall, but the storm events at each location were different. Thus, data for each site were analyzed separately and stormwater runoff volume discharged to the combined sewer systems were normalized to one inch of rainfall.

3.1.1 Permeable concrete at Eads Ave.

This alley is located in Eads Ave., St. Louis MO, 63104. It is parallel to Compton Ave., between Eads and Henrietta. Figure 6 shows the location of this alley. The surface cover of the alley was impermeable asphalt in 2008 before replacing it with permeable concrete for the purpose of the pilot study. In 2008, during the monitoring period between March 26 and July 17, a total of 37 storms were recorded in the rain gauge station. In 2011, after the installation of the concrete permeable pavement in the site and during the monitoring period between March 26 and December 31, a total of 46 storms were recorded in the rain gauge station.

Figure 6. Concrete Permeable Pavement at Eads Ave.

3.1.2 Permeable asphalt at Cardinal Ave.

This alley is located in Cardinal Ave., St. Louis MO, 63104. It is parallel to Park Ave., between Montrose Ave. and Cardinal Ave. The surface cover of this alley was impermeable brick in 2008 before replacing it with permeable asphalt for the purpose of the pilot study. Figure 7 shows the location of the alley. In 2008, during the monitoring period between March 26 and July 17, a total of 42 storms were recorded in the rain gauge station. In 2011, after the installation of the asphalt permeable pavement in the site and during the monitoring period between March 26 and December 31, a total of 48 storms were recorded in the rain gauge station.

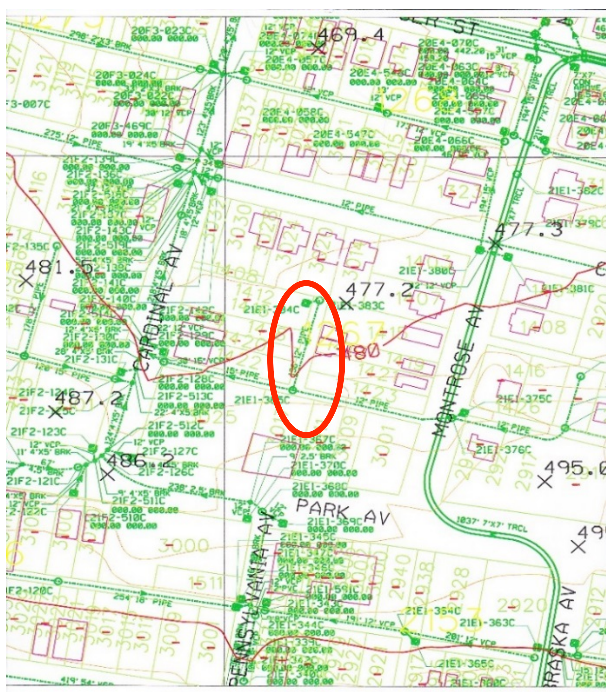


Figure 7. Asphalt Permeable Pavement at Cardinal Ave.

3.1.3 Permeable interlocking concrete blocks at Geyer Ave.

This alley is located in Geyer Ave., St. Louis MO, 63104. It is parallel to Compton Hill Pl., between Geyer Ave and I-44. Figure 8 shows the location of this alley. The surface cover of the alley was impermeable bricks in 2008 before replacing it with permeable interlocking concrete blocks for the purpose of the pilot study. In 2008, during the monitoring period between March 26 and July 17, a total of 38 storms were recorded in the rain gauge station but due to malfunctioning of the flowmeter 4 storms were excluded, thus only 34 storms were included in this analysis. In 2011, after the installation of the interlocking concrete blocks in the site and during the monitoring period between March 26 and December 31, a total of 52 storms were recorded in the rain gauge station, but due to the malfunctioning of the flowmeter between July 17 and Dec 31, a total of 18 storms were excluded. Thus, only 34 storms were included in this analysis.

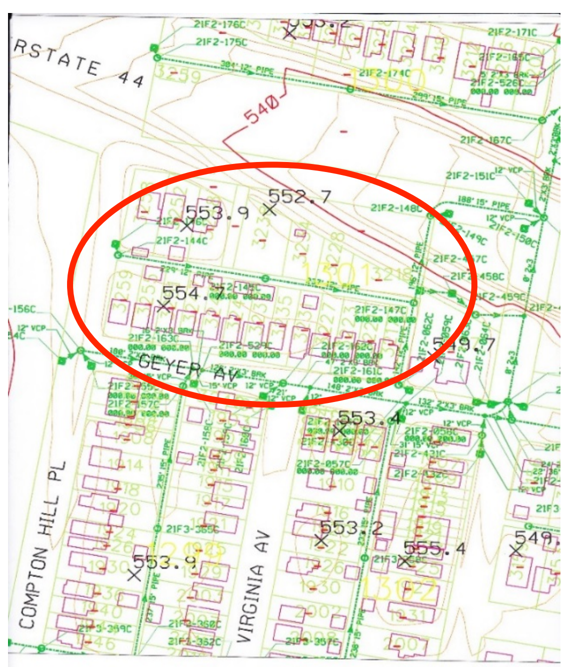


Figure 8. Permeable Interlocking Concrete Block Pavement at Geyer Ave.

3.2 Total Flow in the Combined Sewer System

The data for the CSS were available for each location (Eads, Cardinal, and Geyer) and included the flow rates measured at 15 minute intervals and rainfall depth at each 15 minute interval. For the pre-installation case, the flow and rainfall data were available only from March 26, 2008 to July 17, 2008. For the post installation case, the flow data were available from March 26, 2011 to February 6, 2012 and the rainfall data were available from March 26, 2011 to December 31, 2011. From the available measured flow rates, volume of the total flow in the combined sewer as a result of discharged sanitary (sewage) and surface runoff was calculated for each 15 minutes. Then the volume of total flow for each storm was calculated.

3.3 Separating Sewage Flow from Total Flow

The combined sewer systems convey both sanitary and stormwater. In order to estimate the volume of stormwater discharged to the sewer, the volume of the sewage flow was estimated at the time when the storm occurred and subtracted from the total flow in the sewer. For estimating the sewage flow during the storm period, the first assumption was that the sewage flow in the combined sewer changed a little during 24 hours. Based on this, the sewage flow at the storm period was estimated to be the same as the flow before starting the storm. For checking this assumption, several days were randomly selected and flow charts were drawn. Figure 9 shows the sewage flow rate at the Cardinal site on 3 different dry days.

From Figure 9, it was found that the assumption may be acceptable for short period storms (less than 60 minutes) but not for long period storms. The flow chart showed that during long periods, the sewage flow increased or decreased irregularly. The reason for the change was that in certain times of the day, people consumed water much more than the rest of the day. As more than 75% of the storms occurred during the study period lasted for more than 60 minutes, this method was not accurate.

However, from the drawn charts, it was found that there was a close similarity for the flow rates in the sewer between the dry working days as well as between the dry weekend days. So, as an alternative, it was assumed that the sewage flow rate in the sewer during any period in a wet working day is same as the average of the flow rates for the same period of the dry working days before and after the wet working day. Also, for wet weekend days, the average of the same period from the previous and following dry weekend days were taken as a base to calculate the sewage flow in the sewer during the storm period. In this procedure, holidays and special event days were excluded due to the expectation of sewage flow rate changes during these days. Appendix A shows the date of the dry days were used as a base for estimating the sewage flow for each storm at each site. Then, to calculate the surface flow (i.e. stormwater flow), the sewage flow was deducted from the total measured flow.

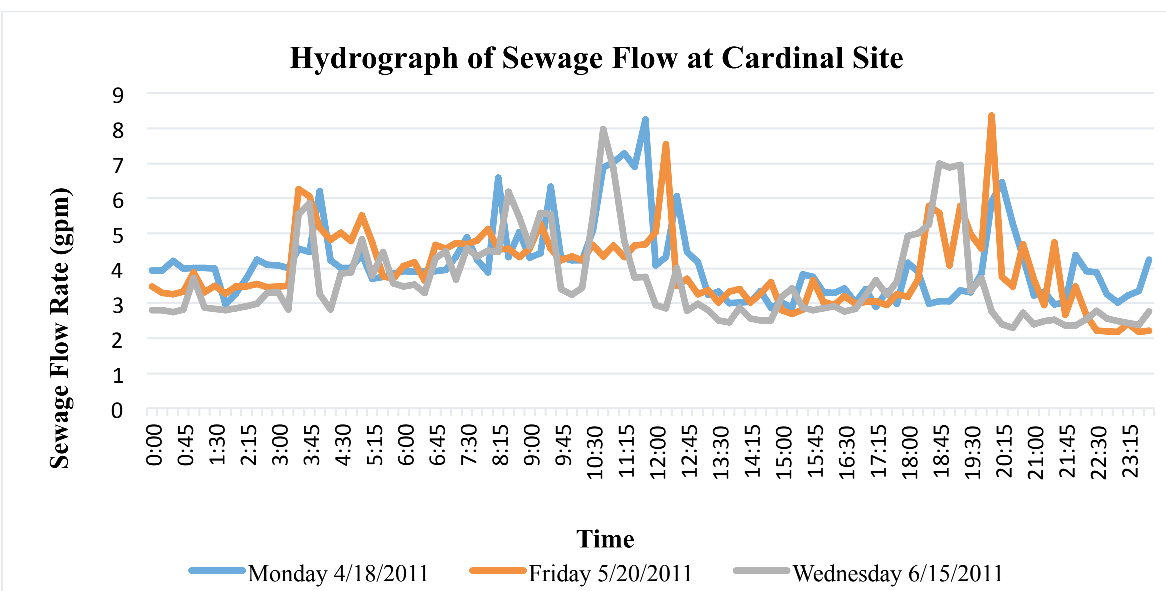


Figure 9. Sewage Flow Rate at Cardinal Site

Based on this method, and for all storm events during the study, the volume of stormwater flow due to rainfall was calculated. Because rainfall depth differed from one storm to another, the volume of stormwater discharged from each storm was normalized for each inch of the rainfall for the purpose of comparison. This was calculated by dividing the volume of the stormwater runoff generated from each storm by the rainfall depth of the storm.

In order to check the quality of the field data, the stormwater flow rate for each storm in each site was compared to the stormwater flow rate calculated by using the rational method for runoff estimation. The result (Appendix B) showed that the differences in the stormwater flow rates in both cases were within 20% for more than 75% of the storms. There are many reasons to cause differences between the flow rates, such as the duration of the storm, temperature, and runoff from adjacent areas. This result provided enough confidence about the quality of the field data so as to be used in the study.

3.4 Data Analysis

For the purpose of comparison, storms which have a similar or close rainfall depths but different rainfall intensities were selected from each site. Then a comparison was made between the volume of stormwater runoff generated per each inch of rain of the storms and the results were analyzed.

Furthermore, by using general regression analysis, the relations between rainfall intensity and stormwater runoff per each inch of rain were found for each site and for both cases, before and after the installation of permeable pavements. Depending on the results, type of the correlations existed between these variables were obtained and evaluated.

For more detailed analysis, four different groups from the rainfall intensities of the storms occurred during the monitoring periods were created depending on the minimum and maximum rainfall intensities observed. Then, the average volume of stormwater runoffs for all storms in each group at each site were calculated for both cases (i.e. pre-and post-installation of permeable pavements). Then for each group at each site, differences between these calculated runoff volumes in both cases were found. Finally, the reduction rate in the stormwater runoff volume for each group at each site was determined and results were evaluated and discussed to show the effects of rainfall intensities.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Data Analysis

When the stormwater volume for each storm was calculated, a detailed table was prepared for each site for pre-installation (2008) and post-installation (2011) including all related data for each storm (rainfall depth, duration, rainfall intensity, total flow volume, sewage volume, stormwater volume, and stormwater volume per an inch of rain). Tables 4 and 5 show the calculated data for Eads site. Tables 6 and 7 and Tables 8 and 9 show these data for Cardinal and Geyer sites, respectively.

Generally, by comparing the average runoff volume per an inch of rain generated from each site and discharged to the sewer system in 2011 with the average runoff volume per an inch of rain generated from the same site in 2008, it was found that there was a considerable reduction in the amount of the runoff volume discharged to the sewer system between 2008 and 2011. Table 10 shows the amount of runoff volume generated at each site before and after the installation of the permeable pavements, the reduction amount and the percentage reduction at each site.

The results show a reduction of 49%, 25% and 53% after installation of permeable concrete, permeable asphalt and permeable interlocking concrete blocks, respectively. Although the reduction percentage was different from one type to another, the result showed the effectiveness of all three types of permeable pavements to reduce the runoff volume. These results are similar to the results of the previous studies discussed in chapter 2.

Table 4
Data at Eads Site in 2008 (i.e. before installing the permeable pavement)

Storm No.	Storm Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Total Flow Volume (gal)	Sewage Volume (gal)	Stormwater Volume (gal)	Stormwater Volume per Inch of Rain (gal/in)
1	3/26/2008	0.95	315	0.18	9,700	71	9,629	10,136
2	3/27/2008	0.13	45	0.17	1,176	123	1,053	8,100
3	3/27/2008	0.33	75	0.26	4,988	185	4,803	14,555
4	3/27/2008	0.33	75	0.26	3,988	12	3,976	12,048
5	3/30/2008	0.57	150	0.23	12,115	40	12,075	21,184
6	3/31/2008	0.92	240	0.23	24,693	420	24,273	26,384
7	4/3/2008	0.47	210	0.13	8,282	256	8,026	17,077
8	4/8/2008	0.19	30	0.38	3,940	24	3,916	20,611
9	4/10/2008	0.92	240	0.23	23,980	290	23,690	25,750
10	4/10/2008	0.84	300	0.32	12,509	420	12,089	14,392
11	4/18/2008	0.43	210	0.12	8,759	29	8,730	20,302
12	4/24/2008	0.10	75	0.08	1,071	45	1,026	10,260
13	4/25/2008	0.10	15	0.40	1,329	14	1,315	13,150
14	4/25/2008	0.10	15	0.40	848	21	827	8,270
15	5/2/2008	0.21	60	0.21	2,710	30	2,680	12,762
16	5/7/2008	0.37	120	0.18	7,248	17	7,231	19,543
17	5/7/2008	0.37	120	0.28	7,248	235	7,013	18,954
18	5/7/2008	0.48	330	0.28	8,493	462	8,031	16,731
19	5/8/2008	0.55	300	0.11	13,003	169	12,834	23,335
20	5/10/2008	0.25	120	0.12	3,915	58	3,857	15,428
21	5/10/2008	0.43	105	0.60	9,695	172	9,523	22,147
22	5/11/2008	0.16	135	0.07	3,777	176	3,601	22,506
23	5/13/2008	0.20	90	0.13	1,180	18	1,162	5,810
24	5/15/2008	0.18	150	0.07	1,438	83	1,355	7,528
25	5/25/2008	0.39	30	0.78	13,793	15	13,778	35,328
26	5/25/2008	0.56	30	1.84	7,995	185	7,810	13,946
27	5/26/2008	0.68	210	0.19	28,595	254	28,341	41,678
28	6/3/2008	0.58	45	0.77	6,581	61	6,520	11,241
29	6/4/2008	0.19	75	0.15	4,811	25	4,786	25,189
30	6/6/2008	1.76	165	0.64	43,975	195	43,780	24,875
31	6/6/2008	0.43	60	0.68	10,756	235	10,521	24,467
32	6/20/2008	0.19	90	0.13	3,851	41	3,810	20,053
33	6/22/2008	0.11	30	0.22	429	16	413	3,755
34	6/24/2008	0.16	45	0.21	2,403	37	2,366	14,788
35	7/2/2008	0.42	210	0.12	4,672	228	4,444	10,582
36	7/8/2008	0.49	30	0.98	21,467	21	21,446	43,767
37	7/11/2008	0.26	60	0.26	3,882	26	3,856	14,831

Table 5
Data at Eads Site in 2011 (i.e. after installing the permeable pavement)

Storm No.	Storm Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Total Flow Volume (gal)	Sewage Volume (gal)	Stormwater Volume (gal)	Stormwater Volume per Inch of Rain (gal/in)
1	4/4/2011	0.40	60	0.40	4,082	28	4,054	10,135
2	4/4/2011	0.18	105	0.10	954	215	739	4,106
3	4/9/2011	0.28	45	0.37	1,927	21	1,906	6,807
4	4/11/2011	0.13	60	0.13	1,144	133	1,011	7,777
5	4/11/2011	0.15	105	0.09	837	448	389	2,593
6	4/15/2011	0.40	105	0.23	3,321	180	3,141	7,853
7	4/15/2011	0.36	90	0.24	3,949	145	3,804	10,567
8	4/19/2011	0.46	90	0.31	7,842	188	7,654	16,639
9	4/19/2011	0.20	120	0.10	1,170	195	975	4,875
10	4/22/2011	0.17	105	0.10	1,986	385	1,601	9,418
11	4/22/2011	0.37	300	0.07	3,120	645	2,475	6,689
12	5/1/2011	0.16	90	0.11	974	271	703	4,394
13	5/14/2011	0.12	105	0.07	1,235	520	715	5,958
14	5/22/2011	0.12	45	0.16	1,093	85	1,008	8,397
15	5/23/2011	0.50	90	0.33	4,664	194	4,470	8,941
16	5/25/2011	1.20	150	0.48	13,986	98	13,888	11,573
17	6/10/2011	0.61	60	0.61	11,328	23	11,305	18,533
18	6/14/2011	0.24	30	0.48	3,277	31	3,246	13,525
19	6/17/2011	0.97	105	0.55	13,689	109	13,580	14,000
20	6/19/2011	0.37	150	0.15	1,497	87	1,410	3,811
21	6/21/2011	0.17	30	0.34	1,250	35	1,215	7,147
22	6/25/2011	2.92	210	0.83	79,621	142	79,479	27,219
23	6/27/2011	0.35	60	0.35	5,702	44	5,658	16,166
24	6/27/2011	0.15	90	0.10	732	155	577	3,847
25	6/27/2011	0.16	75	0.13	1,516	89	1,427	8,919
26	7/3/2011	0.39	75	0.31	3,391	108	3,283	8,417
27	7/3/2011	0.15	105	0.09	1,288	255	1,033	6,887
28	7/4/2011	0.34	120	0.17	3,845	475	3,370	9,912
29	7/7/2011	1.30	120	0.65	32,605	428	32,177	24,752
30	7/12/2011	0.26	30	0.52	4,761	114	4,647	17,873
31	8/19/2011	0.15	90	0.10	735	105	630	4,200
32	9/3/2011	0.19	30	0.38	2,414	35	2,379	12,521
33	9/14/2011	0.22	120	0.11	1,175	86	1,089	4,950
34	9/18/2011	0.20	90	0.13	1,620	81	1,539	7,695
35	9/22/2011	0.15	105	0.09	683	67	616	4,107
36	10/12/2011	0.33	75	0.26	1,845	74	1,771	5,367
37	10/17/2011	0.11	30	0.22	657	25	632	5,745
38	11/3/2011	0.73	225	0.19	7,566	165	7,401	10,138
39	11/8/2011	0.10	105	0.06	559	90	469	4,690
40	11/22/2011	0.42	165	0.15	3,832	85	3,747	8,921
41	11/26/2011	0.18	90	0.12	1,748	43	1,705	9,472
42	12/3/2011	0.38	135	0.17	3,881	95	3,786	9,963
43	12/13/2011	0.22	150	0.09	1,135	78	1,057	4,805
44	12/14/2011	0.31	90	0.21	3,334	82	3,252	10,490
45	12/19/2011	0.65	450	0.09	4,962	305	4,657	7,165
46	12/26/2011	0.44	270	0.10	3,741	185	3,556	8,082

Table 6
Data at Cardinal Site in 2008 (i.e. before installing the permeable pavement)

Storm No.	Storm Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Total Flow Volume (gal)	Sewage Volume (gal)	Stormwater Volume (gal)	Stormwater Volume per Inch of Rain (gal/in)
1	3/26/2008	1.10	360	0.18	3,203	422	2,781	2,528
2	3/27/2008	0.18	45	0.24	1,017	180	837	4,650
3	3/27/2008	0.23	60	0.23	1,207	152	1,055	4,587
4	3/30/2008	0.58	135	0.26	1,275	162	1,113	1,919
5	3/31/2008	0.89	240	0.22	4,029	534	3,495	3,927
6	4/8/2008	0.23	15	0.92	1,605	218	1,387	6,030
7	4/10/2008	0.77	255	0.18	1,900	445	1,455	1,890
8	4/10/2008	0.80	285	0.17	2,551	413	2,138	2,673
9	4/18/2008	0.12	150	0.05	412	239	173	1,442
10	4/18/2008	0.48	210	0.14	1,697	310	1,387	2,890
11	4/25/2008	0.47	30	0.94	1,113	120	993	2,113
12	4/25/2008	0.11	15	0.44	239	74	165	1,500
13	5/2/2008	0.35	60	0.35	2,204	101	2,103	6,009
14	5/7/2008	0.17	45	0.23	273	60	213	1,253
15	5/7/2008	0.38	120	0.19	1,307	153	1,154	3,037
16	5/7/2008	0.48	300	0.10	1,472	340	1,132	2,358
17	5/8/2008	0.56	270	0.12	2,155	405	1,750	3,125
18	5/9/2008	0.10	105	0.06	533	218	315	3,150
19	5/10/2008	0.27	120	0.14	675	240	435	1,611
20	5/10/2008	0.49	105	0.28	2,585	406	2,179	4,447
21	5/11/2008	0.27	210	0.08	934	438	496	1,837
22	5/13/2008	0.18	90	0.12	755	325	430	2,389
23	5/15/2008	0.12	90	0.08	832	230	602	5,017
24	5/25/2008	0.73	45	0.97	5,768	85	5,683	7,785
25	5/25/2008	0.48	30	0.96	2,888	68	2,820	5,875
26	5/26/2008	0.58	195	0.18	2,926	310	2,616	4,510
27	5/27/2008	0.10	75	0.08	213	94	119	1,190
28	5/30/2008	0.87	120	0.44	7,199	460	6,739	7,746
29	5/30/2008	0.30	60	0.30	1,927	280	1,647	5,490
30	5/31/2008	0.10	90	0.07	827	223	604	6,040
31	6/3/2008	0.57	45	0.76	4,689	446	4,243	7,444
32	6/4/2008	0.34	90	0.23	1,788	526	1,262	3,712
33	6/6/2008	1.46	150	0.58	9,308	660	8,648	5,923
34	6/6/2008	0.33	75	0.26	1,842	118	1,724	5,224
35	6/13/2008	0.11	30	0.22	407	260	147	1,336
36	6/20/2008	0.67	105	0.38	2,108	450	1,658	2,475
37	6/24/2008	0.15	45	0.20	460	236	224	1,493
38	7/2/2008	0.47	195	0.14	1,245	664	581	1,236
39	7/3/2008	0.47	45	0.63	2,250	256	1,994	4,243
40	7/8/2008	0.61	30	1.22	3,112	63	3,049	4,998
41	7/9/2008	0.19	135	0.08	1,385	485	900	4,737
42	7/11/2008	0.24	60	0.24	807	140	667	2,779

Table 7
Data at Cardinal Site in 2011 (i.e. after installing the permeable pavement)

Storm No.	Storm Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Total Flow Volume (gal)	Sewage Volume (gal)	Stormwater Volume (gal)	Stormwater Volume per Inch of Rain (gal/in)
1	3/27/2011	0.18	75	0.14	306	124	182	1,011
2	4/4/2011	0.34	30	0.68	1,678	65	1,613	4,744
3	4/4/2011	0.17	30	0.34	738	108	630	3,705
4	4/9/2011	0.24	45	0.32	753	62	691	2,879
5	4/11/2011	0.13	60	0.13	557	145	412	3,166
6	4/11/2011	0.20	135	0.09	617	235	382	1,910
7	4/15/2011	0.38	105	0.22	1,273	137	1,136	2,989
8	4/15/2011	0.36	60	0.36	1,447	110	1,337	3,713
9	4/19/2011	0.45	30	0.90	2,351	24	2,327	5,171
10	4/19/2011	0.34	60	0.34	744	84	660	1,941
11	4/27/2011	0.26	120	0.13	1,230	445	785	3,019
12	4/27/2011	0.86	300	0.17	3,071	465	2,606	3,030
13	5/1/2011	0.16	75	0.13	763	212	551	3,444
14	5/19/2011	0.10	60	0.10	441	195	246	2,462
15	5/23/2011	0.49	60	0.49	1,333	52	1,281	2,614
16	5/25/2011	0.16	60	0.16	236	67	169	1,056
17	5/25/2011	0.83	165	0.30	3,667	348	3,319	3,999
18	6/10/2011	0.96	105	0.55	4,021	210	3,811	3,970
19	6/11/2011	0.17	30	0.34	687	170	517	3,041
20	6/14/2011	0.10	30	0.20	138	28	110	1,104
21	6/14/2011	0.28	45	0.37	1,145	182	963	3,439
22	6/17/2011	0.68	90	0.45	2,784	189	2,595	3,817
23	6/18/2011	0.75	120	0.38	3,613	311	3,302	4,403
24	6/19/2011	0.40	165	0.15	1,517	458	1,059	2,648
25	6/21/2011	0.14	30	0.28	544	26	518	3,699
26	6/26/2011	2.99	210	0.85	14,416	523	13,893	4,646
27	6/27/2011	0.29	60	0.29	1,322	241	1,081	3,728
28	6/27/2011	0.20	135	0.09	612	130	482	2,410
29	6/27/2011	0.17	90	0.11	518	104	414	2,435
30	7/3/2011	0.19	30	0.38	899	54	845	4,447
31	7/3/2011	0.51	210	0.15	1,205	291	914	1,791
32	7/4/2011	0.10	30	0.20	143	39	104	1,040
33	7/4/2011	0.13	45	0.17	354	117	237	1,823
34	7/4/2011	0.13	30	0.26	462	89	373	2,868
35	7/4/2011	0.34	60	0.34	1,355	215	1,141	3,355
36	7/7/2011	1.46	105	0.83	9,594	510	9,084	6,222
37	7/12/2011	0.23	30	0.46	804	85	719	3,125
38	8/5/2011	0.31	30	0.62	1,323	25	1,298	4,187
39	8/19/2011	0.18	120	0.09	303	118	185	1,028
40	9/9/2011	0.13	30	0.26	325	41	284	2,185
41	9/14/2011	0.42	180	0.14	638	140	498	1,186
42	9/18/2011	0.23	90	0.15	359	89	270	1,174
43	11/3/2011	0.81	255	0.19	1,385	168	1,217	1,502
44	11/8/2011	0.12	75	0.10	153	52	101	842
45	11/26/2011	0.17	75	0.14	169	16	153	900
46	12/3/2011	0.46	180	0.15	763	195	568	1,235
47	12/14/2011	0.32	60	0.32	890	80	810	2,531
48	12/26/2011	0.47	285	0.10	1,240	530	710	1,511

Table 8
Data at Geyer Site in 2008 (i.e. before installing the permeable pavement)

Storm No.	Storm Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Total Flow Volume (gal)	Sewage Volume (gal)	Stormwater Volume (gal)	Stormwater Volume per Inch of Rain (gal/in)
1	3/26/2008	0.95	315	0.18	3,166	535	2,631	2,769
2	3/27/2008	0.13	45	0.17	686	83	603	4,638
3	3/27/2008	0.33	75	0.26	1,182	66	1,116	3,382
4	3/31/2008	0.92	240	0.23	4,107	121	3,986	4,333
5	4/8/2008	0.19	30	0.38	386	31	355	1,868
6	4/10/2008	0.92	240	0.23	2,182	71	2,111	2,295
7	4/10/2008	0.84	300	0.17	3,356	155	3,201	3,811
8	4/25/2008	0.44	30	0.88	1,569	10	1,559	3,543
9	5/2/2008	0.21	60	0.21	1,005	45	960	4,571
10	5/7/2008	0.20	30	0.40	187	21	166	830
11	5/7/2008	0.37	120	0.19	906	25	881	2,381
12	5/7/2008	0.48	330	0.09	1,819	120	1,699	3,540
13	5/8/2008	0.55	300	0.11	1,865	129	1,736	3,156
14	5/10/2008	0.25	120	0.13	670	39	631	2,524
15	5/10/2008	0.43	105	0.25	1,873	115	1,758	4,088
16	5/11/2008	0.16	135	0.07	608	24	584	3,650
17	5/13/2008	0.20	90	0.13	676	17	659	3,295
18	5/15/2008	0.18	150	0.07	431	48	383	2,128
19	5/25/2008	1.21	60	1.21	5,132	84	5,048	4,172
20	5/25/2008	0.45	45	0.60	1,426	18	1,408	3,129
21	5/26/2008	0.15	45	0.20	810	29	781	5,207
22	5/26/2008	0.61	195	0.19	2,106	188	1,918	3,144
23	5/30/2008	1.23	135	0.55	3,757	160	3,597	2,924
24	6/3/2008	0.50	45	0.67	1,249	119	1,130	2,260
25	6/4/2008	0.24	75	0.19	629	246	383	1,596
26	6/6/2008	1.46	135	0.65	5,178	248	4,930	3,377
27	6/6/2008	0.38	60	0.38	1,644	45	1,599	4,208
28	6/20/2008	0.38	105	0.22	1,457	54	1,403	3,692
29	6/20/2008	0.11	90	0.07	702	150	552	5,018
30	6/24/2008	0.17	45	0.23	914	37	877	5,159
31	7/2/2008	0.48	195	0.15	636	142	494	1,029
32	7/8/2008	0.78	30	1.56	948	38	910	1,167
33	7/9/2008	0.23	165	0.08	455	96	359	1,561
34	7/11/2008	0.38	60	0.38	2,512	45	2,467	6,492

Table 9
Data at Geyer Site in 2011 (i.e. after installing the permeable pavement)

Storm No.	Storm Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Total Flow Volume (gal)	Sewage Volume (gal)	Stormwater Volume (gal)	Stormwater Volume per Inch of Rain (gal/in)
1	3/30/2011	0.13	135	0.06	31	8	23	177
2	4/4/2011	0.46	30	0.92	969	42	927	2,015
3	4/4/2011	0.32	60	0.32	1,314	648	666	2,081
4	4/9/2011	0.32	45	0.43	674	50	624	1,950
5	4/15/2011	0.45	90	0.30	841	45	796	1,769
6	4/15/2011	0.22	75	0.18	308	48	260	1,182
7	4/19/2011	0.52	45	0.69	1,204	89	1,115	2,144
8	4/19/2011	0.41	135	0.18	982	637	345	841
9	4/22/2011	0.14	30	0.28	338	113	225	1,607
10	4/22/2011	0.41	45	0.55	1,169	110	1,059	2,583
11	4/22/2011	0.40	30	0.80	1,200	48	1,152	2,880
12	4/24/2011	0.25	105	0.14	581	263	318	1,272
13	4/25/2011	0.58	210	0.17	802	28	774	1,334
14	4/25/2011	0.11	45	0.15	260	120	140	1,273
15	4/27/2011	0.26	120	0.13	333	119	214	823
16	4/27/2011	0.98	300	0.20	1,622	457	1,165	1,189
17	5/14/2011	0.13	135	0.06	124	65	59	454
18	5/19/2011	0.18	90	0.12	168	43	125	694
19	5/23/2011	0.52	90	0.35	727	8	719	1,383
20	5/25/2011	1.14	180	0.38	1,669	162	1,507	1,322
21	6/10/2011	1.04	105	0.59	1,924	85	1,839	1,768
22	6/11/2011	0.17	15	0.68	423	6	417	2,453
23	6/14/2011	0.10	30	0.20	105	12	93	930
24	6/14/2011	0.14	45	0.19	206	25	181	1,293
25	6/17/2011	0.92	105	0.53	1,659	32	1,627	1,768
26	6/21/2011	0.16	30	0.32	236	25	211	1,319
27	6/26/2011	3.22	210	0.92	10,975	187	10,788	3,350
28	6/27/2011	0.43	75	0.34	783	92	691	1,607
29	6/27/2011	0.16	90	0.11	213	112	101	631
30	6/27/2011	0.23	135	0.10	443	145	298	1,296
31	7/3/2011	0.66	255	0.16	1,387	346	1,041	1,577
32	7/4/2011	0.48	120	0.24	1,164	352	812	1,692
33	7/7/2011	1.54	120	0.77	4,520	240	4,280	2,779
34	7/12/2011	0.25	45	0.33	461	185	276	1,104

Table 10
Runoff Volume Reductions at Each Site

Study Site	2008		2011		Stormwater Volume per Inch of Rain Reduced (gal/in)	Overall Reduction %
	Surface Cover	Average Stormwater Volume per Inch of Rain (gal/in)	Surface Cover	Average Stormwater Volume per Inch of Rain (gal/in)		
Eads	Asphalt	18148	Permeable Concrete	9262	8886	49
Cardinal	Brick	3681	Permeable Asphalt	2774	907	25
Geyer	Brick	3263	Permeable Interlocking Block	1545	1718	53

4.2 Effects of Rainfall Intensity

For the purpose of evaluating the effect of rainfall intensity on the ability of permeable pavements to reduce the volume of the stormwater runoff, sample storms that had similar rainfall depths but different rainfall intensities were selected at each site. Then the stormwater runoff of these storms were compared. The result (Table 11) showed that in some cases the storms with higher rainfall intensity generated more runoff while in other cases the opposite occurred. For example, two storms at Eads site on 5/14/2011 and 5/22/2011 were compared to each other. The rainfall depths for both storms were equal while the rainfall intensities were different. The storm that had a higher intensity (0.16 in/hr) generated more runoff (8397 gal/inch of rain) than the storm that had a lower intensity (0.07 in/hr) which generated less runoff (5958 gal/inch of rain), the difference was 2439 gal/inch of rain.

However, two other storms at the Eads site on 4/22/2011 and 6/21/2011 were compared to each other. The rainfall depths for both storms were equal while the rainfall intensities were different. The storm that had a higher intensity (0.34 in/hr) generated less runoff (7147 gal/inch of rain) than the storm that had a lower intensity (0.10 in/hr) which generated more runoff (9418 gal/inch of rain), the difference was 2271 gal/inch of rain.

There are many reasons for these opposite results. They include but are not limited to uncertainties in calculating sewage flows, errors in the field measurements, and mixing of runoffs from adjacent areas. In order to be sure about these results, further analyses were conducted.

Table 11
Differences in Runoff Volume Due to Different Rainfall Intensities

Site	Cases	Date	Rainfall (in)	Rain Intensity (in/hr)	Stormwater Volume per Inch of Rain (gal/in)	Differences (gal/in)
Eads	Case 1	5/14/2011	0.12	0.07	5958	-2439
		5/22/2011	0.12	0.16	8397	
	Case 2	4/22/2011	0.17	0.10	9,418	2271
		6/21/2011	0.17	0.34	7,147	
Cardinal	Case 1	11/26/2011	0.17	0.14	900	-2141
		6/11/2011	0.17	0.34	3,041	
	Case 2	5/19/2011	0.10	0.10	2,462	1358
		6/14/2011	0.10	0.20	1,104	
Geyer	Case 1	5/23/2011	0.52	0.35	1,383	-264
		4/19/2011	0.52	0.69	2,144	
	Case 2	4/24/2011	0.25	0.14	1,272	168
		7/12/2011	0.25	0.33	1,104	

Several charts were drawn between rainfall intensity and the volume of runoff generated at each site of the study and under both conditions, before and after the installation of the permeable pavements in 2008 and 2011. These charts were drawn using general regression analysis. Figures 10 and 11 show these relations at Eads site, while Figures 12 and 13 show these relations at Cardinal site and Figures 14 and 15 show these relations at Geyer site.

By comparing any two storms that have similar rainfall intensities in both charts for each site (i.e pre installation of permeable pavement and post installation), it was found that the volume of the runoff generated in 2011 is much less than the volume of the runoff generated in 2008. However, from the shape of the relations after the installation of the permeable pavements, it was found that rainfall intensity is positively correlated with the runoff generated from each site (i.e. the rainfall intensity is negatively correlated with the efficiency of permeable pavements to reduce runoff volume). In other words, as the rainfall intensity increased, the efficiency of the permeable pavements was decreased and the volume of stormwater runoff generated due to each storm was increased accordingly. This means that rainfall intensity affected the volume of runoffs generated from each site when the surface was covered by a permeable pavement, while such effect can not be found in the case of impermeable pavements.

Furthermore, when Figures 11, 13 and 15 were compared to each other, it was found that the relation between rainfall intensity and stormwater volume generated for the three sites were similar. This means that the rainfall intensity had a similar effect on the efficiency of different types of permeable pavements in reducing stormwater runoff volume.

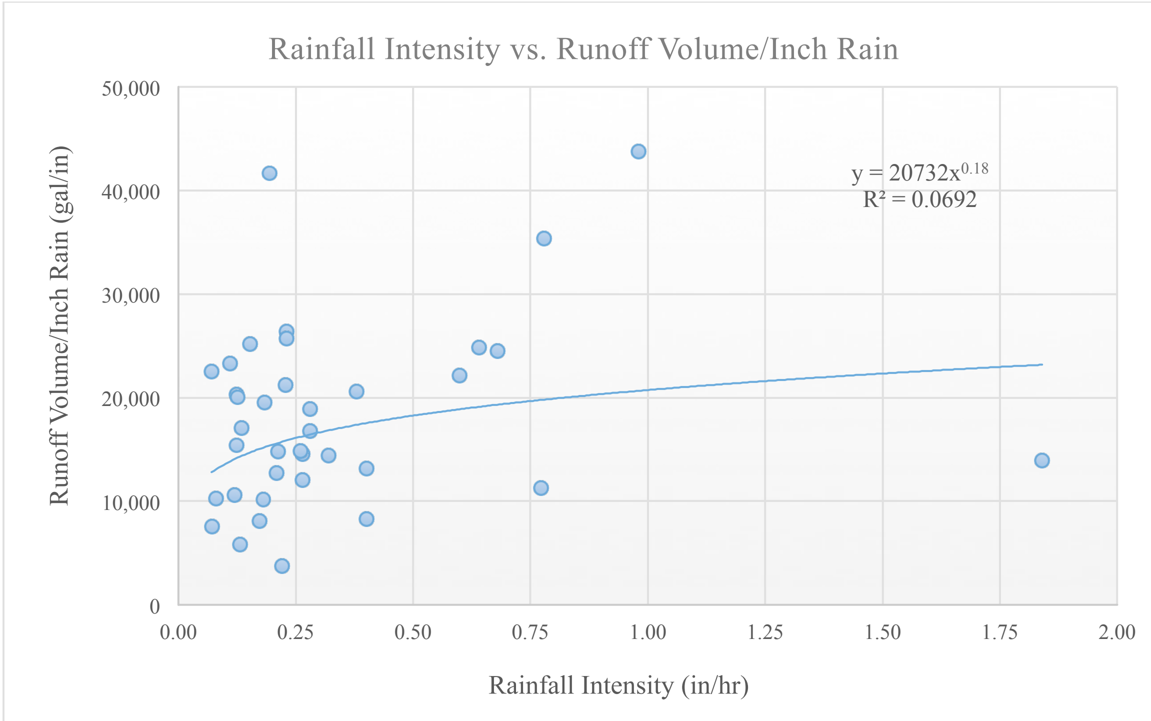


Figure 10. Relation between Rainfall Intensity and Runoff Volume in 2008 at Eads Site

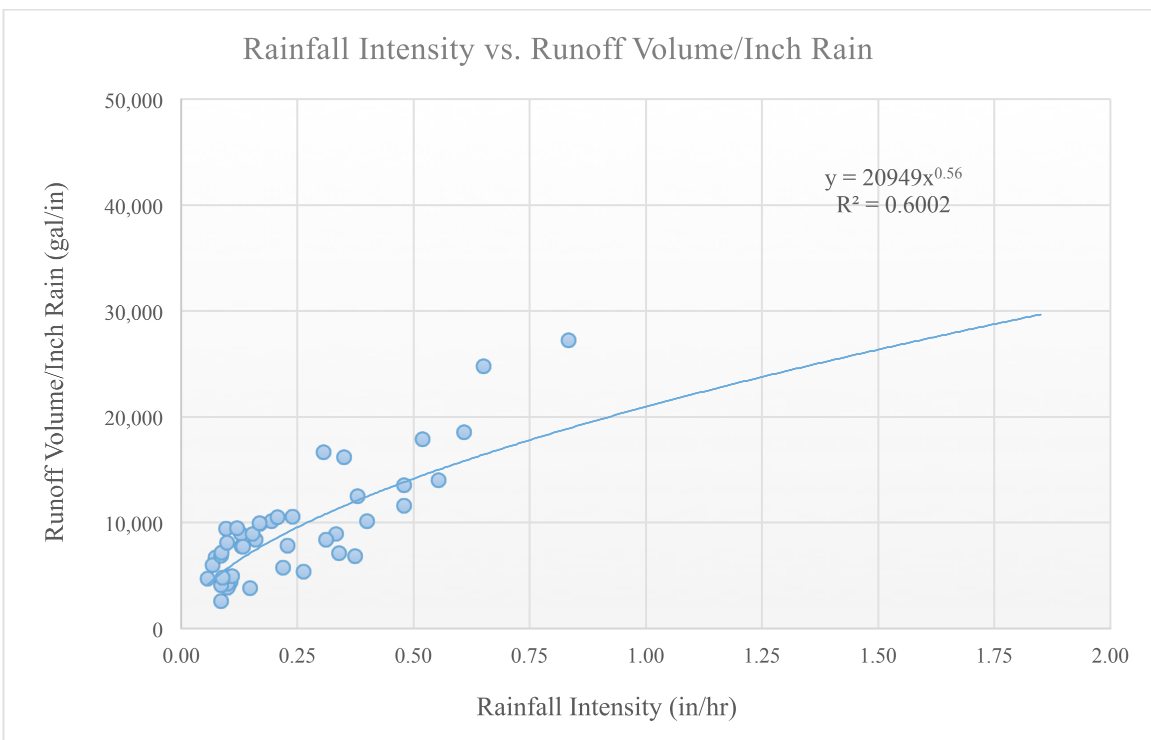


Figure 11. Relation between Rainfall Intensity and Runoff Volume in 2011 at Eads Site

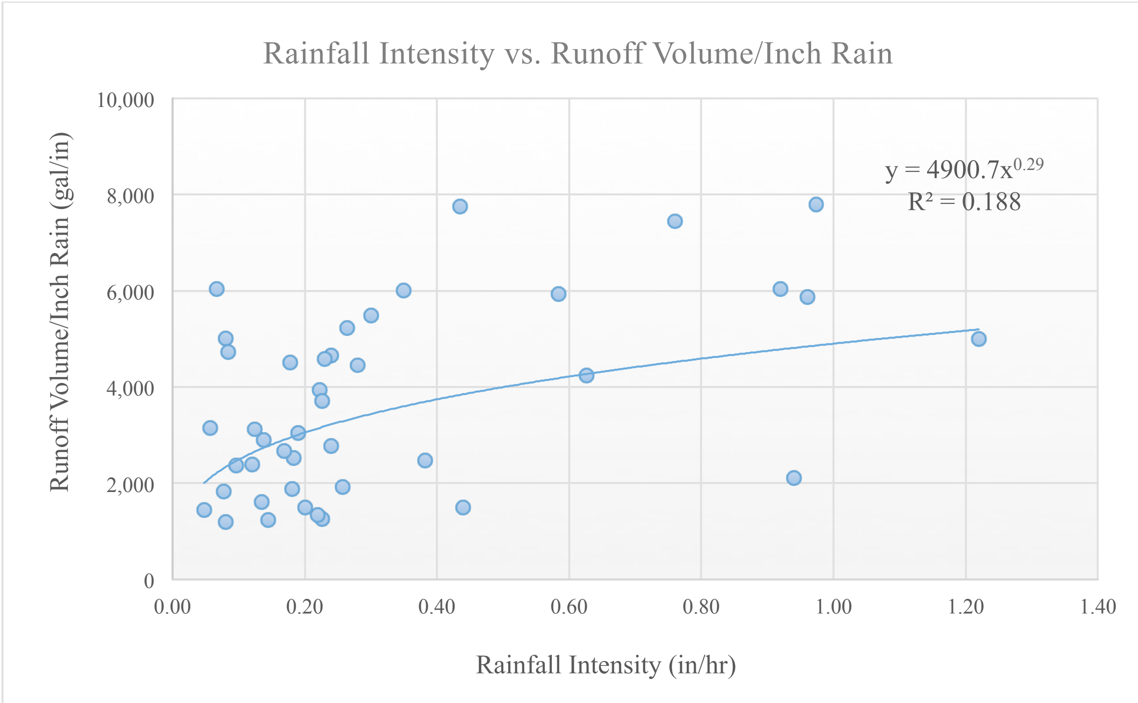


Figure 12. Relation between Rainfall Intensity and Runoff Volume in 2008 at Cardinal Site

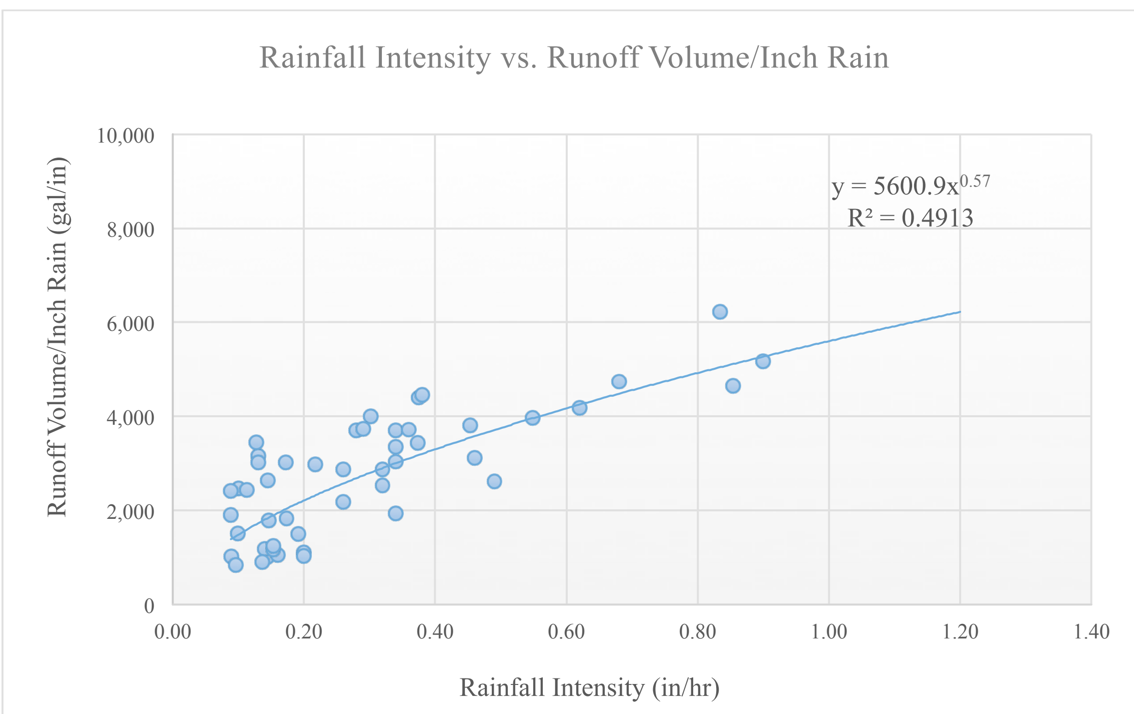


Figure 13. Relation between Rainfall Intensity and Runoff Volume in 2011 at Cardinal Site

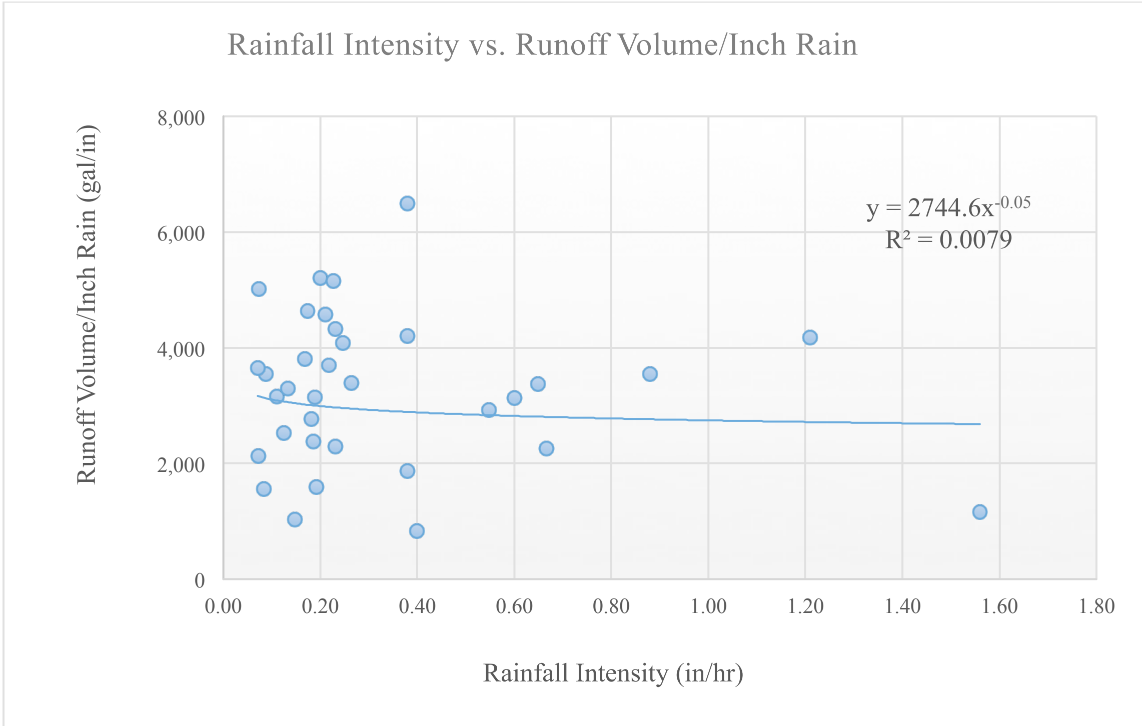


Figure 14. Relation between Rainfall Intensity and Runoff Volume in 2008 at Geyer Site

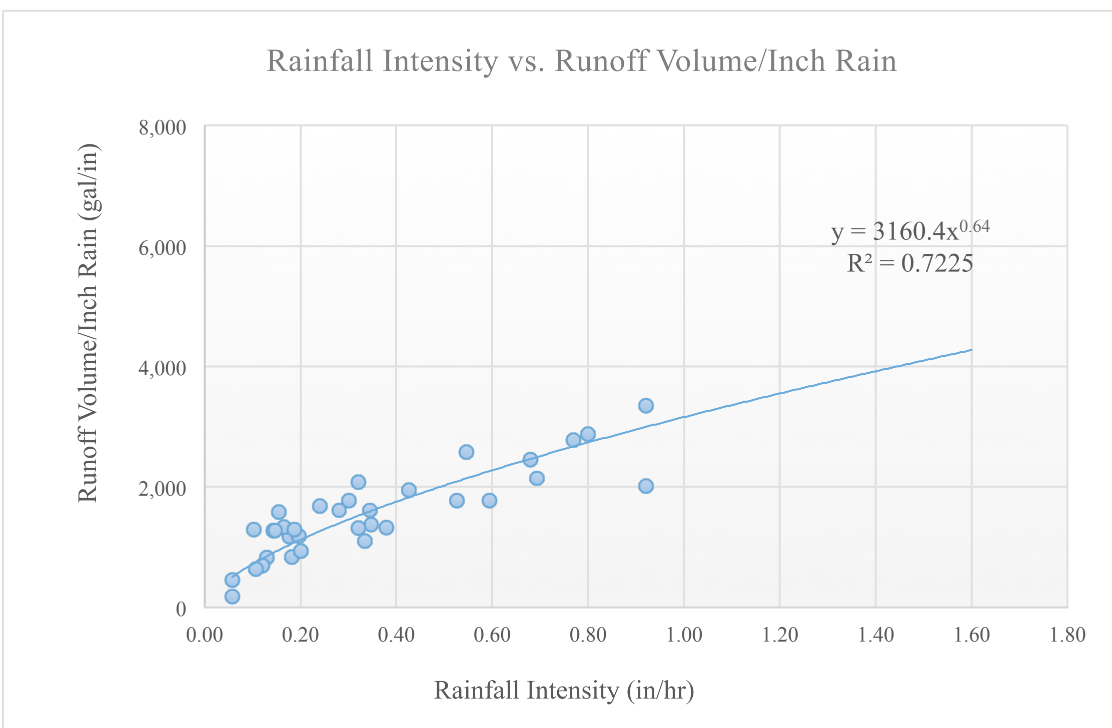


Figure 15. Relation between Rainfall Intensity and Runoff Volume in 2011 at Geyer Site

However, to have more accurate results, more detailed analyses were conducted. Four groups from the rainfall intensities of the storms occurred during the monitoring period were created and then total runoff generated from the storms that their intensities fall in each group were calculated and compared to each other. Table 12 shows the maximum and minimum rainfall intensity for all storms that occurred at each site during the monitoring period of the study before and after the installation of the permeable pavements.

Table 12
Maximum and Minimum Rainfall Intensities at Each Site

Study Sites	Rainfall Intensity (in/hr)			
	2008		2011	
	Minimum	Maximum	Minimum	Maximum
Eads Site	0.07	1.84	0.07	0.83
Cardinal Site	0.05	1.22	0.09	0.90
Geyer Site	0.07	1.56	0.06	0.92

From Table 12, it was found that the minimum and maximum rainfall intensities observed were 0.05 in/hr and 1.84 in/hr in 2008 and 0.06 in/hr and 0.92 in/hr in 2011. For the purpose of comparison, when rainfall intensity intervals were created, storms that had rainfall intensities higher than 1.0 in/hr were excluded so as to be able to compare storms with same rainfall intensities in 2008 and 2011. Table 13 shows the intervals created with the number of storms included from each site in 2008 and 2011. From Table 13, it was found that only 4 storms from 2008 were higher than 1.0 in/hr and were excluded from the comparison.

Table 13
Rainfall Intensity Intervals and Number of Storms at Each Site

Rainfall Intensity (in/hr)	Eads Site		Cardinal site		Geyer Site	
	No. of Storms in 2008	No. of Storms in 2011	No. of Storms in 2008	No. of Storms in 2011	No. of Storms in 2008	No. of Storms in 2011
0.01 – 0.25	21	30	26	24	22	16
0.26 – 0.50	9	11	8	18	5	9
0.51 – 0.75	3	4	2	3	4	5
0.76 – 1.00	3	1	5	3	1	4
Number of Storms Included in the Comparison	36	46	41	48	32	34
Number of Storms Included in the Study	37	46	42	48	34	34

Tables 14, 15 and 16 show the amount of total runoff volume generated per each inch of rain for each group of intensities in both years 2008 and 2011 with the percentage of the reduction for each group between 2008 and 2011 at Eads, Cardinal and Geyer respectively.

Table 14
Effects of Rainfall Intensity on the Efficiency of Permeable Concrete

Rainfall Intensity Intervals (in/hr)	Eads Site				Stormwater Volume Reduced per Inch of Rain (gal/in)	Reduction %
	2008		2011			
	Total Rainfall (in)	Average Stormwater Volume per Inch of Rain (gal/in)	Total Rainfall (in)	Average Stormwater Volume per Inch of Rain (gal/in)		
0.01 – 0.25	8.16	17,245	7.79	6,881	10,364	60
0.26 – 0.50	3.00	14,838	4.51	10,658	4,180	28
0.51 – 0.75	2.62	23,830	3.14	18,789	5,041	21
0.76 – 1.00	1.46	30,112	2.92	27,219	2,893	10

Table 15
Effects of Rainfall Intensity on the Efficiency of Permeable Asphalt

Rainfall Intensity Intervals (in/hr)	Cardinal Site				Stormwater Volume Reduced per Inch of Rain (gal/in))	Reduction %
	2008		2011			
	Total Rainfall (in)	Average Stormwater Volume per Inch of Rain (gal/in)	Total Rainfall (in)	Average Stormwater Volume per Inch of Rain (gal/in)		
0.01 – 0.25	9.38	2,900	6.90	1,863	1,037	36
0.26 – 0.50	3.70	4,351	6.08	3,304	1,047	24
0.51 – 0.75	1.93	5,082	1.61	4,300	782	15
0.76 – 1.00	2.48	5,875	4.90	5,346	529	9

Table 16
Effects of Rainfall Intensity on the Efficiency of Permeable Interlocking Concrete Blocks

Rainfall Intensity Intervals (in/hr)	Geyer Site				Stormwater Volume Reduced per Inch of Rain (gal/in)	Reduction %
	2008		2011			
	Total Rainfall (in)	Average Stormwater Volume per Inch of Rain (gal/in)	Total Rainfall (in)	Average Stormwater Volume per Inch of Rain (gal/in)		
0.01 – 0.25	8.96	3,345	5.02	1,041	2,304	69
0.26 – 0.50	1.48	3,356	3.73	1,571	1,785	53
0.51 – 0.75	3.64	2,923	3.06	2,143	780	27
0.76 – 1.00	0.44	3,543	5.62	2,756	787	22

According to Tables 14, 15 and 16, after the installation of permeable pavements in 2011, the runoff volume generated from each site gradually increased with the increase of rainfall intensity. Consequently, the reduction of runoff volume decreased as the rainfall intensities increased. Figure 16 shows the effects of rainfall intensity on the runoff volume reduction for each type of permeable pavement included in this study.

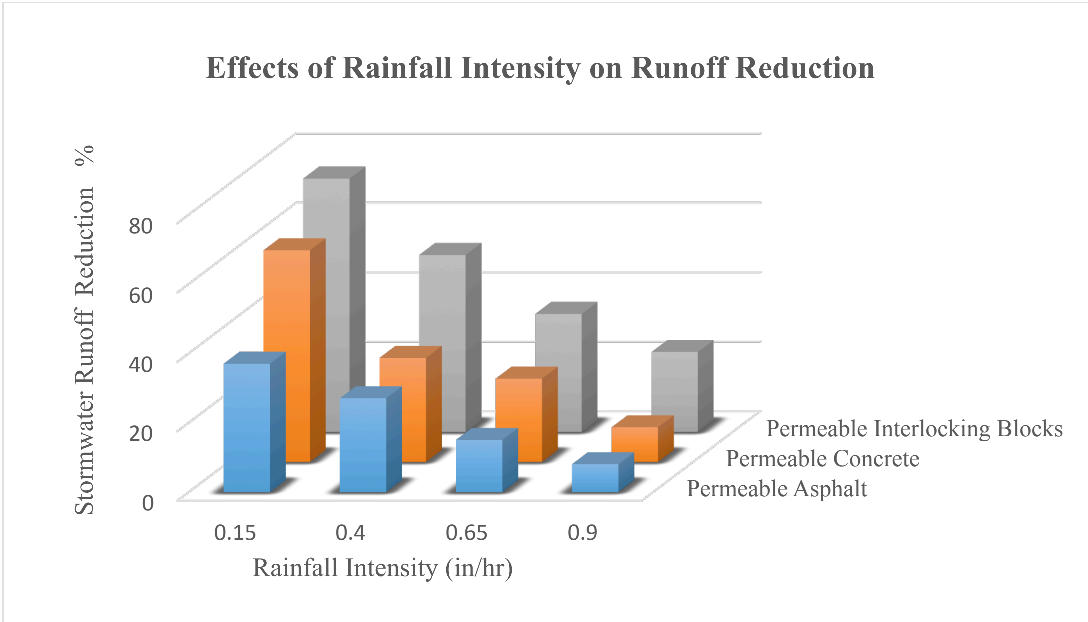


Figure 16. Effects of Rainfall Intensity on Runoff Volume Reduction

Generally, the reason behind generating runoff is the exceeding of the storage capacity of the system, but in case of high rainfall intensity, the runoff is more likely due to the exceeding of rainfall intensity over the infiltration ability of the permeable pavement.

From Figure 16, it is clear that increasing rainfall intensity decreased reduction for all types of permeable pavements included in this study. Furthermore, the results showed that despite the variation in reduction by types of permeable pavements, but the effects of rainfall intensity were similar on the effectiveness of these types of permeable pavements for reducing stormwater runoff volumes.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate the effects of rainfall intensities on the performance of permeable pavements regarding their ability to reduce the volume of stormwater runoff generated and discharged to combined sewer systems due to storm event occurrence. Three alleys in the City of St. Louis were selected and monitored for a period under the conditions existing in 2008. Then the surface pavements of the alleys were replaced with three types of permeable pavements in 2009 and monitored for a period of time in 2011.

After collecting data by using flowmeters and rain gauges, the total flows in the combined sewer system were calculated. Then by estimating the sewage flow in the system, the volume of stormwater runoff generated from each site and both before and after the installation of the permeable pavements were found by subtracting the sewage flow volume from the total flow volume inside the sewer system. Due to having different rainfall patterns between 2008 and 2011, these runoff volumes were normalized per unit of rainfall. After comparing the results, the research showed that the overall runoff reduction at the three sites of the study were different. At the Eads site, where permeable concrete was installed, the runoff was reduced by 49%. At the Cardinal site, where permeable asphalt was installed, the runoff was reduced by 25%, and at the Geyer site where concrete interlocking blocks were installed, the runoff was reduced by 53%.

As the purpose of the study was to find the effect of rainfall intensities on runoff reduction, further analysis was conducted and it was found that rainfall intensity is positively correlated with the volume of runoffs generated from all three sites. When rainfall intensity increased, the volume of the runoff generated per each inch of rain increased as well. The results showed that the reduction in the volume of the runoff generated due to the use of permeable pavements decreased with the increase of rainfall intensities. All storms that occurred during the study period were divided into four groups based on their rainfall intensities. For group 1, which included all storms whose rainfall intensities were between 0.01-0.25 in/hr, the reduction were 60%, 36% and 69% for permeable concrete, permeable asphalt and permeable interlocking concrete blocks, respectively. For group 2, which included all storms whose rainfall intensities were between 0.25-0.5 in/hr, the reduction decreased to 28%, 24% and 53%, respectively. For group 3, which included all storms whose rainfall intensities were between 0.50-0.75 in/hr, the reduction decreased to 21%, 15% and 27%, respectively. For group 4, which included all storms whose rainfall intensities were between 0.75-1.00 in/hr, the reduction decreased to 10%, 9% and 22%, respectively.

Furthermore, the result showed that, although the reduction by type of permeable pavements included in the study varied, the effect of rainfall intensity was similar on the effectiveness of each type of permeable pavement for reducing stormwater runoff volume.

CHAPTER 6

RECOMMENDATIONS

- For future similar studies, it is recommended that the monitoring period be extended to include more rainstorms with higher intensities and to include snowstorms so as to evaluate the performance of permeable pavements in cold weather as well.
- It is recommended to install permeable pavements with impermeable pavements at one site beside each other and conduct the monitoring process for both at the same time.
- It is recommended that the test sites be constructed in such a way that no runoffs from adjacent areas be mixed with the site runoffs.
- It is recommended to include more types of permeable pavers to find the effects of rainfall intensity on the performance of these types as well.
- There is uncertainty in the calculating of sewage flow in the sewer system. It is recommended for future studies to measure the site runoff before discharging to the sewer system.
- Continuous monitoring to the flowmeters is recommended to ensure their proper functioning during the period of the study.

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APPENDIX A

DATES OF DRY DAYS USED IN SEWAGE FLOW ESTIMATION

DATES OF DRY DAYS USED IN SEWAGE FLOW ESTIMATION

Table A-1
Storms at Eads Site in 2008

Storm No.	Storm Date		Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Sewage Flow Date(s)				Sewage Volume (gal)
1	Wednesday	03/26/08	0.95	315	0.18	Tues.	03/25/08	Fri.	03/28/08	71
2	Thursday	03/27/08	0.13	45	0.17	Wed.	03/26/08	Fri.	03/28/08	123
3	Thursday	03/27/08	0.33	75	0.26	Wed.	03/26/08	Fri.	03/28/08	185
4	Thursday	03/27/08	0.33	75	0.26	Wed.	03/26/08	Fri.	03/28/08	12
5	Sunday	03/30/08	0.57	150	0.23	Sun.	03/23/08	Sun.	04/06/08	40
6	Monday	03/31/08	0.92	240	0.23	Tues.	04/01/08			420
7	Thursday	04/03/08	0.47	210	0.13	Wed.	04/02/08	Fri.	04/04/08	256
8	Tuesday	04/08/08	0.19	30	0.38	Mon.	04/07/08	Wed.	04/09/08	24
9	Thursday	04/10/08	0.92	240	0.23	Wed.	04/09/08	Fri.	04/11/08	290
10	Thursday	04/10/08	0.84	300	0.32	Wed.	04/09/08	Fri.	04/11/08	420
11	Friday	04/18/08	0.43	210	0.12	Thur.	04/17/08			29
12	Thursday	04/24/08	0.10	75	0.08	Wed.	04/23/08	Thur.	05/01/08	45
13	Friday	04/25/08	0.10	15	0.40	Thur.	04/24/08			14
14	Friday	04/25/08	0.10	15	0.40	Thur.	04/24/08			21
15	Friday	05/02/08	0.21	60	0.21	Thur.	05/01/08			30
16	Wednesday	05/07/08	0.37	120	0.18	Tues.	05/06/08	Wed.	05/14/08	17
17	Wednesday	05/07/08	0.37	120	0.28	Tues.	05/06/08	Wed.	05/14/08	235
18	Wednesday	05/07/08	0.48	330	0.28	Tues.	05/06/08			462
19	Thursday	05/08/08	0.55	300	0.11	Wed.	05/07/08	Fri.	05/09/08	169
20	Saturday	05/10/08	0.25	120	0.12	Sat.	05/03/08	Sat.	05/17/08	58
21	Saturday	05/10/08	0.43	105	0.60	Sat.	05/03/08	Sat.	05/17/08	172
22	Sunday	05/11/08	0.16	135	0.07	Sun.	05/04/08	Sun.	05/18/08	176
23	Tuesday	05/13/08	0.20	90	0.13	Mon.	05/12/08	Wed.	05/14/08	18
24	Thursday	05/15/08	0.18	150	0.07	Wed.	05/14/08	Fri.	05/16/08	83
25	Sunday	05/25/08	0.39	30	0.78	Sun.	05/18/08	Sun.	06/01/08	15
26	Sunday	05/25/08	0.56	30	1.84	Sun.	05/18/08	Sun.	06/01/08	185
27	Monday	05/26/08	0.68	210	0.19	Tues.	05/27/08			254
28	Tuesday	06/03/08	0.58	45	0.77	Mon.	06/02/08	Tues.	06/10/08	61
29	Wednesday	06/04/08	0.19	75	0.15	Thur.	06/05/08			25
30	Friday	06/06/08	1.76	165	0.64	Thur.	06/05/08	Fri.	06/13/08	195
31	Friday	06/06/08	0.43	60	0.68	Thur.	06/05/08	Fri.	06/13/08	235
32	Friday	06/20/08	0.19	90	0.13	Thur.	06/19/08	Fri.	06/13/08	41
33	Sunday	06/22/08	0.11	30	0.22	Sun.	06/15/08	Sun.	06/29/08	16
34	Tuesday	06/24/08	0.16	45	0.21	Mon.	06/23/08	Wed.	06/25/08	37
35	Wednesday	07/02/08	0.42	210	0.12	Tues.	07/01/08	Thur.	07/03/08	228
36	Tuesday	07/08/08	0.49	30	0.98	Mon.	07/07/08	Wed.	07/09/08	21
37	Friday	07/11/08	0.26	60	0.26	Thur.	07/10/08			26

Table A-2
Storms at Eads Site in 2011

Storm No.	Storm Date		Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Sewage Flow Date(s)				Sewage Volume (gal)
1	Monday	04/04/11	0.40	60	0.40	Tues	04/05/11			28
2	Monday	04/04/11	0.18	105	0.10	Tues	04/05/11			215
3	Saturday	04/09/11	0.28	45	0.37	Sat.	04/02/11	Sat.	04/16/11	21
4	Monday	04/11/11	0.13	60	0.13	Tues	04/12/11	Mon.	04/18/11	133
5	Monday	04/11/11	0.15	105	0.09	Tues	04/12/11	Mon.	04/18/11	448
6	Friday	04/15/11	0.40	105	0.23	Thur	04/14/11			180
7	Friday	04/15/11	0.36	90	0.24	Thur	04/14/11			145
8	Tuesday	04/19/11	0.46	90	0.31	Mon	04/18/11	Wed.	04/20/11	188
9	Tuesday	04/19/11	0.20	120	0.10	Mon	04/18/11	Wed.	04/20/11	195
10	Friday	04/22/11	0.17	105	0.10	Thur	04/21/11			385
11	Friday	04/22/11	0.37	300	0.07	Thur	04/21/11			645
12	Sunday	05/01/11	0.16	90	0.11	Sun.	04/23/11	Sun.	05/08/11	271
13	Saturday	05/14/11	0.12	105	0.07	Sat.	05/07/11	Sat.	05/21/11	520
14	Sunday	05/22/11	0.12	45	0.16	Sun.	05/15/11	Sun.	05/29/11	85
15	Monday	05/23/11	0.50	90	0.33	Tues	05/24/11			194
16	Wednesday	05/25/11	1.20	150	0.48	Tues	05/24/11	Thur.	05/26/11	98
17	Friday	06/10/11	0.61	60	0.61	Thur	06/09/11			23
18	Tuesday	06/14/11	0.24	30	0.48	Mon	06/13/11	Wed.	06/15/11	31
19	Friday	06/17/11	0.97	105	0.55	Thur	06/16/11			109
20	Sunday	06/19/11	0.37	150	0.15	Sun.	06/12/11	Sun.	06/26/11	87
21	Tuesday	06/21/11	0.17	30	0.34	Mon	06/20/11	Wed.	06/22/11	35
22	Saturday	06/25/11	2.92	210	0.83	Sat.	06/18/11	Sat.	06/03/11	142
23	Monday	06/27/11	0.35	60	0.35	Fri.	06/24/11	Tues.	06/28/11	44
24	Monday	06/27/11	0.15	90	0.10	Fri.	06/24/11	Tues.	06/28/11	155
25	Monday	06/27/11	0.16	75	0.13	Fri.	06/24/11	Tues.	06/28/11	89
26	Sunday	07/03/11	0.39	75	0.31	Sun.	06/26/11	Sun.	07/10/11	108
27	Sunday	07/03/11	0.15	105	0.09	Sun.	06/26/11	Sun.	07/10/11	255
28	Monday	07/04/11	0.34	120	0.17	Tues	07/05/11			475
29	Thursday	07/07/11	1.30	120	0.65	Wed	07/06/11	Fri.	07/08/11	428
30	Tuesday	07/12/11	0.26	30	0.52	Mon	07/11/11	Wed.	07/13/11	114
31	Friday	08/19/11	0.15	90	0.10	Thur	08/18/11			105
32	Saturday	09/03/11	0.19	30	0.38	Sat.	08/27/11	Sat.	09/10/11	35
33	Wednesday	09/14/11	0.22	120	0.11	Tues	09/13/11	Thur.	09/15/11	86
34	Sunday	09/18/11	0.20	90	0.13	Sun.	09/11/11	Sun.	09/25/11	81
35	Thursday	09/22/11	0.15	105	0.09	Wed	09/21/11	Fri.	09/23/11	67
36	Wednesday	10/12/11	0.33	75	0.26	Tues	10/11/11	Thur.	10/13/11	74
37	Monday	10/17/11	0.11	30	0.22	Tues	10/18/11			25
38	Thursday	11/03/11	0.73	225	0.19	Wed	11/02/11	Fri.	11/04/11	165
39	Tuesday	11/08/11	0.10	105	0.06	Mon	11/07/11	Wed.	11/09/11	90
40	Tuesday	11/22/11	0.42	165	0.15	Mon	11/21/11	Wed.	11/23/11	85
41	Saturday	11/26/11	0.18	90	0.12	Sat.	11/19/11			43
42	Saturday	12/03/11	0.38	135	0.17	Sat.	12/10/11			95
43	Tuesday	12/13/11	0.22	150	0.09	Mon	12/12/11	Wed.	12/14/11	78
44	Wednesday	12/14/11	0.31	90	0.21	Tues	12/13/11	Thur.	12/15/11	82
45	Monday	12/19/11	0.65	450	0.09	Tues	12/20/11			305
46	Monday	12/26/11	0.44	270	0.10	Tues	12/27/11			185

Table A-3
Storms at Cardinal Site in 2008

Storm No.	Storm Date		Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Sewage Flow Date(s)				Sewage Volume (gal)
1	Wednesday	03/26/08	1.10	360	0.18	Tues.	03/25/08	Thur.	03/27/08	422
2	Thursday	03/27/08	0.18	45	0.24	Wed.	03/26/08	Fri.	03/28/08	180
3	Thursday	03/27/08	0.23	60	0.23	Wed.	03/26/08	Fri.	03/28/08	152
4	Sunday	03/30/08	0.58	135	0.26	Sun.	03/23/08	Sun.	04/07/08	162
5	Monday	03/31/08	0.89	240	0.22	Tues.	04/01/08			534
6	Tuesday	04/08/08	0.23	15	0.92	Mon.	04/07/08	Wed.	04/09/08	218
7	Thursday	04/10/08	0.77	255	0.18	Wed.	04/09/08	Fri.	04/11/08	445
8	Thursday	04/10/08	0.80	285	0.17	Wed.	04/09/08	Fri.	04/11/08	413
9	Friday	04/18/08	0.12	150	0.05	Thur.	04/17/08	Fri.	04/11/08	239
10	Friday	04/18/08	0.48	210	0.14	Thur.	04/17/08	Fri.	04/11/08	310
11	Friday	04/25/08	0.47	30	0.94	Thur.	04/24/08			120
12	Friday	04/25/08	0.11	15	0.44	Thur.	04/24/08			74
13	Friday	05/02/08	0.35	60	0.35	Thur.	05/01/08			101
14	Wednesday	05/07/08	0.17	45	0.23	Tues.	05/06/08	Thur.	05/08/08	60
15	Wednesday	05/07/08	0.38	120	0.19	Tues.	05/06/08	Thur.	05/08/08	153
16	Wednesday	05/07/08	0.48	300	0.10	Tues.	05/06/08	Thur.	05/08/08	340
17	Thursday	05/08/08	0.56	270	0.12	Wed.	05/07/08	Fri.	05/09/08	405
18	Friday	05/09/08	0.10	105	0.06	Thur.	05/08/08			218
19	Saturday	05/10/08	0.27	120	0.14	Sat.	05/03/08	Sat.	05/17/08	240
20	Saturday	05/10/08	0.49	105	0.28	Sat.	05/03/08	Sat.	05/17/08	406
21	Sunday	05/11/08	0.27	210	0.08	Sun.	05/04/11	Sun.	05/18/08	438
22	Tuesday	05/13/08	0.18	90	0.12	Mon.	05/12/08	Wed.	05/14/08	325
23	Thursday	05/15/08	0.12	90	0.08	Wed.	05/14/08	Fri.	05/16/08	230
24	Sunday	05/25/08	0.73	45	0.97	Sun.	05/18/08	Sun.	06/01/08	85
25	Sunday	05/25/08	0.48	30	0.96	Sun.	05/18/08	Sun.	06/01/08	68
26	Monday	05/26/08	0.58	195	0.18	Tues.	05/27/08			310
27	Tuesday	05/27/08	0.10	75	0.08	Mon.	05/26/08	Wed.	05/28/08	94
28	Friday	05/30/08	0.87	120	0.44	Thur.	05/29/08			460
29	Friday	05/30/08	0.30	60	0.30	Thur.	05/29/08			280
30	Saturday	05/31/08	0.10	90	0.07	Sat.	05/24/08	Sat.	06/08/08	223
31	Tuesday	06/03/08	0.57	45	0.76	Mon.	06/02/08	Wed.	06/04/08	446
32	Wednesday	06/04/08	0.34	90	0.23	Tues.	06/03/08	Thur.	06/05/08	526
33	Friday	06/06/08	1.46	150	0.58	Thur.	06/05/08			660
34	Friday	06/06/08	0.33	75	0.26	Thur.	06/05/08			118
35	Friday	06/13/08	0.11	30	0.22	Thur.	06/12/08			260
36	Friday	06/20/08	0.67	105	0.38	Thur.	06/19/08			450
37	Tuesday	06/24/08	0.15	45	0.20	Mon.	06/23/08	Wed.	06/25/08	236
38	Wednesday	07/02/08	0.47	195	0.14	Tues.	07/01/08	Thur.	07/03/08	664
39	Thursday	07/03/08	0.47	45	0.63	Wed.	07/02/08	Fri.	07/04/08	256
40	Tuesday	07/08/08	0.61	30	1.22	Mon.	07/07/08	Wed.	07/09/08	63
41	Wednesday	07/09/08	0.19	135	0.08	Tues.	07/08/08	Thur.	07/10/08	485
42	Friday	07/11/08	0.24	60	0.24	Thur.	07/10/08			140

Table A-4
Storms at Cardinal Site in 2011

Storm No.	Storm Date		Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Sewage Flow Date(s)				Sewage Volume (gal)
1	Sunday	03/27/11	0.18	75	0.14	Sun.	04/03/11			124
2	Monday	04/04/11	0.34	30	0.68	Tues.	04/05/11			65
3	Monday	04/04/11	0.17	30	0.34	Tues.	04/05/11			108
4	Saturday	04/09/11	0.24	45	0.32	Sat.	04/02/11	Sat.	04/16/11	62
5	Monday	04/11/11	0.13	60	0.13	Tues.	04/12/11	Mon.	04/18/11	145
6	Monday	04/11/11	0.20	135	0.09	Tues.	04/12/11	Mon.	04/18/11	235
7	Friday	04/15/11	0.38	105	0.22	Thur.	04/14/11			137
8	Friday	04/15/11	0.36	60	0.36	Thur.	04/14/11			110
9	Tuesday	04/19/11	0.45	30	0.90	Mon.	04/18/11	Wed.	04/20/11	24
10	Tuesday	04/19/11	0.34	60	0.34	Mon.	04/18/11	Wed.	04/20/11	84
11	Wednesday	04/27/11	0.26	120	0.13	Tues.	04/26/11	Thur.	04/28/11	445
12	Wednesday	04/27/11	0.86	300	0.17	Tues.	04/26/11	Thur.	04/28/11	465
13	Sunday	05/01/11	0.16	75	0.13	Sun.	04/24/11	Sun.	05/08/11	212
14	Friday	05/20/11	0.10	60	0.10	Thur.	05/19/11			195
15	Monday	05/23/11	0.49	60	0.49	Tues.	05/24/11			52
16	Wednesday	05/25/11	0.16	60	0.16	Tues.	05/24/11	Thur.	05/26/11	67
17	Wednesday	05/25/11	0.83	165	0.30	Tues.	05/24/11	Thur.	05/26/11	348
18	Friday	06/10/11	0.96	105	0.55	Thur.	06/09/11			210
19	Saturday	06/11/11	0.17	30	0.34	Sat.	06/04/11	Sat.	06/18/11	170
20	Tuesday	06/14/11	0.10	30	0.20	Mon.	06/13/11	Tues.	06/15/11	28
21	Tuesday	06/14/11	0.28	45	0.37	Mon.	06/13/11	Tues.	06/15/11	182
22	Friday	06/17/11	0.68	90	0.45	Thur.	06/16/11			189
23	Saturday	06/18/11	0.75	120	0.38	Sat.	06/11/11	Sat.	06/25/11	311
24	Sunday	06/19/11	0.40	165	0.15	Sun.	06/12/11	Sun.	06/26/11	458
25	Tuesday	06/21/11	0.14	30	0.28	Mon.	06/20/11	Tues.	06/22/11	26
26	Sunday	06/26/11	2.99	210	0.85	Sun.	06/19/11	Sun.	07/03/11	523
27	Monday	06/27/11	0.29	60	0.29	Tues.	06/28/11	Mon.	06/20/11	241
28	Monday	06/27/11	0.20	135	0.09	Tues.	06/28/11	Mon.	06/20/11	130
29	Monday	06/27/11	0.17	90	0.11	Tues.	06/28/11			104
30	Sunday	07/03/11	0.19	30	0.38	Sun.	07/10/11			54
31	Sunday	07/03/11	0.51	210	0.15	Sun.	07/10/11			291
32	Monday	07/04/11	0.10	30	0.20	Tues.	07/05/11	Mon.	07/11/11	39
33	Monday	07/04/11	0.13	45	0.17	Tues.	07/05/11	Mon.	07/11/11	117
34	Monday	07/04/11	0.13	30	0.26	Tues.	07/05/11	Mon.	07/11/11	89
35	Monday	07/04/11	0.34	60	0.34	Tues.	07/05/11			215
36	Thursday	07/07/11	1.46	105	0.83	Wed.	07/06/11	Fri.	07/08/11	510
37	Tuesday	07/12/11	0.23	30	0.46	Mon.	07/11/11	Wed.	07/13/11	85
38	Friday	08/05/11	0.31	30	0.62	Thur.	08/04/11			25
39	Friday	08/19/11	0.18	120	0.09	Thur.	08/18/11			118
40	Friday	09/09/11	0.13	30	0.26	Thur.	09/08/11			41
41	Wednesday	09/14/11	0.42	180	0.14	Tues.	09/13/11	Thur.	09/15/11	140
42	Sunday	09/18/11	0.23	90	0.15	Sun.	09/11/11	Sun.	09/25/11	89
43	Thursday	11/03/11	0.81	255	0.19	Wed.	11/02/11	Fri.	11/04/11	168
44	Tuesday	11/08/11	0.12	75	0.10	Mon.	11/07/11	Wed.	11/09/11	52
45	Saturday	11/26/11	0.17	75	0.14	Sat.	11/19/11	Sat.	12/03/11	16
46	Saturday	12/03/11	0.46	180	0.15	Sat.	12/10/11			195
47	Wednesday	12/14/11	0.32	60	0.32	Tues.	12/13/11	Thur.	12/15/11	80
48	Monday	12/26/11	0.47	285	0.10	Tues.	12/27/11			530

Table A-5
Storms at Geyer Site in 2008

Storm No.	Storm Date		Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Sewage Flow Date(s)				Sewage Volume (gal)
1	Wednesday	03/26/08	0.95	315	0.18	Tues.	03/25/08	Thur.	03/27/08	535
2	Thursday	03/27/08	0.13	45	0.17	Wed.	03/26/08	Fri.	03/28/08	83
3	Thursday	03/27/08	0.33	75	0.26	Wed.	03/26/08	Fri.	03/28/08	66
4	Monday	03/31/08	0.92	240	0.23	Tues.	04/01/08			121
5	Tuesday	04/08/08	0.19	30	0.38	Mon.	04/07/08	Wed.	04/09/08	31
6	Thursday	04/10/08	0.92	240	0.23	Wed.	04/09/08	Fri.	04/11/08	71
7	Thursday	04/10/08	0.84	300	0.17	Wed.	04/09/08	Fri.	04/11/08	155
8	Friday	04/25/08	0.44	30	0.88	Thur.	04/24/08			10
9	Friday	05/02/08	0.21	60	0.21	Thur.	05/01/08			45
10	Wednesday	05/07/08	0.20	30	0.40	Tues.	05/06/08	Thur.	05/08/08	21
11	Wednesday	05/07/08	0.37	120	0.19	Tues.	05/06/08	Thur.	05/08/08	25
12	Wednesday	05/07/08	0.48	330	0.09	Tues.	05/06/08	Thur.	05/08/08	120
13	Thursday	05/08/08	0.55	300	0.11	Wed.	05/07/08	Fri.	05/09/08	129
14	Saturday	05/10/08	0.25	120	0.13	Sat.	05/03/08	Sat.	05/17/08	39
15	Saturday	05/10/08	0.43	105	0.25	Sat.	05/03/08	Sat.	05/17/08	115
16	Sunday	05/11/08	0.16	135	0.07	Sun.	05/04/08	Sun.	05/18/08	24
17	Tuesday	05/13/08	0.20	90	0.13	Mon.	05/12/08	Wed.	05/14/08	17
18	Thursday	05/15/08	0.18	150	0.07	Wed.	05/14/08	Fri.	05/16/08	48
19	Sunday	05/25/08	1.21	60	1.21	Sun.	05/18/08	Sun.	06/01/08	84
20	Sunday	05/25/08	0.45	45	0.60	Sun.	05/18/08	Sun.	06/01/08	18
21	Monday	05/26/08	0.15	45	0.20	Tues.	05/27/08			29
22	Monday	05/26/08	0.61	195	0.19	Tues.	05/27/08			188
23	Friday	05/30/08	1.23	135	0.55	Thur.	05/29/08			160
24	Tuesday	06/03/08	0.50	45	0.67	Mon.	06/02/08	Wed.	06/04/08	119
25	Wednesday	06/04/08	0.24	75	0.19	Tues.	06/03/08	Thur.	06/05/08	246
26	Friday	06/06/08	1.46	135	0.65	Thur.	06/05/08	Fri.	06/13/08	248
27	Friday	06/06/08	0.38	60	0.38	Thur.	06/05/08	Fri.	06/13/08	45
28	Friday	06/20/08	0.38	105	0.22	Thur.	06/19/08	Fri.	06/13/08	54
29	Friday	06/20/08	0.11	90	0.07	Thur.	06/19/08	Fri.	06/13/08	150
30	Tuesday	06/24/08	0.17	45	0.23	Mon.	06/23/08	Wed.	06/25/08	37
31	Wednesday	07/02/08	0.48	195	0.15	Tues.	07/01/08	Thur.	07/03/08	142
32	Tuesday	07/08/08	0.78	30	1.56	Mon.	07/07/08	Wed.	07/09/08	38
33	Wednesday	07/09/08	0.23	165	0.08	Tues.	07/08/08	Thur.	07/10/08	96
34	Friday	07/11/08	0.38	60	0.38	Thur.	07/10/08			45

Table A-6

Storms at Geyer Site in 2011

Storm No.	Storm Date		Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Sewage Flow Date(s)				Sewage Volume (gal)
1	Wednesday	03/30/11	0.13	135	0.06	Tues.	03/29/11	Thur.	03/31/11	8
2	Monday	04/04/11	0.46	30	0.92	Tues.	04/05/11			42
3	Monday	04/04/11	0.32	60	0.32	Tues.	04/05/11			648
4	Saturday	04/09/11	0.32	45	0.43	Sat.	04/02/11	Sat.	04/16/11	50
5	Friday	04/15/11	0.45	90	0.30	Thur.	04/14/11			45
6	Friday	04/15/11	0.22	75	0.18	Thur.	04/14/11			48
7	Tuesday	04/19/11	0.52	45	0.69	Mon.	04/18/11	Wed.	04/20/11	89
8	Tuesday	04/19/11	0.41	135	0.18	Mon.	04/18/11	Wed.	04/20/11	637
9	Friday	04/22/11	0.14	30	0.28	Thur.	04/21/11	Fri.	04/22/11	113
10	Friday	04/22/11	0.41	45	0.55	Thur.	04/21/11	Fri.	04/22/11	110
11	Friday	04/22/11	0.40	30	0.80	Thur.	04/21/11	Fri.	04/22/11	48
12	Sunday	04/24/11	0.25	105	0.14	Sun.	04/17/11	Sun.	05/01/11	263
13	Monday	04/25/11	0.58	210	0.17	Tues.	04/26/11			28
14	Monday	04/25/11	0.11	45	0.15	Tues.	04/26/11			120
15	Wednesday	04/27/11	0.26	120	0.13	Tues.	04/26/11	Thur.	04/28/11	119
16	Wednesday	04/27/11	0.98	300	0.20	Tues.	04/26/11	Thur.	04/28/11	457
17	Sunday	05/15/11	0.13	135	0.06	Sun.	05/08/11			65
18	Friday	05/20/11	0.18	90	0.12	Thur.	05/19/11	Fri.	05/27/11	43
19	Monday	05/23/11	0.52	90	0.35	Tues.	05/24/11			8
20	Wednesday	05/25/11	1.14	180	0.38	Tues.	05/24/11	Thur.	05/26/11	162
21	Friday	06/10/11	1.04	105	0.59	Thur.	06/09/11			85
22	Saturday	06/11/11	0.17	15	0.68	Sat.	06/04/11	Sat.	06/18/11	6
23	Tuesday	06/14/11	0.10	30	0.20	Mon.	06/13/11	Wed.	06/15/11	12
24	Tuesday	06/14/11	0.14	45	0.19	Mon.	06/13/11	Wed.	06/15/11	25
25	Friday	06/17/11	0.92	105	0.53	Thur.	06/16/11			32
26	Tuesday	06/21/11	0.16	30	0.32	Mon.	06/20/11	Wed.	06/22/11	25
27	Sunday	06/26/11	3.22	210	0.92	Sun.	06/19/11			187
28	Monday	06/27/11	0.43	75	0.34	Tues.	06/28/11	Mon.	06/20/11	92
29	Monday	06/27/11	0.16	90	0.11	Tues.	06/28/11	Mon.	06/20/11	112
30	Monday	06/27/11	0.23	135	0.10	Tues.	06/28/11	Mon.	06/20/11	145
31	Sunday	07/03/11	0.66	255	0.16	Sun.	06/26/11			346
32	Monday	07/04/11	0.48	120	0.24	Tues.	07/05/11	Mon.	07/11/11	352
33	Thursday	07/07/11	1.54	120	0.77	Wed.	07/06/11	Fri.	07/08/11	240
34	Tuesday	07/12/11	0.25	45	0.33	Mon.	07/11/11	Wed.	07/13/11	185

APPENDIX B

ESTIMATING STORMWATER RUNOFF USING THE RATIONAL METHOD

ESTIMATING STORMWATER RUNOFF USING THE RATIONAL METHOD

Rational Equation: Q = CiA

Where:

Q = Peak flow (cfs)

C = Runoff coefficient

i = Rainfall intensity (in/hr)

A = Drainage area (acre)

In this study:

Drainage Area at Eads Site = 0.86 acre

Drainage Area at Cardinal Site = 0.075 acre

Drainage Area at Geyer Site = 0.23 acre

Runoff Coefficient (C) = 0.8

Example:

For the storm that occurred at Eads Site on Monday 3/26/2008:

Rainfall Intensity (i) = 0.18 in/hr

Q = CiA

Q = 0.8*0.18*0.86 = 0.124 cfs = 55.83 gpm

Table B-1
Actual and Estimated Stormwater Flow Rate at Eads Site

Storm No.	Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Actual Flow Rate (gpm)	Estimated Flow Rate (gpm)
1	3/26/2008	0.95	315	0.18	30.57	55.83
2	3/27/2008	0.13	45	0.17	23.40	53.48
3	3/27/2008	0.33	75	0.26	64.04	81.52
4	3/27/2008	0.33	75	0.26	53.01	81.52
5	3/30/2008	0.57	150	0.23	80.50	70.40
6	3/31/2008	0.92	240	0.23	101.14	71.02
7	4/3/2008	0.47	210	0.13	38.22	41.46
8	4/8/2008	0.19	30	0.38	130.53	117.34
9	4/10/2008	0.92	240	0.23	98.71	71.02
10	4/10/2008	0.84	300	0.32	40.30	98.81
11	4/18/2008	0.43	210	0.12	41.57	38.29
12	4/24/2008	0.10	75	0.08	13.68	24.70
13	4/25/2008	0.10	15	0.40	87.67	123.51
14	4/25/2008	0.10	15	0.40	55.13	123.51
15	5/2/2008	0.21	60	0.21	44.67	64.84
16	5/7/2008	0.37	120	0.18	60.26	56.82
17	5/7/2008	0.37	120	0.28	58.44	86.46
18	5/7/2008	0.48	330	0.28	24.34	86.46
19	5/8/2008	0.55	300	0.11	42.78	33.97
20	5/10/2008	0.25	120	0.12	32.14	38.29
21	5/10/2008	0.43	105	0.60	90.70	185.27
22	5/11/2008	0.16	135	0.07	26.67	21.86
23	5/13/2008	0.20	90	0.13	12.91	40.76
24	5/15/2008	0.18	150	0.07	9.03	22.23
25	5/25/2008	0.39	30	0.78	459.27	240.85
26	5/25/2008	0.56	30	1.84	260.33	568.15
27	5/26/2008	0.68	210	0.19	134.96	59.90
28	6/3/2008	0.58	45	0.77	144.89	238.38
29	6/4/2008	0.19	75	0.15	63.81	46.93
30	6/6/2008	1.76	165	0.64	265.33	197.62
31	6/6/2008	0.43	60	0.68	175.35	209.97
32	6/20/2008	0.19	90	0.13	42.33	39.03
33	6/22/2008	0.11	30	0.22	13.77	67.93
34	6/24/2008	0.16	45	0.21	52.58	65.46
35	7/2/2008	0.42	210	0.12	21.16	37.05
36	7/8/2008	0.49	30	0.98	714.87	302.60
37	7/11/2008	0.26	60	0.26	64.27	80.28

Table B-2
Actual and Estimated Stormwater Flow Rate at Cardinal Site

Storm No.	Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Actual Flow Rate (gpm)	Estimated Flow Rate (gpm)
1	3/26/2008	1.10	360	0.18	7.73	5.28
2	3/27/2008	0.18	45	0.24	18.60	6.91
3	3/27/2008	0.23	60	0.23	17.58	6.62
4	3/30/2008	0.58	135	0.26	8.24	7.42
5	3/31/2008	0.89	240	0.22	14.56	6.41
6	4/8/2008	0.23	15	0.92	92.47	26.50
7	4/10/2008	0.77	255	0.18	5.71	5.22
8	4/10/2008	0.80	285	0.17	7.50	4.85
9	4/18/2008	0.12	150	0.05	1.15	1.38
10	4/18/2008	0.48	210	0.14	6.60	3.95
11	4/25/2008	0.47	30	0.94	33.10	27.07
12	4/25/2008	0.11	15	0.44	11.00	12.67
13	5/2/2008	0.35	60	0.35	35.05	10.08
14	5/7/2008	0.17	45	0.23	4.73	6.53
15	5/7/2008	0.38	120	0.19	9.62	5.47
16	5/7/2008	0.48	300	0.10	3.77	2.76
17	5/8/2008	0.56	270	0.12	6.48	3.58
18	5/9/2008	0.10	105	0.06	3.00	1.65
19	5/10/2008	0.27	120	0.14	3.63	3.89
20	5/10/2008	0.49	105	0.28	20.75	8.06
21	5/11/2008	0.27	210	0.08	2.36	2.22
22	5/13/2008	0.18	90	0.12	4.78	3.46
23	5/15/2008	0.12	90	0.08	6.69	2.30
24	5/25/2008	0.73	45	0.97	126.29	28.03
25	5/25/2008	0.48	30	0.96	94.00	27.65
26	5/26/2008	0.58	195	0.18	13.42	5.14
27	5/27/2008	0.10	75	0.08	1.59	2.30
28	5/30/2008	0.87	120	0.44	56.16	12.53
29	5/30/2008	0.30	60	0.30	27.45	8.64
30	5/31/2008	0.10	90	0.07	6.71	1.92
31	6/3/2008	0.57	45	0.76	94.29	21.89
32	6/4/2008	0.34	90	0.23	14.02	6.53
33	6/6/2008	1.46	150	0.58	57.65	16.82
34	6/6/2008	0.33	75	0.26	22.99	7.60
35	6/13/2008	0.11	30	0.22	4.90	6.34
36	6/20/2008	0.67	105	0.38	15.79	11.03
37	6/24/2008	0.15	45	0.20	4.98	5.76
38	7/2/2008	0.47	195	0.14	2.98	4.17
39	7/3/2008	0.47	45	0.63	44.31	18.05
40	7/8/2008	0.61	30	1.22	101.63	35.14
41	7/9/2008	0.19	135	0.08	6.67	2.43
42	7/11/2008	0.24	60	0.24	11.12	6.91

Table B-3
Actual and Estimated Stormwater Flow Rate at Geyer Site

Storm No.	Date	Rainfall (in)	Duration (min)	Rain Intensity (in/hr)	Actual Flow Rate (gpm)	Estimated Flow Rate (gpm)
1	3/26/2008	0.95	315	0.18	8.35	14.94
2	3/27/2008	0.13	45	0.17	13.40	14.31
3	3/27/2008	0.33	75	0.26	14.88	21.80
4	3/31/2008	0.92	240	0.23	16.61	18.99
5	4/8/2008	0.19	30	0.38	11.83	31.38
6	4/10/2008	0.92	240	0.23	8.80	18.99
7	4/10/2008	0.84	300	0.17	10.67	13.87
8	4/25/2008	0.44	30	0.88	51.97	72.67
9	5/2/2008	0.21	60	0.21	16.00	17.34
10	5/7/2008	0.20	30	0.40	5.53	33.03
11	5/7/2008	0.37	120	0.19	7.34	15.28
12	5/7/2008	0.48	330	0.09	5.15	7.21
13	5/8/2008	0.55	300	0.11	5.79	9.08
14	5/10/2008	0.25	120	0.13	5.26	10.32
15	5/10/2008	0.43	105	0.25	16.74	20.29
16	5/11/2008	0.16	135	0.07	4.33	5.87
17	5/13/2008	0.20	90	0.13	7.32	11.01
18	5/15/2008	0.18	150	0.07	2.55	5.95
19	5/25/2008	1.21	60	1.21	84.13	99.92
20	5/25/2008	0.45	45	0.60	31.29	49.55
21	5/26/2008	0.15	45	0.20	17.36	16.52
22	5/26/2008	0.61	195	0.19	9.84	15.50
23	5/30/2008	1.23	135	0.55	26.64	45.14
24	6/3/2008	0.50	45	0.67	25.11	55.05
25	6/4/2008	0.24	75	0.19	5.11	15.86
26	6/6/2008	1.46	135	0.65	36.52	53.58
27	6/6/2008	0.38	60	0.38	26.65	31.38
28	6/20/2008	0.38	105	0.22	13.36	17.93
29	6/20/2008	0.11	90	0.07	6.13	6.06
30	6/24/2008	0.17	45	0.23	19.49	18.72
31	7/2/2008	0.48	195	0.15	2.53	12.20
32	7/8/2008	0.78	30	1.56	30.33	128.82
33	7/9/2008	0.23	165	0.08	2.18	6.91
34	7/11/2008	0.38	60	0.38	41.12	31.38

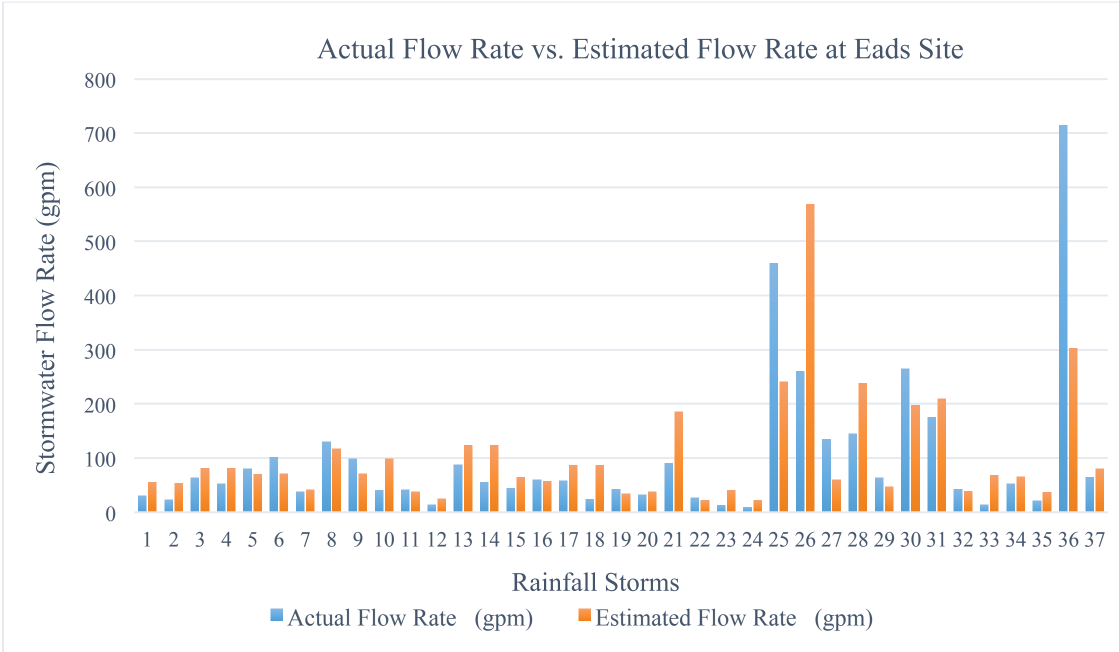

Figure B-1. Actual and Estimated Stormwater Flow Rates for Storms at Eads Site in 2008

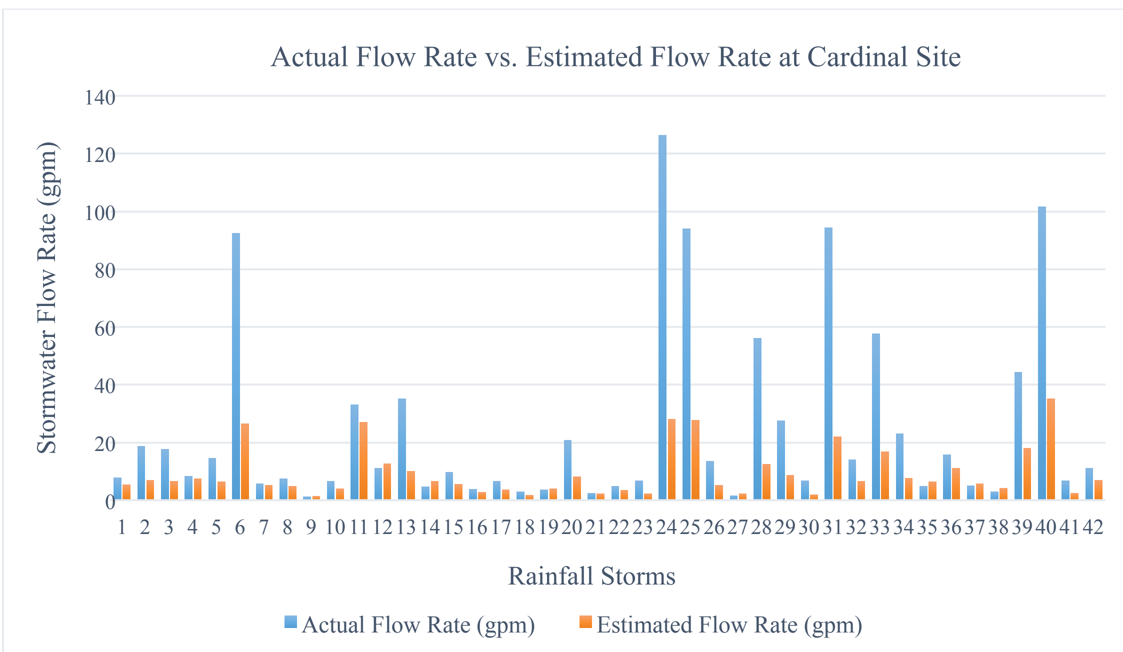

Figure B-2. Actual and Estimated Stormwater Flow Rates for Storms at Cardinal Site in 2008

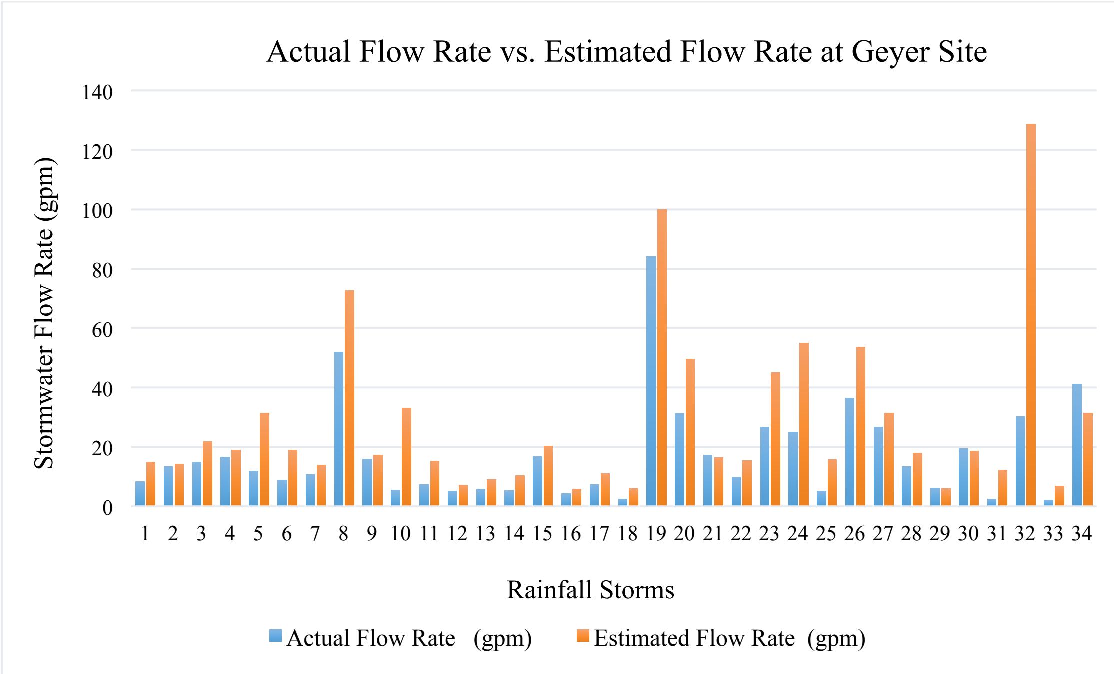

Figure B-3. Actual and Estimated Stormwater Flow Rates for Storms at Geyer Site in 2008