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EVALUATING THE WATER QUANTITY AND QUALITY PERFORMANCES OF UNDERGROUND GRAVEL FILTER BASINS

by
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EVALUATING THE WATER QUANTITY AND QUALITY PERFORMANCES OF UNDERGROUND GRAVEL FILTER BASINS

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April 24, 2018

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DEDICATION

I dedicate this work to my parents, who raised in me the love of knowledge and sense of commitment; my wife, who encouraged me to pursue my goals; my sons, Rayyan and Nady, who have been a great inspiration and motivation; and last but not least, I offer this work to the soul of my grandparents and uncles, whom I dearly miss.

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This document wouldn’t have been completed without the support of my advisors, Dr. Thomas Rockaway and Dr. Arthur Parola. I’m grateful for their insight and support, not only during the course of this study, but throughout my PhD experience at University of Louisville.

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I’d like to express my gratitude to my doctoral defense committee members, Dr. Mark N. French and Dr. Gail W. Depuy, for sharing their experiences and insightful observations and suggestions.

ABSTRACT

EVALUATING THE WATER QUANTITY AND QUALITY PERFORMANCES OF UNDERGROUND GRAVEL FILTER BASINS

Jihad A. Hallany

April 24, 2018

Underground gravel filter basins (UGF basins) are subsurface structures that are used for detention, filtration, and infiltration of stormwater runoff in urbanized areas. The application of these structures is recommended in highly developed urban areas, where land is not available or it is too expensive for surface-level green infrastructures such as stormwater ponds, bio-retention, and infiltration trenches. Objectives of this study are to assess and analyze the effectiveness of two (2) UGF basins in reducing the stormwater runoff peak flow, and to assess water quality parameters in a high-density residential area. The experimental site is located at Red Mile Village, a student housing complex in Lexington, Kentucky.

During the first phase of the monitoring period (June 22 through September 19, 2017) eight storm events were analyzed for both water quality and infiltration performances. An additional six storm events were studied only for infiltration and volume reductions during the second phase of the monitoring period (September 20 through December 22, 2017.

Electronic sensors (pressure transducers and rain gauges) were used to collect the precipitation and water level data continuously during the full course of this study. Grab samples were collected at the basin inflow locations, within the basins, and at the outflow of each basin to evaluate the water quality performance and pollutant load reductions during the first phase of this study. Water quality parameters that were analyzed in this study included pH, temperature, conductivity, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), and *E. coli* which is used as an indicator of fecal contamination.

The result of this study indicated that UGF basins are highly effective in cases of volume reduction and infiltrating the captured water into the underlying soil layers, as well as producing low peak discharge values. The UGF basins were also found to be effective in decreasing the temperature of runoff during summer months and reducing TSS and *E. coli* total loadings.

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1. INTRODUCTION

1.1 Statement of the Problem and Background

Urbanization, including the replacement of natural ground with driveways, parking lots, buildings, and roadways, adversely affects the hydrology of watersheds. Reduced infiltration into the natural ground due to an increase of impervious surfaces, piping, channelization, and modification of flow paths results in higher runoff volumes and an increase of discharge rates.

Stormwater runoff from urban areas may also carry high concentrations of pollutants to the receiving water bodies. The main pollutants typically found in stormwater runoff include sediments, heavy metals, hydrocarbons, bacteria, nutrients, organic carbon, pesticides, and deicers (CWP, 2003). Runoff is also heated by impervious surfaces and could cause thermal enrichment in receiving water bodies during summer months. Increased peak flows and volumes, concentrations of pollutants in the runoff, and increased water temperature pose significant risks to the ecosystem and the public health (Hat et al., 2008; House et al., 1993; Tafuri and Field, 2013). Traditional Stormwater Best Management Practices (BMPs) and the evolving new Green Infrastructure Systems (GISs) were developed to reduce stormwater runoff volume and peak flow to help mitigate adverse hydrologic effects. Both practices are being modified to mitigate high pollutant concentrations and thermal effects.

A wide variety of stormwater BMPs have been used to reduce the runoff volume and peak flow. While these BMPs were not originally designed to remove contaminants, they can provide some benefits with regard to water quality. Many of the conventional BMPs, such as detention basins, are designed to control the peak flow and volume and, to some extent, can remove debris and large sediment particles such as silt and sand-sized particles. These BMPs, however, are generally not effective in removing pollutants such as heavy metals, nutrients, and bacteria such as fecal coliforms and *E. coli* or mitigate for temperature increases.

BMPs that can reduce pollutants effectively include surface infiltration. Surface infiltration involves ponding water in one location long enough for it to infiltrate into the ground. The rate of infiltration is mainly dependent on the underlying soil hydraulic characteristics and the depth of ponding. Generally, a large area of valuable urban real estate is needed for these BMPs.

The underground gravel filter basin (UGF basin) is a relatively new stormwater BMP ideal for uses where land is too expensive or where insufficient space is available for surface basins because of site constraints. The UGF basin uses the void space of stone aggregate as the storage volume for water detention and uses the void space and surface of the aggregate for retention and processing of pollutants. The limestone aggregate is believed to reduce the velocity of the stormwater runoff by creating a longer path, reduction of velocity, and longer resident times, which increases the settling of sediment and particulate matter and adsorbed pollutants. The crushed limestone aggregate may also provide water quality benefits not typically considered in design, including mitigation of increased water temperature.

The UGF basin also contributes to stormwater volume reduction. The volume reduction refers to the volume that enters a BMP and does not discharge to the receiving waters. This volume of water is considered to be retained by the UGF basin and is infiltrated to the bottom and sides of the basin.

Although UGF basins may provide a useful solution for mitigating both hydrologic, pollutant, and thermal problems associated with urban stormwater, several questions still remain with regard to the effectiveness of the UGF basin's design and performance. These questions include their long-term performance for mitigating increased flow peaks and volumes, their effectiveness in removing pollutants, their effectiveness in mitigating thermal impacts, and their performances regarding stormwater volume reduction and infiltration.

1.2 Objectives of the Research

The objective of this research is 1) to evaluate the long-term performance of UGF basins for controlling stormwater runoff volume, 2) to determine the performance of UGF basins regarding the stormwater volume reduction, peak discharge reductions, and infiltration, 3) to assess the ability of these systems to mitigate temperature during the summer months, and 4) to assess their efficiency in removal of TSS and bacterial contamination. The objectives were met by monitoring two UGF basin systems that were designed and constructed in a real urban environment. The construction of these UGF basins was completed in the spring of 2011. Monitoring included samples of water quality and measuring stormwater runoff levels in the UGF basins. The data produced from monitoring were used to evaluate the water quality parameter changes of the UGF basins. A performance assessment of these systems was completed based on recommended BMP guidelines and goals by ASCE-EPA (2002) (Table 1).

Table 1. Goals of BMP Implementation Projects (Strecker et al. 2002)

Category	Goal of the BMP System
Water Quantity/ Hydraulics	• Will the BMP improve the flow characteristics upstream and/or downstream of the BMP?
Water Quantity/ Hydrology	• Will the BMP result in flood mitigation and improve runoff characteristics and reduce the peak flow?
Water Quality	• Will the BMP reduce the downstream pollutant loads and concentrations?
Water Quality	• Will the BMP improve/minimize downstream temperature impacts?
Water Quality	• Will the BMP achieve the desired pollutant concentrations in the outflow?
Water Quality	• Will the BMP improve the removal of litter and debris from the runoff?

1.3 Method

The project site for this study is a student housing complex located at 1051 Red Mile Road, Lexington, Kentucky. The pre-development condition of the site was a mobile home park for 88 units, and post-development conditions include a student housing facility of 528 beds with an associated club house and a pool. Two UGF basins were designed and constructed, one each on the southeast and southwest discharge points of the property. Since construction of these UGF basins was completed in the spring of 2011, there are six years of data to evaluate the long-term performance of these basins.

Pressure transducers (3001 LT Levelogger Junior Edge, M10/F30) were used in the entrance manholes in each UGF basin and at the outlet structures. The pressure transducer in entrance manholes measured the water level in each basin, which was used to obtain the volume captured by each basin and to monitor the infiltration. The pressure sensors at the outlet structures were used to measure the outflow and the volume leaving each basin.

Water quality samples were collected from the runoff at the pavement surface, at the inflow point of the UGF systems, and also from the outflow during eight storm events between June 22 and September 19, 2017. Water quality parameters measured are shown in Table 2.

Table 2. Water Quantity and Quality Parameters Measured

Parameter	**Units**
Laboratory Parameters	
TSS	mg/L
E. coli	MPN/100 mL
In-situ Measurements	
Temperature	(°F)
pH	
Conductivity	(us/cm)
Dissolved Solids	(ppm)
Water Quantity Parameters	
Precipitation	(in.)
Water Levels	(in.)

2. LITERATURE REVIEW

2.1 Introduction

With increased urbanization, natural ground is replaced by impervious surfaces such as driveways, parking lots, buildings, and roadways. Construction of impervious surfaces, which reduces infiltration, modified runoff and flow paths, increased velocity of overland flow, concentration of flow in gutters and pipes, and reduced evapotranspiration, contributes to increases in runoff volumes and increases in peak flows (Rushton, 2001). Increased peak flows can result in erosion and flooding in urban streams that ultimately cause damage to property and infrastructure. (Kazemi, 2014).

Pollutants from exhaust emissions, pavement and vehicle wear, application of chemical fertilizers, deicing material, and atmospheric deposition are commonly deposited on impervious surfaces during wet or dry conditions (Abdollahian, 2015; Burns, 2012). The stormwater runoff picks up and deposits these pollutants in nearby streams, bodies of water, and the groundwater resources, which will cause a degradation of water quality of these receiving waters.

A common and relatively new approach to counter the adverse effects of urbanization on the hydrology of watersheds and the degradation of water quality is the use of Green Infrastructure Systems (GISs), which include permeable surfaces, infiltration trenches, bio-retentions, rain gardens, wetlands, and tree boxes. The GISs are used to reduce the peak flow and volume. These structures can also have a considerable impact on reducing the pollution loads and concentrations carried by the stormwater runoff (Bean et al., 2007) and may have an effect on water temperature and reducing stream warming (Drake et al., 2016).

UGF basins are subsurface GISs used for detention, treatment, filtration, and infiltration of stormwater runoff. The application of these structures is recommended in highly developed urban areas where land is either not available or is too expensive for surface-level green infrastructures.

2.2 Effect of Urbanization on the Hydrology of Watersheds

The hydrological cycle (Figure 1) represents the constant movement of water between atmosphere, land, and bodies of water (Winter et al., 1998). According to this cycle, the major portion of global water resides in the oceans, and only a fraction of it is considered useable freshwater (Winter et al., 1998).

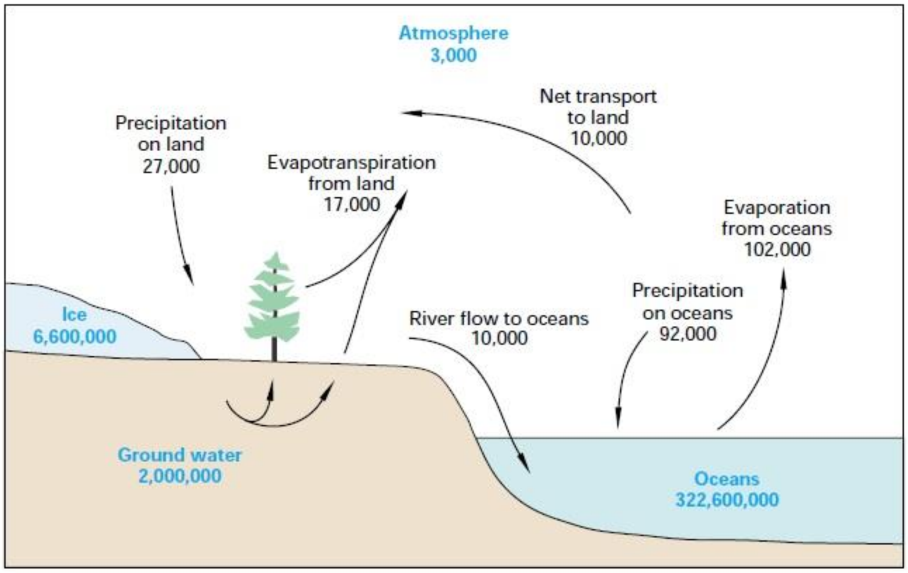


Figure 1. Hydrologic cycle (Winter et al., 1998); pools are in cubic miles and fluxes are in cubic miles per year.

In a natural system, rainfall typically infiltrates into the ground, evaporates, and/or flows into water bodies such as lakes and oceans through streams and rivers. Urbanization, however, disrupts this cycle and alters the relative proportions of these actions (U.S. EPA, 2003). The increase in impervious surfaces directly reduces the amount of water infiltrating into the ground, and the effects of piping, channelization, and modification of flow paths result in more stormwater runoff (Arnold and Gibbons, 1996). Figure 2 shows a schematic comparison between an urbanized area with approximately 75 to 100% of impervious surfaces and an environment with natural ground. In this figure, the U.S. EPA characterizes the differing percentages of runoff, infiltration, and evaporation.

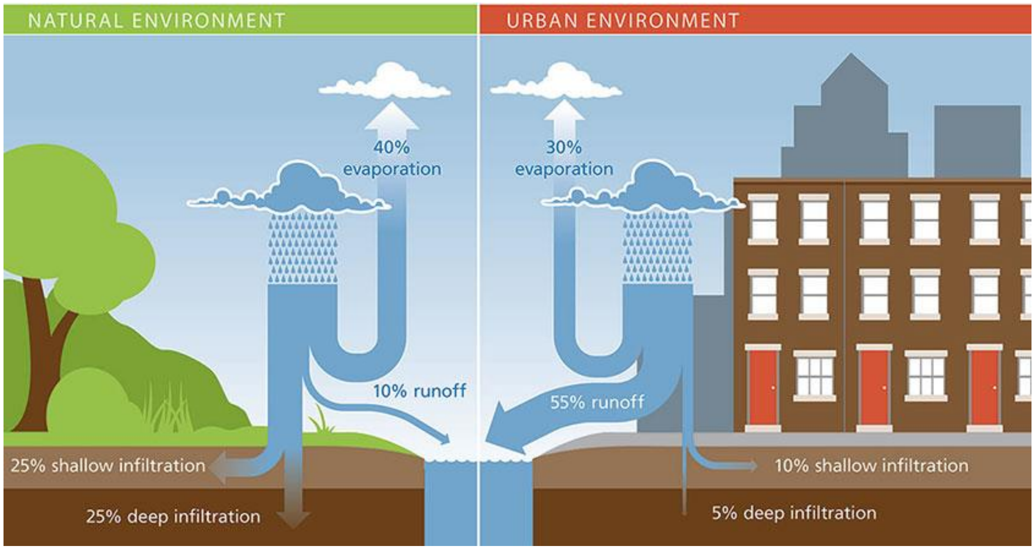


Figure 2. Effect of urbanization on runoff, infiltration, and evaporation (U.S. EPA 2003).

Urbanization can radically affect the movement of water across the landscape (Booth and Leavitt, 1999). The impacts of urbanization on the stream hydrology include:

1. Increased runoff volume; increasing the urban cover and land alterations will decrease the infiltration rates, which will result in lower lag time and significantly higher runoff volume.
2. Increased discharge rates, which are often used to define the flooding risk.
3. Increased magnitude, frequency, and duration of bankfull flows, which is a result of the increase in the peak flow and runoff volume.
4. Decreased base flow; lower infiltration values will result in a potential decrease of stream flow during dry periods (CWP, 2003). The effect of urbanization on the hydrograph is shown in Figure 3.

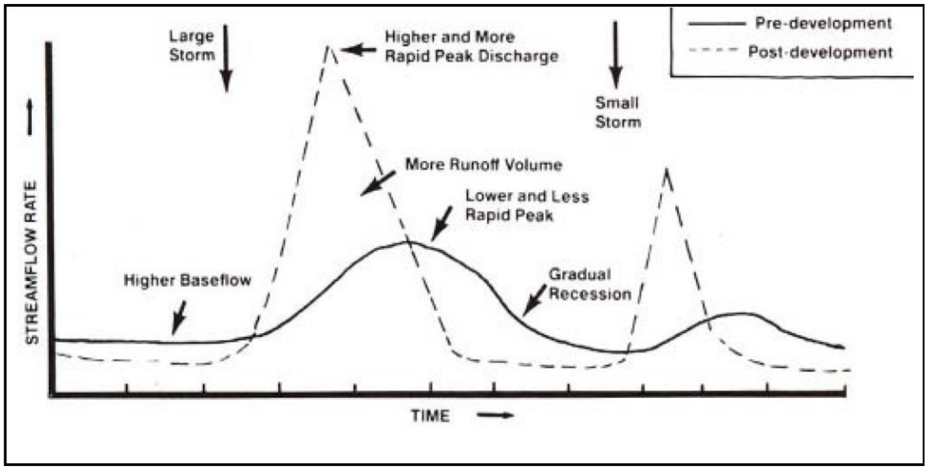


Figure 3. Effect of urbanization on the hydrograph (Schueler, 1987).

2.3 Effect of Urbanization on Stormwater Quality

Stormwater runoff contributes to the transport of a range of pollutants from urbanized watersheds to nearby streams and degrades the water quality of the receiving waters. The main categories of pollutants frequently identified in stormwater runoff include:

1. sediments
2. metals
3. hydrocarbons
4. bacteria
5. nutrients
6. organic carbon
7. Methyl Tert-Butyl Ether (MTBE)
8. pesticides
9. deicers
10. thermal effects

A list of pollutants in stormwater runoff and their sources is presented in Table 3.

Table 3. Summary of Pollutants Found in Stormwater Runoff and Their Sources

	Coal Plants/Incinerators	Gasoline/Diesel Fuel Combustion	Metal Corrosion/Metal Protection	Road Salts	Deterioration of Brake Pads/Tires	Asphalt	Fertilizers/Pesticides/Soil Treatments	Wood Preservatives	Paints and Stains	Plastics	Soil Erosions	Sanitary Waste	Manufacturing	Animal Waste	Atmospheric Deposition	Grass Clipping and Plant Materials	Coal tar–Based sealants for Driveways
Metals																	
Copper	✓		✓		✓		✓	✓	✓	✓		✓	✓	✓			
Lead		✓	✓	✓	✓		✓		✓	✓			✓		✓		
Zinc			✓	✓	✓		✓		✓	✓			✓	✓			
Nutrients																	
Nitrate/Nitrite		✓					✓				✓	✓	✓	✓	✓	✓	
Nitrogen/Ammonia Un-Ionized	✓	✓	✓				✓					✓		✓	✓	✓	
Nitrogen, Total Kjeldahl (TKN)							✓				✓	✓		✓	✓	✓	
Phosphorus, Total	✓	✓			✓	✓	✓				✓	✓	✓	✓	✓	✓	
Phosphorus, Dissolved	✓	✓					✓				✓	✓		✓	✓	✓	
Other Pollutants																	
Arsenic	✓						✓	✓			✓		✓	✓	✓		
Bacteria, *E. coli*											✓	✓		✓			
Chloride, Total	✓	✓		✓						✓		✓					
Oil and Grease		✓			✓	✓							✓				
Polycyclic Aromatic Hydrocarbons (PAH)	✓	✓				✓	✓					✓	✓				✓
Sulfate	✓	✓				✓			✓	✓		✓		✓	✓		✓
Volatile Organic Compounds (VOC)	✓	✓		✓		✓	✓		✓	✓		✓	✓	✓	✓		
Sediments and Other Solids																	
Total Dissolved Solids (TDS)	✓			✓		✓	✓					✓		✓	✓	✓	
Total Suspended Solids (TSS)	✓		✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	
Laboratory Analysis Parameters																	
Biochemical Oxygen Demand (BOD)							✓				✓	✓		✓	✓	✓	
pH	✓		✓	✓													

Heavy Metals

Heavy metals, or trace metals, such as zinc, copper, lead, chromium, etc., are among the most common pollutants in stormwater. Sources for metal in the runoff include tires, fuel combustion, auto brake linings, paints and stains, and galvanized pipes and surfaces. Source areas for metals in a developed environment include roadways, parking lots, snowpack and rooftops. Metals in runoff are usually reported as the total recoverable form or the dissolved form. The dissolved form excludes metals that are attached to suspended solids larger than 0.45 micron in diameter.

A number of these metals are frequently found in runoff with concentrations that could be harmful to human health and the environment (Shaver et al., 2007). The main concern regarding the presence of metals in streams is their potential toxicity to aquatic organisms (CWP, 2003). Bioaccumulation can cause high concentrations of metals in animals that feed on plants and animals that ingest lower levels of metals. (Masterson and Bannerman, 1994).

Nutrients (Nitrogen and Phosphorus)

The presence of nitrogen and phosphorus is essential for aquatic systems, but excessive concentrations of these nutrients can be harmful to receiving waters. Nitrogen is commonly reported in four forms: 1) nitrate (NO_3) , 2) nitrite (NO_2), 3) total nitrogen (TN), and 4) total Kjeldhal nitrogen (TKN). Phosphorus is typically reported as Total phosphorus (TP) or as soluble phosphorus, which is the form of phosphorus available for uptake by plants and animals (Shaver et al., 2007).

The main sources of nitrogen and phosphorus in the stormwater runoff are fertilizers, organic matter, atmospheric deposition, stream bank erosion, and pet waste

(Pitt, 2004). Areas such as lawns, landscaped areas, and common open spaces within urbanized areas where chemical fertilizers are commonly applied, are known to be the main source areas for nutrients (Bannerman et al., 1993).

Lakes, reservoirs, and estuaries experience eutrophication when exposed to excessive loads of nutrients. Eutrophication refers to an excessive richness of nutrients in a body of water, which causes a dense growth of plant life and death of animal life from lack of oxygen. High nitrogen and phosphorus concentrations in stormwater runoff can contribute to algae growth and eutrophic conditions that can affect the dissolved oxygen in these waters (U.S. EPA, 1998).

Sediment

Sediment is an important factor in evaluating the water quality in stormwater runoff. Water quality studies commonly measure sediment or the effects of sediment as: (1) total suspended solids (TSS), (2) total dissolved solids (TDS), and (3) turbidity. Measuring TSS of runoff is an indirect measure of sediment load. TDS is a measure of minerals and dissolved particles in the runoff and provides an indicator regarding the purity of the water for drinking. Turbidity represents the effect of suspended solids on the ability of light to penetrate the water column. Presence of suspended solids will reduce the light penetration in water and can affect the aquatic biota (CWP, 2003).

Primary sources of sediment in stormwater runoff are construction sites, erosion from the exposed soils, wash-off from the impervious surfaces, and stream bank erosions (CWP, 2003). Sediment wash-off is the process by which sediments are removed from urban surfaces by the action of rainfall and runoff (Muthusamy et al., 2018).

The main negative impact of high levels of sediments (TSS, TDS, and turbidity) in stormwater are the effect on the habitat of receiving waters, reduction in flow capacity where sediment is deposited, and stream warming which is caused by reflecting radiant energy due to increased turbidity (Kundell and Rasmussen, 1995; Leopold, 1973).

Bacteria and Pathogens

Bacteria are single-celled organisms that can be found in large numbers in stormwater runoff. Coliform bacteria exist in the digestive system of warm-blooded animals. Species of coliform found in runoff include *E. coli*, fecal coliform, and fecal streptococci. Presence of the coliform bacteria in water confirms the presence of animal waste or sewage (Abdollahian, 2015; CWP, 2003).

The primary source of bacterial contamination in runoff is waste from humans, pets, and wildlife. Transportation of bacteria to receiving waters is through direct runoff or indirect secondary sources such as leaking septic systems or sanitary sewer overflows (Schueler, 1999).

The presence of elevated levels of *E. coli* and fecal coliforms in water is an indicator of other potential harmful microorganisms and viruses. Table 4 shows the standards that have been established to protect human health based on exposure to waters contaminated with elevated levels of bacteria (U.S. EPA, 1998).

Table 4. Fecal Coliform and *E. coli* Standards for Different Water Uses (U.S. EPA, 1998)

Water Use	**Microbial Indicator**	**Typical Water Standard**
Water Contact Recreation	Fecal Coliform	<200 MPN* per 100 ml
Drinking Water Supply	Fecal Coliform	<20 MPN* per 100 ml
Shellfish Harvesting	Fecal Coliform	<14 MPN* per 100 ml
Treated Drinking Water	Fecal Coliform	No more than 1% coliform positive samples per month
Freshwater Swimming	Fecal Coliform	<126 MPN* per 100 ml

* MPN = most probable number

Thermal Effects

Urban areas can release excess heat as a result of both the high combustion of fossil fuels and a lack of vegetation, which acts as a natural cooling system. Previous studies have shown that urbanization can result in an increase in temperature of six to eight degrees Fahrenheit in the warmer summer months and two to four degrees Fahrenheit during the cooler winter months (CWP, 2003),

Water temperature is subsequently affected by local air temperatures. Studies by Galli (1990), and Johnson (1995) have shown that summer temperatures in urban streams increased by as much as five to 12 degrees Fahrenheit in response to watershed development. Increased water temperatures can endanger the temperature-sensitive species in receiving waters.

2.4 Types of Green Infrastructure Systems (GISs)

Several types of GISs have been used in urban areas to minimize the impact of urbanization on water quality and quantity. Some of these GISs include: infiltration trenches, bioretention systems, surface sand filters, underground gravel filter basins, stormwater wetlands, wet swales, permeable surfaces (permeable pavers, porous asphalt, porous concrete), dry ponds, and underground storage basins.

A description of some of the most prevalent GISs, their advantages, and disadvantages are described below.

2.4.1 Bioretention Systems

Rain gardens and planter boxes are both forms of bioretention systems, in which shallow vegetated surfaces with porous backfill can collect stormwater runoff from roadways, parking lots, and rooftops. These systems can enhance ground water recharge, pollutant removal, and runoff detention. Bioretention also offers an effective approach to stormwater management where open space is limited (U.S. EPA, 2013). Bioretention systems contain engineered soils with high organic content, and they feature vegetation that can stand periodic inundation.

There are two main designs for bioretention systems: (1) infiltration-based systems, used in cases where the underlying soils are permeable and there are no concerns of groundwater or soil contamination, and (2) flow-through systems in which an impermeable liner and an underdrain are used to direct the treated stormwater runoff to a collection system (SFPUC, 2010) .

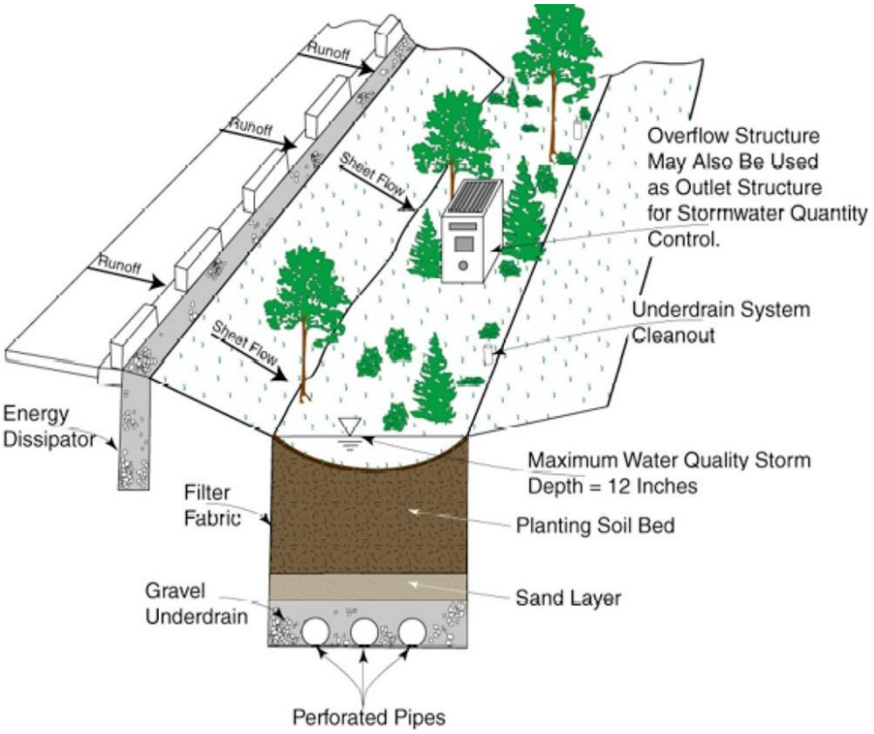


Figure 4. A cross-sectional view of a bioretention basin (Rusciano and Obropta, 2005)

Advantages

- Reducing the runoff volume and the peak flow
- Improving the water quality
- Improving the ground water recharge (only in infiltration-based designs)
- Low cost and easy to install.

Limitations

- Relatively flat sites and sufficient hydraulic head are required for filtration
- Maintenance is required for the vegetation

2.4.2 Infiltration Trenches

Infiltration trenches are shallow excavations that are lined with filter fabric and filled with stones to create underground reservoirs for stormwater runoff (Barr

Engineering Co., 2001). Pretreament of the stormwater runoff is required for these GISs to remove coarse sediments that can clog the system and reduce efficiency. Some of these pretreatment measures include: sediment basins, vegetated swales, and grit chambers. The pretreated runoff is stored in the void space of the stone media and is infiltrated through the bottom of the structure, which results in groundwater recharge (SFPUC, 2010).

Infiltration trenches are usually designed for a frequent, small storm such as the one-year storm event. These GISs can be used when the infiltration rates of the underlying soils are 0.5 inches per hour or greater.

Advantages

- Reducing runoff volume and peak flow
- Improving the water quality by removing sediment, nutrients, organic matter, and metals from the runoff
- Improving the ground water recharge
- Low costs for construction and maintenance

Limitations

- Not suitable for drainage areas of greater than five acres.
- Frequent maintenance and inspections are required.
- A risk of groundwater contamination may exist, based on the depth of the groundwater, soil conditions, and the land use.

- Not appropriate for industrial or commercial sites where high concentrations of pollutants can be released into the runoff (Barr Engineering Co., 2001).

2.4.3 Underground Filters

Underground filters are similar to surface filters except that the filter media and underdrains are installed in a vault below grade level. The vault is typically made of reinforced concrete that is designed to accommodate a permanent water pool (SFPUC, 2010). These systems are suitable for small urban sites where space is limited and soil or groundwater contamination concerns would not support the infiltration systems. Underground filters are primarily used for water quality purposes and not quantity control.

The general design for the underground filters is known as underground sand filters, which are known to be effective in removing many of the common pollutants from stormwater runoff, especially pollutants that are in particulate form or those attached to suspended solids (MDE, 2000).

<u>Advantages</u>

- Suitable for small drainage areas (between 1 to 10 acres)
- Effective in removing suspended solids from runoff
- May require less space compared with other treatment GISs, and is suitable for sites with steep slopes
- Good retrofit capability

Limitations

- Frequent maintenance may be required depending on the watershed
- The costs for excavation and installation are relatively high
- Generally used for stormwater quality control; quantity control will not be provided
- Freezing conditions in the underdrains and filter media will reduce performance (Barr Engineering Co., 2001)

2.4.4 Permeable Pavements

Permeable pavement is referred to as any porous load-bearing surface that can temporarily store stormwater runoff prior to infiltration or drainage to a controlled outlet. The stormwater runoff is stored between the voids of an underlying aggregate layer before infiltration or being routed to a collection system (SFPUC, 2010).

These GISs are effective for reducing imperviousness in areas with light to medium-duty loads such as parking lots, driveways, sidewalks, and street side parking areas. They can be used in residential, commercial, and industrial projects (MDE, 2000). Permeable pavements are known for reducing runoff volume, attenuating peak flows, and removing pollutants such as oil and grease, metal, and suspended solids from the runoff.

Advantages

- Reducing the runoff volume and the peak flow
- Facilitate the groundwater recharge
- Can be used as a design element for aesthetic purposes
- Effective for roadway noise reduction

Limitations

- Can only be used in areas with low and medium traffic loads
- Requires more maintenance compared with traditional pavements
- Depth to the bedrock or the ground water levels should be more than four feet (SFPUC, 2010)
- Costs are higher than traditional pavements

2.4.5 Underground Storage

Underground storage refers to the practice of collecting and detaining stormwater runoff in underground structures such as pipes, chambers, or modular structures. The stormwater collected by these systems is planned to be directed back to the surface drainage system or storm sewer systems at a reduced rate, so the system will be completely drained prior to the next storm event. Since storage systems are not known to provide high water quality and pollutant removal benefits, the use of pretreatments or additional GISs would be required when water quality improvements are needed (MSD, 2013).

The use of underground storage systems is appropriate for different land use applications including commercial, industrial, or multi-family high-density residential areas where land is not available or is too expensive. Different materials such as concrete, steel, or plastic can be used in these systems. However, selecting the appropriate material depends on different factors such as desired useful life, earthwork requirements, overburden support, and potential for the system to float (MSD, 2013).

Advantages

- Reducing the number of bankfull events, which will result in reducing stream bank erosion
- Relatively less installation time compared with other GISs
- Can be used in properties with unusual shapes
- More public safety compared with surface GISs

Limitations

- Very limited water quality benefits
- Pretreatment is required to reduce maintenance costs and efforts

Table 5 summarizes the pollutant removal, volume reduction, and peak flow reduction of the green infrastructure systems that were discussed in this section. This table was created based on data reported by a number of green infrastructure design manuals, including the California Stormwater BMP Handbook, the Maryland Stormwater Design Manual, and the Louisville Green Infrastructure Design Manual.

Table 5. Pollutant Removal, Volume Reduction, and Peak Flow Reduction of Green Infrastructure Systems

GIS	**Pollutant Removal**	**Volume Reduction**	**Peak Flow Reduction**
Infiltration-Based Bioretention Systems	High	High	Moderate
Flow-Through Bioretention Systems	High	Moderate	Moderate
Infiltration Trenches	High	High	High
Underground Filters	Moderate	Low	Low
Permeable Pavements	Moderate	High	Moderate
Underground Storage Systems	Low	High	High

2.5 Infiltration in GISs

A portion of precipitation (rain or snow) will infiltrate into the subsurface soil and rock. The amount of infiltration depends on various factors such as precipitation, base flow, soil characteristics, saturation in the subsurface material, land cover (pervious and impervious), slope of the land, and evapotranspiration (USGS, 2016).

Some of the precipitation may infiltrate deeper, recharging groundwater aquifers. Infiltration GISs enhance groundwater recharge, mitigating the impact of development on the hydrologic cycle. These systems also use the subsurface soil as a filter that can treat the polluted runoff as it percolates into the ground.

Porous surfaces such as permeable pavements and porous asphalts, infiltration basins, and infiltration trenches are examples of infiltration GISs that can achieve pollutant removal through infiltration.

The design criteria for infiltration GISs according to the Center for Watershed Protction (1997) are:

- The infiltration rate of the underlying soils should be 0.5 inches per hour or higher
- Hotspot runoff should not be infiltrated (e.g., runoff from gas stations)
- Infiltration should not be located on steep slopes
- The bottom of the infiltration system should be separated from the groundwater table by two to four feet
- GISs should be separated from water supply wells by a minimum of 100 feet

- An overflow channel is required if erosive velocities are anticipated
- Clogging of the system should be avoided during construction
- Infiltration systems should fully dewater the water quality volume within 48 hours

The primary goals of these criteria are to protect the groundwater from pollutants in stormwater runoff and to avoid clogging in the GIS (CWP, 1997).

2.6 Pollutant Removal Performance of Stormwater GISs

Previous studies show that GISs have frequently been used to remediate stormwater quantity concerns. Some GISs have been shown to reduce the loads and concentrations of pollutants in stormwater runoff (Abdollahian, 2015; Fraley-McNeal et al., 2007). The GISs are expected to reduce pollutant loadings such as nutrients (nitrogen and phosphate), suspended solids, and pathogenic bacteria from stormwater runoff (Brattebo and Booth, 2003; Hunt et al., 2008).

According to the data presented in the National Pollutant Removal Performance Database (2006), high removal rates of total suspended solids (TSS), total phosphorus (TP), zinc (Zn), and copper (Cu) have been reported for permeable pavements and infiltration trenches. A study by Bean et al. (2004) also showed significant removal rates of total nitrogen (TN) and total phosphorus for permeable pavements.

Detention basins have been one of the most widely used systems for stormwater management and urban drainage (Brabec et al., 2002; Fraley-McNeal et al., 2007). Previous studies have shown that stormwater ponds are capable of improving the water quality by reducing the concentrations of sediments, metals, nutrients, and bacteria (Carpenter et al., 2014).

Underground detention chambers are also known to reduce suspended solids, thermal effects, and metal concentrations in stormwater runoff (Drake et al., 2016).

Table 6 below, presented by the National Pollutant Removal Performance Database, summarizes the pollutant removal efficiencies of the more widely used GISs. The median, maximum, and minimum pollutant removal percentages are reported in this table.

Table 6. Summary of Removal Efficiency Data for Green Infrastructure Systems (Fraley-McNeal et al., 2007)

Pollutant	TSS	TP	Sol P	TN	NO_x	CU	ZN	Bacteria
Infiltration Systems (Data is collected from the studies on permeable pavement systems and infiltration trenches)								
Median (%)	89	65	85	42	0	86	86	N/A
Min (%)	0	0	10	0	-100	0	39	N/A
Max (%)	97	100	100	85	100	89	99	N/A
# of Studies	4	8	4	7	5	4	6	0
Dry Ponds (Data is collected from the studies on quantity control ponds and dry extended detention ponds)								
Median (%)	49	20	-3	24	9	29	29	88
Min (%)	-1	0	-12	-19	-10	10	-38	78
Max (%)	90	48	87	43	79	73	76	97
# of Studies	10	10	6	7	7	4	8	2
Wet Ponds (Data is collected from the studies on wet extended detention ponds, multiple pond systems, wet ponds)								
Median (%)	80	52	64	31	45	57	64	70
Min (%)	-33	12	-64	-12	-85	1	13	-6
Max (%)	99	91	92	76	97	95	96	99
# of Studies	44	45	28	22	29	23	34	11
Wetlands (Data is collected from the studies on shallow marsh, detention wetland, and submerged gravel wetlands								
Median (%)	72	48	25	24	67	42	47	78
Min (%)	-100	-55	-100	-49	-100	-67	-74	55
Max (%)	100	100	82	76	99	84	90	97
# of Studies	37	37	26	24	33	12	19	3
Sol P = Soluble Phosphorus; NO_x = Nitrate and Nitrite Nitrogen, Cu = Copper; Zn = Zinc								

2.6.1 Pollutant Removal Processes in Stormwater GISs

Pollutant removal in GISs involves physical, chemical, and biological processes (Scholes et al., 2008). These mechanisms will be briefly explained in this section.

2.6.1.1 Physical Processes

Physical processes are the dominant form of treatment in most GISs. These processes are also the basis of many preliminary and primary mechanisms in wastewater treatment (NCHRP, 2006). Physical processes include filtration, settling, flotation, and volatilization.

Filtering. This process refers to the removal and physical sieving of the pollutants that are in particulate form. Porous media in the GIS is mainly responsible for this type of pollutant removal. GISs that provide higher contact time between the stormwater runoff and the porous media, such as permeable pavements, infiltration trenches, and infiltration basins, will have higher potential for filtration compared with other GISs with a lower contact time between the runoff and a porous media (Scholes et al., 2008).

Sedimentation. Sedimentation (also called settling) refers to the separation of particles downward due to different densities between the sediment and water. Settling is known to be a two-phase process. The first phase occurs during the storm runoff under turbulent flow conditions. The second phase is the intermittent settling between storm periods (Urbonas, 1994). Pollutants targeted by this mechanism include total suspended solids, large sediments (silt and sand size particles and larger), and pollutants that are attached to suspended solids, such as heavy metals. A wide variety of GISs use sedimentation as one of the fundamental processes for pollutant removal (NCHRP, 2006).

Flotation. Flotation is the reverse of settling and sedimentation. The density differential between pollutants and water will cause the pollutants to be separated upwardly (NCHRP, 2006). Pollutants that could be removed by flotation include petroleum hydrocarbons, trash, and debris. Oil/water separators utilize the flotation removal mechanism.

2.6.1.2 Chemical Processes

Chemical and physiochemical processes play an important role in removing nutrients, heavy metal, and petroleum hydrocarbons. The main chemical processes are adsorption and absorption, ion exchange, flocculation, and chemical disinfection (Scholes, 2008).

Adsorption and absorption. Sorption refers to the processes of absorption and adsorption. Absorption is a physical process in which a substance in one state is absorbed by another substance in a different state. Adsorption is the physiochemical bonding of ions and molecules. Petroleum hydrocarbons are targeted by absorption while nutrients, dissolved metals, and organic toxicants are removed by adsorption (NCHRP, 2006).

Chemical disinfection. Chemical agents such as chlorine and ozone reduce the concentrations of stormwater-borne pathogens. Chemical disinfections immobilize pathogens by damaging the cell walls, altering the cell-wall permeability, alteration of pathogen DNA or RNA, and/or inhibition of the pathogen enzyme activity (Metcalf and Eddy, 2003). The use of chemical disinfections is highly recommended in projects where high concentration of pathogens is a concern.

2.6.1.3 Biological Processes

Biological treatment is the use of living organisms such as microbes, algae, and plants to transform or remove pollutants from stormwater runoff. Plant uptake and microbially mediated transformations are the main categories of the biological processes that transform or remove pollutant from runoff (Scholes et al., 2008).

Plant and algae uptake. The presence of vegetation (terrestrial or aquatic) in a GIS provides pollutant removal via plant uptake. GISs that provide sufficient contact between the stormwater runoff and aquatic or terrestrial vegetation will have a higher potential for plant uptake compared with the GISs with little or no contact between the runoff and aquatic or terrestrial vegetation. GISs that use plant and algae uptake are wetlands, bioswales, and filter strips (Scholes et al., 2008).

Microbially mediated transformations. These mechanisms refer to microbial activity that promotes or catalyzes redox reactions and transformations. Degradation of organic pollutants and oxidation and reduction of inorganic pollutants result from microbial activity that promotes or catalyzes redox reactions and transformations. Microbially mediated transformations occur mainly by bacteria, algae, and fungi in water, in soil, along the root zone of plants, and on wetted surfaces such as leaves and stones. Constructed wetlands, infiltration basins, and filter drains are examples of GISs with medium to high potential for microbially mediated processes (NCHRP, 2006; Scholes et al., 2008).

Table 7 summarizes the relative importance of mechanisms such as filtering, settling, adsorption, plant uptake, and microbial degradation in different GISs.

Table 7. Relative Importance of Pollutant Removal Mechanisms in Different GISs (Scholes et al., 2008).

GIS	**Filtration**	**Settling**	**Adsorption to Substrate**	**Microbial Degradation**	**Plant Uptake**
Porous Asphalt	High	Low	Low/ Medium	Low	NA
Porous Paving	High	Moderate	High	Low	Low
Swales	Medium	Low/ Medium	Medium	Low/ Medium	Medium
Infiltration Trenches	Medium/ High	Low/ Medium	Medium/ High	Medium	Low
Infiltration Basin	Medium/ High	High	High	High	Low/ Medium
Retention Ponds	Low	High	Low/ Medium	Medium	Low
Detention Basins	Low	Medium/ High	Medium	Low/ Medium	Low
Constructed Wetland (SSF)*	Medium/ High	Medium	Medium/ High	High	Medium/ High
Constructed Wetland (SF)*	Medium	Medium	Medium	Medium	Medium

* SSF = Sub-surface Flow; SF = Surface Flow

2.7 The First Flush Phenomenon

The first flush phenomenon usually occurs in single rainfall events and can be described as a concentration-based first flush (CBFF) or mass-based first flush (MBFF). A CBFF refers to a situation when a high concentration of constituents is detected during the rising limb of the hydrograph storm event (Sansalone and Cristina, 2004). However, an MBFF is flow dependent and occurs when concentration and initial runoff are high compared to mass emission rates in the later runoff (Kayhanian and Stenstrom, 2005).

A seasonal first flush refers to higher concentration or larger mass of the first storm or the first few storms in the beginning of a rainy season compared with events later in the season. Both the first flush and the seasonal first flush apply to any water quality pollutant or parameter. The first flush transport has been reported for heavy metals from rooftops by Foster (1996); for oil and grease from roadway surfaces by Kayhanian and Stenstrom (2005); nutrients from roadway surfaces by Lee and Bang (2000); and TSS and particulate pollutants by Lee et al. (2004).

2.7.1 Factors Affecting the Presence of an MBFF

There are several factors that can affect the development of an MBFF: the size of the watershed, land cover or imperviousness of the watershed, rainfall and climate characteristics, and the type of the pollutant.

2.7.1.1 Size of the Watershed

First flushes are usually not observed in a very large watershed because the stormwater runoff must be transported a great distance in a large watershed to reach a single discharge point or mouth of the watershed. Travel times of the runoff from subwatershed to the discharge point are different, causing the first flush from each subwatershed to arrive at the monitoring point at different times. The combination of the smaller subwatershed first flushes diffuse into a broad discharge pattern (Kayhanian and Stenstrom 2005).

2.7.1.2 Watershed Imperviousness

Imperviousness of the watershed is another factor that can highly affect the occurrence of first flush (Schueler, 1994). Watersheds with high percentages of impervious surfaces will create runoffs with sufficiently high velocities that can easily transport the pollutant from surfaces. The quickly occurring runoff or the short time of travel, which is a result of high percentages of impervious surfaces in the watershed, will increase the possibility of the first flush occurrence (Kayhanian and Stenstrom 2005).

2.7.1.3 Rainfall and Climate Characteristics

One of the most important climate characteristics affecting the first flush phenomenon is the antecedent dry period. The amount of pollutants accumulated in a watershed are related to the antecedent dry weather period. Storm events with longer antecedent dry conditions are more likely to produce a first flush (Shamseldin, 2011).

2.7.1.4 Type of Pollutant

According to Lee et al. (2004), the magnitude of the first flush phenomenon is greater for some pollutants and less for others. These differences could be caused by the land use, rainfall intensity, or mechanisms affecting the pollutant build-up (Shamseldin, 2011).

2.7.2 Methods for Identifying the First Flush

Several studies have noted that stormwater runoff is the main cause of degradation of the receiving bodies, especially during the first flush (Butler and Davies, 2000). Therefore, identifying the first flush from data can be helpful in managing the pollutant loads. Concentration-based, mass-based, and the empirical are three frameworks used to identify the first flush phenomenon (Sansalone and Cristina, 2004).

Concentration-Based Framework

The identification of the first flush in this framework is based on whether or not a disproportionately high pollutant concentration occurs in the early part of a storm (Shamseldin, 2011). However, different pollutants may not have the same concentration peak during the same event or during different events in the same watershed.

According to U.S. EPA (1993), the first flush occurs when the pollutant concentration at any given time, C(t), exceeds the baseline concentration C_b. The baseline concentration is the mean concentration of the pollutant during dry weather. The volume of the first flush, known as V_p, can be determined by finding the integral between the time when C(t) becomes greater than C_b and the time when C(t) becomes less than C_b (t_1 and t_2) (see Figure 5).

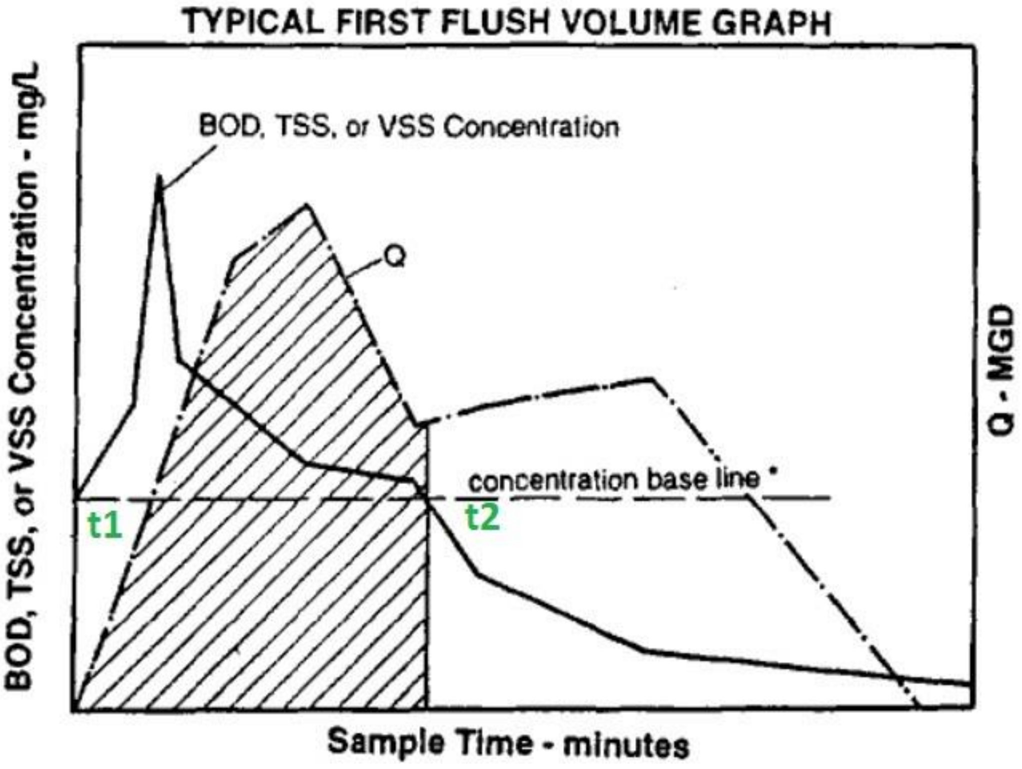


Figure 5. Identifying the first flush using the baseline method (U.S. EPA, 1993).

Mass-Based Framework

The mass-based methods for identifying the first flush data are based on using dimensionless cumulative mass M(t) and volume V(t) curves. These curves can be determined using the following equation for each storm event:

$$V(t = k\mathit{\Delta} t) = \frac{\sum_{i=0}^{k} \bar{Q}(t_i)\, \mathit{\Delta} t_i}{\sum_{i=0}^{n} \bar{Q}(t_i)\, \mathit{\Delta} t_i} \tag{2.1}$$

$$M(t = k\mathit{\Delta} t) = \frac{\sum_{i=0}^{k} \bar{Q}(t_i)\, \bar{C}(t_i)\, \mathit{\Delta} t_i}{\sum_{i=0}^{n} \bar{Q}(t_i)\, \bar{C}(t_i)\, \mathit{\Delta} t_i} \tag{2.2}$$

In these equations, V(t) represents the ratio of the total runoff volume at time (t) divided by the total volume of the event. $\bar{Q}(t_i)$ is the average volumetric flow rate between successive measured runoff rates, $\bar{C}(t_i)$ is the mean pollutant concentration, and M(t) is the ratio of the total pollutant mass at time (t) divided by the total mass of the storm event (Kayhanian and Stenstrom, 2005; Shamseldin, 2011).

Different definitions for the first flush have been proposed using these curves. For example, according to Saget et al. (1996), the first flush will occur when at least 80% of the total pollutant load is transported during the first 30% of the volume. Wanielista and Yousef (1993) proposed that the first flush will happen when at least half of the total pollutant mass is transported in the first 25% of the runoff volume.

The equation below can be used to quantify the occurrence of the first flush (Acharya et al., 2010) in which b is the first flush coefficient and shows the gap between the M-V curve.:

$$M(t) = V(t)^b \tag{2.3}$$

Different values of this coefficient will correspond to different possibilities for the first flush to occur (see Table 8).

Table 8. First Flush b values and Descriptions (Shamseldin, 2011)

First Flush Coefficient (b)	Zone	Description
$0.000 \leq b < 0.185$	1	Strong first flush
$0.185 \leq b < 0.862$	2	Moderate first flush
$0.862 \leq b < 1.00$	3	Weak first flush
$1.000 \leq b < 1.159$	4	No first flush
$1.159 \leq b < 5.395$	5	No first flush with moderate pollutant delay
$5.395 \leq b < \infty$	6	No first flush with strong pollutant delay

Empirical Framework

There are other design methods to determine the first flush which do not fall under either of the methods describe earlier. These methods include multiple-linear regression based on establishing relationships between the pollutant loads in the first flush and variables such as the rainfall duration, rainfall intensity, and antecedent dry conditions (Gupta and Saul, 1996). According to Schueler (1987), first flush refers to the first 0.5 inches of runoff per impervious area. Similarly, Grisham (1995) defines the first flush as the first 1.27 cm of runoff per drainage area, and the State of California defines first flush as the volume of water created by 0.75 inches of rainfall (Shamseldin, 2011).

First flush can be used to determine the critical initial runoff volume that needs to be captured and treated. This critical volume is known as the water quality volume (WQv) (Deletic, 1997). According to Barco et al. (2008), focusing on treatment of the first flush in GI systems/BMPs is a more economical approach to reduce pollutants from the runoff than treating the entire runoff from a storm event.

2.8 Groundwater Movement and Darcy's Law

The flow through porous media is proportional to the head loss ($Q \sim h_L$) and inversely proportional to the length of the flow path ($Q \sim \frac{1}{L}$). This statement is known as Darcy's law (Todd and Mays, 2005). Introducing a proportionality constant K will lead to the equations:

$$Q = -KA\frac{h_L}{L} \tag{2.4}$$

$$Q = -KA\frac{dh}{dL} \tag{2.5}$$

$$v = \frac{Q}{A} = -K\frac{dh}{dL} \tag{2.6}$$

In the above equations, Q is the flow rate, v is the flow velocity, and A is the area of the porous media introduced to the flow. The velocity in equation 2.4 is known as the *Darcy velocity*, and it is calculated under the assumption that flow occurs through the whole intersection of the porous media, but the flow is only limited to the pore space. Dividing the Darcy velocity by the effective porosity (α) will result in the average interstitial velocity:

$$v_a = \frac{Q}{\alpha A} \tag{2.7}$$

The porosity of the media is a measure of the contained interstices or voids expressed as the ratio of the volume of the voids to the total volume.

$$\alpha = \frac{v_v}{v_t} = \frac{v_t - v_s}{v_t} \tag{2.8}$$

In this equation v_v is the volume of the voids, v_s is the volume of solids or particles, and v_t is the total volume of the media (Todd and Mays, 2005).

It is important to know if Darcy’s law is applicable, i.e., what is the range of the validity for Darcy’s law. According to Poiseuille’s law, in laminar flow such as water flowing in a capillary tube, the velocity is proportional to the first power of the hydraulic gradient, so it would be reasonable to believe that Darcy’s law also applies to laminar flow in porous media (Todd and Mays, 2005).

A dimensionless ratio of inertial to viscous forces known as the Reynolds number (Re) is used as a criterion to determine if a flow is laminar or turbulent (Zeng and Grigg, 2006):

$$Re = \frac{\rho v D}{\mu} \tag{2.9}$$

In the above equation, D is the pipe diameter, v is the velocity of the flow, ρ is the fluid density, and μ is the dynamic viscosity. In order to use the Reynolds number as a criterion in porous media, Darcy velocity should be used as v, and D should be replaced by the effective grain size (d_{10}). Studies show that Darcy’s law is valid for $Re < 1$ and will not seriously depart up to $Re = 10$. This represents an upper limit which is a range of values instead of a unique value, because as inertial forces increase, turbulence occurs gradually (Todd and Mays, 2005; Hassanizadeh and Gray, 1987).

When turbulence within the fluid flowing through a porous media is significant, additional drag terms, in addition to the viscous ones, will become important. A friction factor is introduced to represent the turbulent flow region in fluid flow through pipes and channels. This analogy can be extended to cover both flow laminar and turbulent regions in porous media (Holdich, 2002). The friction factors in porous media are shown in Figure 6.

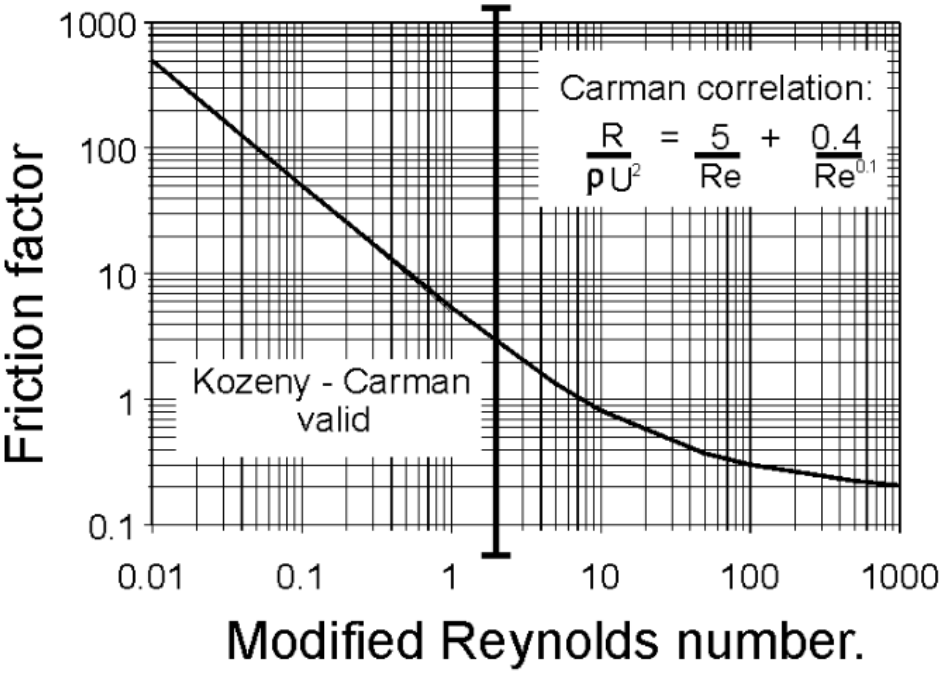


Figure 6. The friction factors in porous media (Holdich, 2002).

The friction factor is $(R/\rho v_a^2)$ in which R is the shear stress or drag force and v_a is the interstitial velocity. The modified Reynolds number can be determined using the equation below:

$$Re_1 = \frac{\rho v}{(1-a)S_v \mu} \tag{2.10}$$

2.8.1 Permeability

Understanding the definitions of these three terms: (1) hydraulic conductivity, (2) intrinsic permeability, and (3) transmissivity, will lead to a better understanding of permeability of fluids in porous media.

Hydraulic Conductivity (K)

A medium has a unit hydraulic conductivity if it takes a unit time for a unit volume of groundwater to be transmitted at a prevailing kinematic viscosity through a cross section of unit area under a unit hydraulic gradient. This parameter will have units of velocity (Todd and Mays, 2005).

$$K = -\frac{v}{{dh}/{dl}} = -\frac{{m}/{d}}{{m}/{m}} = m/day \tag{2.11}$$

Intrinsic Permeability (k)

This refers to the ability of rock or soil to transmit fluid. Intrinsic permeability is a property of the medium and is independent of the fluid properties (Lohman, 1972).

$$k = \frac{K\mu}{\rho g} = \frac{\mu v}{\rho g({dh}/{dl})} \tag{2.12}$$

In this equation, K is the hydraulic conductivity, ρ is the density of the fluid, μ is the dynamic viscosity, and g is the acceleration of gravity.

Transmissivity (T)

This can be defined as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1972; Todd and Mays, 2005).

$$T = Kb = \left({m}/{day}\right)(m) = {m^2}/{day} \tag{2.13}$$

In which K is the hydraulic conductivity and b is the saturated thickness of the aquifer.

2.9 Contaminant Transport Through Porous Media

Pollutants move through groundwater by: (1) advection, which is a result of the flow of groundwater, (2) dispersion, which is a result of mechanical mixing and molecular diffusion, and (3) retardation, which is caused by adsorption (Patil and Chore, 2014). The equations below represent these processes mathematically:

$$\frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial C}{\partial x_i}\right]-\frac{\partial}{\partial x_i}(CV_i)-\frac{C'W'}{n}=R\frac{\partial C}{\partial t} \tag{2.14}$$

$$V_i=\frac{-K_{ij}}{n}\frac{\partial h}{\partial x_i} \tag{2.15}$$

In these equations, D_{ij} is the dispersion coefficient, C is the contaminant concentration, V_i is the average pore water velocity in the x_i direction, n is the effective porosity, C' represents the solute concentration in the source, W' is the volume flow rater per unit volume of the source, R is the retardation factor, h is the hydraulic head, K_{ij} is the hydraulic conductivity, and x_i is the Cartesian coordinate.

Equation 2.15 is a more simplified two-dimensional version of this equation in a homogeneous, isotropic environment with an assumption of unidirectional steady state flow, which can be described as:

$$D_L\frac{\partial^2 C}{\partial x^2}+D_T\frac{\partial^2 C}{\partial y^2}-V\frac{\partial C}{\partial x}=R\frac{\partial C}{\partial t} \tag{2.16}$$

D_L and D_T are the longitudinal and transversal dispersion coefficient.

2.9.1 Advection

The term advection refers to the movement of dissolved solute in the groundwater flow at the seepage velocity in porous media. Advection and hydrodynamic dispersion are the physical properties that control the solute flux (Patil and Chore, 2014). Darcy's law governs the advection process. Using Darcy's law (explained in the previous section), the actual seepage velocity between point 1 and point 2 can be determined using the following equation:

$$V = \frac{Q}{nA} - \frac{K}{n}\frac{h_2 - h_1}{L} \tag{2.17}$$

2.9.2 Dispersion

Dispersion is caused by two processes: (1) molecular diffusion, and (2) mechanical mixing. When the contaminated groundwater reaches the non-contaminated groundwater, mechanical mixing occurs and will result in dilution of the contaminate. This is also known as dispersion.

Molecular diffusion refers to the movement ionic or molecular constituent from regions of higher concentrations to regions with lower concentration. Higher differences in the concentrations will result in higher diffusion rates. Molecular diffusion follows Fick's law and can be calculated as below:

$$F = -D_f \frac{dC}{dx} \tag{2.18}$$

In this equation, F is the mass flux per unit area per unit time, and D_f is the diffusion coefficient. When the law is applied to porous media, the diffusion coefficient will be smaller. An empirical coefficient known as 'w' is used to calculate the apparent diffusion coefficient in porous media (Freeze and Cherry, 1979).

$$D^* = w.D_f \tag{2.19}$$

Longitudinal D_L and transversal D_T mechanical mixing components of dispersion can be calculated using the following equations:

$$D_L = D^* + a_L.V \tag{2.20}$$

$$D_T = D^* + a_T.V \tag{2.21}$$

a_T and $a_L$are longitudinal and transversal dispersivity.

2.9.3 Sorption

Exchange of molecules and ions between solid phase and liquid phase is known as sorption, which includes adsorption and desorption. Adsorption refers to the attachment of ions and molecules from the liquid phase to the particles (solid phase), which will result in reducing the concentration of the pollutant. This is also called retardation. Conversely, desorption is the release of ions and molecules from the particles to the liquid phase (Patil and Chore, 2014). The retardation factor can be calculated using the following equation:

$$R = [1 + \frac{\rho_d K_d}{n}] \tag{2.22}$$

in which K_d is the adsorption coefficient and ρ_d and n are density and porosity of the porous media.

2.9.4 Filtration Mechanisms in Porous Media

The pollutant transport in porous media and the governing equations have been previously reviewed. In this section, different filtration mechanisms and applicability of mechanistic filtration theories to groundwater systems will be discussed.

Surface Filtration

When the pollutant particles are too large to penetrate into the porous media, the particles and aggregates will collect above the porous media. This is known as surface filtration, which results in forming a filter cake above the media. Due to limited hydrostatic pressures under the natural flow, these filter cakes can rapidly become impermeable which can affect the groundwater recharge and will require removal approaches to restore the site recharge capabilities (McDowell-Boyer et al., 1986).

Straining Filtration

Straining filtration is the main cause of removal of suspended particles in groundwater. The most important factor in determining straining in porous media is the ratio of the media diameter to the particle diameter (d_m/d_p). According to Sakthivadivel's (1969) results, for d_m/d_p less than 10 (larger particles compared to the media size), no penetration of particles into the media was observed that would cause cake filtration. Maximum straining occurred in a narrow window of 10 < d_m/d_p < 20, in which particles occupied more than 30% of the pour volume. Less straining was reported for d_m/d_p values greater than 20, which means the particles are relatively too small compared to the media.

Physical-Chemical Filtration

When particles are much smaller compared to the media size, such as bacteria and viruses, filtration will only occur if the attractive forces dominate when particles collide with media (McDowell-Boyer et al., 1986). The main aspects in describing the physical-chemical filtration are particle-media collision mechanisms, particle-media attachment mechanisms, removal kinetics for the media in clean conditions, and removal kinetics for a clogged media.

3. EXPERIMENTAL APPROACH

3.1 Introduction

The purpose of this chapter is to describe the characteristics of the urban watershed at the site of the UGF basins and describe the details of each UGF basin, the monitoring approach, and the data analysis methods. This section will specifically address the study area, experiment description, UGF basin design, instrumentation for water quantity determination, and water quality sampling procedures and locations. In situ measurements, laboratory testing procedures, and the water quantity data analysis will also be discussed in this section.

3.2 Project Site Description

The two UGF basins studied for this dissertation were part of the design for a new student housing complex located at 1051 Red Mile Road, Lexington, Kentucky. The two UGF basins were used to meet stormwater control requirements. The Lexington-Fayette Urban County Government (LFUCG) stormwater manual requires that stormwater BMPs and GISs be designed and constructed to reduce post development peak flow to pre-development condition. Two underground gravel filters basins were designed and constructed on the property: one on the south corner and another on the west corner of the property. The pre-development site conditions (existing conditions) consisted of an 88-unit mobile home park (Figure 7).

The post-development site is a 528-bed student housing facility with associated club house, pool, roads and parking areas (Figure 8). The UGF basins were located under the roadway and parking area. The hydrologic parameters for the pre- and post-development conditions that characterize the site for stormwater runoff computations are provided in Table 9.

The LFUCG stormwater manual regulation states that four storm events (10-year, 6-hour; 100-year, 6-hour; June 18, 1992; and June 26, 1995) are to be used for design. The pre- and post-condition parameters in Table 9, along with the design storm events were used in the HYDROFLO ™ software to ensure that the UGF basins are capable of controlling the discharged peak flow.

Table 9. Watershed Properties

Watershed	Area	Impervious	Curve Number	Time of Concentration
	(acres)	Percent	CN	T_c (min)
Pre-Development W-1	3.43	48%	83.4	6.0
Post-Development W-1	3.43	77%	91.5	5.0
Pre-Development W-2	2.30	56%	85.6	6.0
Post-Development W-2	2.30	74%	90.7	5.0

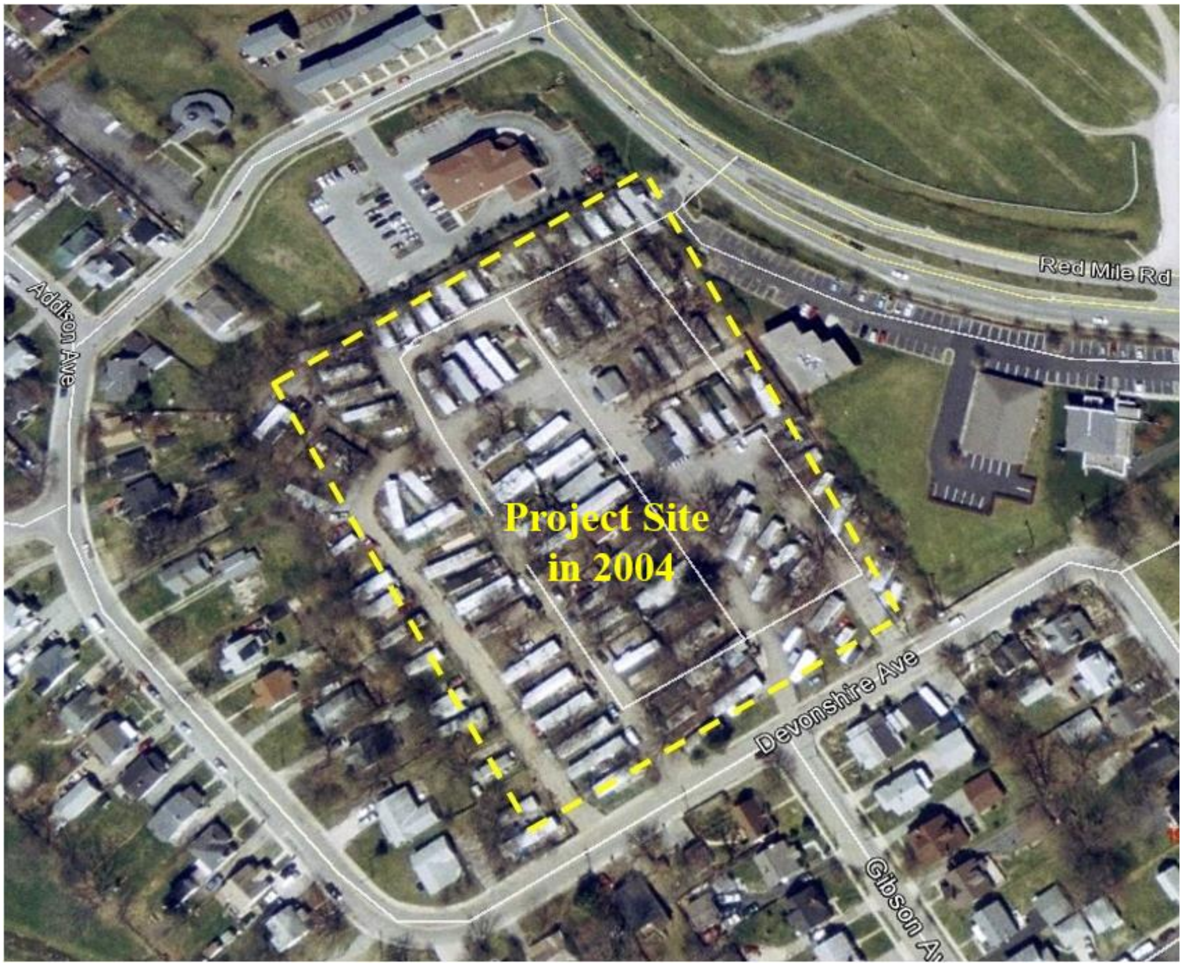


Figure 7. Pre-development conditions of the site (Image source: Google Earth, 2004).

Figure 8. Location of the site and UGF basin systems (Image source: Google Maps).

3.3 Description of Underground Gravel Filter Basins

Stone aggregate #2 (per the Kentucky Department of Transportation Classifications) was used as the filter medium to provide the required void space to meet the storage volume for detention. Previous studies had been done to determine the void ratio of gravel backfill. A 2012 tech sheet published by StormTech®, and studies by Kazemi (2014) and Abdollahian (2015) showed the void ratio for #2 stone aggregate ranges from 40% to 48% with an average of 44.1%. A void ratio of 46% had been used for the proposed underground detention in this study.

A minimum of 6 ounce non-woven geotextile (ASTM D 4632, 4491, & 4355) was used to wrap the gravel in order to protect and separate the stone aggregate from the underlying soils and to prevent contaminated fines from migrating from the basin into the soil and groundwater. The construction process of UGF basin #2 is shown in Figures 9 through 14.

The stormwater runoff is collected by surface inlets and delivered to the manhole structures (entrance manholes) associated with each UGF system through plastic pipes. As the water level rises in the entrance manholes, stormwater will reach the rectangular orifices that are designed to introduce the stormwater runoff to the gravel media. Wire baskets were installed on each of the orifices to prevent the gravel from migrating to the manhole or outlet structures (see Figure 11).

Figure 9. The basin has been excavated to the proper depth (954.5 ft. in UGF-1 and 955 ft. in UGF-2).


02.23.2011 15:15

Figure 10. A non-woven geotextile is being placed on the bottom and the walls of the basin.


03.10.2011 13:00

Figure 11. Stone aggregate # 2 was placed in the basin and storm structures (manholes and outlet structure).

Outlet Spillways

The outlet spillways with two eight-inch orifices and a weir opening are designed to control the discharged peak flow from the underground detention basin. The weir opening in the outlet spillway is designed to pass the 100-year, 24-hour storm to control discharge rates from the design events. For storm events larger than the 100-year, 24-

hour, the UGF basin will reach full capacity, and the storm structures (including inlets, manholes, and outlet structures) within the UGF basins will surcharge and flood into the parking lot and driving lanes.

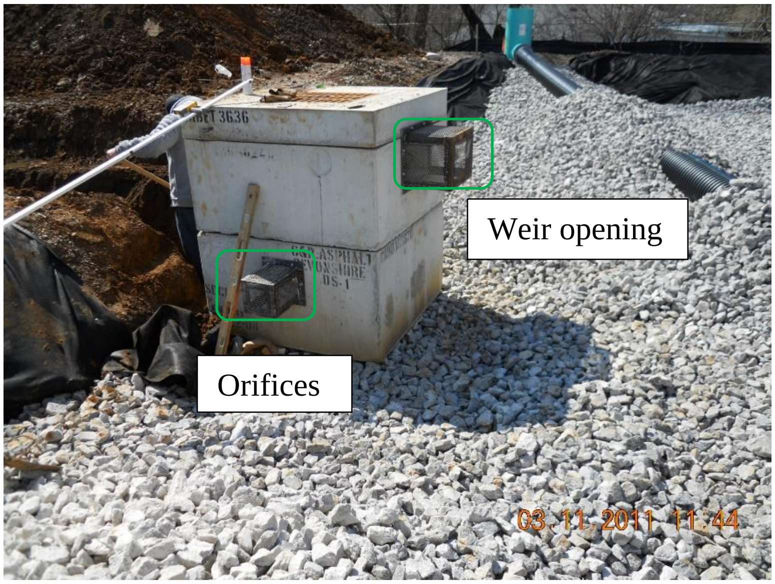


Figure 12. The outlet spillway with orifices in the lower part and the weir opening in the upper part of the structure.

Figure 13. The basin is covered with Dense Graded Aggregate (DGA) and ready for the asphalt layer to be placed.

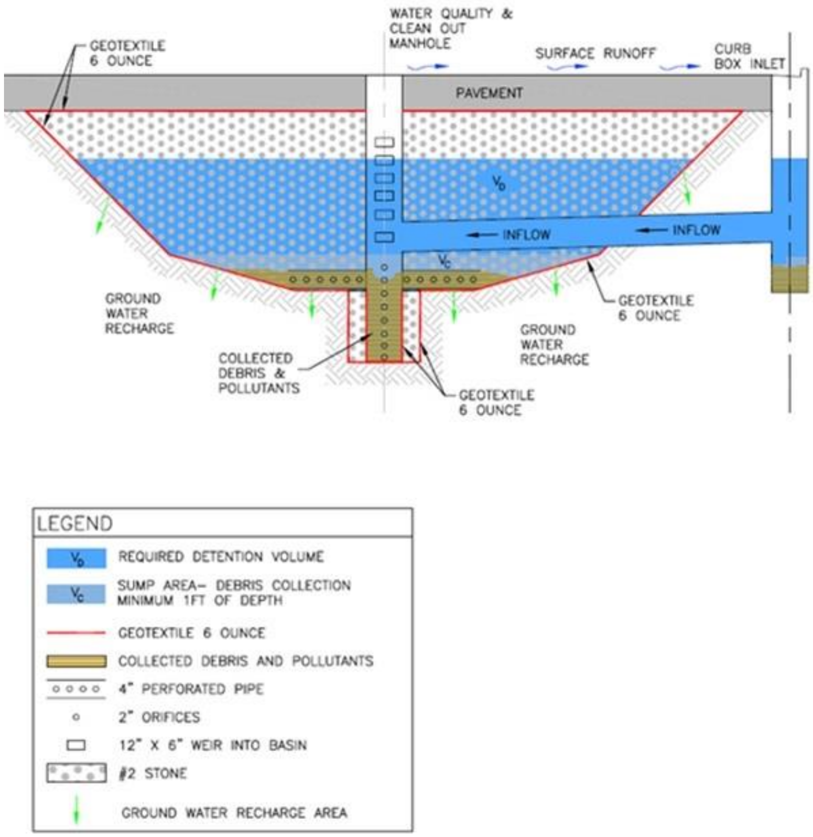


Figure 14. Schematic cross-section view of the UGF basin system.

The Sump Area (V_C) shown in Figure 14 is also referred to as the water quality volume. The water quality volume is the amount of water that can be retained by the UGF basins before discharging to the outlet structures. Infiltration into the underlying soil layers will be the main discharge mechanism for the water quality volume. This portion of the basin is designed to capture the first flush of rain events.

Table 10 presents the stage, area, and capacity for the UGF-1 and UGF-2 basins. This information was used in calculating the runoff volume captured by each basin at different stages and determining runoff volume reduction and infiltration rates.

Table 10. Stage, Area, and Void Area for Each UGF Basin System

UGF-1				UGF-2			
Stage (ft)	Elevation (ft)	Basin Area (ft^2)	Void Area (ft^2)	Stage (ft)	Elevation (ft)	Basin Area (ft^2)	Void Area (ft^2)
0.0	954.5	2,899	1,334	0.0	955.0	1,271	585
1.0	955.5	5,361	2,466	1.0	956.0	5,159	2,373
2.0	956.5	6,200	2,852	1.5	956.5	5,513	2,536
3.0	957.5	7,077	3,255	2.5	957.5	6,245	2,873
4.0	958.5	7,999	3,679	3.5	958.5	7,008	3,224
5.0	959.5	8,968	4,125	4.0	959.0	7,401	3,405

3.4 Geologic Information of the Project Site

According to the USDA Soil Resource Report for the Fayette County area in Kentucky, the project site is underlain with Bluegrass-Maury silt loams (uBlmB), and Maury-Bluegrass silt loams (uMlmC). The Bluegrass-Maury silt loams (uBlmB) have slopes from 2 to 6%, the depth of restrictive feature is more than 80 inches, well drained, and the depth to water table is more than 80 inches. The Maury-Bluegrass silt loams (uMlmC) have slopes from 6 to 12%, the depth of restrictive feature is more than 80 inches, well drained, and the depth to water table is more than 80 inches.

Bedrock was not encountered during the construction of the UGF basins. However, a review of the geologic map of the Lexington West quadrangle, Fayette and Scott Counties, Kentucky – 1967 shown in Figure 15, indicates that the project site is underlain by Grier limestone member and Brannon limestone member.

The Grier limestone member consists of light to dark gray limestone with irregular medium to coarse grained limestone nodules with shale partings separating some of the beds. The Brannon limestone member consists of limestone and shale. The limestone is light gray to light brownish gray with thin beds of dark gray shale.

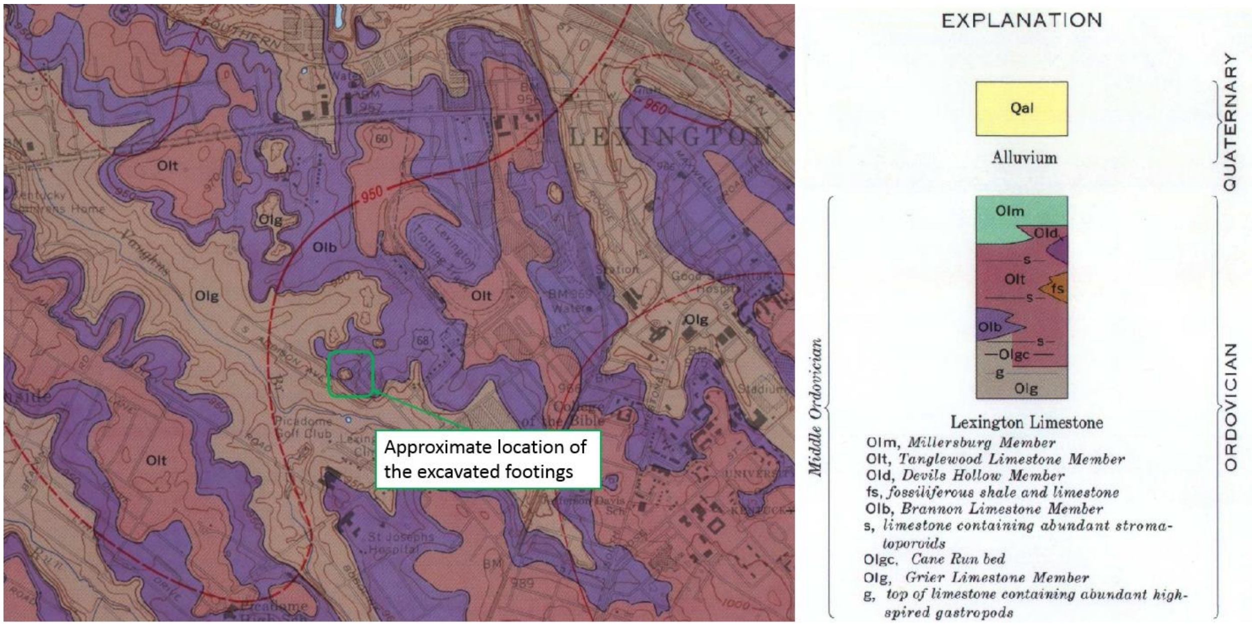


Figure 15. Geologic map of the Lexington West quadrangle, Fayette and Scott Counties, Kentucky – 1967.

3.5 Water Quantity and Instrumentation

Instruments including pressure transducers, barologgers, and rain gauges were installed in the basins to quantify flow into and out of the UGF basins and the volume of water stored in the UGF basins. This section is dedicated to describing these instruments.

3.5.1 Pressure Transducers and Barologgers

Pressure transducers (specifically, the 3001 LT Levelogger Junior Edge, M10/F30) are used to measure the water level at one-minute intervals within each UGF basin (in the entrance manholes) and at the outlet structures. The outlet structures include a headwall in UGF basin #1 and an outlet manhole (MH-4) in UGF basin #2. The Levelogger Edge measures absolute pressure (water pressure plus atmospheric pressure) expressed in feet. The depth of water over the logger is obtained by subtracting the atmospheric pressure measured in feet from the absolute pressure measured by the Levelogger in feet. The elevation of the water surface was then computed by adding the sensor elevation. These Leveloggers were also capable of recording the temperature values during storm events at one-minute intervals. The Levelogger and the Barologger used in this study are shown in Figures 16 and 17.

Figure 16. 3001 LT Levelogger Junior Edge, M10/F30 (image from www.solinst.com).

Figure 17. 3001 LT Barologger Edge, M 1.5/F5 (image from www.solinst.com).

A total of five (5) Leveloggers and one (1) Barologger have been used in this study. Three (3) Leveloggers were installed in UGF basin #1, one in each storm structure, including MH-1, MH-2, and the headwall, which is located at the outlet of the basin (see Figure 18). Two (2) Leveloggers were used in UGF basin #2, one Levelogger in MH-3 and one at MH-4 which is directly connected to the outlet spillway (see Figure 19).

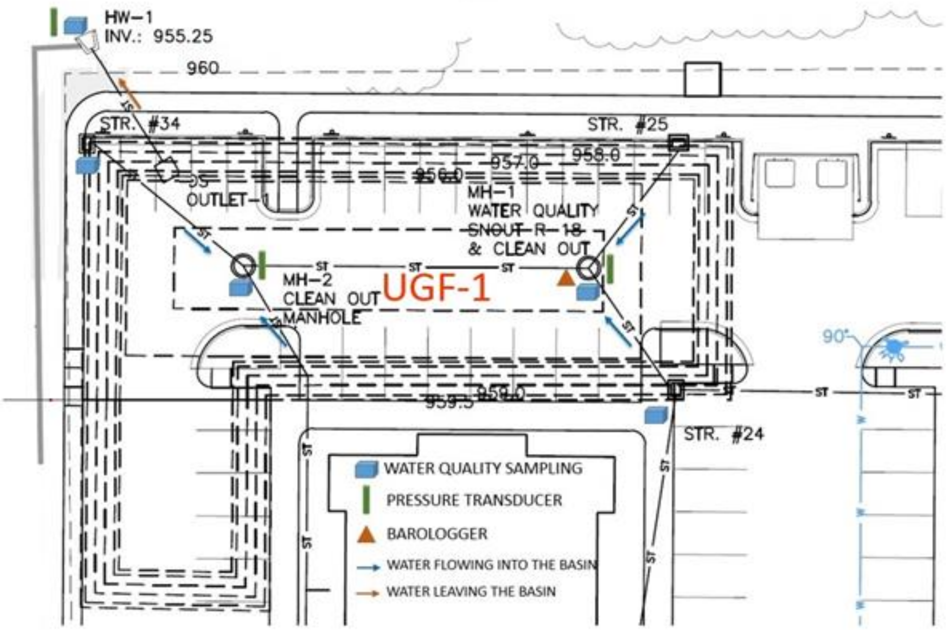


Figure 18. The locations of water quality sampling and water quantity instrumentation in UGF-1.

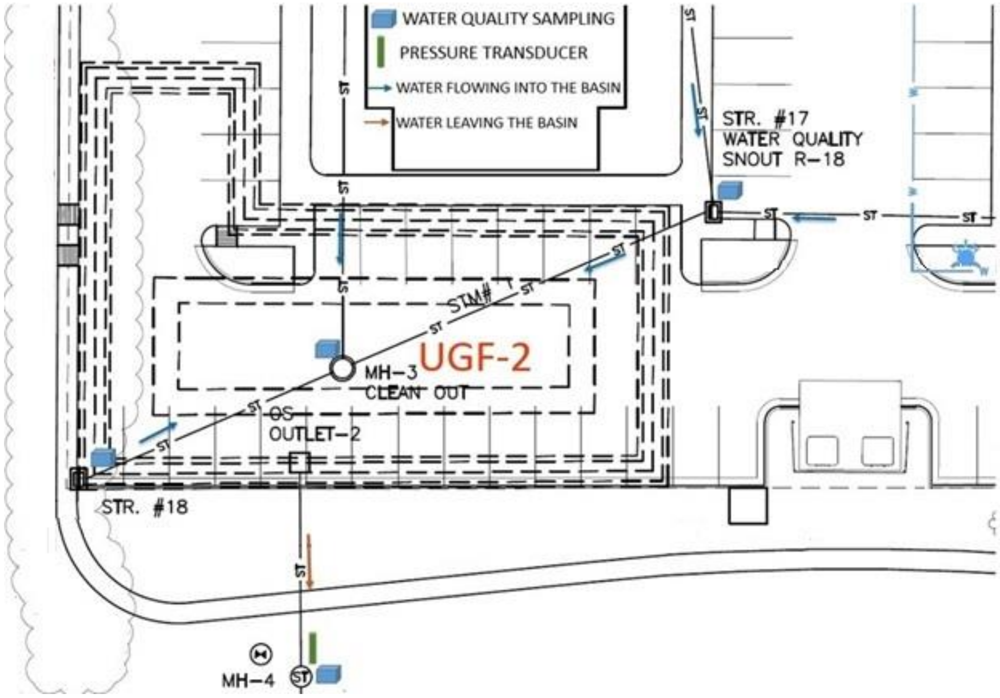


Figure 19. The locations of water quality sampling and water quantity instrumentation in UGF-2.

Weirs were installed on the headwall at the outlet of UGF basin #1 and in MH-4 in UGF basin #2 and the Leveloggers were placed on the upstream side of the weirs. The discharge was calculated using the weir equation (see equation 3.1 and Figures 20 and 21).

$$Q = CLH^{3/2} \tag{3.1}$$

In this equation, Q is discharge in cubic feet per second, C is the weir coefficient, L is the weir length in feet, and H is the head in feet. The head refers to the level of water over the weirs installed on the headwall in UGF basin #1 and in MH-4 in UGF basin #2. H was calculated by subtracting the height of the weirs from readings provided by the Leveloggers. Values of C for a sharp crested weir could be calculated using equation 3.2.

$$C = 3.27 + 0.4(\frac{H}{W}) \tag{3.2}$$

In equation 3.2, H is head in feet, and W is the height of the weir in feet.

Figure 20. The weir installed in front of the headwall in UGF-1.

Figure 21. The weir installed in MH-4 in UGF-2.

3.5.2 Rain gauges

Two Rainwise data loggers supplied with a polypropylene rain collector (tipping bucket) were installed within the site vicinity. The tipping bucket rain gauge was calibrated to 0.01 inches/0.2 mm per tip. The rain gauges were installed approximately 1500 feet apart: one rain gauge on-site and one off-site. The purpose of using two rain gauges was to confirm the accuracy of the rain data, identify any possible structure interference, and to have a backup in case there were a malfunction in one of the rain gauges. Figure 22 shows the rain gauge setup used in this study.

Figure 22. Rainwise tipping bucket and the data logger (image from www.rainwise.com).

3.5.3 Infiltration Rates

Infiltration is the most effective means of controlling stormwater runoff. Infiltration will reduce the volume of runoff that is discharged to receiving waters and will mitigate the associated water quality and quantity impacts that the stormwater runoff can cause to the receiving water.

Infiltration rates were computed using equation 3.3.

$$Infiltration\ Rate\ ({}^{in}/_{hr}) = \frac{V_{inf} \times 12}{(t_{inf})(A_{inf})} \tag{3.3}$$

In the above equation, V_{inf} is the volume of the stormwater runoff infiltrated into the underlying soils in cubic feet, t_{inf} is the duration of infiltration in hours, and $A_{\text{inf}}$is the area of each basin over which infiltration is occurring in square feet.

3.6 Water Quality

3.6.1 Sampling Locations and Procedures

The most common method to assess the water quality performance of the GISs is based on collecting samples from the runoff at specific inflow and outflow points and comparing the pollutant concentration levels (Quigley, 2009). Grab samples were collected from the stormwater runoff at the inflow of the inlet structures, the stormwater in the entrance manholes, and from the outlet structures to achieve this goal.

Two MB470 Mechanical Bladder Pumps were used to collect grab samples from the entrance manholes (see Figure 23). This pump is specifically designed for collecting high-quality and low-turbidity samples from groundwater monitoring wells. Grab samples were also collected from the inlet and outlet structures of the UGF basins. These samples were collected at approximately six- to eight-minute intervals during the first flush of the storm event. The grab samples were mixed to create a composite sample representing the first flush period of each event. The locations of water quality sampling and water quantity instrumentation at each UGF basin are shown in Figures 18 and 19.

Runoff from the first half-inch of the storm event was considered to be representative of the first flush. Several more complex methods have been used to define the first flush phenomenon. Regulatory agencies have simplified design requirements to ensure treatment of the first 0.5 inches of rainfall runoff to capture the high loads and concentrations of contaminants that may be transported as a result of the first flush phenomenon.

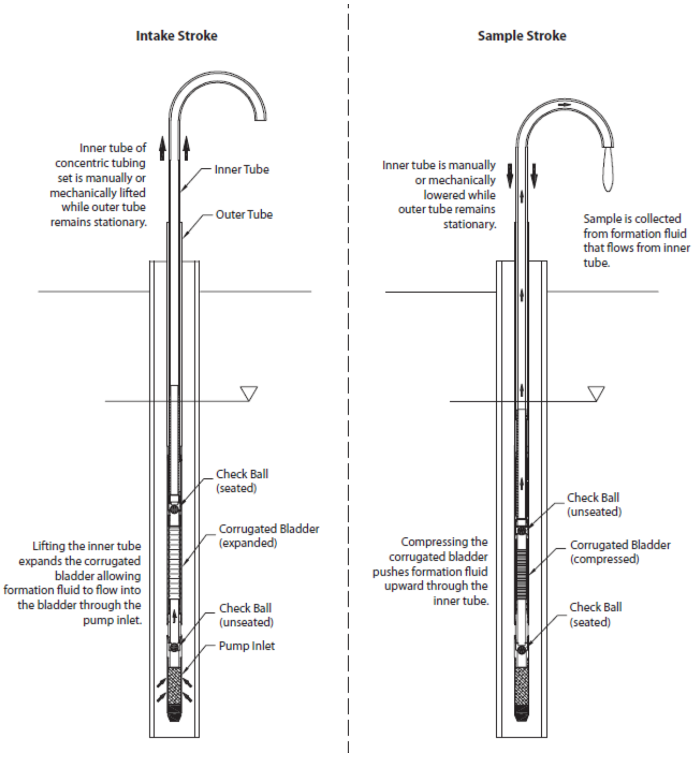


Figure 23. Intake and sample stroke of the MB470 Mechanical Bladder Pump (image from http://geoprobe.com).

3.6.2 In Situ Measurements (pH, Temperature, Conductivity, and TDS)

The in situ parameters, including pH, temperature, conductivity, and Total Dissolved Solids (TDS), were measured on the project site immediately after sampling. These parameters were measured using an Oakton® 450 model waterproof handheld meter (Oakton Instruments, Vernon Hills, Illinois, USA). The probes of this instrument were calibrated before each event. Oakton pH 4, 7, and 10 buffer solutions and the Oakton conductivity solution 1413 µS were used for calibration.

3.6.3 Sample Preservation

TSS and *E. coli* samples were collected in polyethylene and polystyrene sampling bottles. The polystyrene bottles used for *E. coli* contained a chlorine-neutralizing agent. Neutralizing any chlorine is necessary to obtain a valid coliform test. The agent does not interfere with the coliform analysis even if chlorine is not present. The samples were placed on ice in a cooler and were immediately delivered to a laboratory (Microbac®, Lexington, Kentucky, USA). Figure 24 shows the sampling bottles used in this study. Based on U.S. EPA recommendations, the maximum holding times, proper sample containers, and appropriate preservation methods for the parameters in this study are summarized in Table 11.

Table 11. Preservation Protocols for the Investigated Parameters (Law et al., 2008)

Contaminant	Cool down to 4 °C	Minimum Volume (ml)	Holding Time	Container
Conductivity	Required	100	Immediately	Plastic or glass
pH	Not Required	25	Immediately	Plastic or glass
TDS	Required	100	Immediately	Plastic or glass
Temperature	Not Required	1000	Immediately	Plastic or glass
E. coli	Required	100	6 Hours	Plastic
TSS	Required	200	7 Days	Plastic or glass

Figure 24. (left) *E. coli* bottle (120 ml) with chlorine-neutralizing agent, (right) TSS bottle (250 ml).

3.6.4 Total Suspended Solids (TSS) Measurements

The USGS I-3765-85 method (solids, residue at 105 °C, suspended, gravimetric) was used to evaluate the TSS concentrations. This method can be used on any natural, treated, or industrial water samples.

According to USGS, an appropriate volume of the unfiltered sample should be mixed thoroughly and rapidly poured into a graduated cylinder. The suspended solids were collected on a glass-fiber filter, and the insoluble residue was dried at 105 °C and weighed (Fishman and Friedman, 1989). The TSS was computed from the mass of the dried residue.

$$TSS\ \left({}^{mg}/_{L}\right) = \frac{1000}{mL\ sample} \times mg\ dried\ residue \qquad (3.4)$$

3.6.5 **E. coli** *Measurements*

The *E. coli* concentrations were measured using the SM9223B (Colilert -18). The Colilert-18 test is based on Defined Substrate Technology® (DST). Nutrient indicators that produce color/fluorescence when metabolized with *E. coli* and coliforms are used in this method. When *E. coli* metabolize the nutrient indicator (MUG), the sample fluoresces. When total coliforms metabolize ONPG, the sample changes color to yellow.

Colilert-18 is approved by the U.S. Environmental Protection Agency (U.S. EPA, 2007). This method can simultaneously detect these bacteria at 1 cfu/100 ml after an 18-hour period of incubation at 35 °C ± 0.5 °C when as many as two million heterotrophic bacteria per 100 ml are present (see Figure 25).

Figure 25. Yellow wells are total coliforms, and yellow/fluorescent wells are *E. coli* (image from https://www.idexx.com).

Table 12 summarizes the parameters, methods and equipment, and the frequency of sampling or measurements for each water quality parameter.

Table 12. Summary of Parameter, Methods, and Frequency of Sampling or Measurements

Parameter	Method	Frequency of Sampling/Measurements
TSS	USGS I-3765-85 (solids, residue at 105 °C, suspended, gravimetric)	6-8 minutes (sampling)
E. coli	Method SM9223B (Colilert -18)	6-8 minutes (sampling)
Temperature	Oakton® 450 model waterproof handheld meter	6-8 minutes (sampling)
pH	Oakton® 450 model waterproof handheld meter	6-8 minutes (sampling)
Conductivity	Oakton® 450 model waterproof handheld meter	6-8 minutes (sampling)
Dissolved Solids	Oakton® 450 model waterproof handheld meter	6-8 minutes (sampling)
Precipitation	Rainwise® data logger	1-minute intervals (Measurements)
Water Levels	3001 LT Levelogger Edge, M10/F30	1-minute intervals (Measurements)

4. WATER QUANTITY AND QUALITY PERFORMANCES OF THE UGF BASINS

4.1 Introduction

The water quality data in this section consist of the (1) precipitation data and water level in the UGF basins, (2) the infiltration rates, (3) on-site measurements of pH, conductivity, and dissolved solids, (4) temperature variations, and (5) TSS and *E. coli* concentrations.

4.2 Data Analysis

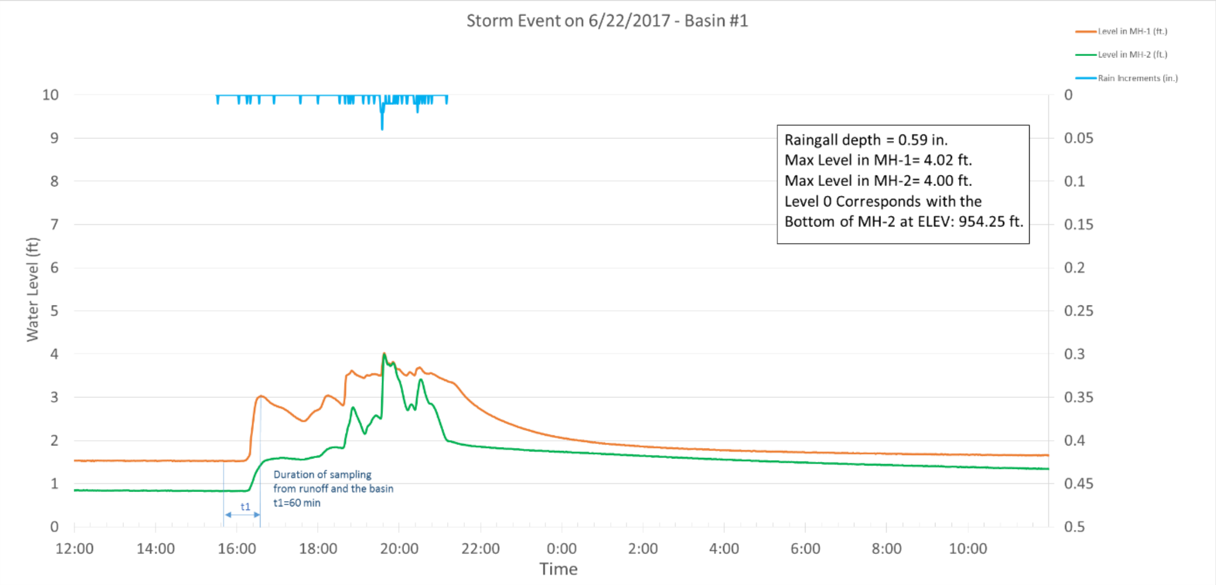
4.2.1 Analysis of Precipitation and Water Level in UGF Basins

Table 13 summarizes the precipitation data for the 14 rainfall events that were studied between June 22 and December 22 of 2017. The first eight rainfall events were analyzed for both water quality and infiltration performances of the basins. Only infiltration rates and runoff volume reductions were analyzed in the last six events. The antecedent dry period is defined as the number of hours since a previous rainfall event of at least 0.10 inches.

Table 13. Summary of the Precipitation Data for Sampled Rainfall Events

Event#	Date	Beginning time	Duration of the Event (hrs)	Antecedent Dry Period (hrs)	Time of Sampling from Runoff and Entrance Manholes	Time of Sampling from the Outlet	Rainfall Depth
1	6/22/2017	15:30	5.64	37.0	15:30 - 16:30	-	0.59
2	7/23/2017	3:20	7.82	363.0	11:00 - 11:45	12:00 - 12:45	0.63
3	7/28/2017	11:10	3.30	11.0	13:30 - 14:00	14:00 - 14:30	0.64
4	8/4/2017	7:30	1.03	38.5	7:30 - 8:30	-	0.11
5	8/14/2017	7:50	3.27	171.0	8:30 - 9:30	9:30 - 10:15	0.37
6	8/22/2017	13:00	6.08	83.0	13:00 - 13:20	13:45 - 14:05	1.25
7	8/28/2017	10:40	3.35	138.0	10:40 - 11:20	11:30 - 12:00	1.16
8	9/19/2017	10:00	4.08	50.5	13:00-13:30	13:30-14:00	0.76
9	10/8/2017	1:40	27.50	441.5	-	-	4.51
10	10/23/2017	7:15	15.50	295.5	-	-	0.95
11	11/7/2017	2:50	7.65	18.0	-	-	0.66
12	11/18/2017	4:10	18.50	59.0	-	-	0.57
13	12/5/2017	5:20	6.35	111.0	-	-	0.68
14	12/22/2017	17:00	21.04	120.0	-	-	1.79

Figures 26 to 41 present the data collected by the Leveloggers, the precipitation data (rain increments), and the sampling times from the runoff and the outflow for the eight rainfall events that were sampled for water quality.


Storm Event on 6/22/2017 - Basin #1

Raingall depth = 0.59 in.
Max Level in MH-1= 4.02 ft.
Max Level in MH-2= 4.00 ft.
Level 0 Corresponds with the
Bottom of MH-2 at ELEV: 954.25 ft.

Duration of sampling
from runoff and the basin
t1=60 min

Figure 26. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (06/22/2017 rain event).

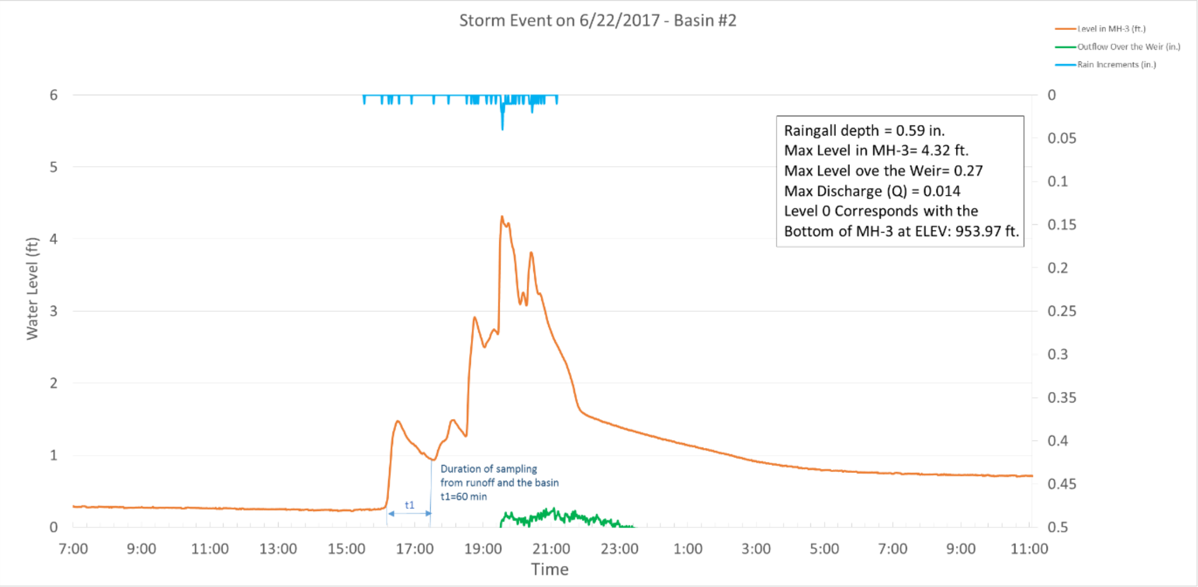


Figure 27. Data collected by the Leveloggers and the rain gauge in UGF basin #2 (06/22/2017 rain event).

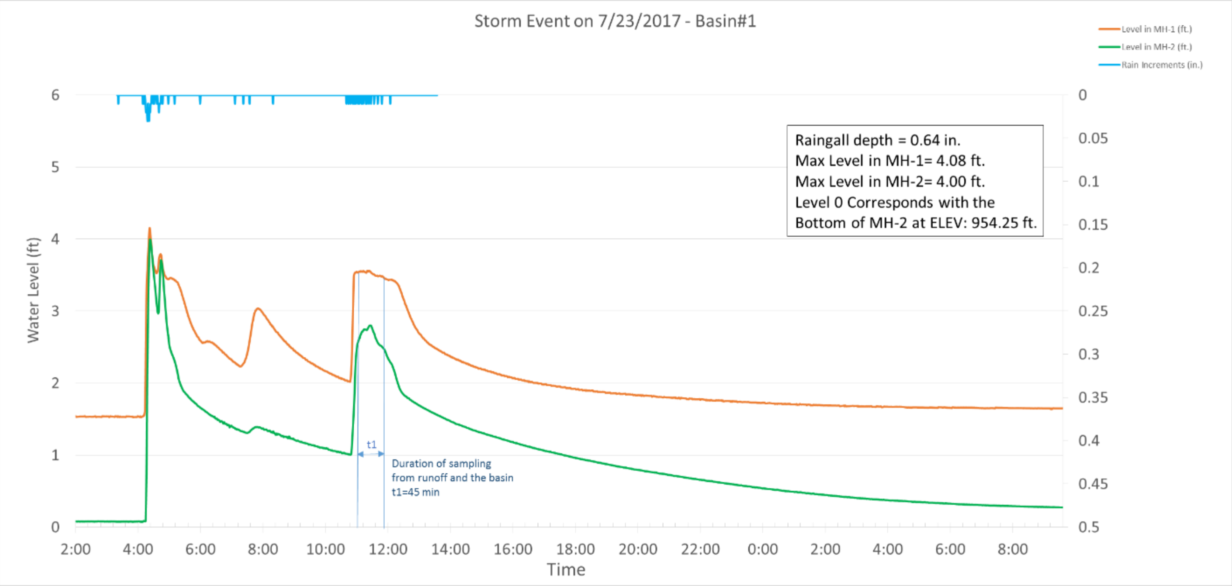


Figure 28. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (07/23/2017 rain event).

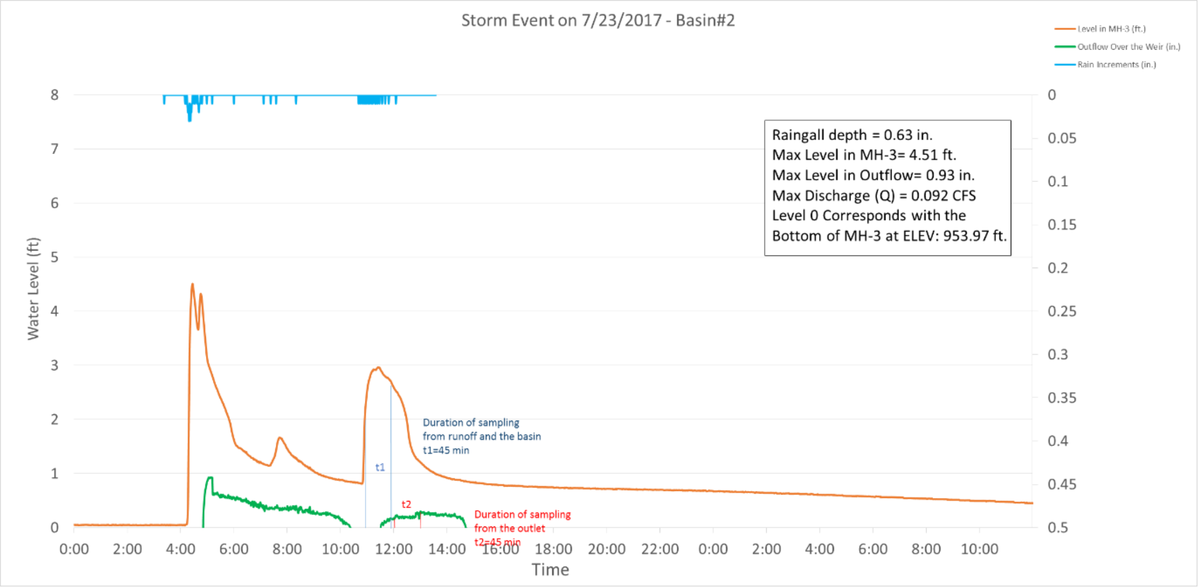


Figure 29. Data collected by the Leveloggers and the rain gauge in UGF basin #2 (07/23/2017 rain event).

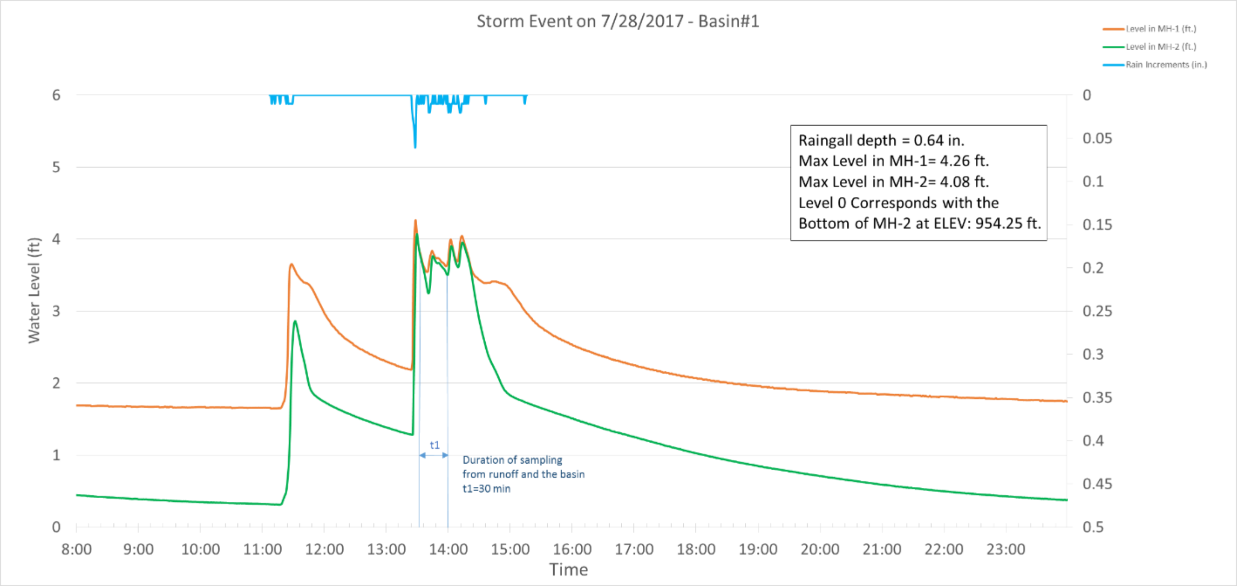


Figure 30. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (07/28/2017 rain event).

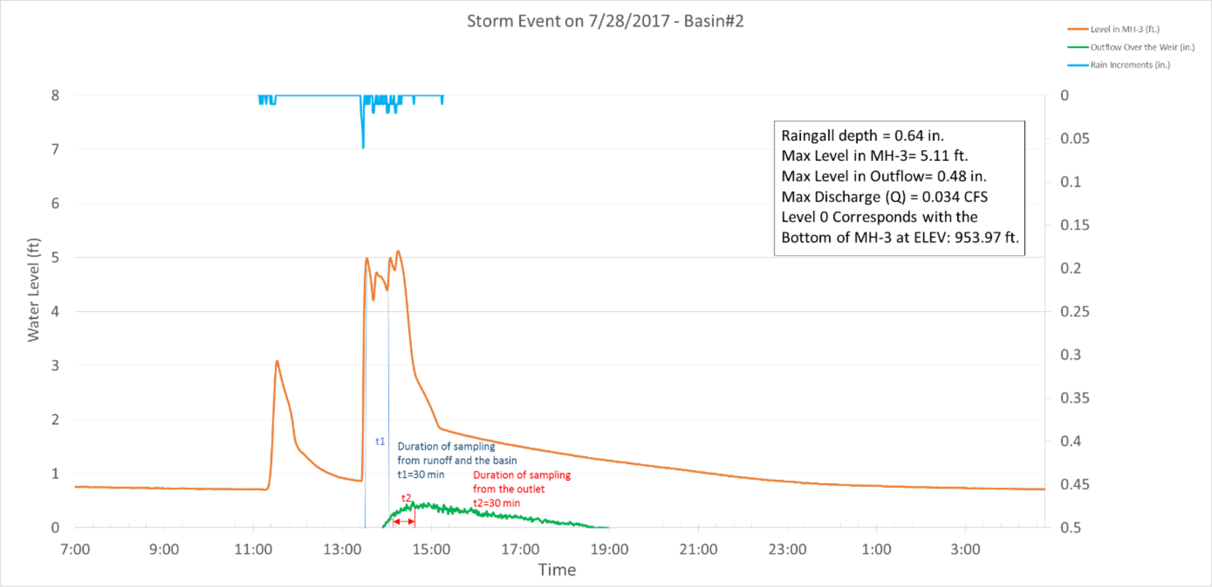


Figure 31. Data collected by the Leveloggers and the rain gauge in UGF basin #2 (07/28/2017 rain event).

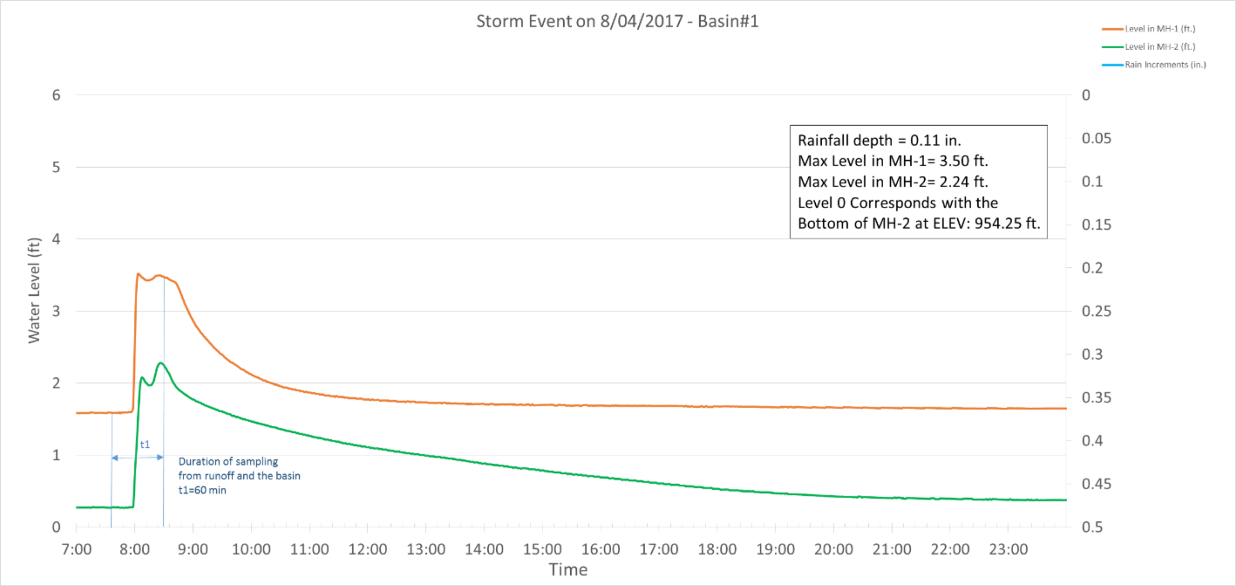


Figure 32. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (08/04/2017 rain event).

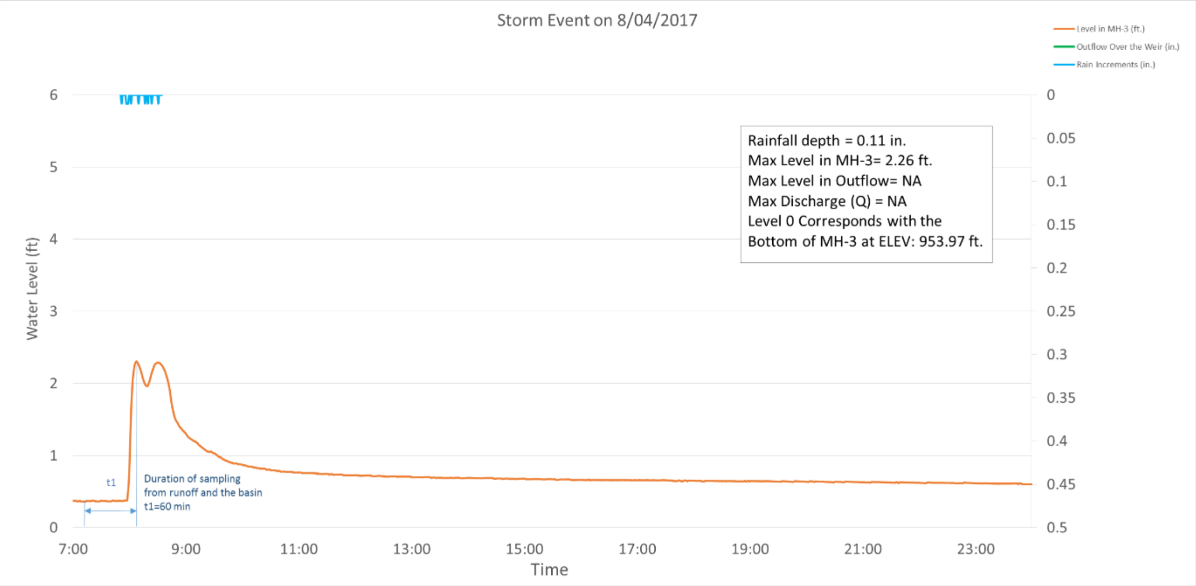


Figure 33. Data collected by the Leveloggers and the rain gauge in UGF basin #2 (08/04/2017 rain event).

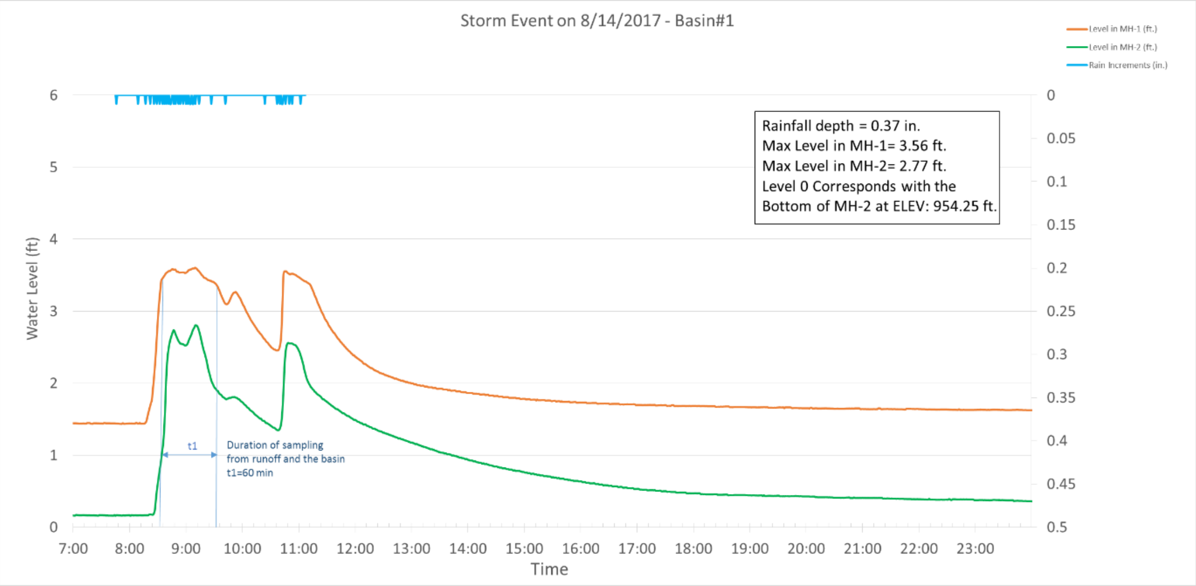


Figure 34. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (08/14/2017 rain event).

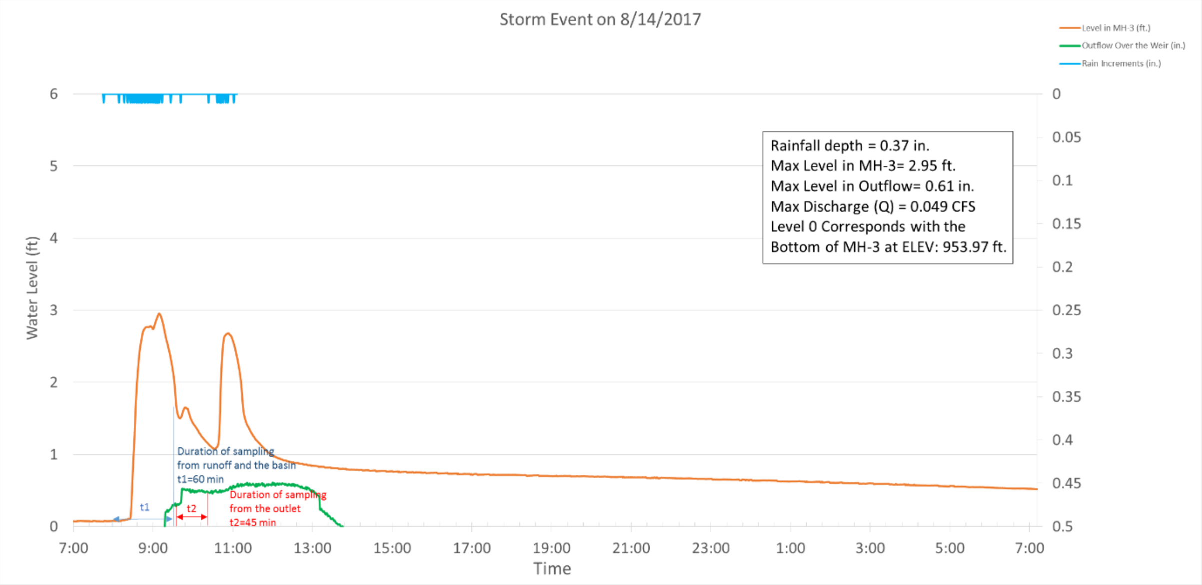


Figure 35. Data collected by the Leveloggers and the rain gauge in UGF basin #2 (08/14/2017 rain event).

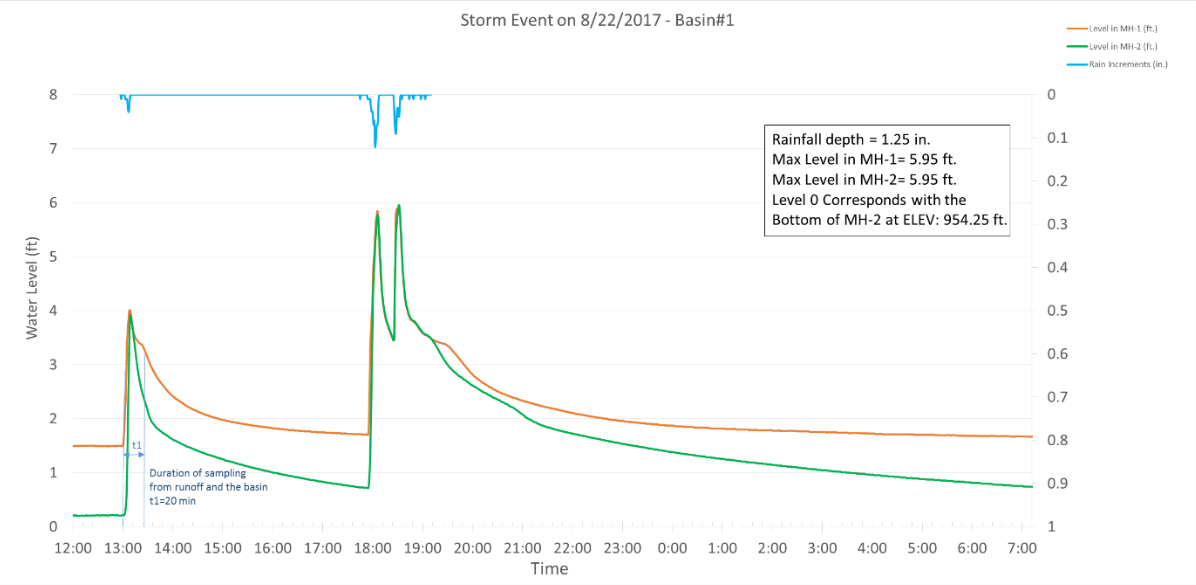


Figure 36. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (08/22/2017 rain event).

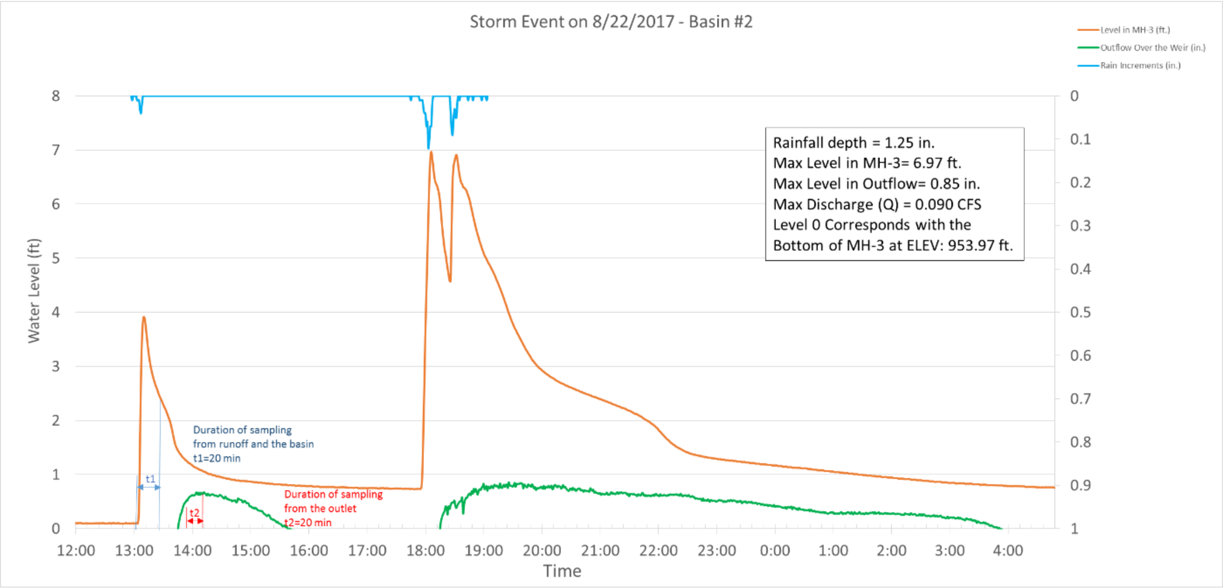


Figure 37. Data collected by the Leveloggers and the rain gauge in UGF basin #2 (08/22/2017 rain event).

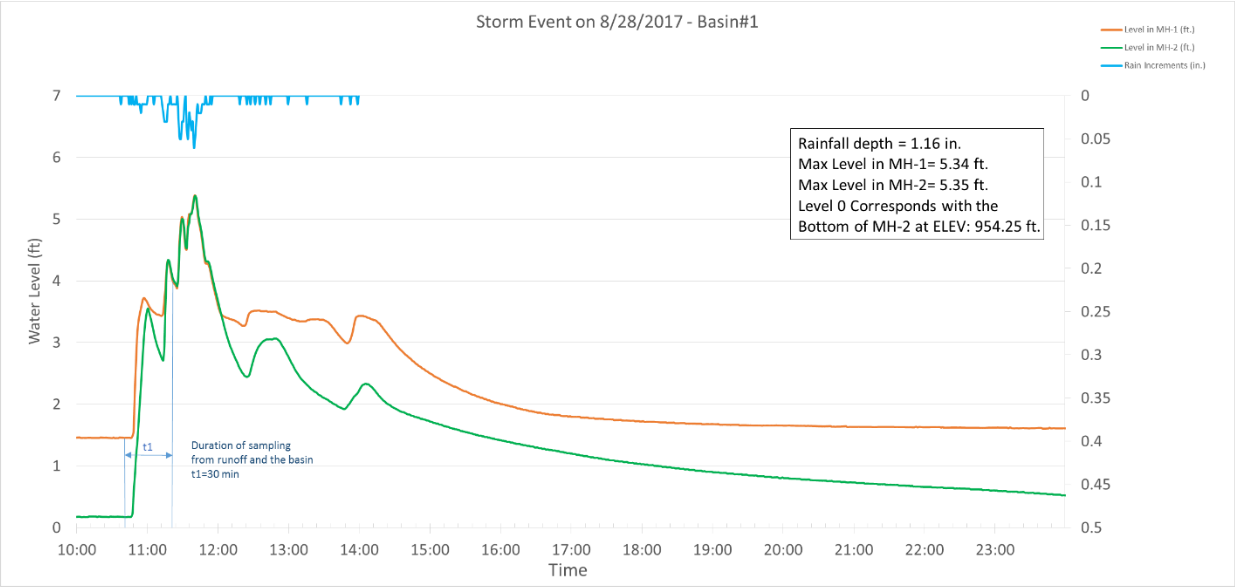


Figure 38. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (08/28/2017 rain event).

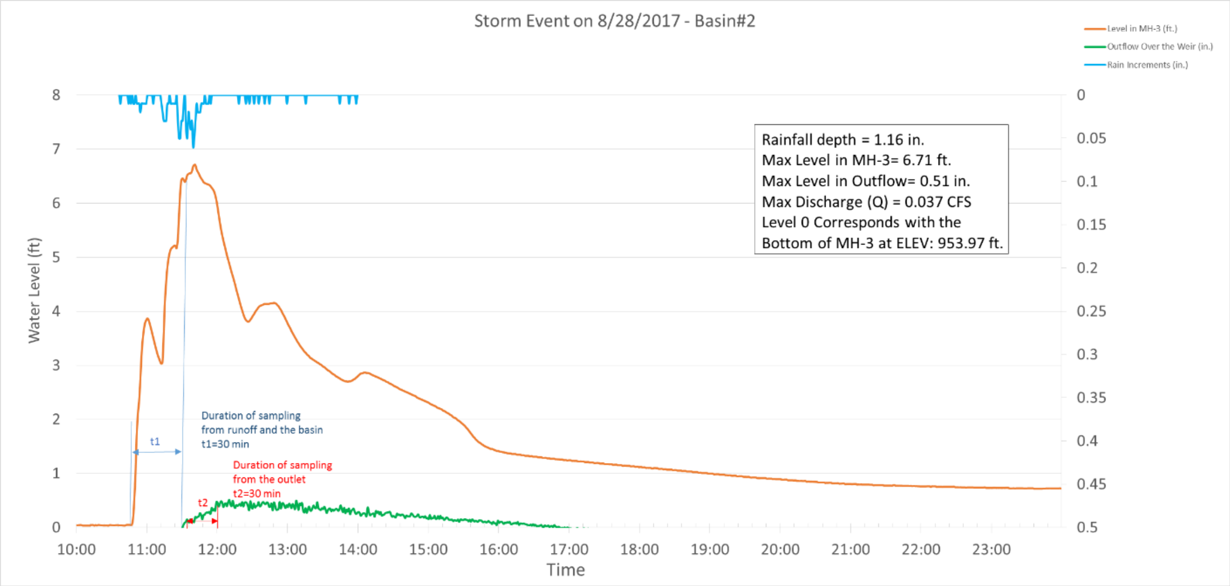


Figure 39. Data collected by Leveloggers and the rain gauge in UGF basin #2 (08/28/2017 rain event).

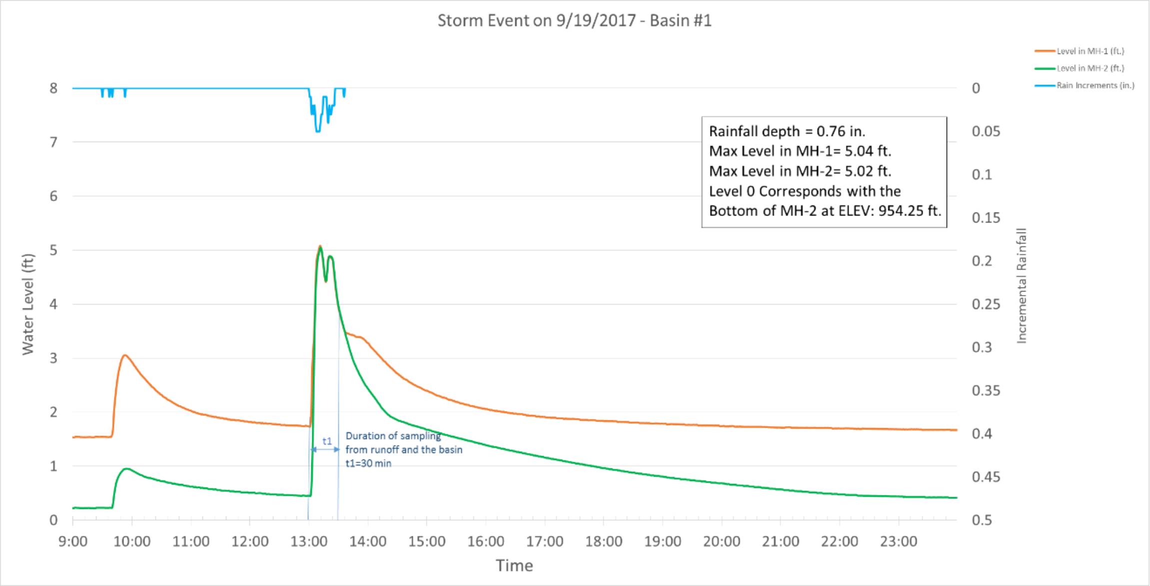


Figure 40. Data collected by the Leveloggers and the rain gauge in UGF basin #1 (09/19/2017 rain event).

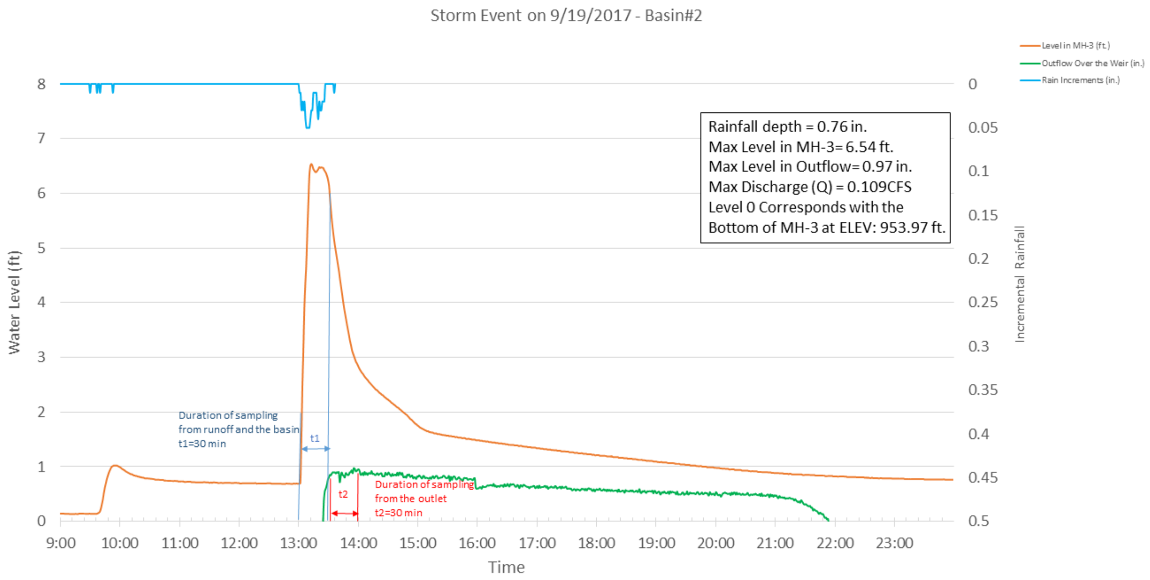


Figure 41. Data collected by the Leveloggers and the rain gauge in UGF basin #2 (09/19/2017 rain event).

As can be seen in Figures 26, 28, 30, 32, 34, 36, 38, and 40, these events did not produce an outflow in UGF basin #1. However, according to Figures 27, 29, 31, 33, 35, 37, 39, and 41, an outflow was observed in UGF basin #2 during these events, and the stage of runoff over the weir is displayed with the green line in Figures 27, 29, 31, 33, 35, 37, 39, and 41. It should be noted that level of runoff in the basins is presented in feet, where the outlet stage is presented in inches.

During the sampling period, an outflow occurred in seven out of the eight rainfall events (all except for event #4) that were sampled for water quality in basin #2. However, no outflow was observed in any of these rainfall events in basin #1.

The maximum level in the outflow (head over the weir) and the maximum discharge values for basin #2 are also shown in the figures above. The results showed that the maximum discharge values were not significant, ranging between 0.014 CFS in event #1 and 0.109 in event #9.

4.2.2 Infiltration Rates

The infiltrated volume and the infiltration rates of the underlying soils for each UGF Basin were calculated for each of the 14 storm events (Table 14).

Two different infiltration areas were used to compute estimated maximum and minimum rates for each event. The area at the bottom of each basin provides a maximum infiltration rate. The area at the water quality elevation provides an estimated minimum infiltration rate.

Table 14. Infiltration Ranges for UGF Basins 1 & 2

Event	Infiltration	Infiltration Rates for Basin #1		Infiltration Rates for Basin #2	
#	period (hr.)	Max (in/hr.)	Min (in/hr.)	Max (in/hr.)	Min (in/hr.)
1	8.40	1.95	1.02	2.55	0.63
2	11.50	1.91	1.00	2.11	0.52
3	8.75	2.72	1.42	2.70	0.67
4	4.50	0.74	0.39	0.94	0.23
5	6.25	2.18	1.14	1.86	0.46
6	16.00	3.01	1.57	3.18	0.78
7	7.25	5.41	2.83	6.33	1.56
8	10.00	2.91	1.52	2.23	0.55
9	41.00	4.19	2.19	4.51	1.11
10	13.00	2.85	1.49	2.16	0.53
11	13.50	1.65	0.86	1.12	0.27
12	11.00	2.02	1.05	1.73	0.43
13	10.50	2.52	1.32	1.35	0.33
14	26.00	2.69	1.41	2.24	0.55
Average		***2.62***	***1.37***	***2.50***	***0.62***

According to the USDA soil resource report for Fayette County, Kentucky, the basins are underlain with Bluegrass-Maury silt loams. The Hydrologic Soil Group for Bluegrass-Maury silt loams is “B,” and the range for the infiltration rates for this Hydrologic Soil Group is reported to be between 1.42 (in./hr.) and 5.67 (in/hr.). The range of estimated values agrees well with the range of reported values except for some of the minimum infiltration rates in UGF basin #2, which were below the lowest values reported by the USDA for these soils (Table 15).

The runoff volumes, outflow volumes, and volume of the runoff infiltrated in each basin are presented in Tables 15 and 16. There was no outflow reported in UGF basin #1 except for during event #9, where a relatively small amount of runoff (approximately 2%) had left the basin. All of the runoff flowing into the basin is assumed to have infiltrated into the underlying soils. The infiltration volume in UGF basins is determined by subtracting the outflow volume from the volume of runoff flowing into the basin.

Table 15. Runoff and Infiltrated Volume for UGF Basin #1

Event #	Runoff Volume (ft^3)	Outflow Volume (ft^3)	Infiltrated Volume (ft^3)	% Infiltrated
1	5590	0	5590	100
2	5969	0	5969	100
3	6064	0	6064	100
4	1042	0	1042	100
5	3506	0	3506	100
6	11843	0	11843	100
7	9853	0	9853	100
8	7200	0	7200	100
9	42729	751	41978	98
10	9001	0	8991	100
11	6064	0	6053	100
12	5400	0	5388	100
13	6443	0	6430	100
14	16959	0	16945	100
Total	***137662***	***0***	***136842***	***99***

Table 16. Runoff and Infiltrated Volume for UGF Basin #2

Event #	Runoff Volume (ft3)	Outflow Volume (ft3)	Infiltrated Volume (ft3)	% Infiltrated
1	3645.2	66	3579	98
2	3892.3	724	3168	81
3	3954.1	226	3728	94
4	679.6	0	680	100
5	2286.0	592	1694	74
6	7722.8	1635	6088	79
7	7166.8	283	6884	96
8	4695.5	1727	2969	63
9	27864.0	6595	21269	76
10	5869.3	2218	3651	62
11	4077.7	2154	1924	47
12	3521.6	1022	2500	71
13	4201.2	2179	2022	48
14	11059.1	4037	7022	63
Total	***90635***	***23456***	***67179***	***74***

4.2.3 On-site Measurements

On-site measurements for the first eight events in UGF basin #1 and UGF basin #2 are presented in Tables 17 and 18. These measurements include pH, temperature, dissolved solids, and specific conductivity.

Table 17. On-site Water Quality Measurements for UGF Basin #1

Event#	Date	pH			Temperature (F)			Conductivity (uS)			Dissolved Solids (ppm)		
		Runoff	Entrance Manholes	Outlet	Runoff	Entrance Manholes	Outlet	Runoff	Entrance Manholes	Outlet	Runoff	Entrance Manholes	Outlet
1	6/22/2017	7.25	7.5	-	77	74.4	-	138	120	-	77	67.5	-
2	7/23/2017	7.64	7.66	-	76	76.6	-	75.2	80	-	43	45.8	-
3	7/28/2017	7.76	7.74	-	86.2	79.3	-	64.2	58.2	-	36.9	33.6	-
4	8/4/2017	7.83	7.74	-	72.7	75.6	-	85.5	75.4	-	48.8	43.4	-
5	8/14/2017	7.62	7.67	-	72.7	72.9	-	52.6	56	-	30.2	32.4	-
6	8/22/2017	7.58	7.66	-	86.6	79.2	-	129.3	65.5	-	74	37.7	-
7	8/28/2017	7.76	7.89	-	73.5	73.7	-	98	74.5	-	56.4	42.9	-
8	9/19/2017	8.19	7.76	-	71	71.8	-	38.68	29.98	-	22.31	19.34	-
Average		***7.70***	***7.70***	-	***76.96***	***75.44***	-	***85.19***	***69.95***	-	***48.58***	***40.33***	-

No significant differences of average pH and temperature between basin inflow and entrance manholes were observed for UGF basin #1. However, the specific conductivity and dissolved solids values were slightly lower in the samples collected from the entrance manholes compared to the those of the inflow.

Table 18. On-site Water Quality Measurements for UGF Basin #2

Event#	Date	pH			Temperature			Conductivity (uS)			Dissolved Solids (ppm)		
		Runoff	Entrance Manhole	Outlet	Runoff	Entrance Manhole	Outlet	Runoff	Entrance Manhole	Outlet	Runoff	Entrance Manhole	Outlet
1	6/22/2017	7.65	7.5	NS	77	75.5	74.1	112	100	NS	65	66	NS
2	7/23/2017	7.75	7.7	7.64	76.1	77.1	76.9	74.8	86.4	132.8	43.1	49.7	76.4
3	7/28/2017	7.71	7.7	7.77	86	79.7	79.1	75.1	79.5	107.4	42.6	45.4	61.8
4	8/4/2017	7.84	7.87	-	74.7	76.1	-	73.9	73.4	-	40.6	42.3	-
5	8/14/2017	7.65	7.78	7.73	76.5	74.6	74.9	54.2	70.3	106.2	31.2	40.5	60.8
6	8/22/2017	7.66	7.72	7.67	90.9	83.5	80.7	82.6	70.9	119.8	49.2	40.9	68.9
7	8/28/2017	7.96	7.92	7.84	73	72.46	73.2	62.8	65.8	87.4	36.1	37.8	50.2
8	9/19/2017	8.09	7.98	8.02	70.5	72	72.3	41.56	22.89	40.6	23.96	13.17	40.6
Average		***7.79***	***7.77***	***7.78***	***78.1***	***76.4***	***75.9***	***72.12***	***71.15***	***99.03***	***41.47***	***41.97***	***59.78***

No significant differences were observed between samples of inflow, inside of the entrance manhole in UGF basin #2, and from outflow for average pH values.

An average temperature reduction of 2.2 °F was observed between outlet samples and inlet samples. The outflow temperatures were cooler by approximately 7 to 12 °F in two of the monitored events (event #3 and event #6) where high temperatures were reported in the runoff samples.

The changes in temperature in the entrance manhole in basin #2 and in the outlet are shown for seven events in Figures 42 through 48. Data for the rainfall event #4 is not presented here since no outflow was observed.

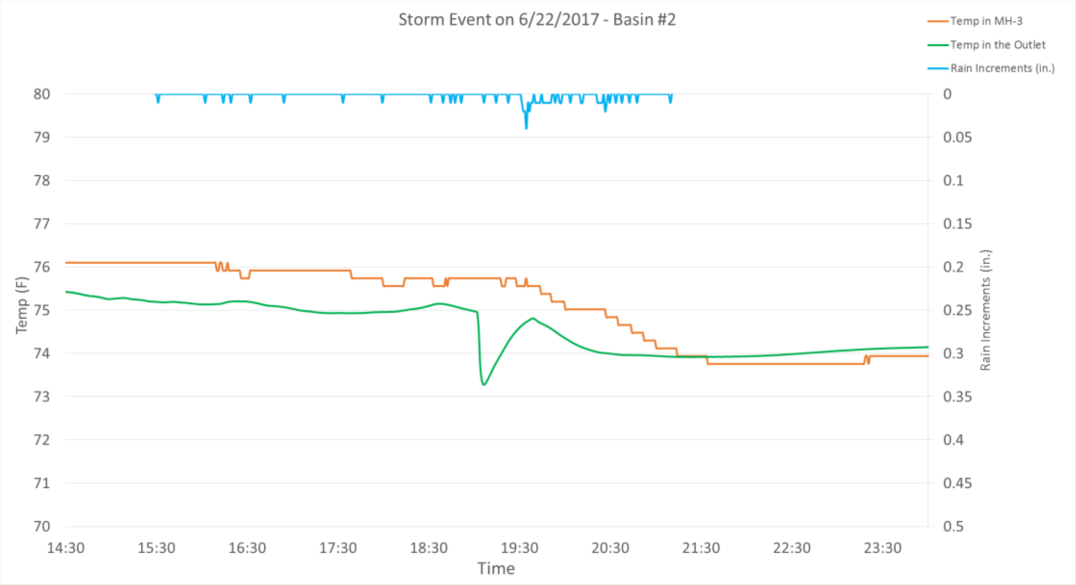


Figure 42. Temperature values recorded by the Leveloggers in the entrance manhole and at the outlet (Event 06/22/2017).

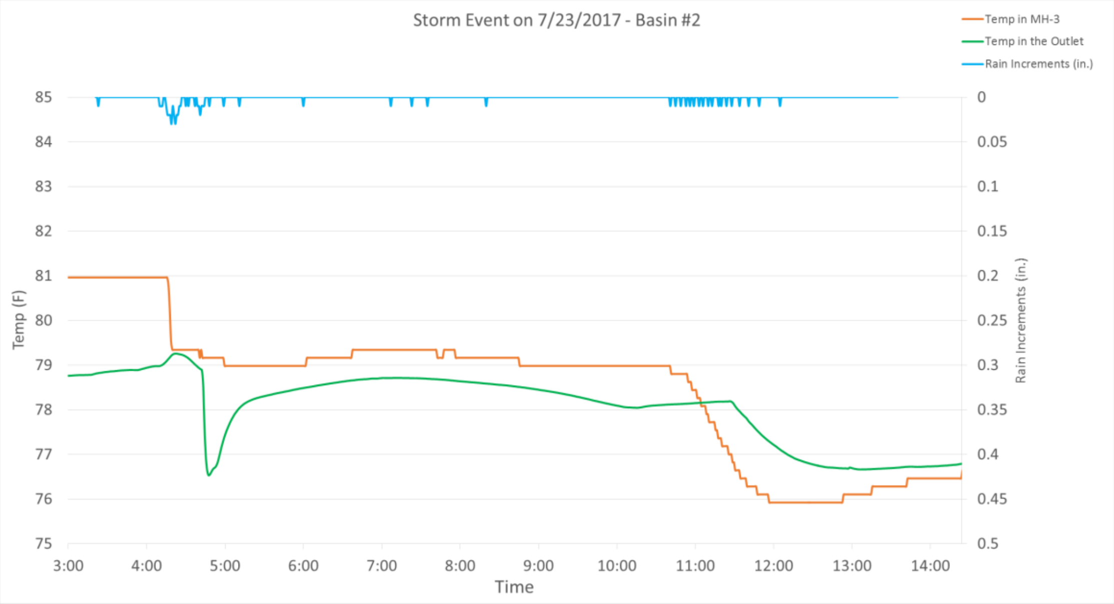


Figure 43. Temperature values recorded by the Leveloggers in the entrance manhole and at the outlet (Event 07/23/2017).

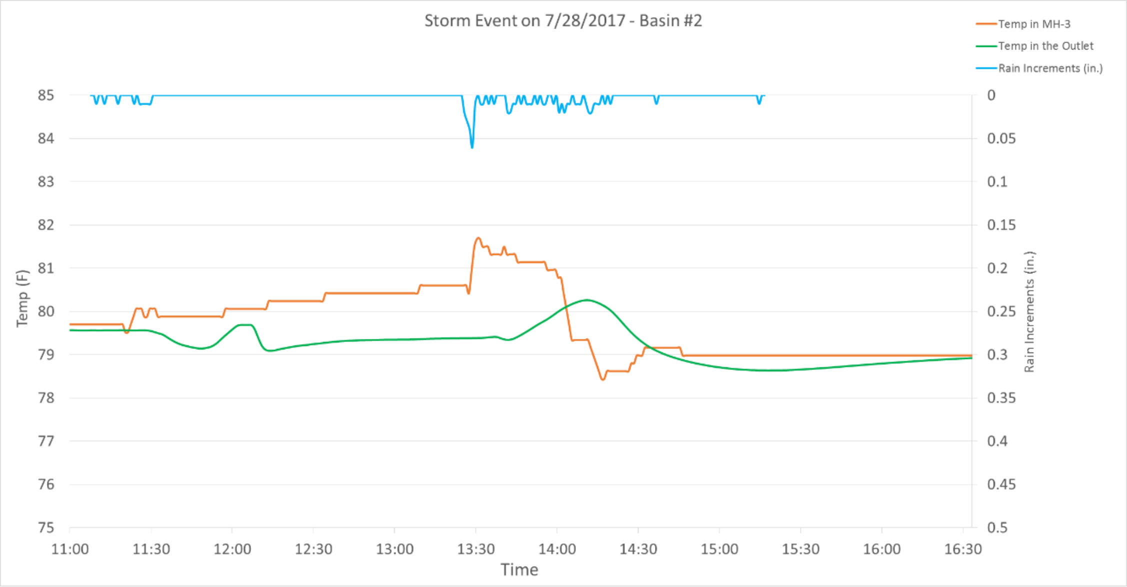


Figure 44. Temperature values recorded by the Leveloggers in the entrance manhole and at the outlet (Event 07/28/2017).

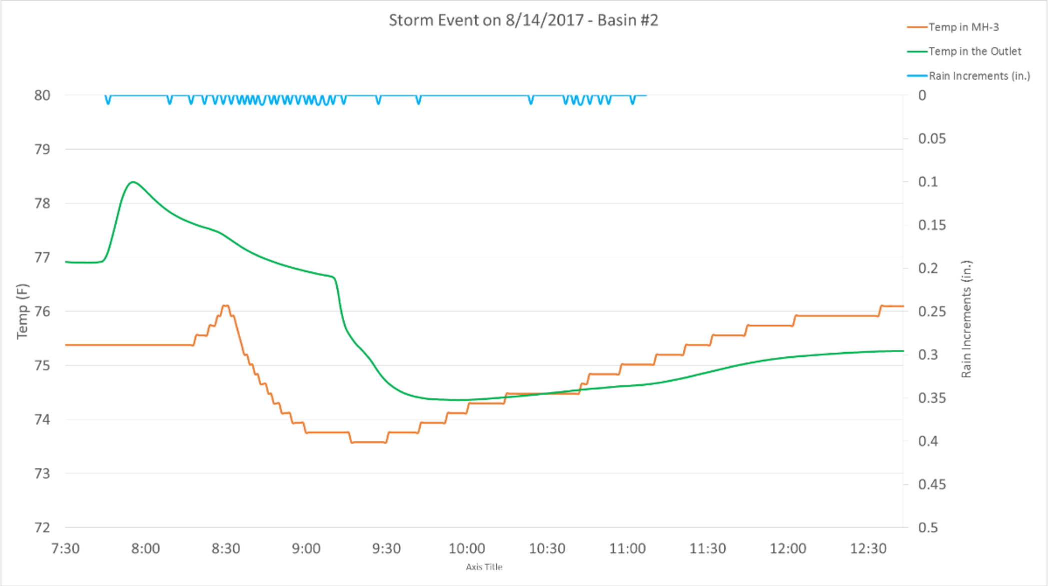


Figure 45. Temperature values recorded by the Leveloggers in the entrance manhole and at the outlet (Event 08/14/2017).

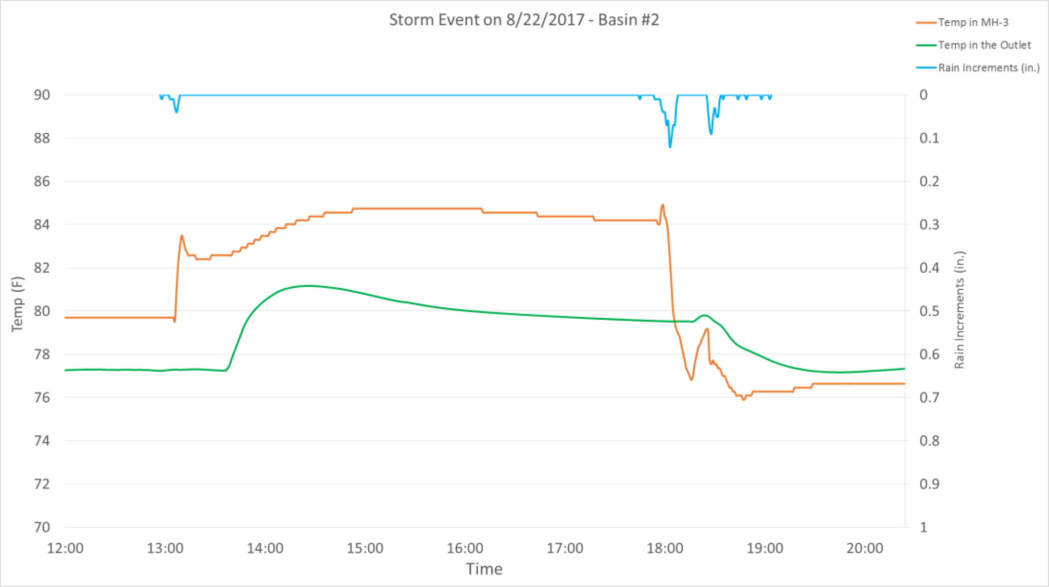


Figure 46. Temperature values recorded by the Leveloggers in the entrance manhole and at the outlet (Event 08/22/2017).

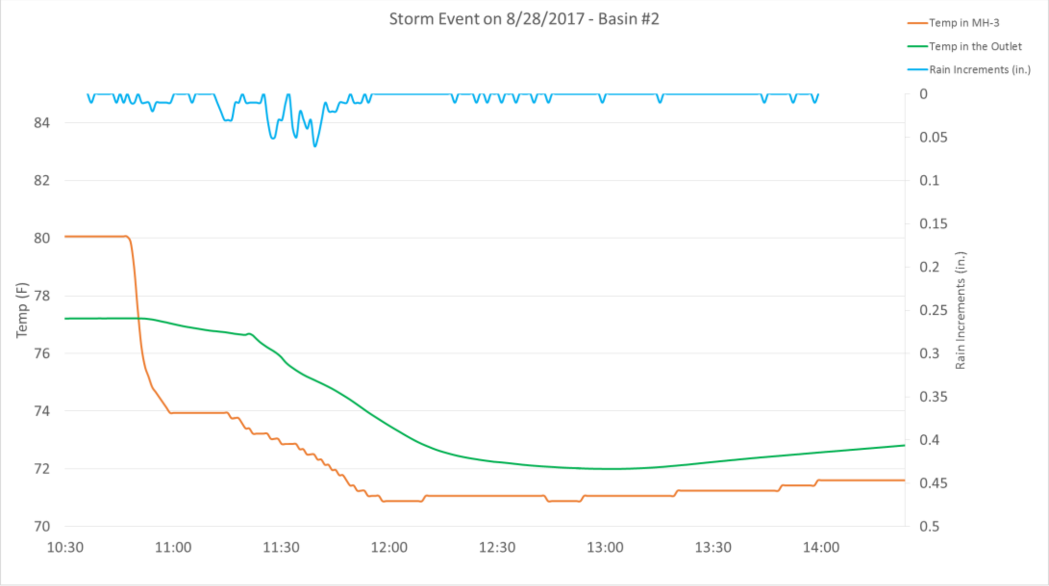


Figure 47. Temperature values recorded by the Leveloggers in the entrance manhole and at the outlet (Event 08/28/2017).

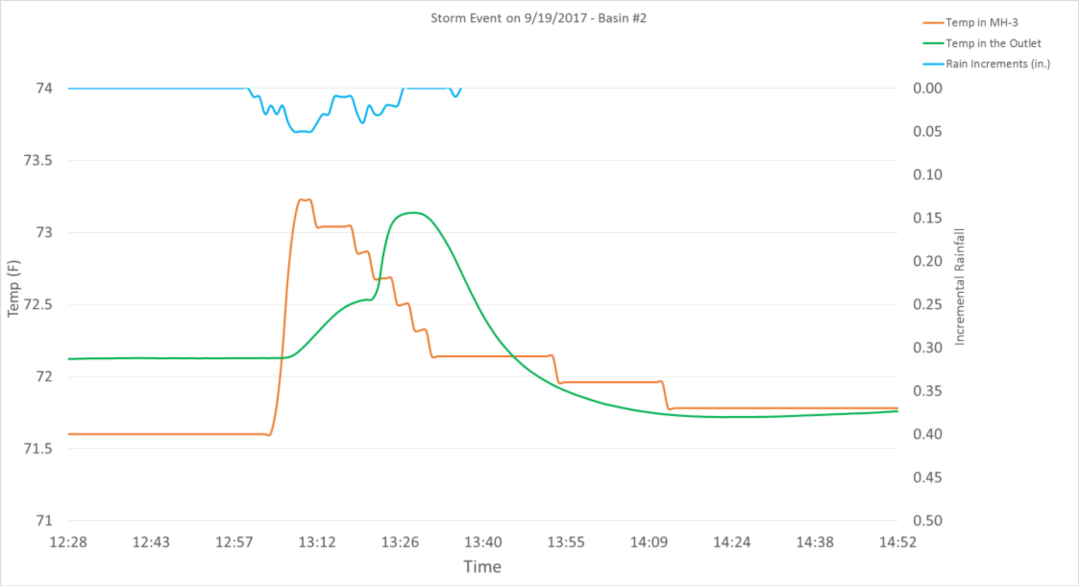


Figure 48. Temperature values recorded by the Leveloggers in the entrance manhole and at the outlet (Event 09/19/2017).

The box plots presented in Figure 49 represent water temperature data collected by the pressure transducers installed in the entrance manhole and at the outlet of UGF basin #2.

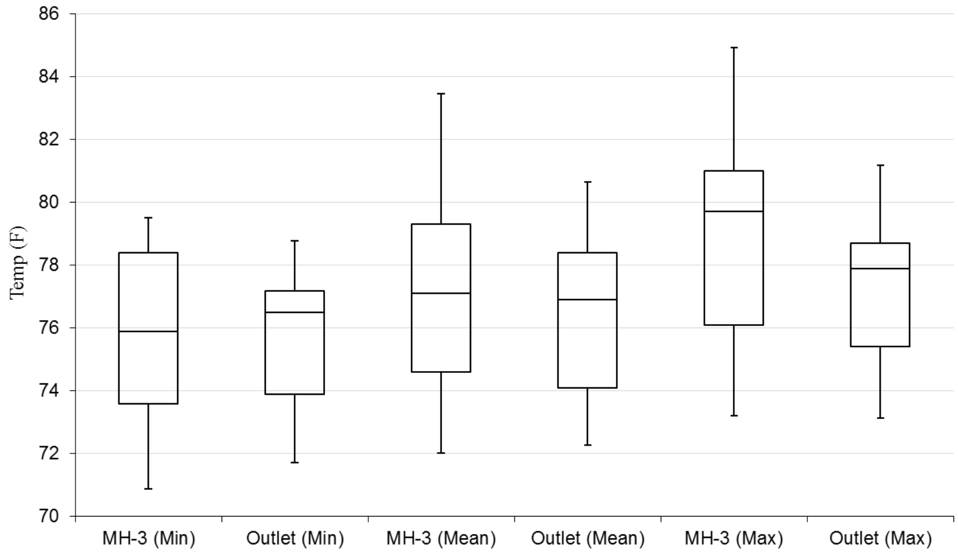


Figure 49. Summer temperatures in the entrance manhole and outflow of UGF basin #2, minimum, mean, and maximum values. The box illustrates the 25th percentile, median, and 75th percentile. The highest and lowest values for each series of data are shown by the top and bottom whiskers.

As shown in Figure 49, the most significant thermal effect is a pronounced reduction in event maximums, where the median values of the outlet maximum temperatures were found to be 1.8 °F lower compared with the temperatures in the entrance manhole. A similar pattern of outflow temperature reduction in underground detention systems was observed in previous studies (Drake et al., 2016; Natarajan and Davis, 2010). This reduction of temperatures in the outflow would prevent thermally enriched runoff during the summer months from discharging into receiving streams.

Higher values of specific conductivity and dissolved solids were observed in the samples that were collected from the outflow compared with those that were collected from the inflow and the entrance manhole. Higher conductivity values in the outflow samples of GI systems with a limestone gravel base reservoir were reported in previous studies (Abdollahian 2015; Brattebo and Booth, 2003).

4.2.4 Pollutant Loads and Concentrations

The USGS I-3765-85 (solids, residue at 105 °C, suspended, gravimetric) method was used to evaluate the TSS concentrations. *E. coli* concentrations were measured using the EPA approved method SM9223B (Colilert -18).

The volume of runoff for each storm event, outflow runoff volume (which only occurred in UGF basin #2), and the pollutant concentrations were computed. The pollutant loads for each event were calculated as follow.

$$L = C \times V \times K \tag{4.1}$$

In the above equation, L is the event pollutant load (Kg for TSS and MPN for *E. coli*), C is the pollutant concentration (mg/L for TSS and MPN/100mL for *E. coli*), V is the runoff or the outflow volume (ft^3), and K is a conversion factor (2.83168×10^{-4} to Kg for TSS and 2.83168 to MPN for *E. coli*).

The runoff volume for each storm event was calculated by multiplying the impervious area in each watershed by the total rainfall of that event. The outflow volumes were computed using Equation 3.1 and the associated time of outflow.

4.2.4.1 Pollutant Loads and Concentrations in UGF Basin #1

TSS concentrations and TSS event loads for UGF basin #1 are presented in Table 19 and Figure 50.

Table 19. TSS Concentrations and Event Loads in UGF Basin #1

Event#	Date	Runoff Volume (ft3)	Outflow Volume (ft3)	TSS (mg/L)			TSS Loads (Kg)	
				Runoff	Entrance Manholes	Outlet	Runoff	Outlet
1	6/22/2017	5589.84	0.00	61	28	-	96.6	-
2	7/23/2017	5968.81	0.00	39	46	-	65.9	-
3	7/28/2017	6063.55	0.00	18	68	-	30.9	-
4	8/4/2017	1042.17	0.00	74	39	-	21.8	-
5	8/14/2017	3505.49	0.00	18	233	-	17.9	-
6	8/22/2017	11842.88	0.00	22	87	-	73.8	-
7	8/28/2017	10990.19	0.00	144	84	-	448.1	-
8	9/19/2017	7200.47	0.00	134	144	-	273.2	-
Total		***52203.39***	***0.00***	***510***	***729***	**-**	***1028.2***	**-**

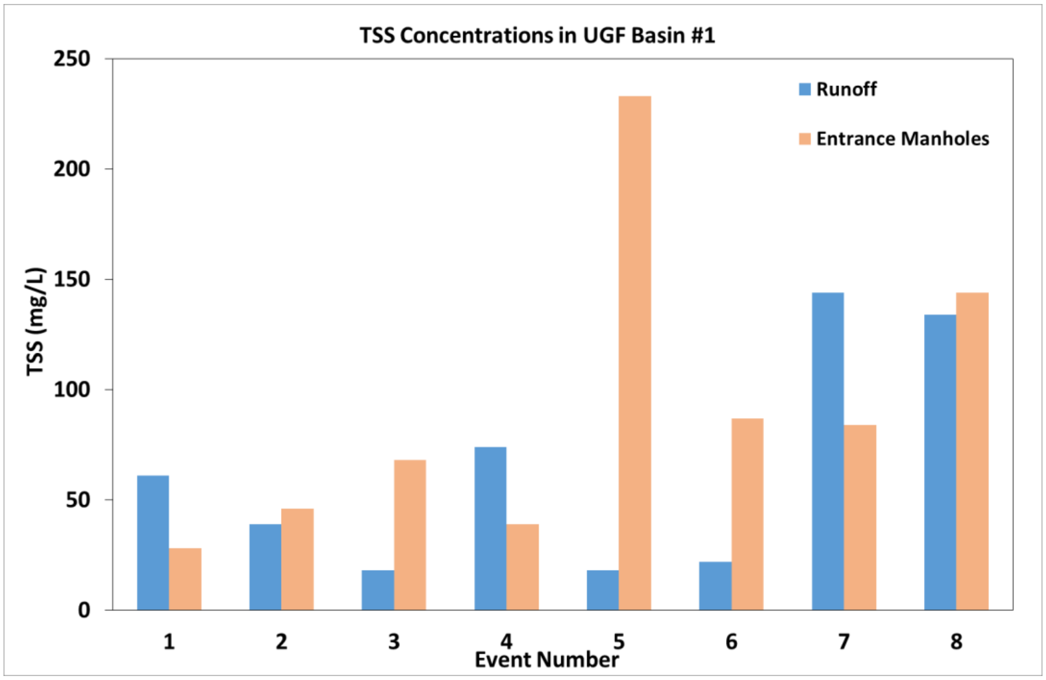


Figure 50. TSS concentration in the runoff and in the entrance manholes for UGF basin #1.

Samples that were collected from the entrance manholes showed higher TSS concentrations compared with the runoff samples in five out of eight runoff events. However, no outflow occurred in any of those eight events, and no outflow samples were collected from this basin. This could be a result of the basin being overdesigned.

Table 20 and Figure 51 present the *E. coli* concentrations and loads for UGF basin #1.

Table 20. *E. coli* Concentrations and Event Loads in UGF Basin #1

Runoff Volume (ft3)	Outflow Volume (ft3)	*E. coli* (MPN/100mL)			*E. coli* Load (MPN)	
		Runoff	Entrance Manholes	Outlet	Runoff	Outlet
5589.84	0.00	1732.9	>2419.6	-	2.74E+09	-
5968.81	0.00	>2419.6	2419.6	-	>4.09E+09	-
6063.55	0.00	1850	3873	-	3.18E+09	-
1042.17	0.00	17329	1789	-	5.11E+09	-
3505.49	0.00	15531	3076	-	1.54E+10	-
11842.88	0.00	3255	565	-	1.09E+10	-
10990.19	0.00	364	1236	-	1.13E+09	-
7200.47	0.00	520	2755	-	1.06E+09	-
52203.39	***0.00***	***43002***	***18133***	**-**	***4.36E+10***	**-**

The *E. coli* concentrations in the samples collected from the entrance manhole in event #1 and from the runoff in event #2 were higher than the laboratory maximum detection limit (2419.6 MPN/100mL). The maximum detection limit values are used in figures below. Similar to TSS, *E. coli* concentrations in the samples collected from the entrance manholes were higher compared with the runoff samples in half of the storm events. Since no outflow occurred in these events, all of the *E. coli* loads in the runoff were also contained by UGF basin #1 or infiltrated into the groundwater. The higher concentrations of pollutants in the entrance manholes could be a result of pollutant buildup in the manholes from previous storm events. It could also be due to the roof drains being directly connected to the manhole structures, which can deliver pollutants deposited on the roofs, such as suspended solids and bird waste. These pollutants can result in higher TSS and *E. coil* concentrations in the entrance manholes. The particulate matter and attached solids to the crushed limestone in the basins could also cause higher pollutant concentrations, especially TSS, in the entrance manholes.

Another reason for the higher concentrations of *E. coli* in the entrance manhole compared to the runoff, could be the suitable environment for *E. coli* growth which is provided in the manhole structures. According to Van Elsas et al. (2011), this suitable environment for *E. coli* growth includes stable pH levels (between 6 and 8), adequate moisture levels, sufficient sources of nutrients, and stable temperatures (73 °F–99 °F). Based on the onsite measurements in this study, most of these conditions for the *E. coli* growth were provided in the manhole structures inside the basins.

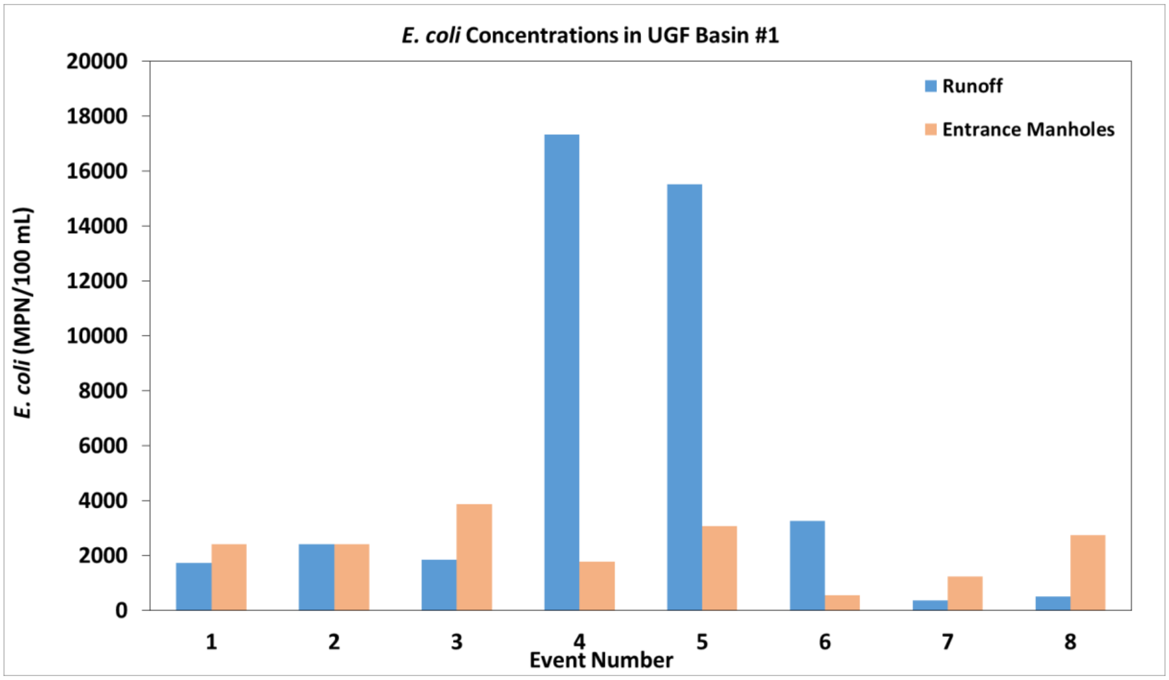


Figure 51. *E. coli* concentration in the runoff and in the entrance manholes for UGF basin #1.

4.2.4.2 Pollutant Loads and Concentrations in UGF Basin #2

The data for TSS loads and concentrations, runoff and outflow volumes, and load reduction percentages for UGF basin #2 are presented in Table 21.

Table 21. TSS Concentrations and Event Loads in UGF Basin #2

Event#	Date	Runoff Volume (ft3)	Outflow Volume (ft3)	TSS (mg/L)			TSS Loads (Kg)		Load Reduction (%)
				Runoff	Entrance Manhole	Outlet	Runoff	Outlet	
1	6/22/2017	3469.55	66.00	33	25	NS	32.42	NS	NS
2	7/23/2017	3704.78	724.00	23	66	5	24.13	1.03	95.8
3	7/28/2017	3763.58	226.00	11	53	<5	11.72	<0.5	96.0
4	8/4/2017	646.87	0.00	22	65	-	4.03	-	-
5	8/14/2017	2175.82	591.50	<5	12	<5	<3	<1	N/A
6	8/22/2017	7350.75	1634.70	18	22	9	37.47	4.17	88.9
7	8/28/2017	6821.50	283.00	62	61	19	119.76	1.52	98.7
8	9/19/2017	4469.26	1726.60	147	16	8	186.04	3.91	97.9
Total		***32402.11***	***5251.80***	***321***	***320***	***51***	***386.15***	***12.13***	***96.9***

NS: No sample was collected, N/A: Not applicable since there is no accurate result for the outlet concentration

The TSS concentrations in samples collected from the outlet of UGF basin #2 during event #3 and from the runoff and the outlet during event #5 were found to be lower than the minimum laboratory detection limit (5 mg/L). The minimum detection values were used to calculate the TSS loads in those events (Figures 52 and 53).

Figure 52 presents the TSS concentrations in the runoff, entrance manhole, and the outflow. During event# 1, the outflow occurred after the sampling team had left the site. No outflow sample was collected for that event. No outflow was observed for event #4. Higher TSS concentrations were observed in the samples collected from the entrance manhole in five events (events #2, 3, 4, 5, and 6). However, the TSS concentrations in the samples collected from the outflow were lower compared with the runoff and the entrance manhole samples in all of the storm events.

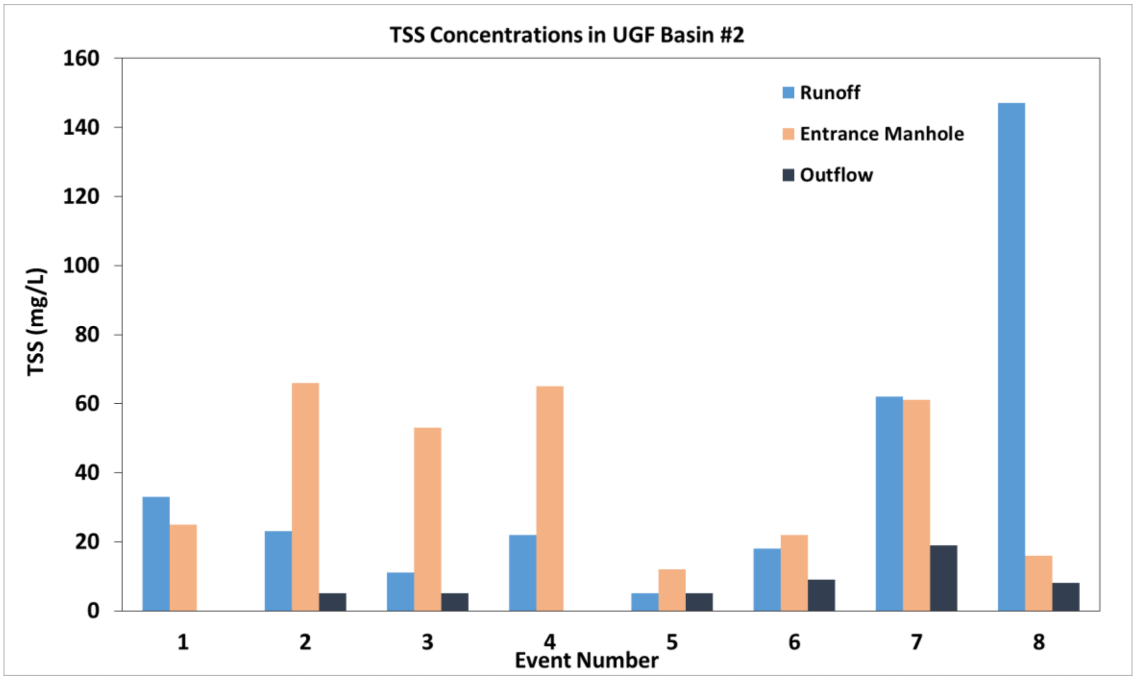


Figure 52. TSS concentration in the runoff, the entrance manhole, and the outflow for UGF basin #2.

Figure 53 shows that the TSS loads that left UGF basin #2 were significantly lower compared with those of the runoff. The total load reduction percentage for TSS was found to be 96.9%. Event #1 was not considered in calculating the total TSS load because samples were not collected from the outflow.

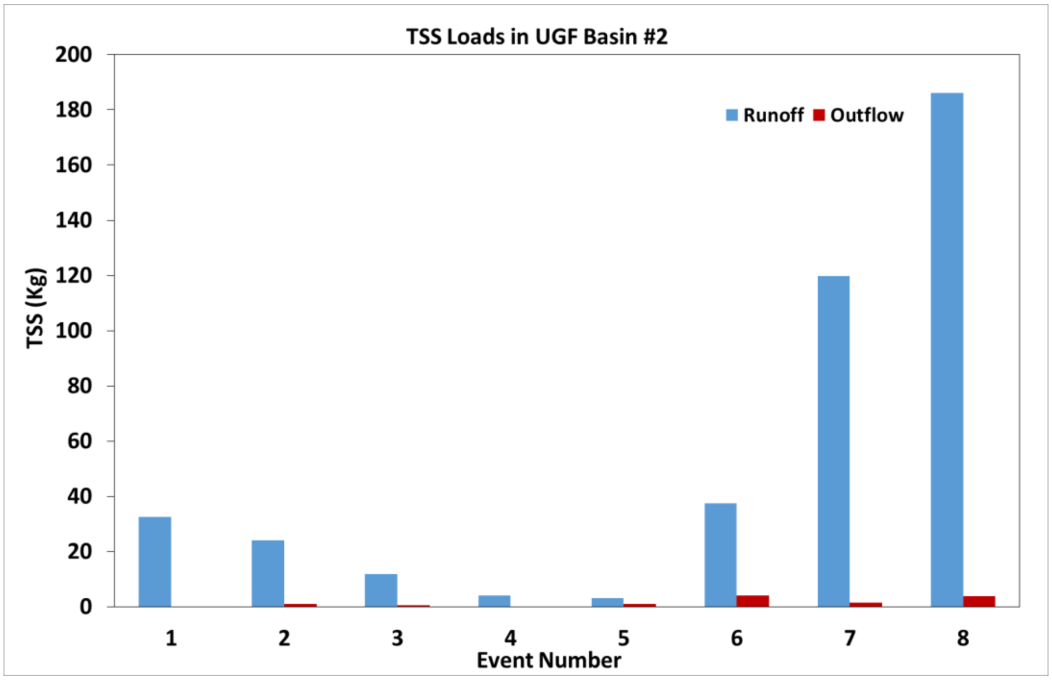


Figure 53. TSS loads in the runoff and outflow for UGF basin #2.

Table 22 contains the data for *E. coli* concentrations, loads, and the load reduction percentages for *E. coli* in UGF basin #2.

Table 22. *E. coli* Concentrations and Event Loads in UGF Basin #2

Event#	Date	Runoff Volume (ft3)	Outflow Volume (ft3)	*E. coli* (MPN/100mL)			*E. coli* Load (MPN)		Load Reduction (%)
				Runoff	Entrance Manhole	Outlet	Runoff	Outlet	
1	6/22/2017	3469.55	66.00	1046.2	2419.6	NS	1.03E+09	NS	NS
2	7/23/2017	3704.78	724.00	1299.7	>2419.6	>2419.6	1.36 E+9	N/A	N/A
3	7/28/2017	3763.58	226.00	1201	5794	3654	1.28E+09	2.34E+08	81.7
4	8/4/2017	646.87	0.00	4884	7270	-	8.95E+08	-	-
5	8/14/2017	2175.82	591.50	135	644	389	8.32E+07	6.52E+07	21.7
6	8/22/2017	7350.75	1634.70	173	1017	298	3.60E+08	1.38E+08	61.7
7	8/28/2017	6821.50	283.00	63	211	496	1.22E+08	3.97E+07	67.3
8	9/19/2017	4469.26	1726.60	749	422	341	9.48E+08	1.67E+08	82.4
Total		***32402.11***	***5251.80***	***1194***	***20197***	***7598***	***3.69E+09***	***6.43E+08***	***82.6***
NS: No sample was taken, N/A: Not applicable since there is no accurate result for the outlet concentration									

E. coli concentrations in the runoff, entrance manhole, and outflow samples are illustrated in Figure 54. The *E. coli* concentrations in outflow and the entrance manhole samples for event #2 were higher than the laboratory maximum detection limit (2419.6 MPN/100mL). The maximum detection limit values were used in the figures below.

Higher concentrations of *E. coli* were observed in the outflow samples compared with the samples collected from the runoff in events # 2, 3, 5, 6, and 7. However, the low basin discharge in UGF basin #2 has resulted in lower outflow loads than *E. coli* loads in the runoff for the sampled events (see Figure 55). The total load reduction percentage for *E. coli* was 82.6%. Events #1 and #2 were not considered in calculating the total *E. coli* loads.

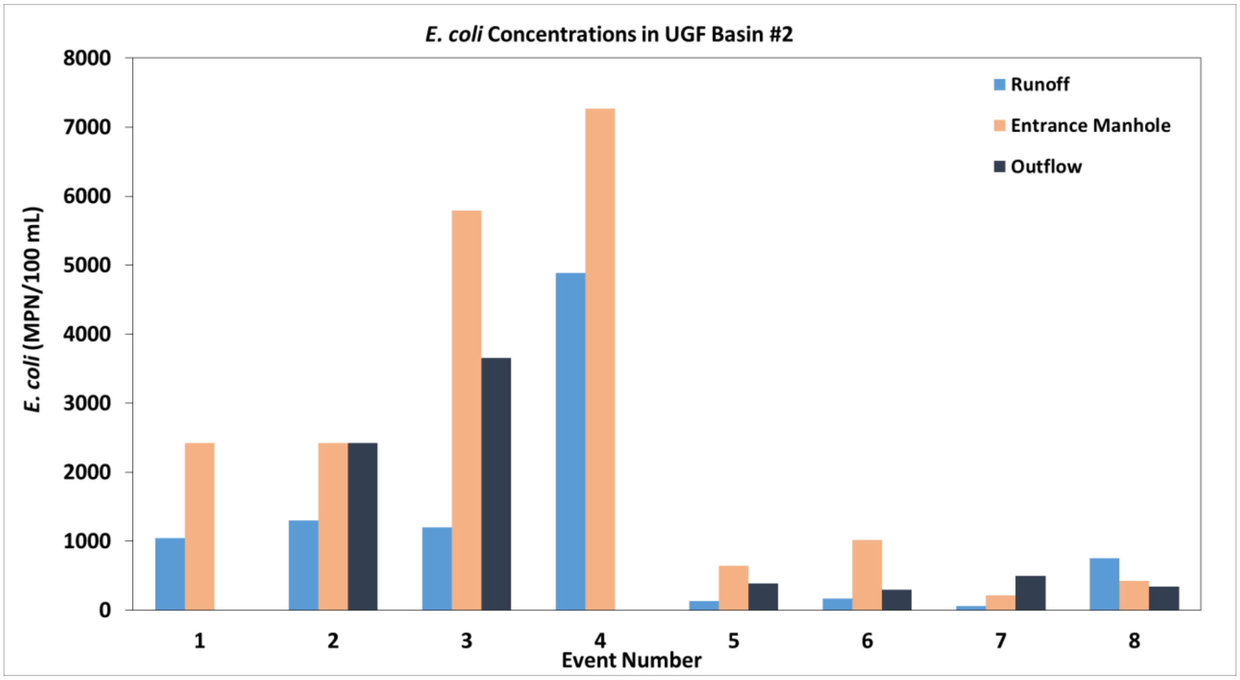


Figure 54. *E. coli* concentration in the runoff, the entrance manhole, and the outflow for UGF basin #2.

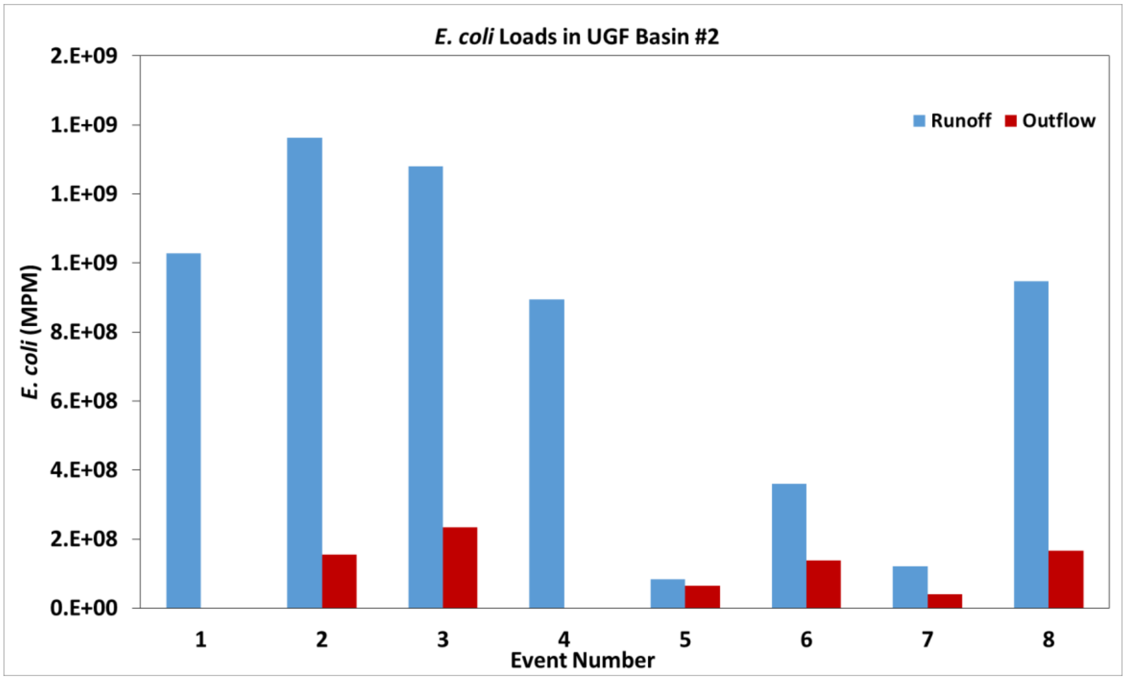


Figure 55. *E. coli* loads in the runoff and outflow for UGF basin #2.

4.3 Discussion of Results

This section is dedicated to discussing the findings from the data presented in the previous sections, which includes infiltration characteristics and volume reductions of the UGF basins, on-site measurements, the TSS and *E. coli* loads and concentrations, and the pollutant removal performances of UGF basins.

4.3.1 Infiltration Data and Runoff Volume Reduction

Based on the data from 14 rain events in which infiltration and volume reduction were monitored in this study, it was observed that 99% of the runoff in UGF basin # 1 and 74% of the runoff volume in UGF basin #2 were collected and infiltrated to the underlying soil layers. The infiltration percentages and stormwater volume reductions evaluated in this study were found to be higher than the average values for different stormwater BMPs reported in the international Stormwater BMP Database (Poresky, et al., 2011). The above database summarizes the volume reduction for a total of 47 BMP monitoring studies, which includes: biofilters (grass strips and grass swales), bioretentions (with underdrains), and detention basins. According to the International Stormwater BMP Database, the highest average value for volume reduction is 61%, which is reported for the bioretention with underdrains.

The infiltration capability of the soil improved the performance of the UGF basin from a water quality and quantity perspective. UGF basins require larger footprints with a factor of 2.2 to 2.5 times that of other stormwater BMPs to compensate for the volume occupied by the stone media. In areas where infiltration is higher than average, UGF basins will have better performance than other stormwater BMPs due the larger surface area for capturing of pollutants and stormwater runoff volume reduction.

4.3.2 Water Quality Parameters

The pH values in the runoff were found to be higher than the range reported by the U.S. EPA for normal, clean rain (5.0 to 5.5). Urban stormwater runoff has higher pH value due to the contact of rainwater with concrete sidewalks, concrete curbs and gutters, asphalt surfaces, and concrete pipes.

In onsite measurements, the basin was found to have no significant change in the pH values between the entrance manhole and the outlet structure. With flow of the runoff through the limestone aggregate media, one would expect an increase in the pH value. This was not observed, which might be the result of having a short flow path and contact time.

It was observed that the average temperature values in the outflow were lower compared with the temperature values in the runoff. The difference between the runoff temperatures and the outflow temperatures was more evident in the events with higher runoff temperatures (>77 °F). During the summer months, the temperature inside the UGF basin is lower than the outside temperature, since the UGF basins are isolated and not exposed to energy inputs such as solar radiation, heat transferred from urbanized surfaces, and atmospheric temperature. During the summer months, the UGF basin serves as cooling media for the heated urban stormwater runoff. Figure 56 presents the average runoff and outlet temperatures, showing a negative correlation between the outlet temperature and the runoff temperature. This relationship is dependent on detention time, flow path from the entrance manhole to the outlet structure, and the depth of the UGF basins. Increasing any of these factors will have a direct impact on lowering the outlet temperature. Reducing water temperature will have a direct environmental benefit since more dissolved oxygen is present in water with lower temperatures compared with water of higher temperatures.

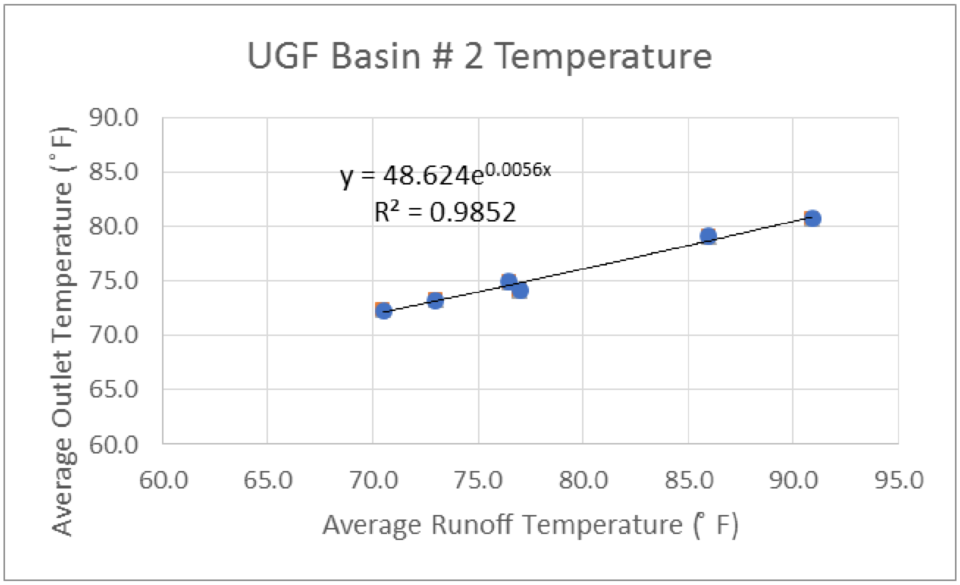


Figure 56. Temperatures in UGF Basin #2.

The average values for conductivity and dissolved solids in the outflow were found to be 30% and 27% higher respectively than the runoff. Limestone media leads to higher conductivity in the runoff because of the dissolved carbonite mineral. Dissolved solids represent the very fine particles such as clay size material that pass 2 micrometer filtration pores or which require at least 25 days of settling times.

4.3.3 TSS and **E. coli** *Data*

The TSS and *E. coli* loads were calculated at the runoff and the outflow based on the concentrations and the runoff volumes. Since there was no outflow reported in UGF basin #1, it was concluded that this basin had completely captured and contained the pollutant loads during this study.

Physical processes including settling and filtration were found to be the main pollutant removal mechanisms in the UGF systems. These mechanisms (settling and filtration) explain the high reductions of TSS concentrations that were reported in this study. The majority of the settling of the suspended solids occurs at the entrance manhole. The sump area will reduce the velocity of the flow at the low flow condition as the entrance manhole surcharges the storms system and reduces the flow velocity, which leads to settling at the entrance manhole.

The inlet manhole provides for the settling of sediment particles before runoff reaches the UGF basin. This eases the long-term maintenance burden and potential failure. To ensure that pretreatment mechanisms are effective, the sump of the inlet manhole should be deep enough to trap medium silt-sized particles and minimize the resuspension of the trapped sediments and pollutants, by reducing the turbulence and the tangential velocity to a level that is below the entrainment velocity. When runoff flows over deposited sediment, the lift and drag force will attempt to move particles out of the sump area, and these resuspended materials will pass through the gravel media in the basin and reach the outlet structure (see Figure 57).

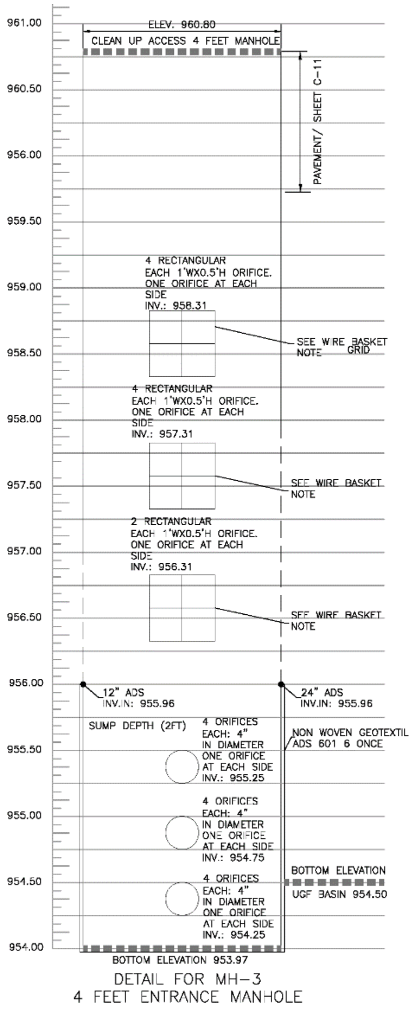


Figure 57. Entrance manhole (sump Depth 2.0 feet).

According to previous studies, TSS concentrations in runoff are highly associated with the concentration of other pollutants, especially heavy metals (Zhao et al., 2009). It can therefore be concluded that high percentages of TSS load reductions can contribute to reducing heavy metals and other pollutant loads from runoff.

There are different factors that could have led to lower removal ratios of *E. coli* compared with TSS. These factors include short retention times in the basins for the biological treatment of *E.coli*, relatively coarse filter media (#2 crushed limestone), the short distances between the entrance manhole structures to the outlet structures, depth of the manholes, a small ratio of the water quality volume in the basins, as well as the presence of other wildlife found in the entrance manholes and at the sampling port of the outflow.

4.4 Design Guidelines for UGF Basins

This section presents the steps required to improve the performance of UGF basins. The minimum volume is the volume that allows the basin to trap portions of the sediments and pollutants targeted by the designer. UGF basins are designed to reduce the load of suspended particles in receiving waters. The higher the first flush flow rate or the smaller the target particles, a larger minimum volume is required for the basin. In practice, basins are generally sized to trap medium silt-sized and coarse particles.

4.4.1 Water Quality Volume

U.S. EPA guidance indicates that an effective post-construction water quality standard is to manage runoff from the 90th percentile storm, known as the water quality volume (WQv). The 90th percentile storm is defined as 90% of the storms occurring annually that will produce a rainfall depth of less than the 90th percentile.

4.4.2 Minimum Surface Quality of Water

UGF basins must have a minimum water quality volume to reduce first flush velocity and should have adequate detention time to capture the target pollutants.

In areas where infiltration is not possible, the water quality volume should be retained for an extended period of time for the pollutants to settle. Settling velocities are generally calculated using Stokes’s Law.

4.4.3 Pretreatment

Pretreatment is required for a UGF basin in order to reduce the sediment load entering the facility and maintain both the infiltration area and the long-term performance of the basin. Pretreatment occurs at the entrance manholes, which provide an opportunity for the sediment particles to settle before the runoff reaches the UGF basin. This eases the long-term maintenance burden and potential failure. To ensure that pretreatment mechanisms are effective, the sump of the inlet manhole should be deep enough to trap medium silt sized particles and minimize the resuspension of the trapped sediment and pollutant, by reducing the turbulence and the tangential velocity to a level that is below the entrainment velocity. When runoff flows over deposited sediment, the lift and drag force will attempt to move particles out of the sump area.

4.4.4 Sediment Storage Volume

Water quality volume of the UGF basin storage capacity decreases gradually as sediment and pollutant accumulate. To maintain the effectiveness of the water quality storage volume, additional storage volume must be added to the required WQv of the basin. The additional storage volume must take into account the annual volume of trapped sediment and pollutant within the basin area.

The additional sediment storage volume can be created by increasing the volume of the entrance manholes or increasing the water quality storage volume by increasing the surface area or increasing the depth.

In June of 1990, the Environmental and Conservation Services Department for the City of Austin determined the total annual loads of pollutants for a 90% impervious site as 1,123 pounds per acre or 12.5 cubic feet per acre. Refer to Table 1 in Appendix A for the annual storm loads for various impervious cover levels.

4.4.5 Maintenance

Maintenance is a key component for the long-term stormwater performance of the UGF basin. Inspection of the entrance manholes and outlet structure should occur at regular intervals and should be maintained when necessary to ensure optimum performance. The rate at which the system collects pollutants will depend heavily on the site activities.

Inspection is critical to have effective maintenance and can be performed easily. Pollutant transport and deposition may vary from year to year, and regular inspection will help ensure that the system is being cleaned out at the appropriate time. At minimum, inspections of the entrance manholes and outlet structures should occur twice a year (spring and fall); however, more frequent inspections may be necessary in areas where land-use or operations may lead to rapid accumulations.

A visual inspection should ascertain that the entrance manholes and the outlet structures are in working condition and that there are no blockages or obstructions at the inlets and weir structures. The inspection should also quantify the accumulation of hydrocarbons, trach, and sediments in the system. Measuring pollutant accumulation can be done with a tape measure or other measuring instruments.

Access to the entrance manholes and outlet structure is achieved through the manhole access covers. Entrance manholes and outlet structures should be cleaned at least annually or when the level of sediment and debris has reached 30% (0.3H) of the capacity of the sump at the entrance manholes (See Figure 58). The level of sediment and debris is easily determined by measuring from finished grade to the top of the sediment and debris pile. Once this measurement is recorded, it should be compared to the as-built drawing for the manholes.

The cleaning process of the entrance manholes and outlet structures should take place during dry weather conditions when no flow is entering the system. The use of a vacuum truck is generally the most effective and convenient method of removing the pollutants from the system. Cleaning by use of a vacuum truck can be achieved by simply removing the manhole covers and inserting the vacuum hose into the sump. The system should be completely drained down and the sump fully evacuated of sediments. The area at the screen should also be cleaned if pollutant build-up exists in that area.

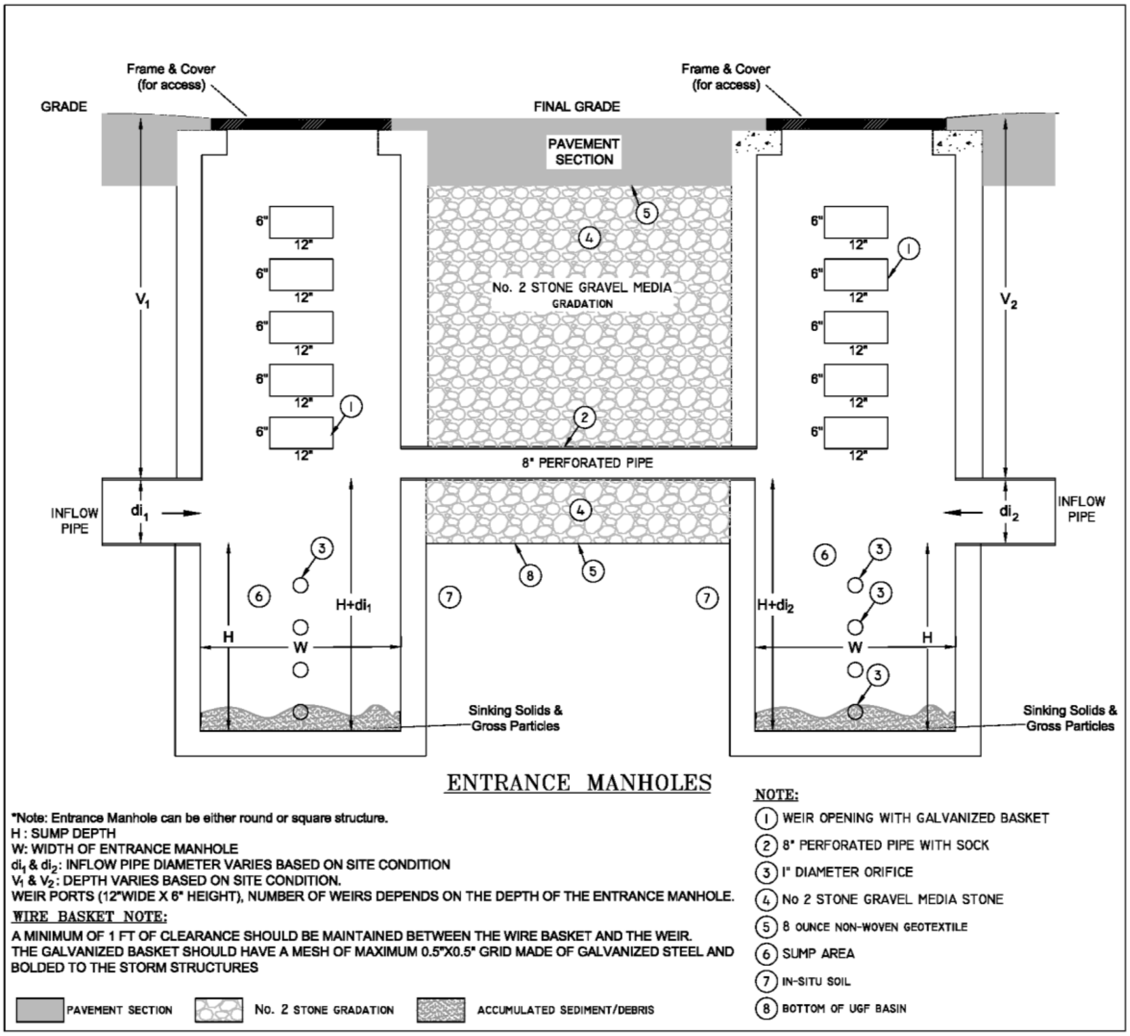


Figure 58. Entrance manholes.

4.5 Overall Performance of the UGF Basins

This study evaluated the performance of the UGF basin during summer months in a soil with above average infiltration rates. UGF basins require a surface area of 2.2 to 2.5 times larger than other stormwarter BMPs to compensate for the volume occupied by the stone media. In an area where infiltration is higher than average, UGF basins will have better performance than other stormwater BMPs regarding capturing the pollutants and stormwater runoff volume reduction, due to the larger surface area. The UGF basin was also efficient in trapping the TSS; regulations require post-construction stormwater management to capture 80% of TSS. The UGF basin was able to capture 97% of TSS for UGF basin #2. The UGF basin was efficient in reducing the load of *E. coli*, and a second treatment might be added for higher efficiency. The UGF basin was able to reduce the average temperature by 2 °F and compress the range of the maximum and minimum temperatures. The UGF basin was not efficient in reducing DS.

Pretreatment and maintenance are key components for the long-term stormwater performance of the UGF basin. Inspection of the entrance manholes and outlet structures should occur at regular intervals and be maintained when necessary to ensure optimum performance. UGF basins #1 and #2 should be cleaned on yearly basis as the load of sediment and pollutant removed from MH-3 is an average of 12 inches, which is equivalent of 12.56 cubic feet or 1,130 pounds.

Figure 59 presents the proposed improvements to enhance the efficiency and long-term performance of the basin. These improvements consist of relocating the entrance manhole MH-3 to MH-3A and adding two additional entrance manholes (MH-3B and MH-3C). All entrance manholes should have a deeper sump to maintain a velocity of less than the resuspension velocity of medium silt particles. All entrance manholes should be connected with perforated pipe to increase the efficiency and minimize dead storage. The outlet structure should be relocated to maximize the flow path from entrance manholes MH-3A and MH-3B.

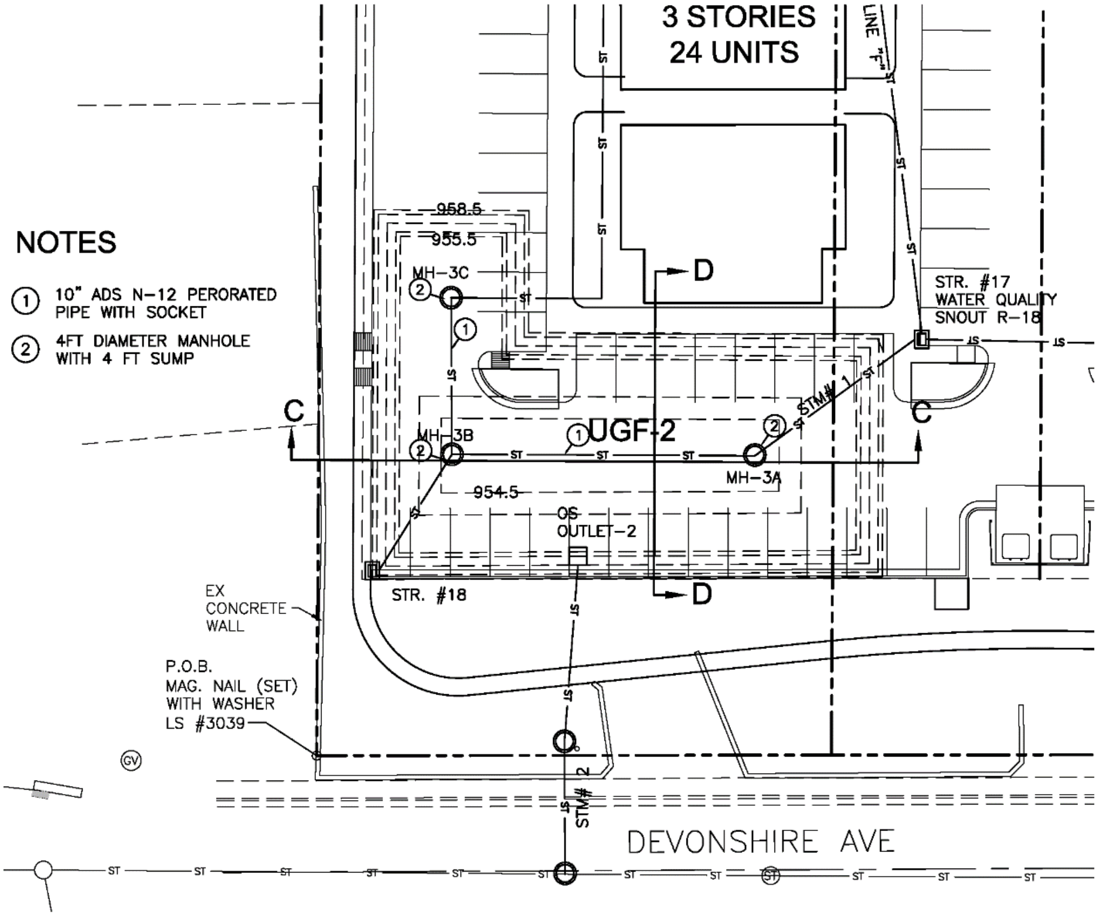


Figure 59. Modified UGF Basin #2.

5. CONCLUSIONS AND FUTURE WORK

The objective of this research was to evaluate the outflow reduction due to storage and infiltration of stormwater runoff, assess the water quality performance of two UGF basins, and to recommend improvements to the design of these systems. Unlike many previous researchers who focused on only water quality or water quantity performance of GISs, this study monitored and evaluated full-scale UGF systems in an urban environment for both water quality and infiltration and volume reduction of stormwater UGF basins.

5.1 UGF Basin Goals and Conclusions

The objectives of this research were addressed, and the following conclusions were drawn from the evaluation of the peak discharge values, basin volume reduction, and infiltration performance:

- <u>Objective 1: to evaluate the long-term performance of UGF basins for controlling stormwater runoff volume.</u> Both UGF basins were effective in the case of volume reduction and infiltrating the captured runoff into the underlying soil layers. This could be a result of the design specifics, which provide a large surface area for infiltration, and also the site conditions and relatively high infiltration rates of the underlying soils.

- Objective 2: to determine the performance of UGF basins regarding the stormwater volume reduction, peak discharge reductions, and infiltration. The UGF basins were highly effective in reducing the peak discharge values.

The following conclusions were drawn from the evaluation of the water quality performance of the UGF basins:

- Objective 3: to assess the ability of these systems to mitigate temperature during the summer months. The UGF basins were effective in reducing the temperature of runoff during summer months. This was especially true when the reduction in temperature is most needed to protect aquatic life during high-temperature (above 85 °F) summer flow events. The UGF basins did not have a significant effect on pH. This could be a result of the short contact time between the runoff and the limestone filter media.
- Objective 4: to assess UGF basins' efficiency in removal of TSS and bacterial contamination.

The UGF basins were not effective in reducing conductivity and removing the dissolved solids from the runoff. This higher value of conductivity was also reported in previous similar studies and could be a result of the runoff water being introduced to the fine limestone particles.

The basins were effective in reducing TSS and *E. coli* total loadings. Since the UGF basins were highly capable of capturing and infiltrating the runoff into the underlying soil, the pollutant loads (TSS and *E. coli*) leaving the basins were significantly reduced.

The UGF basins were effective in reducing TSS concentrations, which is believed to be a result of physical processes such as settling and filtration within the filter media.

5.2 Recommendations for Design Improvements and Future Work

The following parameters and factors that can affect and/or improve the water quantity and pollutant removal efficiency of UGF basins need to be investigated in future research studies: (1) the effect of underlying soil layers, (2) the effect of different filter media, including both the stone media used in the basins, as well as applying additives to the media that can result in enhanced removal rates of bacterial contaminations, (3) improving the physical design of the basins, including the depth, volume, and number of entrance manholes and the geometry of the basins, (4) a review of seasonal changes, (5) a review of a wider range of pollutants and particle size distribution, (6) the effect of the use of an automatic sampler, and (7) the effect of the use of additional monitoring ports throughout the basin.

Below is a list of suggestions for future work to improve the water quality and quantity performances of UGF basins.

Effect of Underlying Soil Layers

The drainage properties of the underlying soils can play a significant role on the infiltration performance of UGF basins. According to the Custom Soil Resource Report for the Fayette County Area, the monitored UGF basins were underlain with Maury-Bluegrass silt loams, which are categorized as well-drained. This could be the factor responsible for the high infiltration rates and volume reduction in these basins. Additional studies in locations with soil types with limited infiltration properties are recommended.

This would evaluate the water quantity efficiency of the UGF basins in areas where infiltration is not a significant factor, unlike the conditions in this study.

Different Filter Media

A change in the filter media could have an improved effect on the water quality performance of the UGF systems.

- Aggregate size: Use of a smaller aggregate size or a more well-graded aggregate as part of the filter media in future studies could improve the physical processes in removing small-sized particles from the runoff. To avoid and minimize clogging that could be caused by fine filter media, the application of a fine filter medium is only recommended in the water quality section of the basins and not in the entire storage volume.
- Secondary treatments: Results of this study indicated that the UGF basins are capable of significantly reducing the peak flow. The low flow rates leaving the basins provide an opportunity to use a secondary treatment method at the outflow structures. This could be achieved by directing the outflow through an amended filter medium. This filter medium can contain industrial byproducts such as fly-ash, steel slag, steel chips, and natural minerals including zeolite, calcite, and/or fine limestone (1 to 4 mm). Application of the secondary treatment can improve the physical and chemical pollutant removal processes. Previous laboratory studies have shown that decreasing the particle size will increase the filtration and pollutant removable performance of the medium, especially in case of fine particles and bacteria pollutant loads. Use of the amended filter media as a

secondary treatment could also increase the adsorption kinetics and will result in reaching higher adsorption rates in shorter time periods (Hooshyari, 2017; Youngblood et al., 2017).

The use of these materials is recommended as a secondary treatment and at the outlet structure of the basins. This could be achieved by directing the outflow through a sump area, or a small sized pipe, filled with the amended filter medium at the outlet structure. The fine material is recommended to be used as a secondary treatment medium and should not be used in the main basin as part of primary treatment because it can lead to clogging and adversely affecting the water quantity performance of the UGF basin.

Improve the Physical Design

Physical design factors that can affect the water quality performance of the UGF basins include the design of inlet manholes and sump volume and the geometry of the basin.

- Design of the entrance manholes: Increasing the number and depth of entrance manholes and the diameter of the sump area could improve the pollutant removal performance of the basins. The design of the manholes includes the number of manholes, the sump depth in each manhole, and the distance between the inlet manholes and the outlet structures. These modifications would also provide more opportunities for particles to settle. A deeper sump area will also decrease the resuspension of the previously deposited material during storm events. Resuspension of the deposited material due to the relatively shallow depth of sump areas in the manholes

(2.0 ft.) in this study could have been responsible for higher concentrations of dissolved solids in the outflow compared to the runoff.

- Geometry: Width, length, and depth of the basin affect retention time and the contact time between the runoff water and the filter media. Future research can focus on evaluating the effects of geometry of the design on the pollutant removal performance of the UGF systems.

Seasonal Changes

Since seasonal changes can affect the pollutant concentrations in runoff, future monitoring plans should include cold-weather conditions to better understand UGF systems' performance during all weather conditions.

Wider Range of Pollutants and Particle Size Distribution

UGF basin systems performances should be conducted for a broader spectrum of pollutants found in stormwater, such as heavy metals, nutrients, and hydrocarbons.

It is also recommended to evaluate the particle size distribution from the runoff, entrance manholes, and at outlet structures. This would help determine the range of particles that are captured by UGF basins.

Use of Automatic Sampler

Grab samples were collected at fixed time intervals during the first portion of storm events (first flush). These samples were mixed to form a single time-weighted composite sample at each sampling location. The use of automatic samplers can provide flow-weighted composite samples during the whole course of the storm event. This would result in more accurate values for Event Mean Concentrations (EMC).

Additional Monitoring Ports and Sensors

The use of additional monitoring ports throughout the basin would lead to a better understanding of changes in the water level and the flow characteristics in the UGF basins. Additional monitoring ports would also provide the opportunity for collecting a more representative water quality sample from different locations in the UGF basin.

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CURRICULUM VITAE

JihadA. Hallany

Principal in Charge at Vision Engineering, LLC

YEARS OF EXPERIENCE: 20 years

EDUCATION: MS, Biosystems & Agriculture, University of Kentucky • BS, Civil Engineering, Water Resources & Structural, University of Kentucky

PROFESSIONAL QUALIFICATIONS: Professional Engineer:
Kentucky #22838 • Indiana #10403666 • Ohio #69566

PROFESSIONAL SUMMARY:

Mr. Hallany serves as the Principal in Charge since founding the firm in 2003, responsible for the operation of a 12+ person office that includes several engineering, environmental, geotechnical, landscape architect, construction service, inspection, and surveying disciplines serving both public and private clients. Mr. Hallany specializes in water resources, environmental design, and civil/site development.

PROJECT-SPECIFIC EXPERIENCE:

1100-1108 South Broadway, Stormwater Study: (Present): Scope of services consist of conducting detailed Hydrological/Hydraulic (H/H) using XP-SWMM model of the existing storm sewer, detention facilities, and channel networks within the study area which is bounded upstream by a railroad culvert at 220 Virginia Avenue and downstream by Picado Golf Course. Goal of the study is to accurately delineate the 25- and 100-year

24-hour storm event and evaluate the impact of raising the site at 1100 and 1108 South Broadway for future development on the upstream and downstream of the subject properties.

Town Branch Floodplain Analysis (2014-2016): Scope of services consisted of public outreach, notification of all residents within the effective floodplain area, installing ISCO stream monitoring gage with velocity sensor at Jimmy Campbell Drive and two (2) stream level loggers (Solinst Model 3001) at Cox Street and Pyramid Park, conducting detail survey for Town Branch and associated structures as per FEMA Appendix M, conducting detailed hydrological/hydraulic modeling as per FEMA Guidelines and Specifications, Appendix C, and LOMR application and process. Our modeling efforts revealed that the effective FEMA map overestimated based flood elevation by two to six feet within the area of interest of LFUCG.

Southland Drive, Wolf Run Stormwater Study (2012-2013): Project divided into two parts. Part I consisted of revising the Effective XP-SMMM model for Wolf Run within the project area which is bounded upstream by Nicholasville Road and downstream by a Norkfolk Southern Railroad culvert near 299 Southland Drive. Our efforts led to major reduction of the floodplain/floodway elevation/boundaries. Scope of services also included LOMR process and update to FEMA Panel # 21006119E.

Part II addressed the flooding along Goodrich Avenue area; scope of services consisted of conducting detailed H/H study (XP-SWMM) for the Goodrich and Hampton Inn watershed, developed engineering solutions by upsizing existing storm system at Goodrich neighborhood and constructing two underground detention basins at Hampton Inn site. Increasing inlet and pipe capacities relieved the flooding along Goodrich Avenue and oversizing underground detentions at Hampton Inn, reduced the combined peak flow at outlet of watershed.

Kentucky Division of Water Statewide FEMA Map Risk Update, Fayette County, FEMA/ KDOW FY2009-FY-2012-FY-2014-FY-2015: Scope of services included hydrological and hydraulic analysis for portion of **North Elkhorn, I-75 Tributary, East I-75 Tributary, portion of Cane Run Tributary, Pleasant Ridge Tributary, Two Ponds Tributary, Brighton Tributary, Iron Works Tributary, Pipeline Tributary, Quarry Tributary, Radio Tower Tributary, portion South Elkhorn Tributary, Stonewall Tributary, Avon, David Fork, Johnson Road Tributary, Shannon Run Tributary, Walnut Hill Church Tributary, Boone Creek Tributary, Jones Creek Tributary, Manchester Branch Tributary, Shelby Branch Tributary, Mary Reynolds Creek, I-64 Tributary, Dixie Tributary, Bryant Road Tributary, Waveland Museum Tributary, Baughman Fork Tributary, East Hickman, West Hickman, and Todd's Road Tributary approximately 230 miles of limited and detail studies**. The hydrological/hydraulic study was conducted per FEMA Guidelines and Specifications for Flood Hazard Mapping Partners Appendix C: Guidelines for Reverie Flooding Analysis and Mapping, November 2009. The outcome is used to establish base flood elevation and delineate the floodplain and floodway for multiple storm events, including 10-, 25-, 100-, and 500-year events. USGS stream gages within the study area were used to calibrate hydrological/hydraulic model. Frequency analysis using the log-Pearson Type III was developed to compare the peak flow for the 100-year, 24-hour storm event.

Hamburg East-Stormwater Management Plan (2010-2014): Scope of services consisted of the modeling, design, permitting with COE/KDOW/FEMA, bidding, construction administration, and inspection of two regional detention basins, five regional water qualities (wetlands), and 100 feet wide of riparian corridor of native species along the Brighton Tributary of approximately 4,000 linear feet. Scope of services also included conducting monthly and semi-annual inspections to monitor grows and survivability of plants within the wetlands and riparian corridor.