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Assessing the water quality benefits of green infrastructure stormwater control measures.

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ASSESSING THE WATER QUALITY BENEFITS OF GREEN INFRASTRUCTURE STORMWATER CONTROL MEASURES

by
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DEDICATION

I dedicate my dissertation work to my always encouraging, ever faithful parents, Ebrahim Abdollahian and Yassamin Yaghmaee.

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ABSTRACT

ASSESSING THE WATER QUALITY BENEFITS OF GREEN INFRASTRUCTURE STORMWATER CONTROL MEASURES

Sam Abdollahian

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Permeable pavements systems and tree boxes are a common type of Green Infrastructure (GI) Stormwater Control Measures (SCMs) that are often used for mitigating the stormwater runoff. In this study two permeable pavement systems and a tree box installed along parking lanes of an urban street in Louisville, KY, were investigated to evaluate their performance on improving stormwater runoff quality. The water quality monitoring was accomplished by analysis of samples collected from stormwater runoff and the captured stormwater volume at the bottom of the permeable pavements' sub-base reservoir and by a drain gauge (lysimeter) installed in the tree box. Pollutants investigated included total suspended solids (TSS), nutrients, dissolved metals, and bacterial contamination (*E. coli*). The results showed that permeable pavements significantly reduced concentrations of TSS and *E. coli,* as well as other pollutants such as total phosphorus and ammonia. It was also observed that the pollutant removal

efficiencies of these two permeable pavement systems were affected by rainfall characteristics such as intensity and antecedent rainfall conditions. This work suggests that to appropriately assess the beneficial water quality components of GIs, it is essential to couple the information with a comprehensive rainfall analysis.

The field investigations on GI controls were followed by a large scale lab study was conducted to mimic the observed behavior within a controlled environment. A 6-ft tall pipe (column) with the same diameter as the shafts that were implemented in permeable pavements and tree boxes (18 inches) was filled with the same aggregate layers which were used in actual GI controls. Semisynthetic stormwater runoff was introduced to the column, pollutant removal mechanism of each layer of aggregates used in the GI controls was investigated.

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1 INTRODUCTION

1.1 Background

In order to restore and maintain the chemical, physical, and biological integrity of surface waters of the United States, the Clean Water Act (CWA), or the Federal Water Pollution Control Act, was passed by Congress in 1972. Section 303 of this act holds the individual states responsible for enforcing water quality and establishing Total Maximum Daily Loads (TMDLs). TMDL is a pollutant measurement standard which refers to the maximum pollutant load a water body can bear and still meet water quality standards for its intended use (Bean 2005). At first, the focus of these standards were point source pollution such as factories and sewage treatment plants. However, approximately half of the identified estuarine water quality impairment cases across the United States were caused by nonpoint sources such as stormwater runoff. As a result, in 1987 Congress amended the CWA by establishing requirements for stormwater runoff quality (Bean et al. 2007).

Many communities are working to address stormwater quality requirements as they pertain to urban runoff. The stormwater problem is compounded, however, as in many areas Combined Sewer Systems (CSSs) are used to convey both stormwater and sanitary sewer flows. In dry weather conditions, the CSSs piping system collects sanitary sewer from residential and industrial users and delivers it to the treatment plant.

In wet weather conditions the CSS piping system will collect both the sanitary sewage and the stormwater runoff. During periods of significant rainfall events, a combined sewer system may not be able to convey the volume, and some of the combined runoff and raw sewage will overflow from the piping system, discharging directly into the nearest waterbody without treatment. The combined sewer overflow (CSO) is considered as a point source pollution, and can cause severe damage to the water quality of the receiving bodies. Figure 1 shows a CSS in both dry and wet weather conditions.

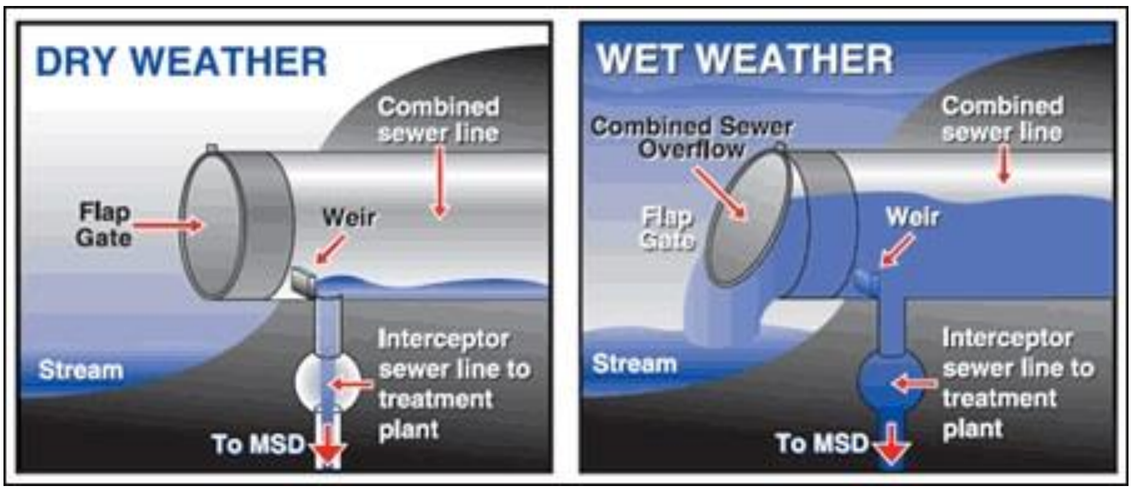

Figure 1- Combined Sewer System (CSS) in dry and wet weather (Louisville MSD)

One of the common techniques to reduce CSOs is to incorporate "green infrastructure" (GIs) practices within the community. GIs are physical systems that work to intercept stormwater before it enters the CSS and divert it into the ground water or other receiving water body. By diverting the stormwater runoff, flow within the CSS and ultimately any associated overflows, are reduced.

Green Infrastructures are highly recommended by the U. S. EPA as a flexible and cost-effective method to overcome the water quality problems caused by CSOs. Some examples of GI practices include tree boxes, porous and permeable pavements, rain gardens, green roofs, pocket wetlands, infiltration planters, and vegetated swales (Kloss 2008). The environmental and economic benefits of GI practices typically include (Foster et al. 2011):

- Land value
- Quality of life
- Public health
- Hazard mitigation
- Regulatory compliance

1.2 Statement of the Problem

Green infrastructure practices are well known to provide many positive benefits with respect to managing stormwater runoff. While GI practices work to effectively reduce the volume of polluted waters associated with CSOs, there is little understanding with respect to quality of the stormwater that is diverted from the GI systems directly into receiving water bodies or the ground water. A wide range of pollutants which originate from transportation activities accumulate on highway surfaces. As a result of the impermeable surfaces in urbanized areas, these pollutants can be conveyed during storm events directly into the receiving waters and degrade water quality (Gan et al. 2008).

The most common pollutants in stormwater runoffs are sediments and nutrients, which are mainly caused from agricultural land, small and medium sized animal feeding operations, and construction sites. Pathogens (bacteria and viruses), heavy metals, deicing salts, oil and grease are some other nonpoint pollutants which are common in stormwater runoffs and could be a danger to the quality receiving waters. GI systems such as permeable pavements, grass and rock channels, and tree boxes will collect the contaminated stormwater runoff water and introduce the captured water to the groundwater; thus, there is concern that while GI systems work to efficiently reduce stormwater runoff quantity, they may adversely work to degrade the water quality of surrounding water systems especially areas around streams, rivers, lakes and coastal environments which represent zones of interaction and transition between the ground water and surface waters (Westbrook et al. 2005).

1.3 Objectives of this Research

Green infrastructure practices are a cost-effective solution recommended by EPA in order to solve the overflow issues of combined sewer systems. While much effort has been focused on mitigating stormwater quantity, little effort has been focused on mitigating stormwater quality issues in field applications. It is believed that GI practices can be effectively designed to mitigate both stormwater quantity and quality concerns. As such, the main goal of this research is to investigate the filtering efficiency of permeable pavements and tree boxes within a real urban environment.

In order to assess the effectiveness of GI systems to achieve water quality goals, a field sampling and laboratory testing program was designed to address specific issues. Per ASCE-EPA (2002), the following questions were used to guide the analysis (Strecker et al. 2002):

i. What degree of pollution control or effluent quality is provided by the GI control under normal conditions?

ii. How does the filtering efficiency of the control vary from pollutant to pollutant?
iii. How does the filtering performance of the GI control vary with large or small storm events?
iv. What is the effect of rainfall intensity on the pollutant removal of the GI control?
v. How would the maintenance approaches affect the efficiency?
vi. How does the efficiency vary over time?
vii. How effective is the GI system compared to other GI systems in case of water quality control?

1.4 Methodology

In order to assess the filtering efficiency and the degree of pollutant control of each GI system, water samples were collected from the runoff before entering the GI control and also from the runoff captured by each control. Also a wide range of stormwater runoff pollutants were selected to investigate the filtering efficiency from pollutant to pollutant in each GI system. Pollutants and water quality parameters measured in this study are listed in Table 1. The important factors considered when selecting the key monitoring parameters suggested by ASCE-EPA (2002) include:

a) The pollutant has been identified as prevalent in typical urban stormwater at concentrations that could cause water quality impairment.
b) The analytical result can be related back to potential water quality impairment.
c) Sampling methods for the pollutant are straightforward and reliable for a moderately careful investigator.
d) Analysis of the pollutant is economical on a widespread basis.

Table 1- Pollutants and water quality parameters measured in this study

Parameter	Units
Conventional	
Total Suspended Solids (TSS)	mg/L
Conductivity	(uS/cm)
Temperature	(°C)
pH	
Bacterial	
E. coli	CFU/100ml
Nutrients	
Phosphorus-Total (TP)	mg/L
Nitrate-N (NO_3)	mg/L
Nitrite-N (NO_2)	mg/L
Ammonia (NH_3)	mg/L
Heavy metals	
Iron (Fe)	μg/L
Copper (Cu)	μg/L
Lead (Pb)	μg/L
Zinc (Zn)	μg/L

The water quality data was collected over a 12 month period to investigate the effect of time and seasonal changes on the filtering performance of the GI controls. Also use of additional monitoring instruments such as pressure transducers and rain gauges in the controls provided the ability to study the effect of the rainfall event characteristics on water quality within the GI controls.

1.5 Case Study

Permeable pavements and tree boxes are the two types of GI controls constructed in CSO130. Two methods are used in these GI systems to reach the underplaying sandy soil with higher hydraulic conductivity, the first method is deep shafts excavated under the tree boxes and a number of permeable pavements sections, and second method which is 2-3 feet wide trenches which are used in the rest of the permeable pavement strips. In order to compare the water quality performance of each one of these GI systems, water quality samples were collected and analyzed from a tree box, a permeable pavement with trench system and a permeable pavement with multiple shafts, during a 12-month period (May 2014 to 2015).

In addition to the field investigations on GI controls, a large scale lab study was conducted to mimic the observed behavior within a controlled environment. A 6-ft tall pipe (column) with the same diameter as the shafts that were implemented in permeable pavements and tree boxes (18 inches) was filled with the same aggregate layers which were used in actual GI controls.

By introducing semisynthetic stormwater runoff to the column, an opportunity has been provided to study the filtering mechanism of each layer of aggregates used in the GI controls.

2 LITERATURE REVIEW

2.1 Introduction

In urbanized areas, the replacement of vegetation with impervious surfaces such as parking lots, roof tops, and roadways will cause an increase in stormwater runoff volumes and pollutant loads (Rushton 2001). As impervious areas increase, the areas available for infiltration decrease, resulting in an increase of both the volume and peak rate of surface runoff. Figure 2 shows an example of how the hydrologic setting is altered by increasing impervious surfaces in urbanized areas.

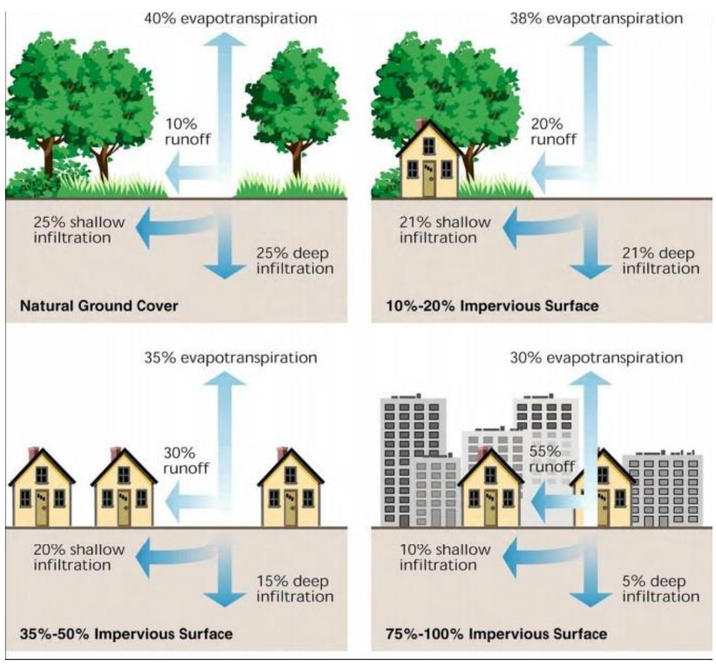

Figure 2- Change in the hydrologic cycle as the percent of impervious surfaces increases (NRC 2009)

In addition to higher amounts of stormwater runoffs resulting from urbanization, the runoff quality also shifts from a relatively low to a high pollutant concentration. Pollutants are commonly deposited on roadways and parking lots during wet or dry conditions form exhaust emissions, pavement and vehicle wear, application of chemicals for fertilization and pest control, atmospheric deposition of pollutants, and deicing material (Burns 2012; NRC 2009). These pollutants will be picked up by the stormwater runoff during rain events, and deposited into surface waters or introduced into groundwater.

In order to control the stormwater runoff, several methods are used by hydrologists and engineers to reduce the volume of water that will reach the surface waters or sewer systems. Green infrastructure (GI) stormwater controls, such as stormwater ponds, infiltration practices, and stormwater wetlands are techniques which are frequently used to reduce peak flow of the runoff. GI controls also believed to have substantial impact on mitigating nonpoint source pollution carried by the stormwater runoff (Bean et al. 2007; Kazemi and Hill 2015).

While a significant amount of work has been completed with respect to using GIs to control stormwater runoff volumes (quantity), only limited work has been completed with respect to using GIs to mitigate stormwater quality issues. Thus, to appropriately design a GI system to address both quantity and quality issues, it is important to have a full understanding of the anticipated pollutant loadings. As such, the first few sections of this chapter are focused on the stormwater runoff characteristics, pollutants in runoff and their sources, and the factors affecting the quality of the stormwater runoff. The next sections of this document are dedicated to a brief literature review on previous studies regarding the pollutant removal efficiency of GI practices and their impact on the water quality, with an emphasis on infiltration practices such as permeable pavements, and then finally different pollutant removal mechanisms in each GI control and their effectiveness regarding different pollutants.

2.2 Pollutants in stormwater runoffs and their sources

The pollutants in urbanized areas typically accumulate on roadways and impervious surfaces during dry conditions. The deposited contaminants then are introduced to the receiving waters during stormwater, and snowmelt runoffs (Brinkmann 1985; Pitt et al. 1995). When the stormwater enters the GI, the contaminants can permanently bond to the matrix material in the control, or be removed during future storm events, maintenance processes or wind erosion (Brinkmann 1985; Burns 2012). The following sections discuss using a simple mass balance to assess the flow of the pollutants in an urbanized area. The mass balance calculation requires the understanding of input loads, permanent and temporary storage, controlled and uncontrolled losses and output (Figure 3).

2.2.1 Pollutant sources in stormwater runoff

For any water quality control program, identifying potential contaminant sources is important. In a typical urban environment, major contributors to stormwater pollution include; 1) Vehicular traffic, 2) Construction sites, 3) Corrosion of materials, 4) Deicing material used in cold seasons, 5) Animal waste, and 6) Littering and trash (Bannerman et al. 1993; Brinkmann 1985).

Vehicular traffic

Vehicle traffic on roadways is a source of liquid, gaseous, and solid pollutants in stormwater runoffs. Leakage of oil and other liquids from the vehicle, combustion exhausts (which contribute to the urban atmosphere significant amounts of carbon monoxide, nitrogen oxides, and lead), abrasion products from tire wear, and breaks or road surfaces will cause contaminants in all three states of matter.

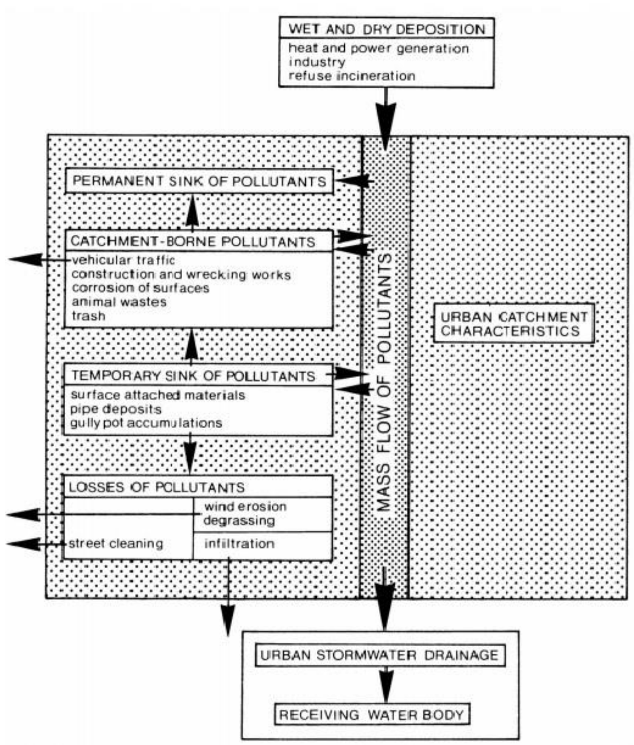

Figure 3- Mass flow of pollutants in an urban catchment (Brinkmann 1985)

Construction sites

Pollutions caused by construction sites are highly dependent on the urban planning and the economic structure of the community which will affect the material used in constructions (brick, stones, wood or cement). Generally particulate materials such as cement and brick debris are distributed on roadways and sidewalks, according to their grain size and wind velocity. High traffic volume transports these materials to the road curbs (Brinkmann 1985).

Corrosion of materials

The main cause of corrosion is known to be acid rain and aggressive gases; they will produce a considerable amount of corrosion on fences, paints and gutters, and will wash into the stormwater runoff (Brinkmann 1985). The rates of corrosion are highly dependent on the availability of corrodible materials, the frequency of these materials being exposed to acid solutions and gases, the drying-rewetting frequency on surfaces, the structure of the materials in the region, and post construction maintenance processes (Malmqvist 1983; Odén 1965).

Deicing material

Excessive application of deicing material and salts such as, sodium chloride, calcium chloride, and magnesium chloride a on the roads can cause serious problems to the receiving water sources, in addition to their adverse effect on the urban vegetation.

Trash and animal wastes

Trash and litter of all kind is commonly found in an urbanized area. This source of pollutants can be easily removed during the street sweeping process. Animal wastes are a source of nutrients and bacterial contaminations in commercial and residential areas which can be a health hazard, particularly for children (Brinkmann 1985).

2.2.2 Pollutants in stormwater

The most important and critical contaminants in highway runoffs are commonly placed into six main categories; 1) physical contaminants (sediments) such as Total

Suspended Solids (TSS), and turbidity (NTU), 2) trace metals (e.g., Lead and Copper), 3) microbial contaminants such as fecal coliforms and *E. coli*, 4) nutrients which refers to nitrogen and phosphorus compounds, 5) chlorides, and 6) petroleum hydrocarbons (Burns 2012; Shaver et al. 2007).

Physical contaminants (Sediments)

Sediments in the stormwater runoff can be measured in three different methods: Total dissolved solid (TDS), Total Suspended Solid (TSS), and turbidity (NTU). Measurements of TSS concentrations helps to estimate the sediment load transported by the runoff, TDS is a measure of minerals and dissolved solids in the runoff, and turbidity can be used to determine the impacts on the aquatic life, such as the ability of aquatic insects to use their gills, or the ability of the submerged vegetation to absorb light (Schueler 2003). In general, high levels of solids and turbidity in a stream will have adverse effects such as, sedimentation, stream warming, and decreased flow capacity. Sediments can also serve as a method of transportation for other pollutants that are attached to them including metals, nutrients and bacteria (Chen and Chang 2014; Crunkilton et al. 1996).

Roadways, erosion from exposed soils, construction sites, lawns and landscaped areas are known as the main sources of sediments in the stormwater runoff. High levels of sediments have been reported in construction site runoffs (Schueler 2003; Shaver et al. 2007).

Trace metals

Trace metals such as zinc (Zn), copper (Cu), lead (Pb), cadmium (Cd), and chromium (Cr), can be found in at potentially harmful concentrations in stormwater runoffs. These metals are mainly caused by the use of motor vehicles, weathering of metals and paints and atmospheric deposition, and usually reported as the total recoverable form or the dissolved form (Pitt et al. 1995; Schueler 2003; Shaver et al. 2007; Wilber and Hunter 1977).

The main concern caused by trace metals in streams is their possible toxicity to aquatic life. Bioaccumulation of metals in plants and animals, potential chronic or acute toxicity, and sediment contamination could be the adverse results of high concentrations of metals in streams (Masterson and Bannerman 1994).

Microbial contaminant

Microbial contamination refers to potentially hazardous concentrations of bacteria, protozoa, and viruses, which are common in the environment or could have a human source (Field and Pitt 1990; Mallin et al. 2000; Young and Thackston 1999). It should be noted that not all the microbes will cause disease and illnesses, and even many of them are naturally occurring and beneficial. Fecal coliform bacteria are a group of bacteria that could be found within the digestive systems of warm blooded animals, the presence of coliforms will indicate the existence of sewage or animal wastes in the water and shows that other harmful bacteria may be present, as well (Schueler 2003). *Escherichia coli (E. coil)*, is known to be a commonly used indicator of fecal contamination in water samples.

Failing septic systems, combined sewer overflows (CSOs), pet waste and natural sources such as wildlife are the main sources of bacterial contaminations . Bacterial pollutions are much more common in urbanized areas compared to undeveloped catchments, evidences indicate that bacterial contaminations can survive and even possibly grow in urban stream sediments, which makes the stormwater infrastructures a potential source of bacterial pollution (Bannerman et al. 1993; Mallin et al. 2000).

Nutrients

All aquatic ecosystems are in need of nutrients (nitrogen and phosphorous); however excessive concentrations of these elements can have an adverse impact on the aquatic system (Shaver et al. 2007). Nitrogen concentrations are reported in several ways; inorganic nitrogen which includes $NO_{3,}$ NO_2, organic nitrogen, total nitrogen (TN) which includes organic and inorganic nitrogen plus ammonia, and total Kjeldhal nitrogen (TKN) which is defined as the sum of organic nitrogen and ammonia. Phosphates are usually reported in two ways; soluble phosphorus which is the dissolved and reactive form of phosphorus, and total phosphorus (TP) which is the sum of organic and inorganic forms of phosphorus (Schueler 2003).

Significant nitrogen and phosphorus sources in urban runoffs are frequently associated with chemical fertilizers applied to lawns, gardens, and golf courses. In some cases, nutrient concentrations in lawn runoff has been four times greater than other urbanized areas such as rooftops and streets (Bannerman et al. 1993). Additional sources of nutrient pollution are known to be: inadequate treatment of waste water discharges, and failing septic systems, and snowmelt in urbanized areas (Schueler 2003; Shaver et al. 2007).

High levels of nutrient concentrations in stormwater runoff will cause eutrophication and excessive algae growth when subjected to sunlight and high temperatures in the receiving waters. Stimulated algae and aquatic plants will die off and be broken down by bacteria; this decomposition of algae and other organic matter carried by the runoff will reduce the amount of dissolved oxygen (DO) in the receiving waters and bottom sediment (Shaver et al. 2007). Low amounts of DO will result in the degradation of habitat conditions, offensive odors, and even fish kills in extreme situations (Carpenter et al. 1998).

Deicers and Chlorides

Sodium chloride, calcium chloride, and magnesium chloride are the main components of deicers which are used to melt the ice and snow on roadways and sidewalks during winter months. While small amounts of chlorides are essential for life, higher levels of chloride (concentrations of 500 to 1000 mg/l) can become toxic to many organisms in water, and contaminate ground water and drinking water supplies (Canadian Environmental Protection Act 2001; Shaver et al. 2007). The high concentrations of chlorides in snowmelt and stormwater runoff in cold weathers is often attributed to deicing operations (Oberts and Council 1994; Schueler 2003).

Petroleum hydrocarbons

Another common pollutant in the stormwater runoff in an urban area is petroleum hydrocarbon compounds, which typically originate from vehicle fuels and lubricants (Hoffman et al. 1982; Kucklick et al. 1997). The hydrocarbons are commonly composed of oil, grease and polycyclic-aromatic hydrocarbons (PAH) (Schueler 2003). Commercial parking lots, industrial highways, convenience stores, and gas stations are known to be significant sources of hydrocarbon compounds (Schueler 2003). The primary negative impact of hydrocarbons on streams is bioaccumulation in aquatic organisms such as crayfish, clams and fish (Moring and Rose 1997).

2.3 Factors affecting the stormwater runoff quality

Many factors such as traffic volume, rainfall characterization, highway surfaces, and local site conditions may affect the pollutant concentrations in stormwater runoff (Burns 2012; Huber et al. 2006; Kucklick et al. 1997; Program et al. 2006). These factors and their effect on the runoff quality are summarized in this section.

2.3.1 Traffic volume

Traffic density plays a significant role in determining the pollutant concentrations in highway runoffs. Traffic volume and vehicles will serve as a source of the accumulation of pollutant on highway surfaces, and also, their motion will cause the removal of pollutant from the road for deposition elsewhere (Barrett et al. 1998; Irish et al. 1995). As a result of this dual role of vehicles, it is difficult to develop a clear relationship between the Average Daily Traffic (ADT) and pollutant concentrations in runoff; therefore some investigators have used the Vehicles During Storm (VDS) as a measure of traffic volume (Barrett et al. 1995; Burns 2012).

Typically higher concentrations of pollutants are reported in the stormwater runoff from urban high-traffic sites, compared to those in low traffic sites (Barrett et al. 1998; Driscoll et al. 1990). Table 2 compares pollutant concentrations in the runoff samples collected from a high-traffic sit and a low-traffic site. However, reported correlations between ADT and pollutants such as; TSS, nitrate , phosphorus or heavy metals in previous studies, have not been strong (Barrett et al. 1995; Horner et al. 1979). On the other hand, VDS showed to be a more significant factor in predicting pollutant loads, and linear regressions have been reported between TSS and VDS (Chui et al. 1981; Horner and Mar 1982).

Table 2- Median concentrations of pollutants in the runoff for urban and rural highways in (mg/L) , (Driscoll et al. 1990)

Pollutant	Urban Highways ADT > 30,000	Rural Highways ADT < 30,000
TSS	142	41
VSS	39	12
TOC	25	8
COD	114	49
Nitrate + Nitrite	0.76	0.46
TKN	1.83	0.87
PO_4	0.4	0.16
Copper	0.054	0.022
Lead	0.4	0.08
Zinc	0.329	0.08

2.3.2 Rainfall characteristics

The intensity of the rainfall event, duration or volume of the rainfall, and the antecedent dry period are known as the main storm event related factors which can affect the pollutant concentrations in the runoff (Barrett et al. 1995; Burns 2012). Rainfall intensity will affect the stormwater runoff velocity and will have a direct influence on the mobility of pollutants in the runoff. The loading of pollutants is generally higher in longer storms, since the transport of at least some of the pollutants continues through the whole duration of the event (Barrett et al. 1995). Antecedent dry conditions are believed to affect the accumulation of the pollutants on the surface, especially those contaminants which are associated with solids (Chui 1997).

Rainfall Intensity

The intensity of the storm event is an important factor in determining the pollutant concentrations in the runoff. Through chemical or physical bonding, many pollutants are associated with solid particles, and these particles are mobilized more easily during the high intensity rain events. Thus, during significant rain events, large pollutant loadings should be expected. Positive correlations have been reported between rainfall intensities and pollutant concentrations such as TSS, heavy metals, Chemical Oxygen Demand (COD) and phosphorus (Hoffman et al. 1985; Horner et al. 1990).

Seven storms were monitored by Horner et al. (1990), and the pollutant loadings were compared for low intensity and high intensity events. The results indicate that the upper range of all contaminants in high intensity events are 2-3 orders of magnitude higher compared to the upper range in low intensity events, see Table 3.

Table 3- Pollutant loading for high intensity and low intensity rainfall events (Horner et al. 1990)

Storm Type	**TSS (mg/h)**	**VSS (mg/h)**	**TP (mg/h)**	**COD (mg/h)**	**Total Cu (µg/h)**	**Total Pb (µg/h)**	**Total Zn (µg/h)**
Low Intensity	7-35.72	2-1631	0.4-31.1	0-920	3-2178	0-354	31-3516
High Intensity	436- $14x10^6$	136- 322,704	5.8- 10,322	0- 195,969	121- 362,529	0- 175,472	343- 571,527

Antecedent Dry Period (ADP)

The number of antecedent dry days before a rainfall event will affect the stormwater runoff quality. As rainfall and stormwater runoff removes pollutants from the road surface, an extended dry period will enable pollutant accumulation. The relation between long ADPs and pollutant loadings, however, is only a weak correlation as pollutant loads are also be reduced as a result of air turbulence, volatilization, oxidation or other removal processes (Barrett et al. 1995)(Figure 4).

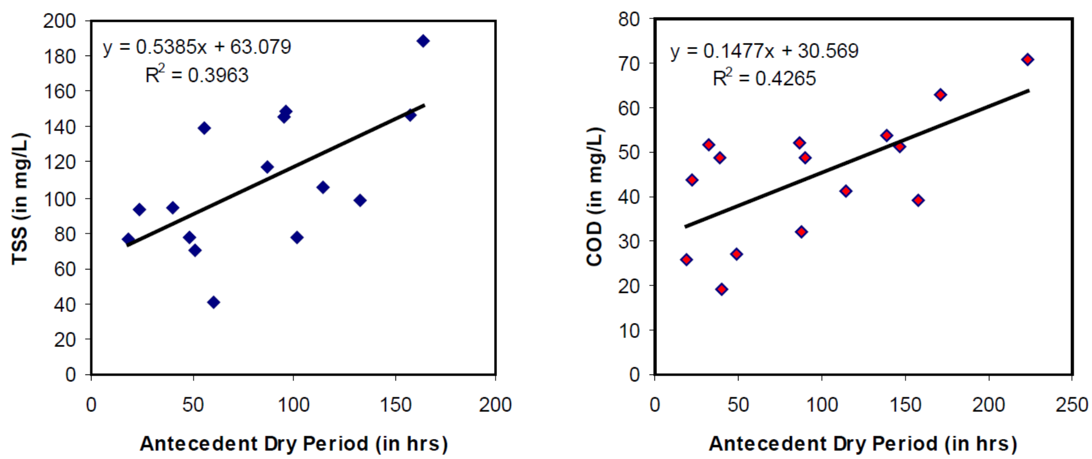

Figure 4- The correlation between TSS and COD and the antecedent dry period (Chui 1997)

Duration or volume of the event

Runoff volume is another rainfall characteristic which has a little effect on the pollutant concentrations; however it is an important factor in determining the total pollutant load flowing in to receiving waters. In general, the pollutant concentrations are higher in high intensity, shorter volume storms during summer, compared to larger storms, in which little or no runoff will occur on the unpaved area, and the runoff is diluted and the pollutant concentrations are lowered (Burns 2012; Dorman et al. 1988).

2.3.3 Highway characteristics

Another factor which may affect the stormwater runoff quality is the roadway characteristics. These characteristics include the materials used in the construction of the roadway, gaur walls, curbs and gutters, and drainage features (Irish et al. 1995). Data in literature suggests that concentrations of COD, TSS, oil and grease, nutrients and heavy metals are generally higher in runoff from asphalt surfaces (Gilbert and Clausen 2006; Gupta et al. 1981) (see Table 4); however the age and condition of the highway seems to have a more dominant effect on the stormwater runoff quality than the material of construction. An older highway will release a larger amount of aggregate in to the runoff, regardless of the material that it is made of, and presence of guard walls and curbs will prevent the pollutants from being removed from the highway surface during dry periods (Driscoll et al. 1990; Gupta et al. 1981).

Table 4- Annual pollutant export from three different types of pavers (Gilbert and Clausen 2006)

Pollutant	**Asphalt (kg/ha/yr)**	**Paver (kg/ha/yr)**	**Crushed stone (kg/ha/yr)**
TSS	230.10	23.10	9.60
NO_3-N	1.78	1.25	0.15
NH_3-N	0.65	0.12	0.03
TKN	13.06	1.08	0.47
TP	0.81	0.25	0.04

2.3.4 Site specific factors

Site specific factors that can affect the runoff quality are; 1) maintenance practices, 2) deicing practices which will affect the chloride concentrations during winters, 3) institutional characteristics such as litter ordinances, speed limits or car emission regulations, 4) topographic cross section of the highway which can affect the pollutants leaving the roadway, (Driscoll et al. 1990), and 5) highway drainage conditions which will affect the pollutant concentrations that will reach the receiving waters (Burns 2012).

2.4 Green infrastructures and their pollutant removal performances

Green infrastructure systems are commonly divided into three main categories based on their method of pollutant removal, which are; 1) detention ponds and wetlands, 2) filtration practices, and 3) infiltration practices. The pollutant removal efficiency of these main categories is summarized in Tables 5 and 6 (according to the National Pollutant Removal Performance Database. The median, maximum and minimum pollutant removal percentages are reported in these tables.

Table 5- Removal efficiency statistics for ponds and wetlands (Winer 2007)

GI System	TSS	TP	Sol P	TN	NO_x	Cu	Zn	Bacteria
Dry Ponds (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 (wet extended detention ponds, multiple pond systems, wet pond)								
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 (Shallow marsh, detention wetland, submerged gravel wetlands)								
Median (%)	72	48	25	24	67	47	42	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								

Table 6- Removal efficiency statistics for filtering practices, infiltration practices, and open channels (Winer 2007)

GI System	TSS	TP	Sol P	TN	NO_x	Cu	Zn	Bacteria
Filtering Practices (Organic filters, surface sand filters, vertical sand filters and perimeter sand filters)								
Median (%)	86	59	3	32	-14	37	87	37
Min (%)	8	-79	-37	17	-100	22	33	-85
Max (%)	98	88	78	71	64	90	94	83
# of studies	18	17	7	9	14	13	18	6
Infiltration Practices (Permeable pavements, 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
Open Channels (Ditches, dry swales, wet swales, and grass channels)								

Median (%)	81	24	-38	56	39	65	71	-25
Min (%)	18	-100	-100	8	-25	-35	-3	-100
Max (%)	99	99	72	99	99	99	94	99
# of studies	17	16	14	9	16	16	16	3
-N/A indicates that data is not available -Sol P = Soluble Phosphorus; NO_x = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn= Zinc								

As it can be seen in the tables, permeable pavements and infiltration trenches showed a relatively high removal percentage for TSS, TP, soluble P, Copper, and Zinc. The removal values for total nitrogen and nitrogen oxides were lower in infiltration practices compared to other GI systems. It should be noted that lowest number of studies on pollutant removal of GI controls is associated with infiltration practices and permeable pavements, and there is no data available on their performance in removing the bacterial contaminations.

2.5 Pollutant removal processes in GI controls

When storm water runoff is captured by a green infrastructure control, the pollutants and other loadings are also carried with the flow. Thus, the GIs can be a barrier to the pollutants such that they do not contaminate receiving waters. GIs commonly provide some level of pollutant removal through a combination of physical, chemical, and biological processes (Huber et al. 2006; Scholes et al. 2008). Knowing these removal processes will lead to better understanding of the pollutant removal potential of a GI control. The following sections provide a conceptual review of unit operations and processes (UOPs) needed to treat the stormwater runoff, along with examples.

2.5.1 Physical processes

The physical removal of pollutants within green infrastructure systems is due to mechanical action as opposed to chemical and biological processes. Main physical mechanisms include, settling, filtration, and volatilization. Physical unit operations are known as the basis of many preliminary and primary treatments in wastewater treatment, and they are also the dominant forms of treatment in stormwater runoff GI controls (Huber et al. 2006; Metcalf and Eddy 2003).

Filtration

This removal process in GI systems occurs by the same mechanisms as those in conventional water treatment plants, in which sand filters remove the particulate pollutants by physical sieving (Ellis et al. 2006). Permeable pavements especially porous asphalts, infiltrations trenches, and infiltration basins are considered to have higher potential for filtration. Other GI controls such as detention basins and retention ponds will have a low filtration potential due to the limited contact between stormwater and the basal substrates (Scholes et al. 2008).

Settling

Settling refers to the vertical movement of suspended sediment particles towards the base of a water column, which highly depends on the retention of a quiescent water volume within the GI control (Scholes et al. 2008). Settling is known to be the main mechanism in infiltration basins, detention basins and retention ponds (Pettersson et al. 1999; Revitt 2004). In contrast, the absence of a persistently still water body in GI systems such as permeable pavements and filter strips will reduce the potential for settling process.

Volatilization

Volatilization is the process in which liquids and solids vaporize and escape to the atmosphere. Compounds that easily evaporate at normal temperatures and pressures are known as volatile compounds. These compounds are not frequently found in the stormwater runoff; however volatile or semi-volatile organic carbons (VOCs/SVOCs) are sometimes present in petroleum hydrocarbons, pesticides, and herbicides. Since these compounds are highly soluble in water and can easily migrate to groundwater resources, it is recommended to remove them from the runoff prior to infiltration process (Huber et al. 2006; Scholes et al. 2008).

The volatilization from water surface occurs in three steps: 1) escape from the water surface, 2) diffusion through the boundary layer, and finally 3) advection and hydrodynamic dispersion in to air (Huber et al. 2006). see Figure 5.

Optimizing surface area exposure to the atmosphere and the exposure time of stormwater runoff, will lead to higher degrees of volatilization. This is the reason that volatilization removal potential is highest in extended detention basins, retention ponds, constructed wetlands, and swales (Scholes et al. 2008).

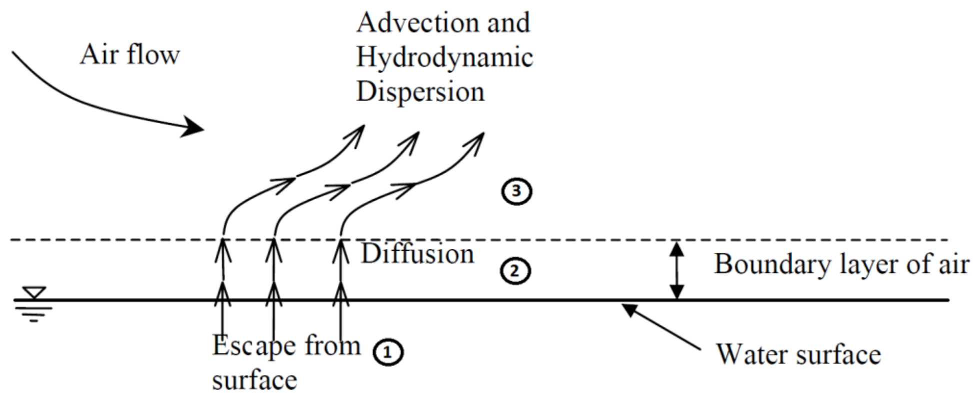

Figure 5- Three steps of volatilization from a free water surface (Huber et al. 2006)

2.5.2 Chemical processes

Chemical characteristics of the stormwater runoff, such as pH, conductivity, ionic concentrations, and hardness, can affect the pollutant removal potential of the GI system; this will dictate the type of the GI control and processes needed to treat the pollutants. The common chemical processes for stormwater runoff treatment applied in GI controls, are: 1) sorption, 2) flocculation, 3) precipitation, 4) coagulation, and 5) chemical agent disinfection (Huber et al. 2006; Scholes et al. 2008).

Sorption

Sorption refers to, adsorption and absorption, which are two separate unit processes. In case of absorption, a substance of one state bond with another substance of a different state (e. g., a pollutant in its gases state being absorbed by water or another liquid). However, adsorption is the bonding of ions and molecules onto the surface of another molecule. Petroleum hydrocarbons in the stormwater runoff are usually targeted with absorption, while nutrients, dissolved metals, and PAHs are targeted by the adsorption process (Huber et al. 2006). Sorption is an important potential removal process in filter drains, porous pavements (Legret and Colandini 1999), constructed wetlands, and infiltration basins (Scholes et al. 2008).

Precipitation, Coagulation, and Flocculation

Precipitation, coagulation and flocculation usually take place simultaneously or in quick succession (Huber et al. 2006). Chemical precipitation is one of the most common processes used to remove metals and other ionic contaminants from the stormwater runoff. Precipitation is referred to the process which causes the contaminants to transform from a dissolved state to a solid state, and settle out of the solution as solid precipitates (Arora et al. 2003). Coagulation is the process which destabilizes the colloidal particles, causing the particle growth to occur. Flocculation is the process in which fine particles collide and form larger particles which can be easily removed using physical processes such as filtering and settling (Huber et al. 2006).

Chemical agent disinfection

Chemical disinfection refers to application of chemical agents such as ozone and chlorine in order to reduce the concentration of pathogens in stormwater runoff. Use of chemical agents immobilizes pathogens through mechanisms such as damaging the cell walls, altering the cell wall permeability, alteration of DNA or RNA of the pathogen, and inhibition of pathogen enzyme activity (Huber et al. 2006; Metcalf and Eddy 2003).

2.5.3 Biological processes

Biological processes take place when live organisms including, plants, algae, and microbes are used to remove or transform the organic and inorganic pollutants. Two main categories of the biological processes are: 1) plant and algal uptake, and 2) microbial degradation (Huber et al. 2006; Scholes et al. 2008).

Plant uptake

Plants will uptake essential nutrients to sustain growth. These nutrients may be assimilated from the stormwater runoff going through the GI system. In addition to nutrients, various algae and plants accumulate organic and inorganic constituents in excess of their immediate needs which is known as bioaccumulation (Huber et al. 2006). The potential of plant uptake is provided in the presence of aquatic or terrestrial vegetation; therefore this process is not applicable in GI systems such as permeable pavement and sedimentation tanks which are non-vegetated, however pollutant bioaccumulation by cell tissues at a low level may occur in porous paving, filter drains, and infiltration trenches as a result of algal growth on the sub-surface gravel or other filler material. On the other hand, the potential of plant uptake will be highest in constructed wetlands, due to high contact between the stormwater runoff and the root system of aquatic macrophytes (Scholes et al. 2008).

Microbial degradation

The microbial degradation process includes the degradation of organic pollutants, as well as the oxidation or reduction of inorganic pollutants by microbial activity (Huber et al. 2006). This mechanism is enabled by the availability of attachment sites and nutrients in the GI system. Since high contact ratio between the stormwater and substrate material will increase both aerobic and anaerobic processes (Scholes et al. 2008), infiltration basins and constructed wetlands will encourage the microbial degradation process (Ellis et al. 2003). The impact of this removal process will be lower in GI systems such as permeable pavements, sedimentation tanks, and filter drains, due to the lower potential for the stormwater runoff to interact with the substrate material, which acts as host for microbial communities (Scholes et al. 2008).

3 MATERIALS AND METHODS

3.1 Introduction

The purpose of this section of the document is to describe the methods and sampling plans used in collecting and analyzing the data. Description of the study area, sampling locations and protocols, instruments used for field measurements, as well as test procedures and data analysis will be discussed in detail.

3.2 Description of the Study Area

Due to the CSOs which occur during heavy rain events, the City of Louisville and the Louisville and Jefferson County Metropolitan Sewer District (MSD) has committed to take remedial actions in order to control overflows under a Federal Amended Consent Decree. The Consent Decree is a federally-enforceable, legally binding agreement between MSD, the US Department of Justice, the EPA, and the Kentucky Department for Environmental Protection (KDEP). In order to meet the requirements of the Amended Consent Decree which is to mitigate the effect of wet weather CSOs and to eliminate sanitary sewer overflows (SSOs), a comprehensive plan known as the Integrated Overflow Abatement Plan (IOAP) was prepared by MSD. After a values-based benefit-cost analysis, the IOAP suggested a balanced combination of GI practices and gray solutions which include options such as storage, treatment, conveyance/transport, and sewer separation to mitigate and control the sewer overflows.

One of the MSD initial steps in mitigating the effect of CSOs using GI practices was installing a set of GI controls in CSO basin 130 (CSO130), which is an 11 hectare (28 acre) portion of the MSD service area located in an urbanized area in East Louisville's Butchertown neighborhood. Eighteen permeable pavement sections were installed in the street as a parking lanes and a series of 29 tree boxes were installed in the sidewalk in two sets of constructions during autumn 2011 and spring 2013.

The 29 tree boxes, which are installed on the sidewalk of Story Ave., are 6-ft (1.8 m) long by 4-ft (1.2 m) wide by 6-ft (1.8 m) deep and receive runoff through curb cuts. The 18 permeable pavement sections, which consist of a layer of articulated concrete blocks (ACB) covering a 2-ft (0.6m) storage gallery are eight feet wide with lengths ranging from 55 to 130ft (16.8m to 39.6m), are installed on the parking lanes of Story Ave., Adam St., E. Washington St., and Webster St. (Figure 6).

The intent of the permeable pavement sections is to capture a large volume of stormwater and redirect it into the groundwater system. Due to the geology of the site, two methods were used to reach the soil layers which were suitable for appropriate exfiltration of the captured stormwater volumes; this is because the sandy layers with high exfiltration rates were located in depths between 10 to 30 feet from the asphalt surface. The first method is a 2 to 3ft wide trench which is used in 6 of the permeable pavement strips in order to reach deeper soils with higher hydraulic conductivity. The second method is using a series of shafts (4 to 14 shafts) which are drilled under the other 12 pavement strips and also the tree boxes. Both trenches and shafts are filled with American Association of State Highway and Transportation Officials (AASHTO) #3 stone.

Two permeable pavement systems (GI control 17G with the trench design and GI control 17H with the shaft design), and one of the tree boxes were chosen to be investigated for their pollutant removal performance during a one year period starting from May 2014.

The two monitored permeable pavement systems were installed along the parking lanes of Webster St., up- gradient of existing sewer system's catch basins, see Figure 1. The specific dimensions of each control are shown in Figure 7 and 8 and Table 7, and the general construction of each system is as follows:

- A layer of 14.35-cm (5.65-inch), Articulating Concrete Block (ACB) on top, leveled with the existing asphalt. The ACBs, unlike other common Permeable Interlocking Concrete Pavers (PICPs) don't require fine aggregates between their joints.
- A 61-cm (2-ft) deep storage gallery is filled with one foot of AASHTO #3 stone on the bottom and 30.5 cm (1 ft) of AASHTO #57 aggregate on top. A geo-grid is also installed between the aggregate layers.
- A series of drilled shafts or a trench were excavated along the 61-cm (2-ft) storage gallery as an access method to the deep soils with higher permeability values and back filled with AASHTO #3 aggregate. The depth of trenches and shafts varied and were off center to avoid existing utility lines.

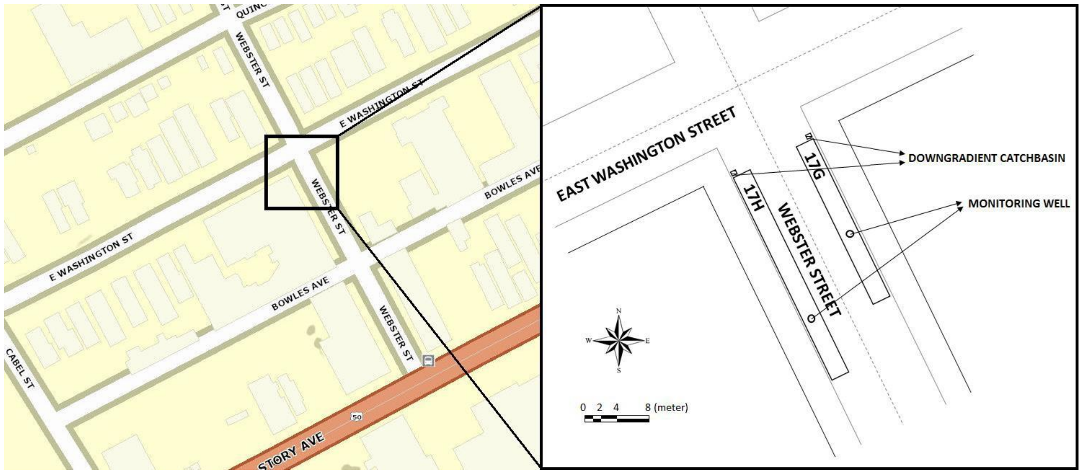

Figure 6-Location of GI Controls 17G and 17H along Parking Lanes of Webster Street

Table 7-Design characteristics for permeable pavement systems

GI Control ID	Electronic Water Quantity Monitoring	Length (m)	Width (m)	Method to access deep soils	Trench width or number of shafts (m)	Depth of Trench/Shafts (m) †
17H	No	27.4	2.4	Shafts	10	2.7
17G	Yes	21.3	2.4	Trench	0.7 m	2.1 – 4.6

The shaft casings in GI Control 17H are 1.5 ft (45.72 cm) in diameter and are drilled to the sand layer, ranging from 2 to 4 meters. The shaft casings have slotted sections on their sides to allow for lateral infiltration as well as infiltration through bottom area. Control 17G has a 2.5-ft (76.2-cm) wide trench excavated along its full length with a variable depth of 4.57 meters (15 feet) at the upgradient edge and 2.13 meters (7 feet) at the downgradient edge. Figure 7 shows a cross sectional view of the two GI controls.

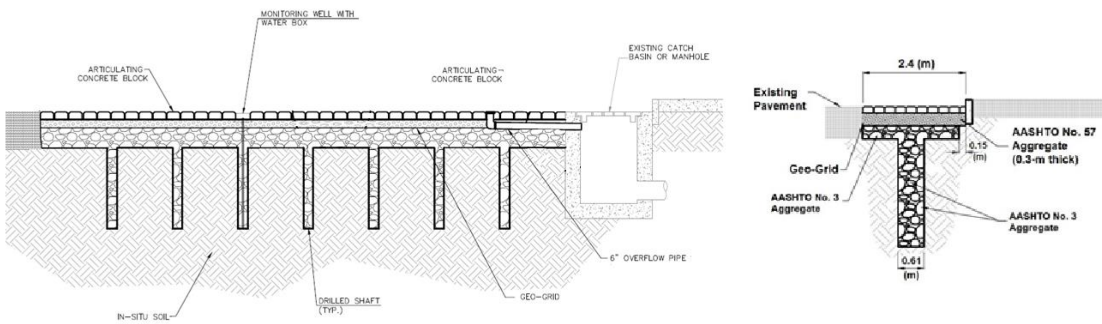

Figure 7 - Longitudinal cross section (left) and cross section view (right) of permeable pavement 17 H (shaft system)

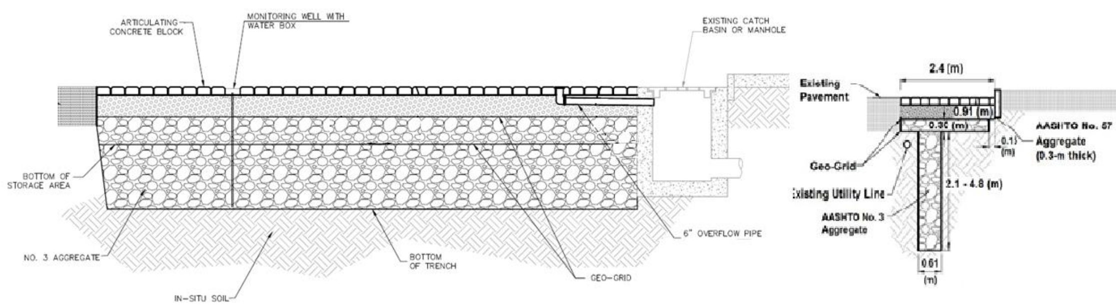

Figure 8 - Longitudinal cross section (left) and cross section view (right) of permeable pavement 17 G (trench system)

In addition to studying the water quality characteristics of the two permeable pavement sections, this study investigated the water quality performance of the tree box 10C. Specifically, tree box 10C was instrumented with a drain gauge (lysimeter) in the bottom that provides the opportunity to collect water quality samples during rainfall events. As mentioned earlier the tree boxes receive runoff through curb cuts along Story Avenue. A precast concrete structure is placed in the excavated tree box pit to provide structural stability. A 2-ft (0.61-m) thick layer of AASHTO No. 3 aggregate was placed at the bottom of the tree box. The gravel was covered by about 4-ft (1.2 m) of selected media. MSD selected a mix of 60% sand, 30% compost, 10% topsoil for the media. A single tree was planted in each tree box. Figure 8 shows a cross sectional view of the tree box and the location of the lysimeter.

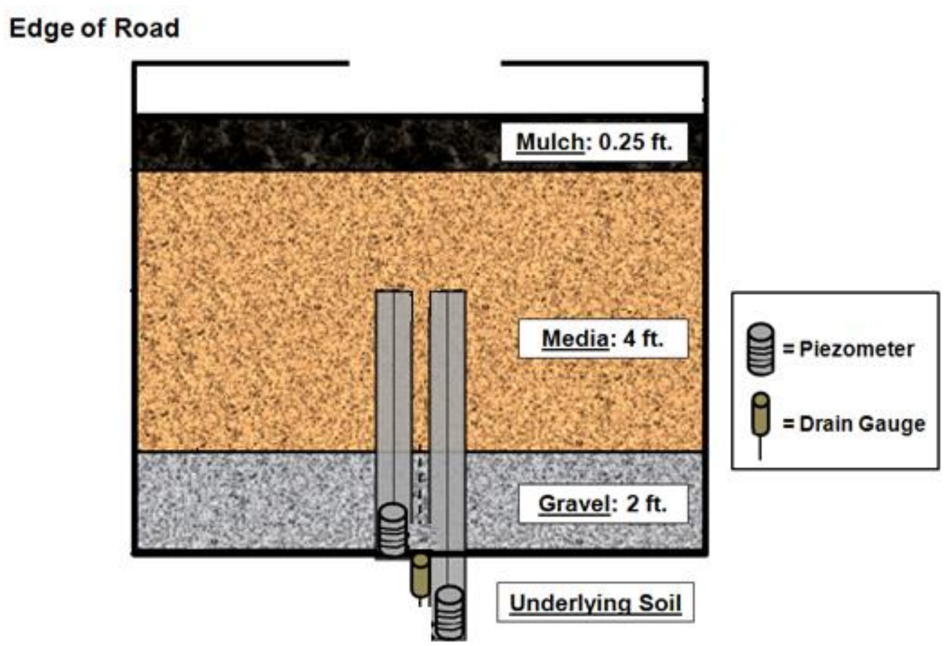

Figure 9-Cross sectional view of the tree box

3.3 Sampling Locations and Strategies

The most commonly used method to evaluate the stormwater best management practices (BMPs) and GI controls such as permeable pavements and tree boxes is based on collecting composite samples and comparing pollutant concentration levels at specified inflow and outflow points (Quigley 2009; Strassler et al. 1999). Since using an automatic sampler was impossible to collect flow-weighted samples from the water exfiltrating the permeable pavements and tree boxes, it was decided to collect time-weighted composite samples during the first half inch of the rain event.

The runoff from the first half inch of precipitation is referred to as 'first flush', which represents a small portion of a storm's total discharge, but a large percentage of the total contaminant loading (Prince Georges County 1999). According to the National Stormwater Quality Database, first flush concentrations of TSS, COD, TDS, total copper, total lead, total zinc and TKN are significantly higher than the composite sample collected during the entire rain event (Maestre and Pitt 2005). It has also been considered that GI control and BMPs focusing on treating the first flush runoff will be a more economical approach for reducing pollutants from the stormwater (Barco et al. 2008).

Collecting samples during the first flush required the sampling team to be ready on site prior to the onset of the storm event; which made the weather forecasting an important aspect of the sampling. The National Weather Service (NWS) was used for the long term forecasts (5 day) to prepare the sampling equipment. The sampling team moved to the site in cases that NWS suggested the storm probabilities greater than 50%.

Three individual grab samples of equal volume (250 ml) were collected at equal time increments (10 minutes) during the first flush of each event; these samples were mixed to form a single time-weighted composite sample for laboratory and on site analysis. The composite samples from the runoff were collected at the upgradient location of permeable pavements at the curb side, and from the runoff water flowing into the tree box at the curb cut.

Time-weighted composite samples (mix of three grab samples collected every 10 minutes) were also collected from the bottom of the trench and shaft systems in GI controls 17G and 17H and from the lysimeter installed in the bottom of the tree box 10C. The samples from the shaft and trench systems were collected through monitoring wells (Figure 6) using a mechanical bladder pump (model MB470, Geoprobe Systems, Salina, Kansas), capable of obtaining high-quality ground water samples (Figure 9), and the water captured by the lysimeter in the tree box was collected using a 60 ml syringe.

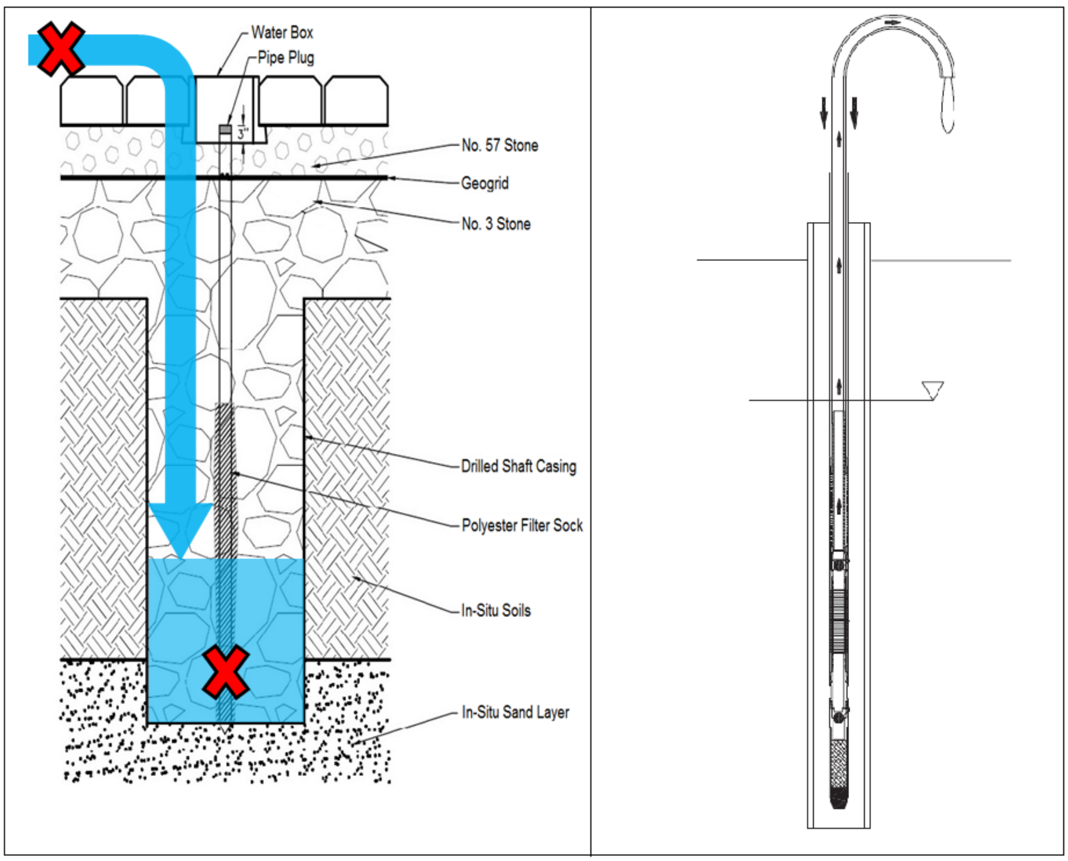

Figure 10-Schematic view of sampling points from the runoff and the captured volume in the bottom of the trench or shaft (left) mechanical bladder pump (right)

3.4 In Situ Measurements

Parameters such as water temperature (T), conductivity, total dissolved solids (TDS), and pH, were measured immediately after sample collections, using a YSI Professional Plus portable temp/conductivity/pH/TDS meter (YSI Inc., Yellow Springs, OH, USA). For pH measurements the electrode was calibrated before each sampling event using buffer solutions of pH 4, 7 and 10 (Fondriest Environmental Inc., Beavercreek, OH, USA), and the conductivity electrode was calibrated with a 1413 μS/cm conductivity standard solution (Fondriest Environmental Inc., Beavercreek, OH, USA).

3.5 Sample Preservation and Hold Times

All samples were collected in high-density polyethylene (HDPE) bottles and placed in a cooler partially filled with ice. Samples were delivered to laboratory within 6 hours for bacterial analysis, and nutrients where tested in a 24 hour period after sampling, except for those that followed special sample preservation protocols. USEPA recommended preservation methods, maximum holding times, and sample containers, for the pollutants measured in this study are listed in Table 8.

Table 8-Sample Preservation and Hold Times (Law et al. 2008)

Pollutant or the parameter	**Preservation**		**Volume required (ml)**	**Maximum Holding Time**	**Sample Container**
	Cool to 4°C?	**Additional**			
Temperature	N	_	1000	Immediately	Plastic or glass
pH	N	_	25	Immediately	Plastic or glass
Conductivity	Y	_	100	Immediately	Plastic or glass

TSS	Y	_	200	7 days	Plastic of glass
E. coli	Y	_	100	6 hours	Plastic
Metals (Dissolved)	N	Filter on site, HNO_3- pH<2	200	28 days	Plastic or glass
Nitrate	Y	H_2SO_4- pH<2	100	28 days	Plastic or glass
Total Phosphorus	Y	H_2SO_4- pH<2	150	28 days	Plastic or glass
Nitrite	Y	_	50	28 days	Plastic or glass
Ammonia	Y	H_2SO_4- pH<2	150	28 days	Plastic or glass

3.6 Analytical Methods

This section of the document is dedicated to a brief discussion of analytical methods used in the laboratory for different water quality parameters and contaminants, measured in this study. Included in each subsection is a description of the test apparatus and overview, or reference to an overview, of the specific test procedures, as well as the limitations and capabilities of each method and instrument. Table 9 summarizes the standard methods and the Minimum Detectable Levels (MDL) for each parameter. In samples with concentrations below the MDL, it was assumed that the concentrations were half of the MDL for statistical purposes.

Table 9- Standard test methods and their Minimum Detection Levels (MDL)

Parameter	Standard Method	MDL
TSS	Standard Methods procedure 2540D	1.0 mg/L
E. coli	EPA Method 1604	1 CFU/100 mL
Phosphorus-	Hach TNT843, Equivalent to	0.05 mg/L

Total (TP)	EPA 365.1	
Nitrate (NO_3)	Hach, TNT835 Approved by EPA	0.23 mg/L
Nitrite (NO2)	Hach TNT839, Equivalent to EPA 353.2	0.015 mg/L
Ammonia (NH_3)	Hach TNT831, Equivalent to EPA 353.2	0.015 mg/L
Copper (Cu)	ICP-OES Spectrometer EPA Method 200.7	5.4 µg/L
Iron (Fe)	ICP-OES Spectrometer EPA Method 200.7	6.2 µg/L
Zinc	ICP-OES Spectrometer EPA Method 200.7	1.8 µg/L

3.6.1 Total Suspended Solids (TSS)

The TSS concentrations were determined following the Standard Method 2540D (APHA 1999). In this method, known volumes of samples were filtered through 1.5 micron pore size, 47 mm diameter pre-weighed glass fiber filters (LabExact®) using a vacuum set. After the filtering and vacuum process, the filters were transferred to pre-weighed tins and were dried at 104 ±2 degrees Celsius overnight. The tins were reweighed the day after, and the mass increase per unit volume gave the total suspended solids. A maximum sample volume of 300 mL was used in this study; however the sample volumes, varied depending upon turbidity of the water and available sample left over from nutrient and *E. coli* analysis. Figure 10 shows the filters and the digital scale used in this study.

Figure 11-Glass fiber filters and the digital scale

3.6.2 Nutrient Analysis (NO_3, NO2, NH_3, and TP)

The concentrations of total phosphorus, nitrate, nitrite, and ammonia nitrogen were measured using a Hach spectrophotometer (Hach DR/3900, Loveland, CO). As mentioned in Table 9, Hach methods applied for these pollutants were equivalent to an USEPA method, or approved by the USEPA. Spectrophotometry refers to the measurement of the light absorbance by the sample; this light absorbance can be related to the concentrations of a chemical in the sample according to the wavelength of the light beam. The light source of the spectrophotometer can produce a wide range of wavelengths, from higher visible wavelengths to lower ultraviolet scale.

The spectrophotometric analyses for all the nutrients were performed in prepared digestion vials. Three different pipets (10 mL, 1 ml, and 0.3 mL) where used to add the accurate volume of the samples and reagents to the vials. The vials were then exposed to the light with a specific wavelength in the spectrophotometer and the concentrations were calculated. In the case of total phosphorus, the vials needed to undergo a digestion period of one hour at 100°C. A Hach dry thermostat reactor (Hach DRB 200, Loveland, CO) was used to achieve the temperature requirements. Figure 10 shows the Hach spectrophotometer reactor and the vials.

Figure 12- Hach DRB 200 dry thermostat reactor (right), Hach DR/3900 spectrophotometer (left) (Image source: Hach.com)

3.6.3 Metals Analysis (Cu, Fe, Zn)

The concentration of dissolved copper, iron, and zinc in solution were measured using an Inductively Coupled Plasma Optically Emitting Spectra (ICP-OES, Perkin Elmer Optima 8000). In this process, a solution containing the sample is introduced into a high energy argon plasma. Materials entering this high energy region are excited; this will result in spectral emissions which can be measured by a spectrometer. The spectrometer is set to a series of wavelengths specific to the metals being measured in this study. The intensity of the response is calibrated to the quantity of metals in the solution. Figure 12 shows a schematic diagram of the mechanism used to measure the metals concentrations.

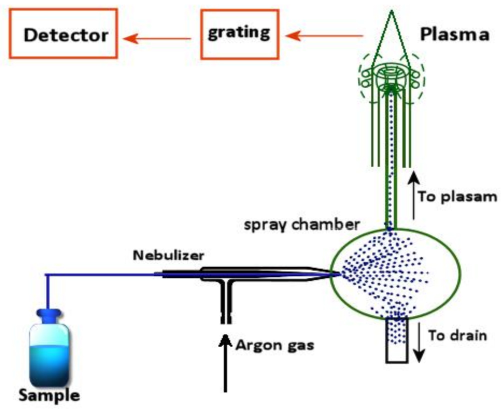

Figure 13-Diagram of sample introduction to ICP-OES (Source: chemiasoft.com)

3.6.4 Bacterial Analysis

E. coli concentrations were measured using the EPA method 1604 (USEPA 2002). In this method MI agar which is a chromogenic/fluorogenic medium used to detect and enumerate *E. coli* and total coliforms is used to culture *E. coli* colonies. A known volume sample (5, 10, 25 mL) was diluted with double distilled water; the diluted samples were filtered through a 0.45 μm pore size sterilized glass fiber filters using a vacuum set (the pore size of the filters were smaller than the *E. coli* cells and this would hold the cells on the filter), (Figure 14). After filtering the samples, membrane filters that retained the bacteria, were placed on the MI agar medium plates. The MI agar plates with the filters were incubated at 35°C for 24 hours. After incubation the bacterial colonies that grow on the plates were inspected for the presence of blue color from the breakdown of Indoxyl-β-D-glucuronide (IBDG) by the *E. coli* enzyme β –glucuronidase. These blue colonies were counted manually and the results were presented in Colony Forming Units (CFU) /100 mL, Figure 15 shows the MI agar plates before and after the incubation.

$$E.coli\ (CFU)/100mL = \frac{Number\ of\ blue\ colonies}{Volume\ of\ sample\ filtered} \times 100 \qquad (3.1)$$

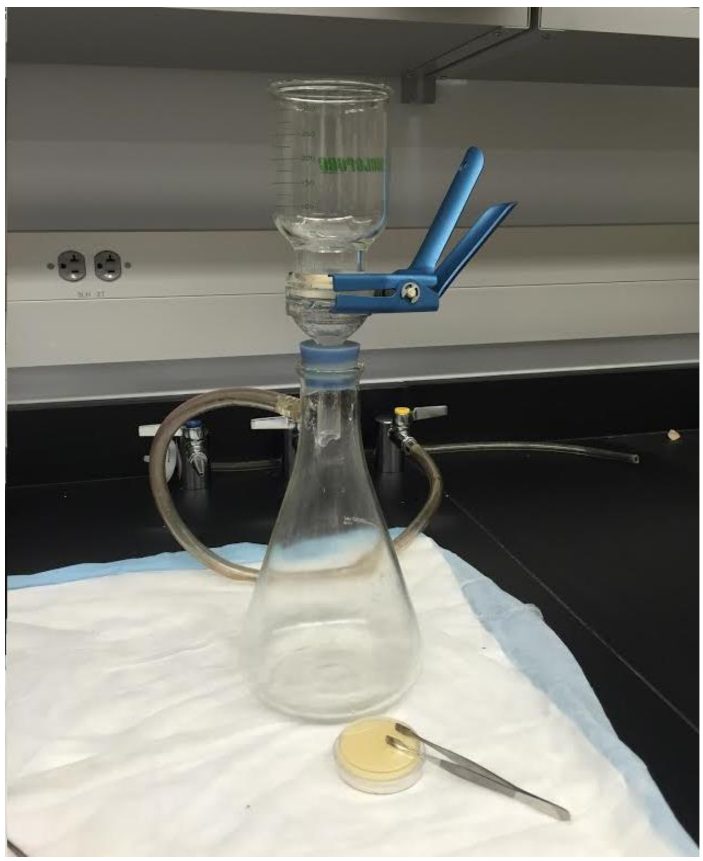

Figure 14-Vacuum set used for filtering the samples

Figure 15-MI agar medium and the filter (left). Filter placed on the plate (Middle), MI agar plates after incubations (right)

3.7 Quality Assurance Quality Control (QA/QC) Plan

The QA/QC plan is a part of the monitoring study which will help limiting the errors that can occur during sampling and laboratory analysis. Implementing the QA/QC plan will increase the efficiency of the study by applying a set of standard rules and procedures, which will provide early detection of problems and errors both on the field and in the laboratory (Law et al. 2008).

3.7.1 QA/QC for Field Sampling

According to USEPA the quality assurance and quality control procedures for field sampling include 1) determining the storms that are 'eligible for sampling', 2) sample collection and transport, 3) equipment decontamination, 4) field sample containers and labeling. To ensure the quality of the sampling, several measures were taken to prevent additional contamination of the samples and to ensure that constituent holding times were not exceeded those that are mentioned in Table 8. Field duplicates were also collected for every 10 samples taken from the runoff and captured volume by the pavements and tree boxes. Duplicate samples were used to identify any possible field variations. These samples were collected at the same time and location as the original sample, and were tested for TSS, *E. coli*, and the nutrients listed in Table 9.

3.7.2 QA/QC for Laboratory Analysis

Three major categories which should be addressed in the QA/QC procedures developed for laboratory analysis are: 1) selection of laboratory to conduct analyses, 2) specifications of analytical methods and procedures to ensure the desired results are produced (e.g. use of blanks and lab replicates samples) and 3) review of data results to meet data quality objectives (Law et al. 2008). The entire laboratory analyses were performed in laboratories within University of Louisville and Georgia Institute of Technology, following standard methods. Lab replicates (a sample that is split into subsamples at the lab) were also tested for TSS, *E. coli*, and nutrients.

Relative Percent Difference (RPD) values were calculated to compare the concentrations in the original samples with the field duplicates and lab replicate samples. A control limit of 20% for the RPD should be used between the original samples and duplicate and replicate samples.

$$RPD = \frac{|S-D|}{(S+D)/2} \times 100 \qquad (3.2)$$

In which, “S” is the concentrations or results from the original samples and “D” is the result obtained from the duplicate or replicate samples.

3.8 Column Study

After a 12-month period of data collection for a total of 21 rain events, a large scale lab study was conducted to mimic the observed behavior within a controlled environment. A 6-ft tall column was filled with the same aggregate layers that were used in the construction of permeable pavements and tree boxes. Aggregate layers were added to the column feet by feet, semi-synthetic stormwater runoff was introduced to the column in each step and pollutant concentrations were measured in the influent and the effluent to determine the pollutant removal efficiency of each layer.

3.8.1 Semi-synthetic stormwater

Suitable concentrations of typical stormwater pollutants were chosen based on the data presented by the National Stormwater Quality Database (NSQD) and the National Urban Runoff Program (NURP). Table 12 shows the median concentrations for a group of water quality parameters.

The following water quality parameters were analyzed in this lab study: 1) TSS, 2) Nitrate (NO_3), 3) Nitrite (NO_2), Ammonia (NH_3), and 4) Total Phosphorus (TP). Specific masses of sediments finer than 300 μm (#40 sieve) were collected from a pond and added to a 208 liter (55 gallon) barrel of water to achieve the suggested TSS concentrations. The nutrient concentrations were achieved by adding laboratory chemicals such as ammonium nitrate (NH_4NO_3) and sodium phosphate tribasic ($Na_3PO_4.12H_2O$). A set of trial and error measurements were made to determine the mass of sediments and chemicals required to achieve the range of concentrations suggested by NSQD and NURP.

A water pump was used in the bottom of the barrel to create a circular action and provide the uniformity of the suspension. Another pump was used to pump the semi-synthetic stormwater to a sprinkler located on top of the column. The sprinkler provided an even distribution of the stormwater runoff over the column (see Figures 16 and 17).

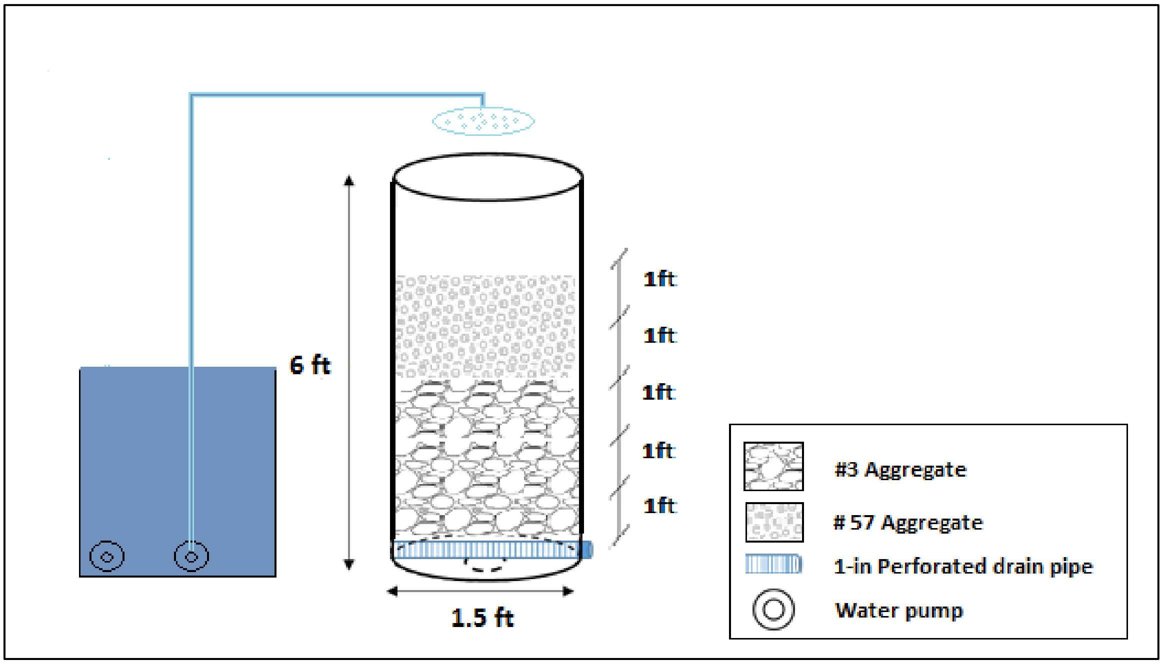

Figure 16-Schematic view of the column setup

Figure 17-From left to right, the test setup, semi synthetic stormwater runoff, surface of the aggregate layer on top of the column, and the sampling pipe.

3.8.2 Aggregate Layers and Experimental Details

The same aggregate layers that were used to backfill the storage galleries, shaft, and trenches of GI controls on the field (ASHTO #3 and ASHTO #57) were used in the column study. One foot of the aggregates was added to the column in each experiment.

The column was then tested for pollutant removal performance, using two different rainfall intensities (1.5 in/hr and 3 in/hr). The last combination of layers of #3 and #57 aggregate which showed the most TSS removal was tested for two additional intensities (2.25 in/hr and 3.75 in/hr). Table 11 summarizes the experimental details such as depth of each layer and rainfall intensities for all 20 experiment runs.

Both #3 and #57 aggregates were soaked in water for 24 hours, pressure washed and finally hand washed, to prevent any overestimating of TSS concentrations in the effluent which could be caused by the solids attached to aggregates.

3.8.3 Physical Properties of the Aggregate Used in the Column

Aggregates used in the column study were tested for their porosity and particle size distributions. Particle size distribution was determined using the standard test method for sieve analysis (ASTM C136), and the porosity of #3 and #57 aggregates were measured following the EPA recommended method. A 5-gallon bucket was used in this method; samples were packed in three lifts of roughly equal depth, bucket was gently tapped with a hammer at each lift. Water was added to the bucket full of aggregates until it flowed through an overflow port built into the bucket, the pore volume of the samples were determined by measuring the amount of overflow and subtracting it from the added water. Figure 18 shows the bucket used for porosity measurements.

Figure 18-Bucket used for the porosity measurements

The result from the sieve analysis for #57 and #3 are presented in figures 19 and 20 respectively.

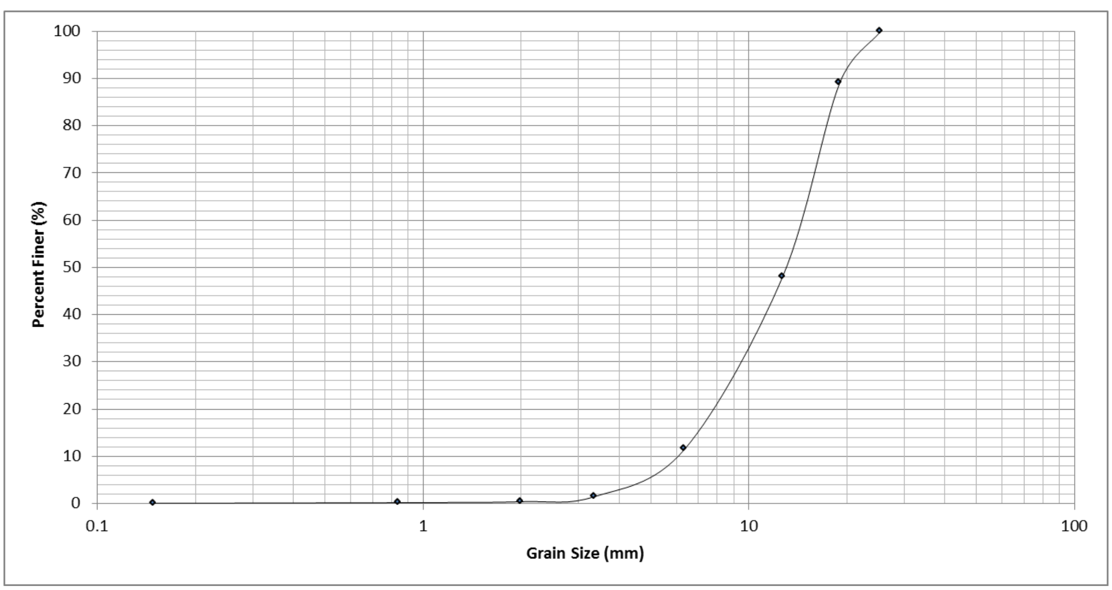

Figure 19-Size distribution of #57 aggregate used in the column study

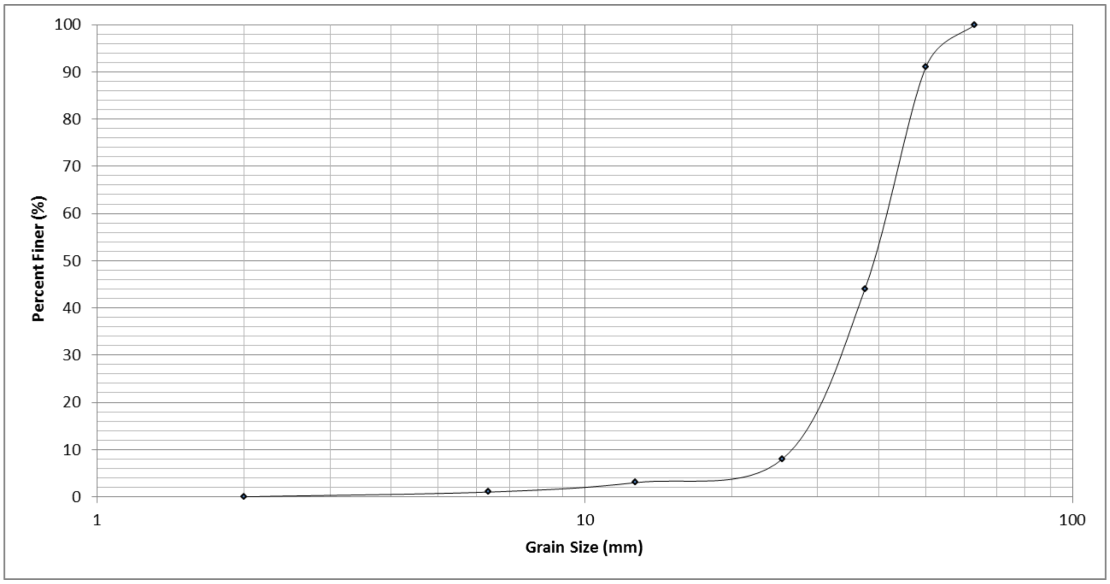

Figure 20- Size distribution of #3 aggregate used in the column study

A set of three tests were conducted on #3 and #57 aggregates to determine the porosity, the values for each test and the mean values are presented in Tables 10 and 11.

Table 10-Porosity values calculated for #57 aggregates

Test	Aggregate	Water added (ml)	Overflowed Volume (ml)	Porosity (%)
1	#57	7000	1040	42.93
2	#57	7000	1210	41.70
3	#57	7000	1170	42.00
			Mean Value	**42.21**

Table 11- Porosity values calculated for #3 aggregates

Test	Aggregate	Water added (ml)	Overflowed Volume (ml)	Porosity (%)
1	#3	7000	995	43.25
2	#3	7000	890	44.01
3	#3	7000	925	43.76
			Mean Value	**43.67**

3.8.4 Test Procedure and Sampling

In the first step of each experiment, a layer of clean aggregate was added to the column and washed by tap water for 30 minutes. At the same time, known masses of sediment and chemicals were added to the water in the barrel and mixed by using one of the water pumps. After the mixing process, the semi-synthetic stormwater was pumped to the sprinkler located on top of the column to introduce an even distribution of stormwater runoff to the surface of the aggregates.

After 10 minutes the first samples were collected from the sprinkler (which represented the runoff samples) and from the perforated drain pipe located in the bottom of the column (representing the samples collected from the bottom of the trenches or shafts). Samples were collected every 10 minutes until all the stormwater in the barrel was pumped over the column. In the next step, samples were mixed to form a composite sample representative of the whole event. Mixed samples were delivered to the laboratories and analyzed for TSS and nutrients, following the procedures explained in sections 3.6.1 and 3.6.2.

Table 12-Median Concentrations, Reported by NURP and NSQD (Maestre and Pitt 2005; USEPA 1982)

	Overall		Residential		Commercial	
Parameter	NSQD Median	NURP Median	NSQD Median	NURP Median	NSQD Median	NURP Median
COD (mg/L)	53	65	55	73	63	57
BOD5 (mg/L)	8.6	9	9	10	11.9	9.3
TSS (mg/L)	58	100	48	101	43	69
NO_x (mg/L)	0.6	0.68	0.6	0.74	0.6	0.57
TP (mg/L)	0.27	0.33	0.3	0.38	0.22	0.2
NH_3 (mg/L)	0.44	NA	0.31	NA	0.5	NA

Table 13-Experimental Details for the simulation experiment

Experiment No.	#3 Layer (ft)	#57 Layer (ft)	Rain Intensity (Inch/hr)
1	-	1	1.5 in/hr
2	-	1	3 in/hr
3	-	2	1.5 in/hr
4	-	2	3 in/hr
5	-	3	1.5 in/hr
6	-	3	3 in/hr
7	-	4	1.5 in/hr
8	-	4	3 in/hr
9	2	-	1.5 in/hr
10	2	-	3 in/hr
11	3	-	1.5 in/hr
12	3	-	3 in/hr
13	4	-	1.5 in/hr
14	4	-	3 in/hr
15	4	1	1.5 in/hr
16	4	1	3 in/hr
17	3	2	1.5 in/hr
18	3	2	2.25 in/hr
19	3	2	3 in/hr
20	3	2	3.75 in/hr

4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter of the document presents the results obtained from the field study during the 12-month period beginning from May 2014, as well as data collected from the large scale column study.

The data collected from the field includes: 1) the rainfall characteristics of 21 rain events in which water quality samples were collected; 2) pollutant removal performances of permeable pavements and tree boxes regarding TSS, *E. coli*, nutrients (nitrate, nitrite, TP, and ammonia), and metals (copper, zinc, and iron); and 3) conventional water quality parameters, such as pH, conductivity, and temperature.

The second part of this chapter is focused on the column study, in which the removal percentages of TSS and nutrients (nitrate, nitrite, TP, and ammonia) are calculated. Along with the removal performance of each layer, the effect of rainfall intensity has been investigated in this section.

4.2 Field Data

4.2.1 The rain fall characteristics

As mentioned in chapter three, in addition to the tree box located in Story Avenue, two permeable pavement sections were chosen for water quality studies (GI controls 17G and 17H). In 17G, a continuous trench is used to reach the deep sandy layers with higher hydraulic conductivity and in 17H, a number of shafts were utilized to reach the same layer.

Water quality samples were collected in the first flush of 18 rain events from the tree box, 17 rain events from 17G and 14 events from 17H. The rainfall characteristics of these events are summarized in Table 14. Sampling was not conducted in all three GI practices in a number of these 21 rainfall events due to sampling limitations such as parked vehicles on monitoring wells.

Table 14- Rainfall Characteristics of Storm Events Sampled for Water Quality Analysis

Event #	**Date**	**Rainfall Duration (hrs)**	**Rainfall Depth (mm)**	**Maximum Rainfall Intensity (mm/hr.)**		**Antecedent Rainfall Depth (mm)**		
				5-min Duration	15-min Duration	3-Day	5-Day	7-Day
1	05/09/2014	12.00	20.8	46.7	21.3	1.9	1.9	1.9
2	05/10/2014	3.00	21.8	56.9	27.7	22.8	22.8	22.8
3	07/07/2014	0.67	12.4	39.6	35.3	0.4	0.4	8.1
4	07/14/2014	1.58	9.1	20.3	12.4	16.1	16.1	40.0
5	08/16/2014	29.25	18.0	12.2	8.1	0.3	0.3	25.0
6	08/22/2014	3.33	6.6	33.5	15.5	0.8	1.2	18.8
7	10/06/2014	6.58	6.4	23.4	11.9	3.9	6.4	6.4
8	10/07/2014	2.50	5.6	12.2	9.4	7.2	13.3	13.3
9	10/13/2014	13.42	22.9	17.3	10.9	11.4	40.9	46.7
10	11/16/2014	14.00	8.8	5.1	4.3	0.3	0.6	1.6
11	11/23/2014	14.42	18.9	14.2	10.4	0.3	0.3	9.6
12	12/05/2014	34.42	38.4	12.2	3.0	8.9	31.1	31.1
13	12/23/2014	3.92	2.5	6.1	7.5	5.6	5.6	5.6
14	02/01/2015	8.92	10.2	5.1	5.1	0.1	1.1	5.1

15	02/21/2015	19.58	30.2	10.2	4.4	1.6	5.5	6.6
16	03/03/2015	50.58	43.9	4.1	9.8	1.4	2.6	2.6
17	03/13/2015	28.17	45.1	7.1	3.4	25.6	28.0	28.0
18	04/02/2015	33.42	110.8	40.6	6.4	0.3	0.3	4.1
19	04/13/2015	22.50	10.1	4.1	19.0	0.2	8.3	37.8
20	05/11/2015	0.58	1.2	4.1	3.4	2.4	2.4	2.4
21	05/16/2015	14.17	11.0	18.3	3.0	1.6	2.8	2.9

4.2.2 In-situ Parameters (Temperature, pH, Conductivity)

Field measurements were conducted to determine the pH, temperature, and Specific Conductivity (SC) values during 17 rainfall events for the tree box, 15 rainfalls for GI control 17G, and 13 rainfalls for GI control 17H, and the values are presented in Tables 15, 16 and 17. In addition to the runoff and captured volume measurements, average values and the *p*-values from the student t-test are presented in these tables. The *p*-values are used to investigate significant differences between the measurements in the runoff samples and captured volume. Differences are known to be significant at a 95% confidence when the *p*-values are lower than 0.05, which are shown in italics and underlined in the tables.

Table 15-In situ water quality measurements for the tree box

Parameter		**Temperature (°C)**		**pH**		**SC (uS/cm)**	
Event #	**Date**	**Runoff**	**Captured**	**Runoff**	**Captured**	**Runoff**	**Captured**
1	05/09/2014	20.8	18.5	8.47	6.35	497.9	89.3
2	05/10/2014	19.5	18.5	8.3	6.35	142.4	89.3
5	08/16/2014	25.5	24.7	7.94	8.04	66.6	105.6
6	08/22/2014	24	25.4	8.37	7.8	167.0	703.6
7	10/06/2014	20.2	19.5	8.3	7.77	180.6	963.2
8	10/07/2014	20.5	20.6	7.87	7.64	45.1	333.0
10	11/16/2014	5.5	10.3	6.69	6.64	1115.4	1109.5
11	11/23/2014	14.5	13.5	7.11	7.08	594.2	1464.7
12	12/05/2014	10.4	10.6	6.89	6.86	966.5	721.4
13	12/23/2014	12.2	13.7	7.1	6.97	129.7	663.1
14	02/01/2015	7.2	8.1	6.9	7.04	560.6	917.0
15	02/21/2015	3	_	6.85	_	12469	_
16	03/03/2015	8.9	9.8	7.21	7.14	297.5	473.5
17	03/13/2015	13	13.5	7	6.85	319.1	689.4
18	04/02/2015	16.3	16	7.05	7.1	221.9	944.3
19	04/13/2015	22	20.4	6.92	6.96	100.8	577.8
21	05/16/2015	24.8	23.7	7.05	7.05	321.2	707.6
Average	-	**16.6**	**16.7**	**7.4**	**7.1**	**329**	**640**
***p*-value**	-	**0.824**		**0.062**		***0.005***	

Results presented in Table 15 shows that average pH values were slightly lower in the samples collected from the captured stormwater within the tree box as compared to the surface runoff, and the difference found to be not significant (p-value > 0.05). Unlike the pH, conductivity values were significantly higher in the samples collected from the captured volume. The higher values of SC in the effluent or exfiltrated samples was also reported in previous studies (Brattebo and Booth 2003; Roseen et al. 2006)

Table 16-In situ water quality measurements for GI control 17H

Parameter		**Temperature (°C)**		**pH**		**SC (uS/cm)**	
Event #	**Date**	**Runoff**	**Captured**	**Runoff**	**Captured**	**Runoff**	**Captured**
2	05/10/2014	19	17.5	7.9	7.84	40.7	126.1
4	07/14/2014	21.5	20	7.89	7.95	45.2	78.5
5	08/16/2014	23.2	21.5	7.53	7.74	45.6	65.5
9	10/13/2014	20.4	20.2	7.02	7.11	29.4	41.8
10	11/16/2014	4.5	8.5	6.8	6.77	164.4	194.0
11	11/23/2014	12.5	14.7	6.8	6.8	90.6	99.6
12	12/05/2014	10	11.3	6.9	6.97	96.7	108.4
13	12/23/2014	13.2	15.5	7.02	7.11	129.1	79.4
14	02/01/2015	7.5	8.5	6.6	6.7	220.1	188.4
16	03/03/2015	9	11	6.7	7.03	136.8	117.4
17	03/13/2015	13	13.4	6.9	6.93	215.4	215.0
18	04/02/2015	16.2	16.5	6.78	6.8	159.9	143.3
21	05/16/2015	24.2	23	6.7	6.85	106.6	105.9
Average	**-**	**14.9**	**15.59**	**7.0**	**7.1**	**114**	**120**
***p*-value**	**-**	**0.27**		***0.001***		**0.509**	

Data presented in Tables 15 and 16 show a similar trend in data collected from GI controls 17G and 17H. The pH and conductivity values were found to be higher in the samples collected from the captured stormwater as compared to the stormwater runoff. These differences were significant in the case of pH, and statistically insignificant for the conductivity measurements.

Table 17-In situ water quality measurements for GI control 17G

Parameter		Temperature (°C)		pH		SC (uS/cm)	
Event #	**Date**	**Runoff**	**Captured**	**Runoff**	**Captured**	**Runoff**	**Captured**
2	05/10/2014	18.4	17.2	7.53	7.74	35.8	36.4
5	08/16/2014	22.8	22.1	7.87	7.94	48.1	90.0
6	08/22/2014	25.5	24.7	7.94	8.04	66.6	105.6
7	10/06/2014	19.5	19.7	8	7.96	93.9	410.6
8	10/07/2014	17	17	7.99	8.11	113.3	257.3
9	10/13/2014	20.4	20.6	7.85	7.93	30.7	58.2
10	11/16/2014	4.7	9.1	6.6	6.85	200.9	248.5
11	11/23/2014	13	15.6	6.84	6.85	415.2	227.9
12	12/05/2014	9.9	11.2	6.8	6.82	50.3	91.0
14	02/01/2015	9	10.8	6.95	6.97	172.8	628.4
15	02/21/2015	4.2	_	6.65	_	3318.3	_
16	03/03/2015	12	13	6.78	6.97	239.5	101.2
19	04/13/2015	22.2	21	6.88	7.03	90.9	170.0
20	05/11/2015	21	_	6.91	_	201.4	_
21	05/16/2015	24.2	23	6.7	6.85	106.6	75.9
Average	-	**16.8**	**17.3**	**7.3**	**7.4**	**121**	**185**
***p*-value**	-	**0.315**		***0.001***		**0.196**	

Most of the SC values measured in the surface runoff were in the range of the values reported in previous studies (Göbel et al. 2007; Kazemi and Hill 2015; Roseen et al. 2006) except for event number 15, in which high values of conductivity were observed in runoff samples collected (12,469 for the tree box, and 3318 for control 17G). These high values were a result of de-icing material used on the highways prior to this event. De-icing salts will contribute ions to the soils and could result in altered soil compositions (Bogemans et al. 1989). However, discontinuous use of these materials allows the plant damage caused by salt stress to recover (Trombulak and Frissell 2000).

Results for all three GI controls showed that the temperature of the captured stormwater within the reservoir structure of the pavements is slightly lower compared to the surface flow in the warm months and slightly higher in the cold weather; however, these differences in temperature values were found to be statistically insignificant, according to the results from the student paired *t*-test.

4.2.3 Pollutant Removal Performances

Samples collected from the tree box and permeable pavements were analyzed for TSS, *E. coli*, nutrients, and metal concentrations. The results for each GI control are presented in this section.

Total Suspended Solids (TSS) Removal

A range of pollutants including phosphates, metals, and bacterial contaminations are known to be in particulate form or associated to sediments in the stormwater runoff (Cr et al. 2003; Prabhukumar 2013). The fact that suspended solids in the surface runoff serve as a method of transportation for pollutants such as bacteria and phosphorus, and filtering the TSS will contribute to lower concentrations of these pollutants, makes the TSS removal an important factor in evaluating the overall water quality performance of a GI control.

TSS concentrations in runoff and in the captured volume by the tree box, GI controls 17G and 17H are plotted in Figures 21-23.

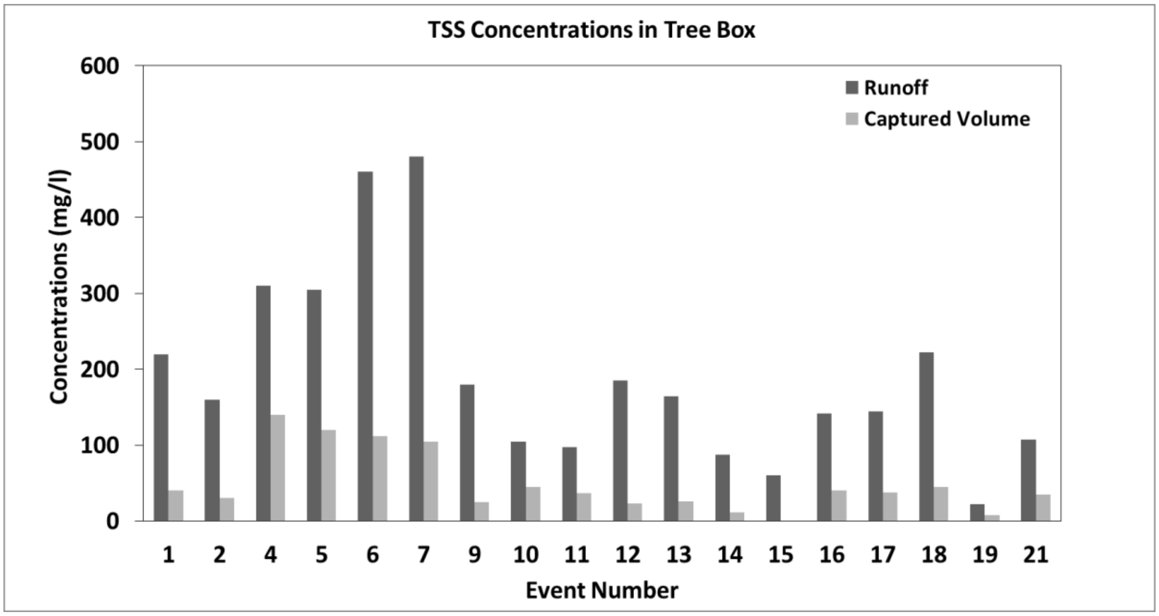

Figure 21- TSS concentrations in samples collected from the tree box for 18 events. Standard Deviations were 125.7 in runoff and 40.48 in the captured volume.

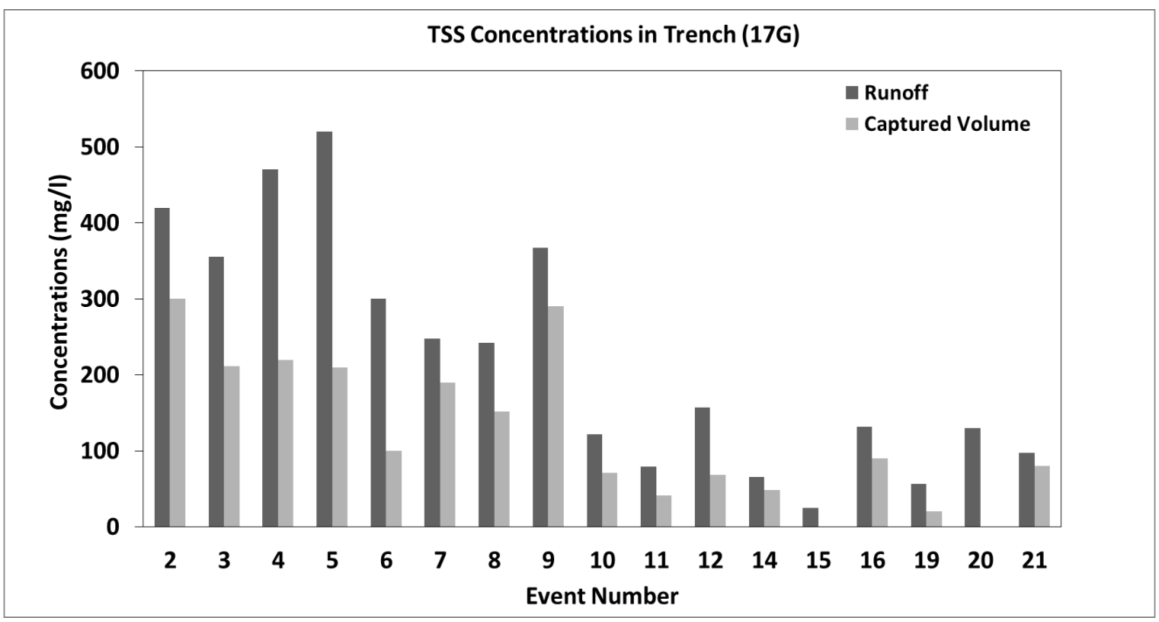

Figure 22-TSS concentrations in samples collected from GI control 17G for 17 events. Standard Deviations were 155.7 in runoff and 91.6 in the captured volume.

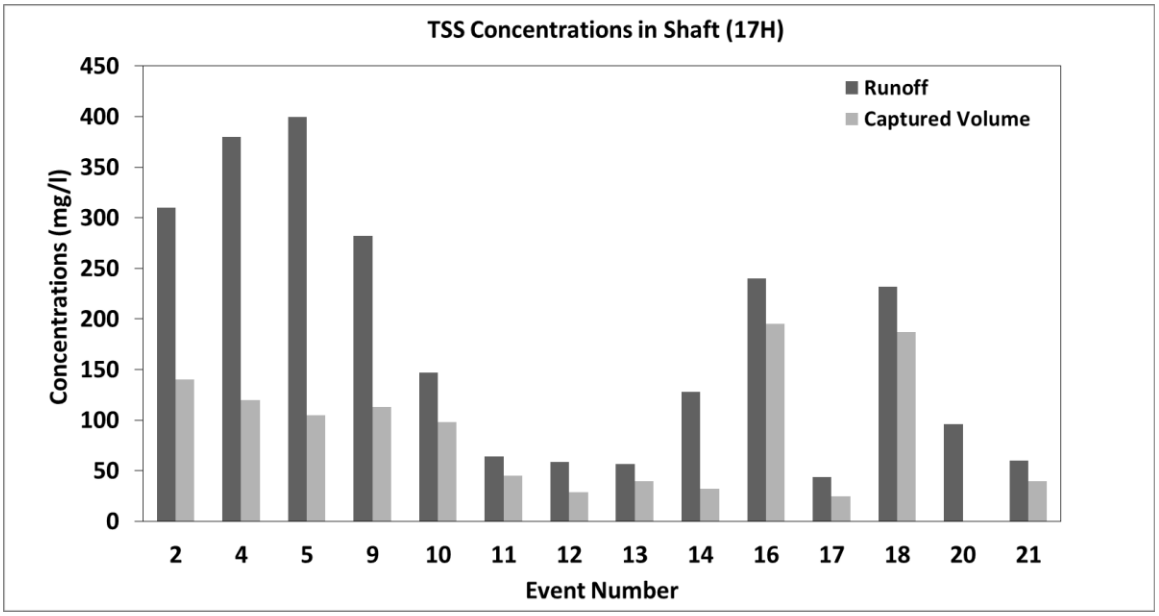

Figure 23-TSS concentrations in samples collected from GI control 17H for 14 events. Standard Deviations were 129.6 in runoff and 59.8 in the captured volume.

These graphs show TSS concentrations in samples collected from captured volumes were lower compared to those collected from the runoff in all the rain events and for both permeable pavement systems and the tree box. Physical filtration by the aggregate layers is known to be the main mechanism causing the TSS removal. However the removal of TSS were higher in samples collected from the tree box compared to controls 17H and 17G. This is a result of smaller pore size of the media used in the tree box which will cause more filtration of particulate material even though the depth of the filter media in the tree box is less than the gravel layers used in the permeable pavements.

The average reduction values of TSS concentrations were 73% for the tree box, 50% for permeable pavement 17H and 37.5% for permeable pavement 17G. TSS data for all three GI controls are presented in box plots in Figure 24. The median values are shown with a line in middle of the boxes, and the boxes represent the 25th and 75th percentile.

The TSS concentrations in the runoff during the first 9 events were relatively high (150-550), and higher than the 143 mg/L mean value for small summer rains in urban areas reported in the National Stormwater Quality Database (NSQD). The high values for TSS in the runoff could be a result of 1) small rain events with high intensities, and 2) possible construction in the area in that period. Figure 25 shows a comparison between TSS concentrations in stormwater runoff reported in NSQD and the data presented in this study.

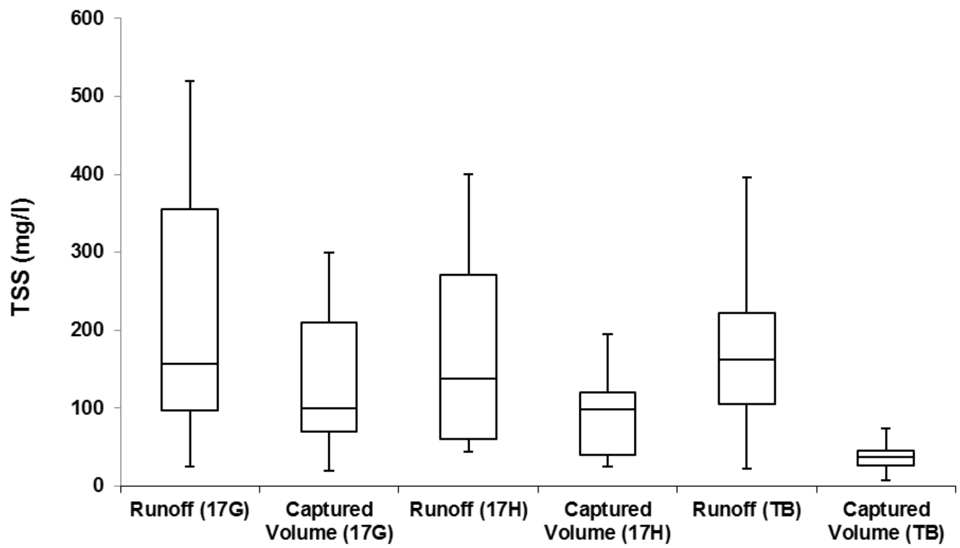

Figure 24-TSS concentrations for runoff and captured volume samples for GI controls 17G and the tree box. The box illustrates the 25th percentile, median, and 75th percentile. The highest and lowest values are represented by the top and bottom whiskers.

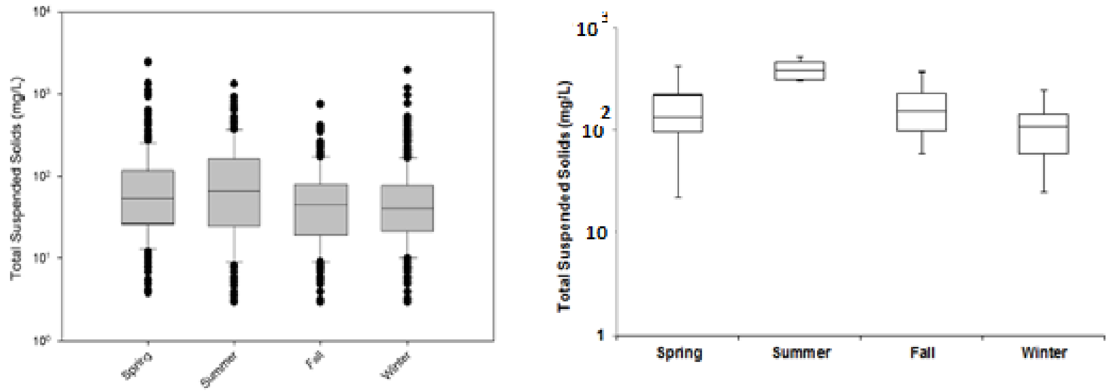

Figure 25- NSQD data for TSS concentrations sorted by season in residential areas (Left), seasonal data of TSS concentrations in the runoff collected in this study (Right).

Higher values of TSS concentrations during summer could be observed in both graphs. This is a result of small rain events with high intensities which will increase the mobility of the particulate material and sediments in the runoff.

E. coli Removal

Escherichia coli is a member of the family *Enterobacteriaceae* which is included in the total coliform and fecal coliform group of bacteria. The *E. coli* cells are present and can grow in human and animal feces and thus can be found in sewage and wastewater treatment effluent (Schubert and Mann 1968). *E. coli* is a commonly used indicator of fecal contaminations, and several studies have shown correlations between *E. coli* concentration and gastrointestinal illnesses (Raina et al. 1999; Strauss et al. 2001).

E. coli concentrations were measured using the colony count method (EPA method 1604). *E .coli* concentrations in the runoff and in the volume captured by the tree box, GI controls 17G and 17H, are plotted in Figures 26-28.

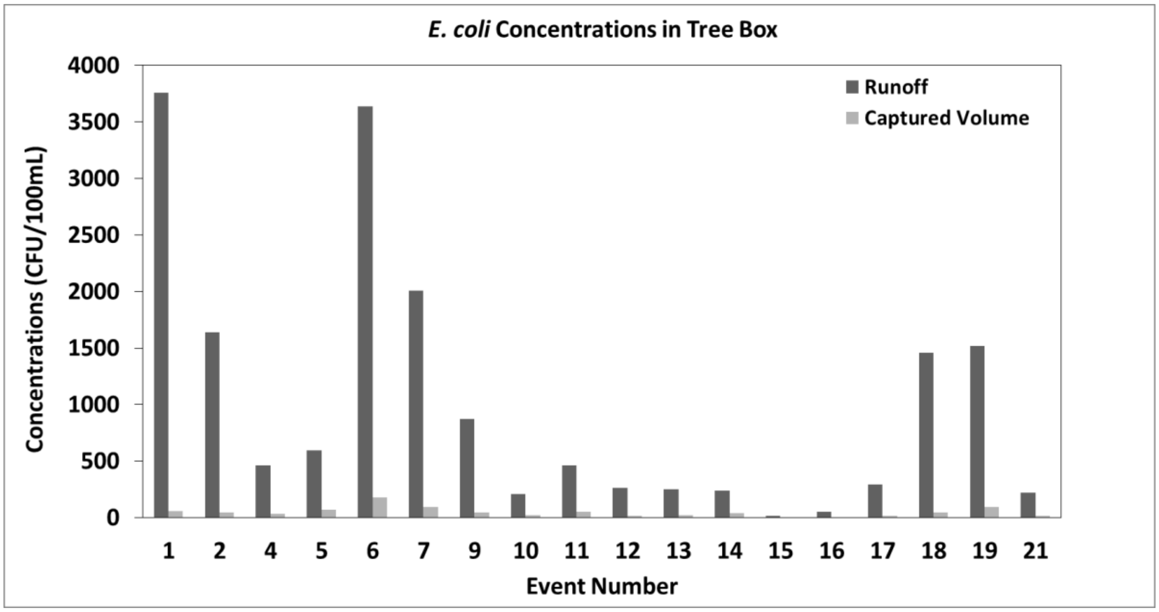

Figure 26-*E. coli* concentrations in samples collected from the tree box for 18 events. Standard Deviations were 1160 in runoff and 42.5 in the captured volume.

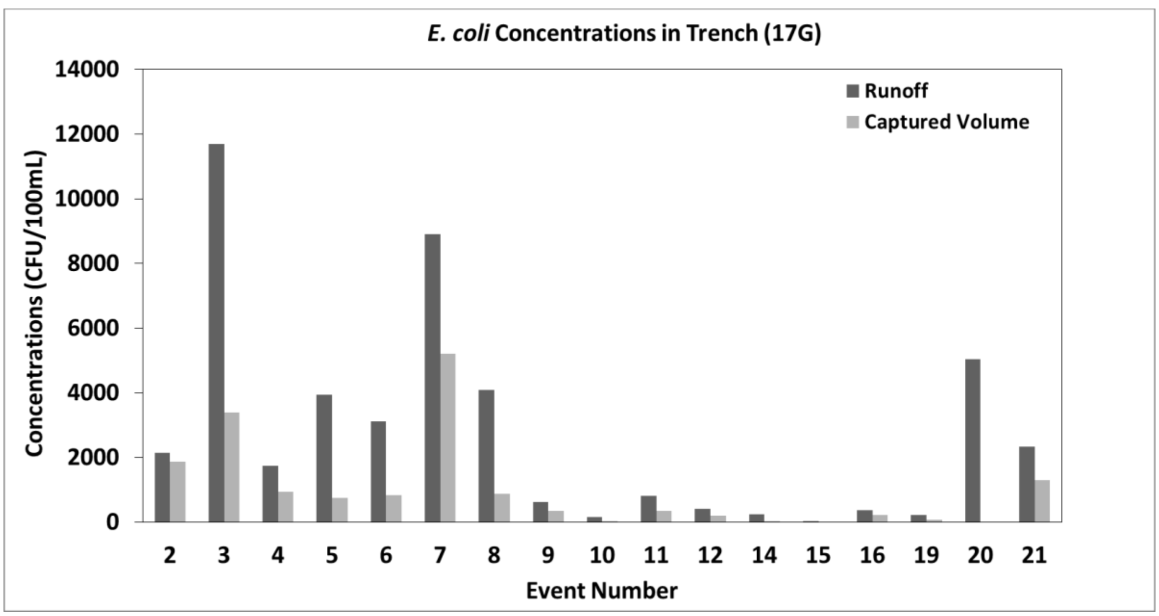

Figure 27-*E. coli* concentrations in samples collected from GI control 17G for 18 events. Standard Deviations were 3398 in runoff and 1439 in the captured volume.

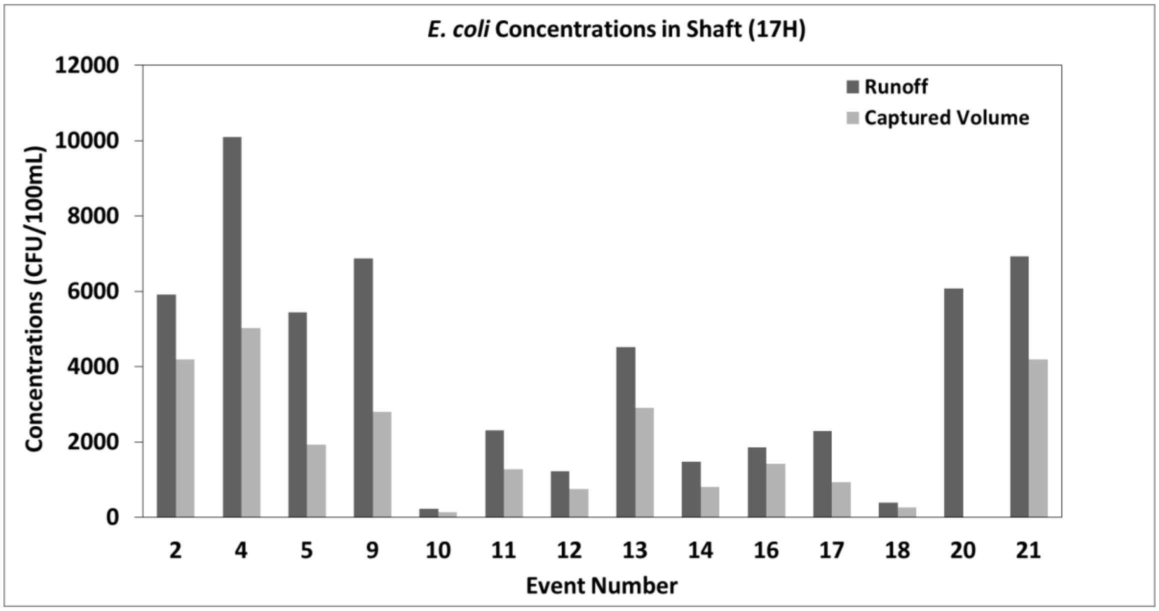

Figure 28-*E. coli* concentrations in samples collected from GI control 17H for 14 events. Standard Deviations were 3047 in runoff and 1626 in the captured volume.

E. coli concentrations were lower in samples collected from the captured volume compared to those from the runoff in all rain events and for both permeable pavements and the tree box. The removal of *E. coli* was found to be more significant in the samples collected from the tree box, which is likely the result of smaller pore size of the soil media used in the tree box.

Median values of *E. coli* concentrations in all GI controls are presented in Figure 26. Results are presented in box plots, in which the box shows the 25th and 75th percentile. The average *E. coli* concentration reduction values were 95% in the tree box, 59% in GI control 17G and 48% in GI control 17H.

The *E. coli* concentrations in the runoff and the captured volume were found to be higher in the rain events which took place during the warm seasons, especially in summer. This trend was also observed in the data presented by NSQD regarding the fecal coliforms. The seasonal changes of *E. coli* concentrations in the runoff are illustrated in Figure 27, along with the data for fecal coliforms from NSQD. Higher bacteria concentrations can be seen in summer in both graphs.

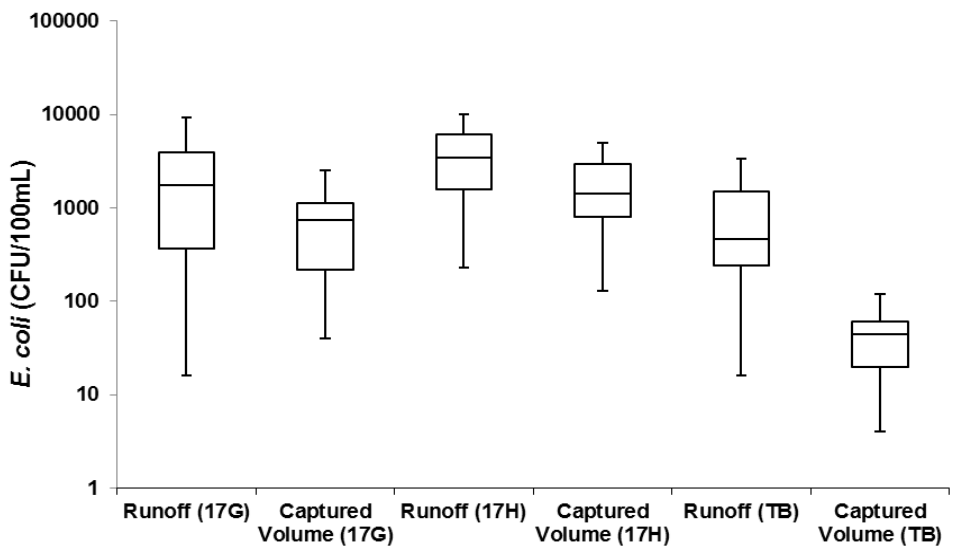

Figure 29-*E. coli* concentrations for runoff and captured volume samples for GI controls 17G and the tree box. The box illustrates the 25th percentile, median, and 75th percentile. The highest and lowest values are represented by the top and bottom whiskers.

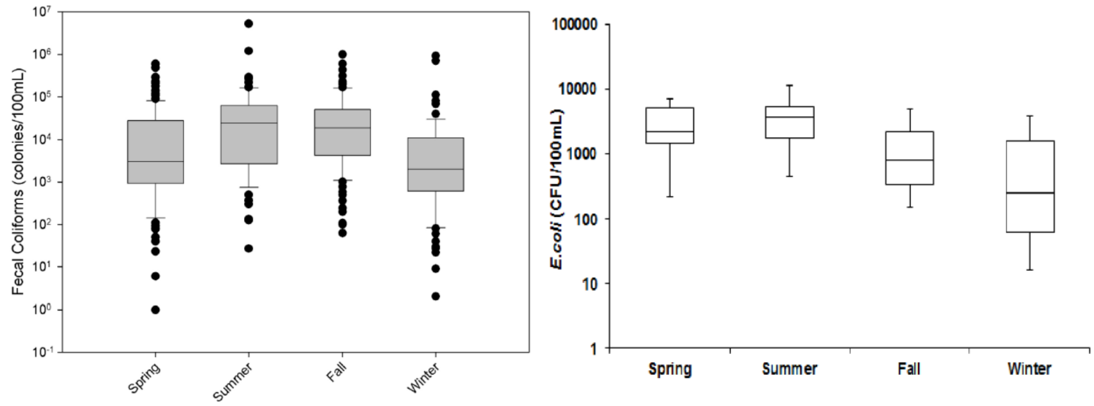

Figure 30- NSQD data for fecal coliforms concentrations sorted by season in residential areas (Left), seasonal data of *E. coli* concentrations in the runoff collected in this study (Right).

Nutrient Removal of the Tree Box

Samples collected from the runoff flowing into the tree box and captured volume by the tree box were analyzed for Total Phosphorus (TP), nitrite, ammonia, and nitrate concentrations, and the results are plotted in Figures 28-32.

TP concentrations were measured for a total of 18 rain events. However, in event number 20 only runoff samples were collected. TP concentrations in the captured volume were lower compared to the runoff in all of these rain events. The large amount of TP removal in the tree box can be explained by two mechanisms; 1) the filtration process by the media which filters the particulate form of phosphorus and 2) the uptake by the root hairs of the plants in the tree box which satisfies 60% of the plant's phosphorus demand (Bratieres et al. 2008).

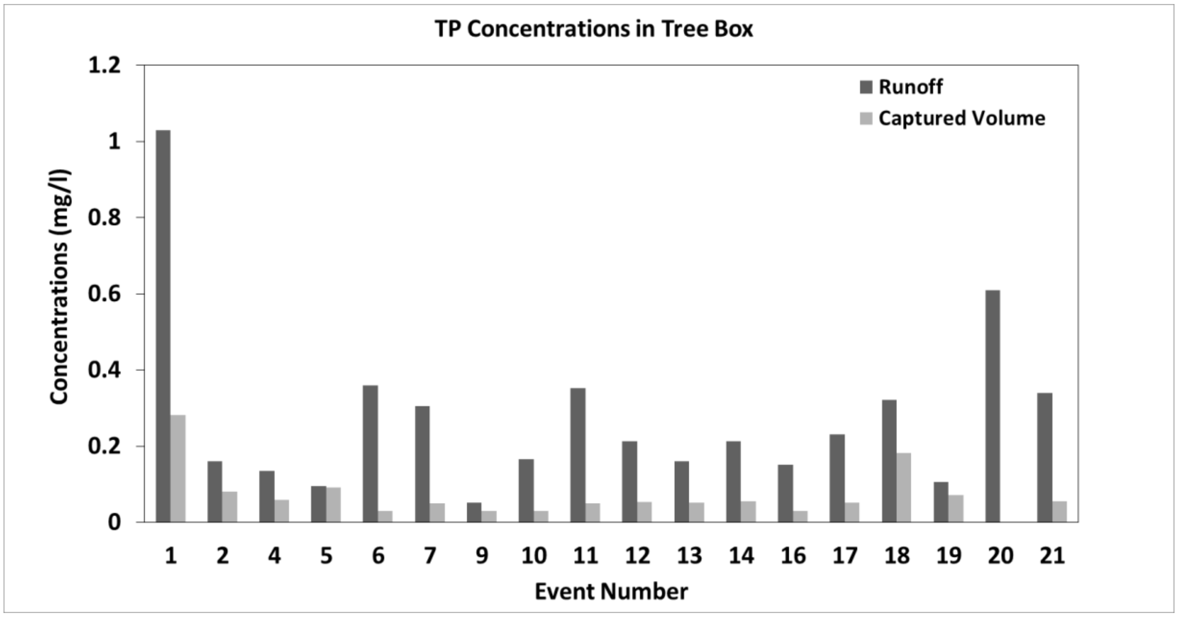

Figure 31-TP concentrations in runoff and captured volume for 18 events. Standard Deviations were 0.221 in runoff and 0.065 in the captured volume.

The concentrations of nitrite and ammonia were measured in 17 rain events, and the results are plotted in Figures 29 and 30. Ammonia concentrations were significantly lower in the samples collected from the captured volume. Reductions in nitrite concentrations were also observed but the reductions were more visible with the ammonia, except in event number 9 and 16, in which nitrite concentrations in the captured volume were higher than the runoff.

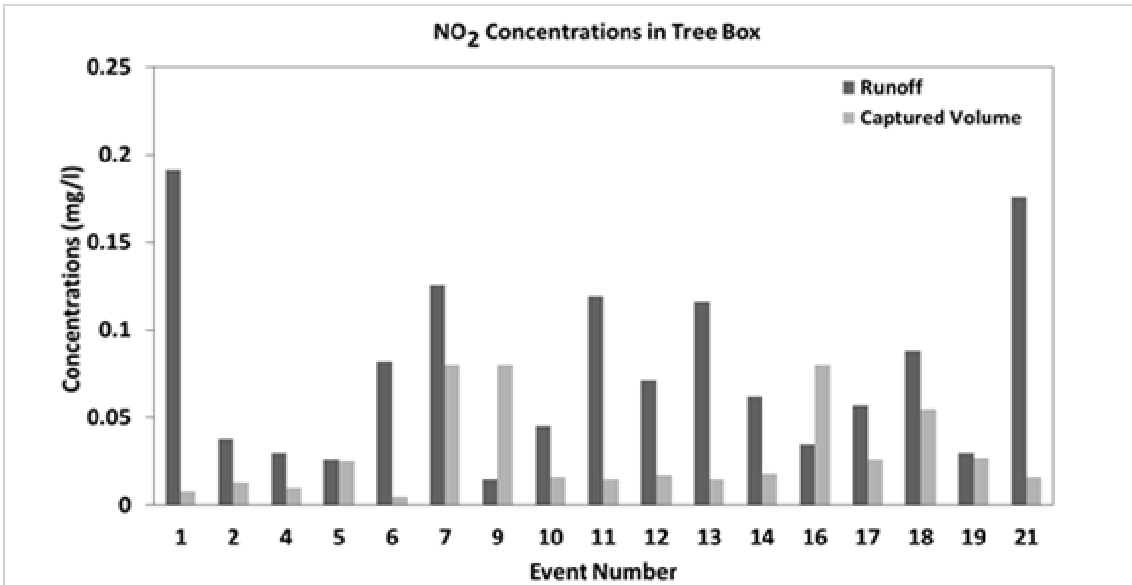

Figure 32-Nitrite concentrations in runoff and captured volume for 17 events. Standard Deviations were 0.053 in runoff and 0.026 in the captured volume.

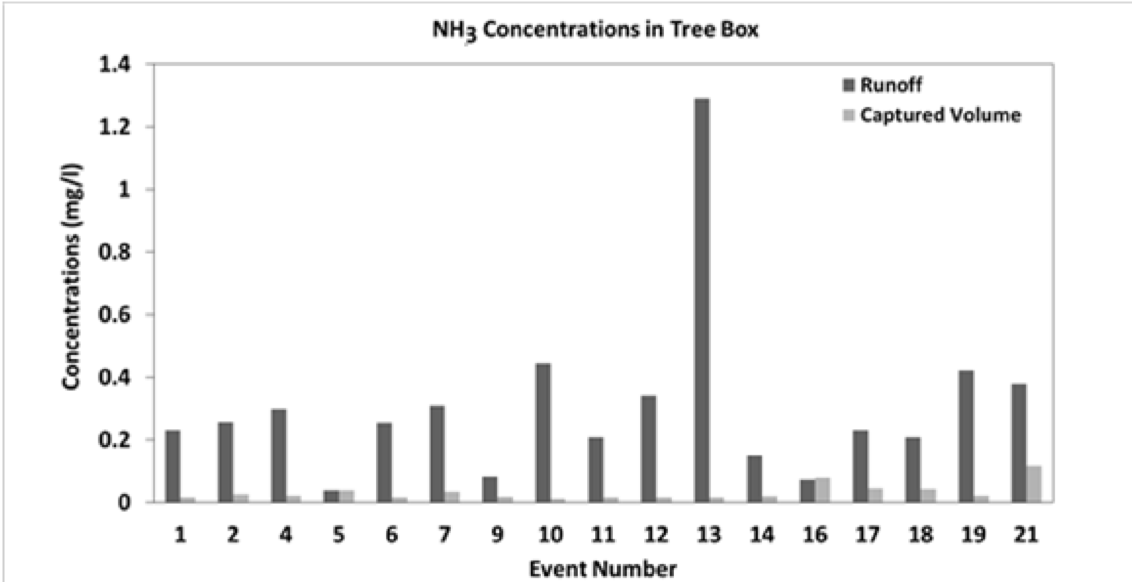

Figure 33-Ammonia concentrations in runoff and captured volume for 17 events. Standard Deviations were 0.279 in runoff and 0.028 in the captured volume.

Nitrate measurements are shown in Figure 31, in which it can be seen that the nitrate concentrations in the runoff samples were lower than the captured volume samples except in the first event. The leaching of NO_3 has also been observed in previous studies, and the likely scenario to explain this phenomenon is the biological transformation of captured ammonia and the organic nitrogen to nitrate between the rainfall events known as nitrification (Bratieres et al. 2008; Davis et al. 2001).

Figure 32 shows the average values of nutrients in the runoff and the captured volume during 17 events (in which samples were collected from both runoff and captured volume) studied for the tree box. The highest reduction was observed for ammonia at 89%. TP and nitrite concentrations were also 73% and 61% lower in the captured volume. However nitrate concentrations were 75% higher in the captured volume as a result of leaching due to nitrification.

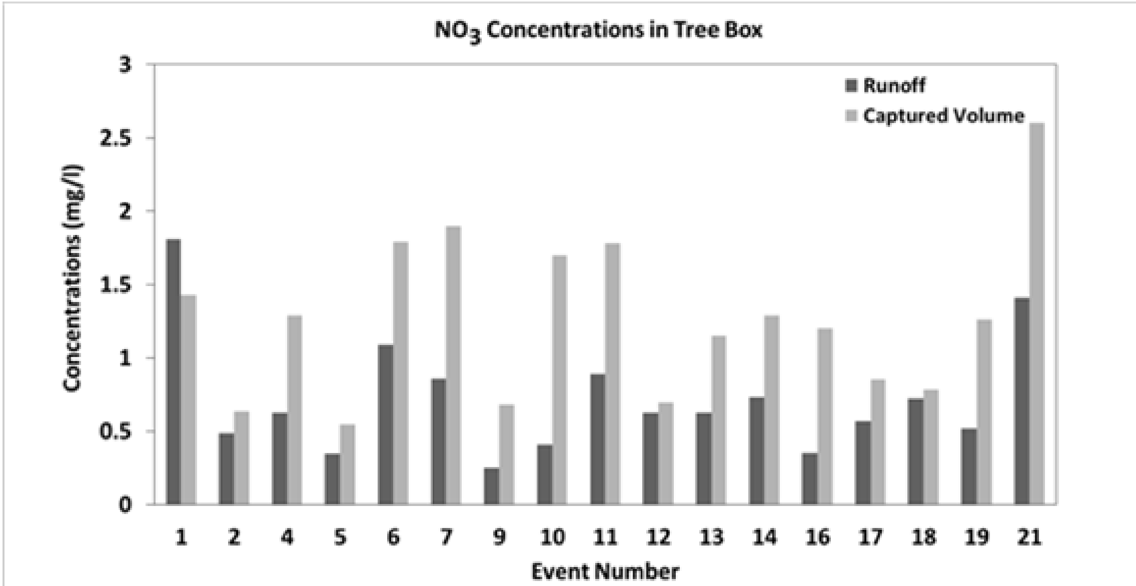

Figure 34-Nitrate concentrations in runoff and captured volume for 17 events. Standard Deviations were 0.402 in runoff and 0.556 in the captured volume.

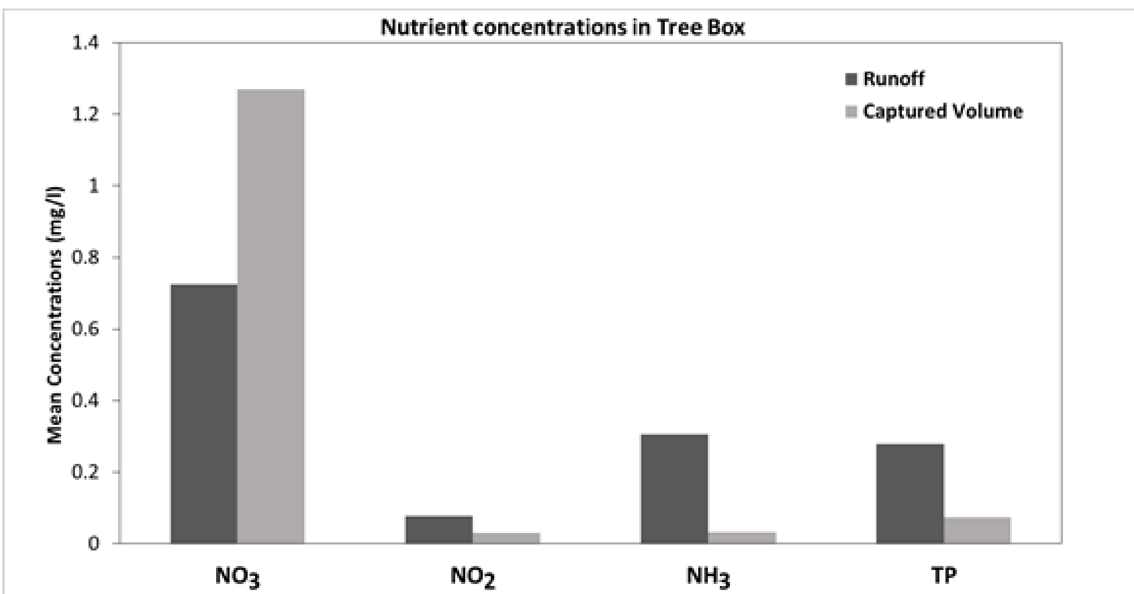

Figure 35-Average concentrations of nutrients nitrate, nitrite, ammonia and TP for 17 events

Nutrient Removal of GI control 17G

Samples from both the runoff flowing into the permeable pavements and from the captured volume in the bottom of the trench were analyzed for nutrients (TP, nitrite, ammonia, and nitrate) and the results are shown in Figures 36-40. In events 15 and 20, samples were only collected from the runoff, due to the low rainfall volumes.

Figure 36 shows TP concentrations of the samples collected from the captured volume in the bottom of the trench are lower compared to the runoff samples in all events except event number 2. The mechanism responsible for the removal of TP from the runoff was probably filtration of the particulate form of phosphorous by the aggregate layers.

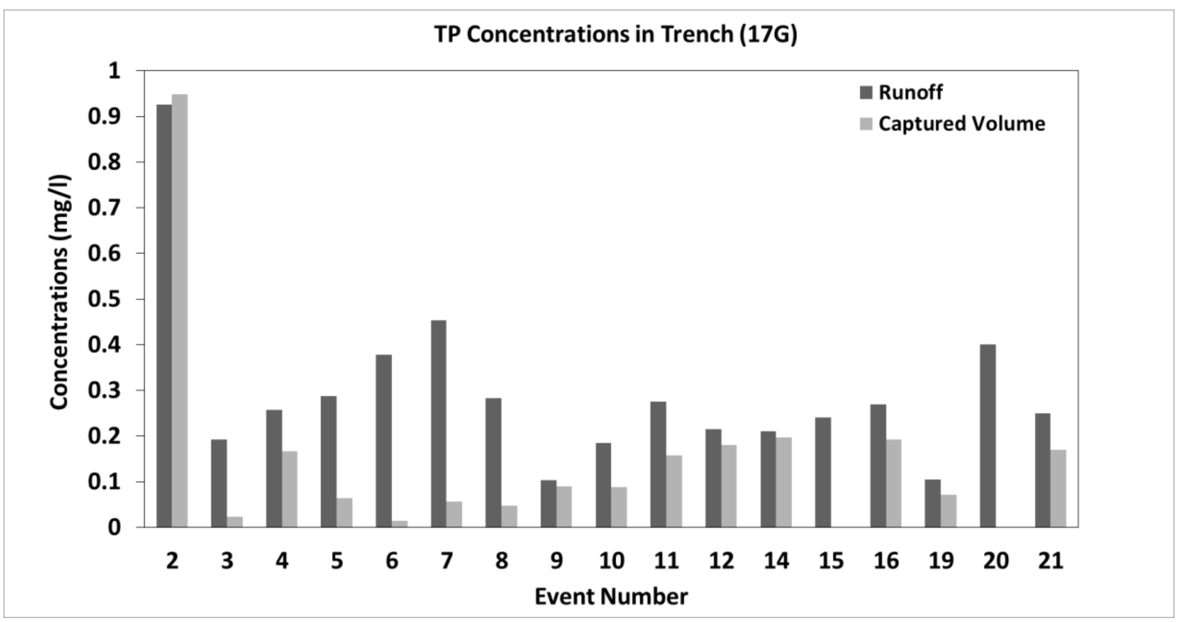

Figure 36-TP concentrations in runoff and captured volume for 17 events. Standard Deviations were 0.197 in runoff and 0.226 in the captured volume.

Nitrite concentrations were found to be lower in the captured volume except for events number 4, 7, 8, 9 and 14 (see Figure 37). Reduction of ammonia concentrations was also observed in most of the rain events except events 8, 9, and 12 (see Figure 38). The removal mechanism for ammonia is known to be adsorption into soil and aggregate layers through electrostatic and ion exchange interaction (Davis et al. 2001). Nitrification will also cause the transformation of ammonia to nitrate and nitrite.

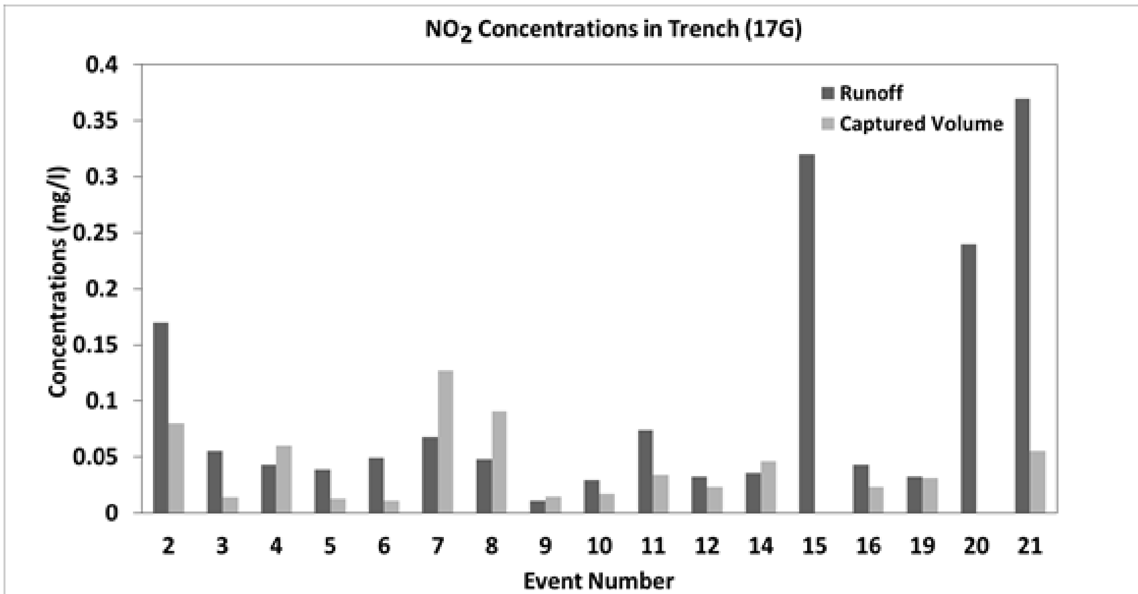

Figure 37- Nitrite concentrations in runoff and captured volume for 17 events. Standard Deviations were 0.0897 in runoff and 0.0343 in the captured volume.

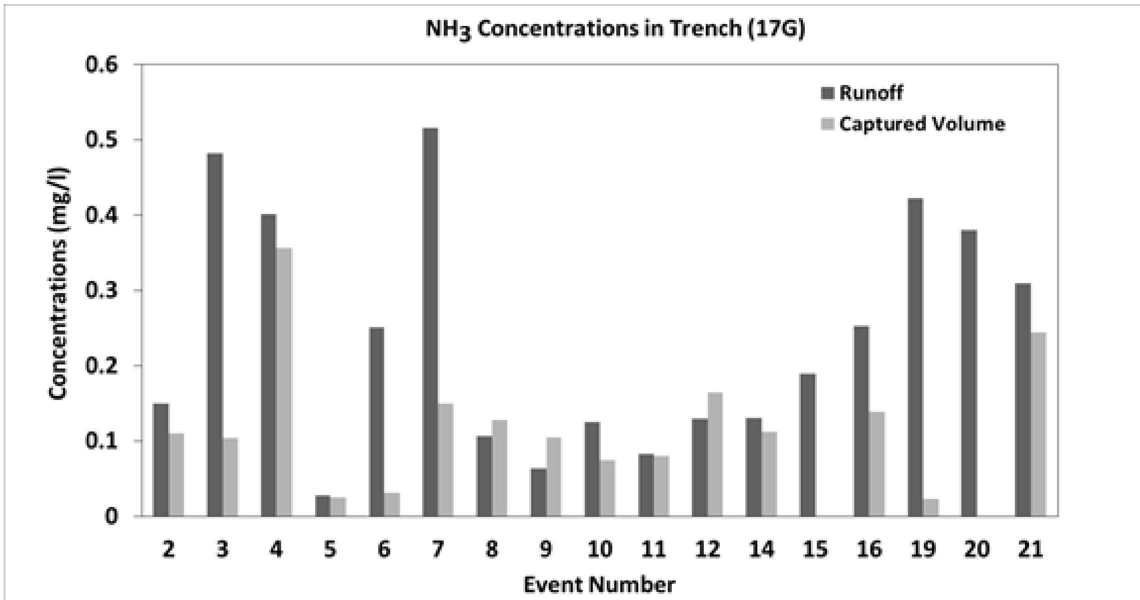

Figure 38-Ammonia concentrations in runoff and captured volume for 17 events. Standard Deviations were 0.1615 in runoff and 0.0865 in the captured volume.

Nitrate concentrations were found to be higher in the captured volume in more than half of the rain events (Figure 39). As previously explained, this is due to transformation of ammonia and organic nitrogen captured by the aggregate layers to nitrate.

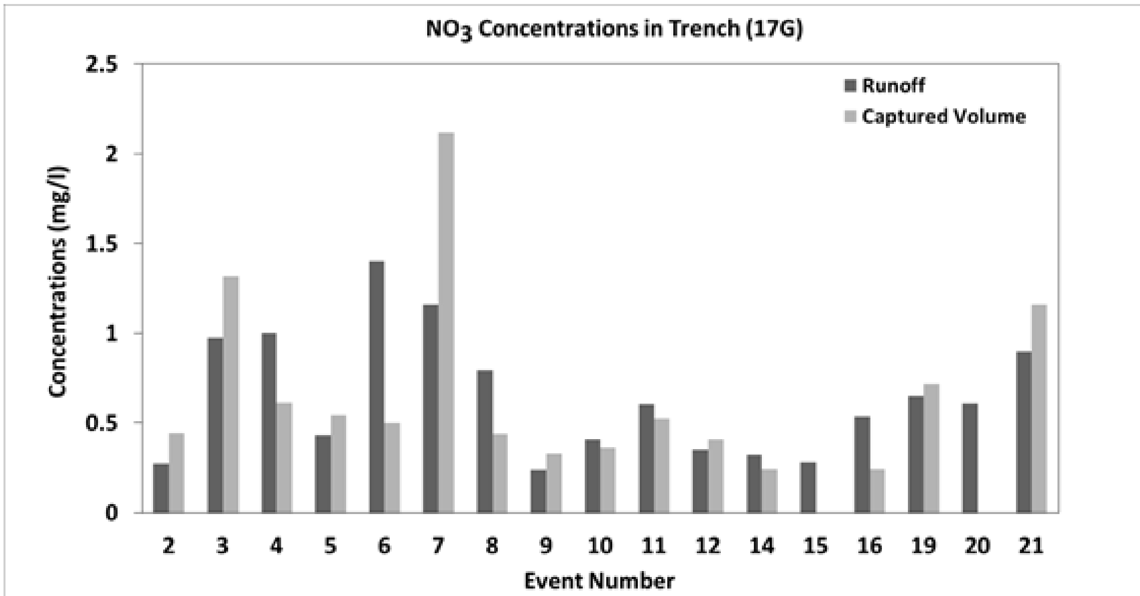

Figure 39- Nitrate concentrations in runoff and captured volume for 17 events. Standard Deviations were 0.354 in runoff and 0.506 in the captured volume.

The average values of nitrate, nitrite, ammonia, and TP in 15 events (in which samples were collected from both runoff and captured volume) are illustrated in Figure 40. Average concentrations of nitrite, ammonia and TP in the captured volume are lower than the runoff. The reduction percentages were respectively 56%, 48%, and 44%. However, the nitrate concentrations were 3.5% higher in the captured volume as a result of nitrification.

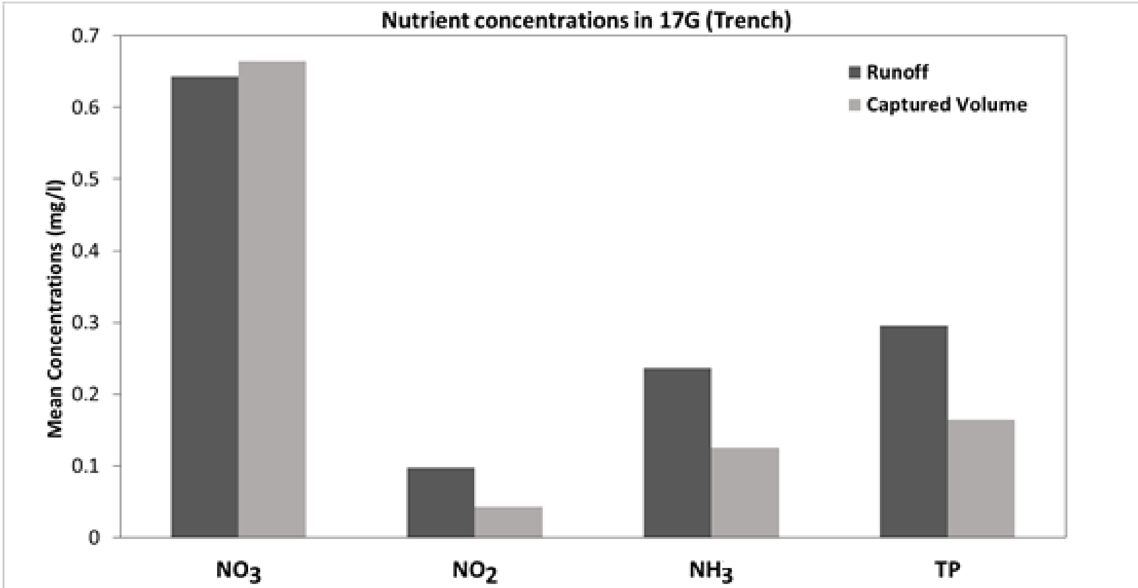

Figure 40-Average concentrations of nitrate, nitrite, ammonia and TP in 15 events

Nutrient Removal of GI control 17H

Nutrient concentrations in runoff and in samples collected from the bottom of the shaft in 14 rainfall events are shown in figures 41-45. In event number 20, samples were only collected from the runoff, due to the low rainfall volume

TP concentrations are plotted in Figure 41; all the TP values in the captured volume were lower compared to the samples collected from the runoff except the first two rain events. Filtration of the particulate portion of phosphorus by the aggregate layers could be the main mechanism responsible for lower concentrations of TP in the captured volume.

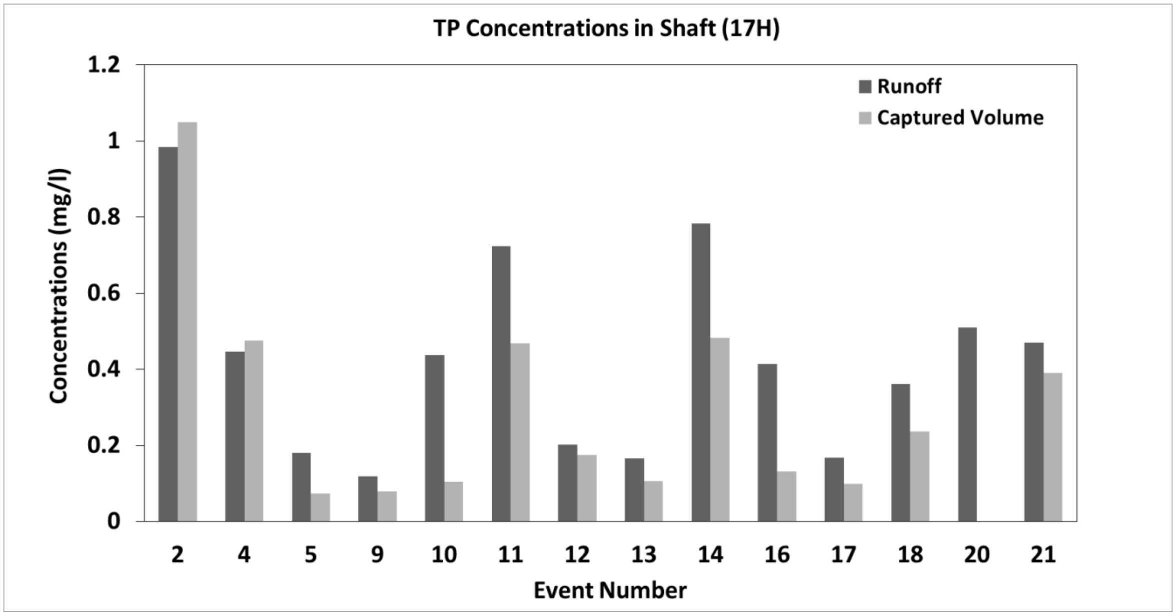

Figure 41-TP concentrations in runoff and captured volume for 14 events. Standard Deviations were 0.270 in runoff and 0.278 in the captured volume.

Nitrite concentrations in captured volume in the bottom of the trench were slightly lower than the runoff, except for events number two and four, in which runoff concentrations were slightly lower (see Figure 42). Ammonia concentrations are plotted in Figure 43, and the captured volume concentrations were found to be lower in all 13 events, but the removal rate of ammonia in this GI control appeared to be lower compared to the tree box and GI control 17G.

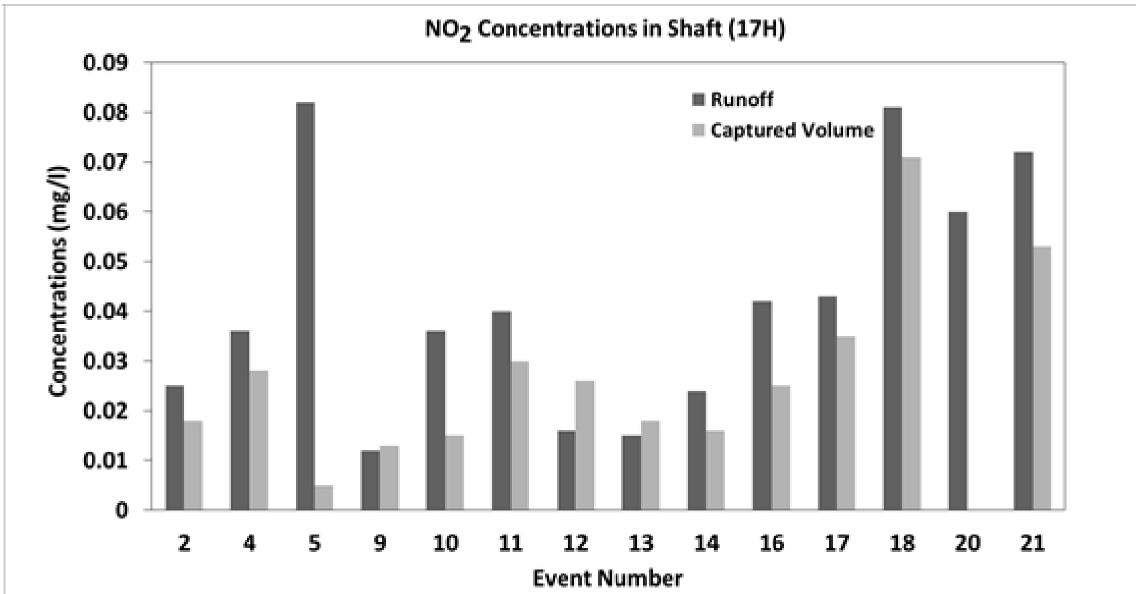

Figure 42-Nitrite concentrations in runoff and captured volume for 14 events. Standard Deviations were 0.024 in runoff and 0.018 in the captured volume.

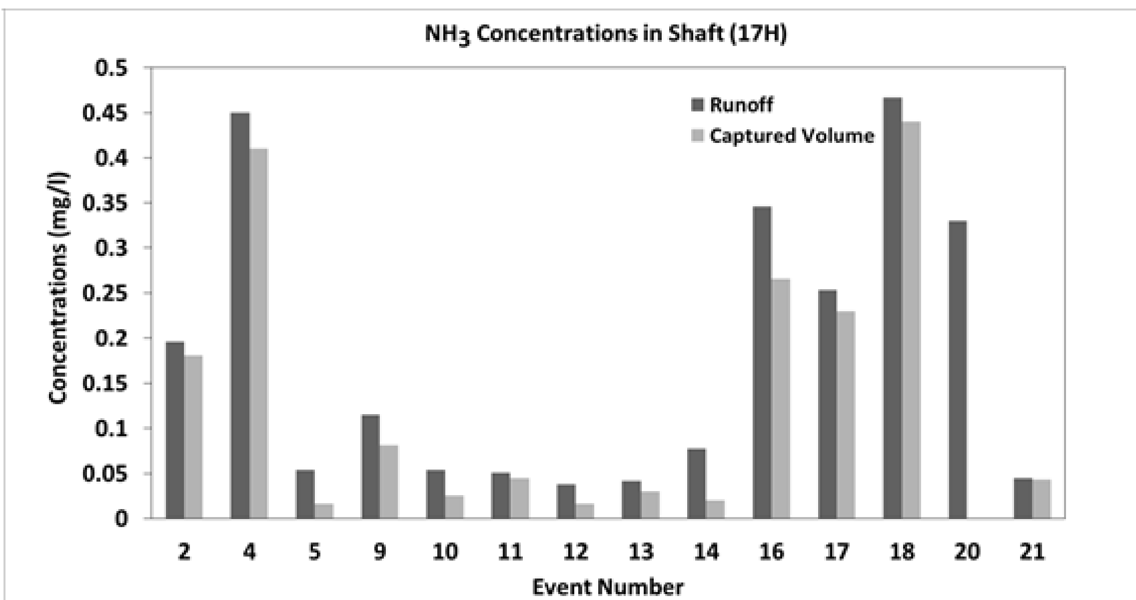

Figure 43-Ammonia concentrations in runoff and captured volume for 14 events. Standard Deviations were 0.160 in runoff and 0.153 in the captured volume.

Analyzing the samples for nitrate showed that more than half of the rain events caused higher concentrations of nitrate in the captured volume by the shaft. This is probably a result of biological transformation of ammonia to nitrate.

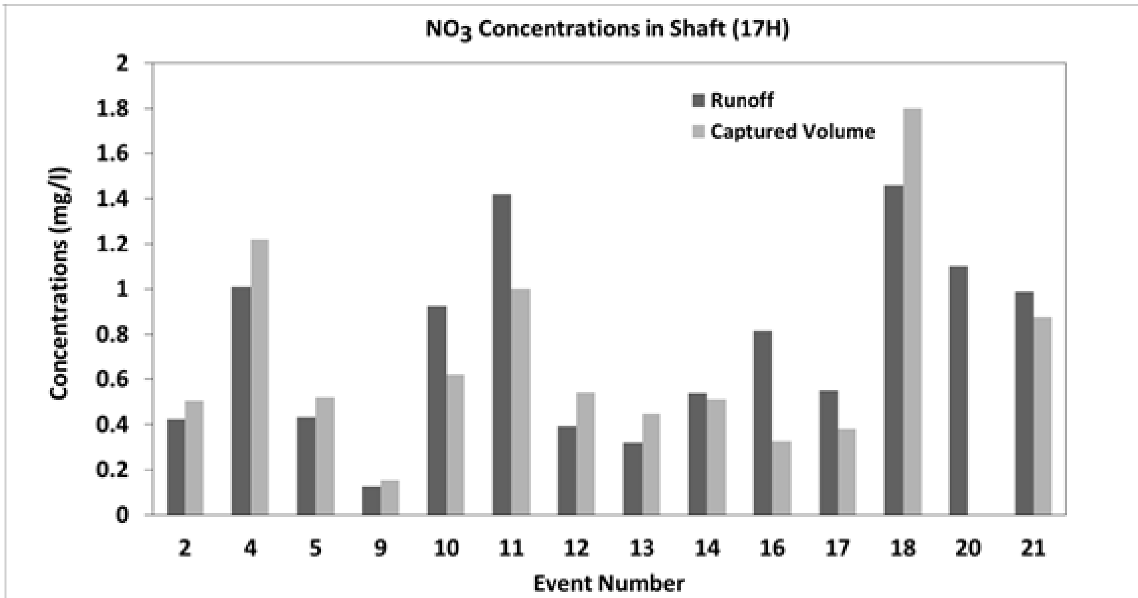

Figure 44-nitrate concentrations in runoff and captured volume in 14 events. Standard Deviations were 0.418 in runoff and 0.442 in the captured volume.

The average values of nutrient removals in this GI control for 13 events were 6% for nitrate, 34% for nitrite, 23% for ammonia and 30% for TP. Lower values of reductions for TP, nitrite and ammonia were observed in this GI control compared to 17G. This could be the result of the shorter path that the runoff travels to reach the bottom of the shaft. Also, lower amounts of nitrate leached to the bottom of the shaft, which shows nitrification did not take place in this GI control as much as it did in 17G and the tree box. Figure 45 shows the average concentrations of nutrients for 13 rain events in GI control 17H.

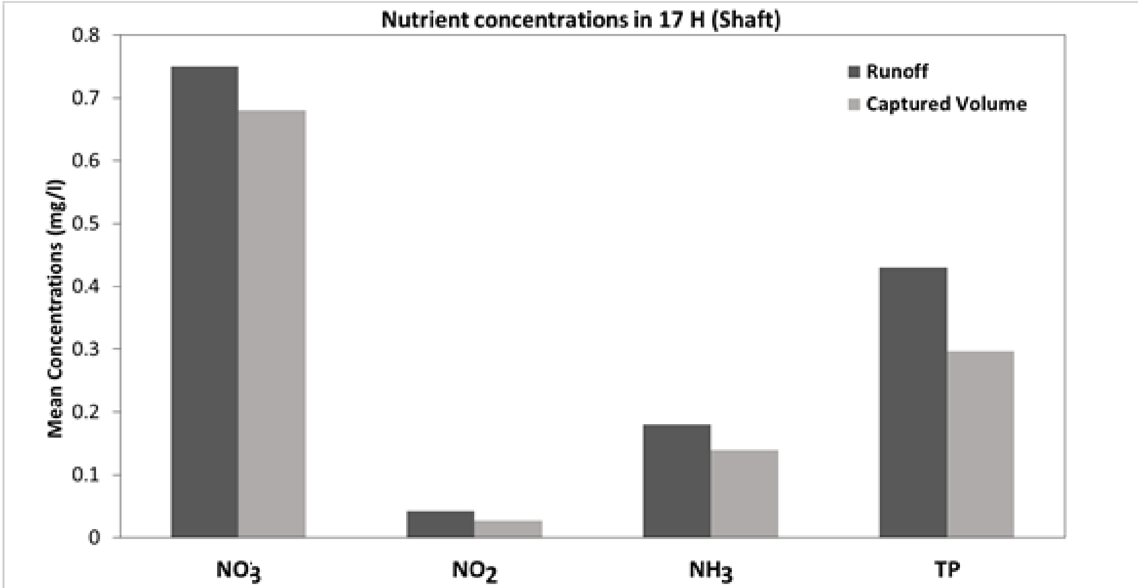

Figure 45-Average concentrations of nitrate, nitrite, ammonia, and TP in 13 events

Metals Removal in GI control 17G

Metal concentrations were measured in the first four events and only in samples collected from GI control 17G. Figure 43 shows the concentrations of zinc in the runoff flowing on the curb side and into the permeable pavement and in captured volume in the bottom of the trench. Zn concentrations were lower in the captured volume in all four events.

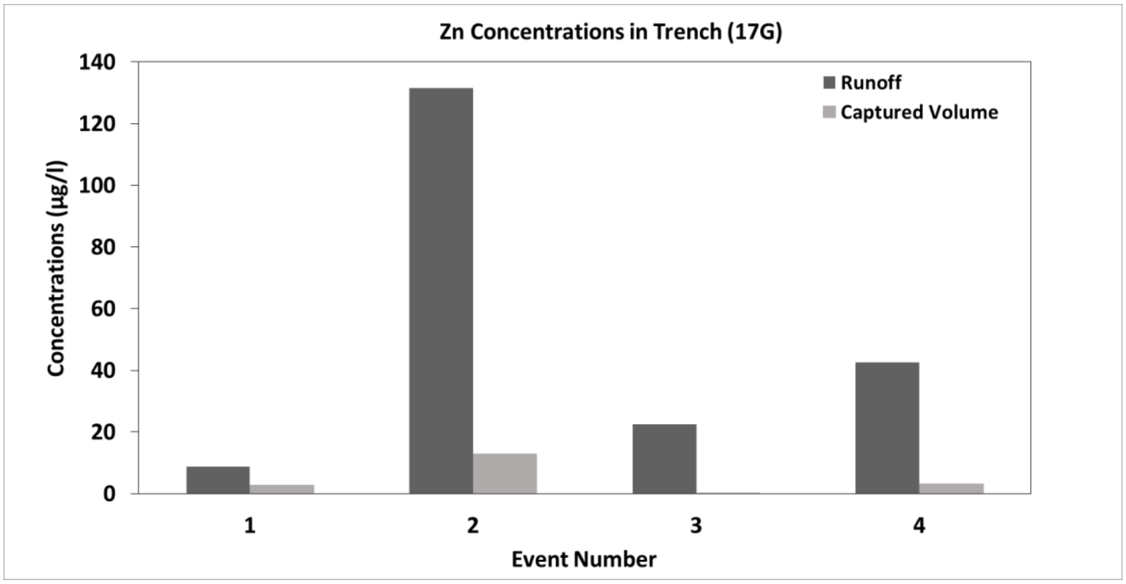

Figure 46-Zinc concentrations in runoff and captured volume for four events

Copper and iron concentrations were also lower in the samples collected from the bottom of the trench compared to runoff samples (see Figures 47 and 48).

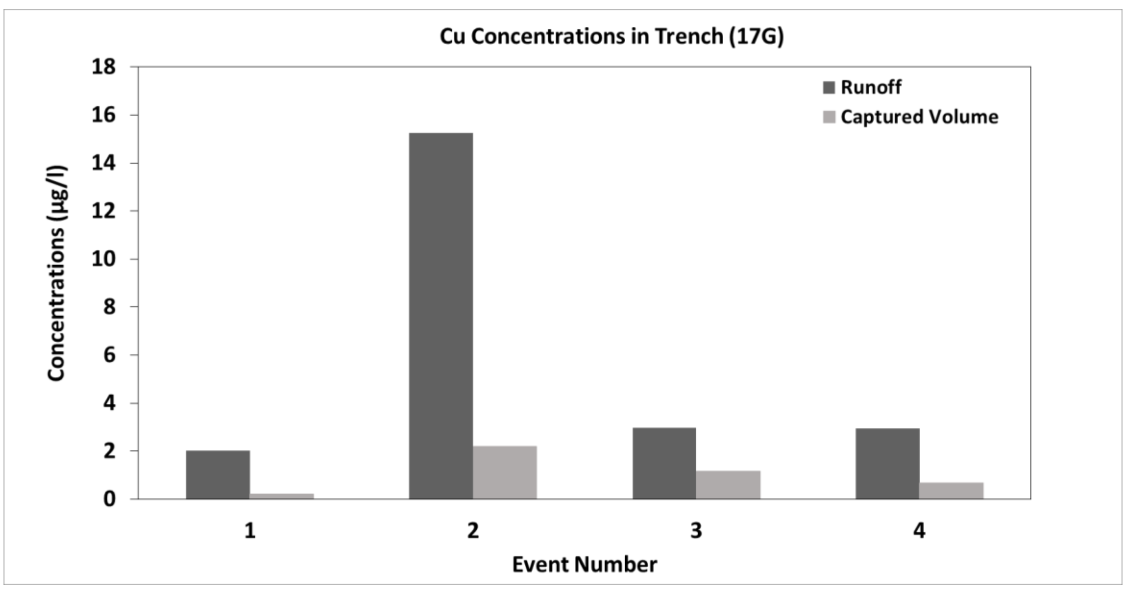

Figure 47-Copper concentrations in runoff and captured volume for four events

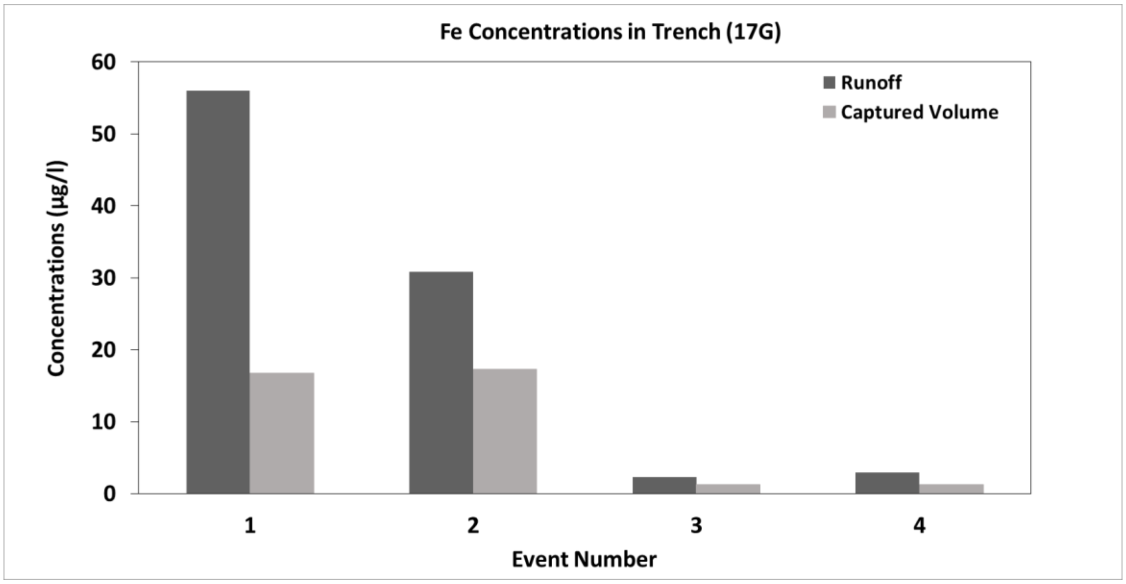

Figure 48-Iron concentrations in runoff and captured volume for four events

The average concentrations for these three metals for the first four events are plotted in Figure 49. The highest reductions were observed for zinc where the captured volume concentrations were 91% lower than the runoff. Reduction percentages were also high for copper (82%) and iron (60%).

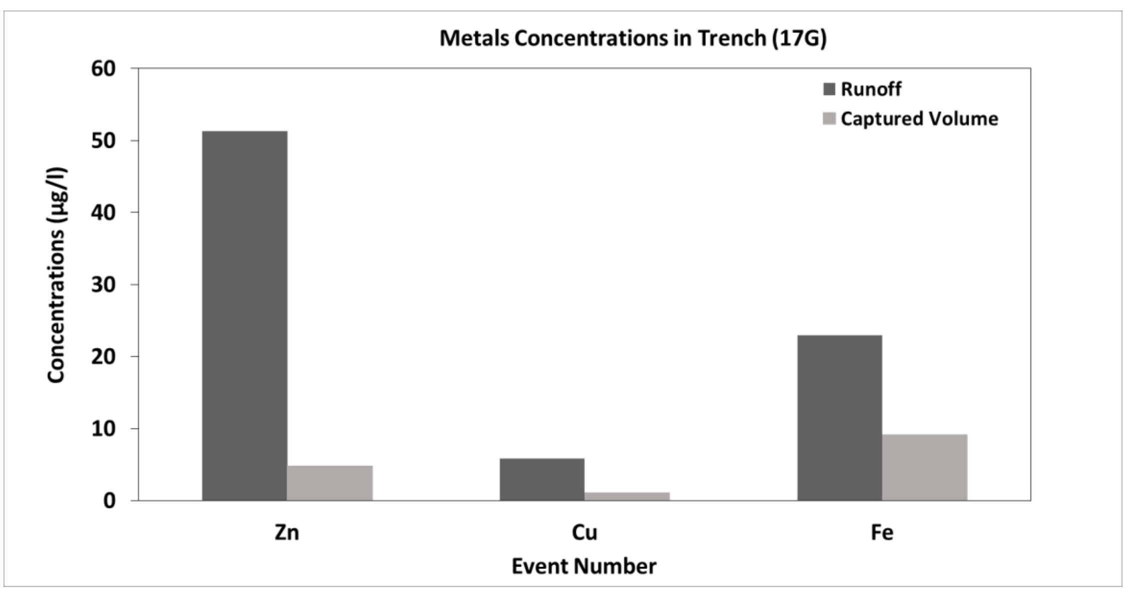

Figure 49-Average concentrations of metals for four events

The removal of metals occurs mainly due to adsorption to the organic matter and the soil layer as the runoff infiltrates through the soil and aggregate layers (Davis et al. 2003). Humic substances, the major components of natural organic matter, strongly affect the heavy metals removal. This is a result of the structure of these compounds which is made of large proportion of functional groups such as hydroxyl, carboxyl, and amino groups (Jang et al. 2005). Organic matter (decaying plants and leaf litter) builds up approximately 30% of the clogging material in between the concrete blocks of the permeable pavement system, and in upper layers of aggregates; this clogging material is probably the main reason of high removal percentages of heavy metals.

4.2.4 Statistical Analysis of Pollutant Concentrations

Mean decrease percentages and *p*-values, in addition to mean and median concentrations of pollutants in the runoff and the captured volume by the GI control, are listed in tables 18-20. Since the distribution of data in this study was normal or log-normal (except for ammonia in control 17G and nitrite in 17H), Student t-tests with a criterion of 95% were performed on non-transformed or log-transformed values of the concentrations. The student t-test determined if the reductions in the concentrations were statistically significant ($p < 0.05$).

Table 18-Mean Concentrations, Median values, Average Decrease Percentages, and the *p*-values for the Tree Box

Pollutant	**Number of Rainfall Events Sampled**	**Events Sampled**	**Mean Concentration Values**		**Median Concentration Values**		**Mean Decrease %**	***p*- value**
			Runoff	*Captured*	*Runoff*	*Captured*		
E. coli **(CFU/100ml)**	17	1, 2, 4-7, 9-19, 21	1055	50	460	44	95.3	< **0.0001**[*]
TSS (mg/L)	17	1, 2, 4-7, 9-19, 21	199.4	51.8	164	38	74.0	< **0.0001**[*]
Nitrate (mg/L)	17	1, 2, 4-7, 9-19, 21	0.725	1.27	0.627	1.26	-75.2	< **0.0001**[*]
Nitrite (mg/L)	17	1, 2, 4-7, 9-19, 21	0.077	0.030	0.062	0.025	61.0	**0.008**
Ammonia (mg/L)	17	1, 2, 4-7, 9-19, 21	0.307	0.033	0.254	0.023	89.2	**0.001**[*]
TP (mg/L)	17	1, 2, 4-7, 9-19, 21	0.258	0.074	0.213	0.0.053	71.3	< **0.0001**

Table 19--Mean Concentrations, Median values, Average Decrease Percentages, and the *p*-values for GI Control 17G

Pollutant	Number of Rainfall Events Sampled	Events Sampled	Mean Concentration Values		Median Concentration Values		Mean Decrease %	*p*-value
			Runoff	*Captured*	*Runoff*	*Captured*		
***E. coli* (CFU/100ml)**	15	2-12, 14, 16, 19, 21	2719	1095	1740	740	59.7	< **0.0001***
TSS (mg/L)	15	2-12, 14, 16, 19, 21	242.1	139.4	242	100	42.6	< **0.0001***
Nitrate (mg/L)	15	2-12, 14, 16, 19, 21	0.667	0.671	0.606	0.499	-0.6	0.965
Nitrite (mg/L)	15	2-12, 14, 16, 19, 21	0.073	0.043	0.043	0.031	41.1	**0.046***
Ammonia (mg/L)	15	2-12, 14, 16, 19, 21	0.229	0.124	0.15	0.11	45.9	-
TP (mg/L)	15	2-12, 14, 16, 19, 21	0.293	0.164	0.258	0.09	44.0	**0.002**
$Cu_{dissolved}$ (µg/L)	4	1 - 4	5.80	1.063	2.96	0.919	81.7	-
$Zn_{dissolved}$ (µg/L)	4	1 - 4	51.40	4.76	32.6	2.94	90.7	-
$Fe_{dissolved}$ (µg/L)	4	1 - 4	23.0	9.16	16.9	9.02	60.2	-

Table 20-Mean Concentrations, Median values, Average Decrease Percentages, and the p-values for GI Control 17H

Pollutant	**Number of Rainfall Events Sampled**	**Events Sampled**	**Mean Concentration Values**		**Median Concentration Values**		**Mean Decrease %**	***p-* value**
			Runoff	*Captured*	*Runoff*	*Captured*		
E. coli **(CFU/100ml)**	13	2, 4, 5, 9 – 14, 16-18, 21	3810	845	2300	1400	77.8	**0.002**
TSS (mg/L)	13	2, 4, 5, 9 – 14, 16-18, 21	184.8	89.9	147	98	51.4	< **0.0001***
Nitrate (mg/L)	13	2, 4, 5, 9 – 14, 16-18, 21	0.723	0.685	0.55	0.521	5.3	0.586
Nitrite (mg/L)	13	2, 4, 5, 9 – 14, 16-18, 21	0.040	0.027	0.036	0.025	32.5	-
Ammonia (mg/L)	13	2, 4, 5, 9 – 14, 16-18, 21	0.168	0.139	0.077	0.045	17.3	< **0.0001**
TP (mg/L)	13	2, 4, 5, 9 – 14, 16-18, 21	0.420	0.297	0.414	0.175	29.3	**0.005**

The pollutant concentration data for the tree box is listed in Table 18. Log-transformed data was used in the case of *E. coli*, TSS, nitrate, and ammonia in order to reduce the skewness of the distribution (Feng et al. 2014). The concentrations of all pollutants in the captured volume were significantly lower ($p < 0.05$) except for nitrate, which had significantly higher concentrations in captured volume due to the nitrification process.

Log-transformed data for *E. coli*, TSS, and nitrite and nontransformed data for nitrate and TP was used in control 17G. Since ammonia data was not normal or log-normal distributed, and the sample size for zinc, copper, and iron were small (4 data points), no student t-test was conducted for these pollutants. Statistically significant differences between runoff and captured volume were observed for all pollutants except nitrate (see table 17).

Table 18 shows significant reductions for all pollutants in GI control 17H except for the case of nitrate in which the *p*-value was greater than 0.05, and nitrite in which the *p*-value was not calculated due to the skewness of data.

4.2.5 Parameter Correlations

Valuable information on the relationship between the pollutants and the effect of rainfall characteristics on pollutant concentrations in the runoff can be provided by correlation plots. Two sets of correlation plots are presented in this section of the document. In the first set of correlations, pollutant concentrations were plotted against the rainfall characteristic including intensity and antecedent dry conditions. And in the second set of correlations, pollutant concentrations and their reduction percentages were plotted against TSS concentrations and TSS reduction percentages.

Effect of Rainfall Intensity on Pollutant Concentrations:

To understand the effect of intensity on pollutant concentrations in the runoff, concentrations were plotted against the 5-minute maximum intensity during the first flush of the rainfall event.

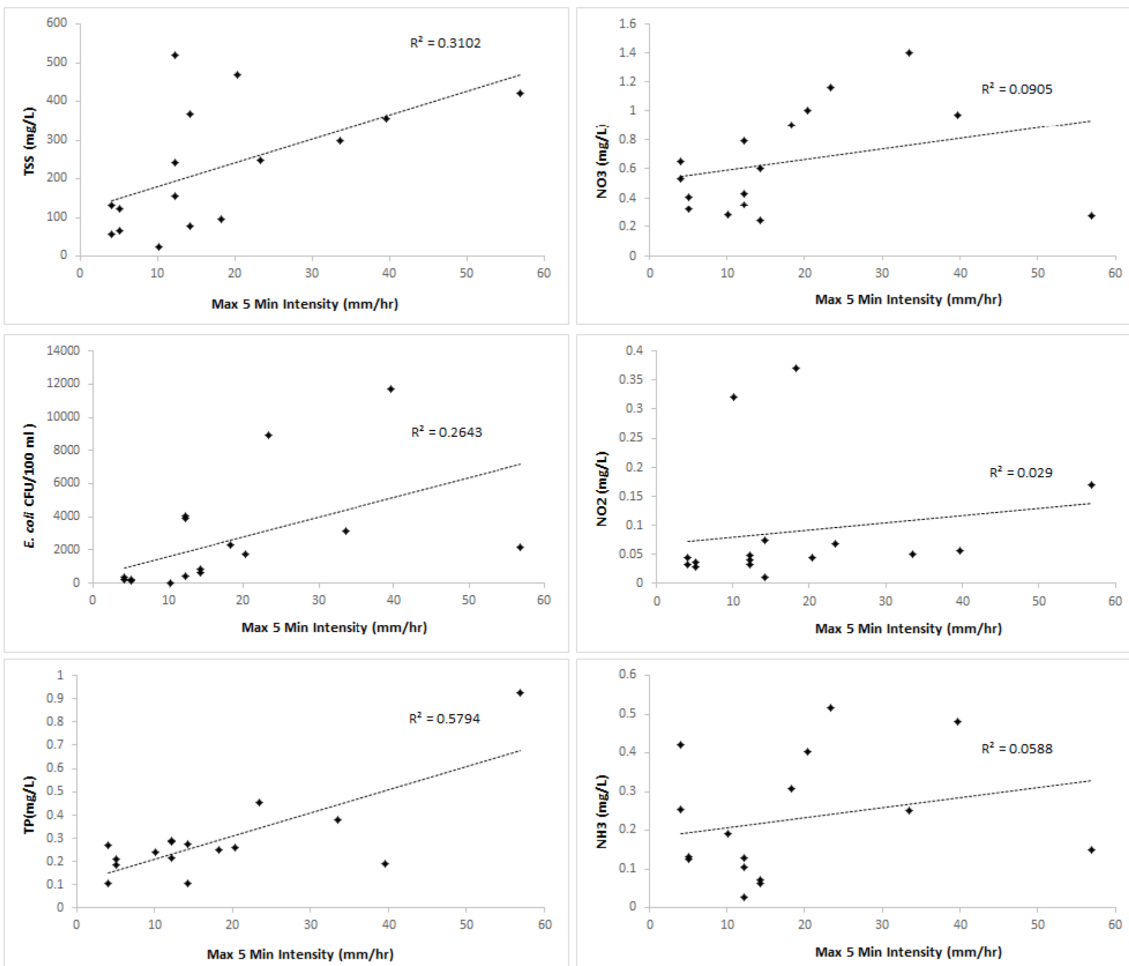

Figure 50-Pollutant concentration vs. 5 minute maximum intensity for GI control 17G

Figure 50 shows the correlations between pollutant concentrations and the maximum 5-minute intensity. Relatively strong and statistically significant ($p < 0.05$) correlations were observed between the intensity values and TSS, TP, and *E. coli* concentrations. However the relationship between the intensity and nitrate, nitrite, and ammonia was found to be weak or negligible, based on the Person's correlation coefficients.

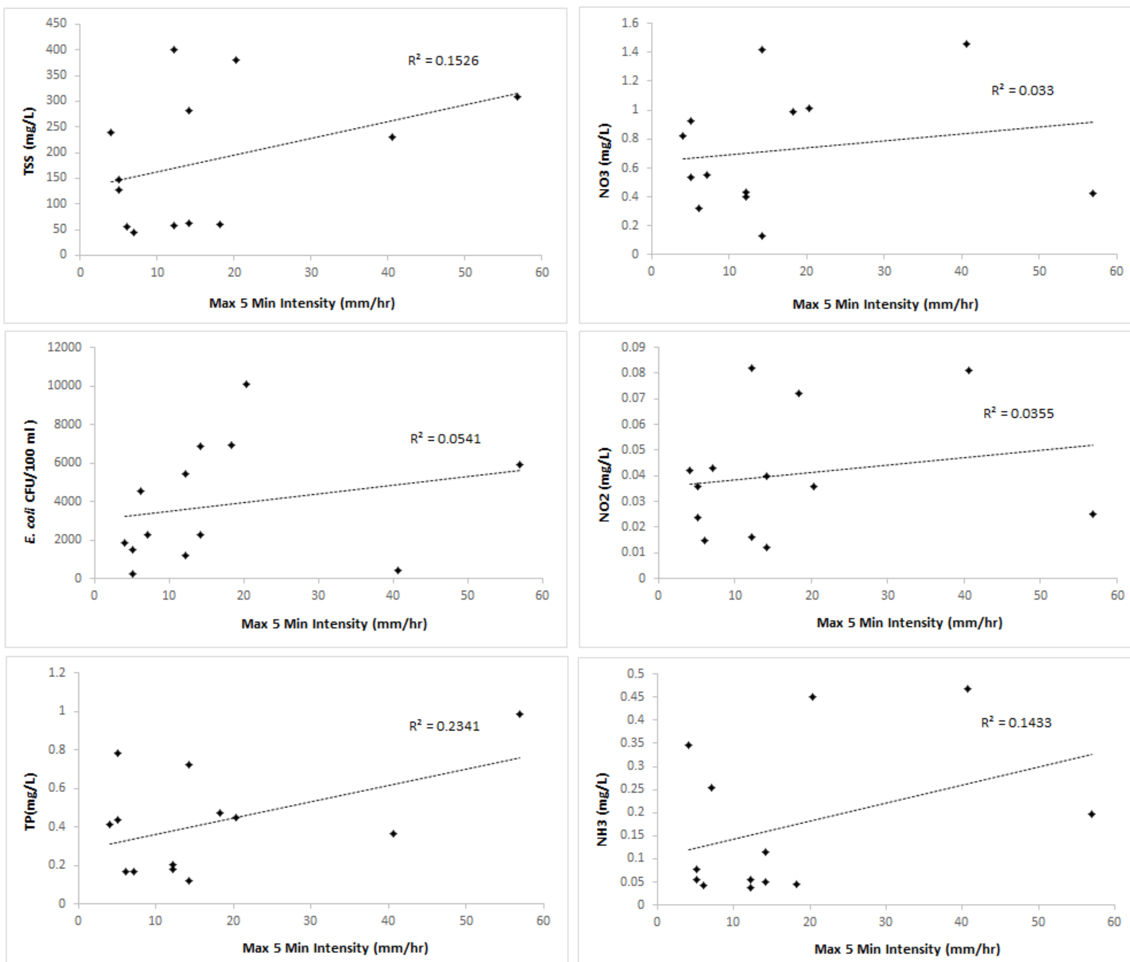

Figure 51-Pollutant concentration vs. 5 minute maximum intensity for GI control 17H

Moderate and weak positive relationships were observed between the maximum 5-minute intensity and the runoff concentrations in GI control 17H, except TP where the correlation was relatively stronger compared to other pollutants, but still not significant ($p > 0.05$) (See Figure 51).

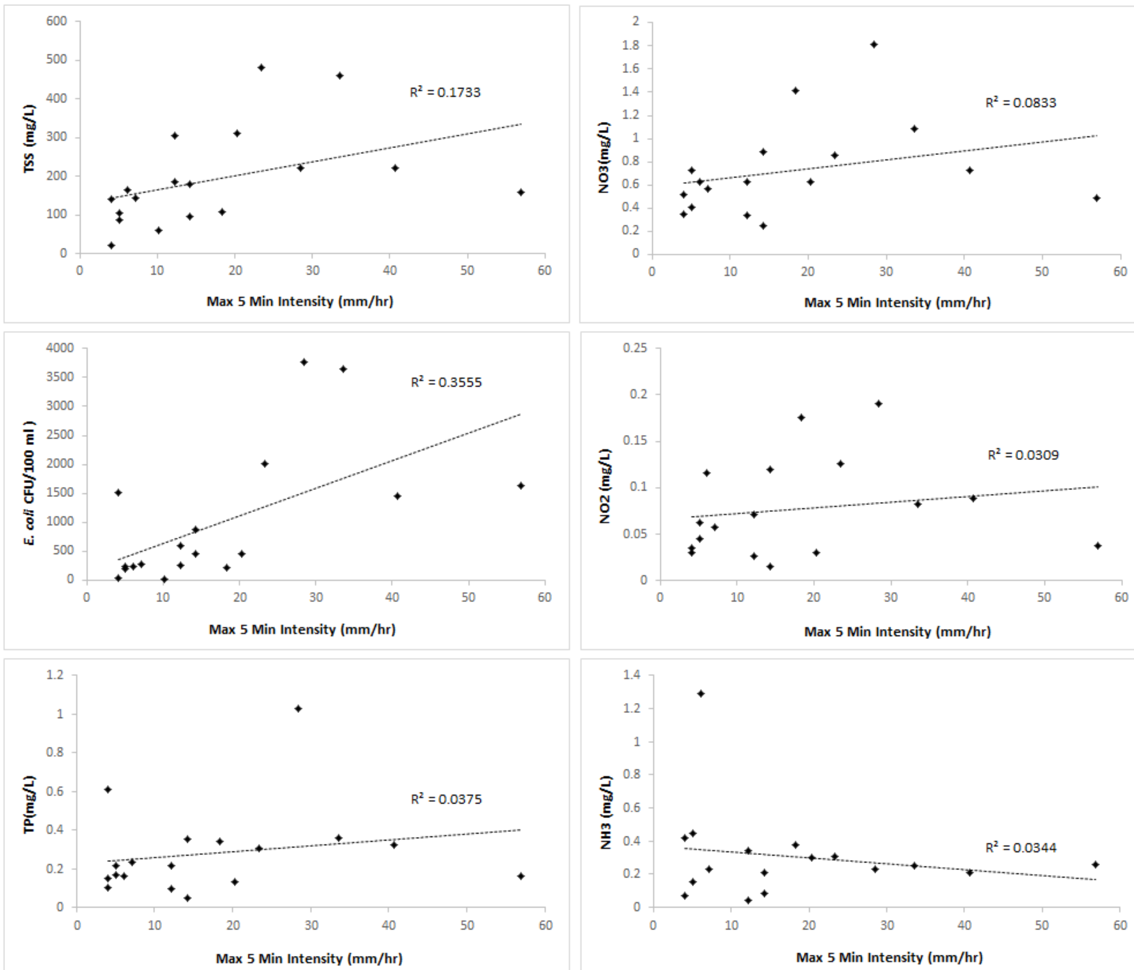

Figure 52-Pollutant concentration vs. 5 minute maximum intensity for the tree box

The correlations between maximum 5-minute intensity and the runoff concentrations of pollutants flowing into the tree box are plotted in Figure 52. These correlations showed a strong and significant relationship between the intensity and *E. coli* concentrations, a moderate to weak positive relationship between TSS, nitrate, TP, and nitrite and a weak negative relationship between ammonia and the intensity of the rainfall event.

Table 21 summarizes the statistical information including Pearson's correlation coefficient (PPC) and the *p*-value of the correlation plots presented in figures 49-52.

Table 21- Pearson's correlation coefficient (PPC) and the *p*-value for correlations between runoff concentrations and 5-minute maximum intensity, *p*-values < 0.05 are typed in bold.

GI Control	**Tree Box**		**GI Control 17G**		**GI Control 17H**	
Pollutant	**PPC**	***p*-value**	**PPC**	***p*-value**	**PPC**	***p*-value**
TSS	0.400	0.112	**0.557**	**0.025**	0.391	0.187
E. coli	**0.587**	**0.013**	**0.514**	**0.042**	0.231	0.445
TP	0.302	0.239	**0.761**	**0.001**	0.484	0.094
NO_3	0.289	0.261	0.301	0.258	0.182	0.553
NO_2	0.176	0.499	0.170	0.528	0.189	0.537
NH_3	-0.185	0.476	0.243	0.365	0.379	0.202

Effect of Antecedent Weather Conditions on Pollutant Concentrations

To investigate the effect of antecedent conditions on the pollutant concentrations in runoff, concentration values were plotted against the 7-Day antecedent rainfall depth and the antecedent dry period. No meaningful relationship was observed in any of the GI controls. Figure 53 shows the correlation plots for GI control 17G.

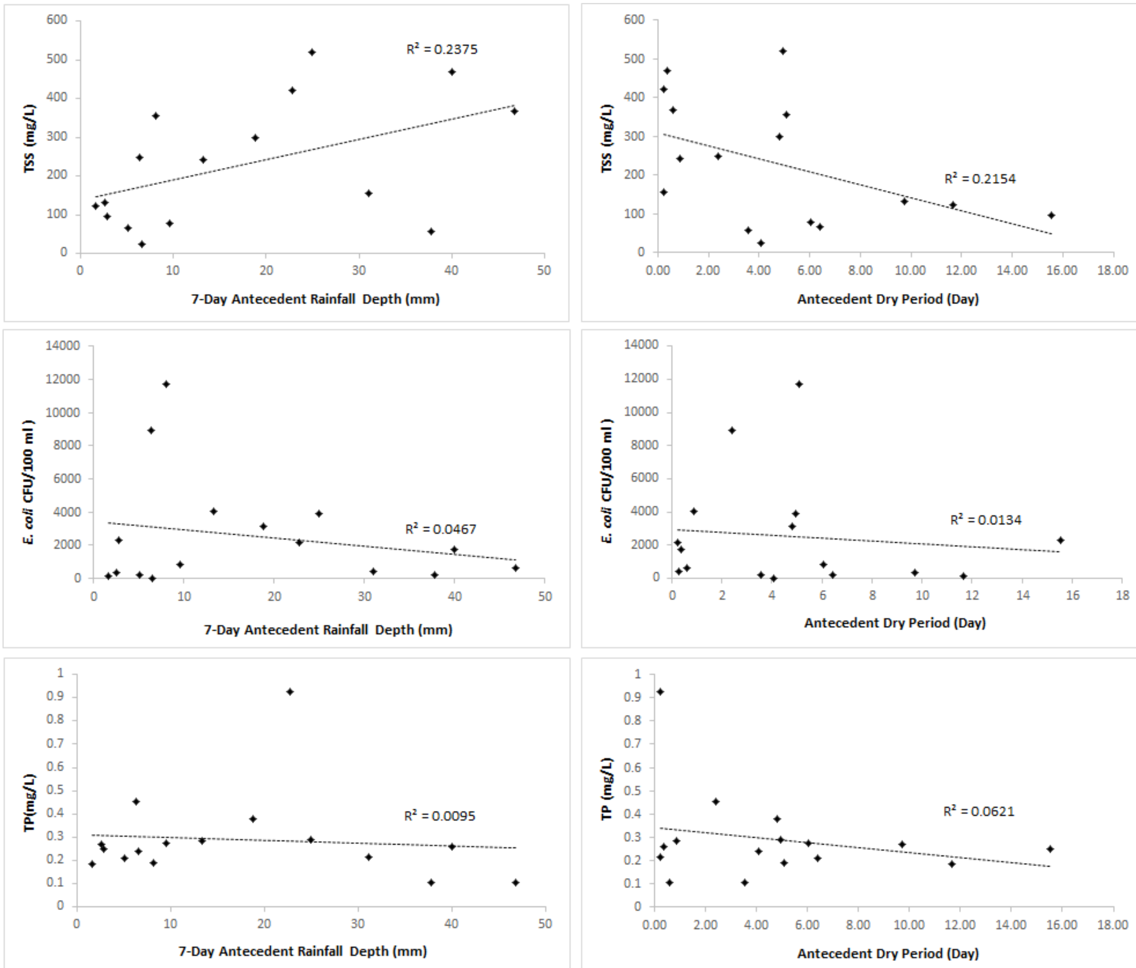

Figure 53-TSS, *E. coli*, and TP concentrations in runoff vs. antecedent conditions in GI 17G

Higher concentrations of pollutants were expected in the runoff as a result of longer dry periods. However this relationship was not observed in any of the GI controls. Also it was predicted that increase of rainfall depth prior to the event would reduce the pollutant concentrations in the runoff, but data from this study showed weak relationships (and in some cases no relationship) between concentrations and the 7-Day antecedent rainfall depth. These weak correlations could be the result of other contributing factors such as construction sites in the area which increased the concentrations, wind, and traffic which could remove some of the accumulated pollutants during the dry periods.

Correlations between TSS and other Pollutants

Correlations between TSS and other pollutants showed that only *E. coli* concentrations have a relatively strong correlation with TSS. Other pollutants showed weak and negligible correlations, except for TP values measured in GI control 17G in which a moderate relationship was observed. Correlation coefficients and *p*-values are presented in Table 22.

Table 22-Pearson's correlation coefficient (PPC) and the *p*-value for correlations between TSS concentrations and other pollutants in the runoff, *p*-values < 0.05 are typed in bold.

GI Control	Tree Box		GI Control 17G		GI Control 17H	
Pollutant	**PPC**	***p*-value**	**PPC**	***p*-value**	**PPC**	***p*-value**
E. coli	**0.557**	**0.016**	0.423	0.102	0.503	0.080
TP	0.157	0.547	0.361	0.169	0.055	0.858
NO_3	0.177	0.497	0.186	0.491	-0.091	0.767
NO_2	0.176	0.499	-0.304	0.253	0.228	0.453
NH_3	-0.125	0.633	0.006	0.982	0.451	0.122

In addition to the correlation between concentrations, reduction percentages were also plotted against the reduction percentages of TSS in each GI control. The *E. coli* reduction percentages showed a relatively strong and positive relationship with TSS reduction values in all three GI controls. However other correlations were found to be weak and negligible except for TP and nitrate in GI control 17G, nitrate in the tree box and ammonia in GI control 17H, in which relatively strong correlations were observed (Table 23).

Table 23-Pearson's correlation coefficient (PPC) and the *p*-value for correlations between TSS reduction percentages and other pollutants reductions, *p*-values < 0.05 are typed in bold.

GI Control	**Tree Box**		**GI Control 17G**		**GI Control 17H**	
Pollutant %	**PPC**	***p*-value**	**PPC**	***p*-value**	**PPC**	***p*-value**
***E. coli* %**	0.202	0.436	0.412	0.127	**0.616**	**0.025**
TP %	0.138	0.598	0.312	0.258	-0.321	0.285
NO_3 %	0.442	0.076	0.395	0.145	-0.524	0.066
NO_2 %	-0.197	0.448	0.260	0.350	0.159	0.605
NH_3 %	0.211	0.416	0.096	0.733	0.505	0.078

Correlation plots for *E. coli* and TP concentrations and reduction percentages versus TSS concentrations and reduction percentages are presented in Figures 54 and 55. Strong correlations can be observed for both *E. coli* concentrations and reduction values in all three GI controls. The TP correlations with TSS were found to be negligible, except for GI control 17G in which a weak relationship was observed between TP and TSS concentrations and reduction values.

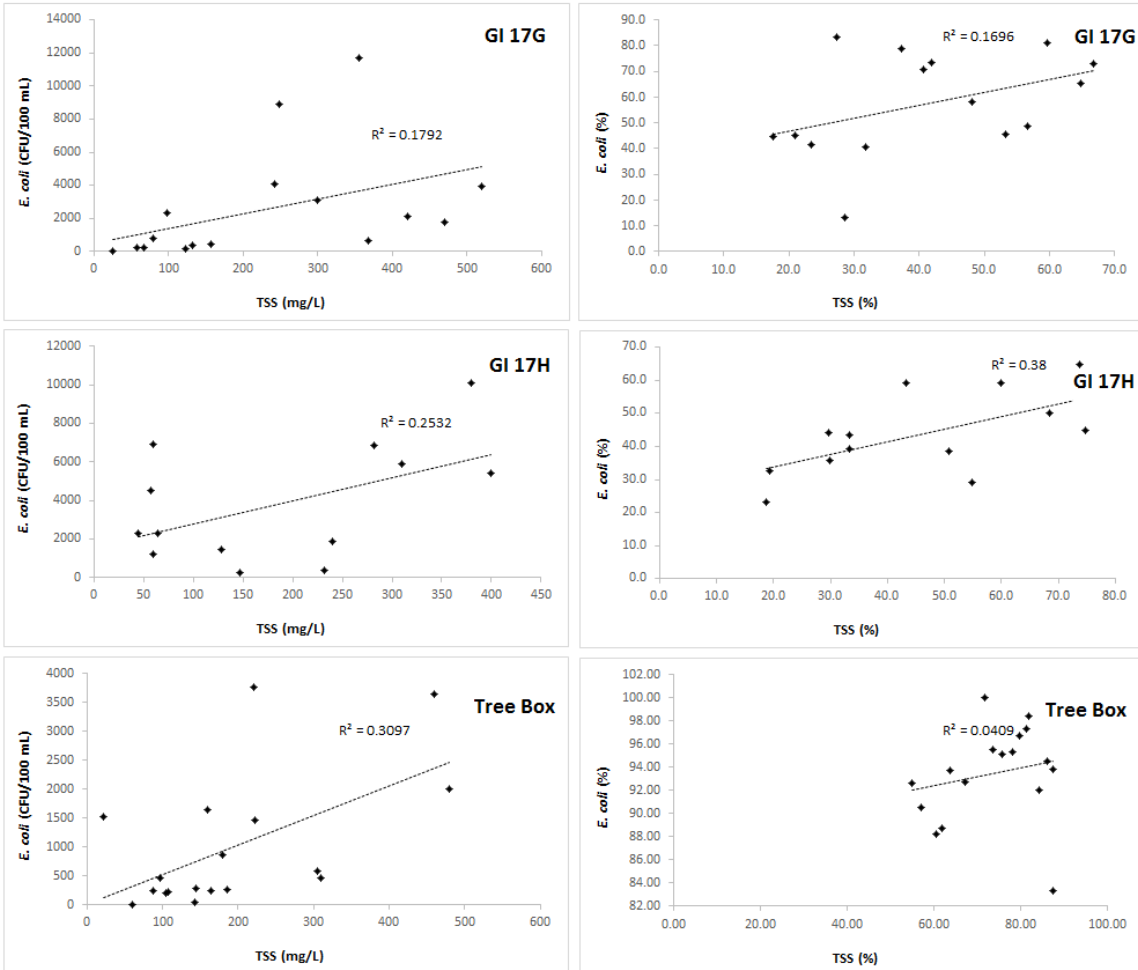

Figure 54-Correlations between TSS and *E. coli* (concentrations and reduction percentages)

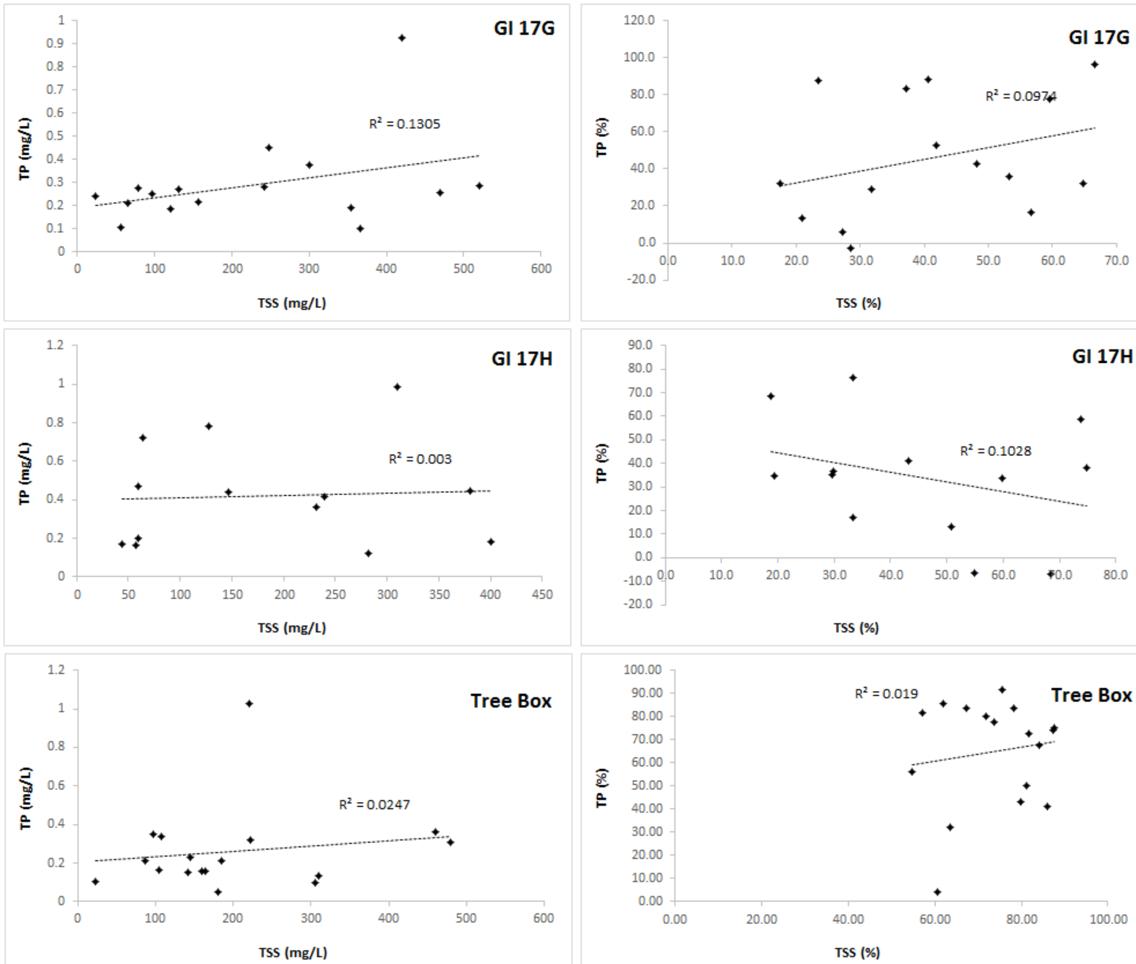

Figure 55-Correlations between TSS and TP (concentrations and reduction percentages)

4.3 Results from the Column Study

As mentioned in section 3.8, lab experiments were conducted to mimic the data collected from the field. This goal was achieved through 20 experiments which investigated the pollutant removal performance of the aggregate layers used in construction of GI controls 17G and 17H. The experimental details were presented in Table 11. The data from the column study is summarized in Table 24.

Table 24-Experimental details, including; the depth of aggregate layers, flow intensities, and pollutant concentrations in inflow and outflow

Test No.	**Depth of Aggregate (ft)**		**Inflow Intensity (in/hr)**	**Inflow Concentrations (mg/L)**					**Outflow Concentrations (mg/L)**					**Removal Percentages (%)**				
	#3	#57		TSS	NO_3	NO_2	NH_3	TP	TSS	NO_3	NO_2	NH_3	TP	TSS	NO_3	NO_2	NH_3	TP
1	-	1	1.5	84.5	1.42	0.028	0.49	0.352	18	1.44	0.036	0.46	0.221	78.7	-1.4	-28.6	6.1	37.2
2	-	1	3	106	1.30	0.049	0.42	0.287	32	1.30	0.059	0.415	0.186	69.8	0.0	-20.4	1.2	35.2
3	-	2	1.5	81	1.57	0.044	0.422	0.253	11	1.49	0.066	0.36	0.163	86.4	5.1	-50.0	14.7	35.6
4	-	2	3	78	1.57	0.066	0.356	0.242	12	1.57	0.1	0.359	0.156	84.6	0.0	-51.5	-0.8	35.5
5	-	3	1.5	84	1.61	0.023	0.46	0.288	5	1.50	0.029	0.43	0.153	94.0	6.8	-26.1	6.5	46.9
6	-	3	3	73	1.48	0.022	0.449	0.284	6	1.28	0.032	0.455	0.162	91.8	13.5	-45.5	-1.3	43.0
7	-	4	1.5	73	1.51	0.032	0.416	0.242	2.5	1.50	0.047	0.40	0.144	96.6	0.7	-46.9	3.8	40.5
8	-	4	3	91	1.66	0.021	0.5	0.233	5	1.66	0.018	0.475	0.147	94.5	0.0	14.3	5.0	36.9
9	2	-	1.5	78	1.39	0.038	0.41	0.314	55	1.34	0.041	0.414	0.284	29.5	3.6	-7.9	-1.0	9.6
10	2	-	3	64	1.28	0.043	0.53	0.278	54	1.24	0.051	0.46	0.254	15.6	3.1	-18.6	13.2	8.6
11	3	-	1.5	79	1.77	0.055	0.45	0.251	30	1.76	0.069	0.455	0.193	62.0	0.6	-25.5	-1.1	23.1
12	3	-	3	62	1.53	0.046	0.46	0.293	30	1.51	0.055	0.47	0.254	51.6	1.3	-19.6	-2.2	13.3
13	4	-	1.5	68	1.72	0.064	0.48	0.271	12	1.81	0.066	0.52	0.136	82.4	-5.2	-3.1	-8.3	49.8
14	4	-	3	89	1.4	0.047	0.538	0.289	18	1.49	0.059	0.527	0.173	79.8	-6.4	-25.5	2.0	40.1
15	4	1	1.5	98	1.42	0.076	0.668	0.302	10	1.46	0.101	0.694	0.166	89.8	-2.8	-32.9	-3.9	45.0
16	4	1	3	96	1.41	0.064	0.572	0.352	12	1.46	0.096	0.605	0.197	87.5	-3.5	-50.0	-5.8	44.0
17	3	2	1.5	72	1.49	0.058	0.657	0.252	3	1.47	0.081	0.618	0.161	95.8	1.3	-39.7	5.9	36.1
18	3	2	2.25	75	1.55	0.05	0.7	0.272	5	1.52	0.054	0.648	0.173	93.3	1.9	-8.0	7.4	36.4
19	3	2	3	80	1.52	0.06	0.655	0.264	5	1.56	0.072	0.551	0.175	93.8	-2.6	-20.0	15.9	33.7
20	3	2	3.75	80	1.51	0.055	0.6	0.264	6	1.53	0.055	0.59	0.171	92.5	-1.3	0.0	1.7	35.2

Pollutant removal performance of #57 AASHTO aggregate was tested in the first 8 experiments, in four depth increments (30, 61, 92, and 122 cm) and two inflow intensities per each increment (38 and 76 mm/hr.). The removal percentages for TSS and TP are plotted in Figures 56 and 57.

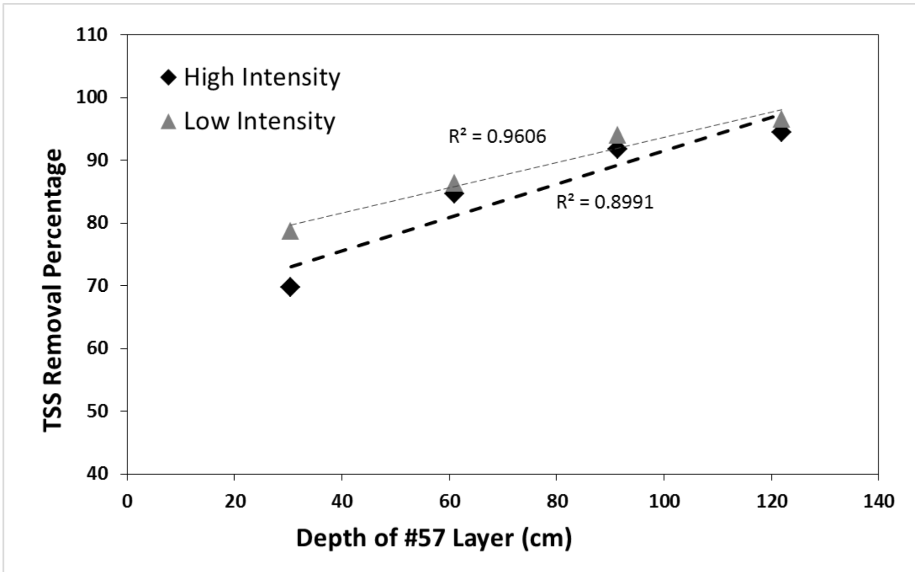

Figure 56-Effect of the depth of filter media (#57) on TSS removal percentages

According to Figure 56, a significant linear relationship was observed between TSS removal percentages and the depth of #57 aggregate. It was also observed that the TSS removal efficiency and the inflow intensity were inversely related, which is a result of greater distance between the particles and the filter media, and reduced contact time. The reduction of TSS removal as a result of higher flow intensities was also reported in previous studies (Adin and Elimelech 1989; FitzPatrick and Swanson 1980).

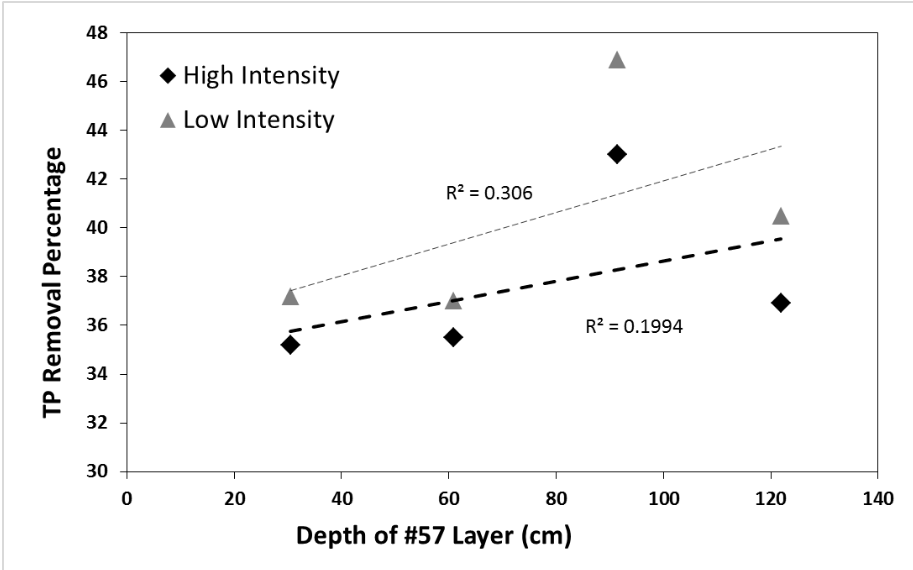

Figure 57-Effect of the depth of filter media (#57) on TP removal percentages

Figure 54 shows, TP removal percentages slightly increased as a result of increasing the depth of #57 layer except for tests No. 5, and 6 (91.5 cm) which showed a higher value than tests number 7 and 8 (122 cm). Similar to the TSS data, the removal of TP was also inversely affected by the flow velocity.

Experiments 9-14 were conducted to study the pollutant removal performance of #3 AASHTO aggregate to achieve this objective, three different depths (61, 92, and 122cm) were tested with high and low-flow intensities (76 and 38mm/hr.). The removal percentages for TSS and TP are plotted in figures 58 and 59.

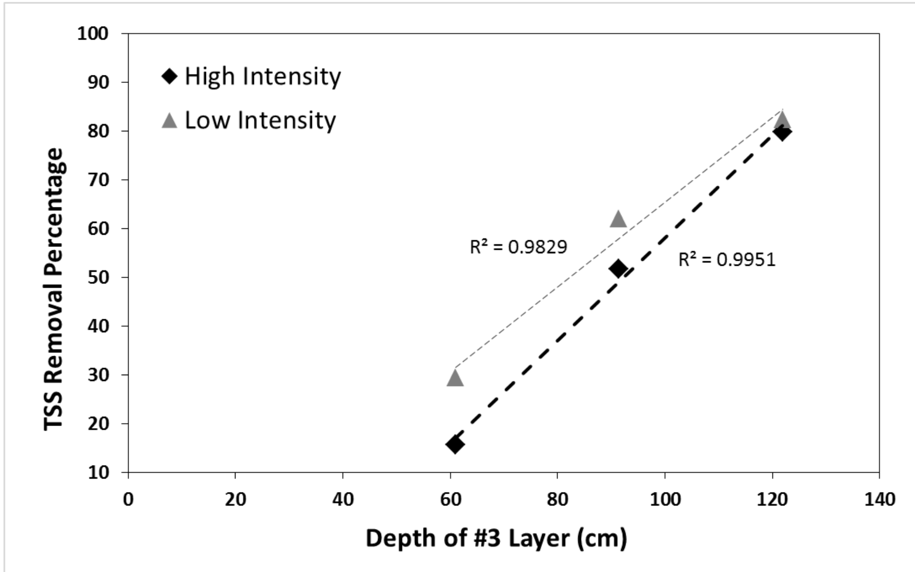

Figure 58- Effect of the depth of filter media (#3) on TSS removal percentages

A strong linear relationship is observed between the depth of #3 aggregate and TSS removal percentages in both high and low inflow intensities. The removal percentages were slightly lower in high-intensity tests which were expected and as mentioned earlier in agreement with results from similar studies (Figure 58).

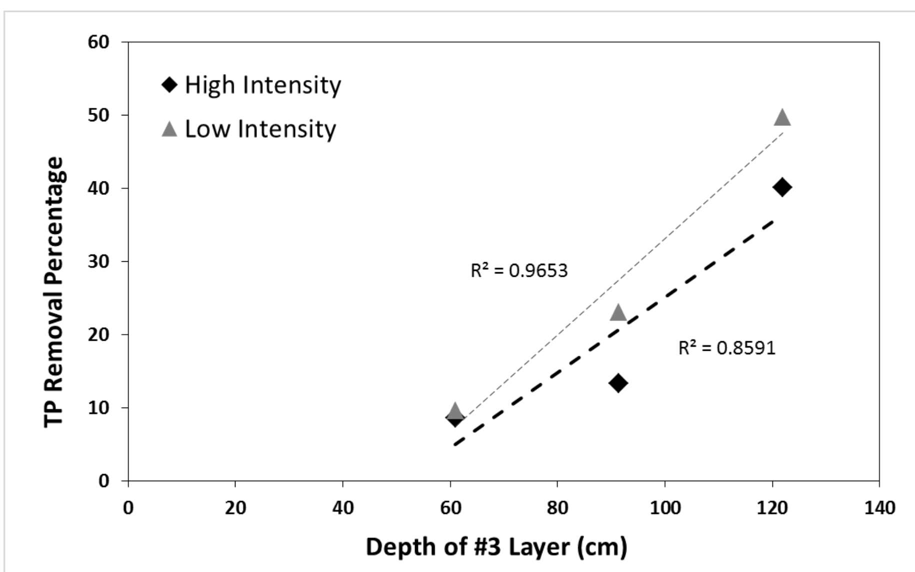

Figure 59- Effect of the depth of filter media (#3) on TP removal percentages

TP removals were also found to have a linear relationship with the depth of #3 aggregate. However the relationship was not as strong as the relationship between TSS and the depth. Similar to TSS, TP removals were also lower in higher intensities.

A wider range was observed for both TSS and TP removal percentages with the increase of #3 aggregate, compared to the results obtained from experiments 1-8 (in which #57 aggregate was tested). This could be understood from the slope of the trendlines in Figures 56-59. The pollutant removal efficiencies for these experiments are summarized in Table 25. Negative or minor positive removal percentages were observed for nitrate, nitrite and ammonia, and positive removal efficiencies were only observed in case of TSS and TP. It is suspected that nitrification did not take place as much as it was observed in the field study. This was a result of the controlled lab environment and use of tap water in creating the semi-synthetic stormwater that limited the growth of microorganisms necessary for the process.

Table 25-Pollutant removal percentages for the first 14 experiments

Experiment No.	**Pollutant Removal Percentages**				
	TSS	NO_3	NO_2	NH_3	TP
1	78.7	-1.4	-28.6	6.1	37.2
2	69.8	0.0	-20.4	1.2	35.2
3	86.4	5.1	-50.0	14.7	35.6
4	84.6	0.0	-51.5	-0.8	35.5
5	94.0	6.8	-26.1	6.5	46.9
6	91.8	13.5	-45.5	-1.3	43.0
7	96.6	0.7	-46.9	3.8	40.5
8	94.5	0.0	14.3	5.0	36.9
9	29.5	3.6	-7.9	-1.0	9.6
10	15.6	3.1	-18.6	13.2	8.6
11	62.0	0.6	-25.5	-1.1	23.1

12	51.6	1.3	-19.6	-2.2	13.3
13	82.4	-5.2	-3.1	-8.3	49.8
14	79.8	-6.4	-25.5	2.0	40.1

Experiments 15-20 were conducted on combinations of #3 and #57 aggregates to simulate the conditions of the permeable pavements installed in the field. In experiments 15 and 16, 122cm of #3, which were topped by a 30cm layer of #57, were tested using two inflow intensities, and in experiments 17-20, 92 cm of #3 and 61cm of #57 were tested with four different flow intensities. Figure 60 and 61 represent the effect of flow intensity on TSS and TP removal experiments 17-20.

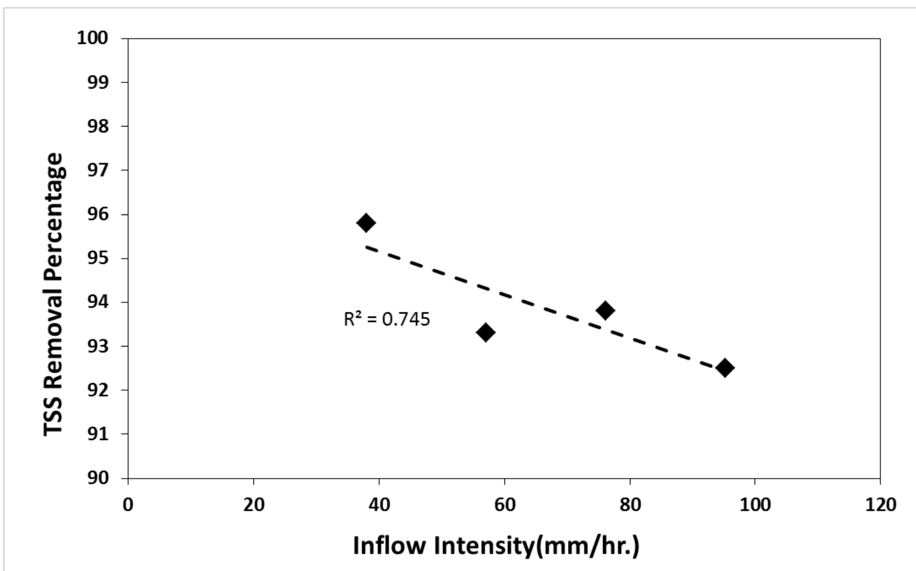

Figure 60-Effect of inflow intensity on TSS removal efficiencies (experiment #17-20)

Figure 60 shows that the removal percentage of TSS decreases as the inflow intensity increases. The relationship is relatively linear with an R-squared value of 0.745. However, the range of changes in the removal percentage was only 4% and occurred by increasing the intensity from 38.1 mm/hr. to 95.25 mm/hr.

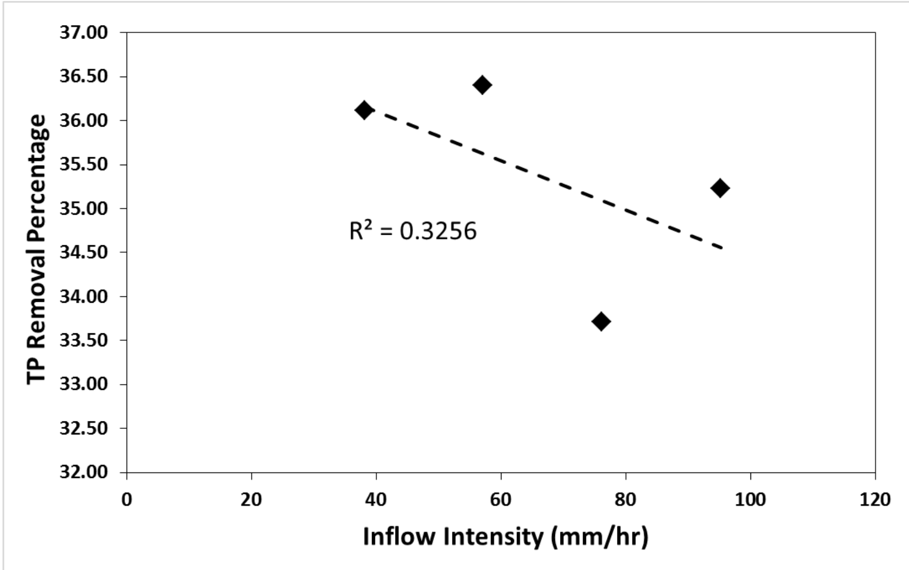

Figure 61- effect of inflow intensity on TP removal efficiencies (experiment #17-20)

A similar, but weaker relationship was observed between the TP removal percentages and inflow intensities can be observed in Figure 61. The range of TP removals were also small (3%), similar to what was observed for TSS removal. The pollutant removal efficiencies for the final 6 experiments are presented in table 24.

Table 26- Pollutant removal percentages for the first 14 experiments

Experiment No.	**Pollutant Removal Percentages**				
	TSS	NO_3	NO_2	NH_3	TP
15	89.8	-2.8	-32.9	-3.9	45.0
16	87.5	-3.5	-50.0	-5.8	44.0
17	95.8	1.3	-39.7	5.9	36.1
18	93.3	1.9	-8.0	7.4	36.4
19	93.8	-2.6	-20.0	15.9	33.7
20	92.5	-1.3	0.0	1.7	35.2

Bubble plots were used to visually compare the TSS removal performances of each experiment setup. In these plots, the x-axis represents the depth of #3 aggregate, y-axis is the depth of #57, and the size of the bubble is associated with the TSS removal percentages (Figures 62 and 63).

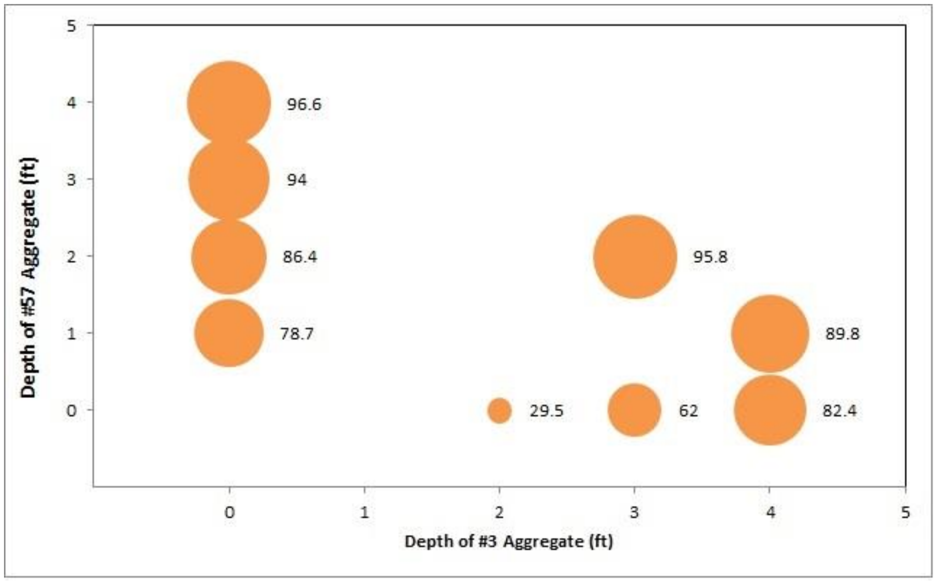

Figure 62-Bubble plot representing the TSS removal efficiencies of #3 and #57 layers and the combination of these aggregate layers in low intensity experiments (38 mm/hr.)

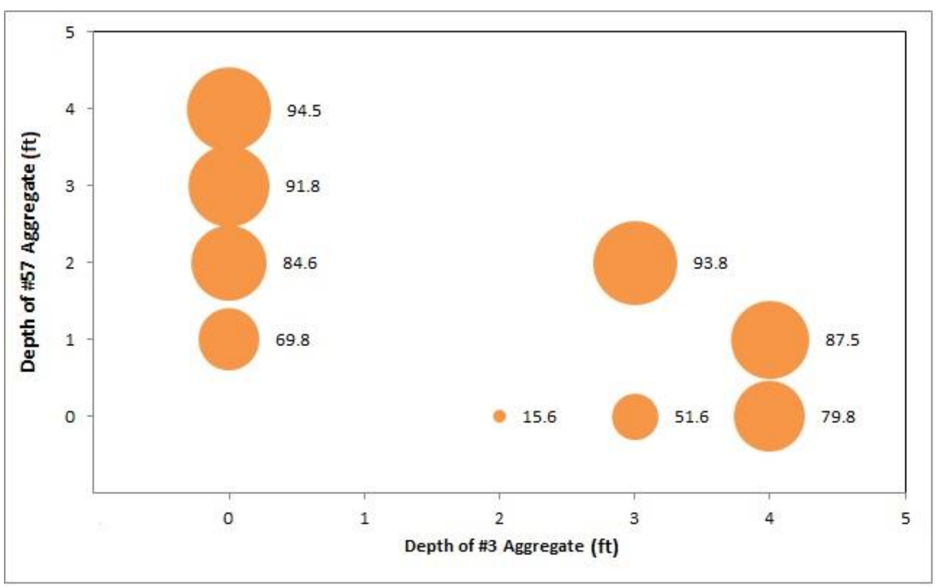

Figure 63-Bubble plot representing the TSS removal efficiencies of #3 and #57 layers and the combination of these aggregate layers in high intensity experiments (77 mm/hr.)

Relatively high TSS removal performances was observed by #57 aggregate in these plots, as it can be seen, TSS concentrations were reduced by 78 and70% after passing through only 30 cm (1 ft.) of #57 with high and low intensities. In contrast with #57, low depths of #3 aggregate showed a poor TSS removal performance especially in the high intensity experiments (15.6%); however these values improved to 80% by increasing the depth of #3 to 122 cm (4 ft.).

4.3.1 Comparison of Field Data with the Lab Study

Since the aggregate layers used in the column study are the same as the layers used in the design of both permeable pavement controls (17G and 17H), the result from the columns study were compared with the results collected from these two controls. Due to safety limitations, bacterial testing was not included in the column study, and the comparison is made for TSS and nutrients (TP, nitrate, nitrite, and ammonia).

As mention in chapter 3, the trench and the shaft in GI controls 17G and 17H were filled with approximately 244 cm (8ft.) of #3 aggregate followed by a 30 cm (1 ft.) layer of #57, which was simulated in lab experiments 15 and 16 (122 cm #3 and 30 cm #57). The pollutant removals values observed from these two experiments and the average reduction values from the field study are presented in Table 27.

The reduction of TSS concentrations in GI controls 17G and 17H were found to be significantly lower compared to the values observed in the lab study, this could be a result of limitations of the sampling procedure, and the filter sock around the monitoring which could cause large sediments to be trapped inside the well. Another factor responsible for low TSS removal in these GI controls could be the sediments which were attached to the aggregates used in the field, since the aggregates used in the storage layers of the permeable pavements were not as clean as the aggregates used in the lab study, a portion of these attached solids were washed and carried by the stormwater passing through the permeable pavement layers, causing the overestimation of TSS.

Table 27-Pollutant removal percentages observed on the field and data from experiments 15 and 16

	GI Control 17H	**GI Control 17G**	**Experiment #15**	**Experiment #16**
TSS %	41.2	45.4	89.8	87.5
TP %	46.0	33.8	45.0	44.0
NO_3 %	-3.3	6.0	-2.8	-3.5
NO_2 %	16.7	20.6	-32.9	-50.0
NH_3 %	18.2	29.6	-3.9	-5.8

Lab data for the removal of TP were found to be similar to what was observed in the field study, similarities were also observed in case of nitrate removals, however ammonia and nitrite had negative removal percentages in the lab study which was in contrast with the positive 20-30% removal of these pollutants observed in GI controls 17G and 17H. This could be the result of organic clogging material present in upper aggregate layers and in the gaps between the pavers, which are responsible for the nitrification process and the removal of nitrite and ammonia in the GI controls.

5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The objective of this research was to evaluate and enhance the water quality benefits and pollutant removal performances of three green infrastructure stormwater control measures. The first phase of the study included monitoring the performance of two permeable pavement strips and a tree box. Water quality data was collected over a 12-month period. Unlike many pervious research studies, the effect of rainfall characteristics on the performances of these GI practices was also investigated.

Following the field study, the second phase worked to develop a large scale laboratory model of the permeable pavement systems. The lab study provided an opportunity for analyzing and better understanding the results observed on the field, and an opportunity to make useful suggestions for future designs and studies. The conclusions and suggestions regarding the removal of each of the pollutants investigated in this research are presented in this chapter.

Conclusions from the research showed that TSS was significantly filtered from the stormwater runoff passing through the permeable pavement layers and the media used in the tree box. However, the filtration was more significant in the tree box (74%) compared to what was observed in the permeable pavements (40% and 50%). The column study simulated the conditions of the permeable pavements but in a clean lab environment and the results showed up to 90% of TSS removal which is nearly twice as much as the percentage removed in the in the field study.

Conclusions of the research showed a marked difference in results between the lab and field study regarding the TSS removals, indicating that sediments attached to the stones used in the permeable pavement layers, and the sampling procedure used in the field, caused an overestimation of the TSS in samples collected from the captured volume. According to the data from the lab study, using double-washed aggregate in the base and sub-base layers of the permeable pavement systems increases the filtering performance by 40%. Data also showed that an additional 4-6 % percent of TSS removal is achievable by altering the design of the stone layers, and replacing one foot of #3 aggregate with #57.

Due to safety reasons, *E. coli* removal was investigated only in the field study. *E. coli* removal was found to be statistically significant in both permeable pavement systems and the tree box. Since the *E .coli* removal percentages were higher than the TSS removal values, it is concluded that adsorption is also responsible for the removal of *E. coli* in addition to straining and physical removal of the cells which were attached to the suspended solids.

Although TP removal was statistically significant in both permeable pavement systems, the percentages were below 50%. These results were confirmed by the column study, and the same removal percentages were observed in the simulated lab experiments. The relatively low TP removal performance of the permeable pavements did not meet the

TP removal goals for permeable pavement systems suggested in the Stormwater Best Management Practices Design Guide provided by US EPA (Clar et al. 2004). However, the captured volume by the permeable pavements is not directly introduced to surface waters or ground water sources and additional filtration is provided by the natural underlying soil layers in the bottom of the trench and shafts. In contrast to the permeable pavements, the tree box showed a relatively high TP removal performance, which is a result of the dual effect of physical filtration caused by the soil media and the uptake by the root hairs of the plants in the tree box.

Comparing the effective removal of ammonia and nitrite from the runoff passing through the tree box with low-removal percentages of these pollutants in the permeable pavement systems leads to the conclusion that the engineered soil and top layer of mulch used in the tree box is the main cause of the high removal percentages. Results from the column study which simulated the permeable pavements also showed a low rate of nitrite and ammonia removal, which confirms the results of the field study.

Leaching of nitrate into the samples collected from the captured volume by the tree box was found to be a result of nitrification. Small amounts of nitrate leaching were also observed in the permeable pavements. However, there was considerably more nitrate leaching in the tree box compared to the permeable pavements. This was due to a more habitable environment provided by the soil media used in the tree box for the microorganisms causing the nitrification process. Results from the column study showed minimal amounts of nitrate leaching. This was a result of the controlled environment and use of tap water in the semisynthetic stormwater runoff which precluded the nitrification process.

Dissolved metals were effectively removed by the permeable pavement system. The removal of metals was a result of precipitation and adsorption to the aggregate layers and especially the organic matter building up the clogging material in the gaps between the pavement blocks. The high removal percentages for the dissolved metals were in agreement with previous studies.

Correlations between the rainfall characteristics and the pollutant concentrations in the runoff showed an increase in the rainfall intensity causes higher pollutant concentrations in the runoff, especially in the cases of TSS, *E. coli*, and TP. This is a result of the higher mobility of these sediment-associated pollutants in more intense rainfall events. The correlations between the pollutant concentrations and the antecedent conditions were not meaningful and significant. The weak correlations were a result of other contributing factors such as construction, wind, and traffic which during the dry periods.

Strong positive correlations were observed between TSS and *E. coli* concentrations in the runoff. The same correlations were observed between TSS removal rates and *E. coli* removal rates in all three GI practices. It can be concluded from these correlations that *E. coli* is largely associated with particulate materials suspended in the stormwater runoff.

5.2 Suggestions for the Design and Future Work

The combination of the results observed on the field and in the laboratory, led to interesting design information and showed the opportunities for future research, to improve the water quality performance of these green infrastructure practices.

Results from the column study suggest that, adding a one foot layer of #57 aggregate will result in a minimum of 90% TSS removal even in high intensity rainfall events. However, the nutrient removal of these aggregates did not meet the recommended values according to the Stormwater Best Management Practices Design Guide. To remove the nutrients from the runoff, the implementation of effective sorption media and filtering layers in future column study experiments is recommended. It should be noted that the media used in the future study should address key issues including design, operation and economics.

Based on the result from the column study, it can be concluded that higher TSS removals can be achievable by using pressure-washed aggregate layers in the permeable pavement base and sub-base, also a design which could utilize automatic samplers in these green infrastructure will provide more precise result for both the first flush and the Event Mean Concentrations (EMCs).

The effect of nitrification was not investigated in the column study used in this research due to the use of tap water and washing the column prior to each test. A series of tests in which rain water is used in creating the semisynthetic stormwater runoff will lead to a better understanding of the effect of nitrification on nitrate leaching in these green infrastructures.

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CURRICULUM VITAE

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Education:

PhD in Civil Engineering at Center for infrastructure Research (CIR), Civil and Environmental Engineering, University of Louisville, KY - Advisor: Dr. Thomas Rockaway, GPA: 3.96. Expected graduation date: December 2015	2012 - Present
M.Sc in Civil Engineering, Geotechnics, K. N. Toosi University of Technology, Iran - Advisor: Dr. Hasan Ghasemzadeh, GPA: 3.9.	2009 - 2011
B.Sc. in Civil Engineering, Ferdowsi University, Iran, GPA: 3.1.	2004 – 2008

Work Experiences:

• Research Assistant at Center for infrastructure Research (CIR) at , University of Louisville	2012-Present
• Active involvement in the construction and installation of research monitoring equipment on permeable pavements and treeboxes installed in Louisville KY, in collaboration with Louisville MSD and U. S. EPA.	2012-2013
• Monitoring the water quality performance of permeable pavements and tree boxes installed in Butchertown neighborhood in Louisville KY, in collaboration with Louisville MSD.	2013-Present
• Teaching Assistant for “Soil Mechanics”- Dr. Qian Zhao, University of Louisville	Fall 2013
• Teaching Assistant for “Environmental Engineering”- Dr. Sarah Lynn Cuningham, University of Louisville	Summer 2013

• Teaching Assistant for “Tunnel Engineering” and “Rock mechanics“- Dr. Hasan Ghasemzadeh, K. N. Toosi University of Technology, Tehran, Iran	Spring 2011
• Laboratory Instructor for “Environmental Laboratory “, K. N. Toosi University of Technology, Tehran, Iran	Spring 2010 Fall 2010
• Laboratory Instructor for “Soil Mechanics Laboratory “, Ferdowsi University, Mashhad, Iran	Fall 2007 Spring 2008
• Working as a laboratory technician in Soil, Asphalt and Concrete laboratories, Jahd Azma, Mashahd, Iran.	Summer 2009

Projects and Research Experience:

• Evaluating and monitoring the pollutant removal performance of stormwater Green Infrastructures (permeable pavements and tree boxes), Center for Infrastructure Research, University of Louisville	2013-Present
• Design and construction of a large scale column study to evaluate the pollutant removal performance of gravel layers	2014-Present
• Investigating the effect of slope and paver characteristics on the performance of permeable pavements, with Dr. A. Ehsaei, Center for Infrastructure Research, University of Louisville.	2012-2013
• Assisting the evaluation of the infiltration performances for permeable pavements, Center for Infrastructure Research, University of Louisville.	2013-2014
• Collaborative demonstration project for water treatment using natural processes and sustainable materials, with Dr. Gullapalli University of Louisville.	2013-2014

Publications:

- **S. Abdollahian**, H. Kazemi, T. Rockaway, Q. Zhao, V. Gullapalli, **Hydrological Performance of Permeable Pavement Systems with Deep Aggregate Layers (Submitted to the Journal of Water Research).**
- H. Kazemi, T. Rockaway, J. Rivard, **S. Abdollahian**, **Assessment of Surface Infiltration Performance and Maintenance of Two Permeable Pavement Applications in Louisville, Kentucky**, (Submitted).
- H. Kazemi, **S. Abdollahian**, T. Rockaway, J. Rivard, **The Water Quality and Quantity Performance of a Permeable Pavement System in Louisville, KY,** Weftec 88th Annual Technical Exhibition and Conference, expected September 2015.
- **S. Abdollahian**, T. Rockaway, J. Rivard, **Filtering Performance of Permeable Pavement System with a Reservoir Structure,** Kentucky Stormwater Action

Annual Conference, July 2015 (Under Revision).

- A. Ehsaei, **S. Abdollahian**, T. Rockaway, **Refining the maintenance techniques for Interlocking Concrete Paver GI,** Conference of Low Impact Development (LID), July 2013.
- H. Ghasemzadeh, **S. Abdollahian**, H. R. Shabanzadeh, R. Bazazzadeh, **Investigation on influence of soil properties on Transport of Escherichia coli in saturated soils,** International Journal of Earth Sciences and Engineering ISSN 0974-5904, Volume 04, No 06 SPL, October 2011, pp. 989-993.

Skills:

Software: ArcGIS, GEO-SLOPE; SEEP/W; SLOPE/W, AutoCAD , Microsoft Office Suite

Testing: Skilled in utilizing geotechnical and material testing instruments

Awards and Honors:

- Certificate of MSD Water Quality Standards Academy, held by Louisville MSD — 2015
- Ranked 1st in Civil Engineering Students, K. N. Toosi University of Technology — 2009-2011
- Certificate of Introduction to Project Management Body of Knowledge, TÜV SÜD Academy, Iran — 2011

Extracurricular Activities:

- President of Iranian Student Organization of University of Louisville — 2014 - Present
- Intramural Soccer champion, University of Louisville — 2014
- Intramural Volleyball champion, University of Louisville — 2013
- National Champion in college Soccer, Student Championships, Iran — 2009
- Member of Ferdowsi team, Iran beach soccer premium league — 2008 - 2011

Languages:

English and Farsi