PROJECT TITLE: DALLAS URBAN CENTER STORMWATER BMPS

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I. Introduction and Background

Urbanization is altering the composition of landscapes nationwide, with urban areas characterized by a high proportion of impervious surfaces that adversely impact the water cycle of the region. The loss of infiltration of runoff into soil reduces ground water recharge. Increased surface runoff, velocity and pollution, all byproducts of rainfall on impervious surfaces, impede urban waterways tremendously. Increase in volume of runoff can lead to flooding, with receiving water bodies exhibiting stream bank erosion and channelization (Arnold and Gibbons 1996). Urban runoff contaminants include nitrogen, phosphorus, heavy metals, oil, grease and sediments, from yards, roads and parking lots (Kim et al. 2007; Davis 2007; Deitz 2007), which have detrimental impacts on aquatic life and human health. Indeed, urban stormwater runoff is determined to be the cause of impairment of 13 % of assessed rivers, 18% of the lakes and 32 % of estuaries nationally (National Academy of Sciences, 2008).

Texas is no exception to the trend, with the second largest urban population in the country (US Census, 2012), its river basins are supporting an increasingly urban population. The Trinity River basin supports the largest population of any river basin in Texas, with three million people in the Dallas/Fort Worth metropolitan area alone (TCEQ 2008). The Dallas-Fort Worth (DFW) metropolitan area is one of the 20 fastest growing metropolitan areas in the country (US Census, 2010) and is mostly urbanized, with an estimated 47 % of impervious surface in 2001(Falcone, 2006), with associated effects on stormwater runoff. The area is characterized by Houston Black soil series (also known Texas Blackland Prairie soils) that have a very high amount of clay content and underlying calcareous layer and has low permeability. This soil is classified as a hydrologic Group D soil.

The Upper Trinity River that drains the DFW metroplex has been designated impaired for chlordane (TCEQ 2008) and bacteria (TCEQ 2010). In addition, total phosphorus, nitrate, chlorophyll-a, and orthophosphate are considered parameters of concern (TCEQ 2010). These water quality impairments underscore the need to evaluate stormwater management in this area.

Low impact development (LID) is considered to be a way to mitigate the adverse effects of increasing impervious cover, using decentralized measures to retain stormwater runoff on-site, and thereby seeking to mimic the natural pre-development hydrology of a site. Also known as green infrastructure, LID includes structural practices such as bioretention, green roofs, rainwater harvesting, and permeable pavements, as well as non-structural practices such as elimination of curbs and gutters, disconnecting downspouts from stormwater conveyance, strategic grading, and utilizing native vegetation (Ahiablame et al. 2012). The primary goals of LID best management practices include reduction of runoff peak flow rate and volume, increasing infiltration and groundwater recharge, reducing stream bank erosion as well as removing pollutants by processes such as filtration, chemical sorption and biological degradation.

Effectiveness of LID practices in various regions in the United States have been evaluated (Ahiablame et al., 2012; Davis, 2007; Davis, 2008; Dreelin et al., 2006; Bean et al., 2007). However, modeling studies have suggested that the adaptability of LID designs to other regions is problematic, requiring modified solutions to be field tested in every location to confirm how they will perform (Gallo et al., 2012). Therefore, there is still a great need to evaluate these practices in the field and to collect quantitative data on LID practices performance, especially in the Southern part of the United States.

The current project evaluates urban stormwater best management practices in a typical urban watershed in the Dallas Fort Worth area. The objectives were to design, construct and demonstrate the effectiveness of green building infrastructure at the Texas A&M AgriLife Research and Extension Center in Dallas. The five LID BMPs targeted in this project are permeable pavements, bio-retention area, rainwater harvesting, green roofs, and detention ponds.

Funding for the project was provided by the CWA 319 (h) NPS grant programs with match provided by AgriLife Research. Data collected as a result of the project is being used to demonstrate the effectiveness of construction of the LID BMPs, in terms of reduction of pollutant loads mentioned above. This demonstration is also being used to promote knowledge, awareness and implementation of the demonstrated BMPs among individuals, businesses and government entities.

The BMPs evaluated in this report were constructed with a CWA 319 (h) NPS grant awarded in 2010 and completed in 2013 (EPA Grant 99614614 TCEQ Contract 582-10-90469). The current contract awarded in 2013 and ending in August 2015, added bacteria testing to project. This report will cover the data collected for both contracts.

II. Project Significance

The outputs of this study will enhance knowledge of effectiveness of porous pavements and bioretention areas in a humid subtropical climate with excessively clayey and alkaline soils.

Any LID construction in North Texas is subject to the extremes of temperature experienced here. Considered subtropical with a mean annual temperature of 68° F, it is common to experience summer temperatures in excess of 100° F and winter temperatures as low as - 8° F (Diggs et al 1999). Climate events such as extreme variability in precipitation, prolonged droughts and large storm events in a short span of time, and ‘false spring episodes’ where warm winters may be punctuated by subfreezing temperatures are also common. These events further complicate issues such as plant selection, surface runoff and infiltration rates due to shrinking and swelling of the soil. This project takes into account challenges specific to this region.

The Upper Trinity (AU ID:TX-0805_03) was classified as impaired for PCBs, dioxins and bacteria in the 2010 Texas Water Quality Inventory. It was also listed as a concern for chlorophyll-a, nitrate, orthophosphate, and total phosphorus. Municipal point source and nonpoint source sources are listed as the main known causes of pollution. White Rock Creek (AU ID:0827) was listed as a concern for nitrate, orthophosphate and total phosphorus. Sources of pollution to White Rock Creek are unknown. As both the watersheds of these two streams are mostly urbanized, the sources of pollution are likely to be urban stormwater runoff. BMPs that address urban stormwater pollution at the source were addressed in this project. Specific pollutants that were tested for during the first contract are nitrate/nitrite, total phosphorus, orthophosphate, total Kjeldahl nitrogen, ammonia and total suspended solids. For this project, Nitrate/Nitrite, Orthophosphate, *E. coli* and total suspended solids were tested

A TMDL Implementation plan (I-Plan) (NCTCOG, 2013) was developed by the North Central Texas Council of Governments and TCEQ. The Plan states the following: “The Coordination Committee encourages 25 percent of municipalities within bacteria-impaired watersheds to adopt GI and/or LID standards for all sizes of development in their comprehensive plans by 2023 and 50 percent of cities do so by 2038”.

This project will provide much needed information on the performance of such BMPs in the North Texas Environment and Blackland Prairie soils. The expected outcome of this study is a reduction in runoff volume of 90% on an annual basis from each of the BMPs which are designed to retain 1.5 inch of runoff based on the engineering design of the BMPs. With regard to contaminant reduction, little data is available on the performance of these BMPs in Blackland soils. However, preliminary data in addition to the literature review on the performance of similar systems in clay soils (e.g. Brown and Hunt, 2011) suggests a reduction in pollutants comparable to studies in other parts of the USA. It is one of the objectives of this project to monitor the performance of the BMPs to determine how comparable these are to other BMPs in the US.

III. Best Management Practices

The five LID BMPs targeted in this study are permeable pavements, bioretention area, rainwater harvesting, green roofs, and detention ponds. These Best Management Practices (BMPs) are being used to provide examples of how LID can be integrated in new buildings and developments or retrofitted to existing developments that aim at reducing sediments (and sediment bound pesticides), and nutrients loadings into urban runoff.

A. Permeable Pavement:

Permeable pavements are alternatives to traditional impervious pavement systems. These are comprised of a load bearing, durable surface layer, with additional underlying layers that temporarily store runoff, letting it infiltrate or drain into a controlled outlet. The main mechanism of runoff reduction is infiltration from the top layer, storage within the underlying structure with appropriate flow control. They allow for stormwater runoff reduction and treatment, with slow infiltration into subsoil. They are typically used in low traffic areas, such as parking lots, driveways, fire lanes, and overflow parking areas.

There are several types of permeable pavements, including pervious concrete, pervious asphalt, permeable interlocking concrete pavers, concrete grid pavers and plastic reinforced gravel pavers and grass pavers, and expanded shale reinforced grass pavers (Dietz, 2007; Jaber, 2014). These pavement all have the same general structure, in that they all have a surface layer that is permeable and a gravel layer underneath for storage that also provides structural support. A wide array of studies on permeable pavements in various locations have shown reduction in runoff and associated pollutant loads (Dietz, 2007; Fassman and Blackbourn, 2010; Collins et al, 2008, 2010). A few studies have been conducted to evaluate permeable pavements over clay soils (Dreelin et al, 2006; Fassman and Blackbourn, 2010). However, region specific studies for comparing effectiveness of various types of permeable pavement is required in order to maximize the utility of these stormwater management systems.

B. Bioretention areas:

Bioretention areas or rain gardens are designed to be a depressed area in a landscape that receives and attenuates stormwater (USEPA 2006). They use the chemical, biological and physical properties of soils, flora and microorganisms to remove or retain pollutants from stormwater (Hinman, 2005). Typically, these areas consist of a soil mixture planted with native or adapted plants that receive stormwater from a small contributing area (Davis, 2008). Bioretention areas promote infiltration, storage and slow release of water (Hinman, 2005). The capacity of bioretention systems to reduce stormwater volume and peak flow rate, in the rage of 40% to 97% has been well documented. The reductions depend on the magnitude of rainfall, with all the runoff from small events being completely captured by these structures (Davis, 2008). However, there exists a need for region specific data, as a large variation has been shown in the reduction capacity of these bioretention areas (Dietz, 2007). In addition, the local nature of the plant and soil material underscores the need for a regional (Texas) evaluation of bioretention systems.

C. Green roofs:

Green roofs are vegetated roof tops that offer an alternative to conventional impervious roofing systems. Also known as ‘living roofs’, they retain and reduce stormwater runoff, as well as delay the time of peak runoff so that there is a reduced chance of flooding.

Typical green roof construction has layers that include a roofing membrane and root barrier that provides protection to the roof structure and stops plant roots from affecting it, a drainage layer that retains water as well as channel excess water away from the roof to a downspout, a geotextile or filter layer that prevents fine particles from being washed away, a growing medium that can be of varying thickness and coarseness according to manufacturers, a vegetation layer that comprises of plants that can withstand extreme conditions such as heat, drought and wind. Green roofs are known to intercept between 15 and 90% of rooftop runoff. However, type of growth medium, thickness and plant cover variability can cause differences in runoff of 50-60%. The green roofs in the current project aim to study differences in runoff in roofs with thicker growth media, and a native plant palette as compared to a conventional commercial green roof design.

D. Rainwater Harvesting:

One of the cost effective approaches in reducing urban runoff is rainwater harvesting (RWH) (Montalto et al., 2007). RWH involves collecting rainwater from the available catchment area during rain events, diverting this water through gutters, channels and pipes into storage containers and reusing the water at a later date. The Texas Water Development Board (2005) defines six stages to describe and facilitate the operation and maintenance of a RWH system: First, a catchment surface which is usually a rooftop; second, a conveyance apparatus diverting rainwater through gutters and downspouts from the roof to the storage container; third, removing debris and dust before it goes to the tank through leaf screens, first flush diverters, and roof washers; fourth, a storage container; fifth, a delivery system that either includes pumps or is gravity-fed; sixth, a treatment and purification system in case the harvested water is used for in-home or potable purposes.

Although rainwater harvesting is commonly mentioned in the literature as a LID structure, there are very few studies that address the effectiveness of the system. Most available research concentrates on the water savings and the necessary treatment for different water uses rather than stormwater (Fengrui et al., 2004; Abdulla and Alshareef, 2009; and Karpiscak et al., 1990). The effectiveness of RWH as a stormwater BMP is impacted by the use of the harvested water and on the sizing of the storage containers.

E. Detention Pond:

Detention Ponds are basins that hold stormwater runoff and release it slowly to a nearby water course or water body. A detention pond can be dry, (i.e. hold water only during and right after storms) or wet (i.e. have a permanent pool of water). Dry detention ponds have outlets (usually a culvert) located at the same level as the bottom of the pond. The culvert’s size limits the outflow thus reduces the flow rate from large storms. Wet detention ponds have a permanent pool of water. By placing the outflow at an elevated location, a wet detention pond stores the water from the previous storm, to release it only during the next storm. This allows for the sediments in the stormwater to settle, and biological and chemical reactions with vegetated benches can then improve the quality of the water. Wet detention ponds are either constructed on low infiltration soils or sealed with a liner at the bottom. Both these designs reduce peak flow rates while the wet detention pond has additional water quality benefits. Neither reduces the total volume of stormwater, an essential feature of LID structures. In certain soil and weather conditions, detention ponds can be modified to act similarly as LID structures where it would be designed to retain a portion of the runoff, in addition to the water quality benefits and the peak flow reduction.

IV. Methods:

In this section, the design, the construction, and the evaluation of the performance of the LID structures will be discussed. In addition, the educational programs held as part of the project will be described.

Four types of permeable pavements, a bioretention area, a LID detention pond, a rainwater harvesting system and experimental green roofs were designed and constructed on the campus, and were monitored for total runoff volume/event, peak flow rate, pH, EC, Total Kjeldahl N (TKN), NO_3/NO_2, ammonia, total phosphorus, orthophosphate, TSS and chlordane.

A. Design and construction

a) Permeable pavement

A parking lot was designed to incorporate five different types of pavements, four of which are permeable. These included permeable concrete, plastic reinforced gravel pavers, permeable interlocking concrete pavers, expanded shale reinforced grass pavers, and impermeable concrete for control. Five parking stalls of each type, forming one monitoring unit, are connected to an automatic sampler that collects runoff from all five stalls (Figure 1). Each parking stall is 18’x10’. In addition, the five stalls collected runoff from half the driveway upstream from it (5’x50’). The four pavements are grass pavers, permeable interlocking concrete pavers, gravel parking, and impervious concrete (control). Runoff quantity and quality is measured, and storage estimated. Rainfall is measured from a weather station (Campbell Scientific) on the property. A perforated drain runs the length of the stalls in the parking median.

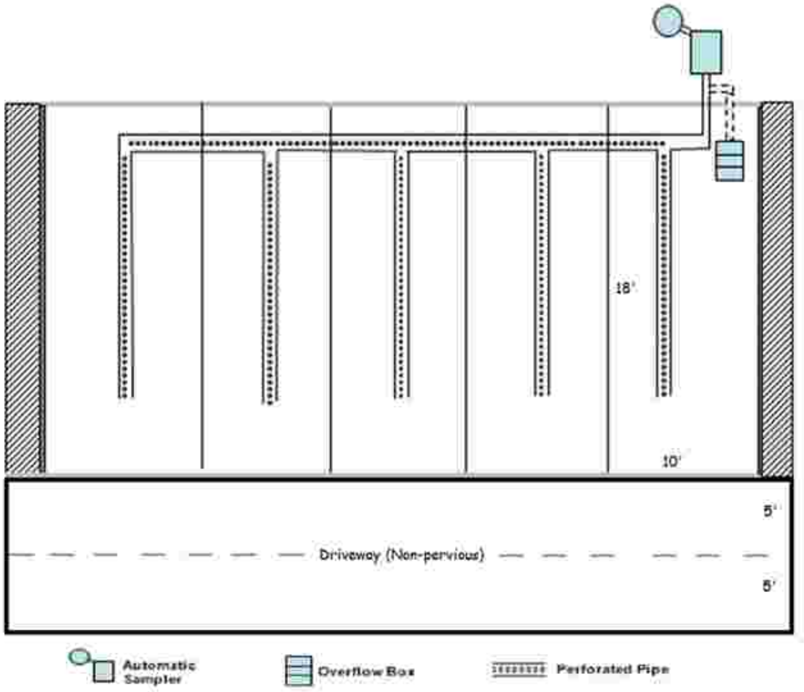

Figure 1. Design of monitoring system (5 parking spots) of permeable pavement

A flow meter (ISCO Bubbler Flow Meter) is used to measure the overflow and the perforated pipe flow in the sub-grade. Flow from the two pipes is combined and water quality samples are collected with an automatic sampler (ISCO 6712 Portable Composite Sampler) located in the median. The structure and placement of the flow meter that measures the combined outflow creates turbulence and ensures adequate mixing before the runoff is collected by the automatic samplers. Automatic sampler measurement is triggered by runoff from storms. Initial triggers were determined such that the automatic samplers would start sampling at flow rates as calculated using the curve number method (CN=90) for a storm of 0.23 inches (0.6 cm) and duration of 3 hours, for the drainage area for each BMP. The 0.23 inches (0.6 cm), 3 hour storm was obtained as the average size storm over 19 years that contributed 10% or less of the total yearly runoff volume and was designated as “trivial” for the purposes of this study and no water quality sampling was done (volume was still measured). An adequate number of sampling across a defined portion of the hydrograph centered around the peak are taken with each significant storm event. If an event triggers sampling but ultimately proves to be trivial, based on daily rainfall data or flow data, the sample(s) are discarded and the equipment is re-set. Outflow is measured using the automatic sampler in the permeable pavement BMP. The initial flow trigger for the outflow is constrained by the accuracy of the flow meter (ISCO Teledyne), and therefore was set to be triggered at the minimum flow rate that can be detected by the flow meter.

The experimental parking stalls are part of a larger parking lot intended to hold approximately 52 stalls. The 32 remaining stalls are constructed of permeable concrete. With the data collected from the 20 experimental stalls, a representation of runoff and pollutant reduction is estimated for the total parking lot (Figure 2).

Figure 2. Constructed parking with all five types of permeable pavement hydraulically separated by a concrete wall.

b) Bioretention area (Rain Garden)

A bioretention area (rain garden) was constructed on the premises of Texas A&M AgriLife Research and Extension Center in Dallas. The bioretention collects runoff from around 36,000 square feet of the parking lot (Figure 3) Curb cuts allow for runoff to drain to a forebay, which is a hundred square feet in area and about one foot deep on average for automatic sampling (ISCO 6712) and flow measurement (flume and bubbler flow meter). Runoff is directed into the bioretention area (100ft x 20 ft). All runoff in the rain garden watershed is routed through the inlet flume. A surface overflow box drains water to an underground pipe to the first inlet of the detention pond. Additionally, the drainage layer of the rain garden houses a perforated pipe that assists with soil infiltration. The underdrain was elevated using a 90 degree elbow, to create an internal water storage (IWS) layer. Use of IWS increases water storage and creates an anaerobic zone that is conducive to denitrification (Brown et al, 2012).

Figure 3. Bioretention area and its watershed (Redline)

An ISCO flow meter was used to measure the overflow and perforated pipe flow and samples were collected with an ISCO 3700 automatic sampler. The outlet for the rain garden acts as one of the inlets for a detention pond constructed on campus, making the rain garden a pre-treatment for the detention pond BMP. The structure and placement of the flow meter that measures the combined outflow creates turbulence and ensures adequate mixing before the runoff is collected by the automatic samplers (Figure 4).

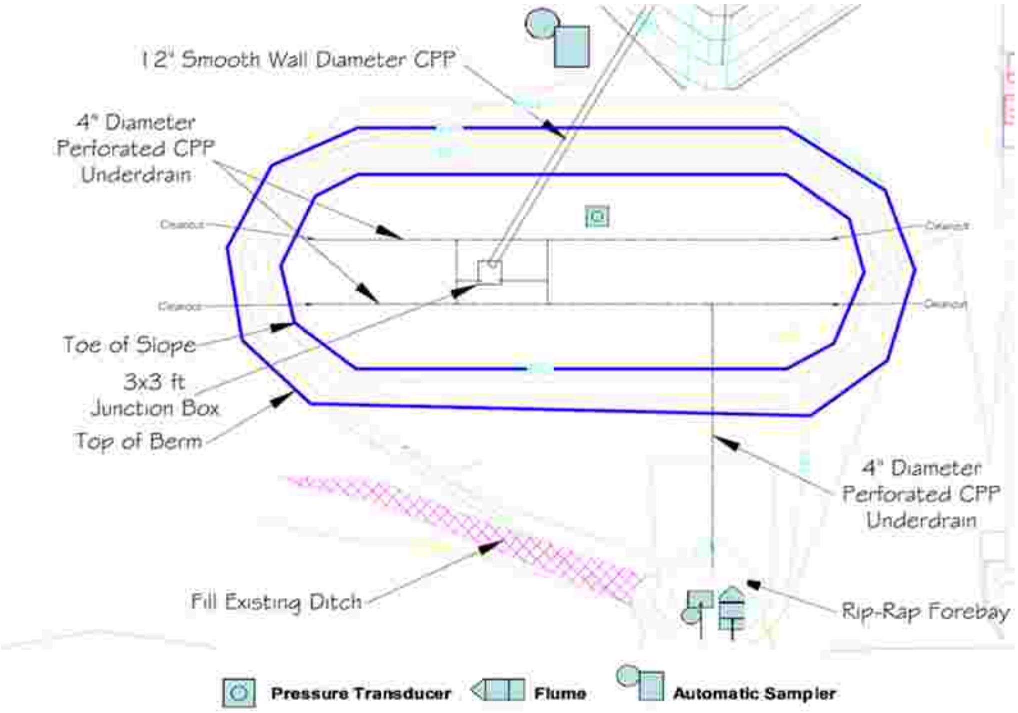

Figure 4. Schematic diagram of monitoring system in the bioretention area

c) Green Roofs

In March 2012, the shelters to hold the green roofs were constructed. The Texas A&M AgriLife team weathered the shelters and then divided them into four parts in order to fit the four treatments. Collection and monitoring systems were also installed and the growing media for the 3 soil treatments were mixed and filled into the roofs. Plants were selected and planted in September 2012. Data collection was started in September 2012 and ended in August 2013.

The green roof BMP consisted of a controlled experimental site (Figure 5). The controlled experiment featured four roof shelters representative of a residential roof with varying green roof designs. Each roof was be divided into four sections to compare four types of growing media that will include different layers of soil, drainage, insulation and roofing membranes.

Each roof (Figure 5 and 6) consisted of four different treatments: a conventional green roof, as made by Hydrotech, Inc.; a green roof design that consists of the plant layer, soil mix, drainage layer, and roofing material; a green roof design consisting of plant layer, soil mix and roofing material; a control roof with no vegetation. Plants were selected to withstand minimal maintenance.

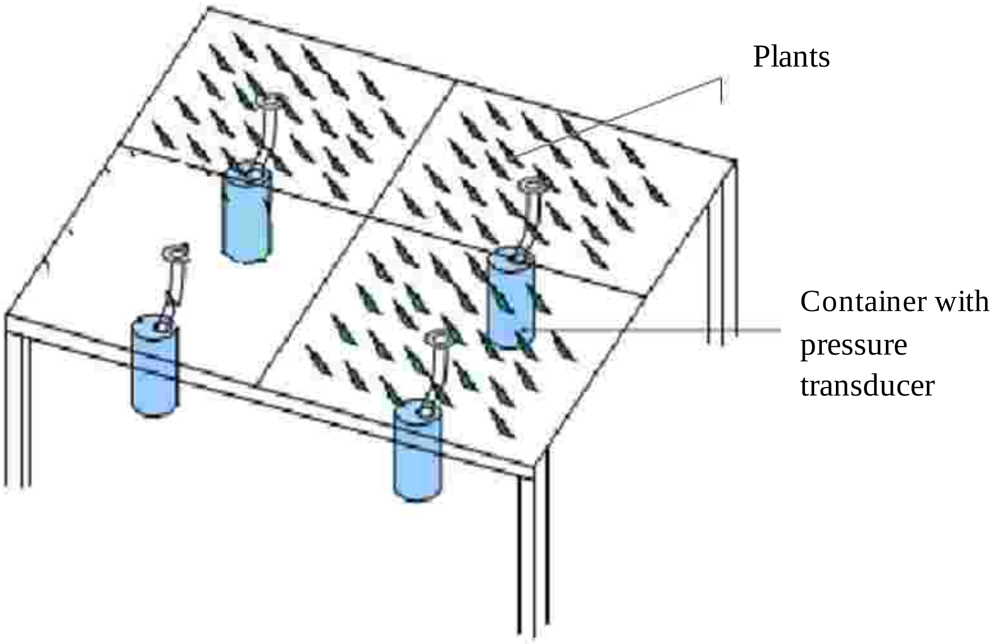

Figure 5. General design of the green roof experimental plot with 4 treatment sections.

All green roofs were monitored for rainfall, soil storage, and runoff on a continuous basis. Water samples were collected from the runoff to demonstrate the effectiveness of green roofs in removing pollutants. The monitoring setup consisted of a downspout that drains to a barrel (55 gal) that is sized to collect all the runoff from a 10 year storm. The runoff was collected in the container from which grab samples were taken at the end of each storm greater than 0.23 inches (Figure 5). A grab sample was taken from the container at the end of each event after stirring to assure the sample was representative. Water samples were collected in water collection bottles as recommended by the NELAC certified lab.

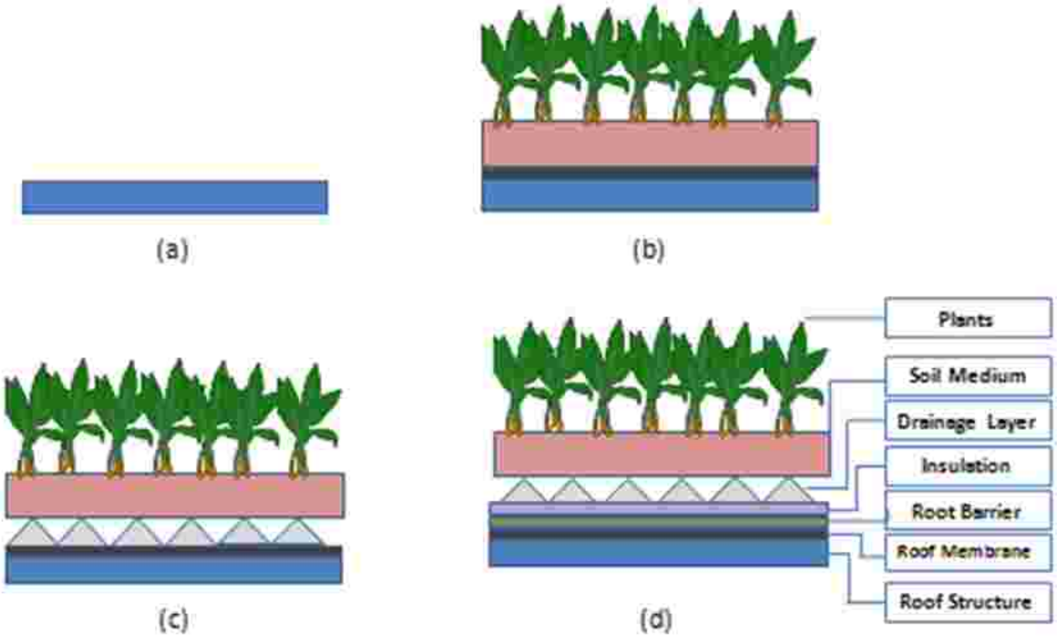

Figure 6. The four treatments in the Green Roof design- a) Control (roof structure only), b)Vegetation, soil medium and roof shelter, c) Vegetation, soil medium, drainage layer, roof structure, d) Commercial green roof (vegetation, soil medium, drainage layer, insulation, root barrier, roofing membrane, and roof structure).

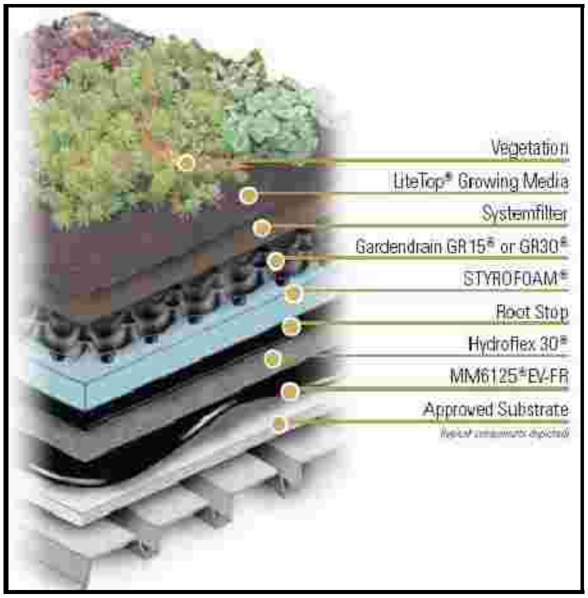

Figure 6e. Cross section of commercial roof.

The commercial green roof made by Hydrotech Inc. consisted of the following layers (Figure 6e):

1. Plants selected for their ability to withstand drought and self–regenerate.
2. Engineered lightweight growing medium that has suitable pH range, nutrients, and porosity for plant growth.
3. Drainage layer that retains water in profiled troughs, and drains away excess water through channels between troughs.
4. Insulation layer that resists moisture and situated above roof membrane and root barrier
5. Root barrier that prevents roots from affecting the roof membrane.
6. Roofing membrane that is made of Hydrotech’s Monolithic Membrane®.
7. Structural support that is designed to support the weight of the green roof.

Figure 7 and 8 show the setup of the green roofs.

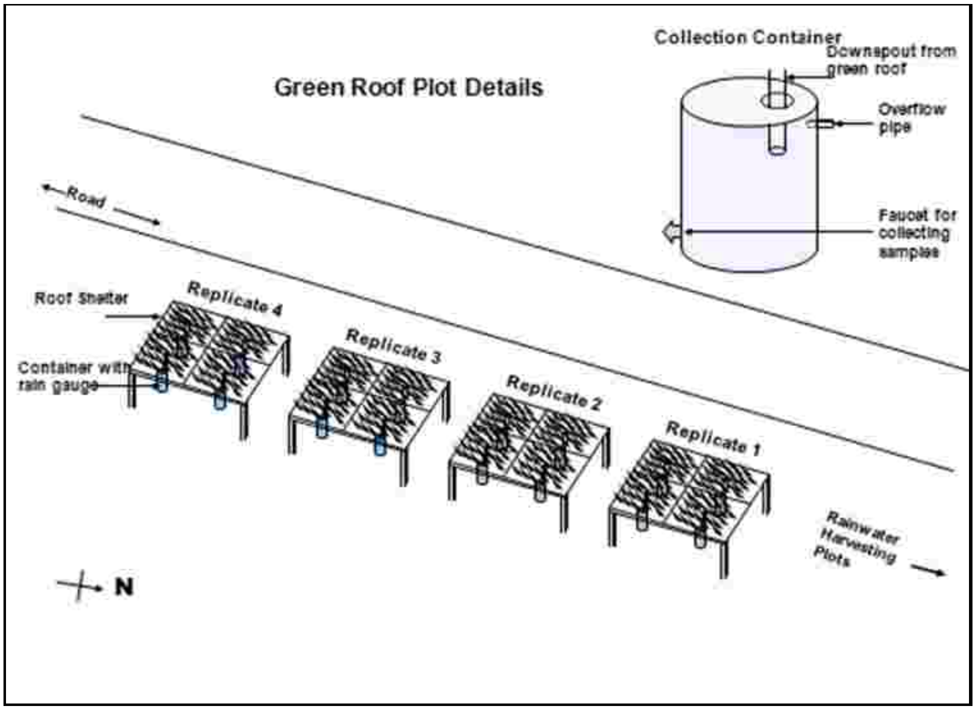

Figure 7. Details of green roof monitoring set up.

Figure 8. Green roofs and collection system

d) Rain Water Harvesting

Similar to the green roof, the rainwater harvesting BMP involved a controlled experiment. The controlled experiment consisted of four roof shelters constructed with a turf lawn beside each, planted with *Zoysia japonica* (Figure 9). Three shelters each had a gutter with leaf guard and a downspout draining to three connected 55 gallons PVC rainwater harvesting barrels for a total capacity of 165 gallons. The lawns connected to these three shelters were irrigated with the harvested rainwater, which was measured using a DLJ Hose Bibb water meter (Daniel L. Jerman Co.). One control plot has a downspout draining directly to the lawn. The collection barrels were equipped with overflow pipes that drained into the lawn.

A roof to lawn area ratio of 1:3 was used, to reflect a typical residential area in the Dallas- Fort Worth Metroplex. The roof and plot area in this study are 100 square feet (9.3 m^2) and 150 square feet (13.9 m^2) respectively, assuming rainfall collection from half the roof. The total runoff volume can be calculated by multiplying area of roof, roof runoff coefficient and rainfall depth. Under the current set up, a 2.64 inch (6.71 cm) rainfall would fill the rain barrels to capacity (165 gallons), with a roof coefficient of 1. The barrels were equipped with pressure transducers that monitor the depth of water continuously. The barrels were equipped with overflow pipes at the top that discharge directly to the lawn. The amount of overflow was not measured directly. Since we will know the volume of water that goes in, and the volume of water in the barrels, any overflow that occurs could be calculated.

Varying irrigation methods were installed on the plots including soil moisture based (SM), evapotranspiration (ET) based, and timed irrigation (HO) (typical homeowner).

The SM plot was equipped with a soil moisture probe (VH 400, Vegetronix Inc.) connected to a pump via a controller. Each time the soil moisture reached a critical threshold (50% depletion), the pump was activated to supply water from the rainwater harvesting barrels to the turf lawn. The pump shut off when the soil moisture reached field capacity estimated as 41% soil moisture for the clay soil in this area.

The ET based method utilized controllers programmed to irrigate based on published ET monthly data (Texas ET Network) and the crop coefficient for warm season turf grass used in the plots.

The HO plot followed a typical homeowner pattern of irrigating the plot various times per week using a timed irrigation system, and city water. This plot had a downspout that drained all rainwater directly onto the lawn, City water was used to fill the three rainwater harvesting barrels to provide uniformity in irrigation.

Pressure transducers (Levelogger Junior, Model# 3001, Solinst) were also placed in the rainwater harvesting barrels to measure water levels. To ensure all water would be accounted for, drip irrigation was used on all plots. Each plot had a gutter spanning the length of one of the ends downstream from the plot, which fed into a pipe system with a rain gauge and a water storage container. The rain gauge measured depth of runoff and a grab sample were obtained for water quality from the container. The gutters that transport the runoff from the lawn to the water collection container were sized and sloped to adequately convey a 1.5 inch design storm without any overflow.

The runoff volume was monitored and samples taken for water quality measurements from the storage container. The monitoring setup consisted of a Rain Gauge with Data Logger (Spectrum Technologies Inc.) for measuring the runoff volume set up in a water storage container. The runoff was collected in the container from which grab samples were taken at the end of each storm greater than 0.23 inches (Figure 9 and 10). A representative portion of the entire storm was collected in the container. A grab sample was taken from the container at the end of each event after stirring to assure the sample was representative. Water samples (450 ml) were collected in water collection bottles as recommended by the NELAC certified lab.

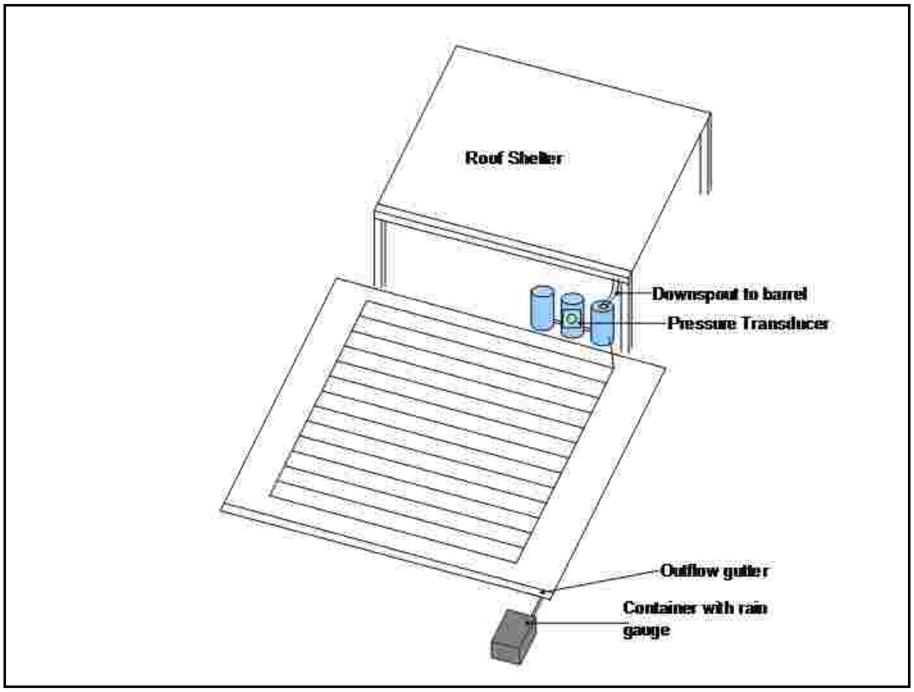

Figure 9. General design of rainwater harvesting experimental plot

Figure 10. Rainwater harvesting and collection system

e) Detention Pond

A detention pond was designed to retain 1.5 inches of runoff and collect inflow/outflow and water quality data. The pond was designed to resemble a meandering river with two inflow points, planted with associated vegetation to reduce erosion as well as act as filter strips, to serve as a demonstration tool for stream restoration. The width to length ratio was also taken into consideration to maximize sediment retention and nutrient uptake. The detention pond has two inlet points, and most of the impervious part of the Texas AgriLife campus (6 acres) runoff (Figure 11) was routed to the pond via the two inlet flumes (Figure 12). One of the inlets of the detention pond is the outlet of the rain garden BMP (Figure 13).

Water samples and flow were measured via automatic sampling with an ISCO 6712 and surface flow measuring device. Table 1 indicates the initial trigger for automatic sampler measurement of inflow and outflow for the detention pond.

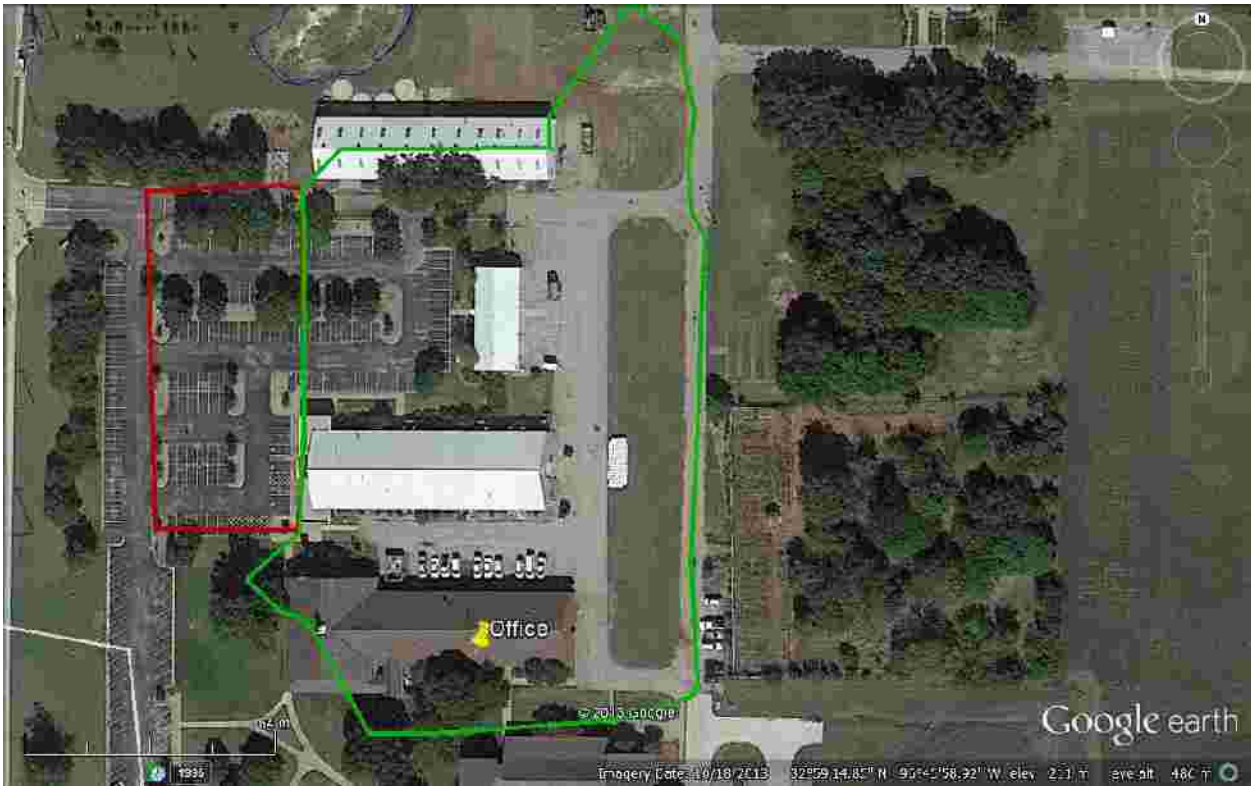

Figure 11. Watershed of the east side of the detention pond (green) and the bioretention area (red line).

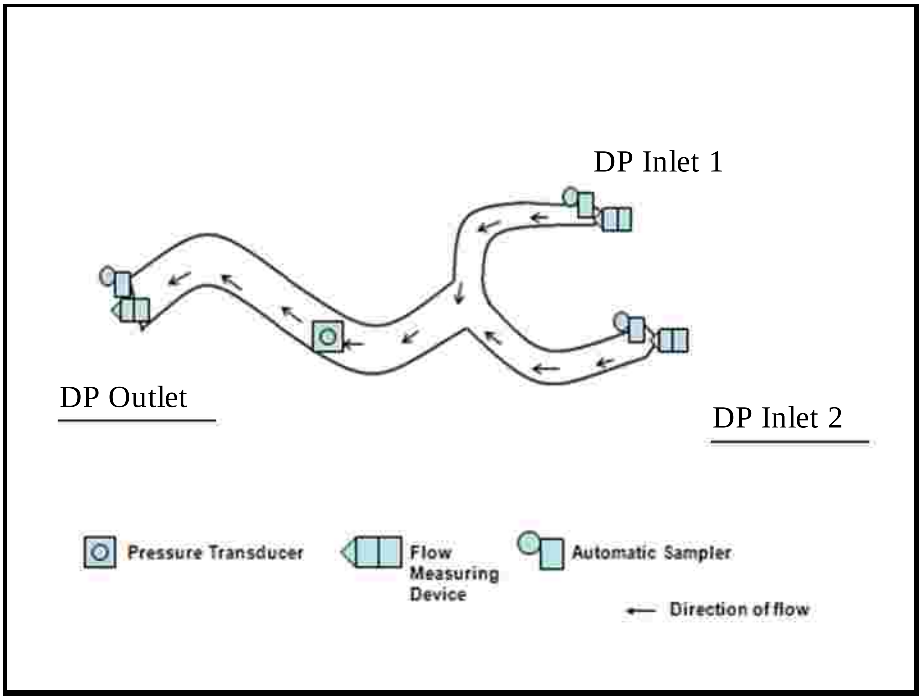

Figure 12. Detention pond monitoring setup, with measurements at the two inlet points and outflow

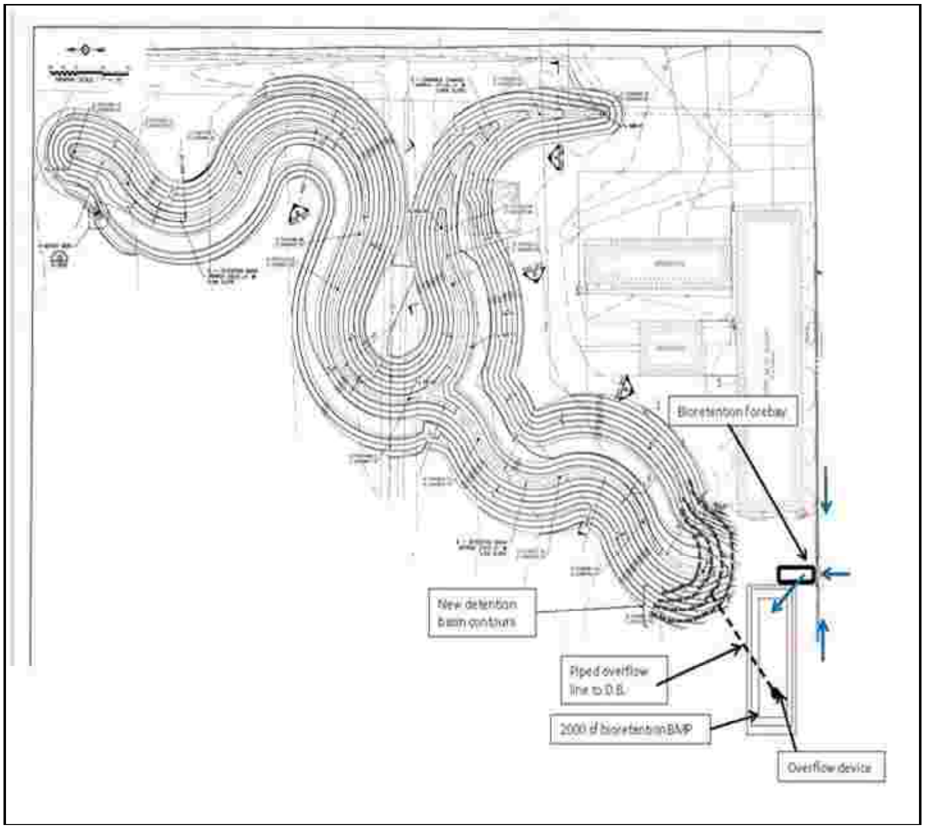

Figure 13. Site Diagram of Detention pond and Bioretention area

f) Monitoring Plan

Initial triggers were determined such that the automatic samplers would start sampling at flow rates (Table 1) determined using the curve number method (Curve Number = 90, Natural Resources Conservation Service, http://www.nrcs.usda.gov), for a storm of 0.23 inches and duration of 3 hours, for the drainage area for each BMP. The 0.23 inches, 3 hour storm was the average size storm over 19 years that contributed 10% or less of the total yearly runoff volume. Hence, such a storm was designated as "trivial" for the purposes of this study and not sampled.

The sampling event protocol were adjusted as needed after the first sample storm event or subsequently, with written concurrence of the TCEQ project manager. Such adjustments were done to avoid sampling trivial storms of 0.23 inch/3hours or smaller, as mentioned above. The adjustments also ensured that an adequate number of sampling across a defined portion of the hydrograph centered around the peak was taken with each significant storm event. If an event triggers sampling but ultimately proved to be trivial, based on daily rainfall data or flow data, the sample(s) were discarded and the equipment was reset. All storm data collected was recorded regardless if samples were analyzed or not.

Each monitoring station has its own set of equipment for sampling, an overview of which is given in Table 2. The permeable pavement, detention pond, and rain garden BMPs were sampled with an automatic sampler for water quality. The water quality of inflow and outflow of the detention pond and rain garden BMPs were sampled via automatic sampler. In the permeable pavement BMP, only the outflow was sampled for water quality via automatic sampler.

Table 1. Summation of the sampling triggers and sampling interval for the BMPs equipped with automatic samplers

BMP	Area of watershed per sampler (Ha)	Inflow			Outflow		
		Automatic Sampling	Initial Trigger	Initial sampling intervals	Automatic Sampling	Initial Trigger	Initial sampling intervals
Permeable Pavement	0.0056	No	NA	NA	Yes	$2x10^{-6}$ m^3/s	30 min
Bioretention (Rain Garden)	0.3345	Yes	$1.118x10^{-4}$ m^3 /s	15 min	Yes	$2x10^{-6}$ m^3/s	30 min
Detention Pond	1.5385	Yes	$5.41x10^{-6}$ m^3/s	15 min	Yes	$2x10^{-6}$ m^3/s	30 min

The green roof and rainwater harvesting BMPs were not equipped with automatic samplers. The outflow in each of these BMPs was collected in a container, and samples were collected manually (grab samples).

Table 2. Monitoring Plan Overview

BMP	Location Monitored	Flow/ Volume Measurement	Water Quality	
			Equipment	Nutrients/ Pollutants Measured
Permeable pavement	Inflow	Campbell Scientific Weather station[1]	None	None
	Combined outflow from Perforated pipe and overflow	Flow meter (ISCO Teledyne)	ISCO 3700 Automatic sampler	N, P, TSS, Chlordane
Bioretention	Inflow	Flume	ISCO 3700 Automatic sampler	N, P, TSS, Chlordane
		Pressure transducer (Levelogger, Jr., Solinst)		
	Water storage	Pressure transducer (Levelogger Jr, Solinst)	None	None
	Combined outflow from Perforated pipe and overflow	Flume	ISCO 3700 Automatic sampler	N, P, TSS, Chlordane
Green roof	Inflow	Campbell Scientific Weather station[1]	None	None
	Outflow	Rain Gauge with Data Logger (Spectrum Tech. Inc.)	Water storage container & manual sampling	N, P, TSS
Rainwater Harvesting	Inflow	Campbell Scientific Weather station[1]	None	None
			Rain Barrels	N, P, TSS
	Outflow	Rain gauge & water storage container	Water storage container & manual sampling	N, P, TSS, Chlordane
Detention Pond	Inflow #1	Flow measuring device	ISCO 3700 Automatic sampler	N, P, TSS, Chlordane
	Inflow #2	Flow measuring device	ISCO 3700 Automatic sampler	N, P, TSS, Chlordane
	Water storage	Pressure transducer(Levelogger Jr, Solinst)	None	None
	Outflow	Flow measuring device	ISCO 3700 Automatic sampler	N, P, TSS, Chlordane

[1] Data used from the Campbell Scientific Weather station represented the rainfall recorded from the initiation of the storm event to the time at which the water quality sampling ended for the permeable pavement, green roof, and rainwater harvesting. The end time varied for each BMP.

Table 3 gives a description of each of the monitoring sites and approximate frequencies of sampling for each parameter. Sampling frequencies depended on the frequency of rainfall. The BMPs were designed to retain storms up to 1.5 inches, and to generate outflow only for events greater than 0.75 inches.

Table 3. Field sampling collection details

Site Number	Site Description	Latitude, Longitude	Mode of Sampling	Sample Matrix	Comments
1	Porous Asphalt outflow point	32° 59’ 11.67”N, 96° 45’ 57.93”W	Automatic, Discrete	Water	Sampling tied to rainfall
2	Impervious asphalt (Control) outflow point	32 59’ 11.21”N, 96 45’ 57.93”W	Automatic, Discrete	Water	Sampling tied to rainfall
3	Grass paver outflow point	32° 59’ 10.70”N, 96° 45’ 57.93”W	Automatic, Discrete	Water	Sampling tied to rainfall
4	Pervious concrete outflow point	32° 59’ 10.64”N, 96° 45’ 57.20”W	Automatic, Discrete	Water	Sampling tied to rainfall
5	Interlocking blocks outflow point	32° 59’ 11.16”N, 96° 45’ 57.22”W	Automatic, Discrete	Water	Sampling tied to rainfall
6	Bioretention Inflow point	32°59'16.64 "N 96°45'02.39"W	Automatic, Discrete	Water	Sampling tied to rainfall
7	Bioretention Outflow point	32° 59’ 17.16”N 096° 45’ 02.45”W	Automatic, Discrete	Water	Sampling tied to rainfall
8	Rainwater harvesting Control plot	32°59'12.80"N 96°45'44.72"W	Grab	Water	Sampling tied to rainfall
9	Rainwater harvesting Homeowner Schedule (Rainwater) plot	32°59'12.57"N 96°45'44.75"W	Grab	Water	Sampling tied to rainfall
10	Rainwater harvesting Evapotranspiration plot	32°59'12.32"N 96°45'44.80"W	Grab	Water	Sampling tied to rainfall
11	Rainwater harvesting soil moisture plot	32°59'12.10"N 96°45'44.84"W	Grab	Water	Sampling tied to rainfall
12	Green roof 1 outflow point # 1(Control)	32°59'11.02"N 96°45'45.24"W	Grab	Water	Sampling tied to rainfall
13	Green roof 1 outflow point # 2 (Plants +soil)	32°59'10.93"N 96°45'45.26"W	Grab	Water	Sampling tied to rainfall
14	Green roof 1 outflow point # 3(Plants+ Drainage layer+Soil)	32°59'10.93"N 96°45'45.35"W	Grab	Water	Sampling tied to rainfall
15	Green roof 1 outflow point # 4 (Commercial)	32°59'11.02"N 96°45'45.34"W	Grab	Water	Sampling tied to rainfall
28	Detention pond inflow point # 1	32° 59’ 17.16”N 096° 45’ 2.45”W	Automatic, Discrete[1]	Water	Sampling tied to rainfall
29	Detention pond inflow point # 2	32° 59’ 17.81”N 96° 45’ 59.09”W	Automatic, Discrete[1]	Water	Sampling tied to rainfall
30	Detention pond outflow point	32° 59’ 20.96”N 96° 45’ 59.79”W	Automatic, Discrete[1]	Water	Sampling tied to rainfall

B. Determination of LID practices performance

a) Permeable pavement

For evaluating the treatments of the pervious pavement, the outflow data were compared to the impervious concrete control treatment. Percentage reductions in volume, pollutants concentration and loads were calculated.

Missing data in this BMP was a result of the malfunction of the ISCOs during certain events. For the control treatment, the flow was calculated using the curve number method with a curve number of 98. Flow volume for all other treatments was calculated based on the average reduction rate from measured events. Concentrations for missing events were calculated as the average of the concentrations in measured events.

b) Bioretention

The bioretention (rain garden) performance was evaluated by comparing volumes, pollutant concentrations and loads from the inflow (before the forebay) and the outflow (combined perforated pipe flow and overflow). A percentage reduction rate was calculated for the volume and each of the pollutants concentration and loads.

Missing data in the bioretention resulted from the malfunction of the ISCOs at the inflow and outflow. Missing inflow volumes were calculated using the curve number method using a curve number of 89. Concentrations for the inflow and outflow were replaced by the average concentrations of the measured events. Missing outflow volumes were calculated based on the average percent reduction rate for the measured events.

c) Green Roof

The green roof BMP is the only treatment that was replicated. The original setup included 4 replicates. Shifts in the earth due to the expansion and shrinkage of the clay soil around the poles of the green roof, reduced the replicates to three as the fourth green roof became unbalanced, resulting in erroneous data. Data from the three replicates were averaged and each of the treatments was compared to the “no green roof” control for the volume, the concentrations of the pollutants and the loads reduction (%).

Missing data occurred in the green roof setup when strong winds caused the collection pipe to move away from the collection barrel. In addition, the pressure transducer malfunctioned on a couple of occasions. For the control treatment, the volume was measured as 98% of the rainfall falling on the treatment. For the other treatments, volume was calculated as the average reduction from the other events as compared to the control. The missing pollutant concentrations in all green roofs were calculated as an average of the concentrations from the rest of the event for the specific treatment.

d) Rainwater Harvesting

Rainwater harvesting volumes, pollutant concentrations and loads of the three treatments were compared to the control treatment. Percent reduction in runoff and pollutant concentrations and loads were calculated.

Missing data in rainwater harvesting were a result of the malfunction in the water collection system. Also on a couple occasions, water samples were discarded due to contamination from mice in the boxes. The estimation of runoff for missing data is a little more complex due to the soil/plant interaction. A method developed by Shannak and Jaber (2014 in review; Appendix A) was used to estimate missing volume data. Missing concentration data were replaced by the average concentrations of the measured events.

e) Detention pond

The first inflow data was collected with ISCO 6712 samplers and bubbler flowmeters in a 16" diameter pipe. The second inflow was the outflow of the bioretention. The outflow from the weir was also measured with an ISCO 6712 and a bubbler flowmeter. The total water volume and loads of pollutants retained were calculated.

Missing data in the inflow of the detention pond was a result of a malfunction of the ISCO resulting in loss or no collection of data during an event. The missing events were estimated using the curve number method. A curve number was back calculated for each measured event and correlated with the storm size. A regression equation was developed linking curve number to storm event was generated to account for the Standard Behavior (Hawkins, 1993) when larger storms have smaller curve numbers due to lower intensity over a longer period.

C. Educational Programming

Education and outreach has been a seminal part of this project. Texas A&M AgriLife research, in collaboration with others such as the North Carolina State University and Belgard Hardscapes, Trinity Materials, Inc., Texas Industries, Inc. We have conducted several workshops and tours of the green infrastructure practices to educate the public, and various city officials about different options that exist for stormwater control in the metropolitan area, either as de novo construction practices or as retrofit to already existing structures. The total hours of education, the total number of attendees, and surveys of increased knowledge were all collected.

V. Results and Observations

A. BMP Performance

a) Permeable Pavement

The permeable pavement data collection system malfunctioned several times. The ISCO samplers occasionally malfunctioned which resulted in the deletion of storm data. On other occasions the bubbler tube got clogged during a storm by sediments and stopped recording flow. In addition, the Bubbler flowmeter gave erratic data when the temperature dipped below 32°F. The volumes for the Control (C) were predicted for missing data using the curve number method. The average curve number recorded for the events that were measured was used for the rest of the events. The volumes for the grass pavers, permeable interlocking concrete blocks (PICP), the gravel pavers and the porous concrete were predicted from the average percent reduction recorded in the measured events. The results show that the average volume reduction for the grass pavers, PICP, gravel pavers and the porous concrete ranged from 73% to 85% and were 85%, 73%, 81% and 79%, respectively (Figure 14).

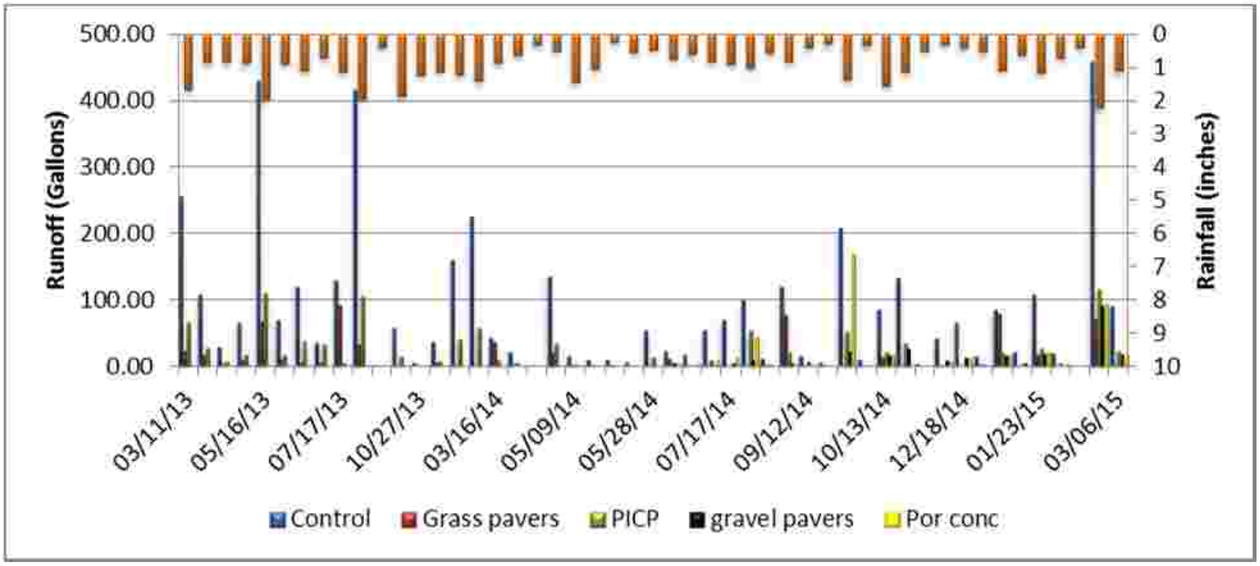

Figure 14. Runoff comparison between the 5 pavement types during the project duration.

The pH, EC, and the concentrations of nitrate nitrogen, orthophosphate, total suspended solids and *E.coli* are shown in Figures 15, 16, 17, 18, 19, and 20, respectively. Average pH values for the control, gravel pavers and the porous concrete were 8.17, 8.02, and 8.23, respectively. The PICP and grass pavers had consistently higher pH with averages of 8.9 and 9.23, respectively. This could be explained by leaching of pH raising element (e.g. calcium and magnesium oxides) from both the concrete pavers for ICP and the expanded shale in the grass pavers. An electrical conductivity meter (EC meter) measures the electrical conductivity in a solution. It is commonly used to monitor the amount of nutrients, salts or impurities in the water. The more ions in the water, the higher the conductivity value. The EC values were clearly higher for the grass pavers indicating leaching of salts from the growing media. There were noticeably higher nitrate nitrogen concentrations in the treatments as compared to the control especially for the gravel pavers. Higher orthophosphate was only seen in grass pavers and to a lesser extent in the gravel paver treatment. TSS was lower in all treatments as compared to the control. *E.coli* varied among the treatments with randomly one or two high count events for each of the control, Porous pavement, Grass pavers, and PICP probably caused by activity of wildlife around the parking lot before the rain event.

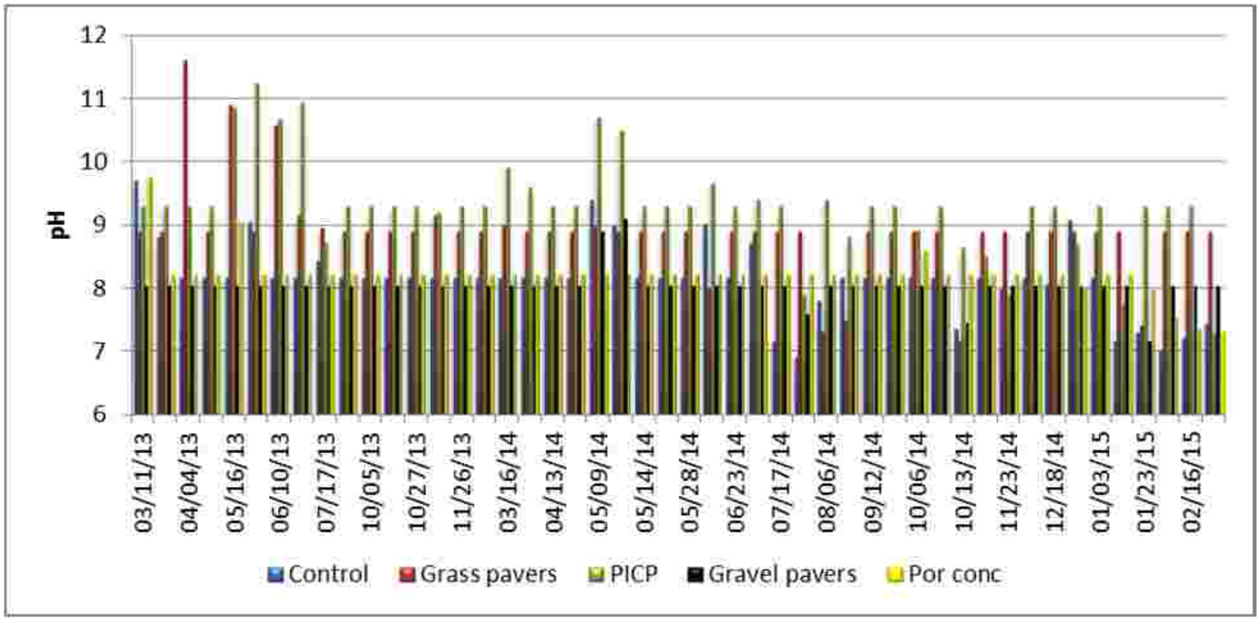

Figure 15. pH values for the three treatments of the permeable pavement BMP during the project period.

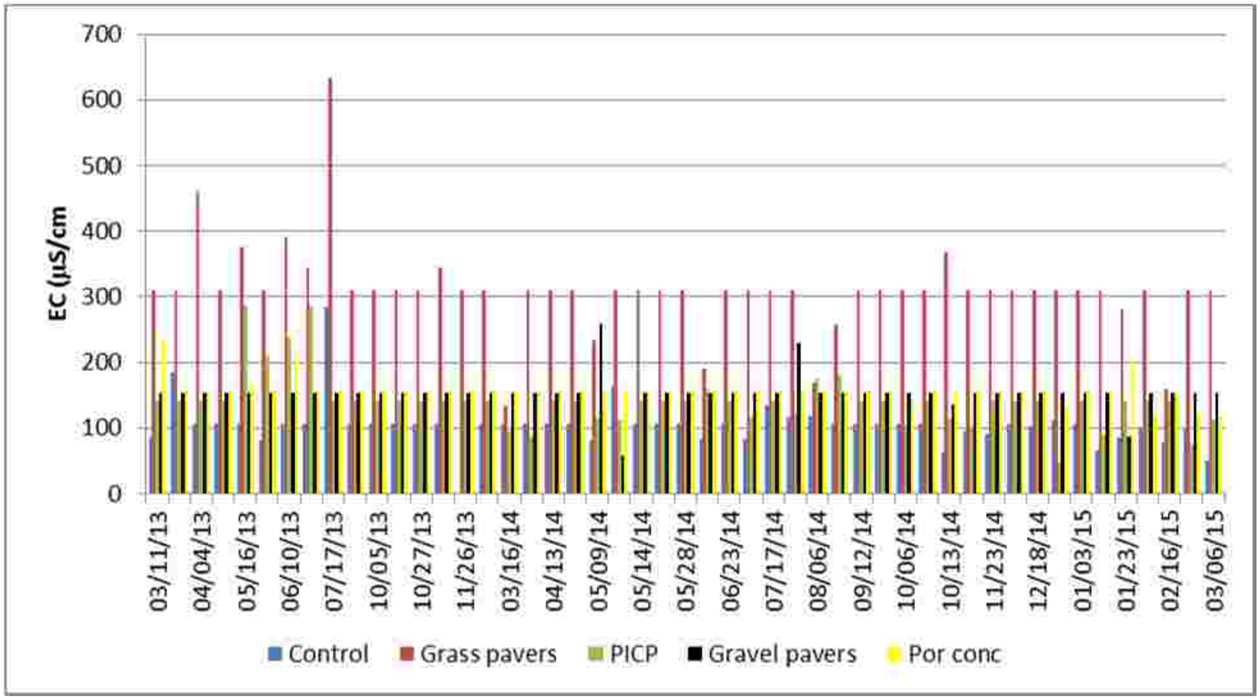

Figure 16. EC values in mS/cm for the three treatments of the permeable pavement BMP during the project period.

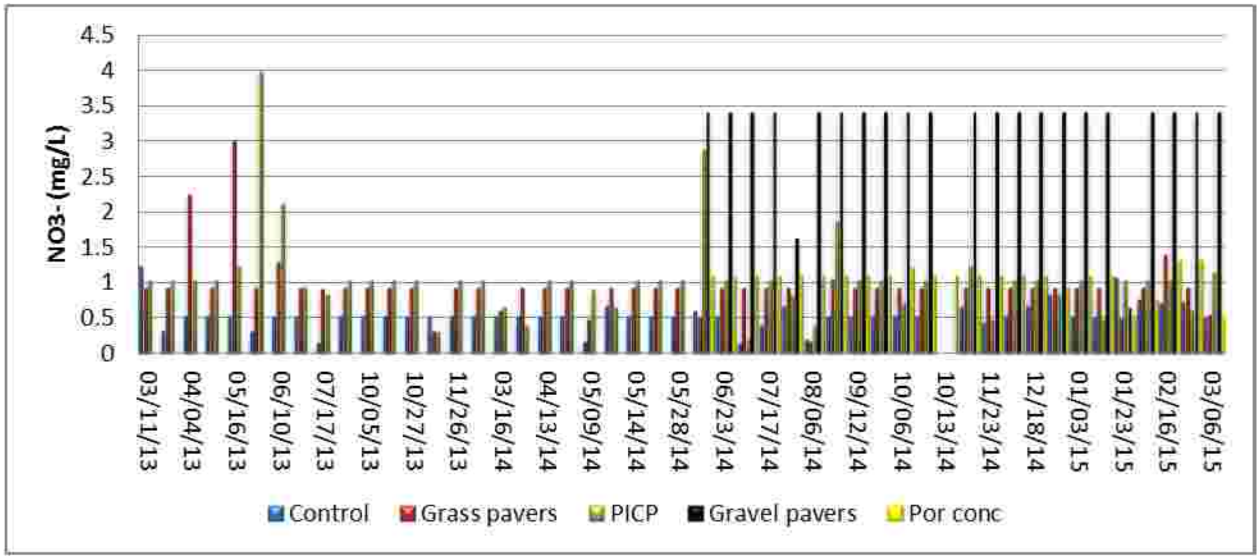

Figure 17. Nitrate Nitrogen concentrations in mg/L for the five treatments of the permeable pavement BMP during the project period.

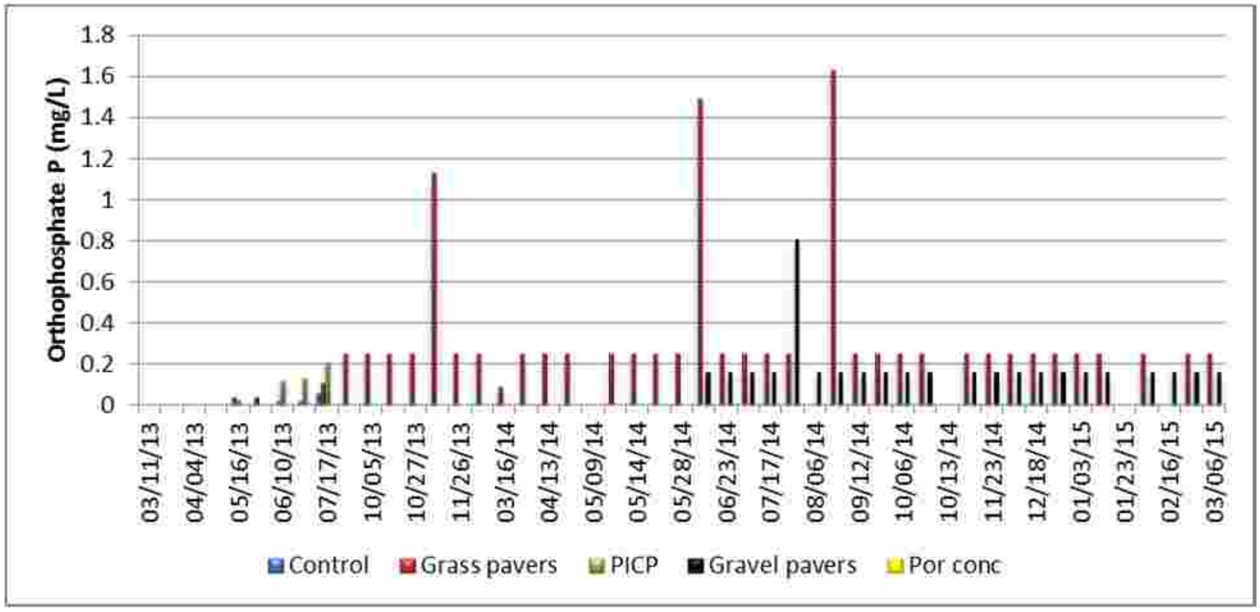

Figure 18. Orthophosphate concentrations in mg/L for the five treatments of the permeable pavement BMP during the project period.

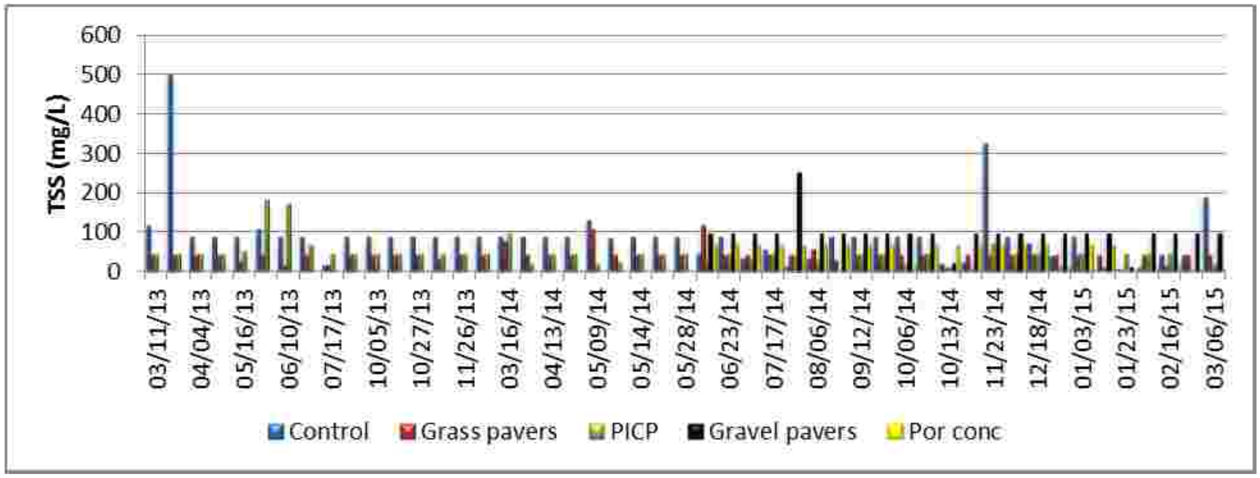

Figure 19. Total Suspended Solids concentrations in mg/L for the five treatments of the permeable pavement BMP during the project period.

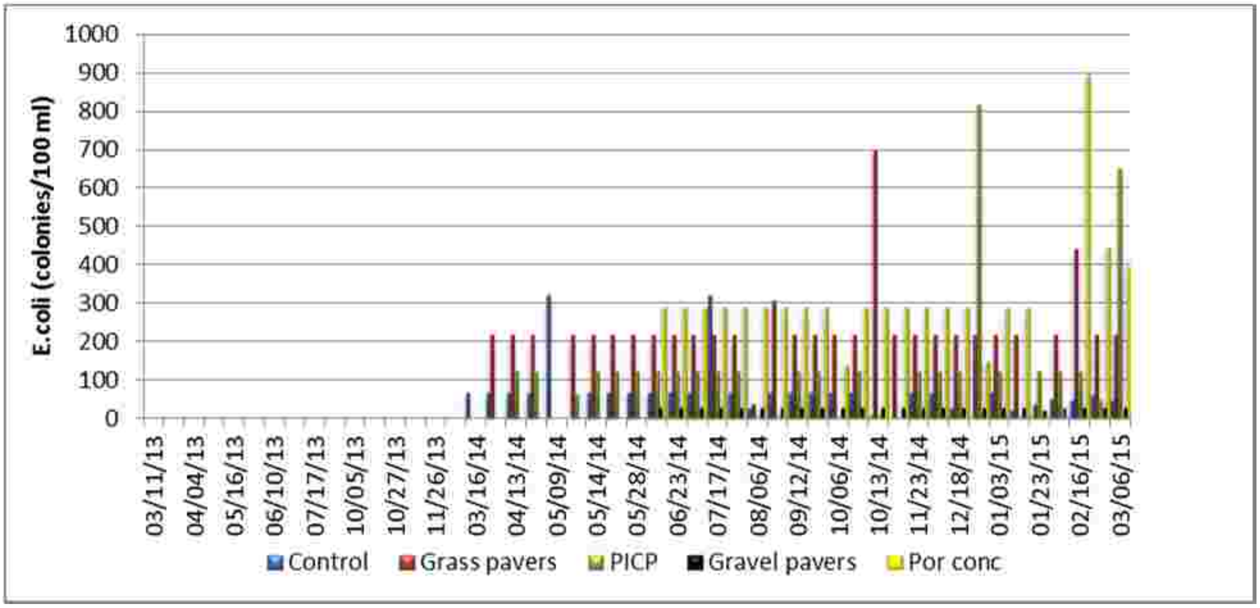

Figure 20. E. coli concentrations in counts/100ml for the five treatments of the permeable pavement BMP during the project period.

The pollutant loads from the treatments are shown in Figures 21-24. The average loads of pollutant are shown in Table 9. The results show that all treatments had lower nitrate-N loads. Orthophosphate loading was generally low in all treatments with the exception of the grass pavers, with the control having an average concentration close to zero. Reductions in loadings greater than 75% were recorded for TSS for all the treatments as compared with the control. Significant reduction in *E. coli* was also recorded in all treatments except for Porous concrete. The very high *E.coli* count from the porous concrete could have been caused by compost and mulch backing up into the drain from the landscape island due to the location of that treatment near the stormwater outlet. Commercial composts (including composted manure) are a common source of *E. coli* (J.G. Davis and P. Kendall, 2012; http://www.ext.colostate.edu/pubs/foodnut/09369.html).

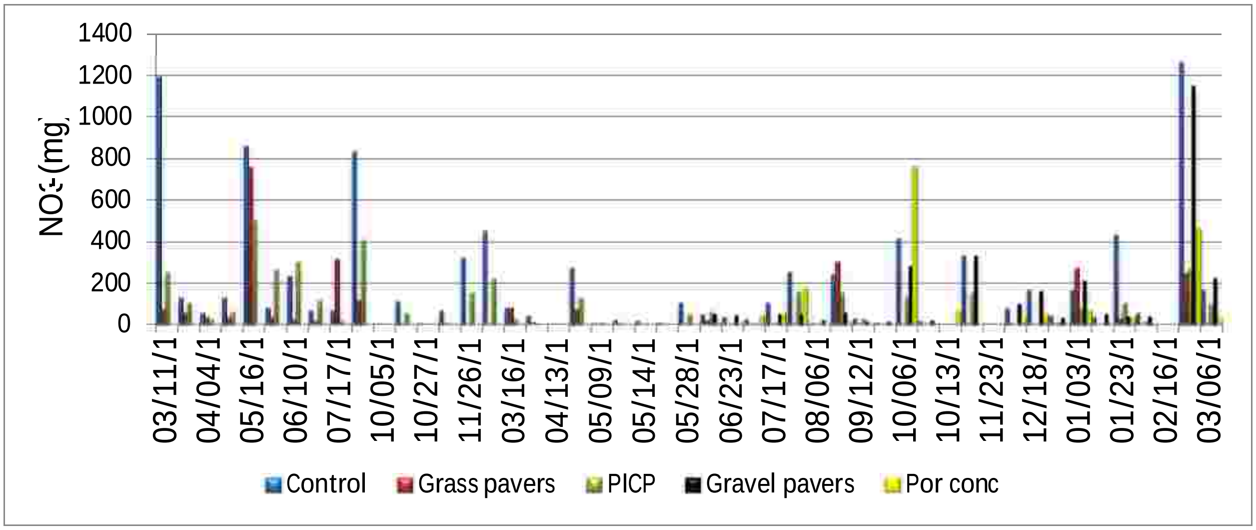

Figure 21. Nitrate Nitrogen loadings in mg for the five treatments of the permeable pavement BMP during the project period.

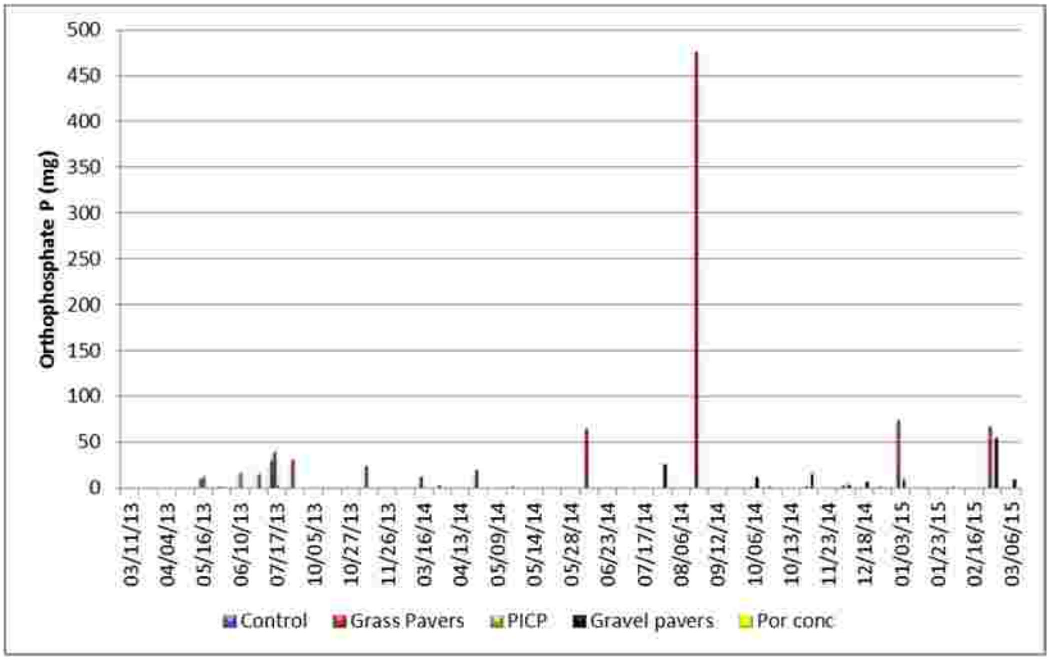

Figure 22. Orthophosphate loadings in mg for the five treatments of the permeable pavement BMP during the project period.

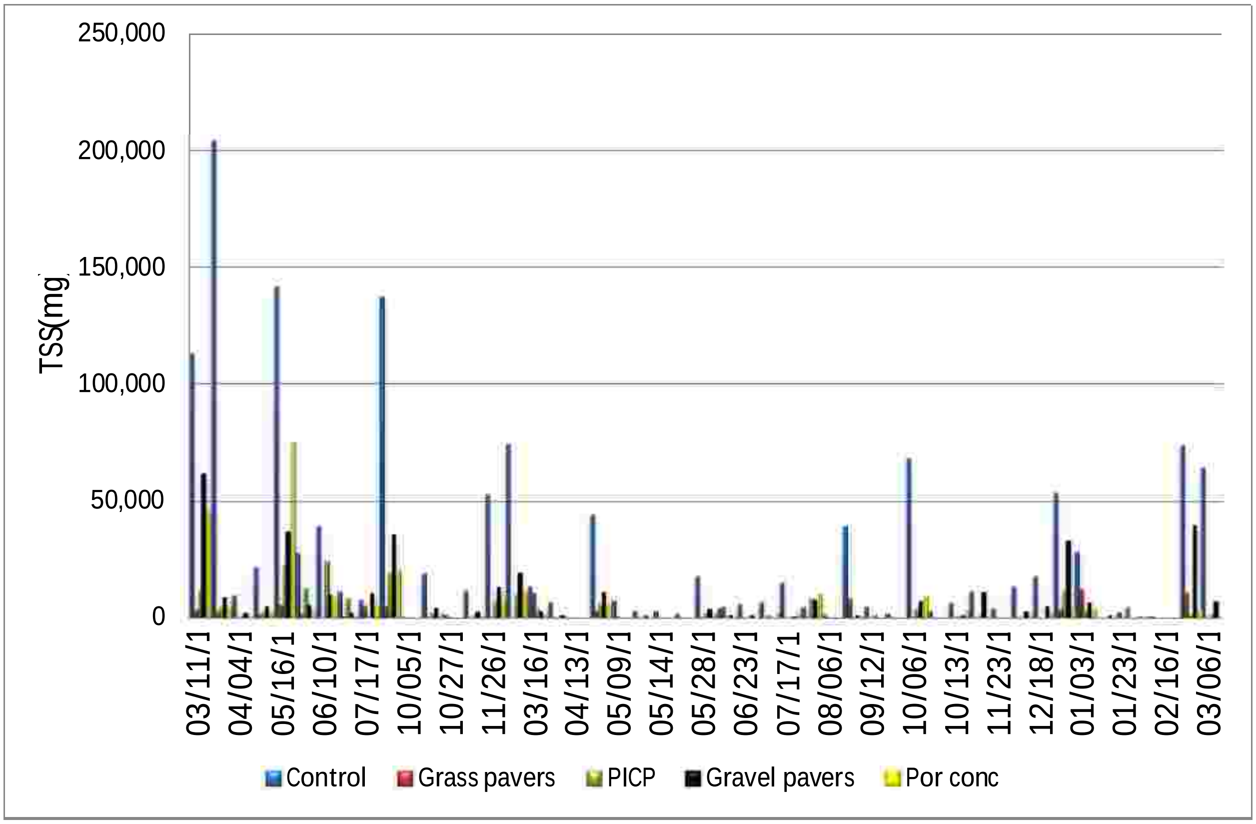

Figure 23. Total Suspended Solids loadings in mg for the five treatments of the permeable pavement BMP during the project period.

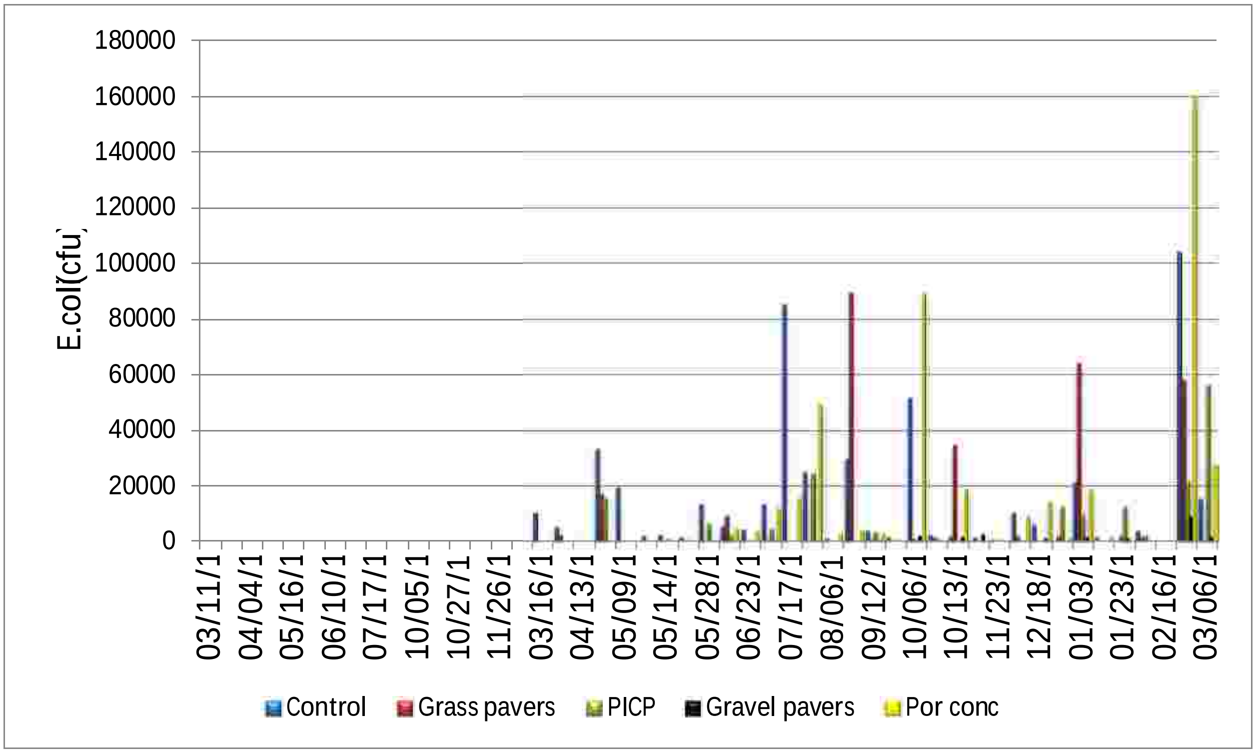

Figure 24. *E.coli* colony forming unit (cfu) for the five treatments of the permeable pavement BMP during the project period.

Table 4. Average loadings of pollutants in the permeable pavement BMPs.

	Control	Grass Pavers	ICP	Gravel Pavers	Porous Concrete
NO3 (mg)	187.92	53.57	84.58	125.98	81.68
Orthophosphate (mg)	0.60	17.16	1.03	6.86	0.24
TSS (mg)	27736	1773	3524	3825	2180
***E. Coli* (cfu)**	20600	10597	8842	1121	18500

b) Bioretention

Bioretention volumes were calculated from flume equations for the inflow and partial pipe flow for the outflow. Depth in both was measured by the ISCO bubbler. The results show that the combination of overflow and drainage pipe flow was reduced by 49% compared to the inflow (Figure 25). Figures 26-31 show the concentrations of the inflow and outflow for all measured events. pH remained similar for the inflow and outflow with averages of 7.7 and 7.5 respectively. On average EC of the outflow (average 0.25 mS/cm) exceeded the inflow (average 0.098 mS/cm) but the outflow water EC was still low. The reductions in nitrate nitrogen, orthophosphate, total suspended solids and *E. coli* concentrations were 42%, 86%, 86%, 33%, respectively.

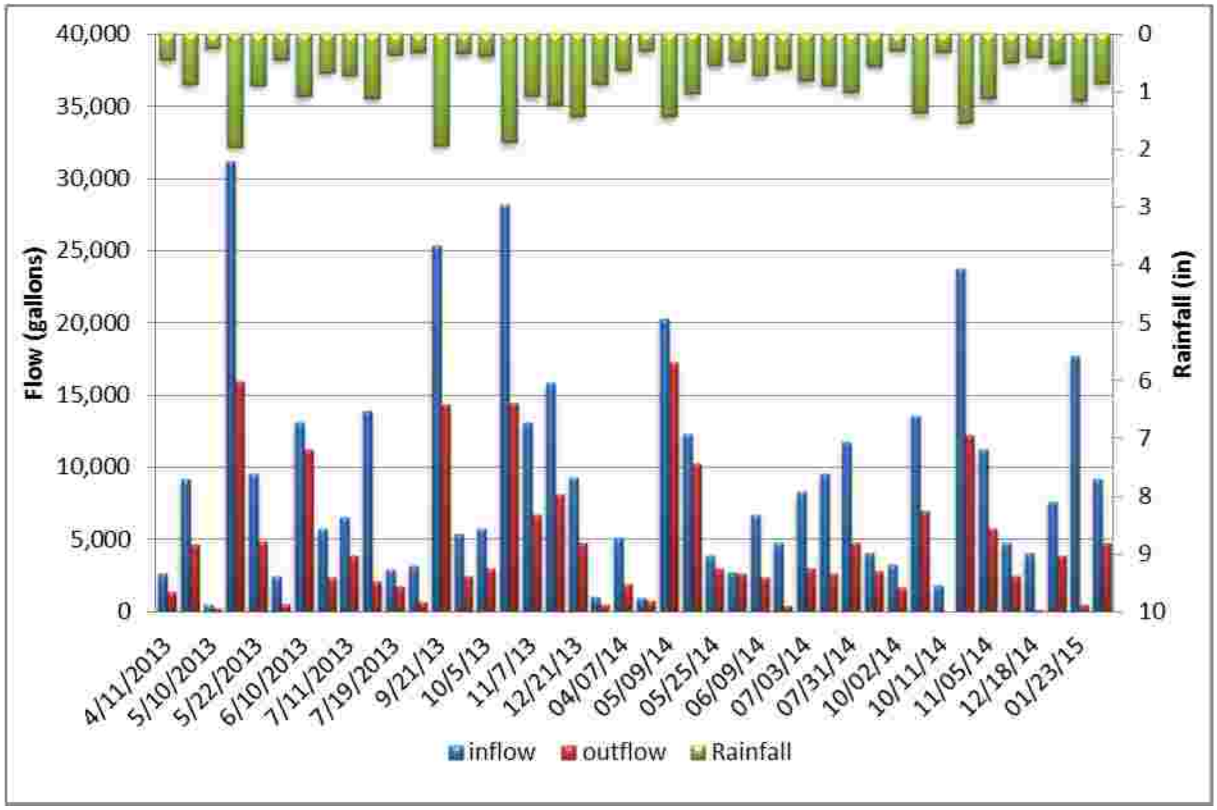

Figure 25. Rainfall, inflow and outflow volumes from the bioretention area during the project period.

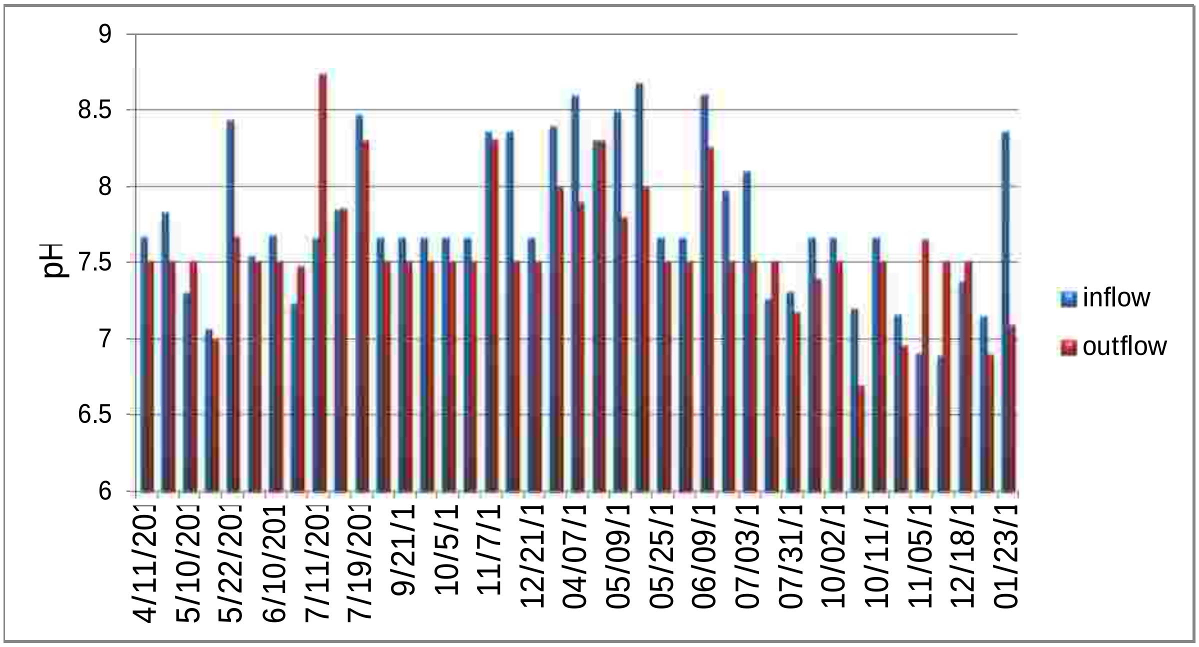

Figure 26. pH values for the inflow and outflow of the bioretention area during the project period.

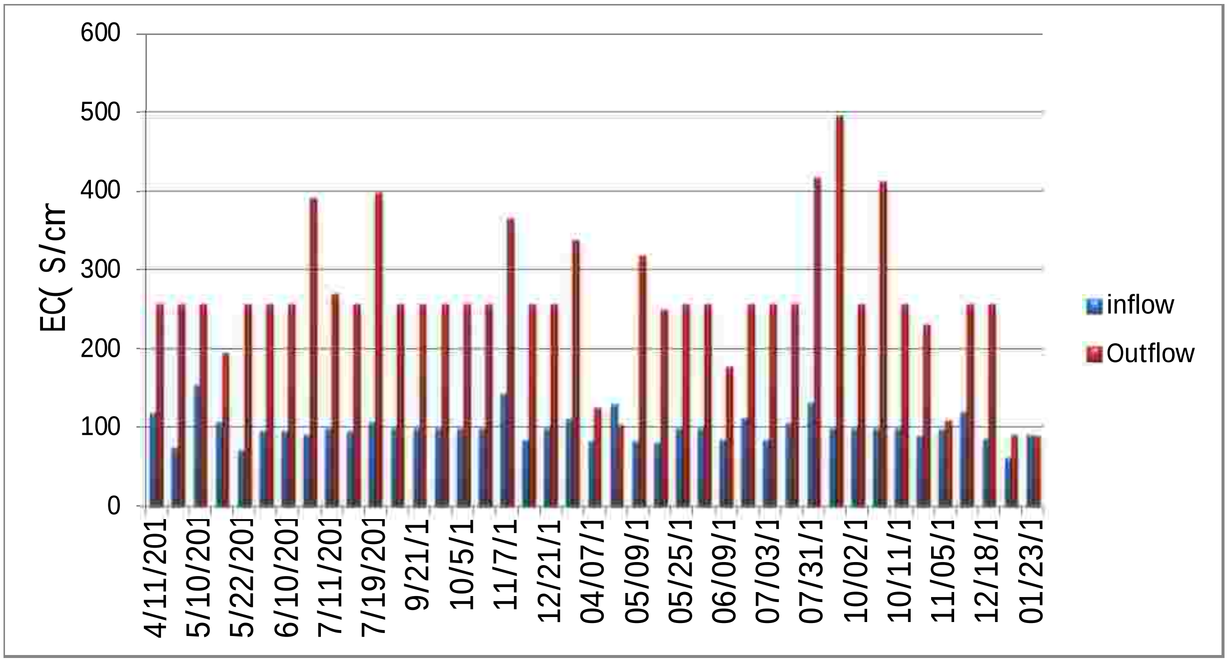

Figure 27. Electrical conductivity in mS/cm for the inflow and outflow of the bioretention area during the project period.

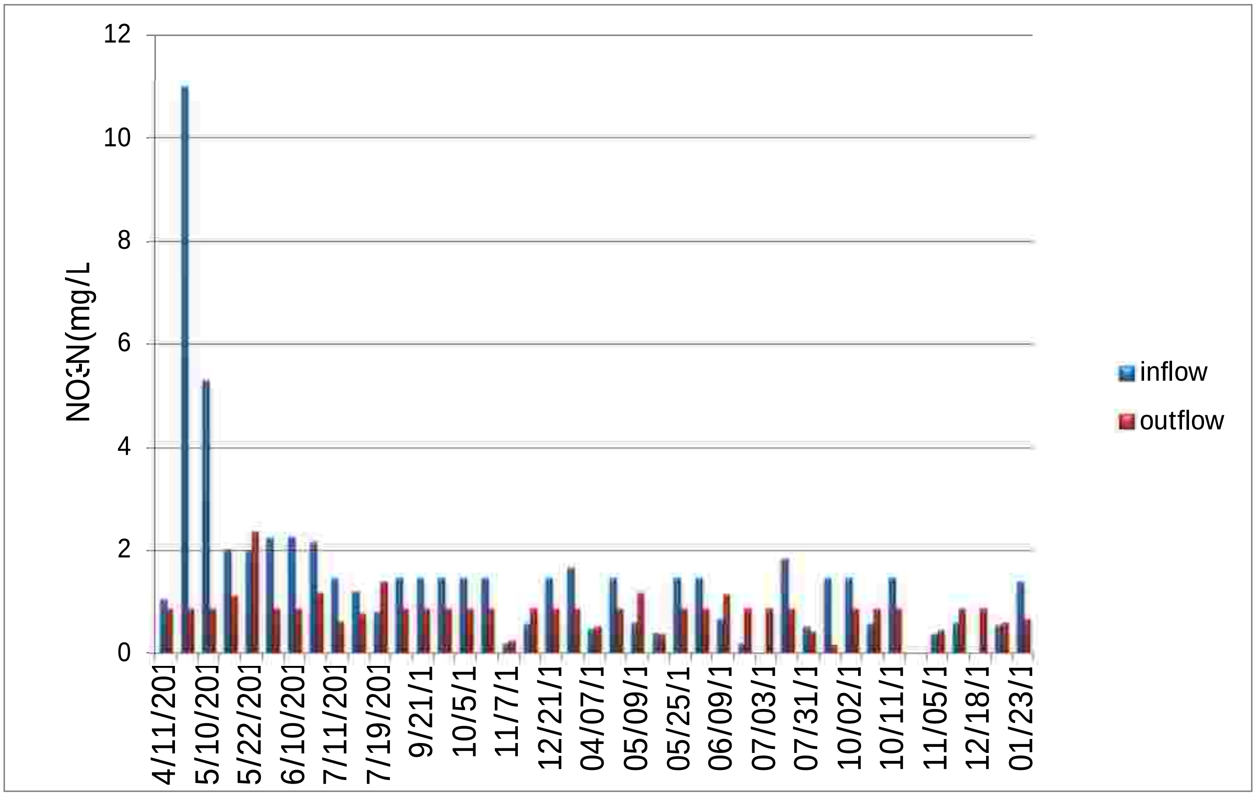

Figure 28. Nitrate Nitrogen concentrations in mg/L for the inflow and outflow of the bioretention area during the project period.

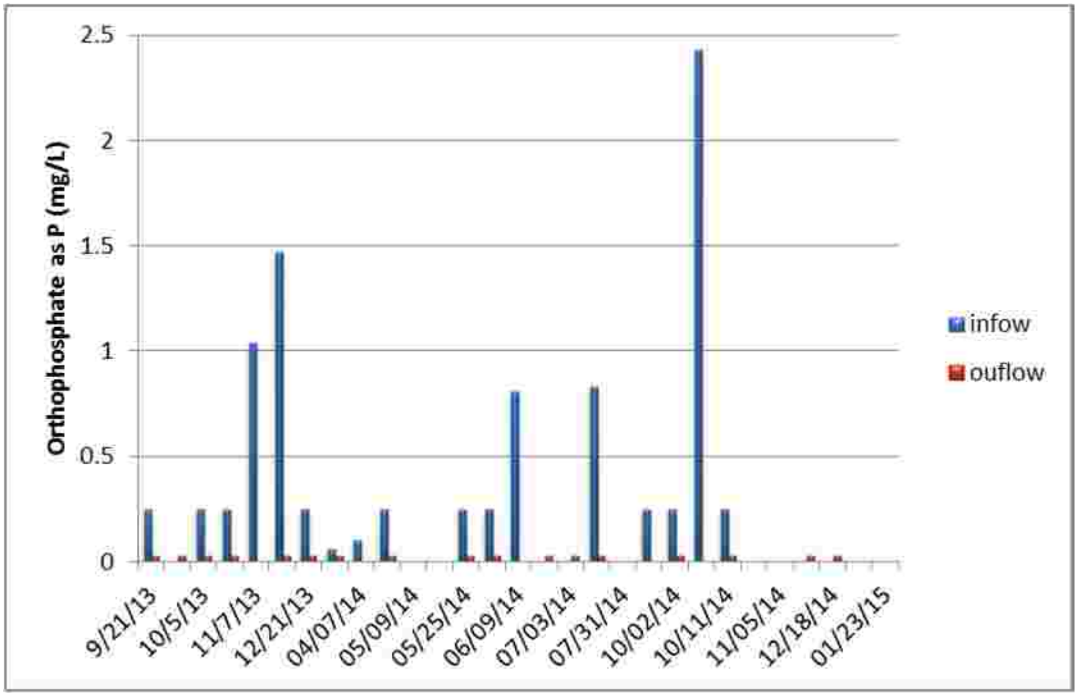

Figure 29. Orthophosphate concentrations in mg/L for the inflow and outflow of the bioretention area during the project period.

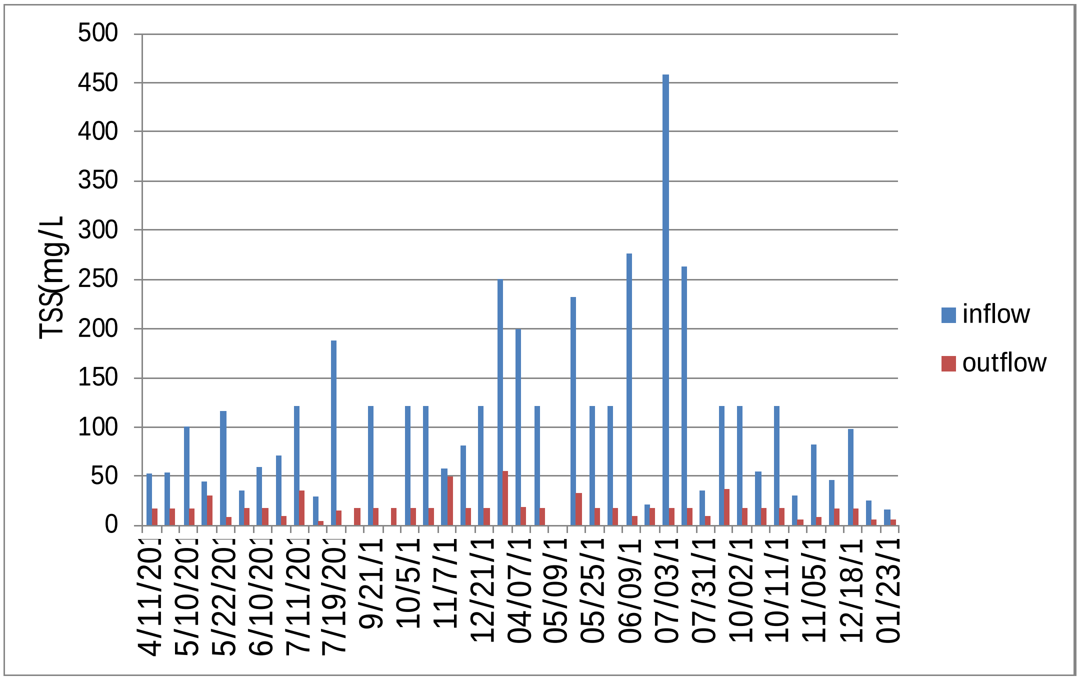

Figure 30. Total Suspended Solids concentrations in mg/L for the inflow and outflow of the bioretention area during the project period.

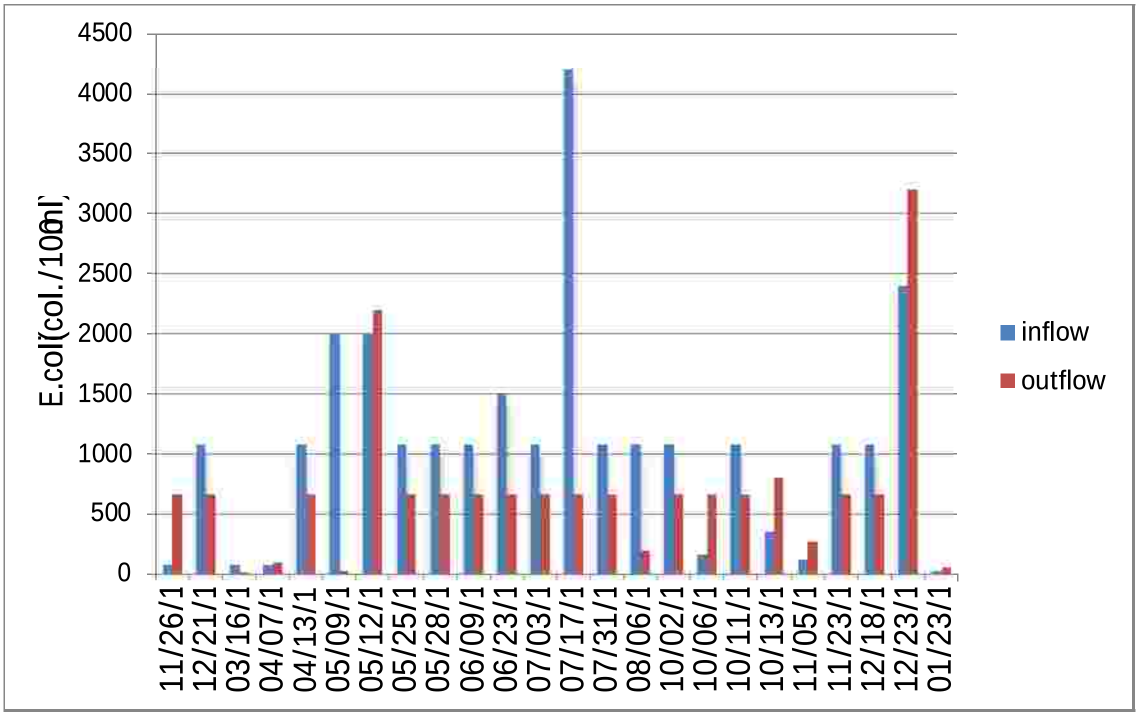

Figure 31. E. Coli concentrations in colonies/100ml for the inflow and outflow of the bioretention area during the project period.

The loads of pollutants during the data collection period in the bioretention are shown in Figures 32-35. For all pollutants, the average outflow loads were lower than the average inflow. The total load during the data collection period were reduced by 70%, 95%, 90%, and 64% for nitrate nitrogen, orthophosphate, total suspended solids, and *E. coli* respectively.

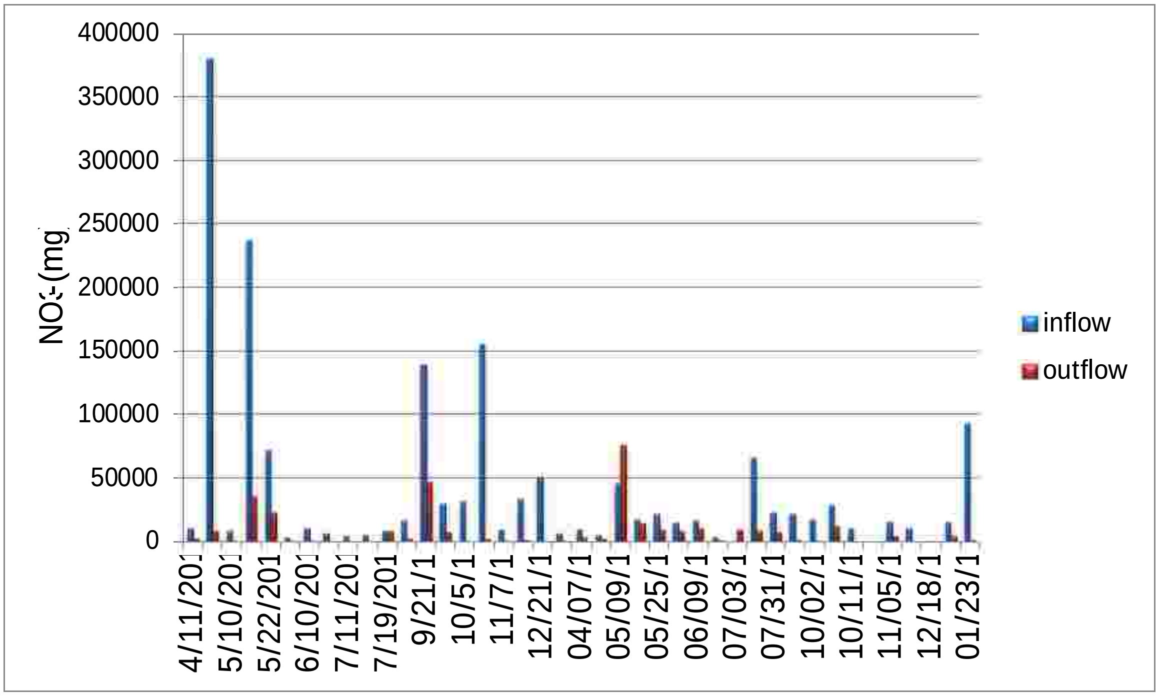

Figure 32. Nitrate Nitrogen loadings in mg for the inflow and outflow of the bioretention area during the project period.

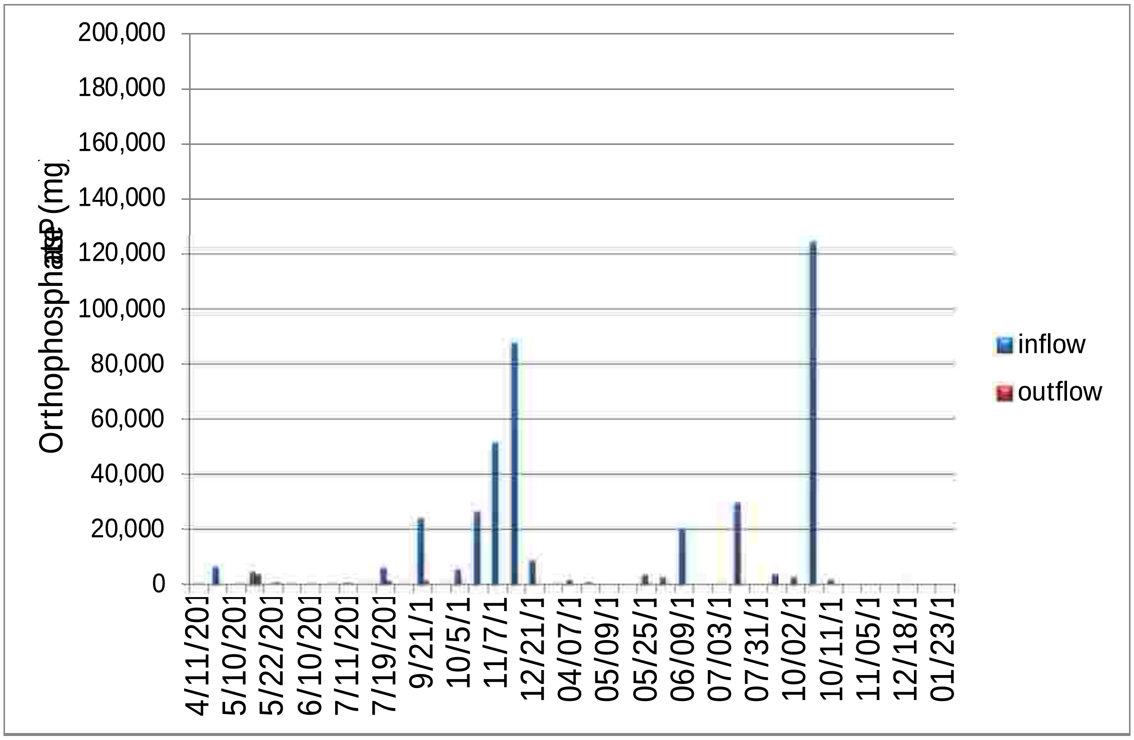

Figure 33. Orthophosphate loadings in mg for the inflow and the outflow of the bioretention area during the project period

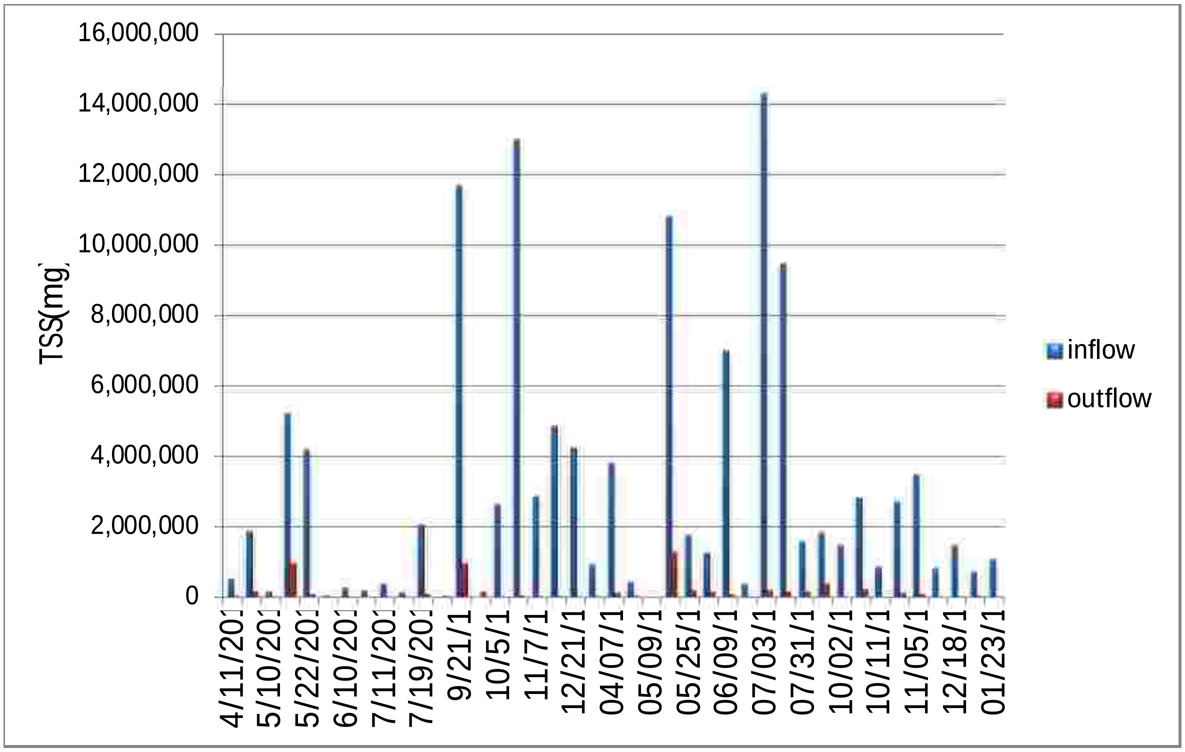

Figure 34. Total Suspended Solids loadings in mg for the inflow and the outflow of the bioretention area during the project period

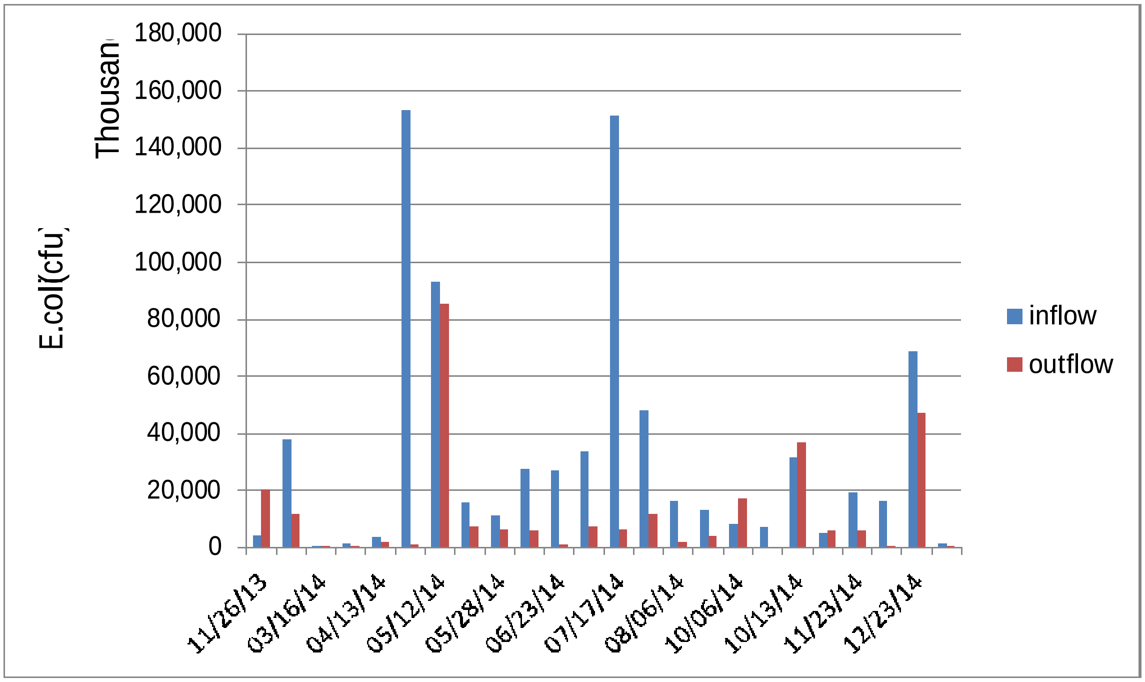

Figure 35. ***E. coli*** **colony forming unit (cfu) for the inflow and outflow of the bioretention area during the project period.**

Table 5. Average loads and reduction rate for the Bioretention area during the project period.

Pollutant	Inflow	Outflow	% reduction
NO3 (mg)	45,476	13,804	70%
Orthophosphate (mg)	10,351	565	95%
TSS (mg)	3,214,417	307,276	90%
E. coli (cfu)	31,855,184	11,489,962	64%

c) Green roofs

The volume of runoff collected from the green roof experiment is shown in Figure 36. The data shows that the average reduction rates were 68%, 79%, and 78% for the Hydrotech (H), Soil(S), and Soil with drainage (SD), respectively. The lower reduction in the H treatment is probably due to the smaller soil depth used in that treatment.

The pH comparison between the treatments is shown in Figure 37. The data showed consistently higher pH values among the treatments compared to the Control with pH averages of 7.11, 7.87, 8.29 and 8.08 for C, H, S, and SD treatments, respectively. This is probably due to the inclusion of expanded shale in the treatment mixes which has been reported to increase pH of leachate (Sloan et al., 2002).

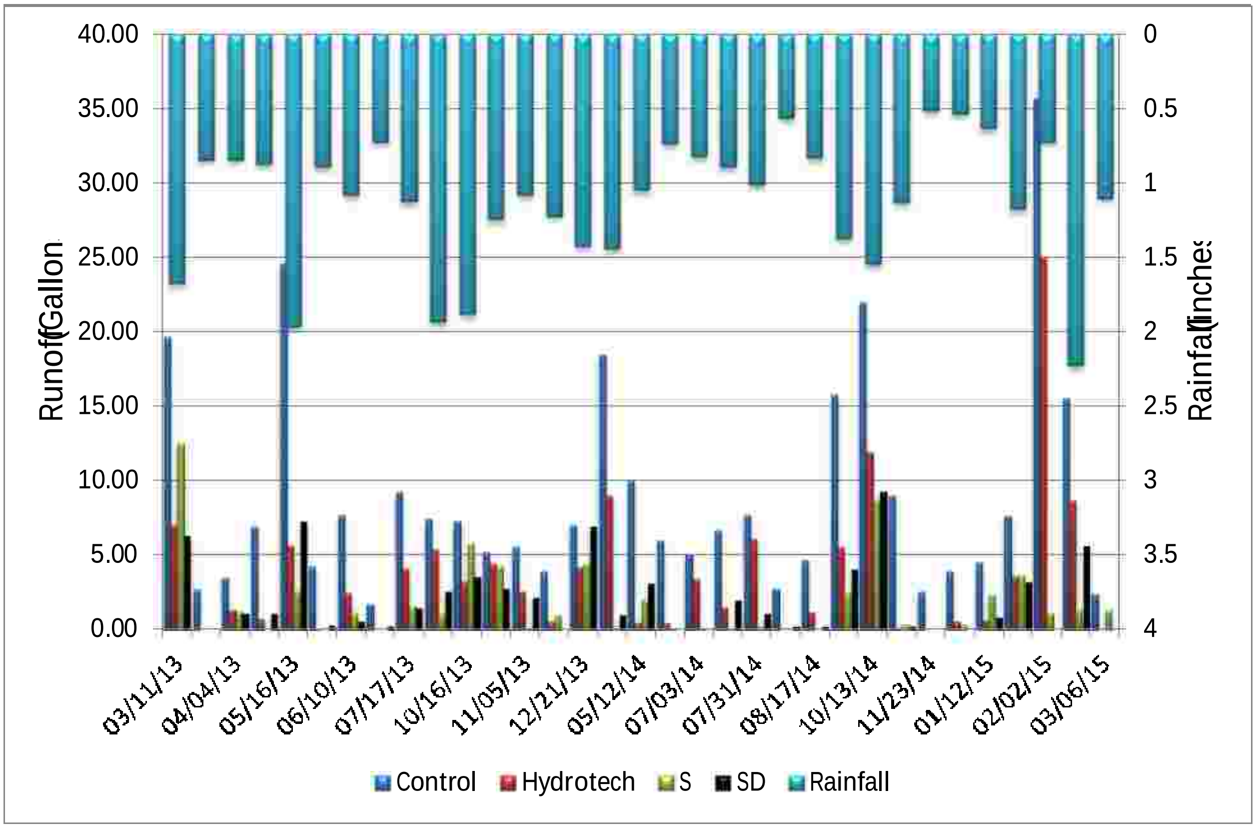

Figure 36. Rainfall, inflow and outflow volumes from the green roofs during the project period.

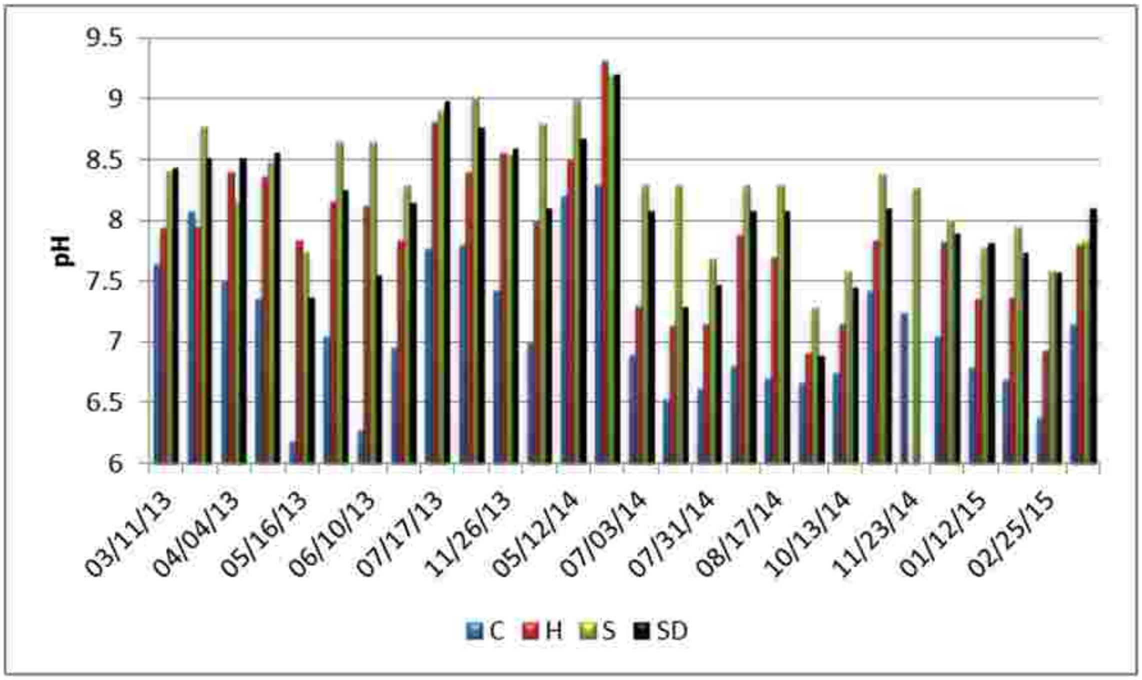

Figure 37. pH values for the 4 green roof treatments during the project period.

The runoff from the Control shows a consistently lower EC value. The H treatment had higher EC values compared with the C but lower than the two Soil treatments (SD & S) that behaved similarly (Figure 38). The average EC values were 75, 390, 809, and 724 µS/cm for C, H, S, and SD treatments. No value during the experiment exceeded the permissible conductivity of 2000 µS/cm for irrigation water quality.

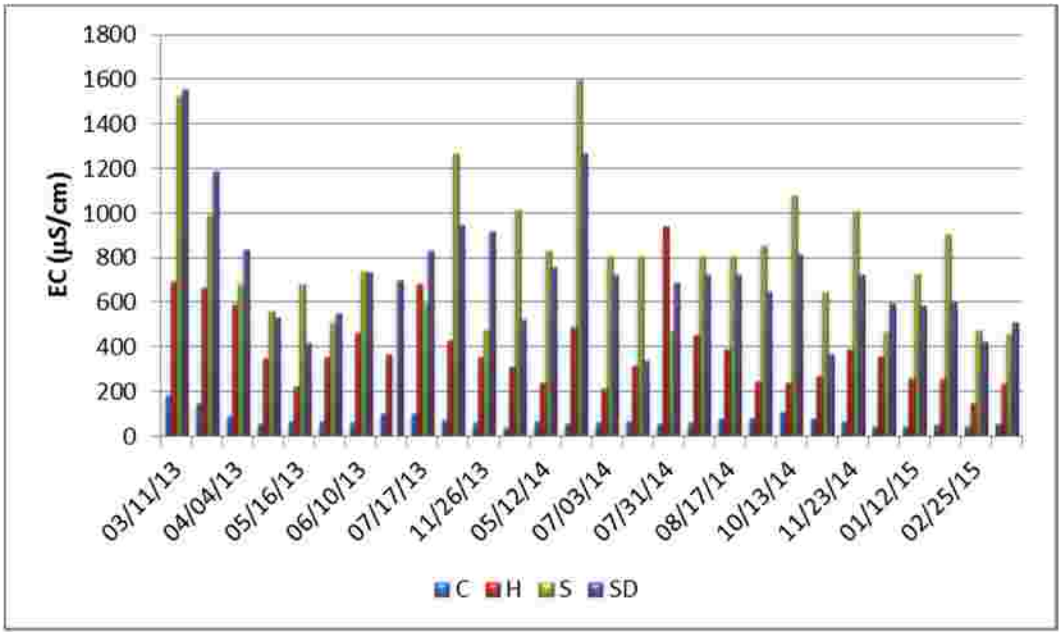

Figure 38. Electrical Conductivity (EC) values for the 4 green roof treatments during the project period.

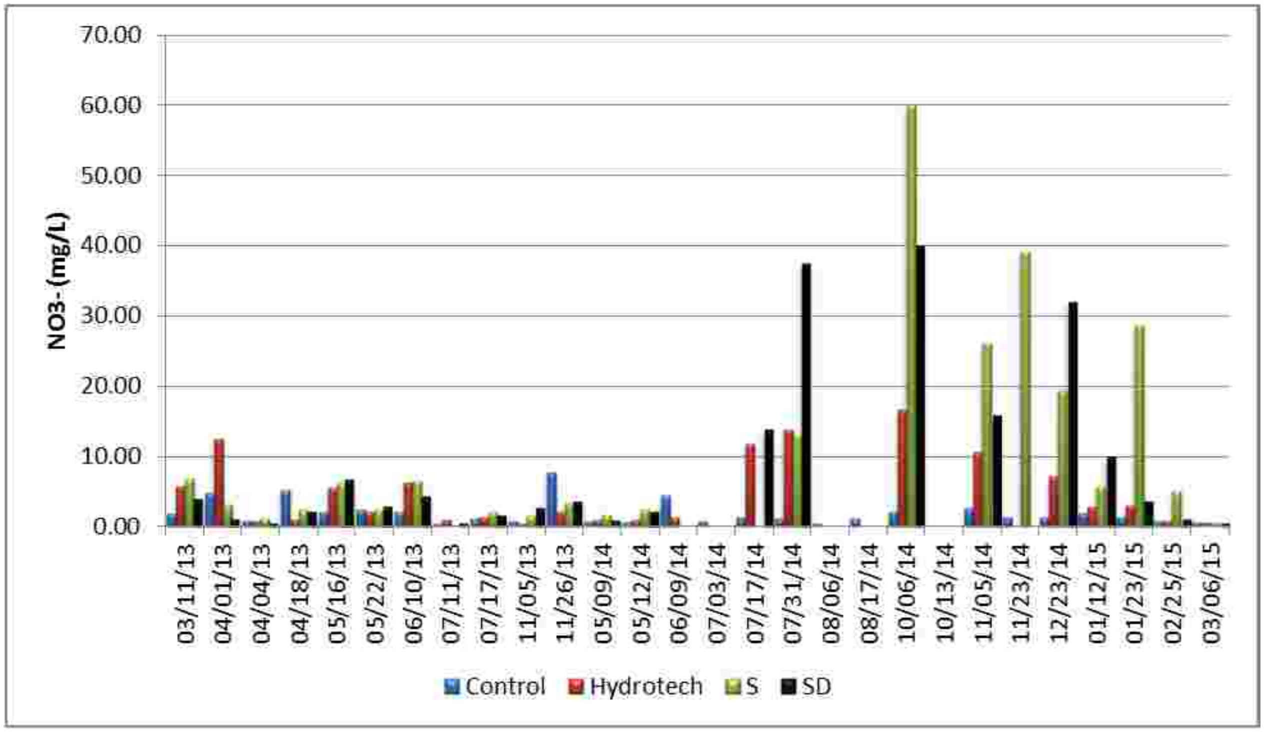

Figure 39. Nitrate Nitrogen Concentrations (mg/L) for the 4 green roof treatments during the project period.

Nitrate nitrogen concentrations of the treatments were consistently higher than the control as expected (Figure 39). The control without soil or vegetation was the lowest. For the first year of data collection, concentrations were low. Beginning July 2014, the concentrations increased dramatically for all three treatments and at a higher rate for S and SD. This is probably caused by the high mass of vegetation that grew in the green roofs including weeds and the decay of these plants throughout the year. Given the deeper soil in SD and S, more vegetation was present in these 2 treatments providing more soil to leach during storm events. The average concentrations for Nitrate nitrogen were 1.80, 3.85, 8.76, and 6.67 mg/L for C, H, S and SD treatments, respectively.

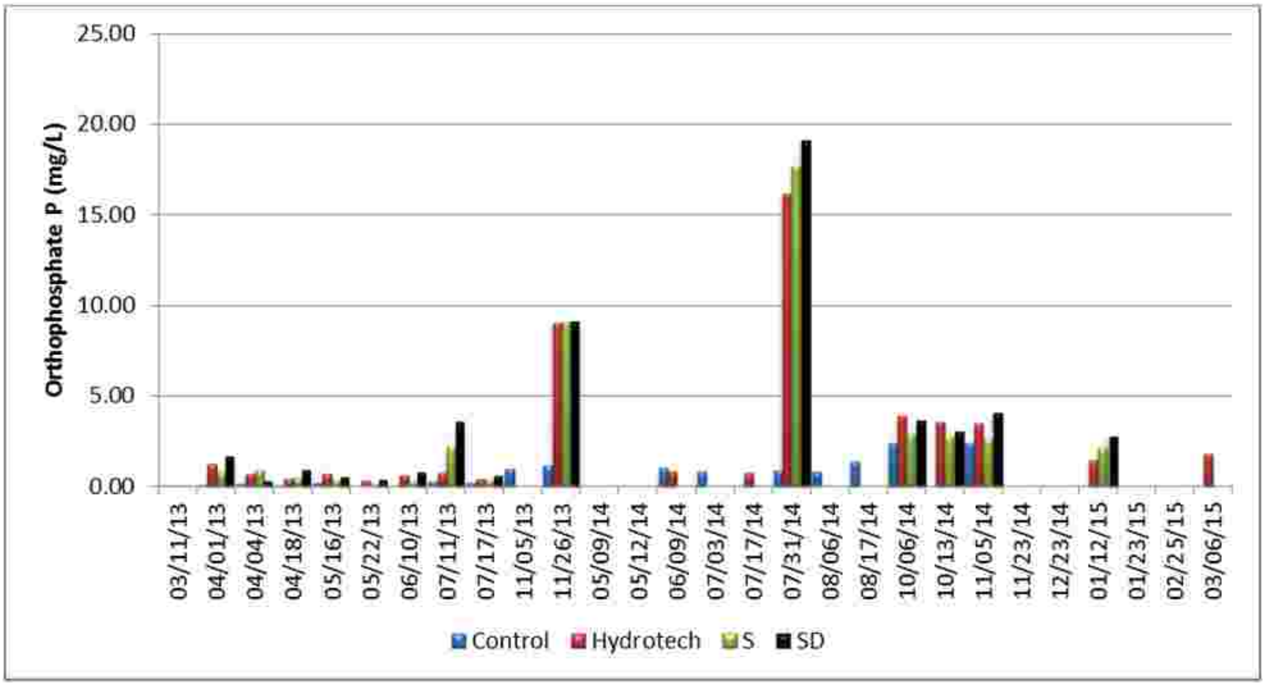

Figure 40. Orthophosphate concentrations (mg/L) in the 4 green roof treatments during the project period.

Orthophosphate (Figure 40) measured in the green roof treatments did not follow the same trend as Nitrate. While some high events were recorded in late 2013 and summer 2014, these values subsided later in the season. These high values could be related to the vegetation growth and decay after establishment but adsorption of phosphorus to soil particles might have reduced the leaching after that period. The average concentrations of orthophosphate were 0.48, 1.85, 1.77, and 2.02 mg/L for the C, H, S, and SD treatments respectively.

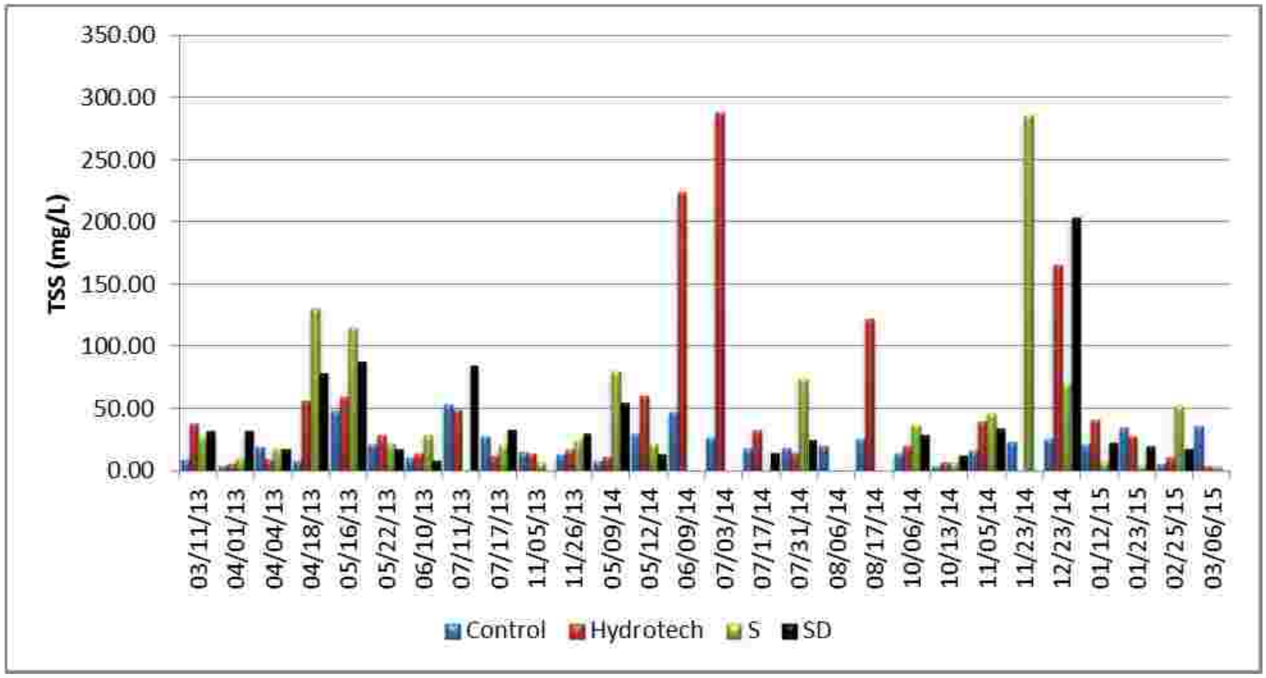

Figure 41. Total suspended solids (TSS) concentrations (mg/L) in the 4 green roof treatments during the project period.

Higher concentrations of TSS were found in the runoff coming off the green roofs for all treatment as compared to the Control (Figure 41). The average concentrations (mg/L) were 21.56, 49.04, 40.52, 31.88 mg/L for the C, H, S and SD treatments, respectively.

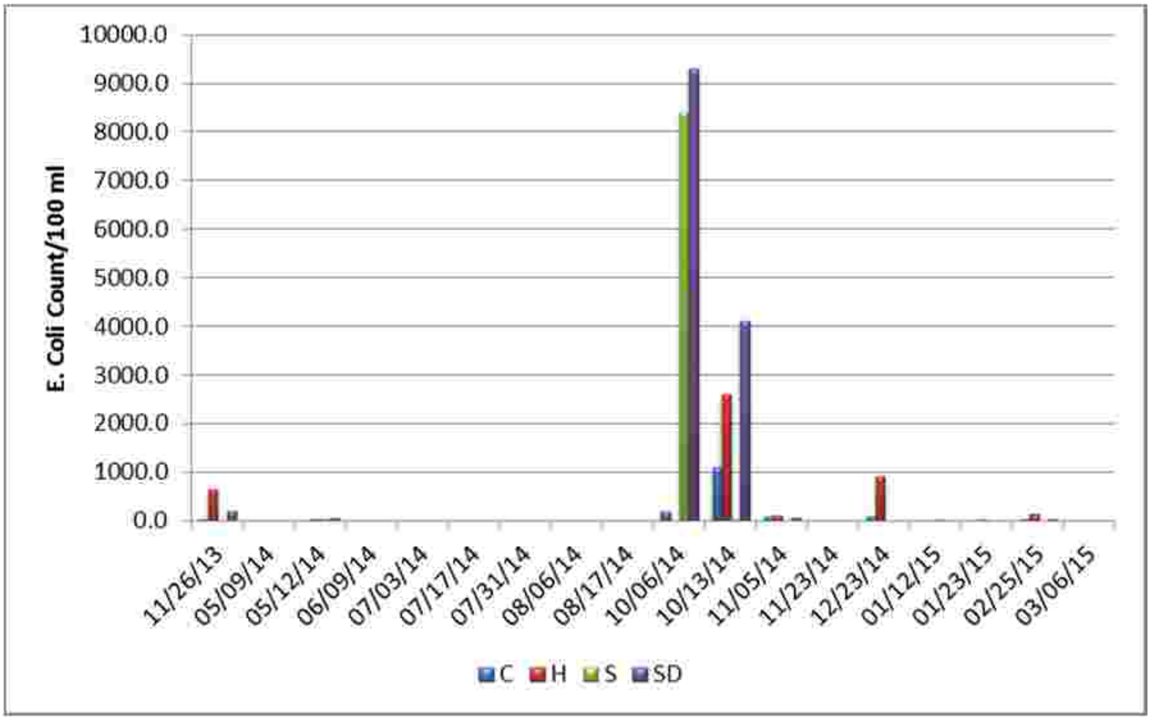

Figure 42. *E. coli* concentrations in colonies/100ml 4 green roof treatments during the project period.

E. coli were not present in most samples from the green roof, and excluding a period in October 2014, the counts were low. In October 2014, concentrations above 1000 were recorded in the treatments and in the control. The source of the bacteria might be birds or animals that were able to get to the roofs. In general concentrations of *E. coli* were 104, 346, 715 and 1149 counts/100ml in C, H, S and SD, respectively.

Loadings (mg) represent the total weight of pollutants that are in stormwater flow. Loading values are calculated by multiplying the pollutant concentration by the volume. The loads for the four green roof treatments: Control (C), Hydrotech (H), Soil only (S) and Soil with a drainage layer (SD) are presented below. Figures 43-46 show the treatment loading during the data collection period for nitrate nitrogen, orthophosphate, total suspended solids, and E. coli, respectively.

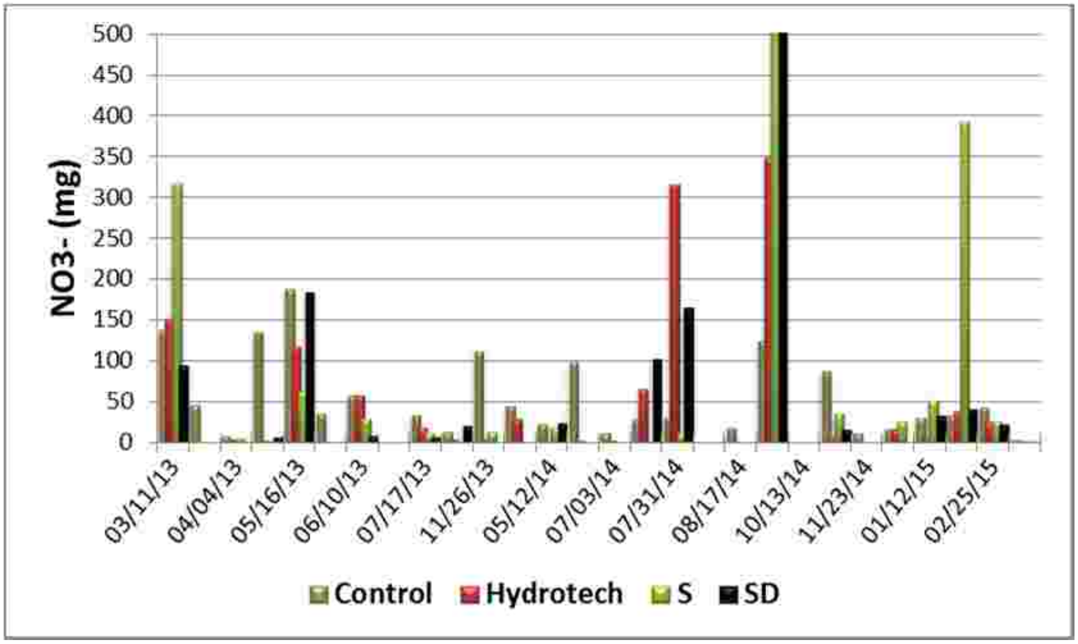

Figure 43. Nitrate Nitrogen Loadings in mg in the 4 green roof treatments during the project period.

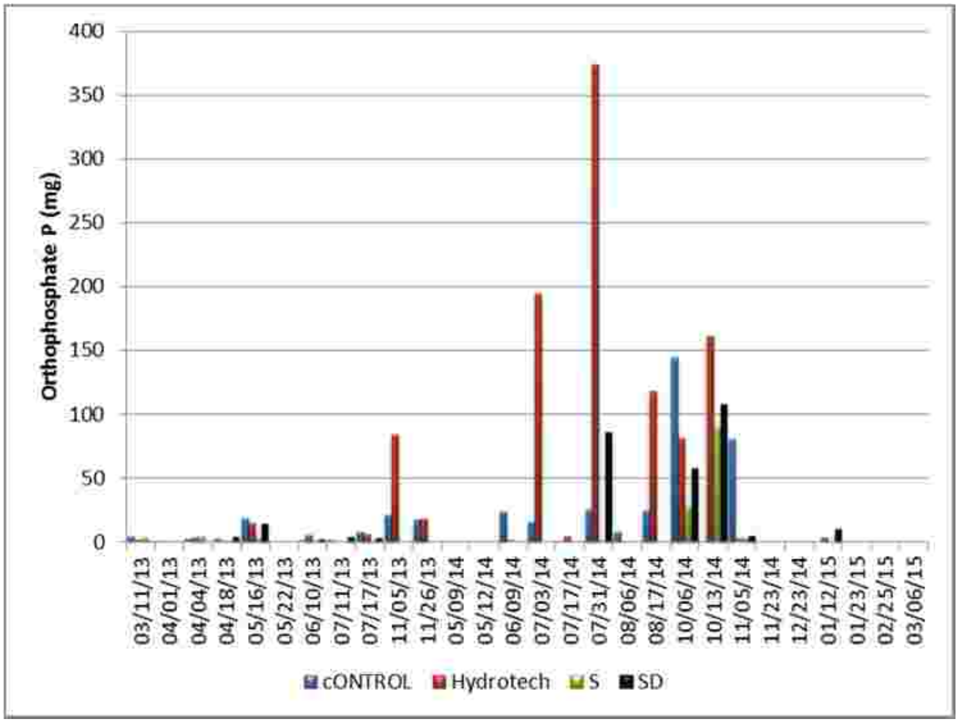

Figure 44. Orthophosphate as P Loadings in mg in the 4 green roof treatments during the project period.

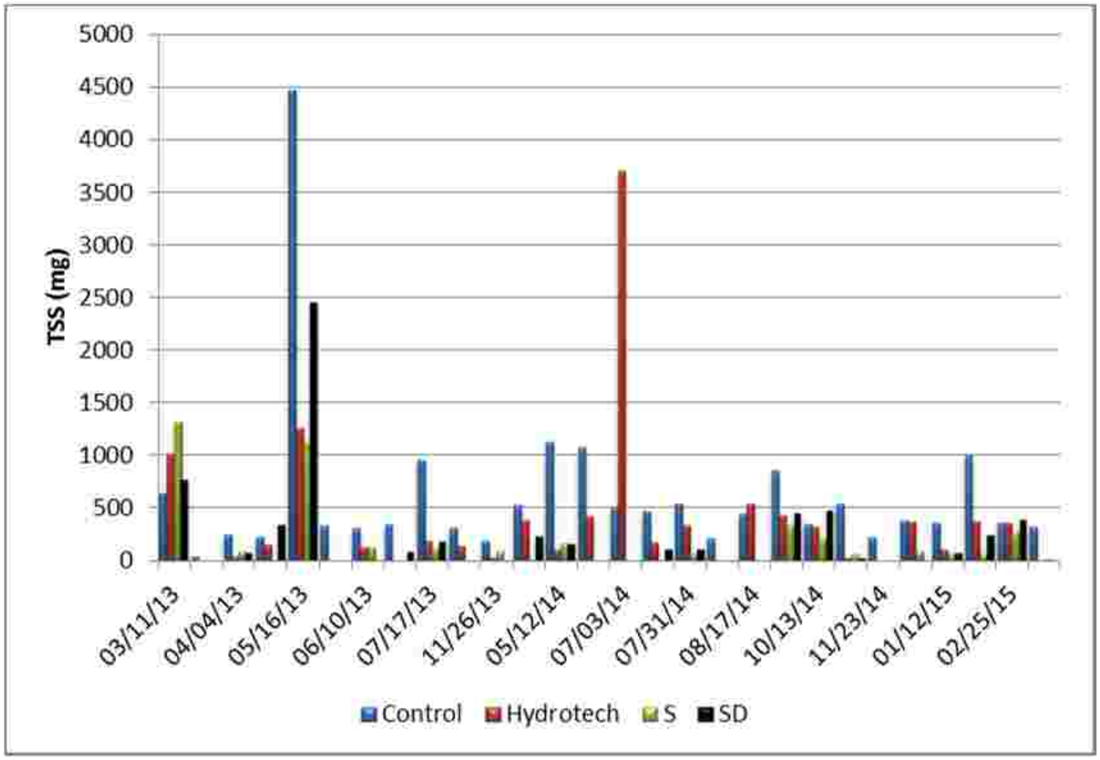

Figure 45. Total Suspended Solids loadings in mg in the 4 green roof treatments during the project period

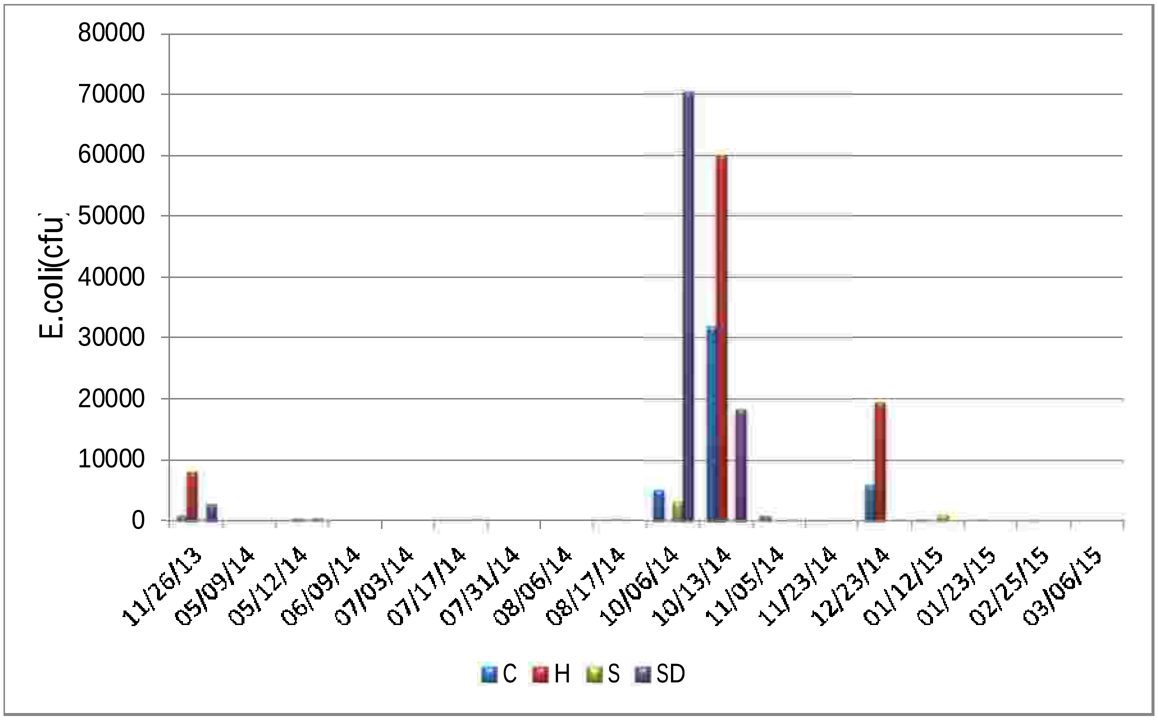

Figure 46. *E. coli* colony forming unit (cfu) for the outflow of the green roof for all treatments during the project period.

Table 5 shows the average pollutant load per storm during the collection period and the reductions in pollutants in all treatment as compared to the no green roof control. Nitrate-nitrogen was nearly unchanged with some reduction in H and SD and minor contribution in S. orthophosphate was reduced in S and SD but H contributed orthophosphate. Total suspended solids were reduced in all three treatments. E. coli was reduced in S and contributed in H and SD. The reduction of volume in the green roof had a considerable impact on reducing pollution from green roofs as the comparison of reduction in loads to the reduction in concentrations shows. It is likely if green roof drainage is released on a grassed area, the pollutant concentrations could be reduced to be similar rates as ambient flows for Nitrate, phosphate and E. coli with considerable reductions in TSS.

Table 6. Percent reductions in the 4 green roof treatments during the project period.

Pollutant	H % reduction	S% reduction	SD% reduction
NO3	14	-11	2
Orthophosphate	-69	49	26
TSS	39	75	63
E. coli	-107	89	-135

d) Rainwater Harvesting

The rainwater harvesting BMP compared evapotranspiration based irrigation (ET), homeowner standard irrigation (HO), and soil moisture based irrigation (SM) with rainwater harvesting to a control (C) consisting of a homeowner standard irrigation without rainwater harvesting.

Table 7. Volumes and reduction rates comparing the 4 treatments in the rainwater harvesting system for the project period.

Event	Rainfall	C	ET	ET % reduction	HO	HO %reduction	SM	SM %reduction
12/15/2012	0.39	0	0	0.00%	0	0.00%	0	0.00%
12/28/2012	1.52	94	94	0.00%	52.79	43.84%	94	0.00%
1/10/2013	2.61	224.75	224.75	0.00%	198.32	11.76%	224.75	0.00%
1/30/2013	0.39	0	0	0.00%	0	0.00%	0	0.00%
2/11/2013	0.9	29.1	29.1	0.00%	11.28	61.24%	29.1	0.00%
2/13/2013	0.41	1.38	1.38	0.00%	1.38	0.00%	1.38	0.00%
2/21/2013	0.37	0	0	0.00%	0	0.00%	0	0.00%
3/11/2013	1.67	51.56	51.56	0.00%	31.2	39.49%	51.56	0.00%
4/1/2013	0.84	11.64	11.64	0.00%	1.03	91.15%	11.64	0.00%
4/4/2013	0.84	14.11	11.54	18.21%	5.22	63.00%	9.95	29.48%
4/11/2013	0.46	2.46	2.46	0.00%	0	100.00%	2.46	0.00%
4/18/2013	0.87	26.59	26.59	0.00%	5.11	80.78%	26.59	0.00%
5/10/2013	0.25	0	0	0.00%	0	0.00%	0	0.00%
5/16/2013	1.96	75.56	18.83	75.08%	18.83	75.08%	21.6	71.41%
5/22/2013	0.89	70.54	37.34	47.07%	40.7	42.30%	70.54	0.00%
6/7/2013	0.45	2.16	0	100.00%	0	100.00%	0	100.00%
6/10/2013	1.08	45.51	28	38.48%	11.71	74.27%	25.16	44.72%
6/17/2013	0.67	9.9	9.9	0.00%	0.69	93.03%	9.9	0.00%
7/11/2013	0.72	15.42	1.9	87.68%	1.9	87.68%	1.9	87.68%
7/17/2013	1.12	3.22	0	100.00%	0	100.00%	0	100.00%
7/19/2013	0.36	0	0	0.00%	0	0.00%	0	0.00%
Total	18.77	677.9	548.99	19.02%	380.16	43.92%	580.53	14.36%

All treatments showed some reduction in runoff volume, but the homeowner treatment with rainwater harvesting showed a significant reduction of 43% compared to 19% and 14% for the ET and SM treatments.

The concentrations of pollutants in the runoff for pH, EC, nitrate nitrogen, orthophosphate, and total suspended solids are shown in Figures 47-51, respectively. There were no specific trends of concentration reduction in any of the treatments for any of the pollutants since this BMP is mainly a volume reduction BMP.

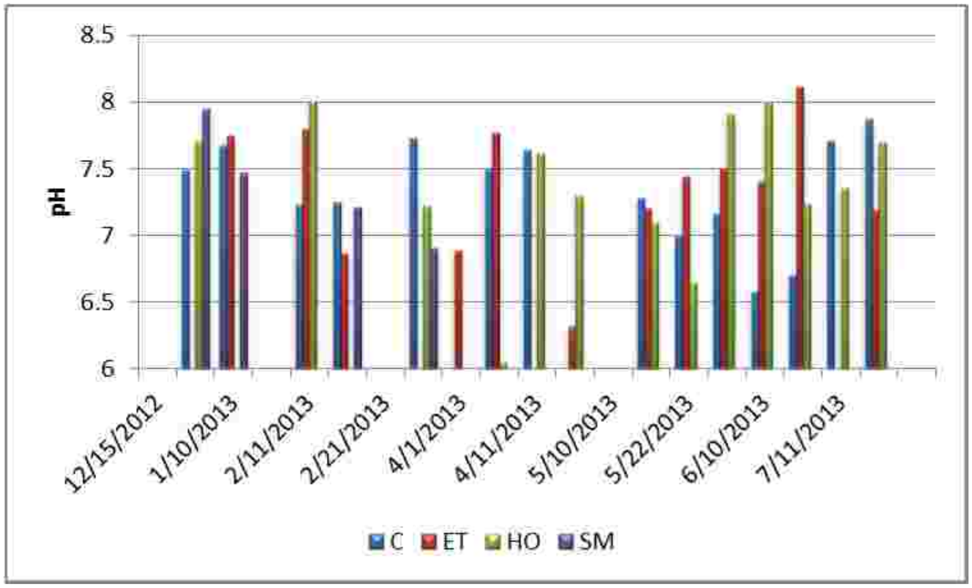

Figure 47. pH values for the 4 rainwater harvesting treatments during the project period.

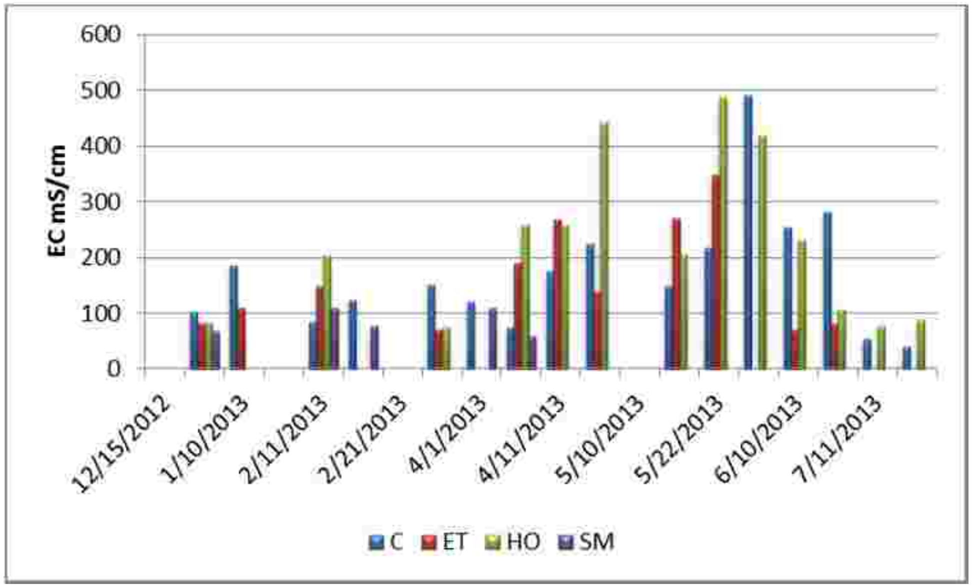

Figure 48. Electrical conductivity (mS/cm) for the 4 rainwater harvesting treatments.

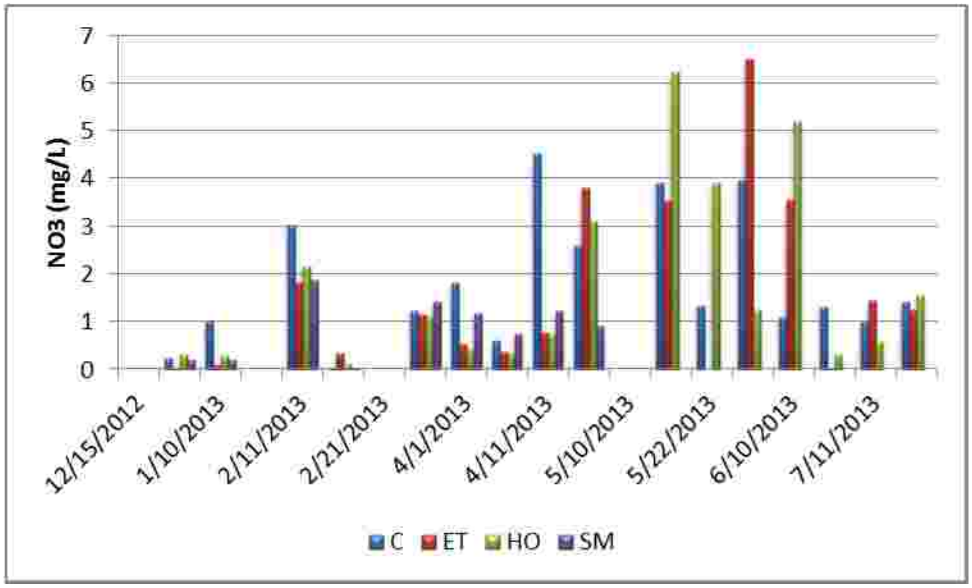

Figure 49. Nitrate Nitrogen concentrations in mg/L for the 4 rainwater harvesting treatments.

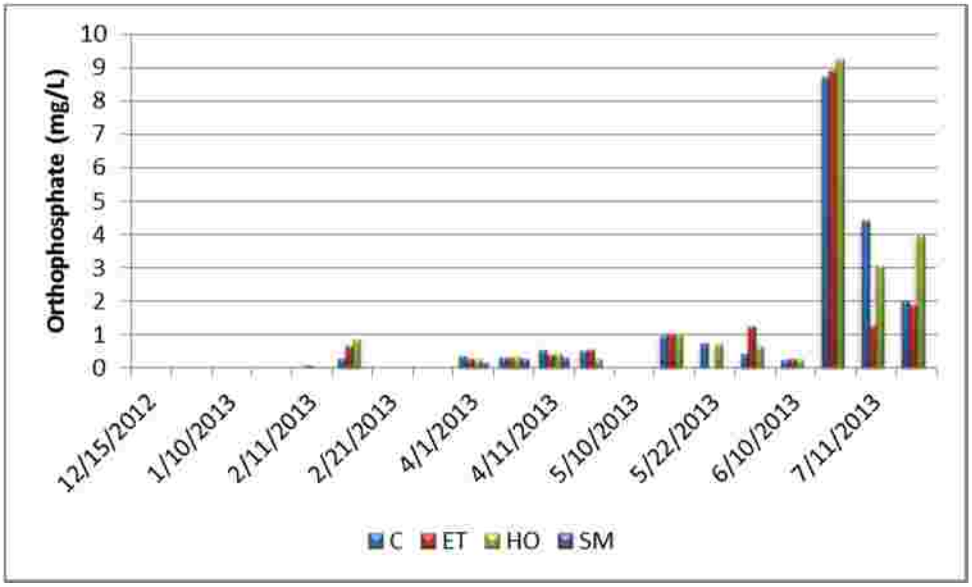

Figure 50. Orthophosphate concentrations in mg/L for the 4 rainwater harvesting treatments.

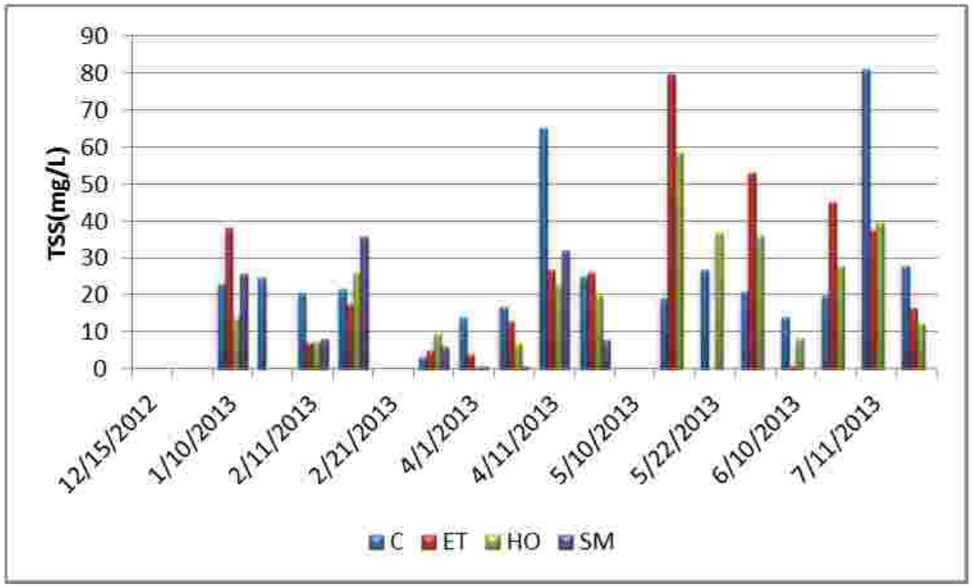

Figure 51. Total suspended solids (TSS) concentrations (mg/L) for the 4 rainwater harvesting treatments during the project period.

The loadings for the rainwater harvesting treatment show that there was a high reduction in orthophosphate and nitrate for all treatments (Table 8 and Figures 52-54). Total suspended solids were not reduced in the ET treatments but were reduced 52% in the HO treatment. This is caused by the fact that all major storms >1.5 inches happened in the winter when the barrels were full and no difference existed in flows between the ET treatments and the control. The over-irrigation schedule of the HO treatment meant that the barrels were at least partially empty even during the winter season. This allowed rainfall to be collected in the barrels, resulting in flow and TSS reduction from the large storms.

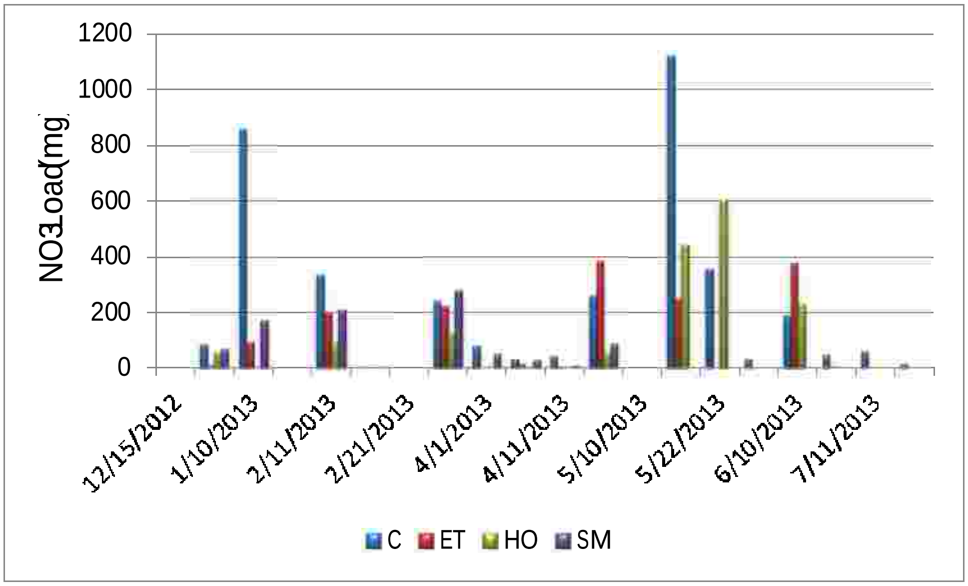

Figure 52. Nitrate Nitrogen loadings in mg for the 4 rainwater harvesting treatments.

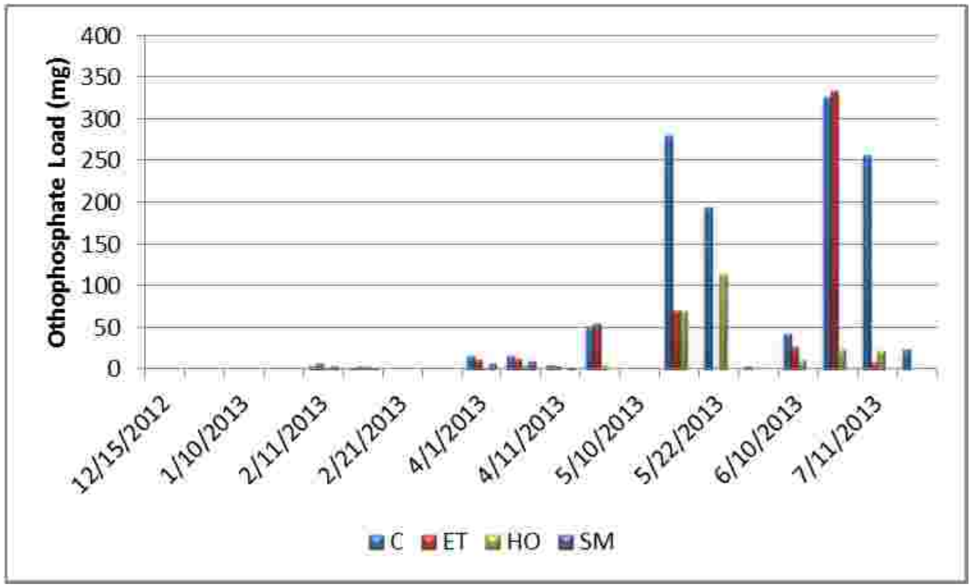

Figure 53. Orthophosphate as P loadings in mg for the 4 rainwater harvesting treatments.

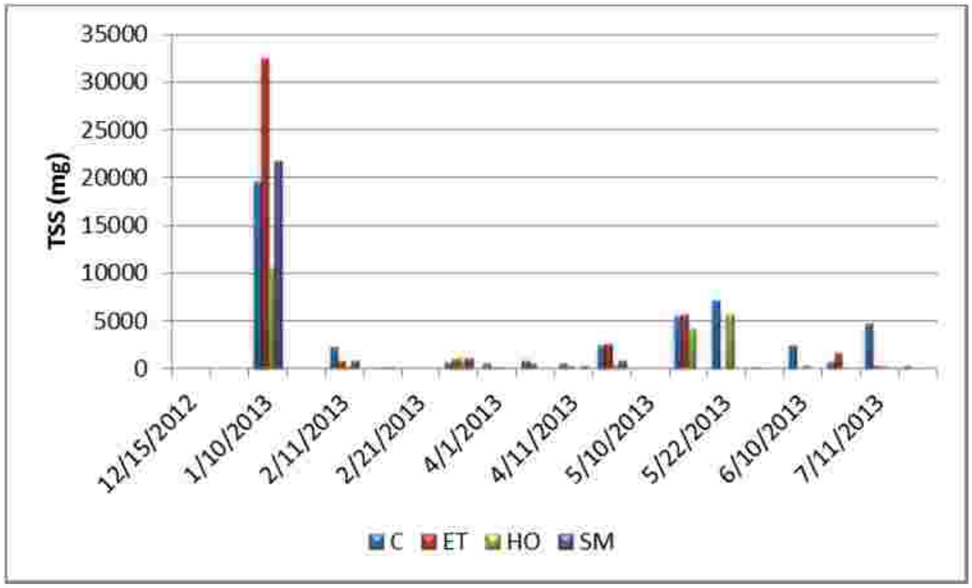

Figure 54. Total Suspended Solids loadings in mg for the 4 rainwater harvesting treatments.

Table 8. Average loadings (mg) and % reductions for the 4 rainwater harvesting treatments.

	C	ET	% reduction	HO	% reduction	SM	% reduction
NO_3	235.09	120.35	49%	117.16	50%	90.77	61%
Orthophosphate	94.26	44.71	53%	20.07	79%	5.05	95%
TSS	3226.96	3266.01	-1%	1558.27	52%	3160.55	2%

e) Detention Pond

The detention pond collected runoff from 45% (which included most of the impervious surfaces (Figure 67) of the built up watershed (440,248 sq. ft.) of the Texas A&M AgriLife campus (excluding agricultural research fields). In addition to the 165,000 square feet of watershed feeding the east branch of the pond includes a large portion of the buildings (green line in Figure 55); the pond collects the outflow from the rain garden (36,000 sq.ft/ red line in Figure 55).

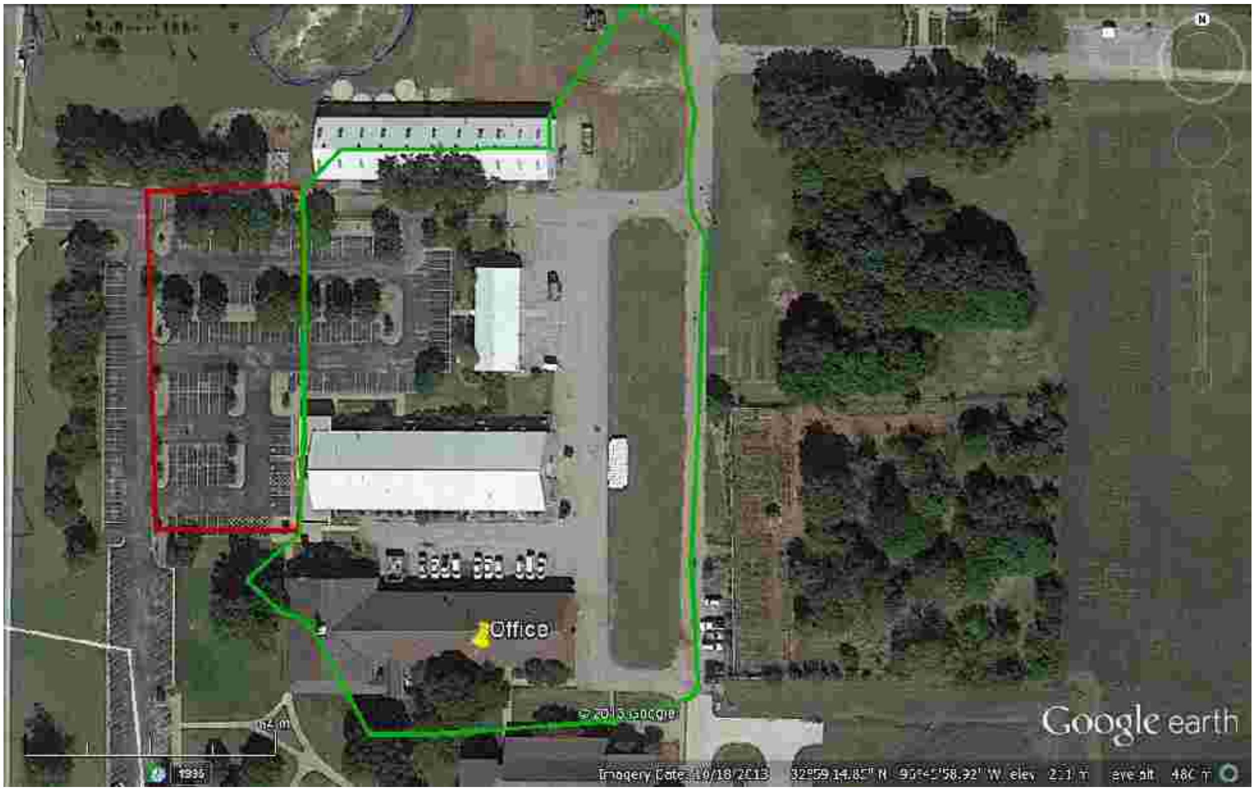

Figure 55. Watershed of the east side of the detention pond (green) and the bioretention area (red line).

A curve number was back calculated from the runoff measurement from the east branch and it was noticed that the curve numbers decreased with larger storms (Figure 56). Hawkins (1993) noted that this phenomenon occurs in about 70% of watersheds in the US. This behavior, known as Standard Behavior, is caused by the fact that larger storms usually fall at lower intensity over longer period thus reducing the volume of runoff. As such, an equation relating storm to curve number was developed for the detention pond east branch watershed (Figure 56) and was used to estimate missing data. It is worth noting that the detention pond was designed to retain 1.5 inches from the combined watrshed of the detention pond and the bioretention as the bioretention was not originally planned at this location. This increase in treatment area and the decreasing runoff curve number with higher storms both resulted with no outflow during most of the project period until April 2015. From March 2015 to end of May 2015, the Center received 23 inches and the detention pond outflowed almost continuously during this period. The inflow volumes and outflow from February 2015 to May 2015 are shown in figure 57. Prior to this period, 555,626 gallons of water were collected in the detention pond and infiltrated or evaporated. Average water quality results are shown in Table 9, and the loads removed prior to February 2015 are shown in Table 10.

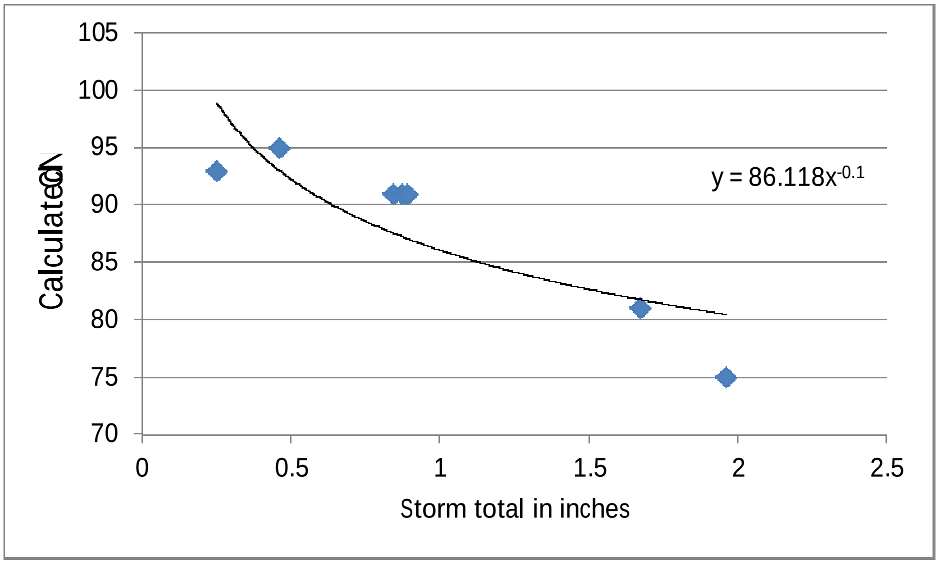

Figure 56. Curve numbers variation with storm size for the detention pond.

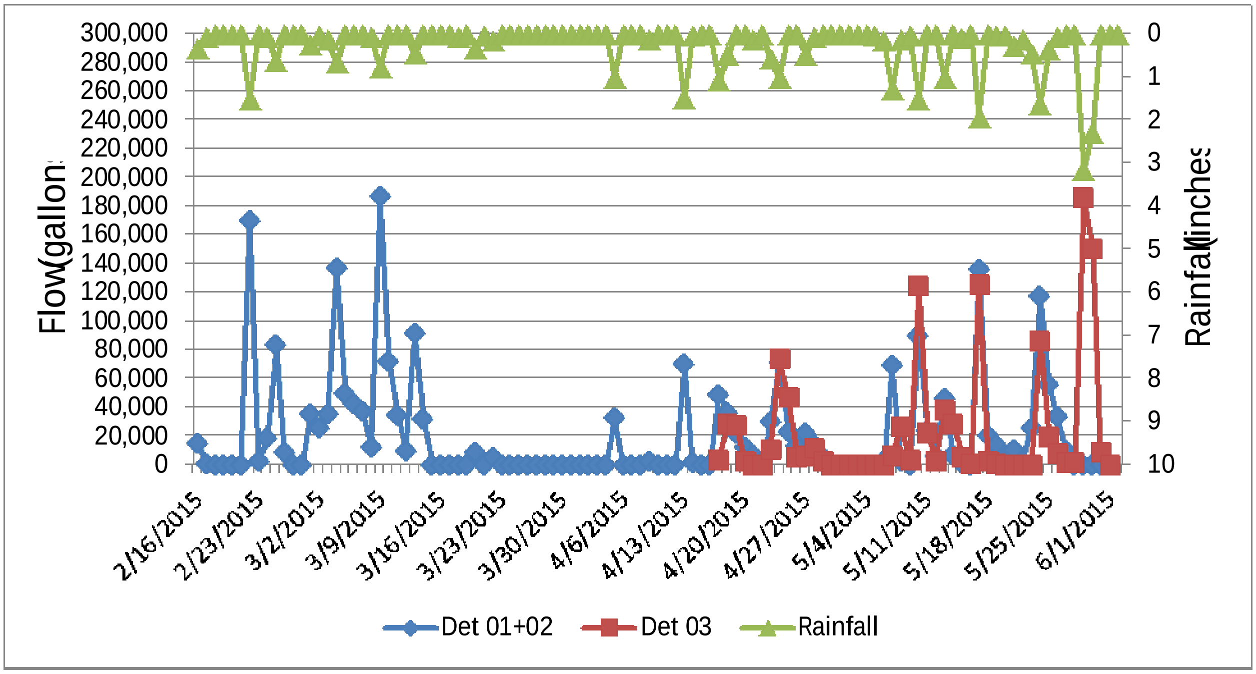

Figure 57. Inflow and outflow volume in the detention pond from February to May 2015.

Table 9. Average concentration (mg/L) of the inflow into the northern branch of the detention pond.

POllutant	Inflow
pH	7.64
EC (mS/cm)	90
NO3	2.22
Orthophosphate	0.11
TSS	15.91
E. coli (Count/100ml)	930

Table 10. Total load (mg) in the inflow into the detention pond during the project period.

Pollutant	Inflow
NO3	1,233,489
Orthophosphate	61,119
TSS	8,840,010
E. coli (cfu)	516,732,180

From February 2015 to the end of May 2015, flow was reduced by 62%, nitrate by 91%, TSS by 18%, and *E. coli* by 81%. No orthophosphate was found in the inflow or outflow during that period.

B. Educational programming

Since the construction of this project BMPs, several educational programs have been offered to various groups and individuals that have requested to visit. In addition several formal half day workshops were organized to educate the public. In the final report of contract 582-10-90469 we reported the presentation of five workshops that totaled 22 hours and were attended by 219 attendants. As part of this contract, 2 workshops were offered that were 4 hours each. The first was entitled permeable pavement and green roofs and was attended by 35 people. The second workshop was attended by 29 people and was entitled Bioretention areas (Rain Gardens and Retention Ponds). The attendees were consulting engineers, contractors, city and agency employees and a few Master Gardeners. 100% of the attendees that returned surveys reported increase in knowledge. In addition we have hosted tours for institutions such as the NRCS, EPA, and visiting scholars from within and outside the country.

VI. Discussion

This project provides the first performance evaluation of LID practices in the Blackland Prairie region of Texas. Performance data published previously from other regions in the US needed to be validated for Texas and the region’s ecosystem, soils and weather patterns before being used as non-point source pollution reduction measures in urban areas. The 3 year project included periods for design, periods for construction as well as periods for data collection and measurements. The project was not without its challenges. Despite donations in material and labor for the project and an engineer’s estimate within the project budget, all construction bids were double to triple the engineer’s estimate. This was probably due to the lack of expertise from contractors in the field of LID construction. A reasonable bid by a Texas A&M AgriLife sole provider was later accepted and with help from the Texas A&M AgriLife ($90,000), the project was constructed.

Additional challenges were encountered when contractors that originally committed to installing donated pervious concrete and pervious asphalt retracted their offers and we were not able to find a replacement. The treatments for permeable parking material were reduced to 3 from 5.

Also, like any data monitoring project, equipment malfunction and other factors contributed to missing data during the monitoring period. Interpolation techniques described in the methods and results sections above were used to estimate missing data.

Overall, this project did provide 3 years data for large scale green infrastructure applications in Texas and in the challenging Blackland Prairie soils. Details of the performance of the green infrastructure practices are detailed below.

A. BMP Performance

a) Permeable Pavement

Results from the grass pavers the permeable interlocking concrete pavers, gravel pavers and porous concrete were obtained and compared to the impervious concrete. Outflow volume was reduced by 75-84% among all types of impervious pavers. High pH was common among all treatments and the control. This was probably caused by the expanded shale in the grass pavers and the high pH of concrete. Both treatments had volume reduction around 65%. The treatments were mainly efficient in reducing TSS, *E. coli* and nitrate. Orthophosphate was added to the system by all treatments with the grass pavers and the gravel pavers had the largest contribution. While the percent contribution number appeared high because of the minute amounts found in the control runoff, the orthophosphate concentrations were still low in general from all treatments with only 3 events exceeding 1 mg/Land most events being under 0.2 mg/L. Orthophosphate in the Trinity river main stem ranged from 1 to 2 mg/L on a consistent basis. Permeable pavement is usually constructed to collect runoff from paved areas with a minimum amount of soluble chemicals in the water and TSS is the major target pollutant.

a) Bioretention

The bioretention data showed that runoff volume was reduced by 49% with the majority of the flow coming out as drainage from the perforated pipe. This runoff from the perforated pipe was treated through the bioretention system even if it left the bioretention as drainage. The data shows pollutant reduction rates of 70% for nitrate, 95% for orthophosphate, 90% for total suspended solids and 65% for bacteria. The bioretention provided the highest treatments other than the detention pond and had the highest treatment area/watershed area of all treatments.

b) Green roofs

Green roofs reduced total runoff in similar ways regardless of the type of green roof. The range of volume reduction over the data collection period was from 68-79% as compared to a no-green roof control. While the concentrations for all pollutants were higher than the control concentrations, loads reduction of pollutants were found in all treatments for TSS and no significant nitrate and orthophosphate contribution was recorded. The green roofs did export bacteria in the runoff in the H and SD treatments, while the S treatment reduced bacteria by 89%. In the case of H and SD, the volume reduction from the green roof results in average 485 CFUs per 100 ml for a typical house which is approximately a quarter of the recommended CFU value for stormwater in the TMDL I-plan for the Trinity river.

c) Rainwater Harvesting

The Rainwater Harvesting Site compared different irrigation scheduling regimes with rainwater harvesting methods to a control site without rainwater harvesting. When implementing a typical residential over-irrigation schedule, harvesting rainwater without changing the irrigation schedule resulted in a runoff reduction of 44%. On the other hand, using less water consuming methods such as the ET or SM regimes reduced water used from the barrels. There was a 50% savings in water in both of these treatments. Because of this fact, these two treatments were less effective in reducing runoff (19% for ET and 14% for SM). Most of the runoff in all treatments occurred in the winter season when little or no irrigation was occurring. This indicates that a management approach could be to empty barrels before a predicted storm by the expected rainfall value, as posted by weather forecasting systems (e.g. weather.gov), to reduce runoff even when using water conservation irrigation scheduling.

Water quality also improved as a result of the lower flow rates in rainwater harvesting systems and a reduction in loads for all pollutants except TSS was recorded in all treatments. TSS was not reduced as the highest load of TSS occurred during large storms both of which occurred in the winter when the water conserving treatments (ET and SM) barrels were full. The HO treatment reduced TSS as the barrels were completely or fully empty during all storms due to over-irrigation.

d) Detention pond

As mentioned previously the detention pond captured all the runoff leaving its watershed area (including the rain garden outflow) until April 2015. The design was modified from a wet detention in the fact that it did not have an impermeable layer underneath, a typical design feature of wet detention ponds. During the wet April and May 2015 period when 23 inches of rain fell on the center, the detention pond showed the following results: flow was reduced by 62%, Nitrate by 91%, TSS by 18%, and E. coli by 81%. No orthophosphate was found in the inflow or outflow during that period.

B. Education and Outreach

The educational programming that was provided by this project coincided with an increased awareness by the cities and the water resources community about LID practices. As a result, the educational programs attracted attendance from the major cities in the DFW area as well as engineers from the main engineering consulting firms. In addition to the events provided, we received requests for tours from various entities such as the city of Dallas Public Works Department, the Texas Watershed Coordinator Round Table, and The City of Fort Worth.

The design and progress of the project was also presented at a variety of conferences such as Texas Water, EPA region 6 MS4 operators conference and the American Society of Biological and Agricultural Engineers (ASABE) annual conferences. A video of the project was also filmed of the project by AgriLife and posted on youtube.com: http://www.youtube.com/watch?v=odl0j8DHuZE

VII. Conclusion

A low impact regional design study was undertaken at the Texas A&M AgriLife Research and Extension Center in Dallas, TX. Five types of BMPs were, designed and constructed. A monitoring plan was developed and installed for each BMP. Volume and water quality data were measured from the end of construction in late 2012 until March 2015. The results show that all the BMPs resulted in volume reduction. The green roofs reduced the volume by a range of 68-79% for the various soil mixes tested. The rainwater harvesting system varied greatly among the different irrigation scheduling methods with water conserving system resulting in volume reduction that ranged from 15- 19% while the high water using treatment reduced runoff volume by 44%. This higher reduction with the over watering schedule was the result of empty rain barrels, an unexpected consequence. Permeable pavement reduced the runoff volume by 65%, while bioretention reduced the runoff by 50%. The detention pond retained all runoff during the testing period.

As for water quality, the bioretention reduced nitrate, orthophosphate, TSS and bacteria the most, while the permeable pavements reduced all pollutants but contributed orthophosphate to the system. Green roofs reduced volume but there was an unexplained significant bacterial contribution from two of the treatments. This was a negative finding which should be addressed in any future green roof construction.

Modifications to typical design have been deduced from this study. It is clear that for rainwater harvesting to be a successful BMP for water conserving irrigations plans, barrels would have to be emptied in expectation of upcoming storms. The detention pond design showed that using a wet pond design without a seal would allow for all retained runoff to infiltrate before the next storm in Dallas' typical weather pattern. In addition, despite the soil being a D hydrologic group, the water completely percolated in less than 2 weeks, including rain from a 2 inch storm except for the exceptionally wet March to May 2015 period when outflow was recorded. This infiltration reduced the potential harboring of mosquito larvae a beneficial outcome. A potential recommendation that needs to be further tested is the reduction of the size of the perforated drainage pipe at the bottom of the bioretention. This pipe released 50% of the inflow on a regular basis. Given that storms were 2 weeks or more apart in general, there is no need for fast drainage of the bioretention. The reduction of the size of the drainage pipe might result in higher runoff retention. This issue should be further investigated.

This project has now provided a set of BMPs that not only reduced the pollution from the Texas A&M AgriLife Research Center in Dallas, but also has become a site for demonstration of various types of BMPs in the DFW area. The educational programming from this project has advertised this site and it will hopefully be a resource on LID practices design, construction and performance in Texas for years to come.

VIII. Acknowledgment

This project would not have been possible without the help of several organizations and individuals. These are the Texas AgriLife Research agency, Belgard, Trinity materials, Alan Plummer associates, Daniel Applegate, Tim Noack, Taner Ozdil, Clint Wolfe, William Hunt, Jack Sinclair Andrew Anderson, Ryan Winston, Justin Mechell, Ryan Gerlich, Brent Clayton, and Bruce Lesikar. I would like to especially mention the team that made this possible at Texas A&M AgriLife, Ms. Michelle Wood-Ramirez, Dr. Sunehali Sharma, Ms. Sandhya Mohan, Dr.. Saed Shannak, and Ms. Angelica Huerta and at TCEQ Mr. Bill Carter and Ms. Faith Hambleton.

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Appendix A: Rainwater harvesting volume estimation

In this model, a mass balance approach was adopted in order to estimate total volumes of water runoff leaving lawn area and total volumes of supplemental water used for irrigation. Change in soil water storage is considered a crucial factor and can be reflected on several other factors such as: volumes of irrigation required, frequency of irrigation, deep percolation, runoff, and supplemental water. Change in soil water storage (? S) for the whole system can be expressed as:

$$? S = I_n - O_t \qquad (1)$$

where:

$? S$ = change in storage (m^3)

I_n= inflow (m^3)

O_t= outflow (m^3)

The inflows to the system (I_n) are represented by: rain falling on lawn area, irrigation applied, and overflow from cistern. I_n can be expressed as:

$$I_n = P+I+O \qquad (2)$$

where:

P = Precipitation (m^3)

I= volume of irrigation applied (m^3)

O= overflow from cistern (m^3)

O is equal to any additional water that exceeds the total volume of cistern size. I varies based on the irrigation scheduling method applied and it is discussed in detail in the following section.

Precipitation was calculated by multiplying rainfall depth by total lawn area.

Total water outflow (O_t) from the whole system accounts for total water runoff leaving lawn area, deep percolation (F) and crop water requirement (D). Crop water requirement is expressed as:

$$D = (ET \times A_p \times K_c) - (P \times A_p) \qquad (3)$$

where:

D= crop water requirement (m^3) for values greater than 0

ET= evapotranspiration (m)

A_p= plot area (m^2)

K_c= crop coefficient (Table 1)

O_t is then expressed as:

$$O_t = RO_p + F + D \quad (4)$$

where:

RO_p= water runoff leaving the plot (m^3)

F= deep percolation (m^3)

Deep percolation (F) was assumed to be any volume of water above field capacity and below water content at saturation and can be expressed as:

$$F = (T \times A_p \times R) - (FC \times A_p \times R) \quad (5)$$

where:

F= deep percolation (m^3)

T= soil moisture above FC (unitless)

FC= field capacity (unitless)

R= depth of root zone (m)

Overflow from cistern (O) was calculated as:

$$O = RO_r + S_{prev.} - S_m - I \quad (6)$$

where:

RO_r= Water runoff from roof (m^3)

S_m= maximum storage capacity of the cistern (m^3)

S_{prev}= storage in cistern from previous day (m^3)

Overflow is considered to be 0 if it is negative..

RO_r is expressed as

$$RO_r = (P \times A_r) \times RC \quad (7)$$

where:

A_r= roof area (m^2)

RC= roof runoff coefficient

To account for potential loss in volume of water harvested by roof and estimate net runoff from a catchment surface; roof runoff coefficient was used. Storage in a cistern was calculated on a daily basis. Volume of rainwater captured and used for irrigation is calculated as:

$$S_c = S_{prev.} + RO_r - I \quad (8)$$

where:

S_c= storage in cistern (m^3)

Total water storage in a cistern cannot exceed the total volume of a cistern and additional water input will result in overflow.

Supplemental water (I_s) is used for irrigation when water in cistern (S_c) is not sufficient to meet crop water requirement at a scheduled irrigation time. I_s can be expressed as:

$$I_s = I - S_c \qquad \text{For } I > S_c \text{ otherwise} = 0 \quad (9)$$

where:

I_s= supplemental irrigation from potable water (m^3)

Total water runoff (RO_p) leaving plot area/ lawn was calculated by applying (SCS Curve Number Method).

$$RO_p = (P + O - I_a)^2 / (P + O - I_a) + S \tag{10}$$

where:

S= potential maximum retention after runoff begins and is expressed as:

$S = (1000 / CN) - 10$, where CN is Curve Number value.
I_a= initial abstraction equal to: $I_a = 0.2 \times S$

The CN method was applied using Antecedent Soil Moisture Conditions (AMC) during growing and dormant Seasons. The growing season for the studied turfgrass falls between April and November, while the dormant season falls between December and March. Soil Conservation Service has defined three antecedent moisture conditions; AMC I, represents dry soil moisture condition but above wilting point, AMC II represents average soil moisture condition, and AMC III represents wet /saturated soil moisture condition (Marek, 2011). These three conditions can be distinguished through antecedent rainfall condition shown in Table A.1. Wet AMC III condition was applied to adjust the value of CN if the depth of rainfall or volume of irrigation applied for the last five previous days exceeded 2 inch or 53 mm for the growing season stage and 1 in. or 28 mm during the dormant season. Average AMC II condition was applied if the condition of the wet AMC III does not apply (Marek, 2011).

CN value can be adjusted from average condition to dry and wet conditions by applying the following equations (Marek, 2011).

$$CN_{III} = \frac{23 CN_{II}}{10 + 0.13 CN_{II}} \tag{11}$$

$$CN_{I} = \frac{4.2 CN_{II}}{10 - 0.058 CN_{II}} \tag{12}$$

Another condition was added to balance the model and that is if the summation of rainfall and overflow from cisterns is less or equal to I_a then total runoff equals zero, otherwise it is the calculated value.

Table A.1. Rainfall Groups for Antecedent Soil Moisture Conditions during Growing and Dormant Seasons (Marek, 2011)

Antecedent Condition	**Description**	**Growing Season**	**Dormant Season**
		5-Day Antecedent Rainfall	**5-Day Antecedent Rainfall**
Dry AMC I	An optimum condition of watershed soils, where soils are dry but not to the wilting point, and when satisfactory plowing or cultivation takes pace	Less than 1.4 in. or 35 mm	Less than 0.05 in. or 12 mm
Average AMC II	The average case for annual floods	1.4 in. to 2 in. or 35 to 53 mm	0.5 to 1 in. or 12 to 28 mm
Wet AMC III	When a heavy rainfall, or light rainfall and low temperatures, have occurred during the five days previous to a given storm	Over 2 in. or 53mm	Over 1 in. or 28 mm

The volume of irrigation applied was calculated based on an assumed depletion ratio. This value represents the percentage of total available soil water which may be safely depleted before irrigation water is applied again. The depletion ratio is a function of crop as well as evaporation (Allen et al., 1998). A value of 0.75 depletion ratio was used in this study. As a result the total irrigation volume was calculated as the difference between the minimum water content (IWC_{min}) and the maximum water content for irrigation (IWC_{max}). IWC_{min} (in depth units) can be expressed as:

$$IWC_{min} = PWP + ((1-DR)/2 \times AWC) \times R \qquad (13)$$

where:

PWP = permanent wilting point (unitless)

DR = depletion ratio (%)

AWC= soil available water content (unitless)

R= depth of root zone (in)

and IWC_{max} can be expressed as:

$$IWC_{max} = IWC_{min} + (DR \times TAWC \times R) \quad (14)$$

where: TAWC= total available water content as a fraction of total soil depth

FC – PWP), where PWP is permanent wilting point.

Figure A.1 provides a graphical explanation of the terms in equations 13 and 14.

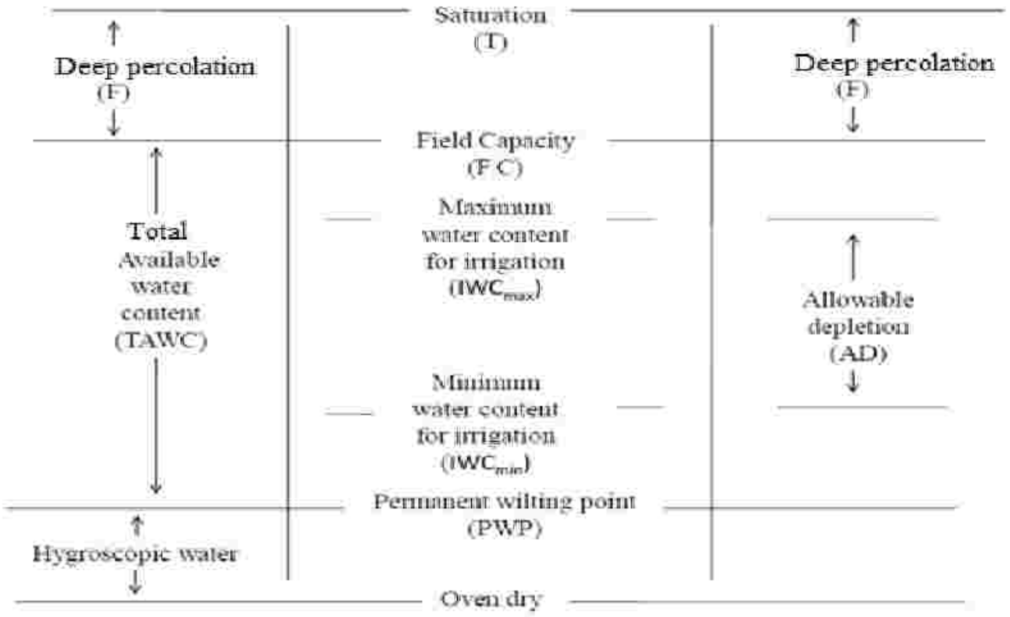

Figure A.1. Soil water profile

Soil Available Water Content (AWC) was estimated in Equation 15 below and if AWC is greater than FC value then the AWC will be equal to the FC value, otherwise it will be the calculated value.

$$AWC = AWC_{prev.} - D + (P \times A_p) + O - RO_p \tag{15}$$

where:

AWC= soil available water content (m^3)

$AWC_{prev.}$= available water content from previous day (m^3)

Soil hydraulic properties used for the various soil types in this study are described in Table A.2.

Table A.2. Soil hydraulic properties considered as an input data in the simulation.

Parameter/ Soil Type	**Sand**	**Sandy Loam**	**Loamy Sand**	**Silty Clay**
Field capacity (%)	0.1	0.18	0.12	0.41
Permanent witling point (%)	0.04	0.08	0.05	0.28
Available water content (%)	0.06	0.10	0.07	0.14
Saturation (%)	0.45	0.46	0.47	0.54
Free drainage (%)	0.35	0.28	0.35	0.13
Curve Number for lawns, good condition	55	71	65	80

The following initial and boundary conditions were used in this study. The initial overflow from the cistern was assumed to equal zero, while the initial cumulative storage in the cistern equals to the volume capacity size of cistern. In other words, the initial irrigation event was made by considering full water storage in the cistern. If the cistern storage size is less than the irrigation requirements and irrigation is to occur, then potable water is added to complement the difference between irrigation required and current cistern storage volume (Equation 9). Furthermore, if the volume of runoff from roof plus the initial volume of the cistern is greater than the maximum storage capacity of the cistern, then overflow from the cistern occurs (Equation 6).

Irrigation scheduling method

Irrigation starts and shuts off based on factors that were measured, assumed or estimated. In this study three irrigation scheduling methods were simulated on the plots: soil moisture- based, ET-based, and time-based irrigation (typical homeowner).

Soil moisture-based irrigation: This method uses feedbacks based on soil moisture conditions measured onsite with one or more soil moisture sensors. An appropriate volume of irrigation to is applied when needed to maintain adequate soil moisture levels (Muñoz-Carpena and Dukes, 2005).

ET- based irrigation: Evapotranspiration (ET), defined as the evaporation from the soil surface and the transpiration through plant canopies (Allen et al., 1998). This method triggers irrigation automatically based on historical or daily ET data (CIMIS, 2011).

Time-based /homeowner irrigation: This method accounts for applying water based on time regardless plant water requirements and soil moisture conditions. The user would assign irrigation events ahead of time for a certain week or month with a certain frequency and a known period of time for each event.

The control plot follows typical homeowner schedule using city water for irrigation.

For a soil moisture-based irrigation treatment, irrigation event would occur if soil AWC is less than or equal to IWC_{max} and the volume of irrigation applied is going to be the difference between IWC_{max} and current AWC (Equation 16). If AWC value is greater than IWC_{max} then no irrigation is applied (Equation 17).

$$I_s = IWC_{max} - AWC \quad \text{for all AWC values} = IWC_{max} \tag{16}$$

$$I_s = 0 \quad \text{for all AWC values} > IWC_{max} \tag{17}$$

where:

I_s = volume of irrigation applied based on soil moisture irrigation scheduling method.

For ET-based irrigation treatment, four steps were done to estimate volume of water applied. First, published ET data and crop coefficients were utilized to calculate daily irrigation requirements (ETc):

$ETc = ET_0 \times Kc$ (18)

where:

ET_c = crop evapotranspiration

ET_o = rate of evapotranspiration from a reference surface that is not short of water

Kc= crop coefficient that represents crop type, variety and development stage that needs to be considered as well (Allen et al., 1998) (Table 1).

Second, irrigation intervals (V) were calculated to find out how often irrigation should take place:

$V= IWC_{min} / ET_c$ (19)

Third, daily Soil AWC (AWC_m) within soil profile in respect to ET losses (in depth units) was expressed as:

AWC_m= FC for all $(AWC_{mprev.}-ET_c+I_{ET})+ ((P_{prev.}\times A_p)+O_{prev.}-RO_p) > FC$ otherwise,

$AWC_m= (AWC_{mprev.}-ET_c+I_{ET})+((P_{prev.}\times A_p)+ O_{prev.}- RO_p))$ (20)

where:

AWC_m = monitored soil available water content

$AWC_{mprev.}$ = AWC_m from previous day

I_{ET} = irrigation based on ET irrigation scheduling method

P_{prev} = precipitation from previous day

The initial condition of AWC_m was set to equal IWC_{max}.

Note that if $(AWC_{mprev.}-ET_c+I_{ET} < 0$ then $AWC_m= 0)$

Fourth, the volume of irrigation applied based on ET (I_{ET}) is expressed as:

I_{ET} = FC- PWP for all AWC = 0 OR $AWC_m<=IWC_{min}$ otherwise, $I_{ET} = 0$ (21)

For the time-based irrigation scheduling / homeowner method, frequency of irrigation came to simulate most common practices in the Dallas/Fort Worth area and assumed to be as in Table A.3 This schedule was developed based on personal communications with DFW water conservation specialists for various cities and agencies.

Table A.3. Frequency of irrigation when utilizing time-based irrigation method.

Month	**Frequency of irrigation**
Jan –Feb	Biweekly
March	Weekly
April –May	Once every three days
Jun-Aug	Daily
Sep	Once every two days
Oct	Weekly
Nov-Dec	Biweekly

Volume of irrigation applied based on time- irrigation scheduling method was defined as the difference between IWC_{max} and IWC_{min}.

$$I_T = (IWC_{max} - IWC_{min}) \times A_p \qquad (22)$$

where: I_T= volume of irrigation applied based on time-based irrigation scheduling method (in volume units)

The percentage of water runoff and supplemental water reduction was measured in respect to a control treatment that does not utilize a cistern as follows:

$$Re = \frac{C - T}{T} \times 100\% \qquad (23)$$

where:

Re= reduction (%)

C= control

T= treatment

Appendix B: Annualized Load Reductions

Bioretention	2013			2014-15		
	inflow	outflow	% Reduction	inflow	outflow	Reduction %
NO3 (lb)	0.141	0.016	88.65	0.042	0.017	59.52
Ortho P (lb)	0.026	0.001	96.15	0.018	0.0001	99.44
TSS (lb)	6.31	0.311	95.07	12.59	0.51	95.95

Green Roofs	2013					
	Control	H	% red	S	% red	SD	% red
NO3 (lb)	0.0001	0.000071	29	0.000087	13	0.000068	32
Ortho P (lb)	0.000015	0.000027	-80	2.7E-06	82	0.00000628	58.13333
TSS (lb)	0.0016	0.0006	62.5	0.0006	62.5	0.0008	50
Green Roofs	2014-15						
	Control	H	% red	S	% red	SD	% red
NO3 (lb)	0.000081	0.00011	-35.8025	0.00014	-72.8395	0.00013	-60.4938
Ortho P (lb)	0.000042	0.00012	-185.714	0.0000154	63.33333	0.0000341	18.80952
TSS (lb)	0.0012	0.0009	25	0.00018	85	0.0003	75

Parking Lots	2013				
	Control	Grass pavers	% red	PICP	% red
NO3 (lb)	0.0006	0.00	66.66667	0.0004	33.33
Ortho P (lb)	0.000004	0.00	65	0.000007	-75.00
TSS	0.12	0.00	96.66667	0.0183	84.75
Parking Lots	2013				
	Control	Gravel paver	% red	Por conc	% red
NO3 (lb)	0.0006	0.001	-83.33	0.00	50
Ortho P (lb)	0.000004	0.00	-1225.00	0.00	0
TSS	0.12	0.03	74.17	0.03	77.5
Parking Lots	2014-15				
	Control	Grass pavers	% red	PICP	% red
NO3 (lb)	0.0004	0.000076	81	0.00015	62.5
Ortho P (lb)	0	0.00005	0	0	0
TSS	0.035	0.004	88.57143	0.004	88.57143
Parking Lots	2014-15				
	Control	Gravel paver	% red	Por conc	% red
NO3 (lb)	0.0004	0.0004	0	0.00016	60
Ortho P (lb)	0	0.000019	0	0.00000053	0
TSS	0.035	0.011	68.57143	0.005	85.71429