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FINAL REPORT

ALTERNATIVE STORMWATER COMPLIANCE APPROACHES ON GDOT RIGHT-OF-WAY

OFFICE OF PERFORMANCE-BASED MANAGEMENT AND RESEARCH

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16. Abstract

The objectives of this study were to evaluate the field performance of stormwater best management practices (BMPs) and perform a statistical analysis on the impact of dimensions of sand filter BMPs on contaminant treatment. Some of the pertinent conclusions from this study are: (1) the combination dry swale/sand filter successfully treated turbidity, total suspended solids, total dissolved solids, some nutrients, and some heavy metals (zinc); (2) the bioretention basin showed removal percentages of > ~60% for solids, nutrients, and metals; (3) statistical analysis of the performance of sand filters demonstrated that sand filters are highly effective at solids, turbidity, some metal and total phosphorus removal, but less effective at removing dissolved constituents; and (4) it is recommended that the GDOT BMP selection flowchart include BMP longevity as a factor, as well as differentiate between short/intermediate term and long term maintenance burden.

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GDOT Research Project 14-03

Final Report

ALTERNATIVE STORMWATER COMPLIANCE APPROACHES ON GDOT RIGHT-OF-WAY

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Georgia Tech Research Corporation

Contract with
Georgia Department of Transportation

In cooperation with
U.S. Department of Transportation
Federal Highway Administration

June 2019

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

A variety of stormwater Best Management Practices (BMPs) are being used throughout the United States to naturally attenuate contaminated stormwater runoff. Because each BMP has its own specific characteristics and application, any one BMP may not be applicable to all locations and conditions, which makes selecting the optimum BMP for a given site and suite of stormwater contaminants somewhat challenging. The most common complication in selection is optimizing pollutant removal while minimizing right-of-way acquisition. The Department's MS4 permit requires that a "stormwater management system shall be designed to retain up to the first 2.54 cm (1.0 in) of rainfall on the site, to the maximum extent practicable" and if that is not feasible, the remaining runoff must be treated to 80% total suspended solids (TSS) removal, which is taken as a surrogate for other contaminants that are found in stormwater, such as nutrients and heavy metals.

The work performed in this study investigated the field performance of two functioning BMPs: a dry swale/sand filter in Forsyth County, GA and a bioretention basin in Bartow County, GA, as well as a series of steep slopes in the coastal plain region of Georgia (Skidaway Island). During stormwater runoff events, both BMPs demonstrated pronounced first flush peak concentrations, with reduction in the inflow contaminant levels within one hour of stormwater flow. The combination dry swale / sand filter successfully treated turbidity, total suspended solids, total dissolved solids, some nutrients, and some heavy metals. The bioretention basin also successfully treated contaminants and showed better performance in the removal of nutrients when compared

to the sand filter. The impact of high slope angles on the concentrations of nutrients was monitored in the coastal plain hydrogeology, and analysis of surface water samples for total inorganic nitrogen (TIN) revealed that the concentration of TIN measured in surface water samples taken at the base of the slopes increased as slope angle was increased, indicating that removal percentages for nutrients may be negatively impacted by steeper slope angles.

An in-depth statistical analysis of the performance of sand filters, based on an extensive database collected at the GDOT sand filter in Canton, GA and data drawn from the International Stormwater Database demonstrated that optimization of BMP dimensions for contaminant removal is a complex, multi-constrained problem. Dimensions that were optimized for metal removal did not perform as well for solids removal, and vice-versa; consequently, selection criteria based on optimized BMP dimensions is not feasible at this point in time, due to the complexity of other factors such as regional hydrogeology and precipitation events. Based on the concentrations of heavy metals, zinc (Zn) was the most abundant in stormwater runoff (mean 126.8 μg/L), followed by copper (Cu), and lead (Pb). The ratio of mean dissolved to mean total concentration of the pollutants suggests that mitigating the pollution caused by different contaminants would require treatment of both suspended and dissolved solids. In sand filters, mitigation of zinc and phosphorus requires treatment of dissolved pollutants, while mitigation of copper and lead could be treated by removing suspended solids.

Finally, it is recommended that the selection criteria flowchart for BMPs on GDOT right-of-way be expanded to include criteria for longevity, as well as distinction between short/intermediate term maintenance versus long term maintenance burden.

CHAPTER 1. INTRODUCTION

Within recent decades, the Georgia Department of Transportation (GDOT) has been using a variety of permanent stormwater retention/treatment structures, known as high-performance best management practices (BMPs) on right-of-way throughout the State. Typically, the structures are designed for both hydraulic control and for contaminant removal. However, the dimensions of the most commonly implemented BMPs are specified by existing standards, leaving the engineer with limited alternatives in the design and construction of these devices. For example, the Georgia Stormwater Management Manual (i.e., the Blue Book) specifies a maximum slope of 6% on swale-type BMPs constructed for solids removal. This mild slope specification results in strict requirements on the associated right-of-way required along the roadway.

Regulation of post-construction pollutants and their mitigation is controlled by the Department's municipal separate storm sewer system (MS4) permit, which specifies requirements for removal of total suspended solids (TSS), for detention of runoff volume, and for mitigation of overland flow. While the current designs for BMPs specified on GDOT right-of-way are functioning well, this research proposes to monitor if the design of the most currently implemented BMPs could be optimized to reduce the cost of right-of-way acquisition, while still maintaining the required environmental protection.

According to the National Water Quality Inventory Report (US EPA, 2009), an assessment of 5.7 million km of rivers and streams [representing 16% of the total in the US] revealed that 44% were found to be impaired, i.e., not able to support one or more of its designated uses. The most common sources of impairment include runoff from agricultural activities, hydro-modification, habitat alteration, unspecified non-point sources, atmospheric deposition, and urban runoff from stormwater (US EPA, 2009). According to the water quality assessment report for Georgia (US EPA, 2010), for the 19% of the total rivers and streams [112,896 km] that were assessed, 58% were found to be impaired. In all the impaired rivers and streams, the pollutant contribution from non-point sources was highest at 68%, while urban stormwater related runoff contributions to the impairment was second highest, at 25.3%. For GDOT to maintain runoff water-quality by limiting contaminant discharge to receiving waters, understanding the components of runoff originating from highway surfaces in Georgia and the performance of stormwater BMPs to date is important. Therefore, designing and building physically and economically effective solutions to treat pollutants in the highway runoff before they discharge into receiving waters is paramount.

Two of the major questions required to assess the efficiency of any BMP in attaining water quality goals (US EPA 2002) are: (1) How varied is the degree of pollution control performance, i.e., effluent quality, provided by the BMP from pollutant to pollutant? (2) How is stormwater volume mitigated? Hydraulic control is relatively straightforward; however, for contaminants, stormwater runoff contains a variety of pollutants that can impact the quality of receiving waters and some parameters may even be site specific (US EPA 2002). Pollutants may be divided into three basic categories which are useful to assess the efficacy of BMP structures: (1) physical characteristics like temperature, pH, conductivity, etc.; (2) concentration of heavy metals (e.g., lead, copper, etc.); and (3) nutrient loadings (e.g., nitrates, nitrites, phosphates, etc., which impact aquatic life quality).

This project will provide data and a summary of knowledge that allows for modification of the GDOT drainage manual to serve two critical Department needs: (1) selection criteria specified to implement low maintenance BMPs in order to reduce the long term burden on upkeep, and (2) design parameters optimized for design and construction in transportation right-of-way (as opposed to parameters that were optimized for applications with site development criteria).

This project work plan will include:

> (1) A comprehensive literature review to examine the factors that control contaminant removal in a variety of optimized stormwater structures. This will include all factors that act to increase, or decrease, contaminant removal in the BMPs that are commonly specified on GDOT right-of-way.
>
> (2) Performance at three field sites to assess contaminant removal under optimized BMP dimensions with statistical analysis of performance data and comparison to data from the International Stormwater BMP Database.
>
> (3) Statewide guidance for design conditions to optimize contaminant removal, while minimizing right-of-way acquisition for construction of stormwater BMPs, with specific emphasis on refining GDOT specific stormwater parameters for design.

CHAPTER 2. LITERATURE REVIEW

A variety of stormwater BMPs are being used throughout the United States to naturally attenuate contaminated stormwater runoff. Because each BMP has its own specific characteristics and application, any one BMP may not be applicable to all locations and conditions. This tends to make selecting the optimum BMP for a given site and suite of stormwater contaminants somewhat challenging. The current practice is to use selection matrices published in various state DOT manuals to facilitate the selection of an adequate BMP for a particular application. The most common complication is having the desire to optimize pollutant removal while minimizing right-of-way acquisition (Wang et al., 2009). Methods of comparing and balancing these variables have been investigated (Bhatt, 2016), which laid the foundation for implementation of the Analytical Hierarchy Process (AHP), developed by Saaty et al. (1980) and Young (2010). AHP is a hierarchical technique for organizing and analyzing complex decisions, which can be applied to the complex decisions such as development and placement of BMPs.

The Department's MS4 permit (2017) requires that a "stormwater management system shall be designed to retain up to the first 2.54 cm (1.0 in) of rainfall on the site, to the maximum extent practicable" and if that is not feasible, the remaining runoff must be treated to 80% total suspended solids (TSS) removal. Typically, TSS is taken as a surrogate for other contaminants that are found in stormwater, such as nutrients and heavy metals, and treatment for TSS is assumed to reduce those concentrations as well. Previous research (Bhatt, 2016) on specific contaminant removals resulted in the following conclusions regarding the removal performance for highway runoff draining into sand filters (for runoff from GDOT right-of-way into the Canton sand filter): the distribution of most incoming pollutants followed a log normal distribution, implying that the occurrence of extreme contaminant loadings was low, and the historical sand filter data revealed that among nutrients, a majority of the total phosphorus was mitigated by the sand filter whereas neither dissolved phosphorus, total NO_X, nor nitrogen was mitigated. For metals, zinc was mitigated by the sand filter, but copper and lead were not. However, investigation into the mechanisms that contribute to these results is still ongoing.

COMMON BMPS IN USE BY GEORGIA DOT

Bioretention Basins

Bioretention basins are shallow depressions or designed basins used to pool and reduce the velocity of stormwater. Stormwater runoff is drained into the basin, where it is treated through a combination of processes, including infiltration, physical separation, and biological uptake and/or degradation. Overflow runoff from bioretention basins is designed to drain to an additional BMP or into receiving waters. In most instances, pretreatment of stormwater through physical separation is necessary before flow into the bioretention basin, in order to prevent clogging of the drainage media. The basins are most commonly implemented to treat small drainage areas of less than five acres, with ponding depths limited to 0.3 m (1 ft) or less, in order to drain the structure within 12 hours. The GDOT Drainage Manual (section 10.6.7) specifies the maximum ponding volume drain time for GDOT bioretention basins at 24 hours, with the maximum drain time for the entire structure equal to 72 hours.

Bioretention basins are effective at contaminant removal, do not have a large footprint, and can be landscaped for integration into the surrounding areas. Additionally, due to the design of the structure, the basins can be constructed in soils with low hydraulic conductivity, or in areas with impervious cover, such as parking lots. While bioretention basins are effective for contaminant treatment, limitations include their small size, which makes them ineffective for discharge attenuation, as well as their high cost and high level of maintenance.

Recent studies on the performance of bioretention basins have focused on the pollutant removal capacity of bioretention basins in a range of climatic conditions. Removal efficiencies are a function of storm size and antecedent dry days, with high rainfall events resulting in lower pollutant removal in the basin and an increasing number of antecedent dry days increasing nitrate concentrations in the basin (Manganka, et al., 2015). Lucke and Nichols (2015) performed controlled tests in five bioretention basins that had been in operation for ten years. Four synthetic stormwater samples were prepared, with concentrations ranging from no pollutants to five times the expected load. The tested basins attenuated flow and phosphorus, and reduced total nitrogen in the effluent for all cases except the clean water sample. In the case of zero nitrogen in the influent, there was leaching from the basin into the effluent. Lucke and Nichols (2015) also tested the metal and hydrocarbon concentrations accumulated in the filter, and demonstrated the concentrations were below regulatory limits after ten years of operation. Climate and rainfall intensity also impact the removal efficiency of BMPs, because more frequent smaller storms produce a lower event mean concentration and lower concentration in the first flush (Wang et al., 2017). Ninety-six storms were monitored in a tropical climate in Singapore and demonstrated that the limited storage capacity of the tested bioretention basins resulted in overflow and reduced pollutant removal capacity. Basins designed for increased water quality volume and depth would provide better removal performance due to reduction in overflow events (Wang et al., 2017). Hunt et al. (2008) measured performance of an urban bioretention cell in Charlotte, North Carolina from 2004 – 2006. Flow weighted composite samples (23 storms) were used to quantify removal of nutrients, suspended solids, and heavy metals, while grab samples (19 storms) were collected to test for the presence of *Escherichia coli* (*E. coli*). There were measurable decreases in the concentrations of total nitrogen (TN), total Kjeldahl nitrogen (TKN), ammonium (NH_4-N), biochemical oxygen demand (BOD-5), fecal coliform, *E. Coli*, TSS, copper, zinc, and lead, but an increase in the concentration of dissolved iron (330%). Their data also demonstrated that the bioretention basin was effective at reducing peak runoff for small to medium sized storm events (Hunt et al., 2008).

Enhanced Swales

Enhanced swales are vegetated open channels, dry or wet, that are designed with interior cells that control flow and reduce channelized flow velocity with check dams or other similar structures. Swales are constructed on shallow slopes, usually with longitudinal slopes of 4% or less, and bottom widths of 0.6 – 2.4 m (2 to 8 ft), typically. Both dry and wet swales provide runoff reduction and water quality benefits through the settlement of suspended solids and removal of nutrients and metals; however, dry swales demonstrate better removal of contaminants. Yu et al. (2001) tested the field performance of grass swales in northern Virginia and Taiwan to measure pollutant removal efficiency. The efficiency of removal of solids, chemical oxygen demand, total nitrogen, and total phosphorus varied significantly, from 14% removal to 99% removal, and the authors recommend a minimum length of swale of 68.6 m (225 ft) with a 3% longitudinal slope.

Fletcher et al. (2012) performed controlled experiments on grassed swales in Brisbane Australia, with synthetic stormwater as influent. The swales were able to reduce total suspended solids, total nitrogen, and total phosphorus; however, removal efficiency for total suspended solids deceased as the flowrate increased. While grassed swales can remove metals and nutrients, they are most effective at reducing the concentration of suspended solids through sedimentation (Li et al., 2016).

Filter Strips

Filter strips are uniformly sloped, vegetated structures that are designed to treat sheet stormwater flow through filtration of solid particles, infiltration of water into the soil, and by slowing of the flow of runoff. Filter strips have multiple advantages over other BMPs because they are relatively easy to construct, inexpensive, and are easily blended into the surrounding landscape. In addition, they are suitable for a range of site conditions and can be combined with other BMPs to create a treatment train. However, they treat small drainage areas and they do require a large land area, which is especially disadvantageous for the Department as even small additions to right of way can have a large impact on initial cost and maintenance. Filter strips generally provide little control of volume runoff, especially relative to other BMPs, and if not properly maintained, they can erode and concentrate flow.

The Department of Transportation and the Blue Book guidance have recommendations for slopes between 2% and 6%, with the top and the toe of the slope as flat as is feasible. A typical filter strip will be 7.6 to 15.2 m (25 ft to 50 feet) perpendicular to the highway, with the Blue Book recommending a maximum strip of

30.5 m (100 feet) along the treatment direction, i.e. with the length of water flow. The grasses in the filter strip must be able to withstand flows of 1.2 m/second (4 feet per second).

VEGETATED FILTER STRIP PERFORMANCE AS A FUNCTION OF SLOPE

Recent studies of the performance of vegetated filter strips have demonstrated their effectiveness in the reduction of suspended solids and nutrients from the stormwater flow. Robinson et al. (1996) measured the sediment concentration in runoff flowing through a vegetated filter strip as a function of distance, slope, rainfall quantity, and runoff quantity, and showed that filter strips reduce the concentration of suspended solids, with 70% removal occurring in the first 3 m (10 feet) of flow and 85% removal within the first 9 m (30 feet), with little observed reduction in contaminant concentration at lengths greater than 9 m (30 feet). The slope of the filter strip did impact soil loss (or sediment load), with the slope of 12% having increased runoff and soil loss when compared to the slope of 7%. Controlled field tests performed on a grass filter strip in Aberdeen, Scotland and a grass swale in Brisbane, Australia demonstrated that solids content was reduced by approximately 70% at higher slopes, while the Australian tests demonstrated a decrease in nitrogen and phosphorus of approximately 50% (Deletic and Fletcher, 2006). Additional work on the removal of pesticides, nitrogen, and phosphorus from runoff through grass filter strips with lengths ranging from 6 m (20 feet) to 12 m (60 feet) demonstrated 90 – 100% reduction in suspended solids, 40 – 100% reduction in runoff volume, 50 – 100% reduction in nitrate, and 20 – 90% reduction in soluble phosphorus (Patty et al., 1997).

Modeling of the removal of solids and contaminants in a vegetated filter strip has been an area of active research. One of the most sophisticated models, known as VFSMOD-W: Vegetative Filter Strip Modeling System, was developed by Munoz and Carpena (1998) at North Carolina State University and is now maintained at the University of Florida (http://abe.ufl.edu/carpena/vfsmod/). VFSMOD is a finite element solution for overland flow, infiltration, sediment deposition, phosphorus removal (particulate and dissolved), and pesticide removal. The mass balance for removal incorporates runoff, removal of coarse and fine sediments, and infiltration (Figure 1). Field experiments were performed in the Piedmont geology in North Carolina and gave good agreement with model predictions as long as sheet flow was maintained in the filter.

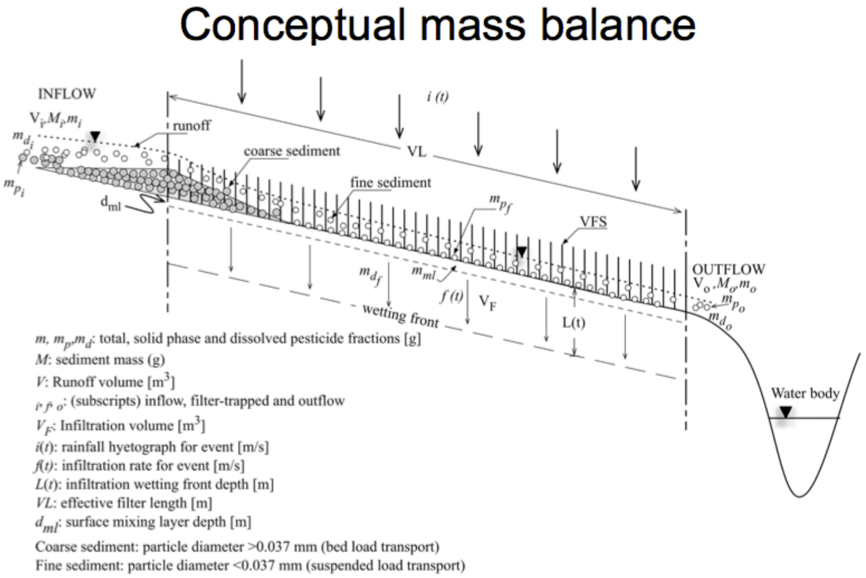


Figure 1. Diagram. Mass balance for flow, infiltration, and deposition in a vegetated filter strip.

(Figure from Munoz and Carpena, abe.ufl.edu/carpena/vfsmod/FOCUS/VFSMOD_Pmassbalance1.ppt).

MAINTENANCE OF STORMWATER BMPS

Maintenance of stormwater BMPs represents a significant long-term cost to GDOT. In order to ensure that a BMP is operating as designed, there are several categories of maintenance that should be performed at regular intervals. The primary types of maintenance include structural, routine, runoff pretreatment, maintenance of conveyance channels, and maintenance of slopes. In terms of structural issues, maintenance includes repairing clogged or broken pipes, repairing missing or broken parts (e.g., valves, seals, manholes), repairing cracked concrete, repairing erosion at outfall or on banks, regrading or dredging, and some landscaping refurbishment. In contrast, routine maintenance is primarily focused on vegetation management such as mowing, removal of vegetative overgrowth and woody plants, replacing dead or diseased landscaping, control of invasive plants, and removal of trash, yard debris, or small amounts of sediment buildup. Runoff pretreatment refers to maintenance of the pretreatment bay by controlling vegetation, sediment, and debris, with similar activities performed for maintenance of conveyance channels and slope maintenance. The GDOT Drainage Manual categorizes the routine maintenance burden for commonly used BMPs as low, medium, or high (Table 1).

Table 1. Stormwater BMP Routine Maintenance Burden (GDOT Drainage Manual).

BMP	**Maintenance Burden**	**Maintenance Tasks**
Filter Strips	Low	• Remove sediments • Maintain vegetation • Inflow/outflow unobstructed • Mow grass •
Grass Channels	Low	
Enhanced Dry Swale	Medium	
Enhanced Wet Swale	Low	
Infiltration Trench	High	
Bioslope	Medium	
Sand Filter	High	
Bioretention Basin	Medium	
Dry Detention Basin	Low	
Wet Detention Pond	Low	
Stormwater Wetlands Level 2	Medium	
Stormwater Wetlands Level 1	Medium	
Open-Graded Friction Course	Low	

Maintenance for slopes is particularly important to ensure contaminant removal efficiency and to reduce erosion. A survey of maximum longitudinal slopes for BMPs in the US demonstrated that the maximum recommended channel slope was generally 4% - 5% but ranged as high as 10% in limited applications in New Jersey (New Jersey Department of Environmental Protection, 2020).

Natural, forested buffers are appealing alternatives for implementation as low cost stormwater BMPs. In general, the primary considerations for good performance of any BMP will include flow path, slope, soil/infiltration, vegetation, and the presence of an organic absorptive zone. The literature on contaminant removal efficiency for forested buffers is scant, but in general, they are limited to low flow applications with gravity drainage in sheet flow but have shown some potential for reduction of nutrients. For applications that rely on grassed buffers or accumulate sediments, similar maintenance burdens will be required.

A comprehensive study of the life cycle costs associated with maintenance of stormwater BMPs was performed by the National Academies (2014) to quantify the economic impact and lifespan of the devices that are currently in place (Table 2 - Table 3). Maintenance activities ranged simple, low cost but high frequency vegetation management to more complex, high cost but low frequency long term maintenance such as sand filter media replacement (Table 2). The limitation on BMP lifespan was sediment accumulation for vegetated strips and swales, and friction courses, and pipe and concrete longevity for detention basins and filters (Table 3). Aside from friction course, the most commonly used BMPs are predicted to function for decades. Guidance on the frequency of BMP maintenance activities was also reported (Table 2).

Table 2. Typical BMP Maintenance Activities and Cost
(Adapted from National Academies of Sciences, Engineering, and Medicine, 2014).

Category	Activity	Frequency	Hours / Staff	Equipment demand	Estimated Cost
Vegetation Management	• Aesthetic repair • Trash and debris removal • Mulch management	3X per year 2X per year 1X per year	4 hours 2 people	Low	$640/event
Interim Maintenance	• Sediment management and removal • Vegetation repair • Erosion/rutting • Slope inspection • Standing water	Every 2 years Every 5 years Every 10 years	8 hours 2 people	Medium *disposal	$1,280/event - $3,800/event
Long Term Maintenance	Sediment management	Every 20 years Every 30 years Every 50 years	8 hours 4 people	High *disposal	$3,800/event - $75,600/event
	Underdrain repair	Every 4 years Every 8 years Every 12 years	24 hours 4 people	High	-
	Sand media replacement	Every 3 years Every 5 years Every 10 years	8 hours 4 people	High *disposal	$3,700/event
Compliance	Inspection/reporting	1X per year	1 hour 2 people	Low	$130/year

Table 3. BMP Expected Life Span
(Table from National Academies of Sciences, Engineering, and Medicine, 2014).

BMP Type	Life Span	Limiting Factor
Vegetated strips	8–60 years (depending on ecoregion)	Sediment accumulation
Vegetated swales	10–50 years (depending on ecoregion)	Sediment accumulation
Dry detention basin	80 years	Pipe material longevity
Bioretention	80 years	Pipe material longevity
Retention pond	80 years	Pipe material longevity
Sand filter	75 years	Concrete longevity
Permeable friction course	14 years	Sediment accumulation

CHAPTER 3. FIELD PERFORMANCE OF THREE GDOT BEST MANAGEMENT PRACTICE (BMP) SITES

Several BMPs were chosen for study with consideration of the type of BMP, location of BMP, and hydrogeology. In the greater metro Atlanta region, the performance of two BMPS were studied: 1) combination dry swale/sand filter and 2) bioretention basin, and in the Coastal Plain, the performance of a series of filter strips were monitored for nutrient impact on surface and groundwater.

BMP FIELD SAMPLING AND TESTING, MATERIALS AND METHODS

For the stormwater monitoring program, three automatic samplers (Sigma 900 MAX PS1 Portable Automatic Sampler) were used. Each automatic sampler was equipped with four one-gallon polyethylene bottles for sample collection. Flow was measured with an integral HACH Sigma Area-Velocity flow meter (#4041) using a pressure transducer for depth of flow measurement and a pair of ultrasonic transducers for velocity measurement. The area-velocity sensors were installed and secured at the base of the tested pipes. In-situ parameters pH, specific conductance (SC), and temperature (T) were measured with an integral pH- temperature probe (Hach, #8793), and integral conductivity probe (Hach, #3227). The three sensors were also securely placed at the base of the pipes to continuously record the three parameters. Rainfall depths at the site were measured with a tipping bucket rain logger (Sigma). In-situ parameters (temperature, conductivity, pH, flow depth and rainfall) were recorded at an interval of 1 minute throughout the duration of an event. The recorded data were transferred to a personal computer using Hach Insight software. Stormwater samples were collected for each sampler using three bottles to capture the first flush for the first 30-45 minutes of the storm. In the fourth bottle, 200 ml grab samples were collected at an interval of 15 minutes for the whole event, or until capacity was reached. Sample collection was automated, and the triggering condition for the initiation of the sample collection was set as 2.5 cm of flow depth. This was selected to ensure that the intake pipe was sufficiently submerged to collect an accurate volume of the sample. The mouth of the intake pipe had a strainer to prevent clogging of the intake pipe, and the samples were collected by a peristaltic pump. The sampler controller was programmed to rinse the intake pipe once before the collection of a sample.

In addition to the in-situ parameters that were recorded continuously, the automatically collected samples were brought from the site to the Geoenvironmental laboratory at the Georgia Institute of Technology within 24 hours (usually within 12 hours) after the completion of sampling program to avoid sample deterioration. The samples were preserved for testing per procedures for different water quality parameters (CFR, 2009). An adequate volume of a sample was passed through a 45μm filter paper and preserved separately to test for dissolved parameter concentrations. The runoff samples were tested for total suspended solids, turbidity, specific conductivity, pH, total dissolved solids, nutrients (total nitrogen, nitrate and nitrite and total phosphorus) and metals (total copper, total lead, total zinc, dissolved copper, dissolved lead, and dissolved zinc). Samples were analyzed for metals using Perkin Elmer Optima 7300 DV Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Nutrients were measured using a Shimadzu UV-1800-Vis Spectrophotometer. All lab ware, sample bottles and intake tubing utilized for testing or collection of samples were rinsed with 1% nitric acid (HNO_3) and de-ionized water (Barnstead, E-pure).

BMP: DRY SWALE WITH SAND FILTER IN FORSYTH COUNTY, GA

Site 1 is located in Forsyth County (at the Gwinnett County border), Georgia on State Road 20 (SR 20), with outfall to the Chattahoochee River (latitude of 34.127489 and longitude -84.094186). The site contains three different dry swale pond BMPs, which drain the bridge and some watershed surrounding SR 20 at the Chattahoochee River. The dry swale that was monitored was located in the north west corner of the SR 20 / Chattahoochee River crossing. Therefore, the purpose of this BMP was to treat the roadway surface runoff before it enters the Chattahoochee River (Figure 2, Table 4).

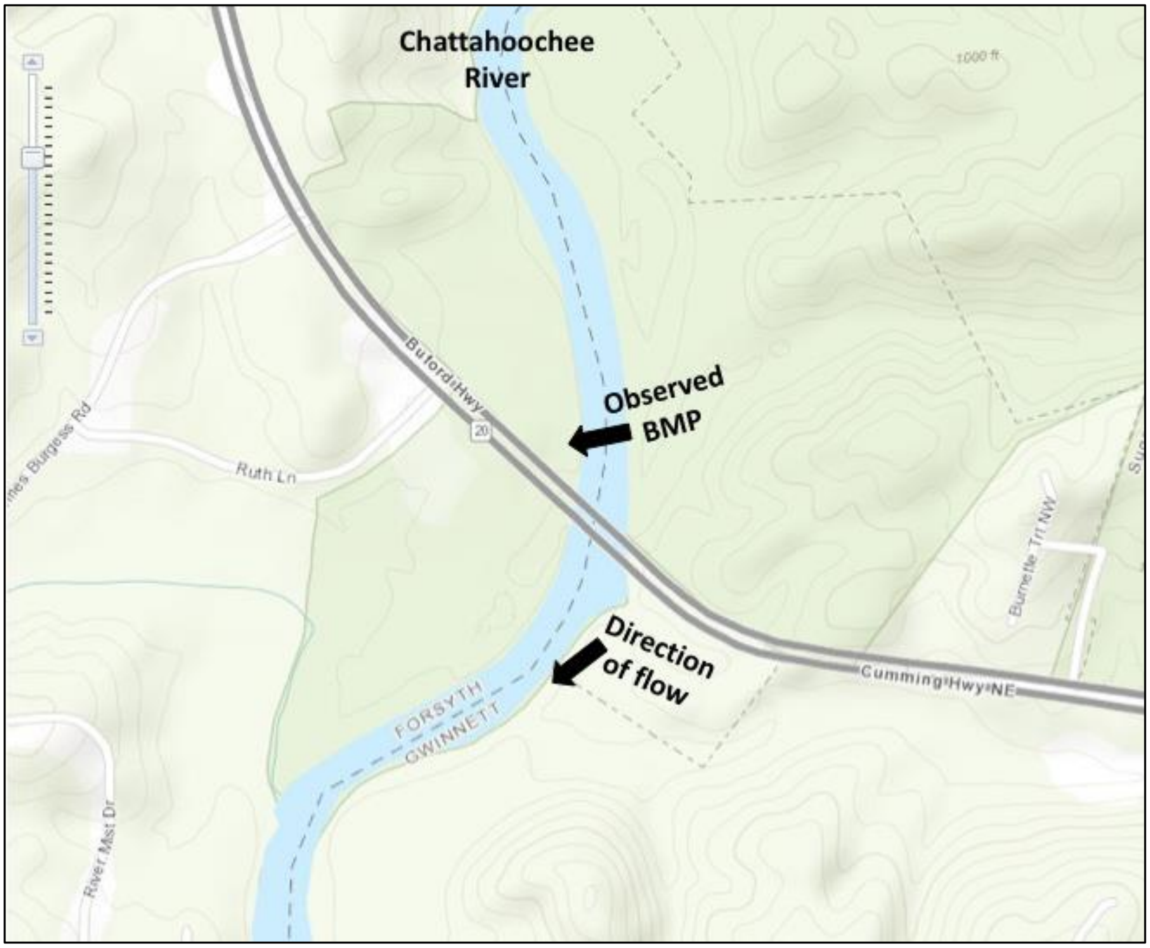


Figure 2. Map. Topographic map of the Cumming GA / BMP location (USGS).

Table 4. Forsyth County, GA Dry Swale/Sand Filter BMP Data.

General Test Site Information	
BMP Test Site Name	SR 20 Dry Swale with Sand Filter
Location	SR 20, Cumming, GA
Elevation at top of bioretention pond	281.6 m (924 ft)
Structural BMP Information	
Structural BMP Name	Dry Swale Pond with Sand Filter
BMP Description	Substantial residence time and storage volume
Treatment Category	Sedimentation, Filtration
Number of Inlets	1
Inlet Description	Concrete spillway w/ rip rap rock filter
Number of Outlets	2
Outlet Descriptions	0.6 m (24 in) storm drain pipe with outlet control structure and an emergency spillway
Catchment Area	2.4 hectare (6.01 acres)
Watershed Stations	
Regional Watershed Name	Upper Chattahoochee
Station	Monitoring stations immediately u/s and d/s of pond
Upstream BMP	None, inflow received directly from SR 113 concrete channel
Downstream BMP	None, effluent discharged to Raccoon Creek

A plan view of this BMP shows the inlet, outlet, and emergency spillway (Figure 3); however, it is important to note that the pre-construction designs went through many variations during construction, and the as built configuration had some variation from the initial design. In the as built configuration, the dry swale pond and sand filter also included a rock filter dam (Figure 4), with the cross-section view of a typical dry swale pond with sand filter (Figure 5). The outlet structure consists of a 15.2 cm (6 in) pipe that brings water into a control structure for gradual release, followed by a 61 cm (24 in) drainpipe that discharges water through a rip rap rock filter to the Chattahoochee River. Monitoring occurred at the inlet concrete spillway (Figure 6) and at the outlet control structure prior to water entering the drain pipe, with sensors positioned to measure water quality during the stormwater runoff period (Figure 7).

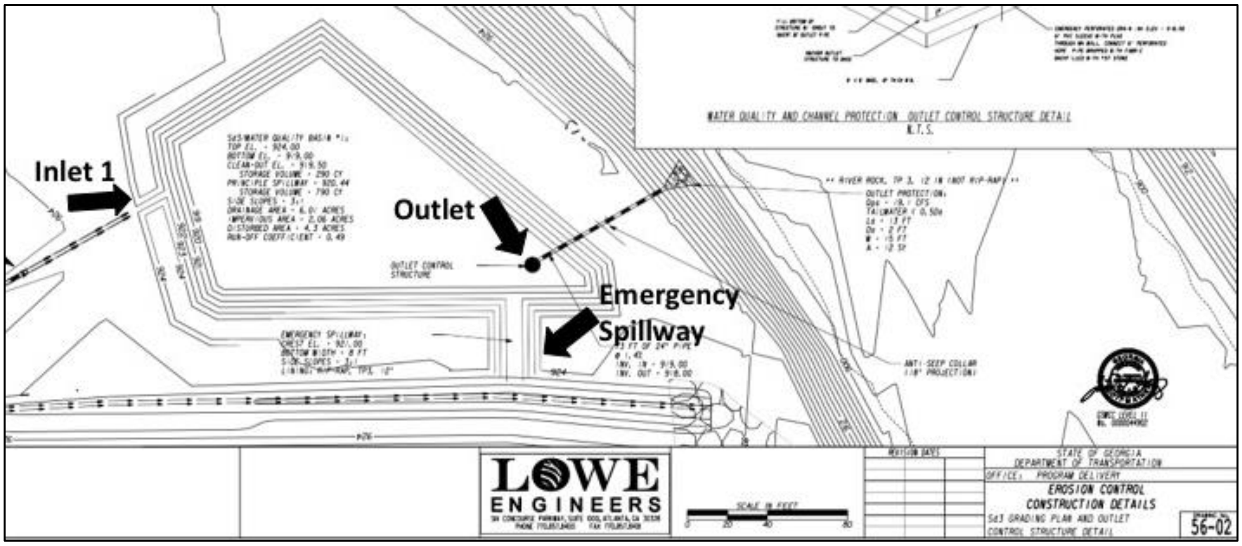


Figure 3. Diagram. Inlet and outlets labeled for the dry swale pond with sand filter.

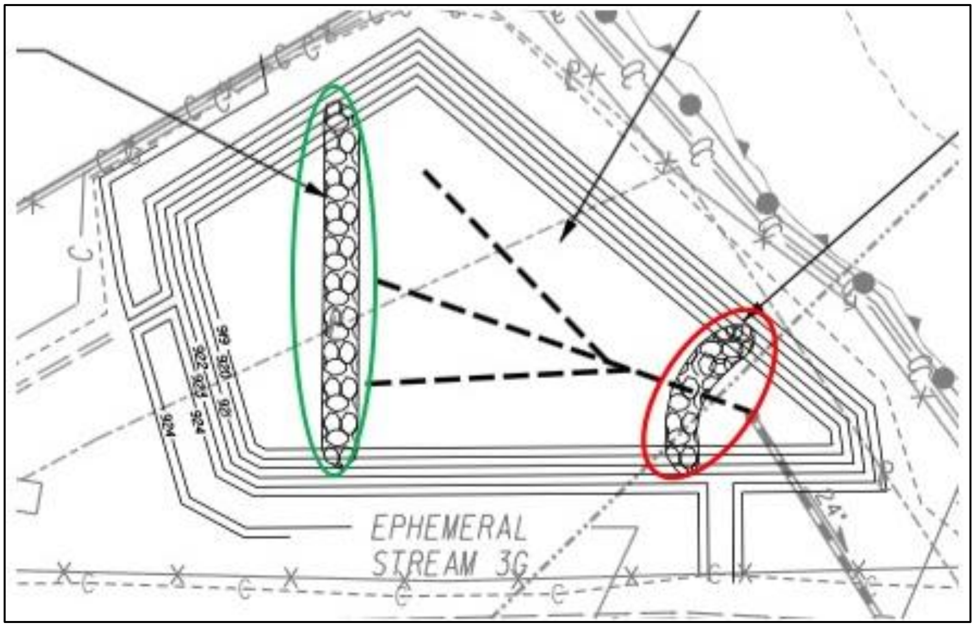


Figure 4. Diagram. Dry swale pond with sand filter showing the rock filter dam (circled in green). The filter ring (circled in red) was removed after construction was completed.

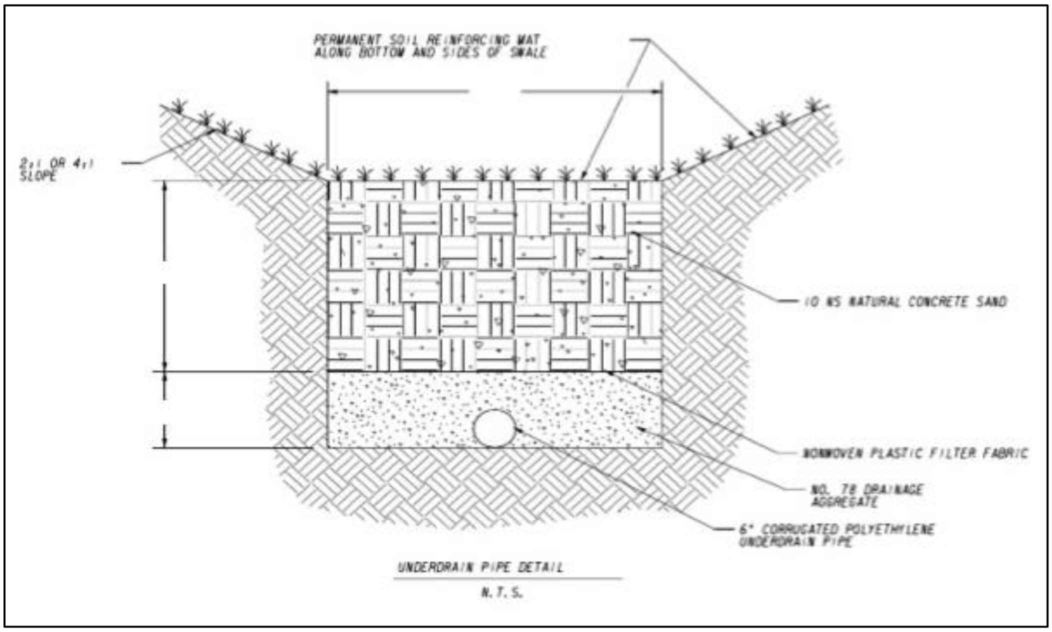


Figure 5. Diagram. Cross-section of the dry swale pond with sand filter.

Figure 6. Photos. Test site (dry swale with a sand filter) at Chattahoochee River.

Figure 7. Photos. Test set-up for stormwater monitoring at BMP inflow and outflow.

Experimental Results

A total of three storm events were monitored (Table 5) with a range of precipitation from 0.3 cm (0.12 in) to 2.9 cm (1.14 in):

Table 5. Summary of Monitored Tests for Dry Swale/Sand Filter, Forsyth County

Test No.	Date	Total Precipitation (cm)	Precipitation Duration (hrs)	Dry Period (Days)	Samples
1	06/22/2018	0.3 (0.12 in)	4	1	Inlet : 2 Outlet: 4
2	02/11/2019	0.7 (0.28 in)	6.5	5	Inlet : 4 Outlet: 4
3	02/19/2019	2.9 (1.14 in)	19	2	Inlet : 4 Outlet: 4

The stormwater samples were collected during the initial phase of runoff to assess the anticipated highest contaminant concentrations flowing into the BMP. For the first test, grab samples were taken at 30 minute intervals after initial flow was detected at the BMP inlet. For all other tests, samples were taken at 15 minute intervals, along with one composite sample that was collected over for the first 4 hours of the storm. Sample results indicated that contaminant levels were the highest in the first flush, and reduced within the first 15 minutes of storm duration (Figure 8 - Figure 17). In almost all tests, the BMP demonstrated characteristic first flush decrease over the 45 minute testing program, with reductions in turbidity, dissolved and suspended solids, copper, lead, zinc, and nutrients.

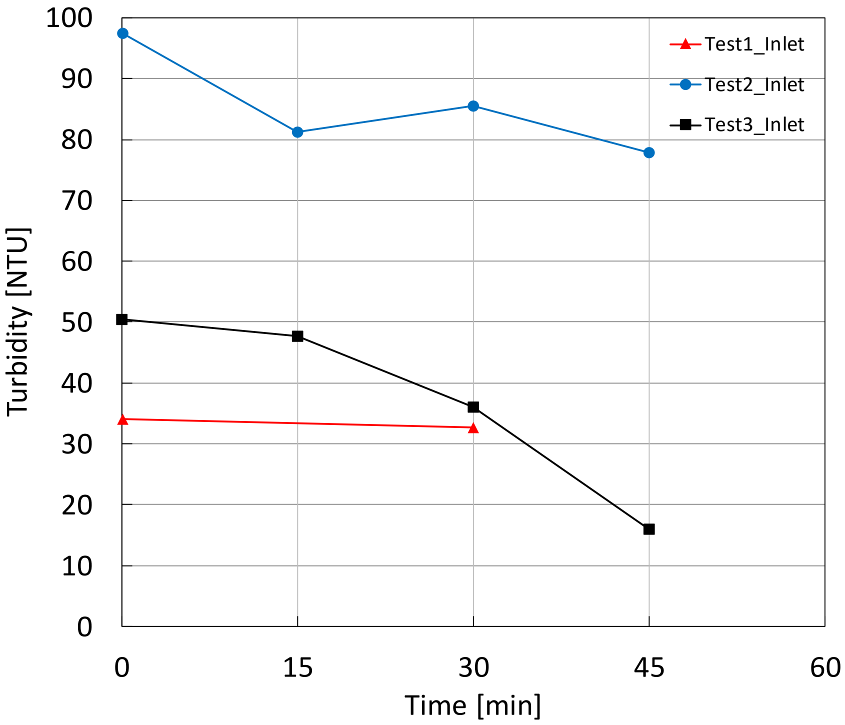


Figure 8. Graph. First flush turbidity at dry swale with a sand filter.

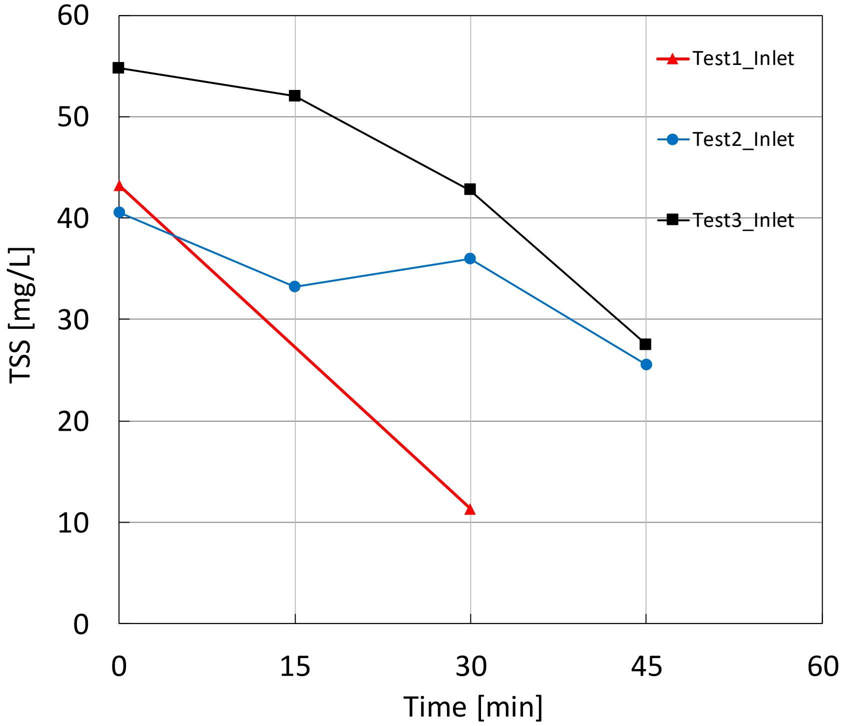


Figure 9. Graph. First flush total suspended solids at dry swale with a sand filter.

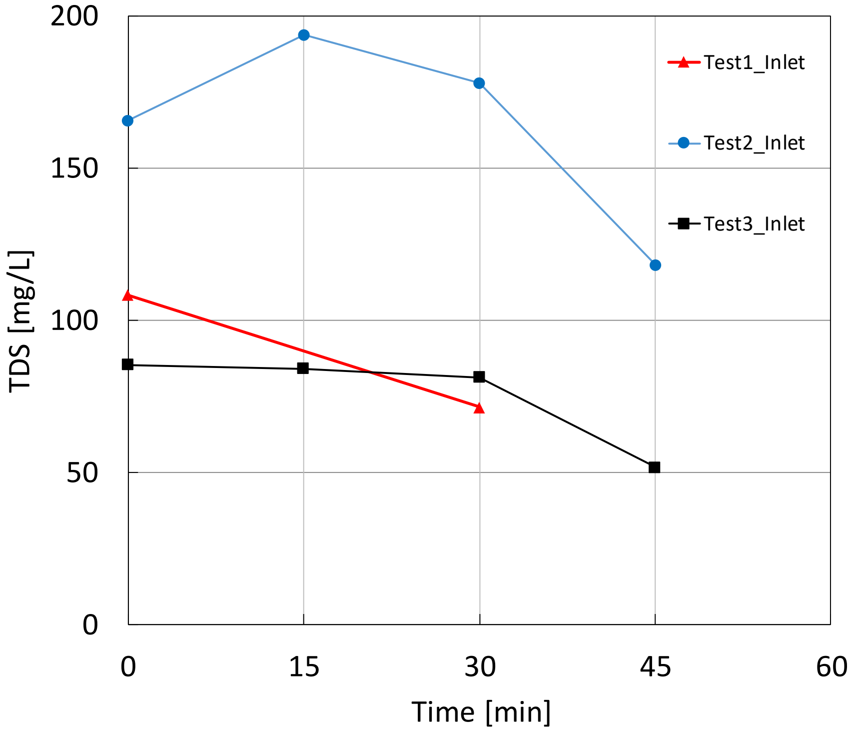


Figure 10. Graph. First flush total dissolved solids at dry swale with a sand filter.

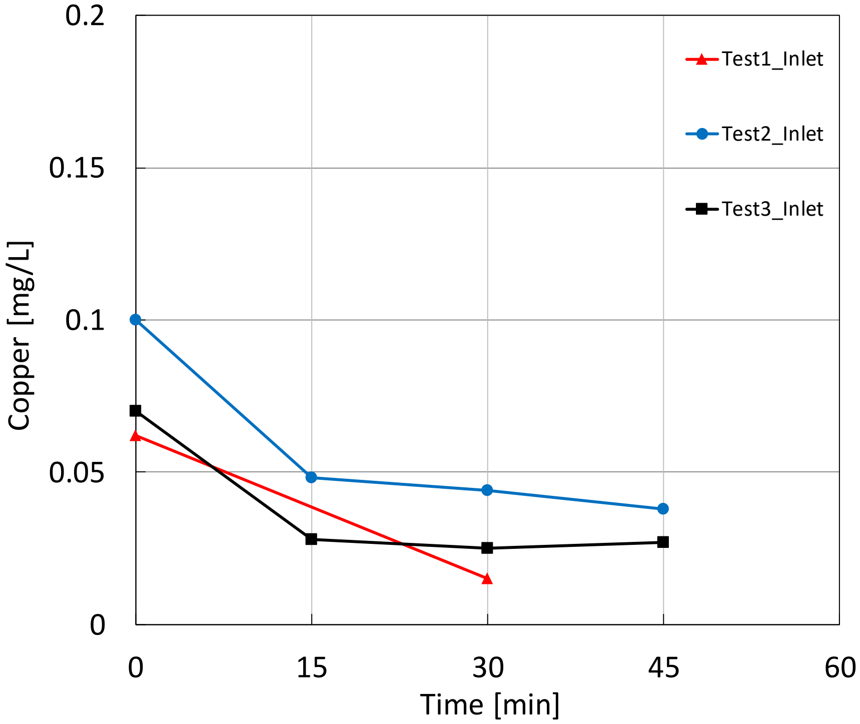


Figure 11. Graph. First flush total copper at dry swale with a sand filter.

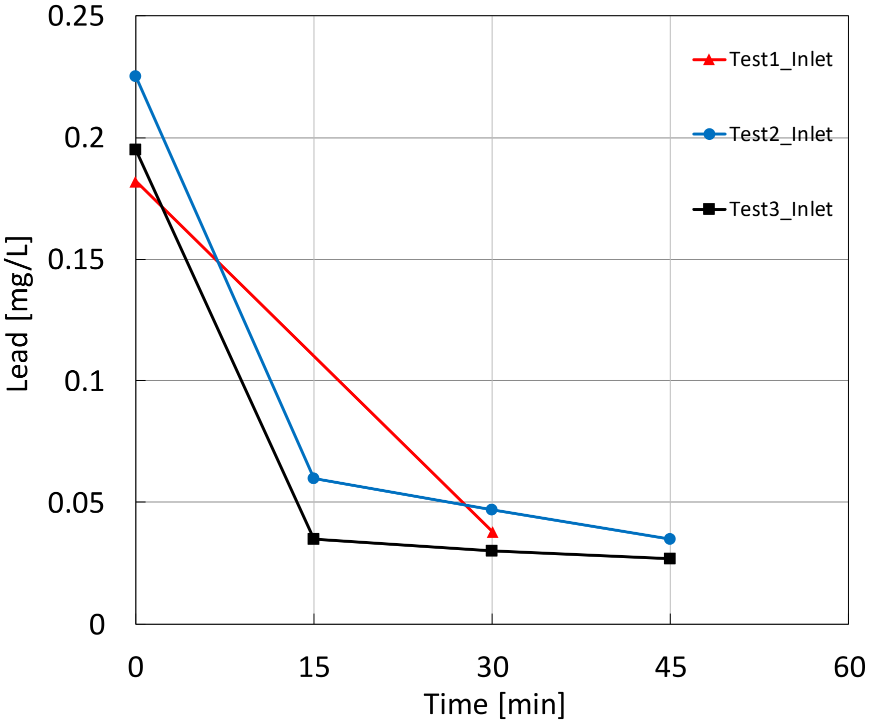


Figure 12. Graph. First flush total lead at dry swale with a sand filter.

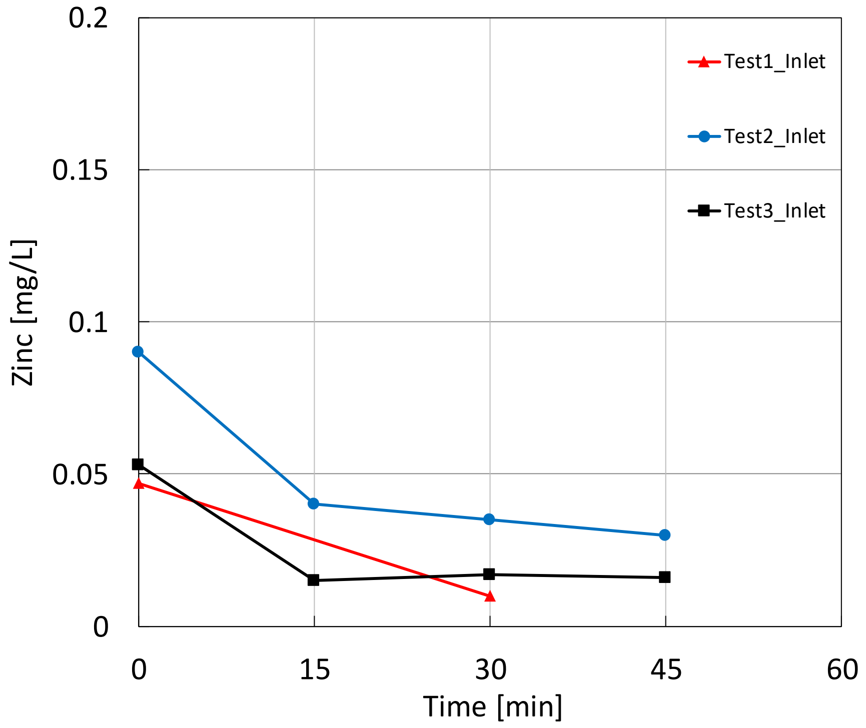


Figure 13. Graph. First flush total zinc at dry swale with a sand filter.

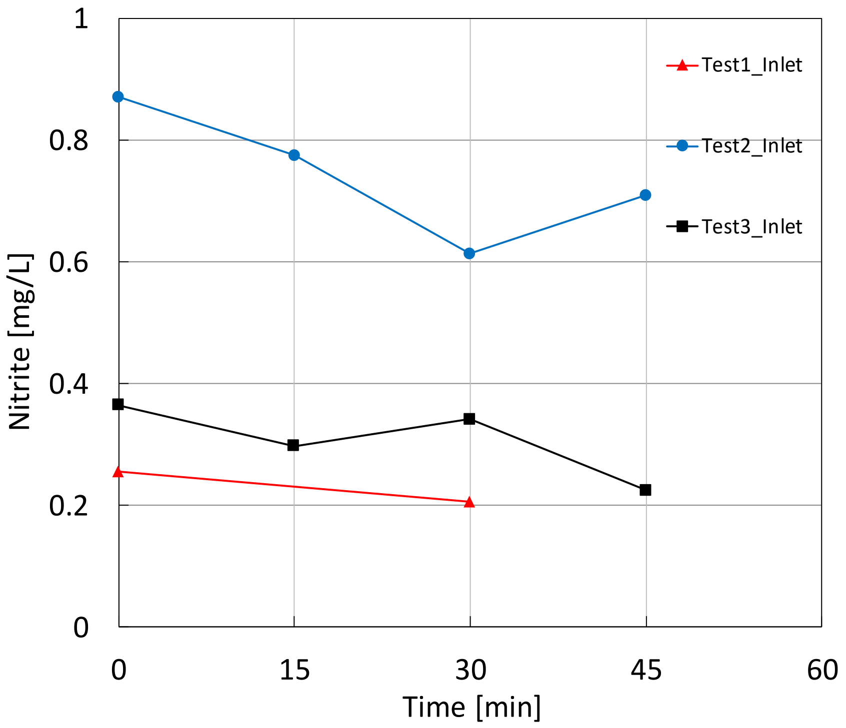


Figure 14. Graph. First flush nitrite at dry swale with a sand filter.

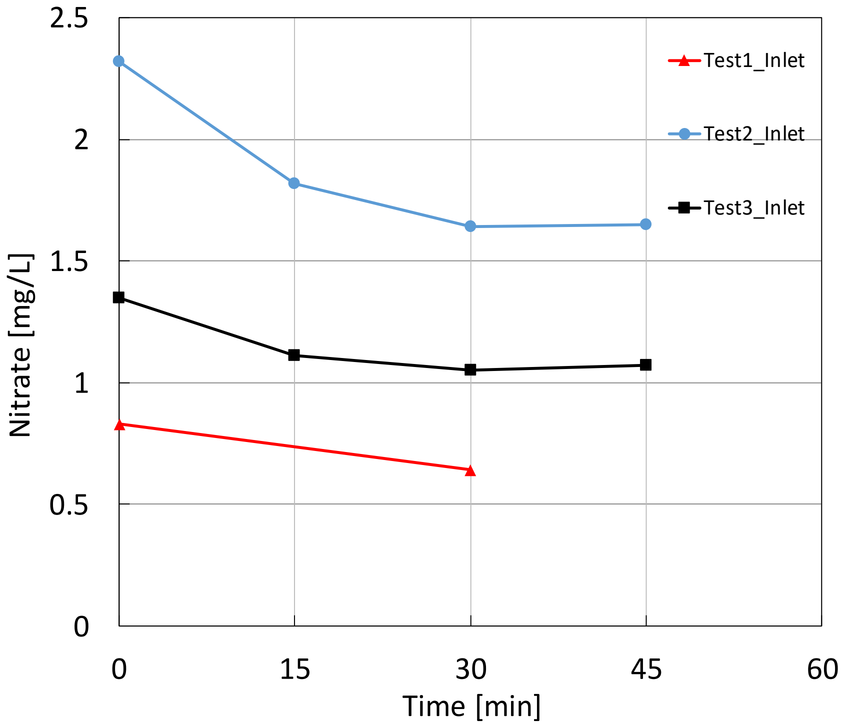


Figure 15. Graph. First flush nitrate at dry swale with a sand filter.

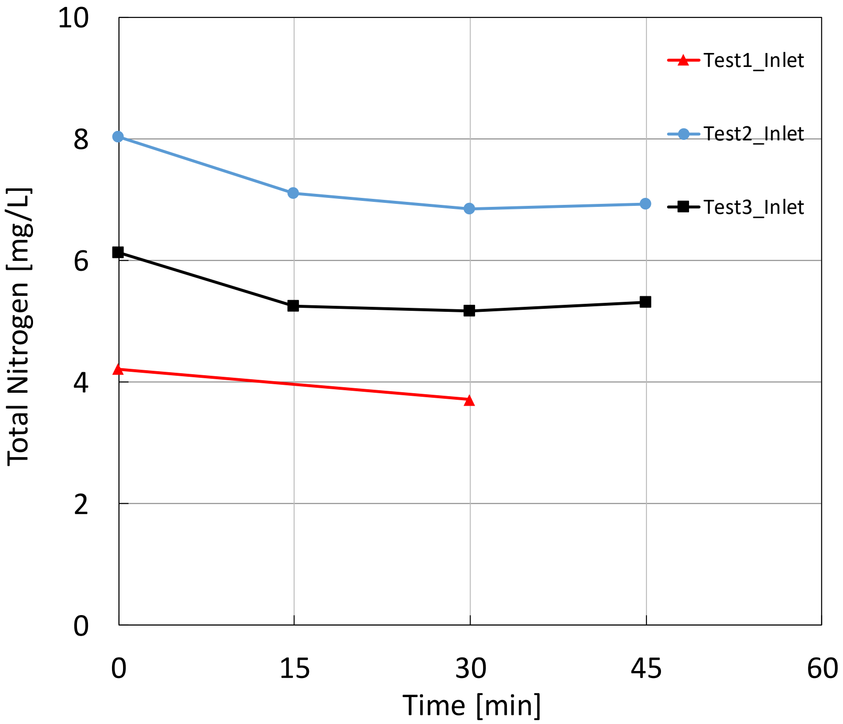


Figure 16. Graph. First flush total nitrogen at dry swale with a sand filter.

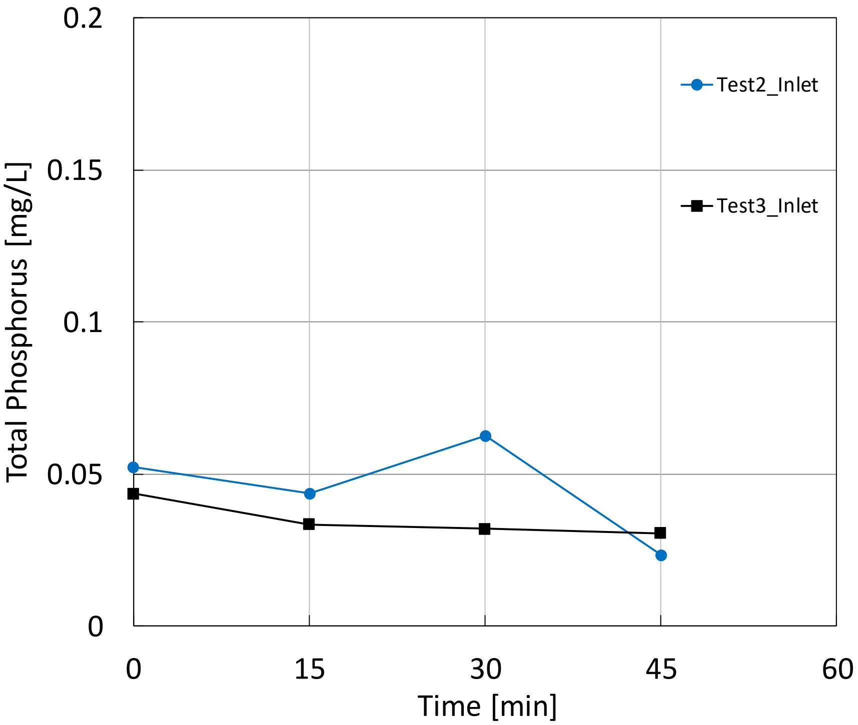


Figure 17. Graph. First flush total phosphorus at dry swale with a sand filter.

In-situ parameters including pH, temperature, and conductivity were measured at intervals of 1 minute during the storm event (Figure 18 - Figure 20). Measured pH values in stormwater runoff were within the state standard (6.0 -8.5), decreasing as the storm progressed. Measured temperature was also within the state standard of < 32 °C (90 °F). Conductivity demonstrated an initial peak due to inflow runoff but decreased and stabilized after the initial 15 minutes of inflow.

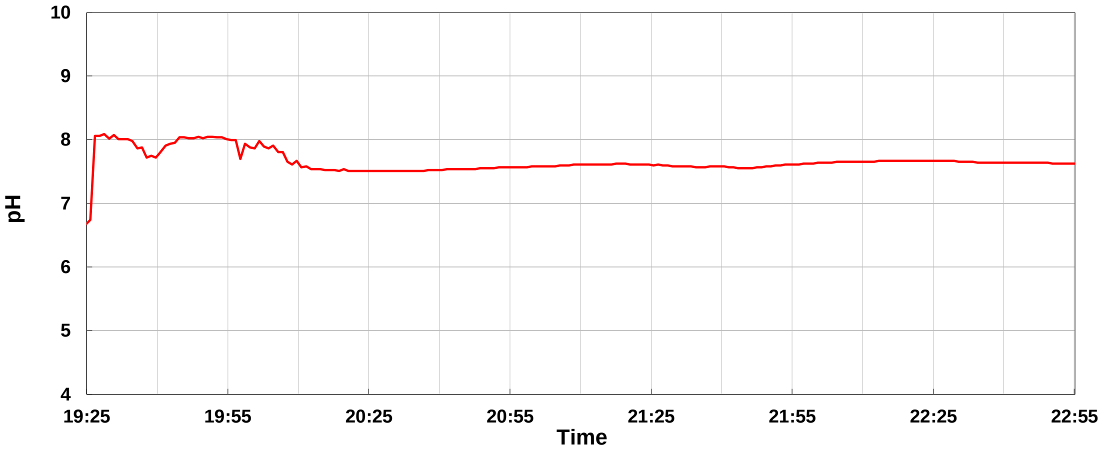


Figure 18. Graph. In-situ pH values during the stormwater runoff (dry swale/sand filter).

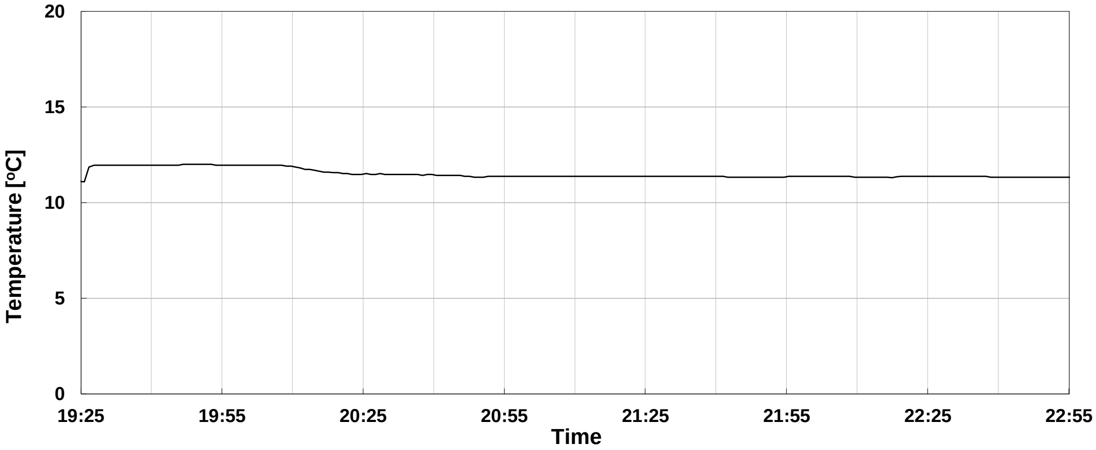


Figure 19. Graph. In-situ temperature values during the stormwater runoff (dry swale/sand filter).

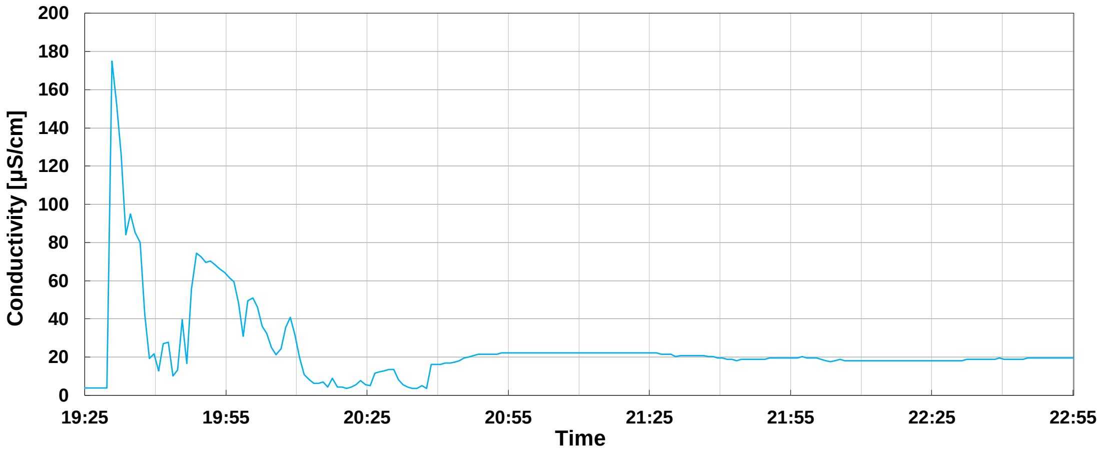


Figure 20. Graph. In-situ conductivity values during the stormwater runoff (dry swale/sand filter).

Conventional parameters including turbidity, total suspended solids, and total dissolved solids were measured for the inlet samples and outlet samples in order to determine percent removals in the BMP. Turbidity was measured using a TB200 portable turbidimeter (Orbeco). Analysis of total suspended solids and dissolved solids were determined using the methodology outlined in EPA 160.2. In all cases, the highest values were measured in the first sample taken at the inlet and concentrations significantly decreased between the inlet and outlet (Figure 21 - Figure 23). Also, suspended solids removal was visually apparent through color change on the microfiber filters used for filtration in the total suspended solids test (Figure 24).

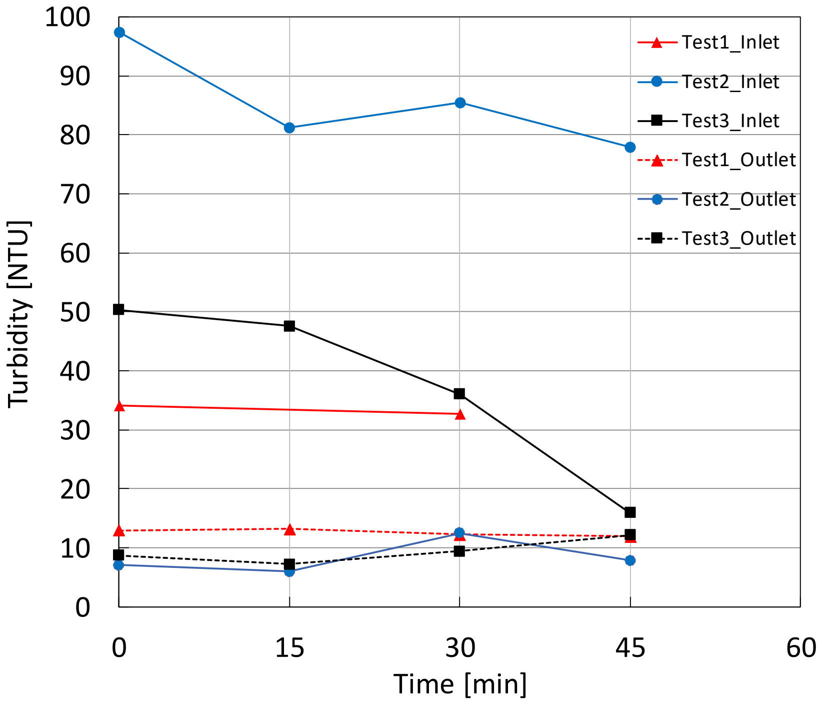


Figure 21. Graph. Turbidity test results for inlet samples and outlet samples (dry swale/sand filter).

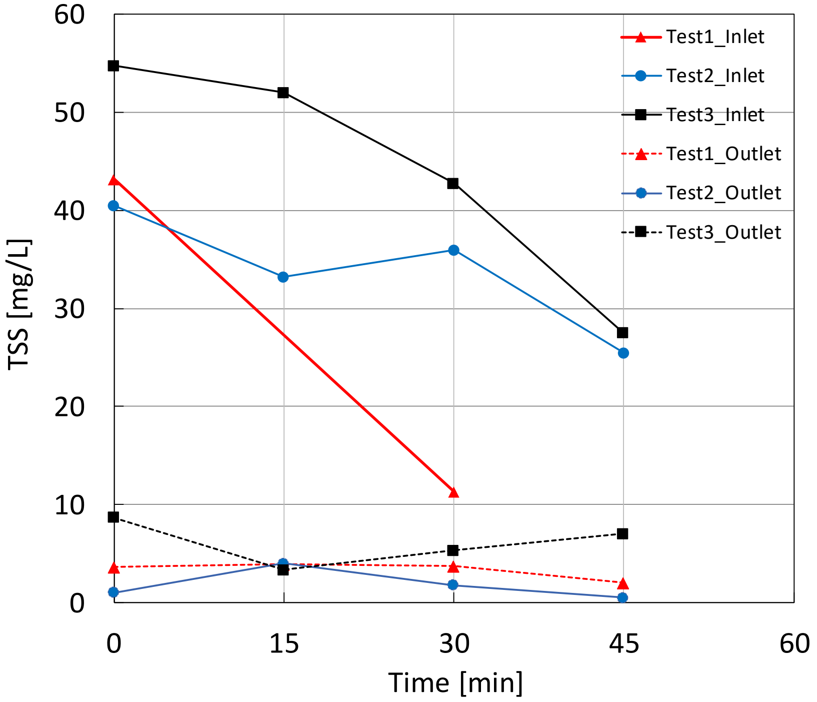


Figure 22. Graph. Total suspended solid test results for inlet samples and outlet samples (dry swale/sand filter).

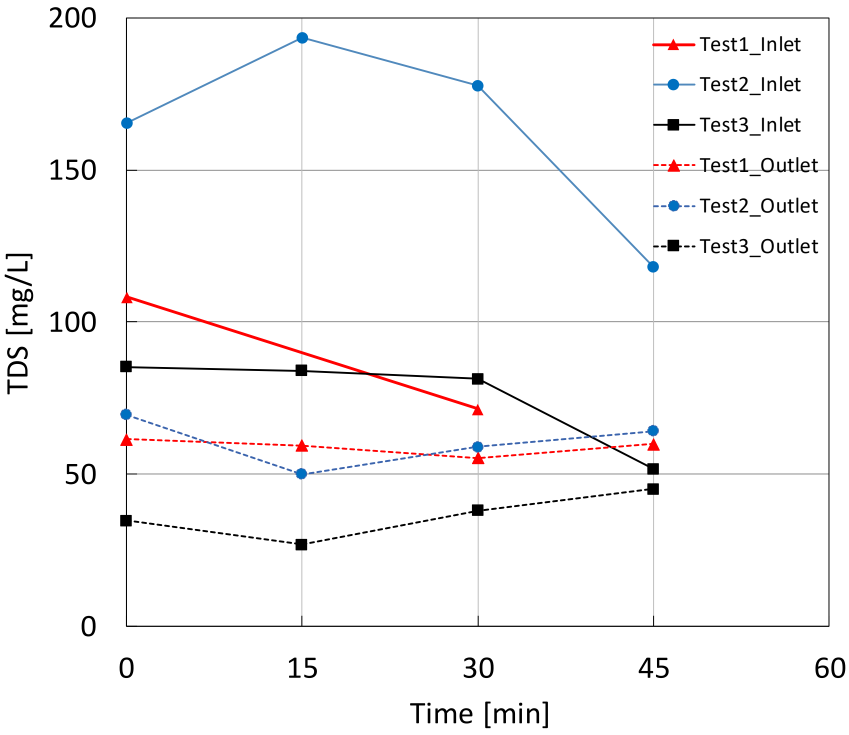


Figure 23. Graph. Total dissolved solid test results for inlet samples and outlet samples (dry swale/sand filter).

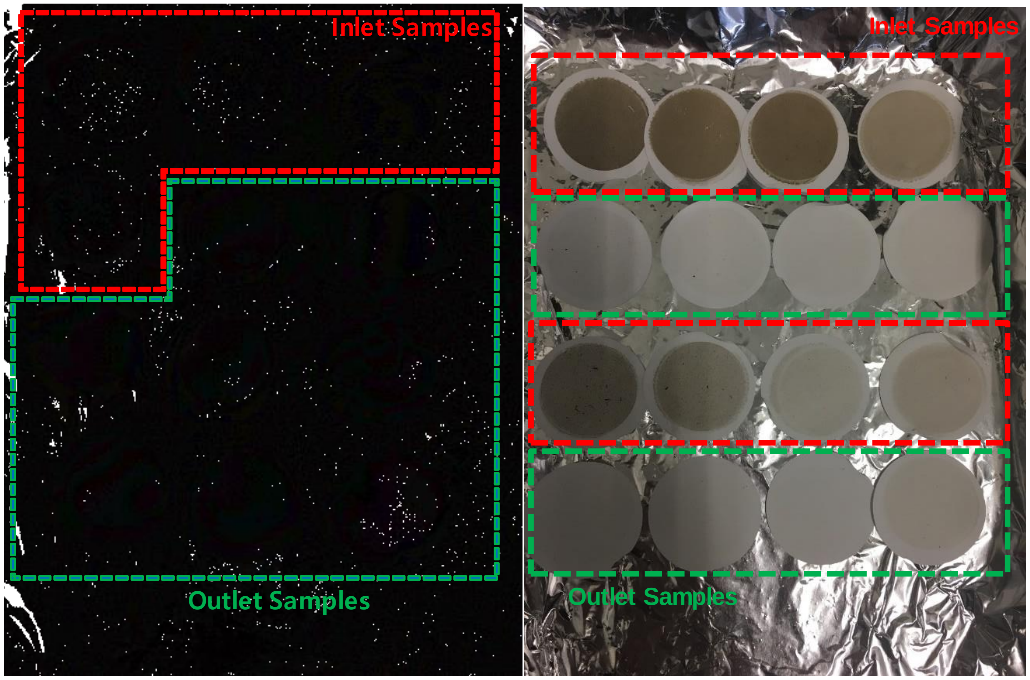


Figure 24. Photos. Microfiber filter results for total suspended solid tests (dry swale/sand filter).

Heavy metals concentrations (copper, lead, and zinc) were measured for the inlet samples and outlet samples in order to determine percent removal using inductively coupled plasma optical emission spectroscopy (ICP-OES). For almost all cases, heavy metal concentration was reduced between measured inlet and outlet concentrations (Figure 25 - Figure 27).

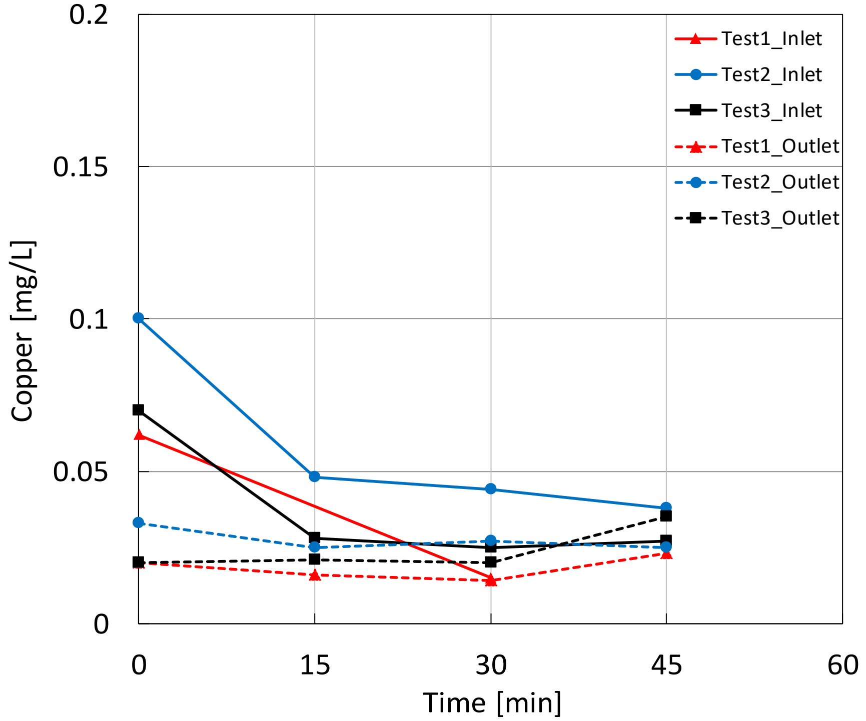


Figure 25. Graph. Total copper at inlet samples and outlet samples (dry swale/sand filter).

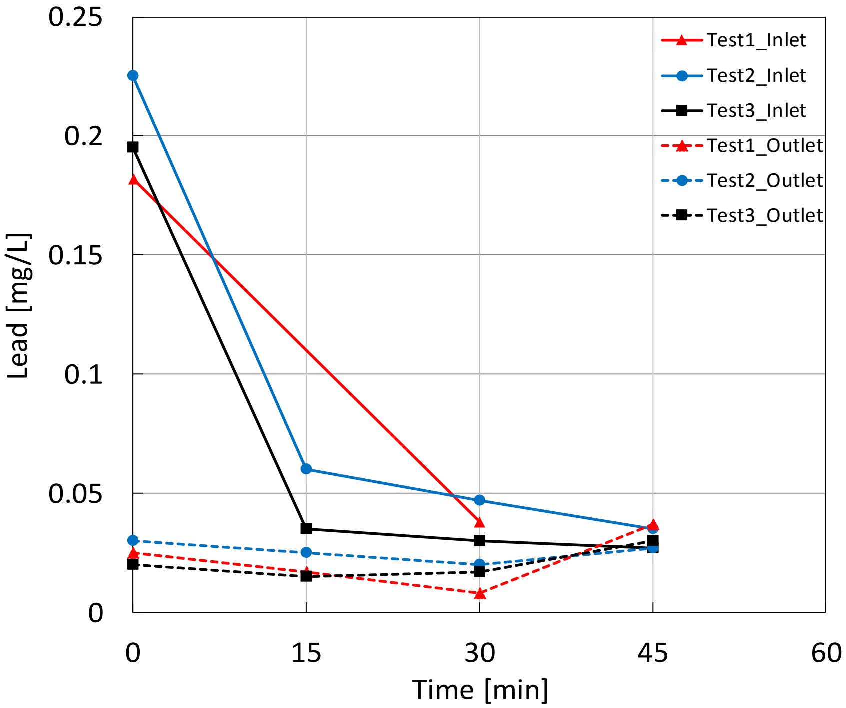


Figure 26. Graph. Total lead at inlet samples and outlet samples (dry swale/sand filter).

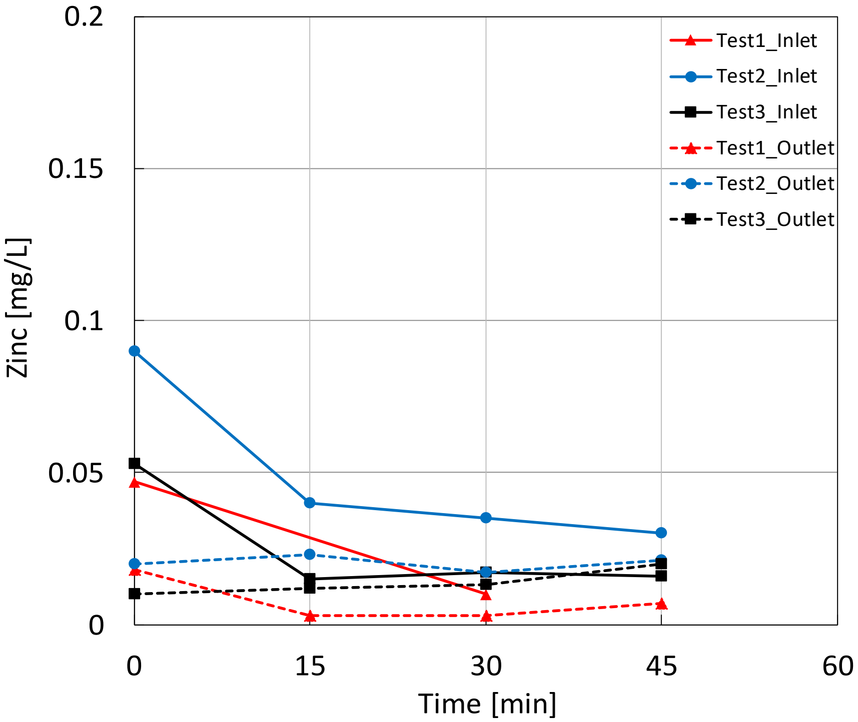


Figure 27. Graph. Total zinc at inlet samples and outlet samples (dry swale/sand filter).

The concentrations of nutrients, including nitrite (NO^{2-}), nitrate (NO^{3-}), total nitrogen, and total phosphorus, were measured for the inlet and outlet samples (total phosphorus was not measured in the first test). For the analysis of nutrients, EPA 352.1 and EPA 365.2 method were followed, using a UV-spectrophotometer for determination of nutrient concentration. In almost all cases, the highest nutrient concentrations were observed in the first flush, with nutrient concentrations at the outlet significantly reduced when compared to the inlet concentration (Figure 28 - Figure 31).

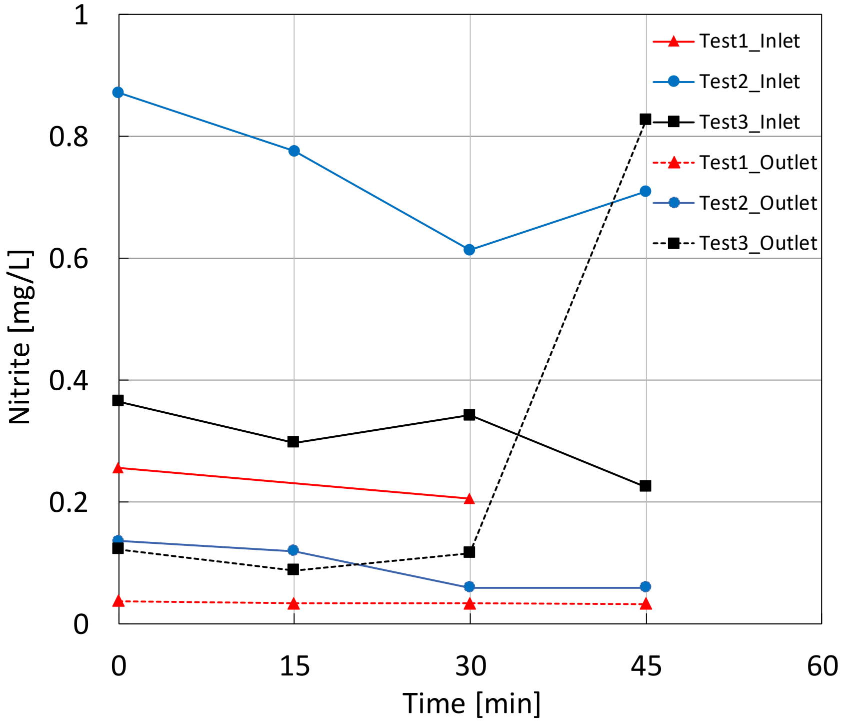


Figure 28. Graph. Nitrite concentration at inlet samples and outlet samples.

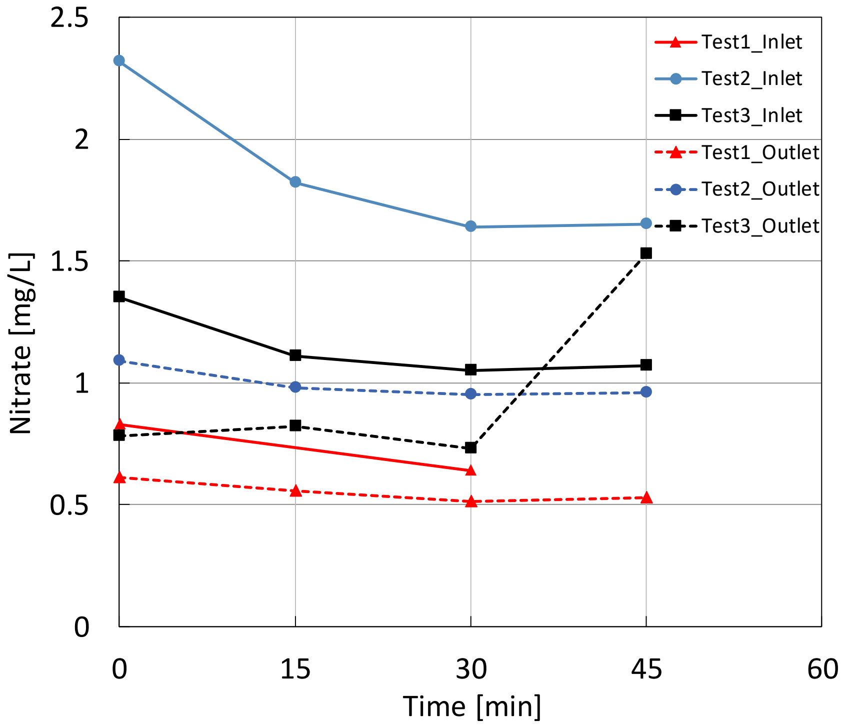


Figure 29. Graph. Nitrate concentration at inlet samples and outlet samples.

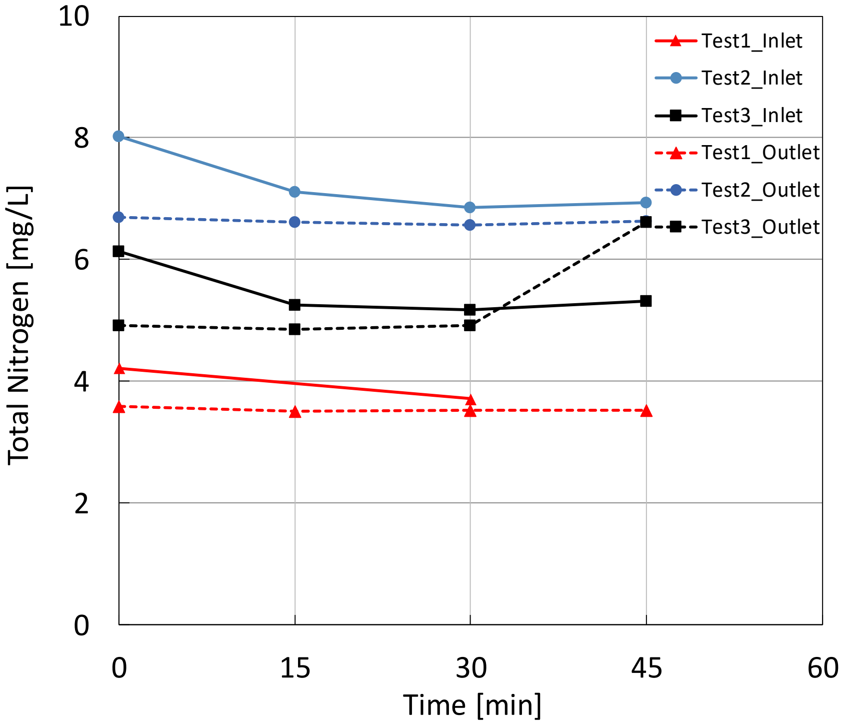


Figure 30. Graph. Total nitrogen concentration at inlet samples and outlet samples.

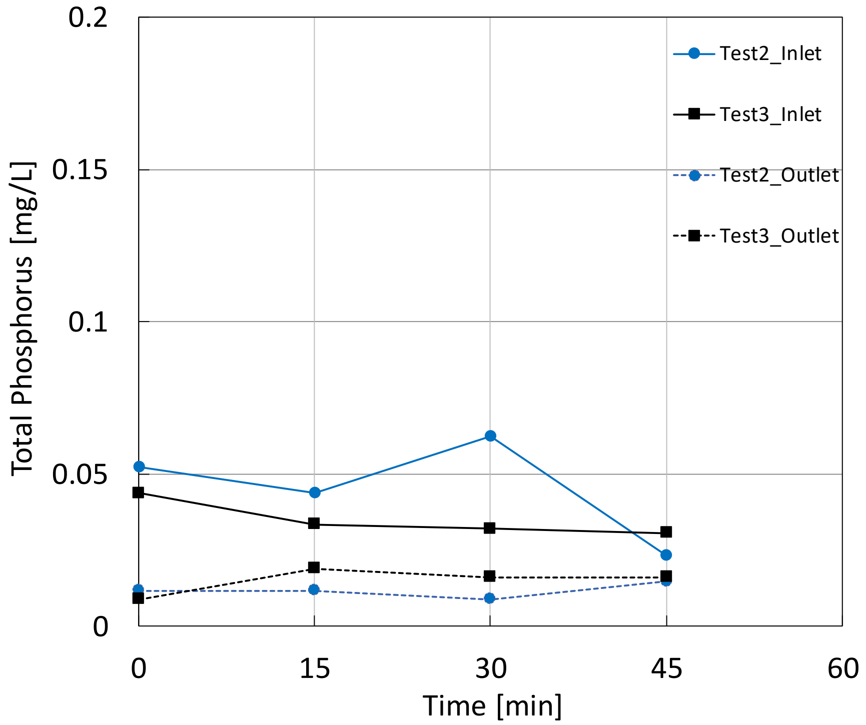


Figure 31. Graph. Total phosphorus concentration at inlet samples and outlet samples.

For the monitored stormwater events, the number of antecedent dry days ranged from 1 to 5 (Table 6), which is evident in the higher concentration measured for inflow for the second monitored storm event. Rainfall data for the second storm event show heavy precipitation with high rainfall intensity that resulted in high inflow and outflow concentrations at the outlet samples. This storm event overtopped the BMP outlet drainage (Figure 32), which allowed stormwater to bypass the sand filter, resulting in higher discharge concentrations from the BMP.

Table 6. Summary of Rainfall Events for Dry Swale/Sand Filter, Forsyth County.

Test No.	Total Precipitation (cm)	Precipitation Duration (hrs)	Dry Period (Days)
1	0.3 (0.12 in)	4	1
2	0.7 (0.28 in)	6.5	5
3	2.9 (1.14 in)	19	2

Figure 32. Photo. Overtopping of stormwater at the BMP outlet drainage control structure.

Summary Removal Efficiency: Dry swale/sand filter Forsyth County, GA

In summary, the dry swale/sand filter effectively functioned to remove solids, metals, and nutrients from the stormwater runoff (Table 7). Solids and turbidity reduction ranged between 60 – 90% removal, nutrient removals were ~40 – 90%, and heavy metal concentrations were reduced between 70 – 90%.

Table 7. Summary of Removal Efficiencies for Dry Swale/Sand Filter, Forsyth County.

Parameter	Removal Efficiency (%) Test 1	Removal Efficiency (%) Test 2	Removal Efficiency (%) Test 3
Turbidity [%]	63	91	83
TSS [%]	92	66	89
TDS [%]	45	63	61
Nitrite [%]	87	89	70
Nitrate [%]	33	57	42
Total Nitrogen [%]	16	17	20
Total Phosphorus [%]	-	87	80
Total Copper [%]	71	73	71
Total Lead [%]	88	89	91
Total Zinc [%]	83	77	78

BMP: BIORETENTION BASIN IN BARTOW COUNTY

Site 2 is located in Bartow County, Georgia (City of Cartersville) along State Road 113 (SR 113) at latitude 34.114389 and longitude -84.890556. This site consists of two bioretention ponds that are located on opposite sides of the SR 113 bridge at Raccoon Creek, which is a 33.8 km (21.0 mile) creek originating in Paulding County, Georgia, joining the Etowah River approximately 2.0 km (1.3 miles) downstream from the observed site. The two bioretention ponds are used to treat the stormwater surface runoff from SR 113, before discharging to Raccoon Creek. The monitored bioretention pond is located on the west side of Raccoon Creek (known as Bioretention Pond A) with approximate dimensions of 6.0 m (20.0 ft) wide and 12.1 m (40.0 ft) long, with length being parallel to the road (Figure 33, Table 8).

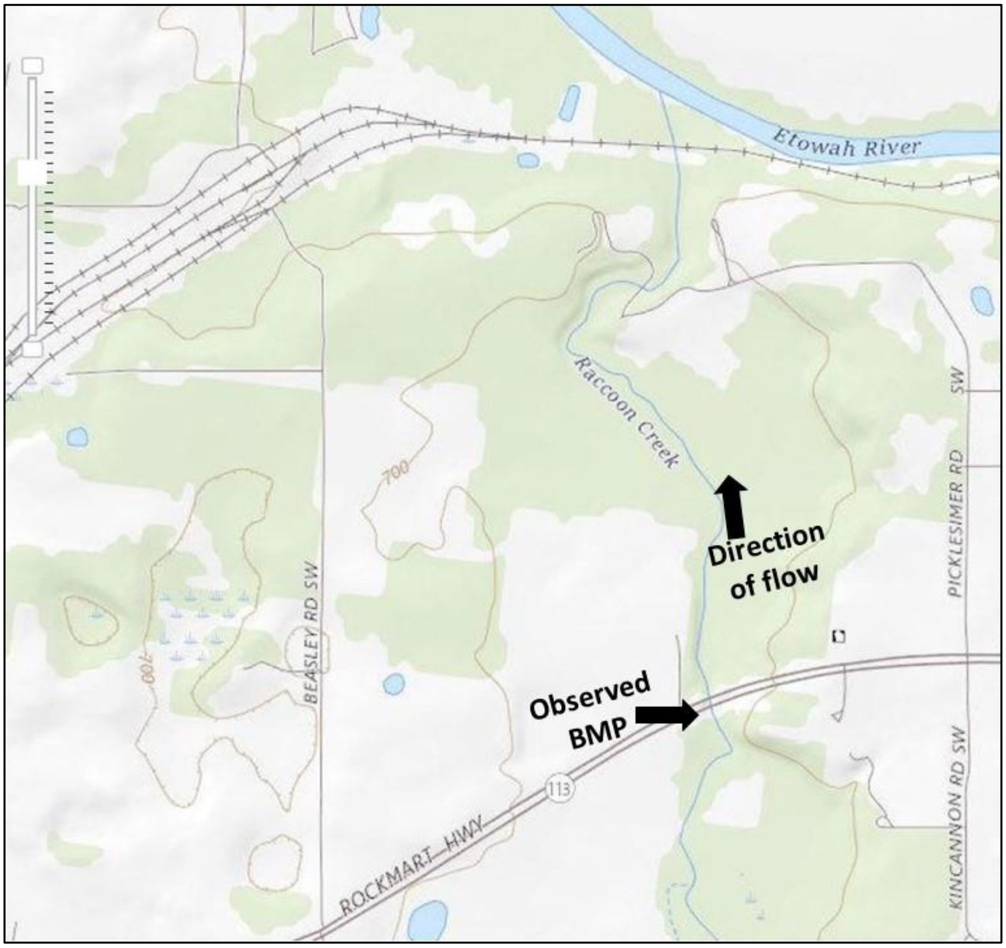


Figure 33. Map. Topographic Map of the Cartersville BMP area (USGS).

Table 8. Bartow County, GA Bioretention BMP Data.

General Test Site Information	
BMP Test Site Name	SR 113 Bartow County Bioretention Pond A
Location	SR 113, Cartersville, GA
Elevation at top of bioretention pond	207 m (679 ft)
Structural BMP Information	
Structural BMP Name	Bioretention Basin
BMP Description	Substantial residence time and storage volume
Treatment Category	Sedimentation, Filtration
Number of Inlets	2
Inlet Description	0.5 m (18 in) storm drain pipe and a concrete spillway
Number of Outlets	1
Outlet Descriptions	Drop inlet
Watershed Stations	
Regional Watershed Name	Etowah
Station	Monitoring stations immediately u/s and d/s of pond
Upstream BMP	None, inflow received directly from SR 113
Downstream BMP	None, effluent discharged to Raccoon Creek

Experimental Results

The bioretention pond was monitored at the inlet and outlets for the BMP (Figure 34- Figure 35). The concrete spillway discharges runoff directly from SR 113, while the 0.5 m (18 in) storm drain pipe inlets runoff water from the median between SR 113 east and west. The outlet consists of a 0.8 m (2.75 ft) drop inlet with a 0.4 m (7 in) weir that flows into a 0.5 m (18 in) storm drain that drains through a riprap rock filter into Raccoon Creek (Figure 36). Samples were taken at the concrete spillway inlet and also at drop inlet (outlet) on February 28, 2019 (Table 9).

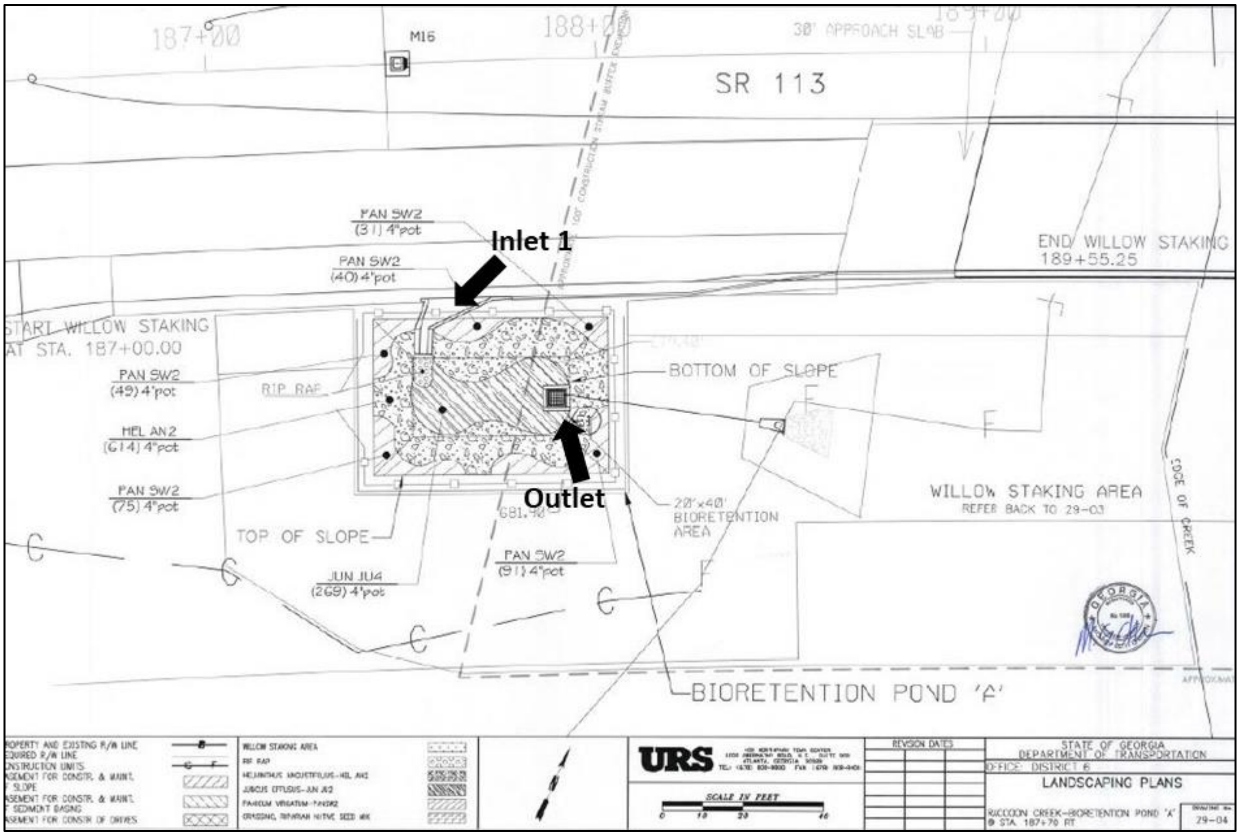


Figure 34. Diagram. Sample Locations at the Raccoon Creek Bioretention Basin.

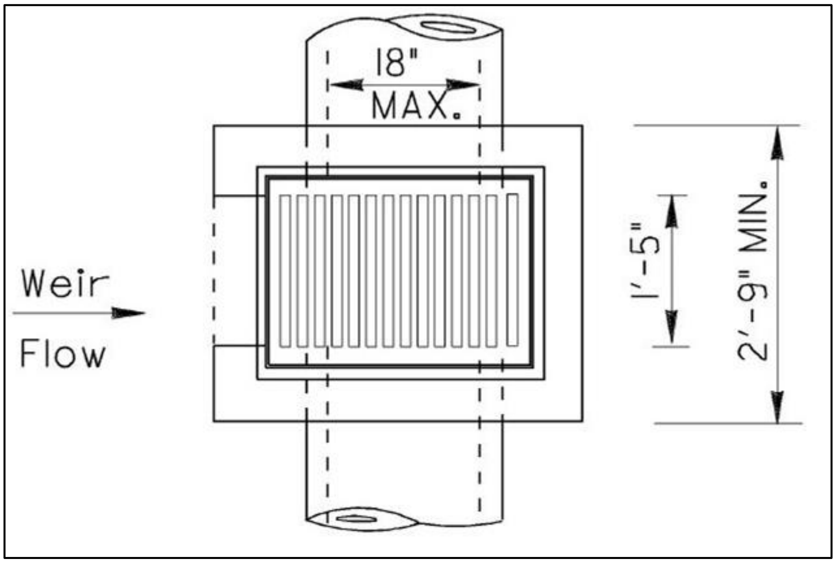


Figure 35. Diagram. Plan view of drop inlet with dimensions.

Figure 36. Photos. Bioretention basin test site at SR 113 and Racoon Creek, Bartow County .

Table 9. Summary of Monitored Tests and Rainfall for Bioretention Basin, Bartow County.

Location	Date	Total Precipitation (cm)	Precipitation Duration (hrs)	Dry Period (Days)	Samples
Lat. 34.114389, Long. -84.890556	02/28/2019	0.2 (0.07 in)	6	4	Inlet : 4 Outlet: 4

First flush grab samples were collected at the inlet and outlet to the BMP at intervals of 15 minutes, and a composite sample was also collected during the first 4 hours of the storm to monitor changes in contaminant levels over the longer storm duration. As anticipated, the results of the first flush monitoring showed the highest concentration of contaminants in the first sample taken, followed by significant decrease after 15 minutes of flow (Figure 37 - Figure 46). For samples taken at 30 minutes and 45 minutes after initiation of flow, the contaminant concentrations were almost invariable with time.

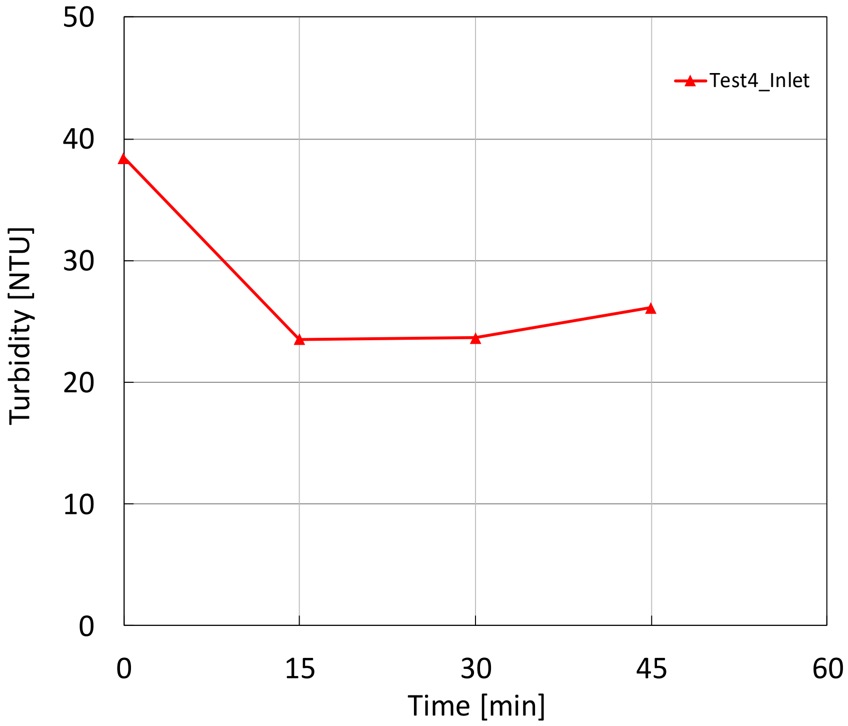


Figure 37. Graph. First flush turbidity concentration for the bioretention basin, Bartow County GA.

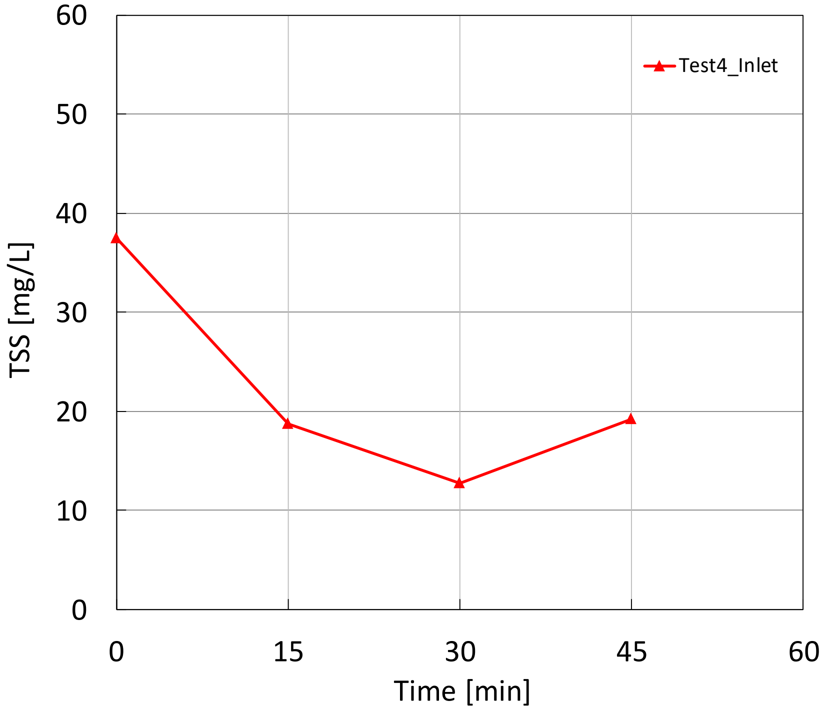


Figure 38. Graph. First flush total suspended solids concentration for the bioretention basin, Bartow County GA.

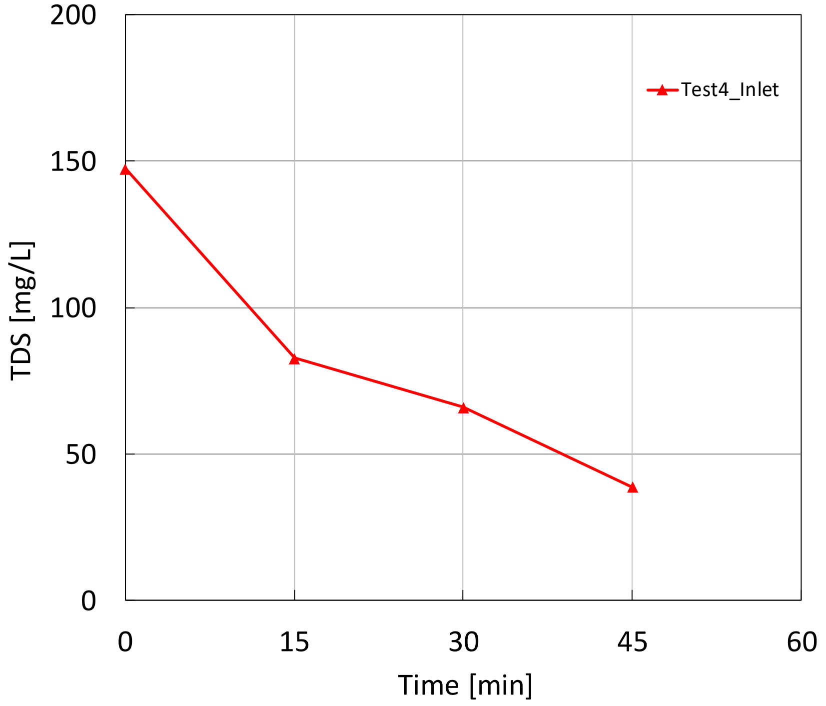


Figure 39. Graph. First flush total dissolved solids concentration for the bioretention basin, Bartow County GA.

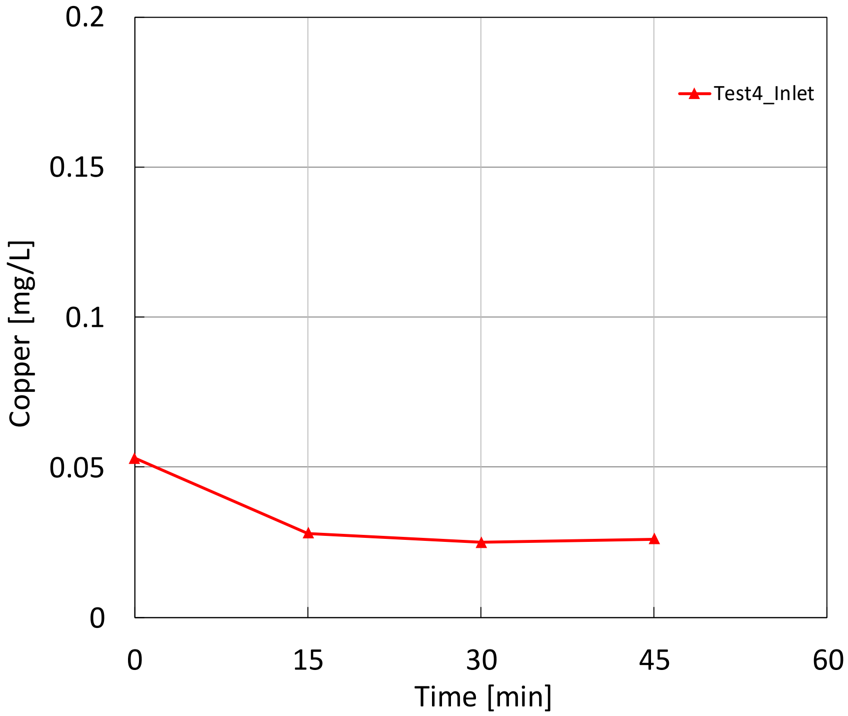


Figure 40. Graph. First flush total copper concentration for the bioretention basin, Bartow County GA.

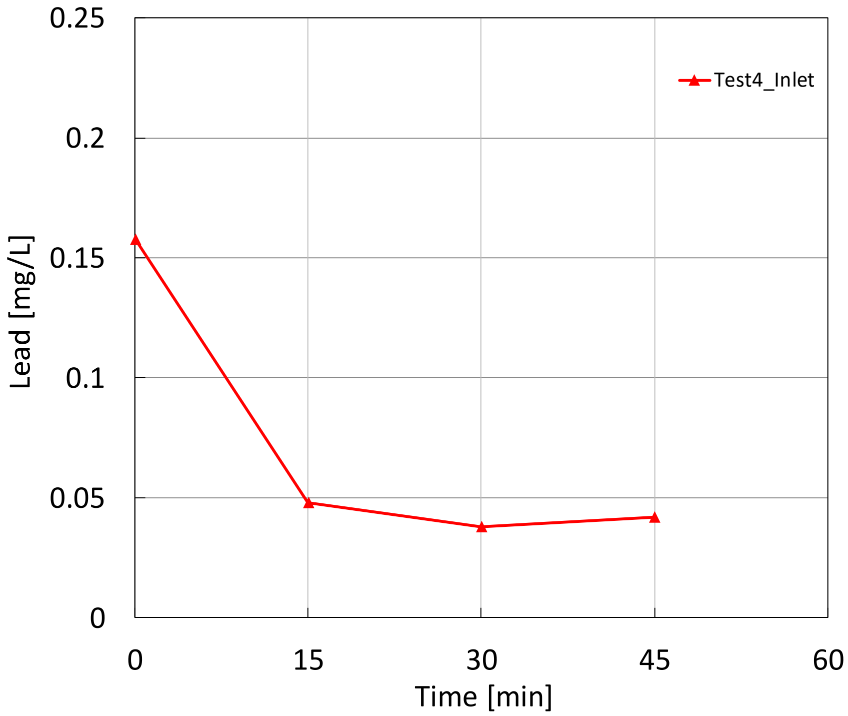


Figure 41. Graph. First flush total lead concentration for the bioretention basin, Bartow County GA.

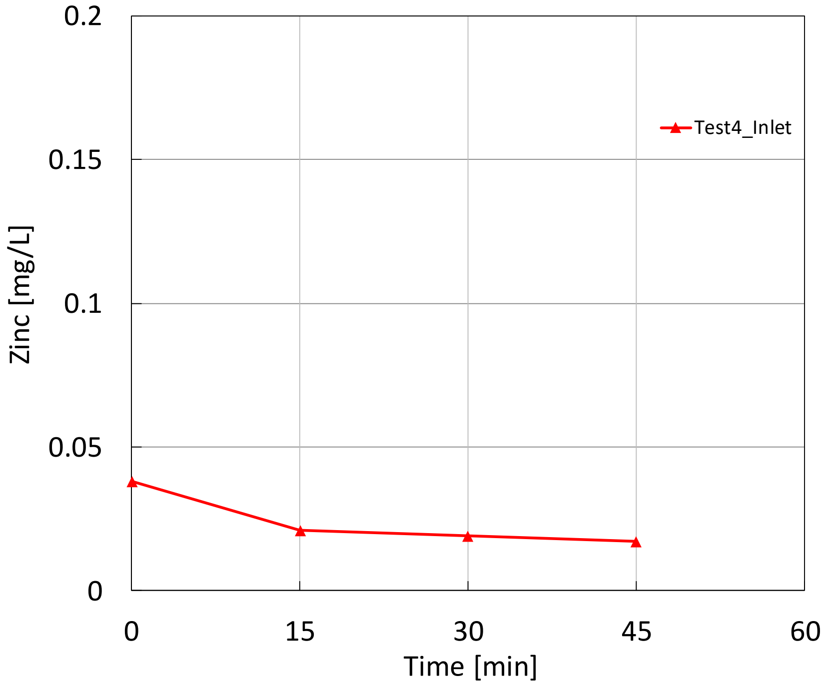


Figure 42. Graph. First flush total zinc concentration for the bioretention basin, Bartow County GA.

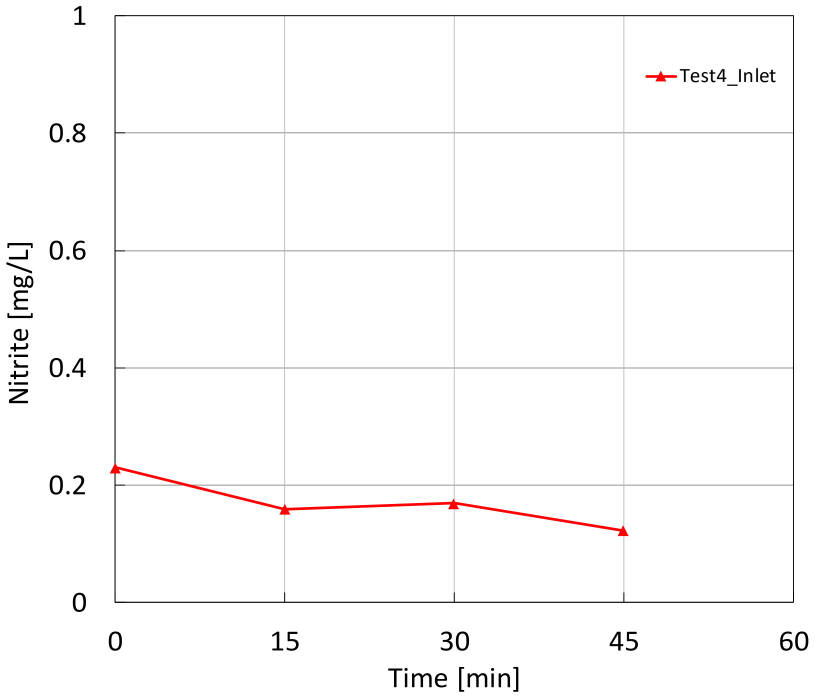


Figure 43. Graph. First flush nitrite concentration for the bioretention basin, Bartow County GA.

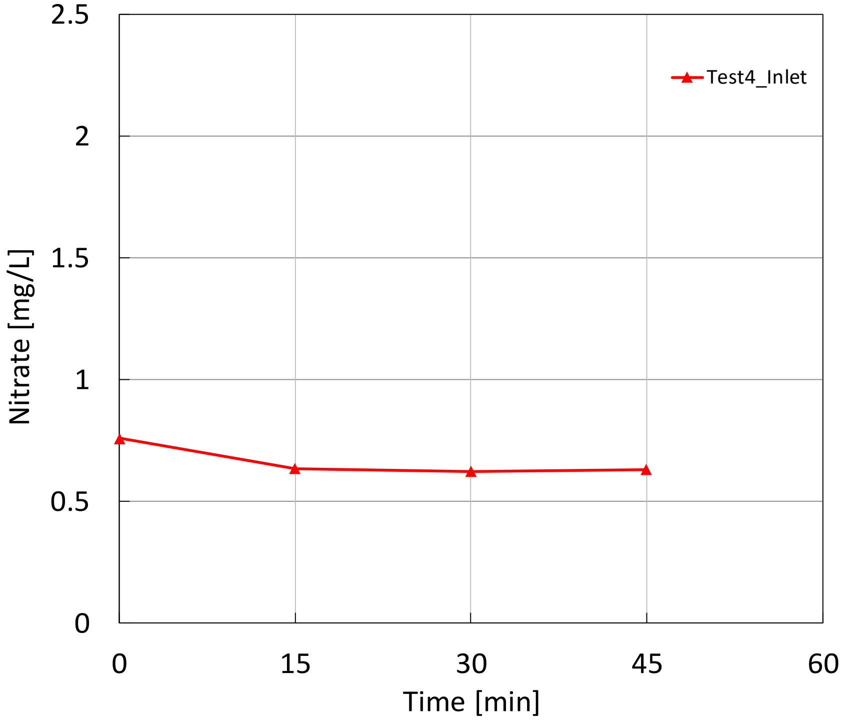


Figure 44. Graph. First flush nitrate concentration for the bioretention basin, Bartow County GA.

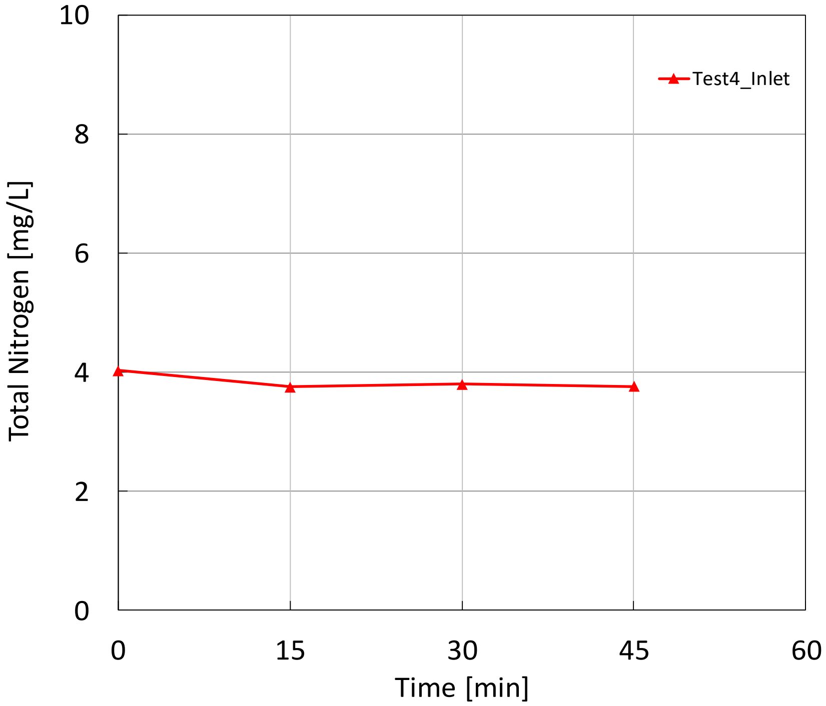


Figure 45. Graph. First flush total nitrogen concentration for the bioretention basin, Bartow County GA.

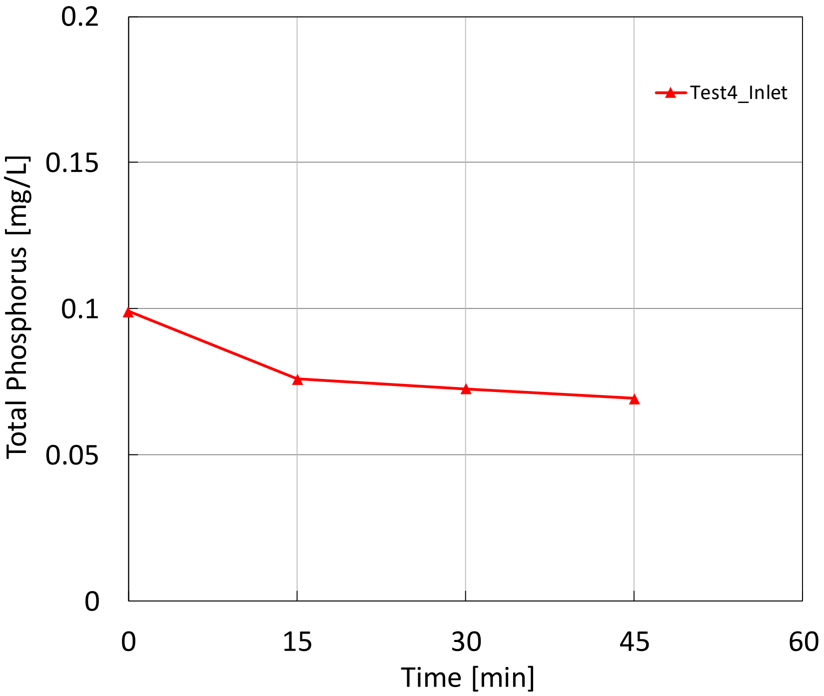


Figure 46. Graph. First flush total phosphorus concentration for the bioretention basin, Bartow County GA.

Measurement of in-situ parameters showed that inflow pH was relatively constant (~7.5 – 8), which was within state standards (Figure 47). Inflow temperature was approximately 15.5 °C (60 °F), which is also within state standards (Figure 48). Similarly to the dry swale/sand filter, the conductivity spiked within the first 15 minutes of runoff, when the initial stormwater runoff into the basin began, and then decreased for the duration of the storm (Figure 49).

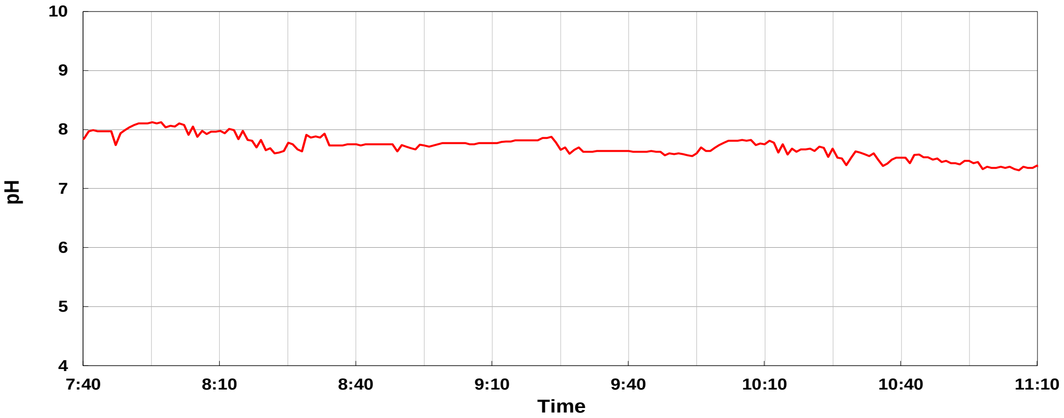


Figure 47. Graph. In-situ pH values during the stormwater runoff for the bioretention basin, Bartow County, GA.

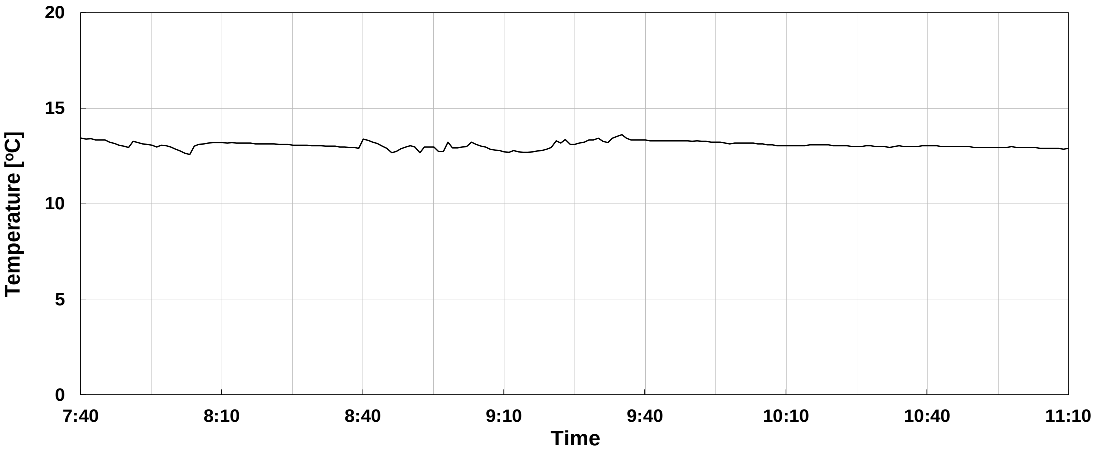


Figure 48. Graph. In-situ temperature values during the stormwater runoff for the bioretention basin, Bartow County, GA.

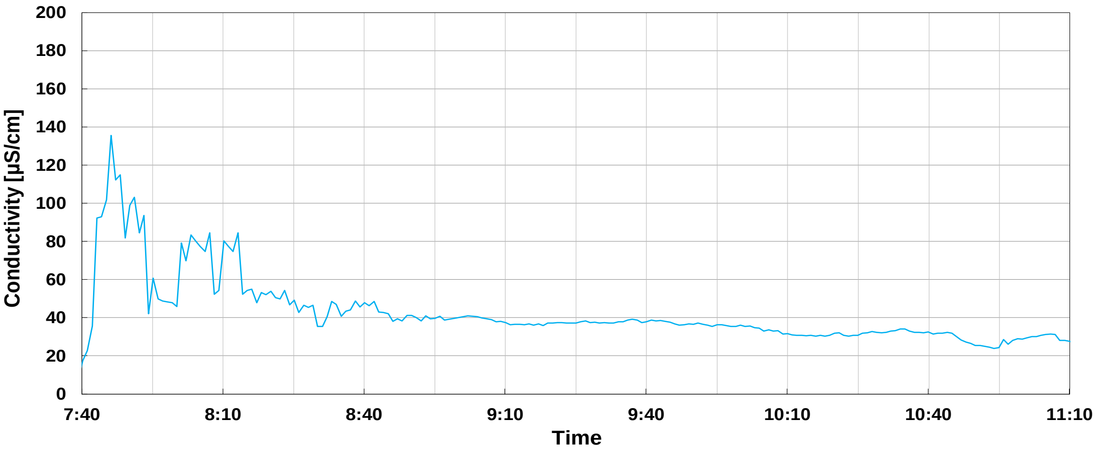


Figure 49. Graph. In-situ conductivity values during the stormwater runoff for the bioretention basin, Bartow County, GA.

Substantial reduction in turbidity, total suspended solids, and total dissolved solids were observed within the bioretention basin (Figure 50 - Figure 52). Initial inflow concentrations were low for the storm monitored at this BMP, with initial turbidity at ~40 NTU and TSS at ~40 mg/L.

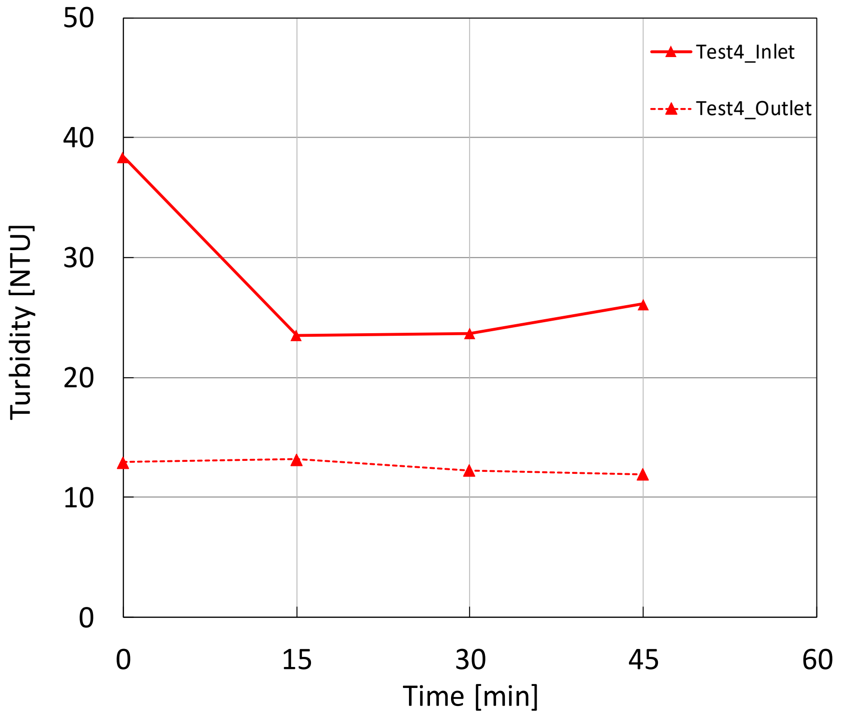


Figure 50. Graph. Turbidity test results for inlet samples and outlet samples for bioretention basin, Bartow County, GA.

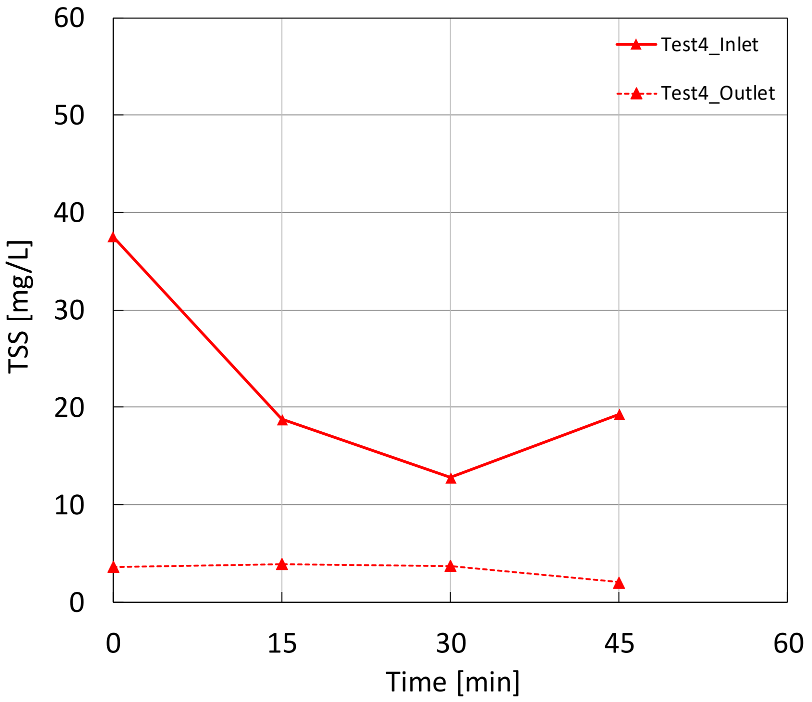


Figure 51. Graph. Total suspended solid test results for inlet samples and outlet samples for bioretention basin, Bartow County, GA.

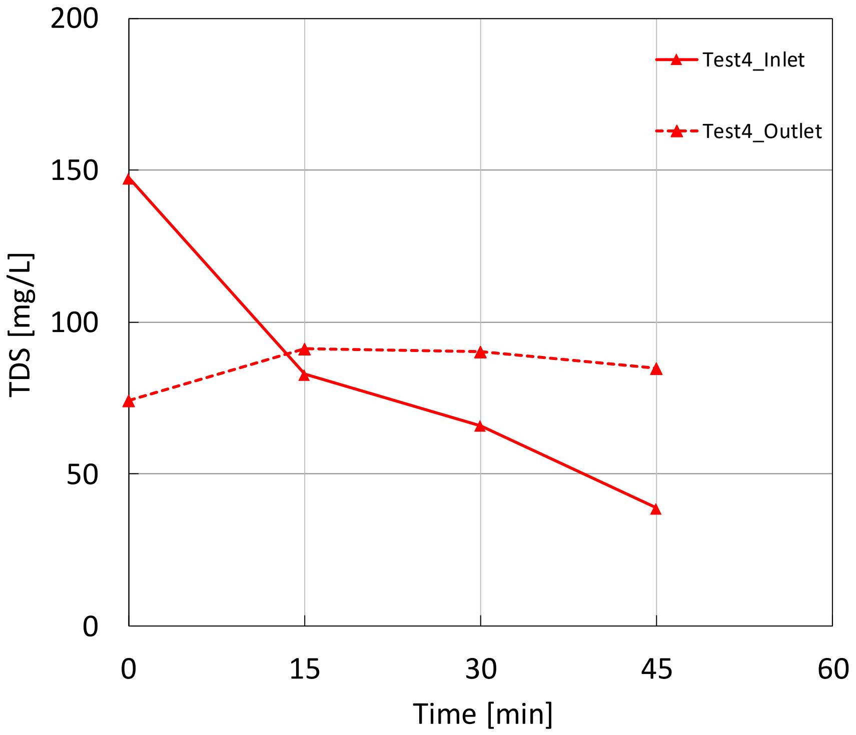


Figure 52. Graph. Total dissolved solid test results for inlet samples and outlet samples for bioretention basin, Bartow County, GA.

Heavy metal concentrations (copper, lead, and zinc) were low, both at the inflow and outflow, with concentrations < 0.2 ppm (Figure 53 - Figure 55). Nonetheless, heavy metal concentration was reduced within the BMP, and when compared to the initial sample concentration at the inlet, concentration of heavy metals in the outlet samples decreased between 60% and 80% as they were filtered by the bioretention basin.

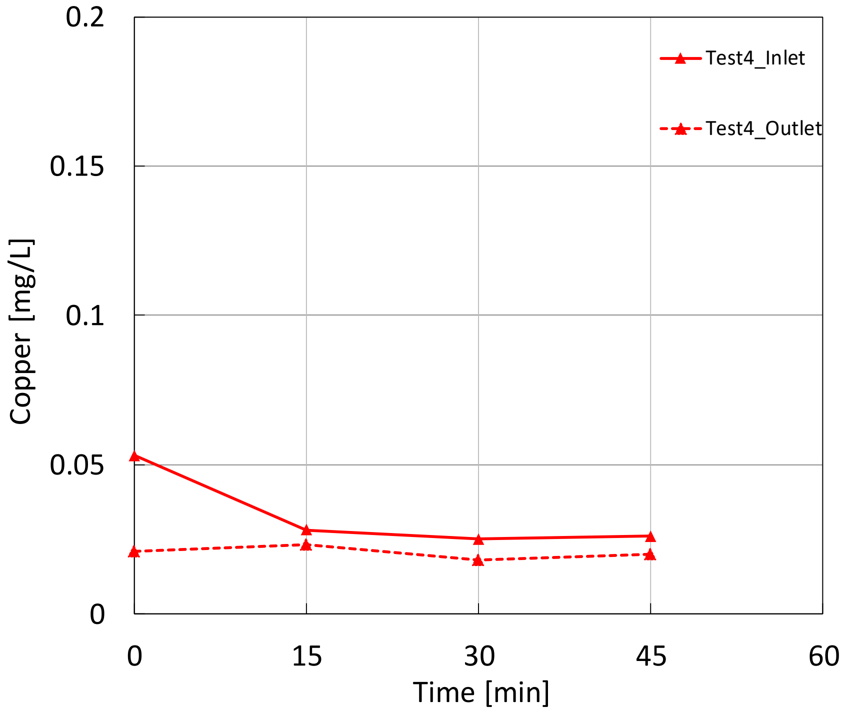


Figure 53. Graph. Total copper at inlet samples and outlet samples for the bioretention basin, Bartow County, GA.

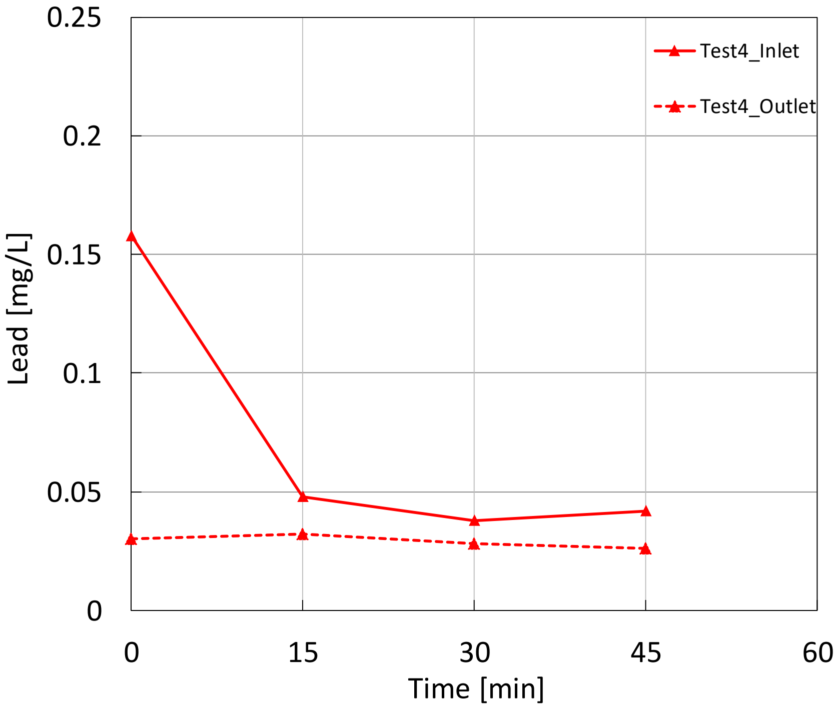


Figure 54. Graph. Total lead at inlet samples and outlet samples for the bioretention basin, Bartow County, GA.

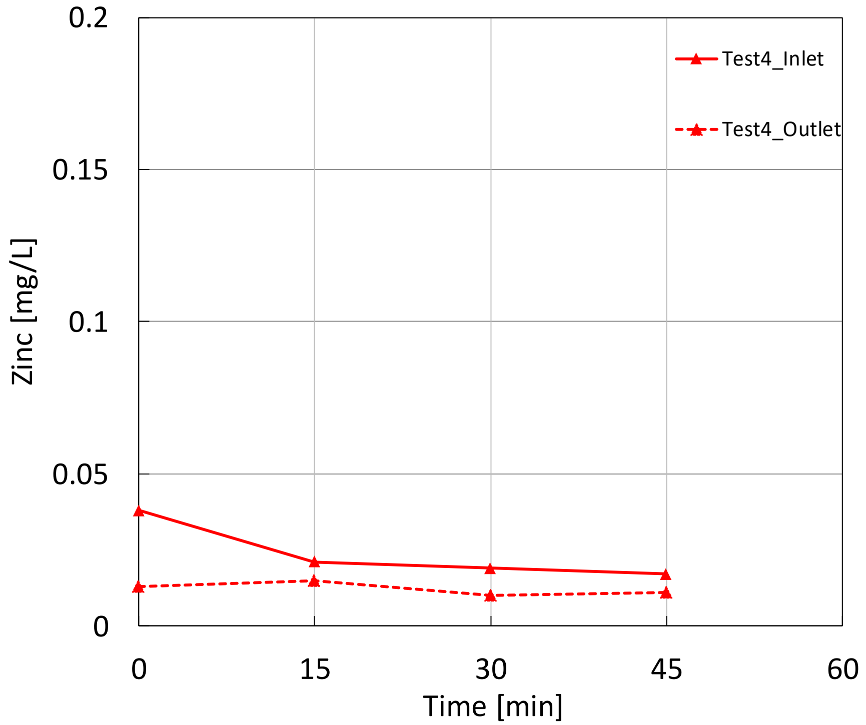


Figure 55. Graph. Total zinc at inlet samples and outlet samples for the bioretention basin, Bartow County, GA.

Consistent reduction of nutrient concentrations occurred within the bioretention basin (Figure 56 - Figure 59). In the case of nitrite and total phosphorus, the reduction was approximately 60%, when comparing inlet and outlet concentrations of stormwater runoff.

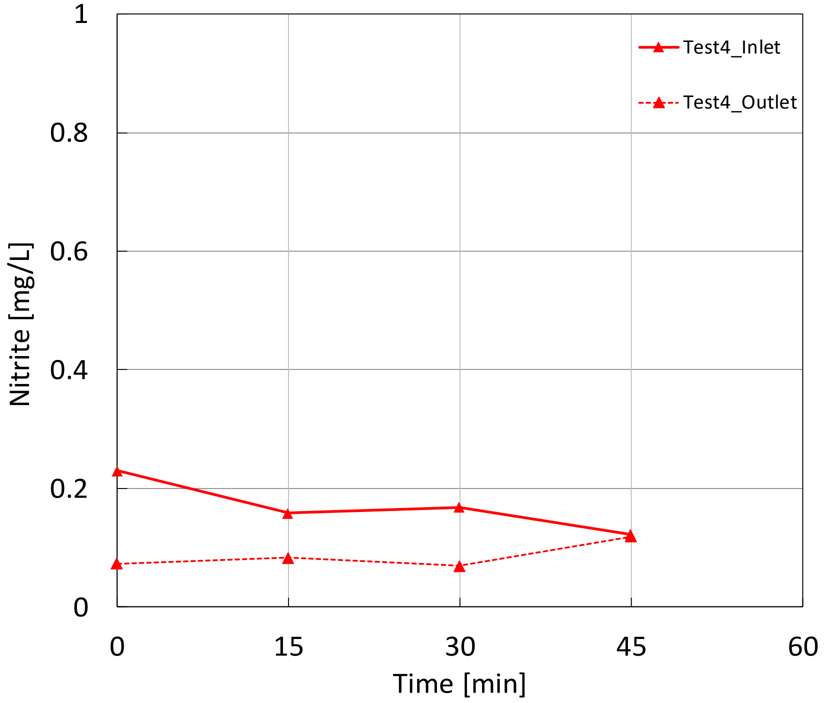


Figure 56. Graph. Nitrite concentration at inlet samples and outlet samples for bioretention basin, Bartow County, GA.

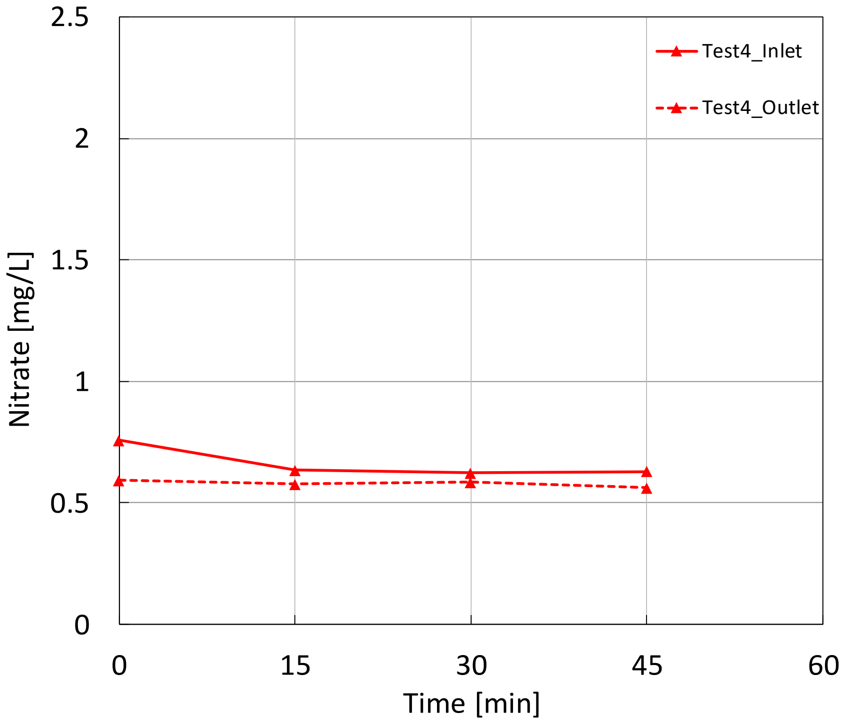


Figure 57. Graph. Nitrate concentration at inlet samples and outlet samples for bioretention basin, Bartow County, GA.

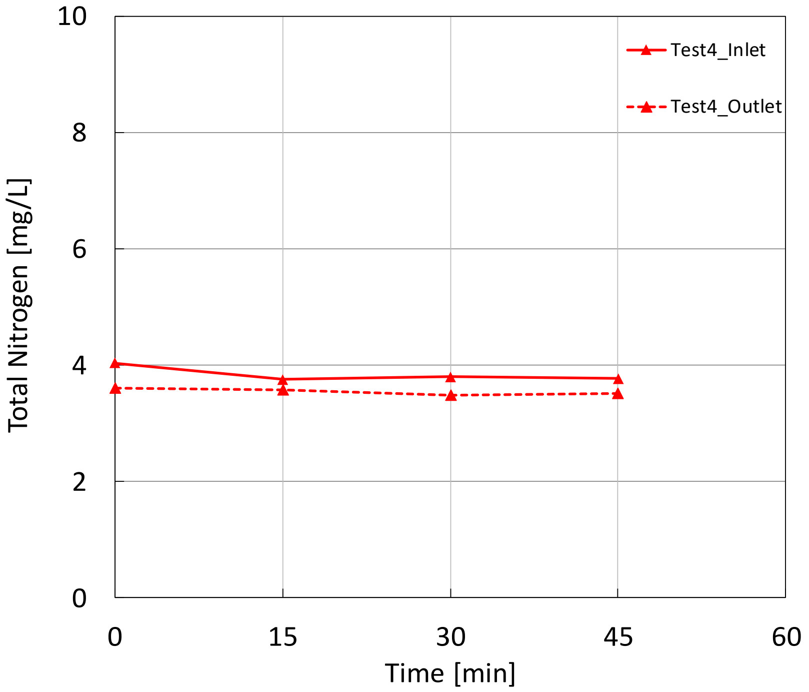


Figure 58. Graph. Total nitrogen concentration at inlet samples and outlet samples for bioretention basin, Bartow County, GA.

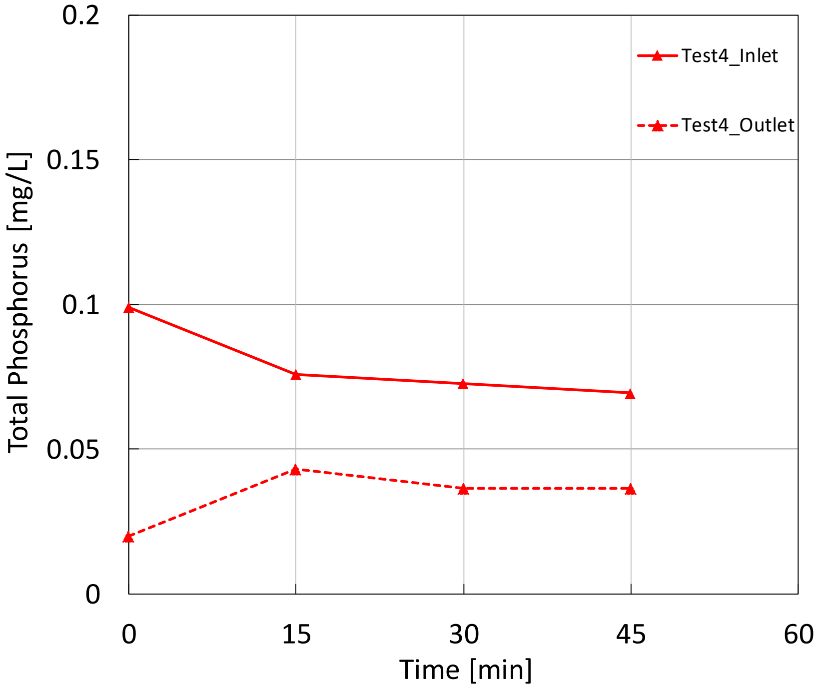


Figure 59. Graph. Total phosphorus concentration at inlet samples and outlet samples for bioretention basin, Bartow County, GA.

Summary Removal Efficiency: Bioretention basin, Bartow County, GA

The bioretention basin monitored in Bartow County was found to be performing well, with removal efficiencies of ~ 60 – 80% for the contaminants that were tested (Table 10).

Table 10. Summary of Removal Efficiencies for Bioretention Basin, Bartow County.

Parameter	Removal Efficiency (%) Test 4
Turbidity [%]	77
TSS [%]	72
TDS [%]	42
Nitrite [%]	63
Nitrate [%]	24
Total Nitrogen [%]	12
Total Phosphorus [%]	66
Total Copper [%]	61
Total Lead [%]	82
Total Zinc [%]	68

BMP IMPACT ON SURFACE WATER AND GROUND WATER SAMPLES IN THE COASTAL PLAIN

A series of field tests were performed on BMPs in the coastal plain of Georgia on Skidaway Island, which is a Pleistocene barrier island on the coast of Georgia, lying just southeast of Savannah, Georgia. The island is bordered by saltwater marshes and rivers that drain into the Atlantic Ocean (Figure 60). The island has yearly temperatures that average 10 °C (50 °F) in the winter and 28 °C (82 °F) in the summer, with approximately 1.2 meters (3.9 ft) of rain per year. Skidaway Island is a particularly interesting area to test for nutrient concentrations, because it has a population of approximately 8,500 people with six 18-hole golf courses located throughout the island, which results in high application rates of nutrients through grass fertilization. The study monitored surface and groundwater concentrations of nitrogen at multiple locations at the base of filter strips that were located throughout the island.

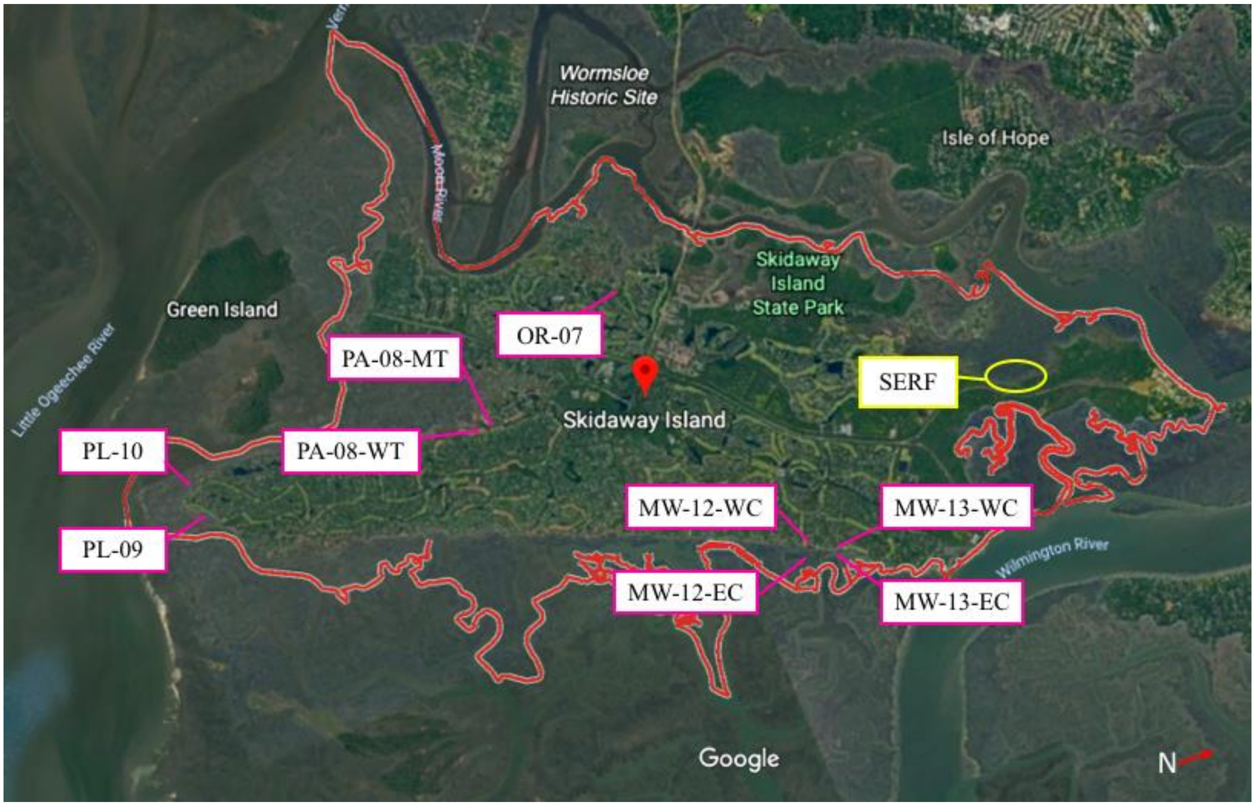


Figure 60. Map. Location of surface water samples taken throughout Skidaway Island, and location of wells for groundwater sampling (at SERF site).

Three of the surface water sample locations were taken at the base of slopes, chosen due to similarity to a stormwater filter strip BMP. However, the slopes were chosen in the field tested sites because they were larger than the 6% limit on filter strips (Figure 61). The length of the filter strip (L_f) and slopes angles were measured in the field, and travel time (T_t) was then determined according to the following equation:

$$L_f = \frac{T_t^{1.25} * P^{0.625} * S^{0.5}}{0.338 * n} \qquad \text{(eq. 1)}$$

where P is the runoff stormwater (3 cm or 1.2 inches, GSWMM, 2014), S is the slope given in percent (V/H), and n is Manning’s roughness coefficient, depending on the density of the grass. Two different n coefficients were used to obtain travel time, because grass density changes throughout the seasons and is maintenance dependent. With this information, a model from the Georgia Storm Water Management Manual (GSWMM, 2014) was used to calculate travel time within the BMP.

Figure 61. Photos. Sites that were surveyed and the results obtained from surveying: A) MW-12, B) MW-13, and C) PL-09.

Alternative Filter Strips in Coastal Plain BMPs

Because the slopes exceeded the 6% maximum in the GSWMM (2014) criteria, the current standards were not met; however, the excess slope allows for determination of the impact of a grassed slope on the surrounding surface and ground water. The locations that were tested were chosen for slopes the drained directly into saltwater marshes or saltwater marsh creeks, where concentrations of nitrogen via transport through stormwater runoff was likely. With slopes all greater than the maximum 6% standard, and all but one travel time less than the standard's minimum 5 minutes, these filter strips would be deemed too short according to Georgia stormwater standards, but they were tested in order to quantify nutrient levels in the runoff.

Nitrogen was found in both surface and groundwater at the sites. Total inorganic nitrogen (TIN) levels found in surface water ranged from 8 µM to 263 µM with an average of 74.0 ± 3.8 µM (Figure 62), with measurable concentrations of nitrate, nitrite, and ammonium detected (Figure 63, Figure 64, nitrite was not mapped as it was only detected in one sample in low concentration (PA-08)).

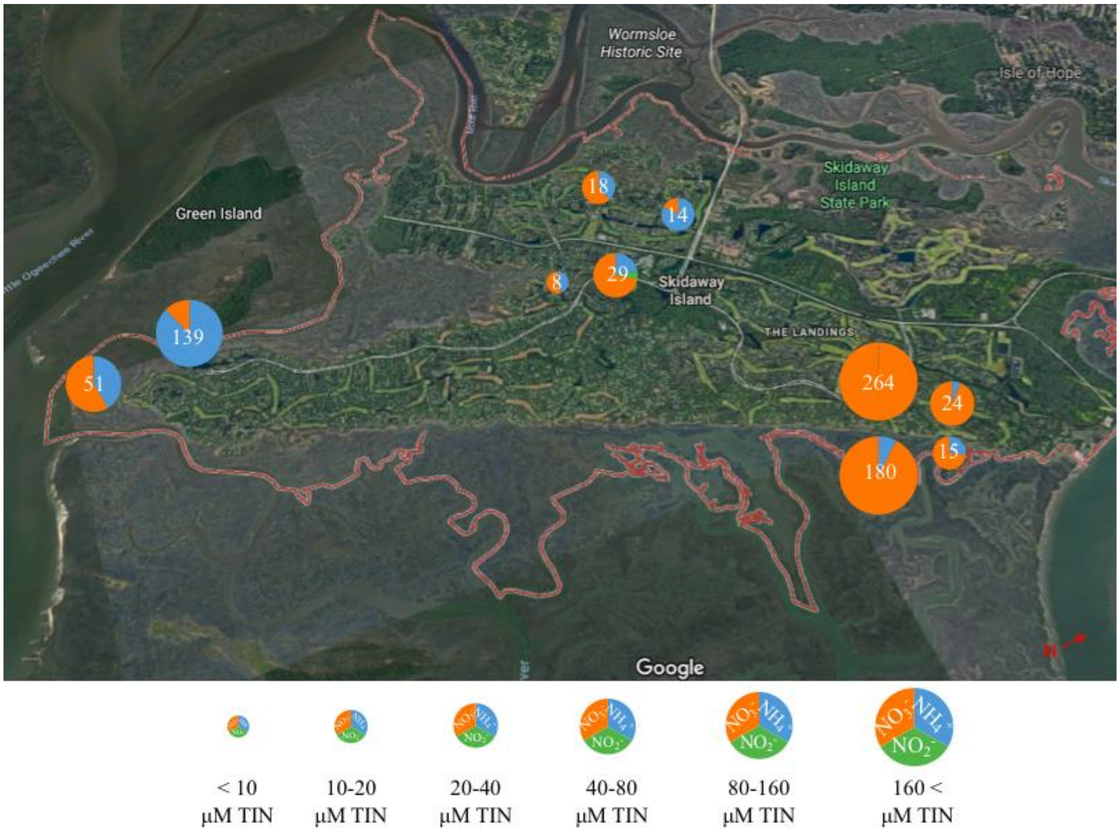


Figure 62. Map-Charts. Values of TIN shown in white, representing percentage of NO3- (orange), NH4+ (blue), and NO2- (green).

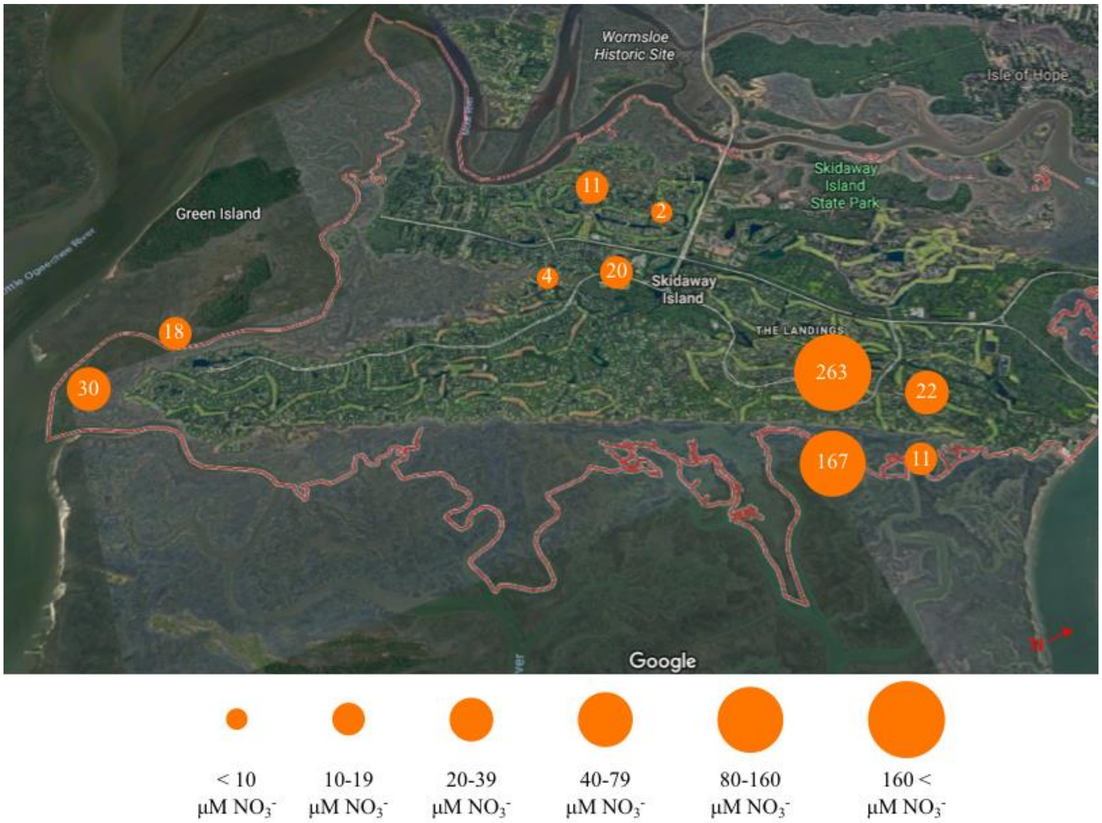


Figure 63. Map-Charts. Nitrate concentrations in surface water around Skidaway Island.

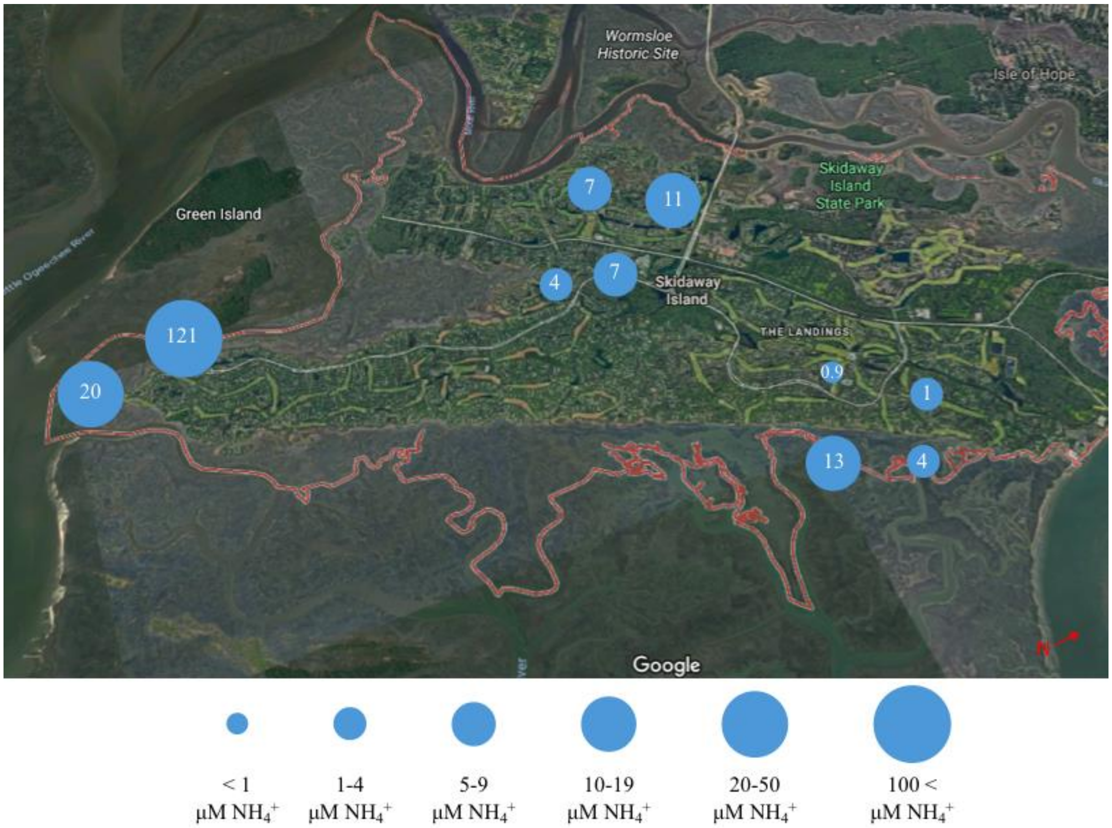


Figure 64. Map. Ammonium concentrations in surface water around Skidaway Island.

For the tested groundwater samples, TIN concentrations ranged from 11.7 µM to 223.9 µM with an average of 84.7 ± 6.2 µM, with no detectable trend (Figure 65). Similarly, nitrate concentrations did not follow a clear trend; however, its concentration (Figure 66) was very similar to that of TIN, indicating that nitrate is the dominant form of nitrogen in the groundwater wells. Ammonium concentrations increased as the wells approached the saltwater marshes (Figure 67).

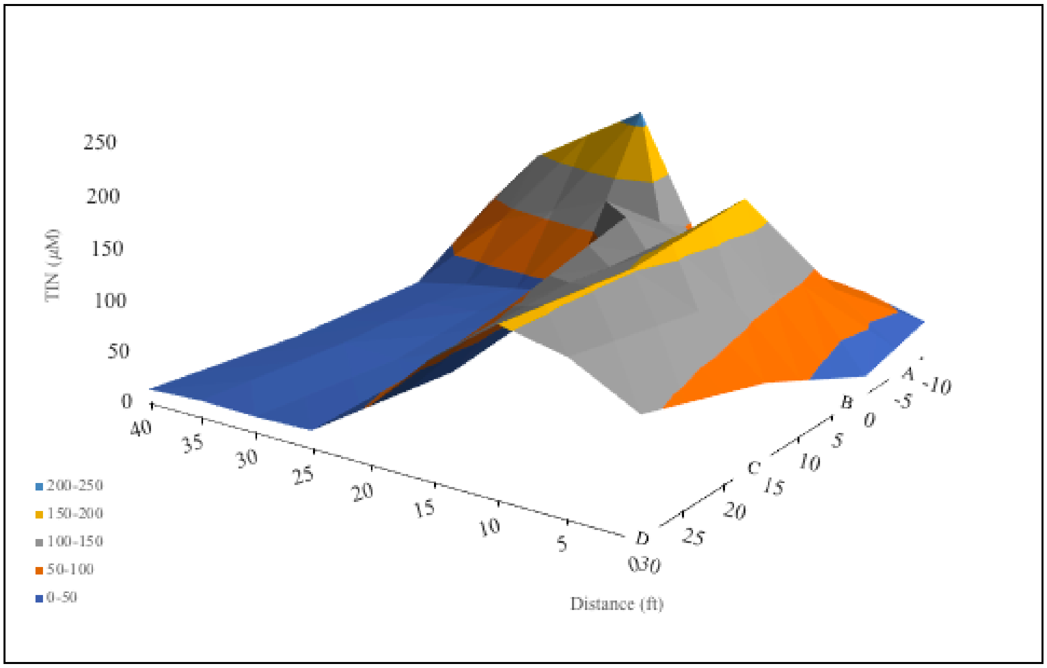


Figure 65. Chart. TIN concentrations found in the groundwater in relation to well location. Distance (0,0) is well B7.5, the well located most closely to the saltwater marshes.

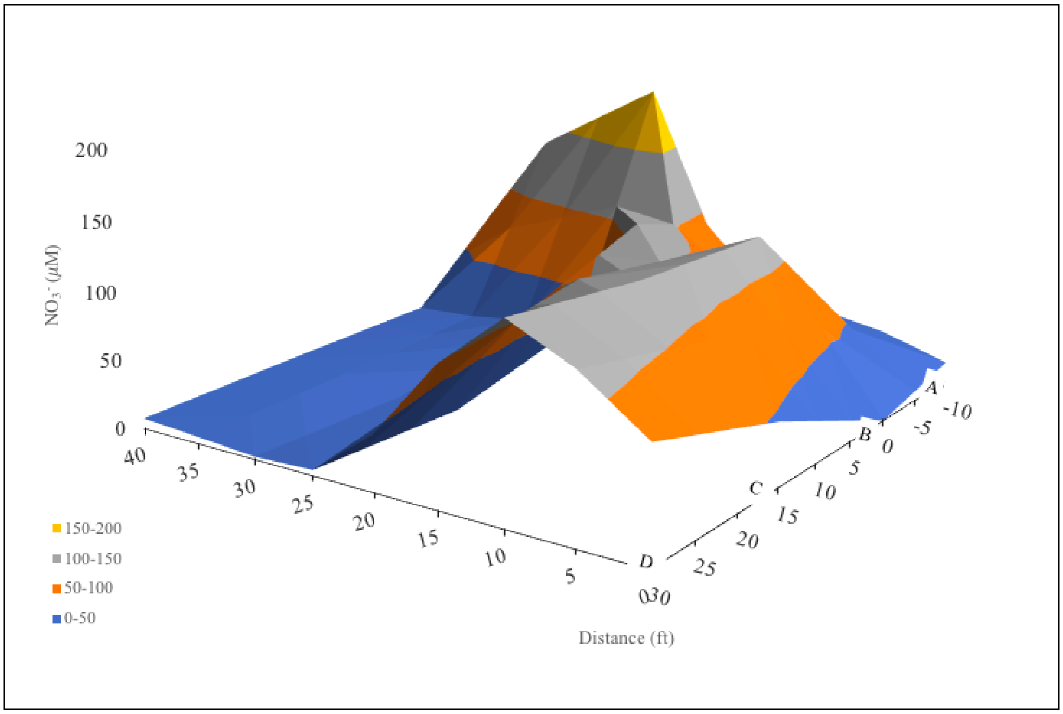


Figure 66. Chart. Nitrate concentrations found in the groundwater in relation to well location. Distance (0,0) is well B7.5, the well located most closely to the saltwater marshes.

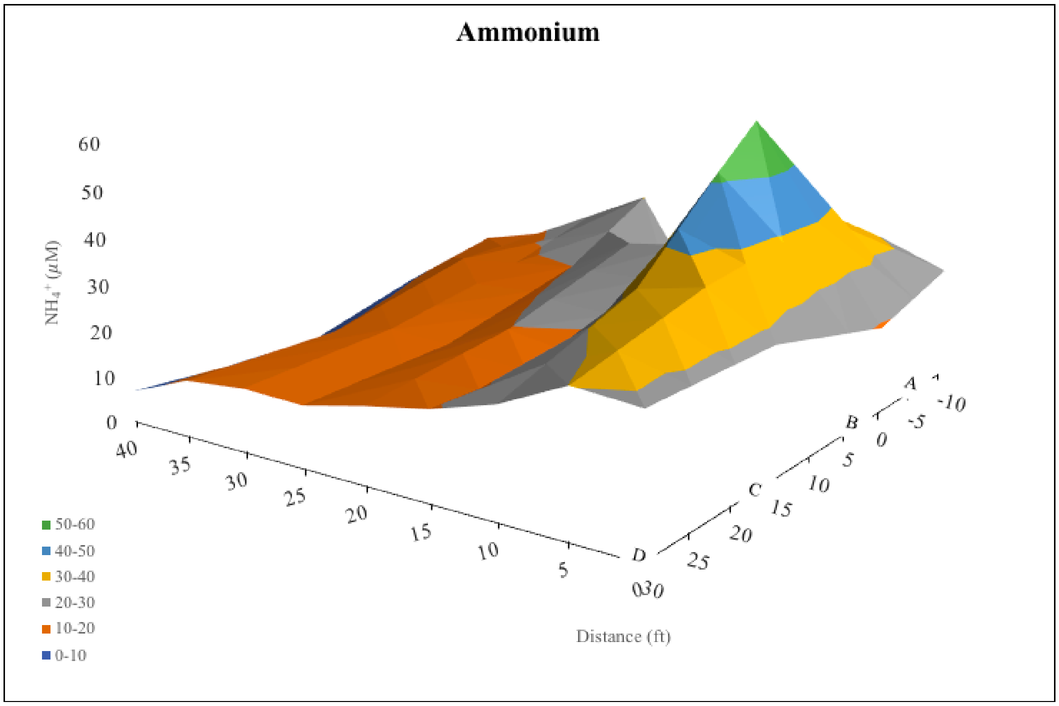


Figure 67. Chart. Ammonium concentrations found in the groundwater in relation to well location. Distance (0,0) is well B7.5, the well located most closely to the saltwater marshes.

SUMMARY: BMP FIELD TESTS

For the dry swale/sand filter BMP and the bioretention BMP that were tested, the measured contaminant levels at inlet and outlet samples showed that the first flush concentrations for the measured contaminants were notably higher at BMP inflow compared to the BMP outflow at the initiation of the storm event. For the case of the sand filter, contaminant concentrations (including turbidity, total suspended solids, total dissolved solids, nutrients, and heavy metals) were significantly decreased as the stormwater was treated by the sand filter. Based on the measured contaminant concentration in the first flush, removal efficiencies of each BMPs (dry swale with a sand filter and bioretention basin) were determined (Table 7 and Table 10). In addition, stormwater conditions such as antecedent dry condition, precipitation amount, and rainfall intensity influenced the contaminant levels measured at the inlet and outlet of BMPs. Based on the monitored storm events, both types of BMPs have been performing effectively under current field conditions. Detailed results for individual samples taken at each BMP can be found in Appendix A. For the coastal plain hydrogeology, tests were performed on slopes that were selected to mimic filter strips, but with higher slope angles than are constructed for GDOT under Georgia Stormwater rules. Analysis of surface water samples for total inorganic nitrogen revealed that the concentration of TIN measured in surface water samples taken at the base of the slopes increased as slope angle was increased (Figure 68), indicating that removal percentages for nutrients may be negatively impacted by steeper slope angles. As part of this scope of this project, GDOT requested measurement of the hydraulic conductivity of the GDOT specified mix for topsoil for use in BMPs such as bioretention basins; those data are included in Appendix B.

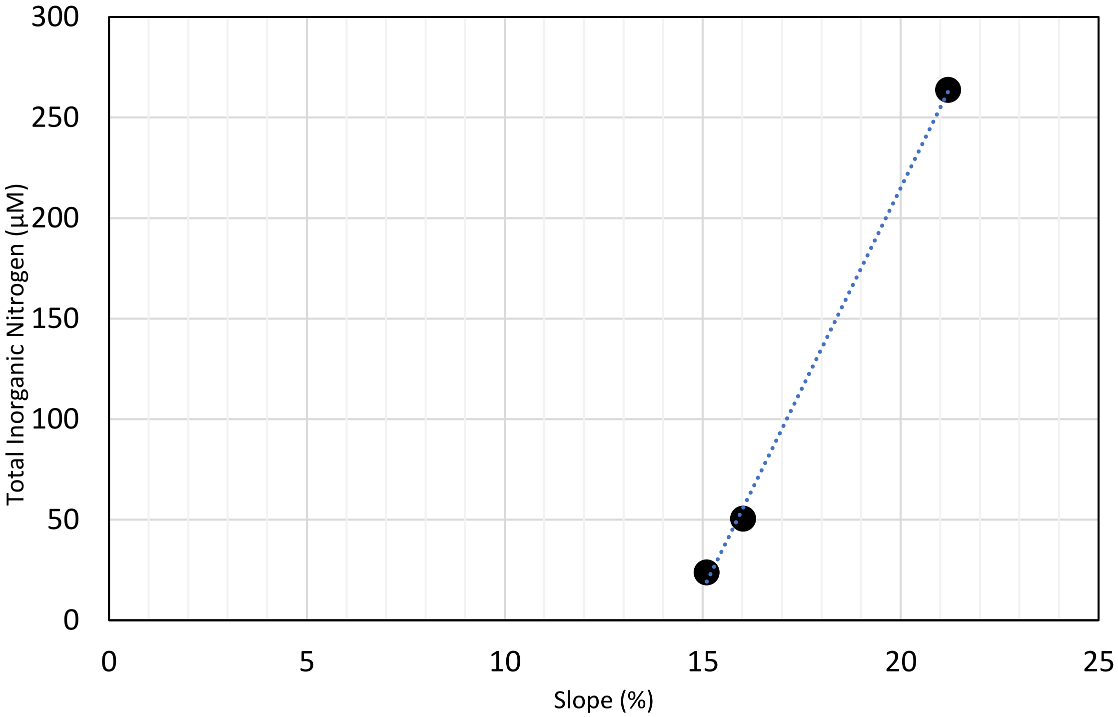


Figure 68. Graph. TIN concentrations in surface water determined as a function of slope angle.

CHAPTER 4. STATISTICAL ANALYSIS OF THE EFFICIENCY OF SAND FILTERS FOR TYPICAL POLLUTANTS

In order to assess the impact of dimensions of a BMP on field performance, data for evaluating the removal performance and dimensions of sand filters was obtained from the International Stormwater BMP Database (International Stormwater Database). The original objective of the database was to enable long-term scientific research regarding the factors affecting BMP performance. It was developed using a combination of literature review, of studies conducted prior to 1999, along with ongoing data entry from various agencies and independent researchers. The influent and effluent pollutant data specific to sand filters (Table 11) was extracted from the database for the purpose of this analysis. The pollutants selected to assess the performance of the sand filter were pH, turbidity, temperature, total suspended solids (TSS), total dissolved solids (TDS), dissolved and total heavy metals namely, lead (Pb), zinc (Zn), copper (Cu), dissolved and total phosphorus (P), nitrogen and oxides of nitrogen.

Table 11. Design Details of Sand Filters Used in the Analysis (International Stormwater Database).

BMP Name	Permanent Pool Volume Upstream of Filter Media	Permanent Pool's Surface Area	Permanent Pool's Length	Media Filter's Surface Area	Type and Depth (or Thickness) of Each Filter Media Layer
Appleyard Drive Delaware Sand Filter	13.5 m^3	0.0022 ha	24.38 m	0.0022 ha	20" layer of sand in concrete box
Foothill SF	216.6 m^3	0.0102 ha	12.49 m	0.0039 ha	18 in. sand; geotextile layer; 6 in. gravel
La Costa PR	285.7 m^3	0.0179 ha	14.93 m	0.0072 ha	18 in. sand; geotextile layer; 6 in. gravel
Eastern SF	115.5327 m^3	0.0053 ha	8.99 m	0.0026 ha	18 in. sand; geotextile layer; 6 in. gravel
Delaware Sand Filter	3.7 m^3	71 ft^2	7 ft	71 ha	2" DE #57 stone; 1.5' sand ASTM C-33; Geotextile Fabric
7/8	105.6218 m^3	0.0056 ha	7.92 m	0.0031 ha	18 in. sand; geotextile layer; 6 in. gravel
Shasta Maintenance Station Full Sedimentation Austin Sand Filter	370 m^3	518 m^2	37 m	280 m^2	450 mm sand
Mountain Gate Sand Filter	-	-	-	108 m^2	460 mm sand
Termination	222.3 m^3	0.011 ha	11.9 m	0.006ha	18 in. sand; geotextile layer; 6 in. gravel
SE Landfill Sand Filter	118.8 m^3	0.144 ha	0.8 m	0.144 ha	The sand filter is constructed in a basin and consist of 0.6 meter of sand over a 0.225 meter bed of graded # 8910 stone.
Lakewood Sand Filter (95)	9.2 m^3	0.001 ha	8.2 m	0.0015 ha	12 inches of ASSHTO C-33 type sand (d50-0.85mm) underlain by a 12 inch deep fine gravel layer that is drained by a perforated pipe. The coefficient of uniformity is 5.0.
Escondido	12.2 m^3	0.002 ha	24.9 m	0.0027ha	12 in. sand; geotextile layer; 6 in. Gravel
Megginis Ck. Sand Filter	163001.5 m^3	8.150 ha	1 m	1.7993 ha	1. Graded sand to a depth of 0.76 m; 2. Filter fabric; 3. 0.91 m dolomite limestone under drain.
Airpark Sand Filter	11.8 m^3	0.0024 ha	28.8 m	0.0022 ha	17.4 in,The filter media was sand, specified to meet the requirements of ASTM C-33 concrete sand. Sieve analyses in the supply sand yielded the following results: - Effective Size: 0.125 mm - Uniformity Coefficient: 7.8
Parkrose SF	-	-	-	0.0014 ha	Sand - 2.8 ft deep

FIELD STUDY SITE AND DATA DESCRIPTION

The GDOT field site selected for monitoring stormwater runoff in a sand filter BMP was located in the City of Canton, Cherokee County, Georgia on I-575 at SR-20. I-575 is a 50 km (31 mile) long interstate spur located in north Georgia, which connects the Atlanta metropolitan area with the north Georgia mountains. Motivation for the construction of the Canton sand filter was to limit roadway runoff to the habitat of the Cherokee darter fish, which is a threatened species endemic to the Etowah river system in North Georgia. The sand filter was constructed under an agreement between GDOT and the U.S. Fish and Wildlife Service. Detailed BMP description and stormwater monitoring program for this site has been previously described (Bhatt, 2016).

The efficiency of typical sand filters for treating individual pollutants was assessed using the pre-existing data (field and database) in 3 ways. The efficiency of the various sand filters was evaluated for each rainfall event for each pollutant using scatter plots. A statistical analysis for the performance of sand filters for mitigating the different pollutants was conducted by computing the box-plots and probability plots of the influent and effluent concentrations.

The efficiency of sand filters to mitigate the various categories of pollutants (metals and total solids) was simultaneously evaluated using the k-means (Loyd, 1982) clustering algorithm. The k-means clustering algorithm partitions a dataset [X_1, X_2, X_3,….. X_p] with each 'X' being n dimensional into a pre-specified number k<n, of clusters, S = [S_1, S2, S_3,….. S_k] such that each cluster is statistically different from each other.

$$argmin_S \sum_{i=1}^{k} \sum_{X \in S_i} ||X - \mu_i||$$

μ_i= mean of S_i

The X_i dataset was 3 dimensional including the removal efficiency of the total metals (copper, lead, and zinc) and 2 dimensional including total solids. The k-means clustering algorithm then clustered the sand filters in accordance with the ability to mitigate all metals as a group, as well as for the removal of total solids. The design parameters of each cluster were then evaluated to assess the performance of sand filters in mitigating various pollutants simultaneously.

$$C = \frac{(P_i - P_o)}{(P_i)}$$

C = Removal efficiency of a pollutant

P_i = influent concentration of the pollutant

P_o = effluent concentration of the pollutant

TYPICAL HIGHWAY RUNOFF CHARACTERISTICS

Because the dominant treatment mechanism of sand filters is filtration, they are typically used for removal of suspended solids. However, when combined with the use of sedimentation basins sand filters may also assist in attenuation of runoff and settlement of suspended solids. The statistical characteristics of the pollutants obtained from International Stormwater Database are given in Figure 69 - Figure 72, with the distribution of most incoming pollutants following a log normal distribution, implying that the occurrence of extreme loadings is less probable. The mean and standard deviation of the concentration of the total dissolved solids is higher than that of total suspended solids implying that treatment of dissolved solids in stormwater runoff is an important component (Figure 69). The mean pH value of stormwater runoff is slightly acidic (pH = 6.9) and is slightly acidic (pH < 7) rather than basic (pH > 7). The mean temperature of stormwater runoff is 9.2 ˚C (48.6 °F) while the lognormally distributed turbidity values have a mean of 47.8 NTU.

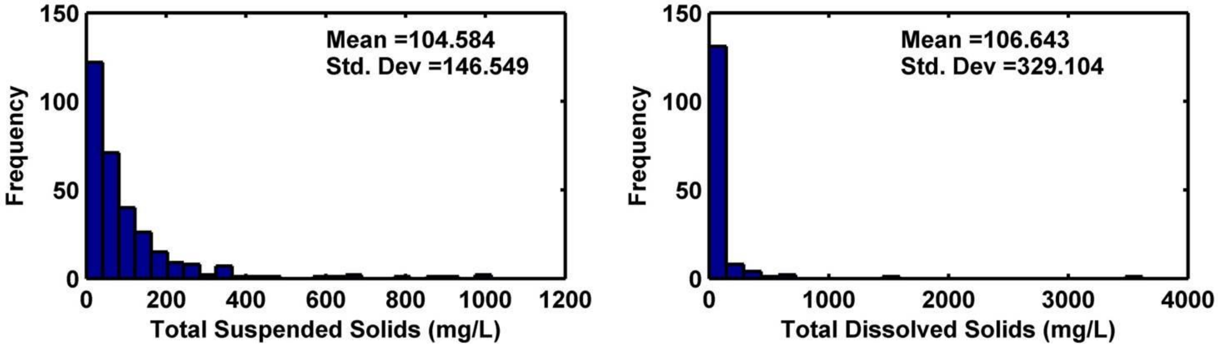


Figure 69. Charts. Distribution of total suspended and dissolved solids observed at inlet of sand filters (International Stormwater Database).

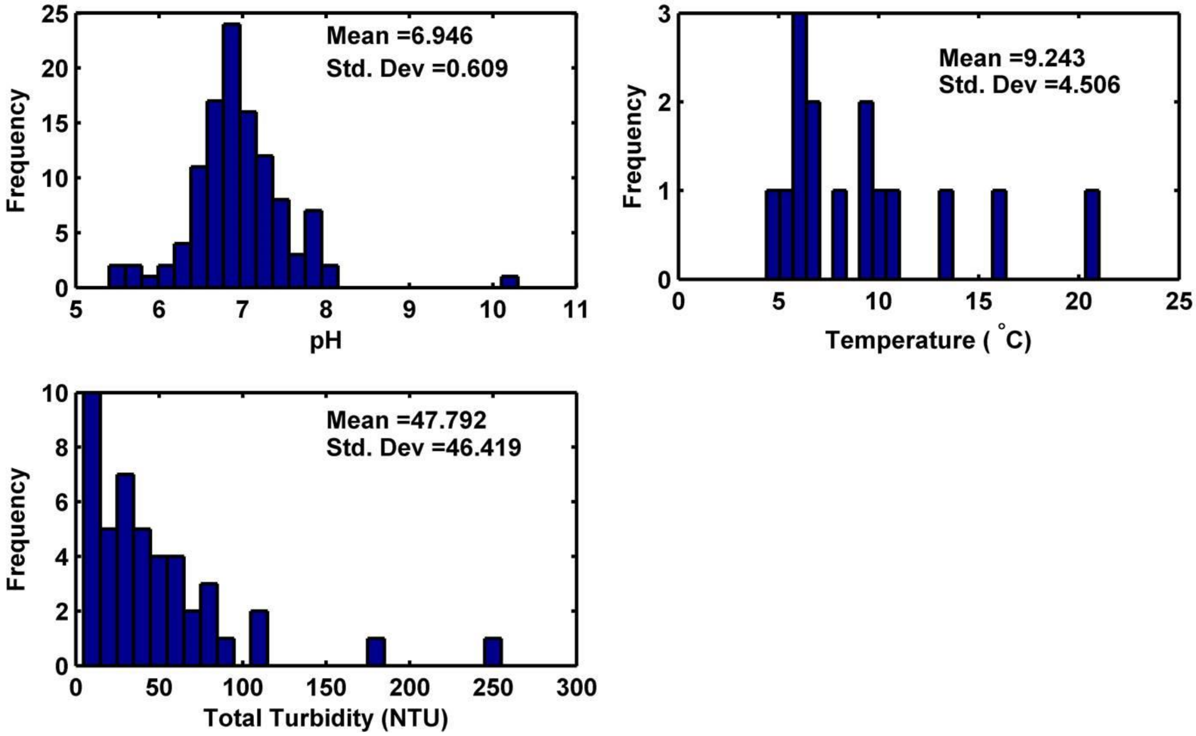


Figure 70. Charts. Distribution of pH, temperature and turbidity observed at inlet of sand filters (International Stormwater Database).

The total concentrations (suspended + dissolved) of nutrients as well as heavy metals and the dissolved concentrations of the pollutants are provided in Figure 71 and Figure 72, respectively. The log normal form of distribution for the pollutants implies that the frequency of events where the concentration of pollutants is extremely high is less than those for low concentrations. Based on the concentrations of heavy metals, zinc (Zn) is the most abundant (mean 126.8 μg/L), followed by copper (Cu), and lead (Pb). The ratio (R) of mean dissolved to mean total concentration of the pollutants (Zn = 0.61, Cu = 0.38, Pb = 0.12, P = 0.56) suggests that mitigating the pollution caused by different contaminants would require treatment of both suspended and dissolved solids. Mitigation of Zn and P (R > 0.5) would require treatment of dissolved pollutants, whereas most of Cu and Pb could be treated by treating for suspended solids.

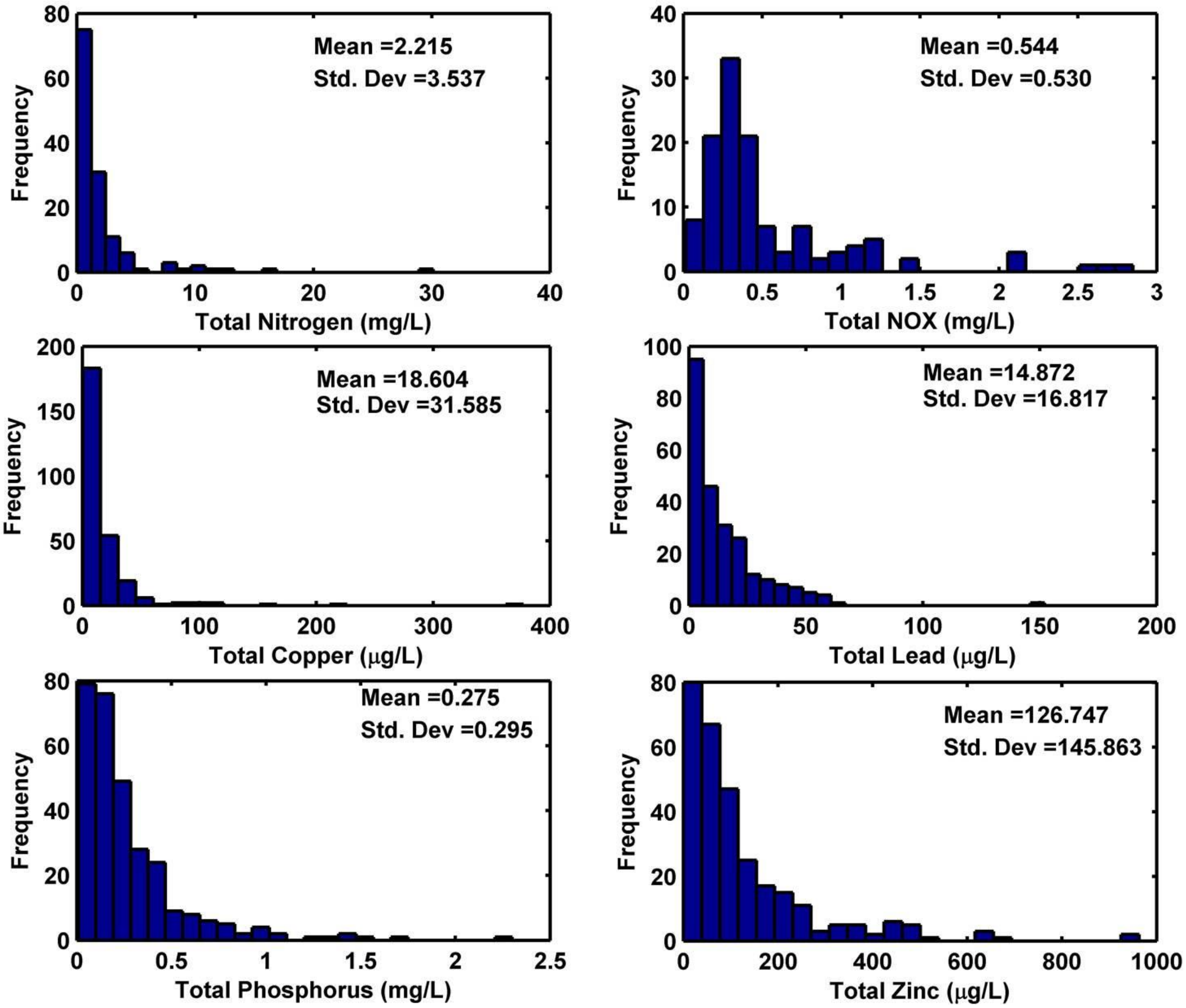


Figure 71. Charts. Distribution of total nitrogen, NO_X, copper, lead, phosphorus and zinc observed at inlet of sand filter (International Stormwater Database).

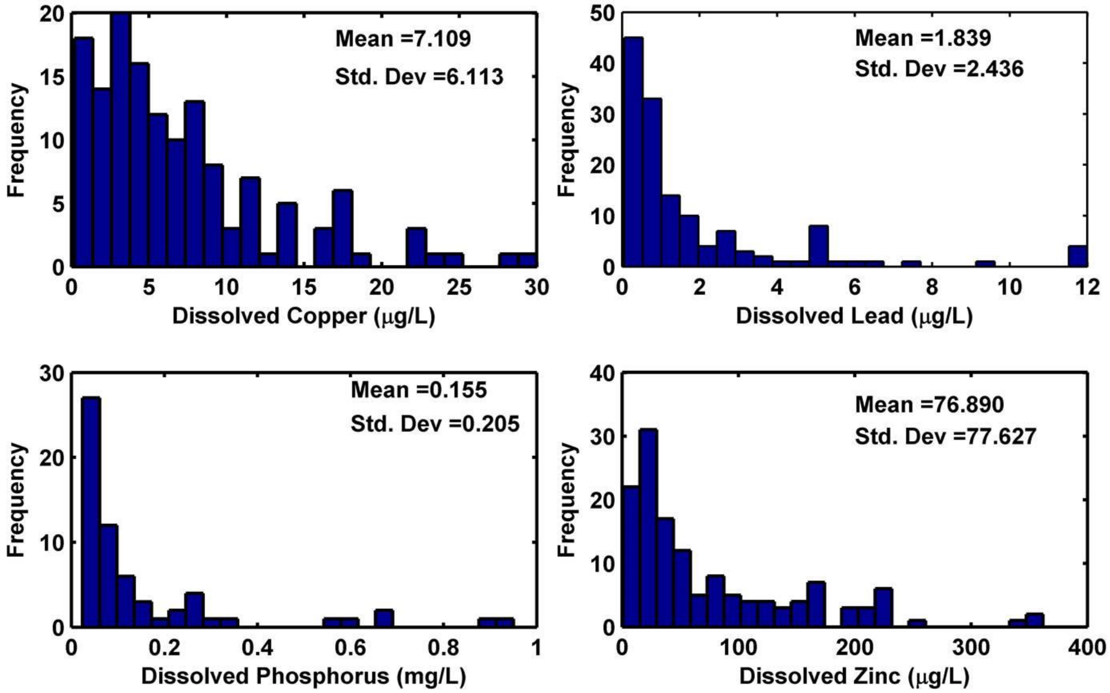


Figure 72. Charts. Distribution of dissolved copper, lead, phosphorus and zinc observed at inlet of sand filter.

The efficiency of sand filters in treating suspended and dissolved pollutants was chosen for statistical analysis to quantify the impact of BMP dimensions on field performance and is described using three types of plots. The first type is scatter plots, which describe the respective effluent concentrations of different pollutants given the influent concentrations for different storm events. The second type is box plots, which describe the distribution of influent and effluent concentrations of different pollutants and the third type are the probability plots of the influent and effluent concentrations, which statistically explain the efficiency of sand filters in treating pollutants based on different influent concentrations.

The scatter plots delineate the effluent concentrations corresponding to influent concentrations for different storm events. The scatter plot for the total suspended and dissolved solids (Figure 73) reveals the high removal efficiency of sand filters (data points below the 1:1 line) in treating suspended solids, but not dissolved solids. This follows from the typical understanding of sand filter treating solids through the process of filtration and removal of solid particles. The absence of a correlation between the influent and effluent concentration of suspended solids signifies that regardless of the input suspended solid concentration, the sand filter performs well for removal.

The pH of the effluent is typically a little higher (Figure 74) than the influent concentration and is highly correlated, implying that the effect on pH treatment by the sand filter is dependent on the input pH. The temperature of the effluent concentration of the stormwater is similar to the influent temperature except for when the temperature of the influent concentrations is relatively high (~20°C). This could potentially be attributed to detention basins which allow time for the cooling of incoming water or thermal diffusion in the filter media indicating filter media acts as a heat sink. Similar to results for suspended solids, turbidity of effluent is also not correlated to influent concentrations and gets treated relatively well. This occurs because most of the turbidity is caused as a result of suspended solids.

The scatter plots for the nutrient concentrations reveal that a majority of the total phosphorus is mitigated by the sand filter whereas neither dissolved phosphorus, total NO_X or nitrogen is mitigated. On the contrary, the amounts of NO_X compounds tended to increase slightly in the effluent. NO_X represents the quantity of nitrite and nitrate together. The increase in effluent concentration of NO_X could potentially be due to oxidation of nitrogen in the stormwater runoff before reaching the BMP outlet. The results for metals show that total and dissolved copper is not mitigated well by the sand filter whereas zinc and lead (total and dissolved) is mitigated relatively well.

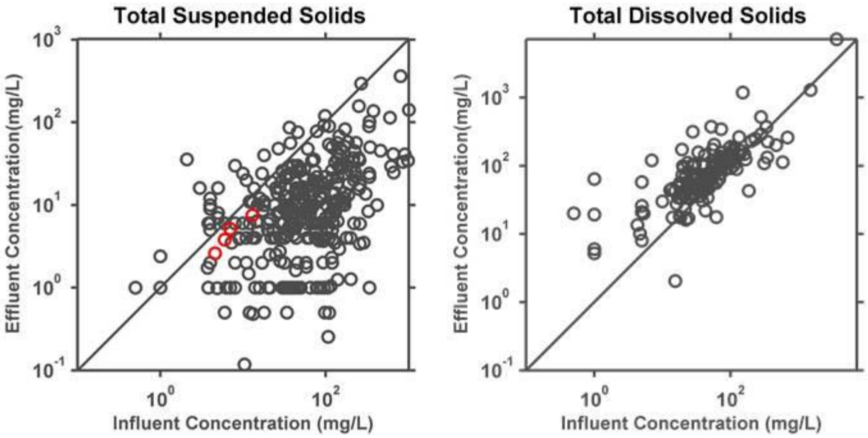


Figure 73. Charts. Scatter plot of influent v/s effluent concentration of total suspended and dissolved solids in stormwater runoff.

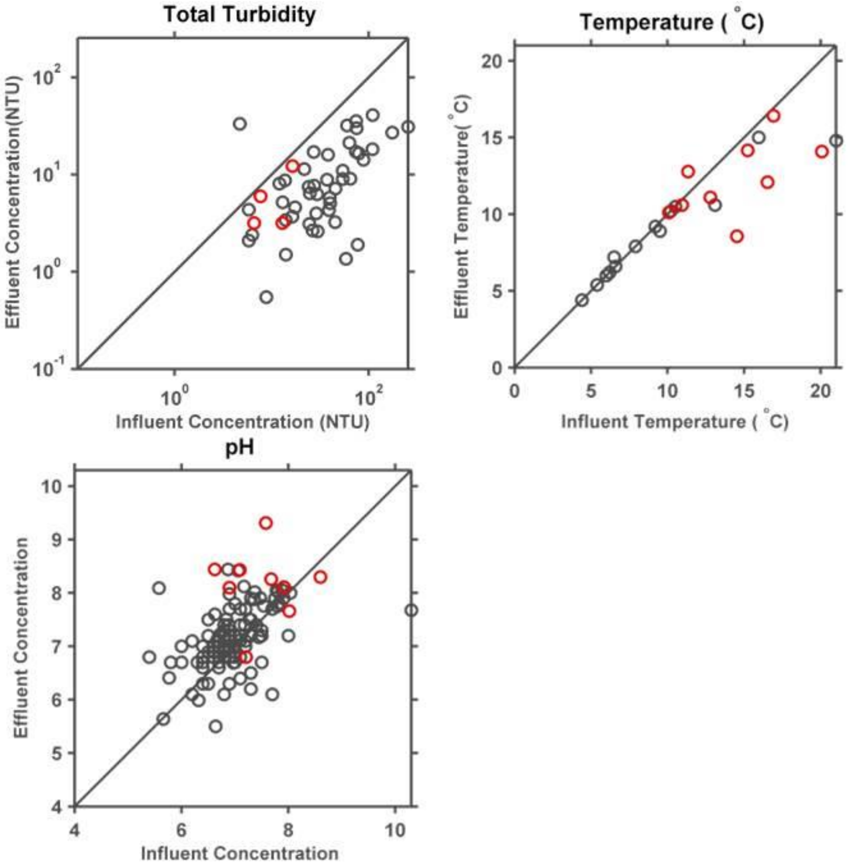


Figure 74. Charts. Scatter plot of influent vs effluent concentration of total pH, temperature and turbidity in stormwater runoff.

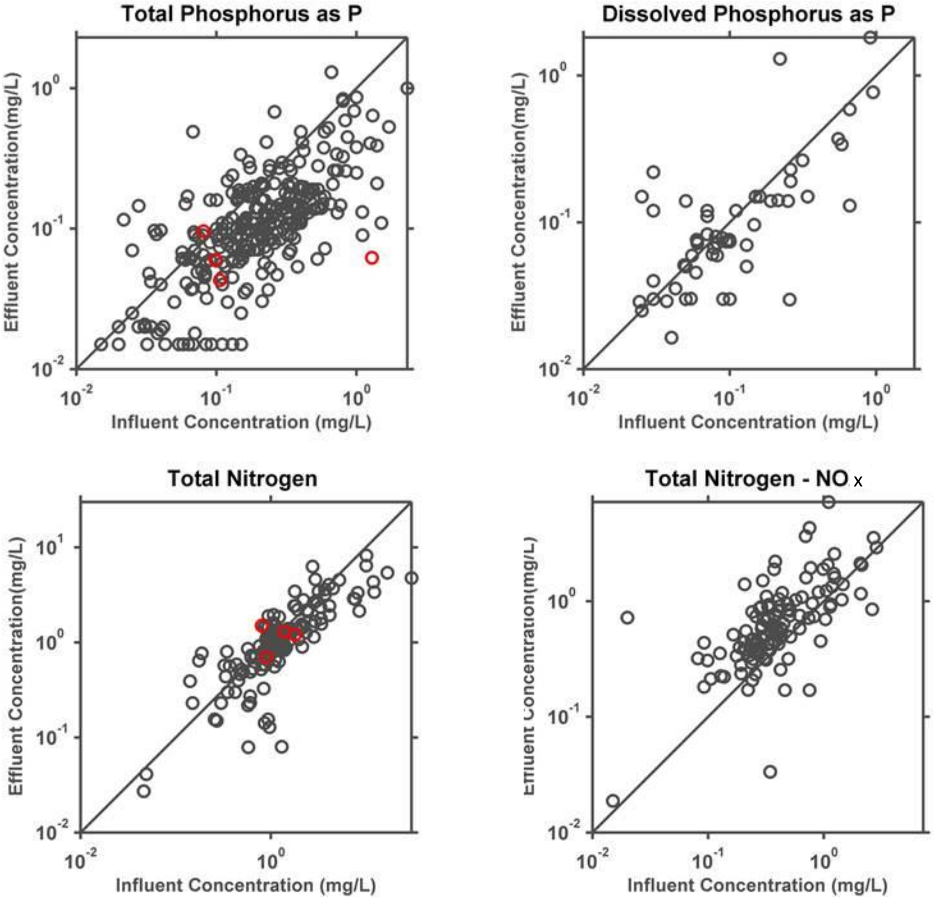


Figure 75. Charts. Scatter plot of influent vs effluent concentration of total and dissolved phosphorus, total NOx and Nitrogen in stormwater runoff.

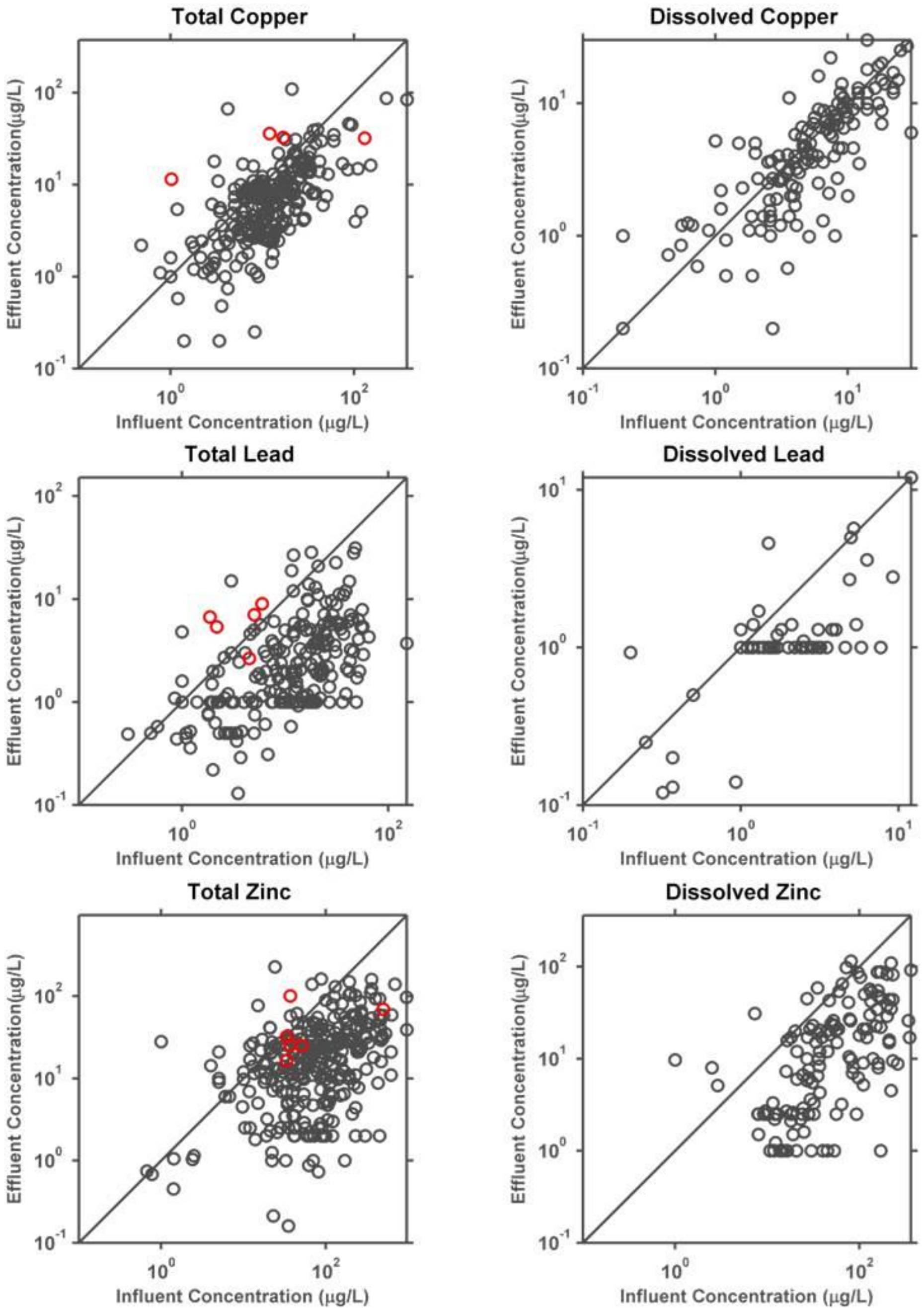


Figure 76. Charts. Scatter plot of influent vs effluent concentration of total and dissolved metals in stormwater runoff.

Kruskal-Wallis test (or the non-parametric equivalent of ANOVA) was employed to assess a statistically significant difference in median values of influent and effluent concentrations of the various pollutants. The p-values for the test are provided in

Table 12 while the corresponding box plots are provided in Figure 77 - Figure 80. It was found that a statistically significant difference (p-values < 0.05) in median concentrations was found in all parameters except temperature, total nitrogen, dissolved phosphorus, and dissolved copper.

While the median concentration of total suspended solids decreased, the median concentration of total dissolved solids increased slightly in the effluent (Figure 77). This implies the effectiveness of the sand filters in treating suspended solids but not dissolved solids. The increase in effluent concentration of dissolved solids could potentially occur because of the dissolution of some solids trapped either within the sand filter or detention basins during the transit of the influent stormwater to the BMP outlet. The pH values increased slightly in the effluent, but the turbidity decreased. The decrease in turbidity follows the effective removal of suspended solids by the BMP. The increase of pH on the other hand implies some reduction occurring in the system either during the transit between inlet and outlet or in the detention basin.

Table 12. P-values of the Kruskal-Wallis Test for Influent Versus Effluent Concentrations.

Parameter	**p-value**
TSS	<0.001
TDS	<0.001
pH	0.007
Temperature	**0.917**
Turbidity	<0.001
Total Nitrogen	**0.156**
Total NO_X	<0.001
Total Phosphorus	<0.001
Dissolved	**0.633**
Total Copper	<0.001
Dissolved Copper	**0.113**
Total Zinc	<0.001
Dissolved Zinc	<0.001
Total Lead	<0.001
Dissolved Lead	0.0153

The total copper concentration decreased, but there was no significant difference between the dissolved and total copper concentration. The concentration of the other two metals decreased significantly in terms of both total metals, as well as dissolved metal. Total phosphorus and nitrogen decreased slightly in the effluent, but there were no statistically significant differences between the NO_X and dissolved phosphorus concentrations.

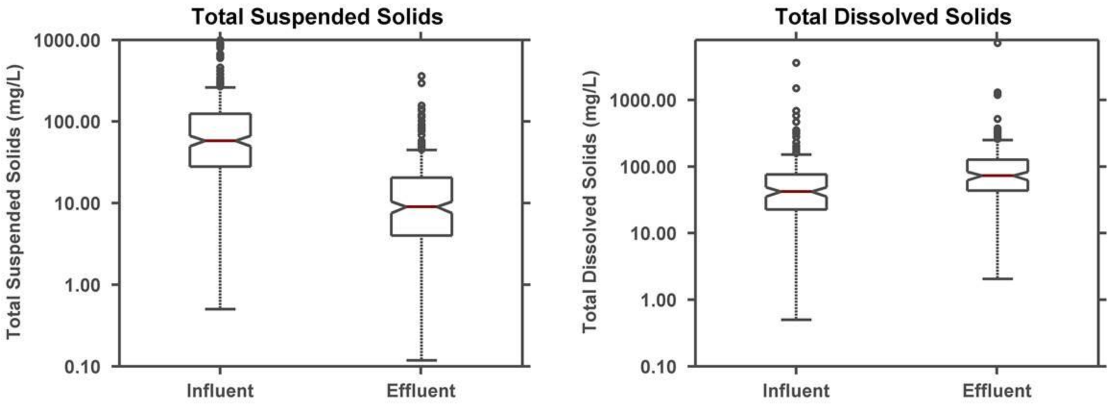


Figure 77. Diagram. Box plot of influent and effluent concentration of total and dissolved metals in stormwater runoff.

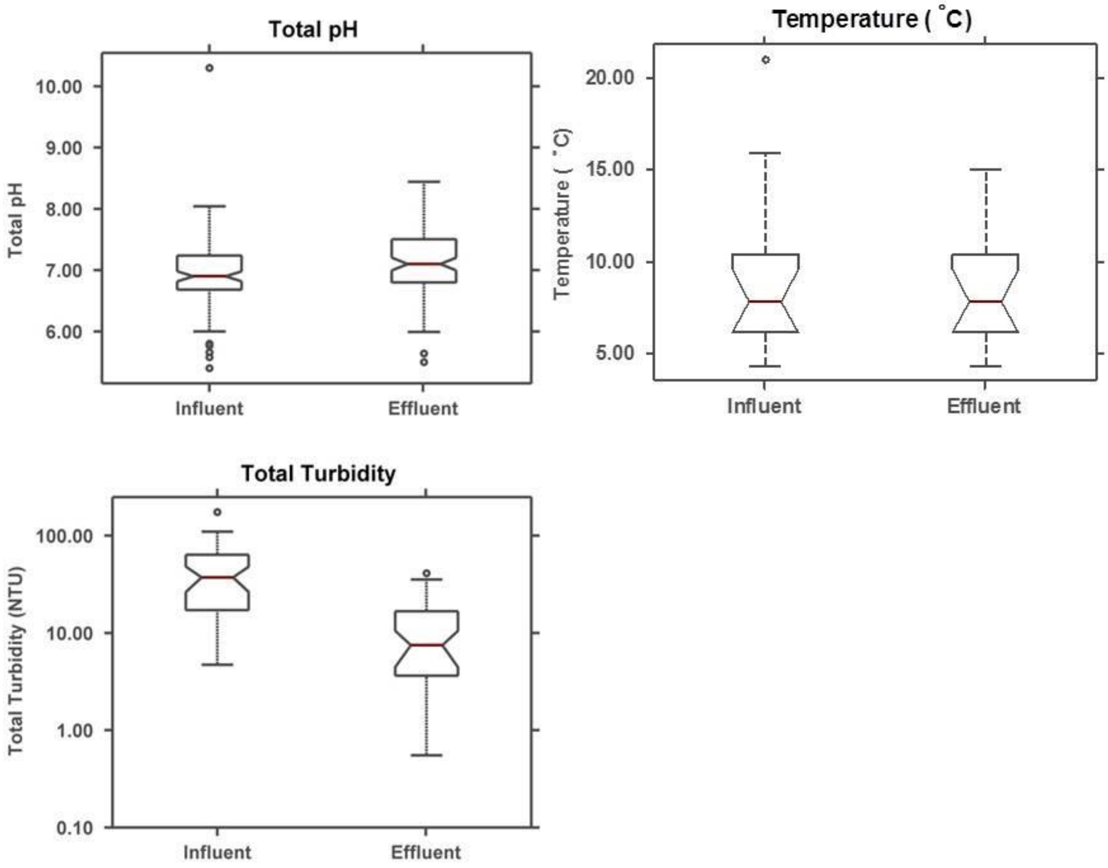
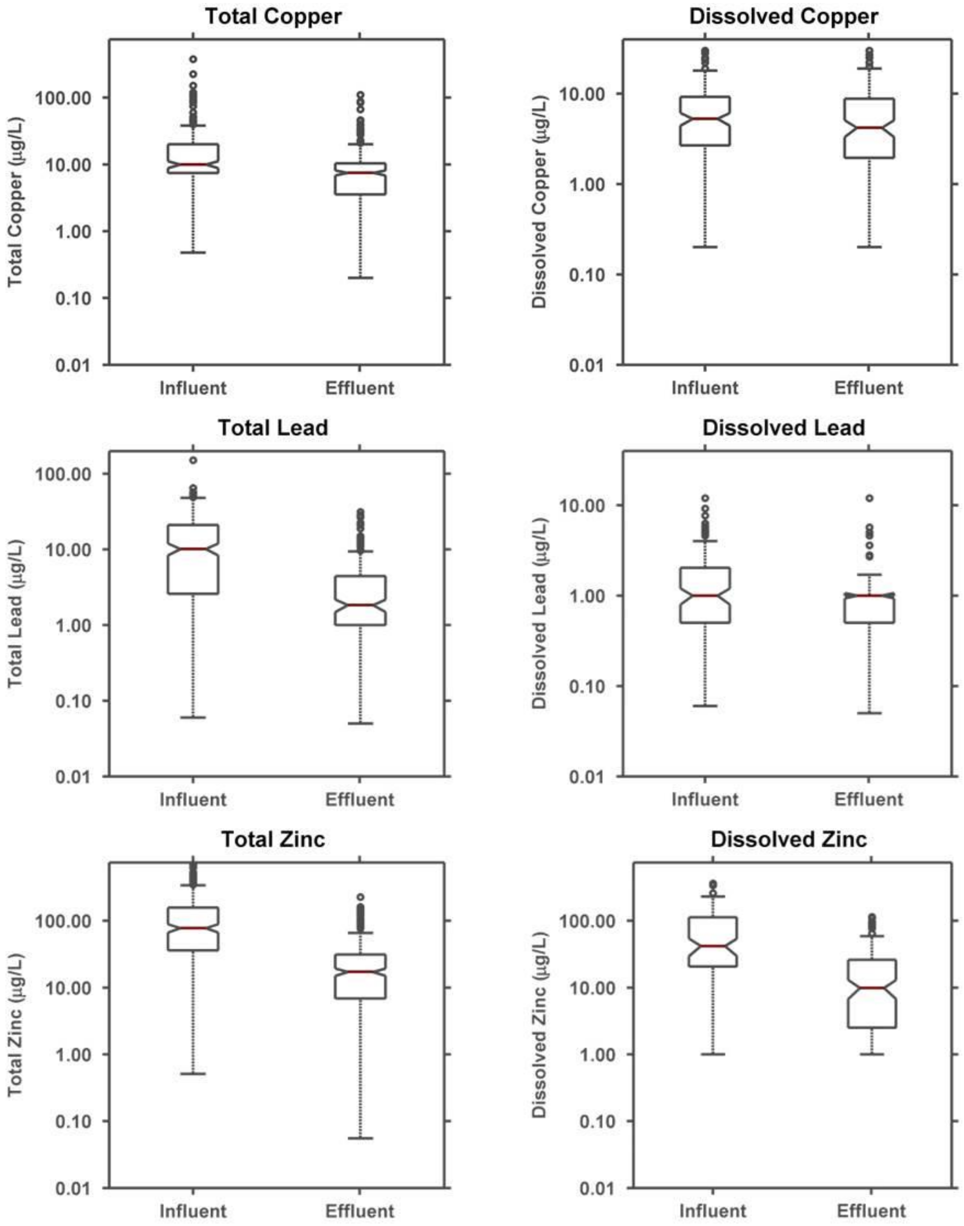


Figure 78. Diagram. Box plot of influent and effluent concentration of total pH, temperature and turbidity in stormwater runoff.



Total Copper

Dissolved Copper

Total Lead

Dissolved Lead

Total Zinc

Dissolved Zinc

Figure 79. Diagram. Box plot of influent and effluent concentration of total and dissolved metals in stormwater runoff.

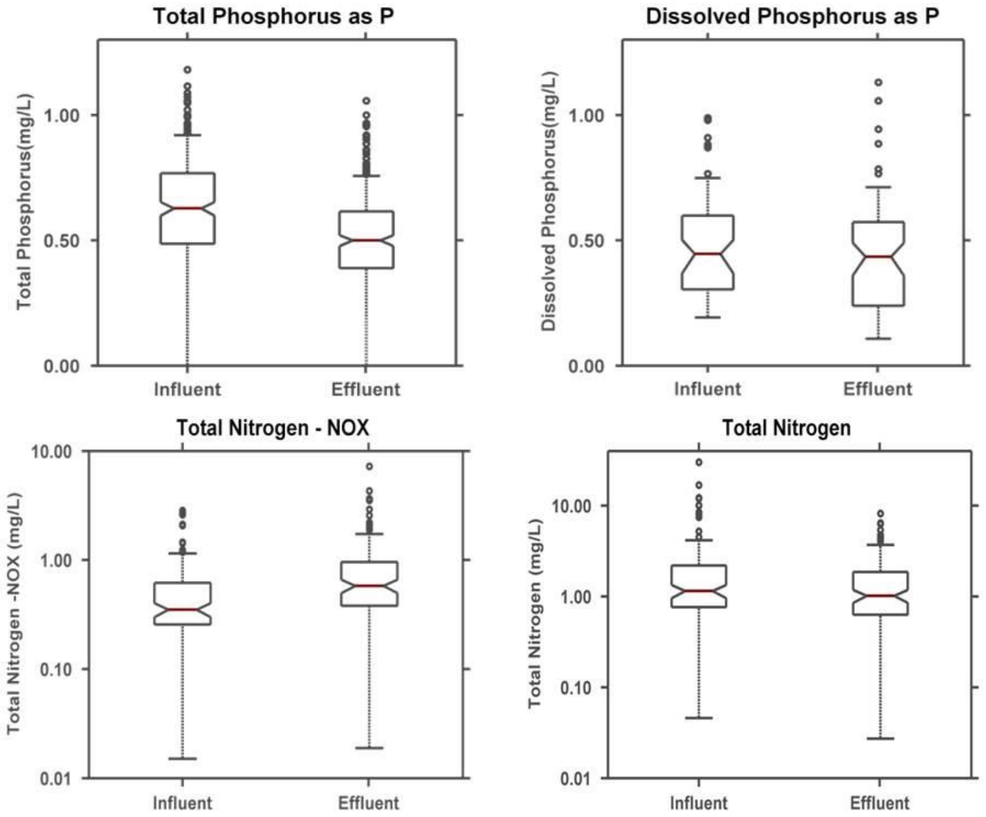


Figure 80. Diagram. Box plot of influent and effluent concentration of total and dissolved phosphorus, total NO_X and nitrogen in stormwater runoff.

The probability plots (Figure 81 - Figure 84) describe the fraction (y-axis) of times, a value less than the corresponding concentration (x-axis) was observed. Distinct influent and effluent probability curves reflect differences between the influent and effluent concentrations, whereas overlapping curves reflect no differences. For example, if the 0.95 (y-axis) values correspond to 100 mg/L on the influent probability curve, it implies that 95% of the time, the influent concentrations remain less than 100 mg/L. If the effluent curve lies to the left of the influent curve, it represents effective mitigation. Figure 81 shows that the total suspended solids are effectively mitigated (effluent curve to the left of the influent probability curve), but the total dissolved solids are not. In fact statistically, the effluent concentration of the total dissolved solids remains higher than the influent (curve lying to the right of the influent curve). Total turbidity is also effectively mitigated (Figure 82), while the probability curves for temperature are almost identical overlapping, implies that there is no effect of sand filters on the thermal pollution. The sand filter does little to alter the pH of the stormwater runoff. It was also observed that the pH of the influent is greater than ~7 over 25% of the times whereas the pH is higher than 7 in the effluent for more events than it is the influent. This implies that the influent is more acidic than the effluent.

The total concentration of metals (Figure 83) reflects some level of mitigation of metals in stormwater runoff through separation between the probability curves for the influent and effluent. The dissolved concentration of zinc also shows distinct mitigation as a result of the sand filter. However, there is no change in the concentration probability curves of dissolved copper and lead, implying the ineffectiveness of the sand filter for the two metals statistically.

The sand filter performs variably with respect to nutrients (Figure 84). The total concentration of phosphorus is effectively mitigated through the sand filter whereas the dissolved phosphorus is not. On the other hand, the concentration of NO_X is statistically higher in the effluent than in the influent. The concentration of total nitrogen as N on the other hand is unaffected by the presence of the sand filter.

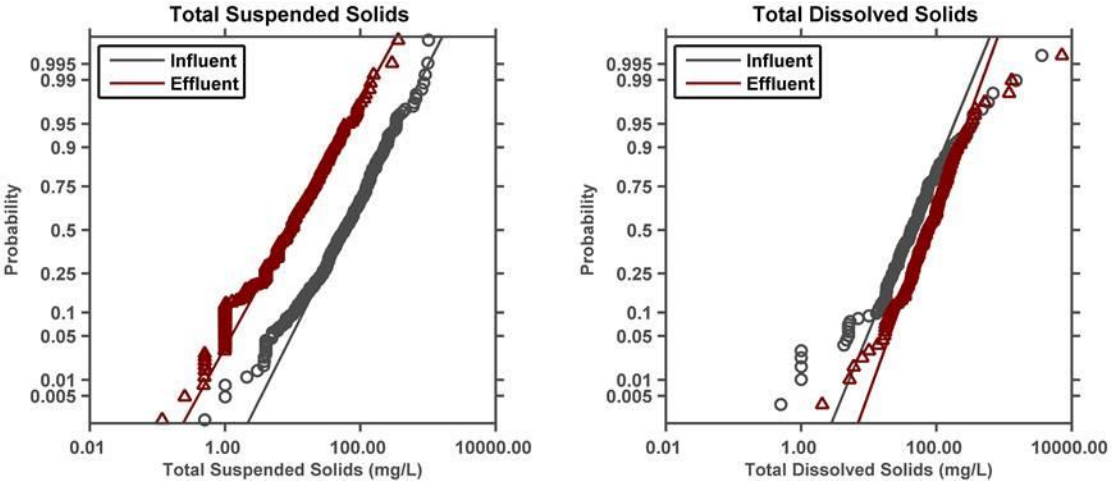


Figure 81. Graph. Probability plot of influent and effluent concentration of total and dissolved solids in stormwater runoff.

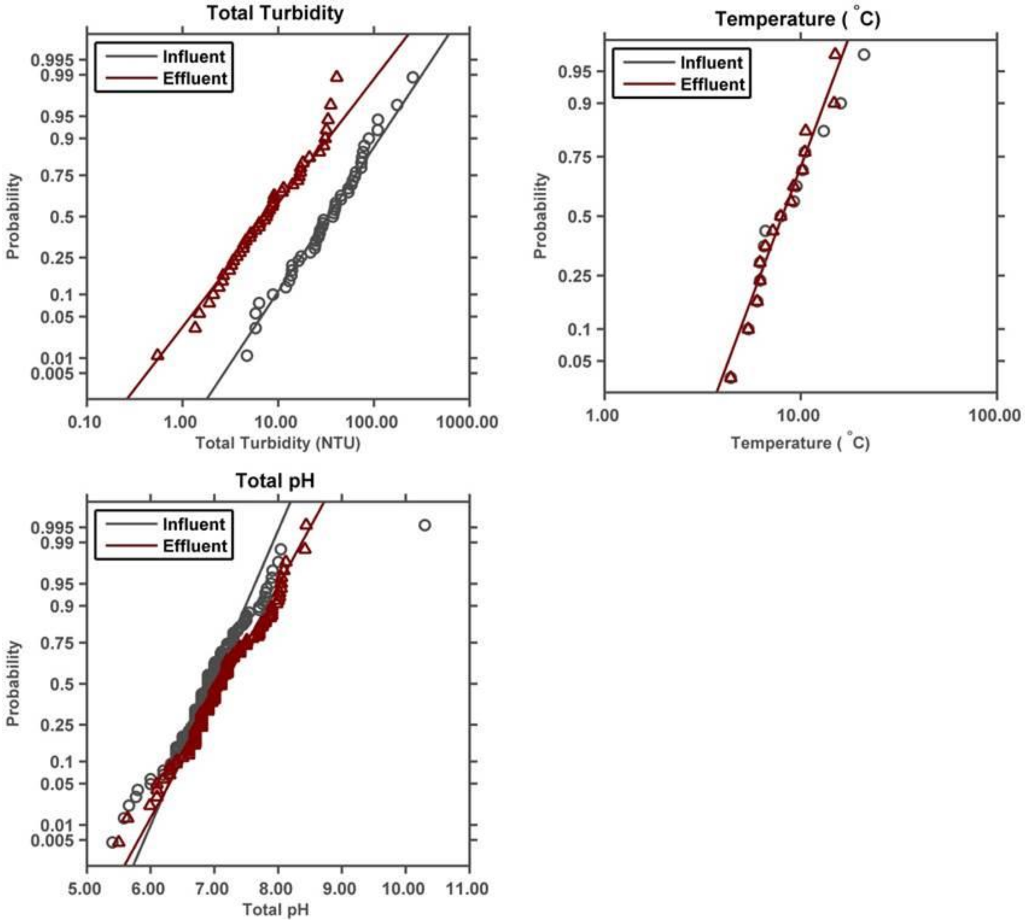


Figure 82. Graph. Probability plot of influent and effluent concentration of total pH, temperature and turbidity in stormwater runoff.

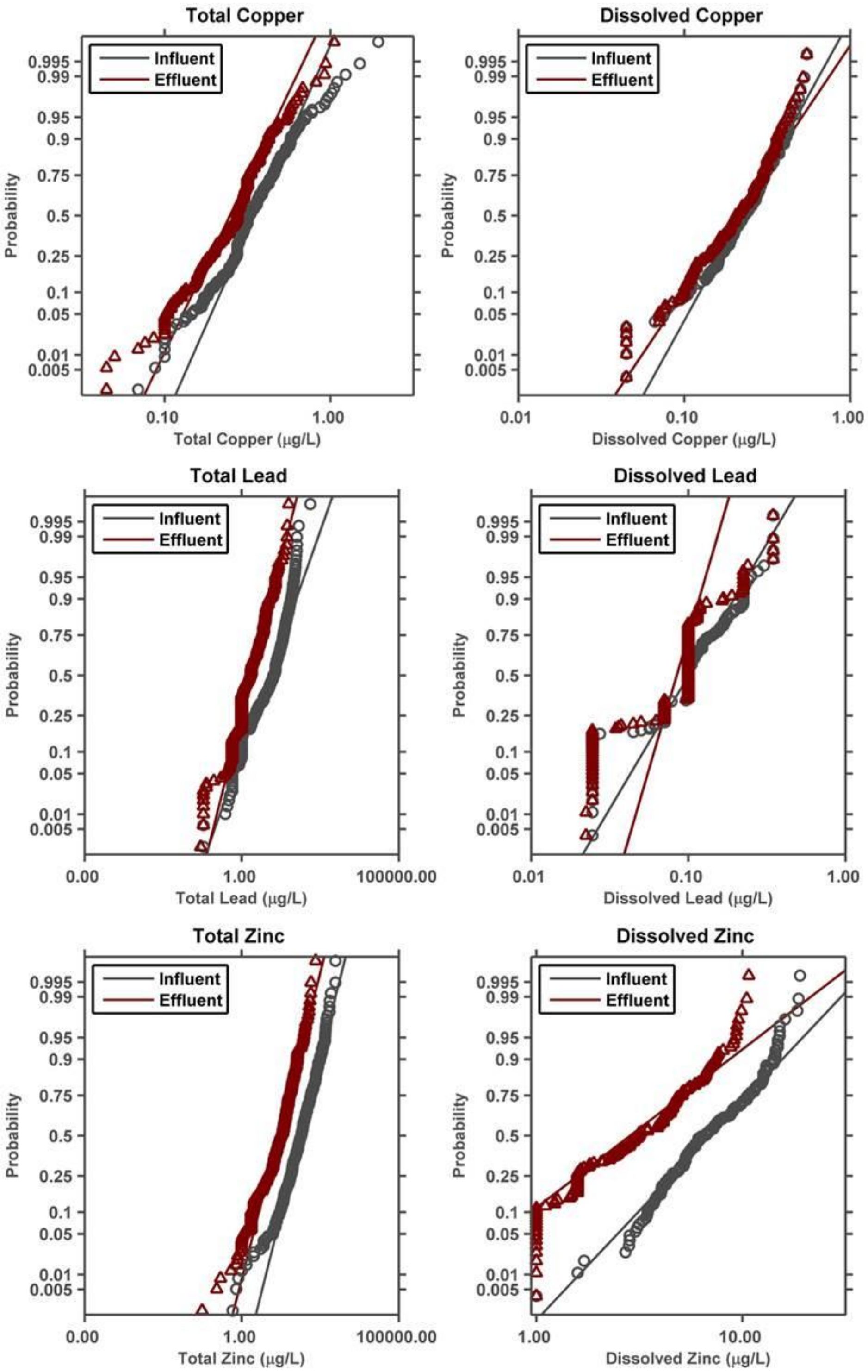


Figure 83. Graph. Probability plot of influent and effluent concentration of total and dissolved metals in stormwater runoff.

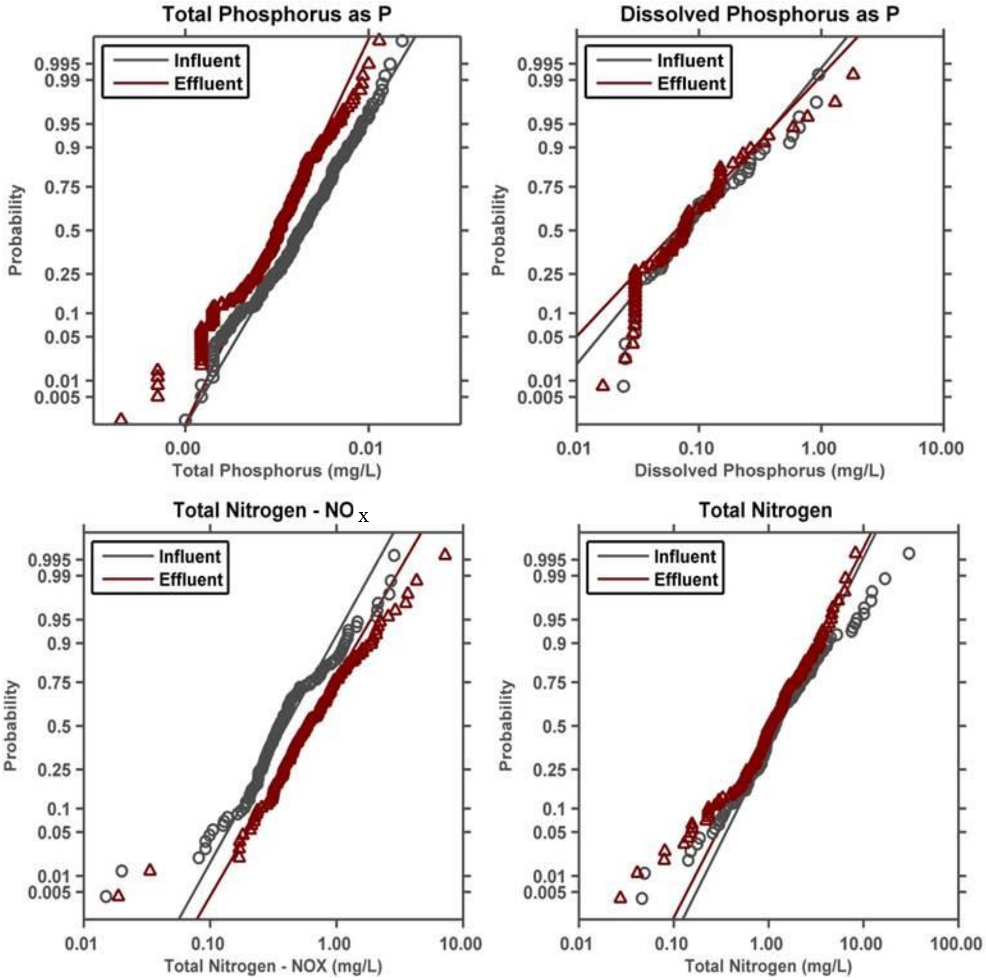


Figure 84. Graph. Probability plot of influent and effluent concentration of total and dissolved phosphorus and total NO_X and nitrogen in stormwater runoff.

SAND FILTER STATISTICAL DESIGN PARAMETERS

The previous analysis focuses on analysing the impact of sand filters on each pollutant individually. In order to evaluate the efficiency of the sand filter to simultaneously mitigate various pollutants, a k-means cluster analysis was set up for the cleaning efficiency of sand filter for total metals (copper, lead and zinc). The clusters were iteratively computed until a cluster was formed for sand filters effectively mitigating all three metals. The design parameters of the sand filters comprising of this cluster were then evaluated to provide an appropriate design criterion for sand filters that conforms to the cleaning efficiency represented by the cluster. The design parameters of the sand filters as well as the cluster locations are shown in Figure 85.

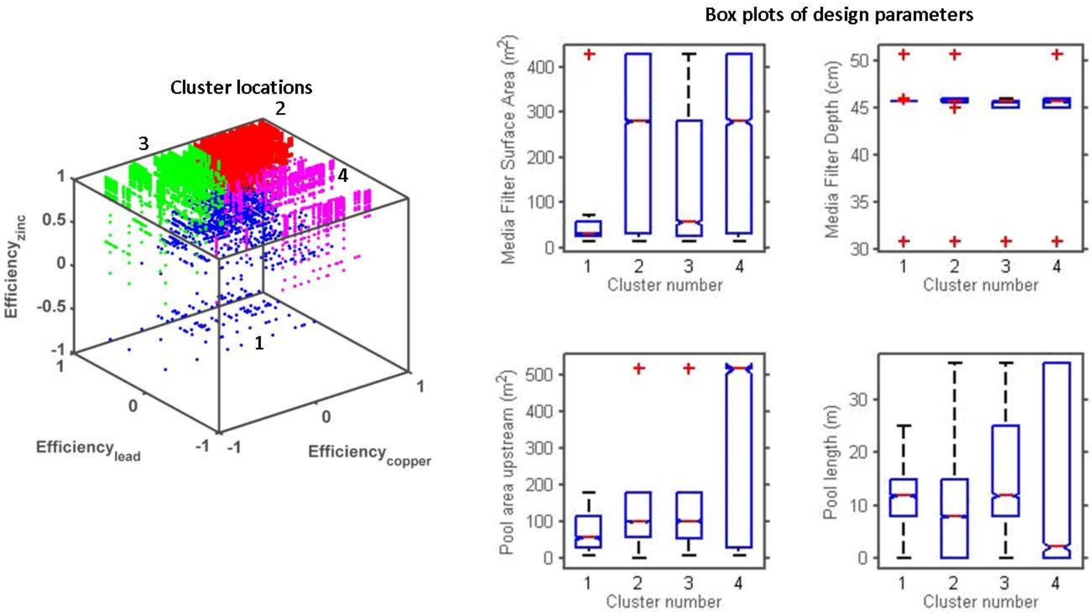


Figure 85. Charts. Clusters of cleaning efficiency of sand filters for total metals and design parameters of the sand filters for each cluster.

The median of the removal efficiency in different clusters is provided in Table 13. Cluster 2 delineates the sand filters that perform relatively better than the others in mitigating metal pollutants.

Table 13. Median Cleaning Efficiency of Clusters (Metals).

Metal	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Copper	0.47	**0.62**	-0.02	0.59
Lead	0.81	**0.87**	0.84	0
Zinc	0.2	**0.91**	0.87	0.90

The median values of the design dimensions of the sand filters comprising different clusters are provided in Table 14. The results indicate that a single design parameter cannot be outlined as controlling the removal efficiency of the sand filter. For example, cluster 2 and 4 have similar pool area and depth, yet because of differences in the pool area and depth, the cleaning efficiency of the 2 clusters is different. The best combination of design parameters based on the data analysed is highlighted in Table 14.

Table 14. Median of Design Parameters for Different Clusters.

Design parameter	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Filter Area (m^2)	31.99	**280**	56.99	280
Filter depth (cm)	45.72	**45.72**	45.72	45.72
Pool area (m^2)	56.02	**102.01**	102.01	518
Pool depth (m)	11.87	**7.92**	11.88	2.13

A similar cluster analysis (Figure 86) was computed for the total suspended and dissolved solids.

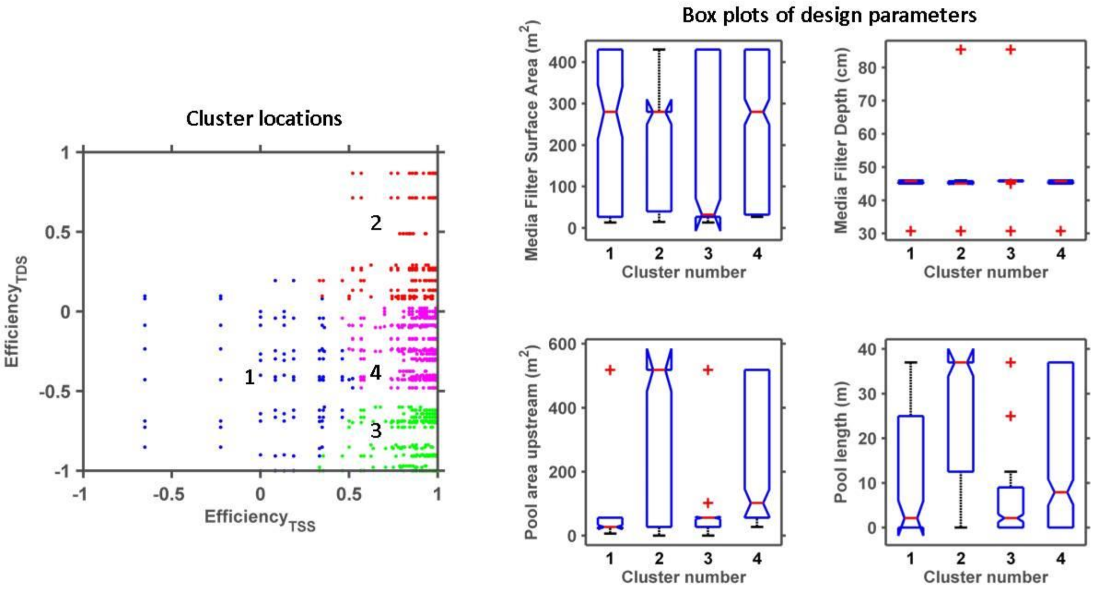


Figure 86. Charts. Cluster analysis and design parameters of sand filters with respect to total solids.

The median values of the removal efficiency and the design parameters of the corresponding clusters are provided in Table 15 and Table 16, respectively. It is seen that cluster 2 performs the best when assessing the cleaning efficiency of sand filters for total suspended and total dissolved solids simultaneously.

Table 15. Median Cleaning Efficiency of Clusters (Solids).

Metal	Cluster 1	Cluster 2	Cluster 3	Cluster 4
TSS	0.19	**0.88**	0.91	0.92
TDS	-0.41	**0.26**	-0.85	-0.24

Table 16. Median of Design Parameters for Different Clusters.

Design parameter	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
Filter Area (m^2)	280	**280**	31.99	280
Filter depth (cm)	45.72	**45**	45.72	45.72
Pool area (m^2)	27.03	**518**	56.02	102.01
Pool depth (m)	2.13	**37**	2.13	7.92

In terms of median values of design parameters, the values of cluster 2 for total solids and cluster 4 for total metals are similar and vice-versa. Therefore, by adopting the median values of cluster 2 (for total metals that corresponds to cluster 4 for total solids) as the design criteria for the sand filter, it may provide efficient cleaning of metals and high efficiency for removal of total suspended solids but not for total dissolved solids. In contrast, if design parameters corresponding to cluster 2 for total solids are used to design BMPs, an overall cleaning efficiency for total solids may be obtained but the sand filter will perform poorly for total metal concentrations in the stormwater runoff.

CHAPTER 5. RECOMMENDATION FOR GUIDANCE ON SELECTION OF STORMWATER BMPS

Specification of a BMP is a complex balance of site hydrogeology, rainfall intensity, contaminant loading, right-of-way restrictions, BMP longevity, and maintenance requirements. Monitoring of the field performance of currently operating GDOT BMPs has demonstrated that the devices are functioning well, with acceptable contaminant removal percentages. Statistical analysis of the performance of sand filters, including the Canton sand filter in addition to BMPs from the International Stormwater Database, demonstrated that the dimensions of a sand filter do impact the contaminant removal percentages; however, the optimum dimensions were different for different contaminants (i.e., heavy metals versus suspended solids). Statistically, the data clearly demonstrated that sand filters are highly effective at solids, turbidity, some metal and total phosphorus removal, but less effective at removing dissolved constituents (solids, nutrients, and metals).

Currently, GDOT specification criteria follow a hierarchy of 1) stormwater requirements, 2) site and soil constraints, and 3) BMP feasibility:

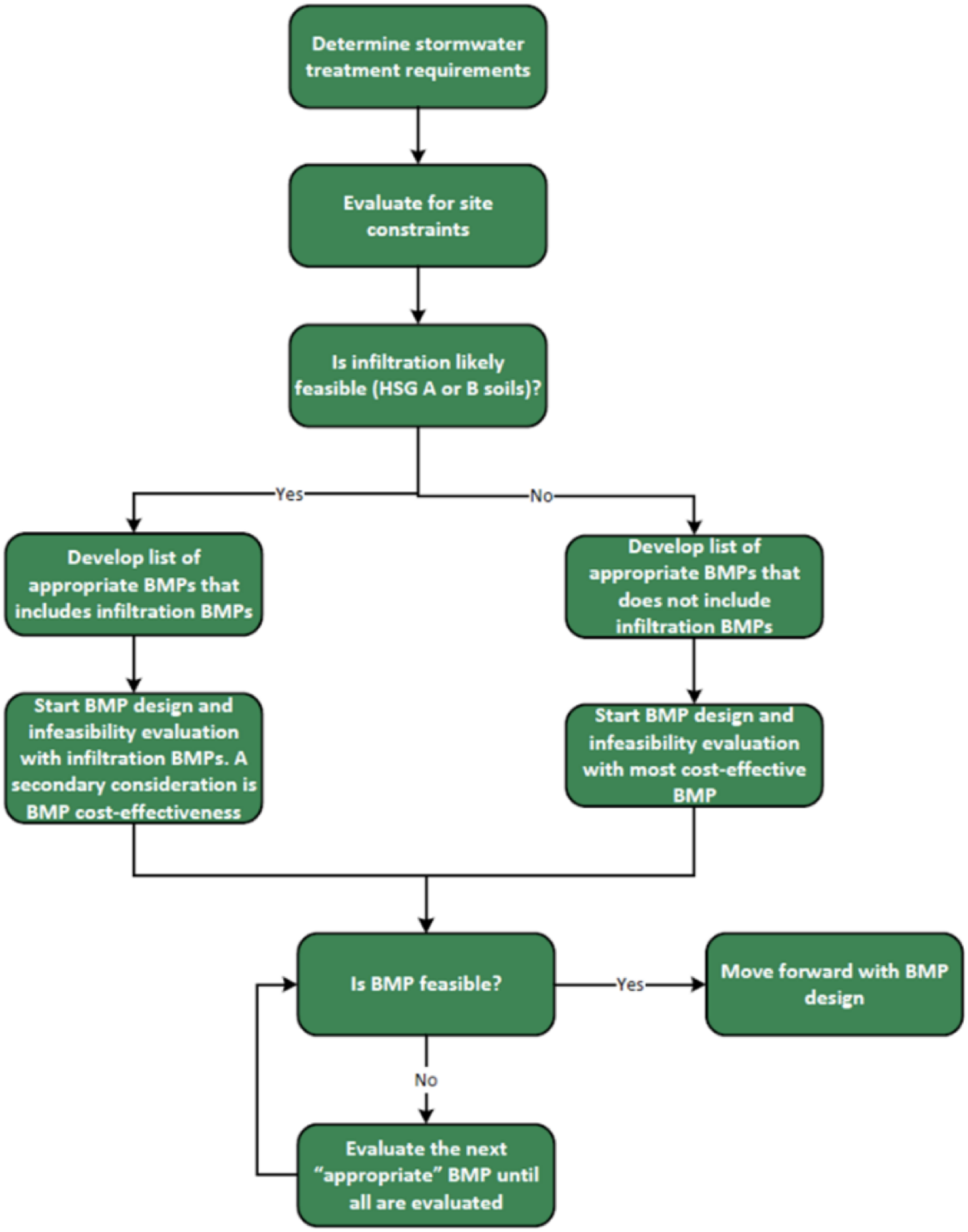


Figure 87. Diagram. BMP selection process flowchart (Figure 10.5-1 from GDOT, 2018).

Based on the review of maintenance and statistical performance, it is recommended that explicit criteria of BMP longevity, and short/intermediate versus long term maintenance burden be added to the BMP selection process flow chart

(Figure 10.5-1) (Table 17). For the BMPs that are commonly implemented on GDOT right-of-way, service life is an important criterion, with the optimal BMP having low maintenance burden coupled with a service life of many decades. Additionally, some BMPS, like sand filters and infiltration trenches have relatively minimal maintenance in the short or intermediate terms, but substantial maintenance in the long term. Distinguishing these periods of low versus high levels of required maintenance is important to developing an accurate assessment of the lifecycle cost of operation.

Table 17. BMP Longevity and Maintenance Burden.

BMP	Longevity (years)	Short-term / Intermediate term Maintenance Burden	Long Term Maintenance Burden
Filter Strips	High	Low	Low
Grass Channels	High	Low	Low
Bioslopes	Medium	Medium	Medium
Enhanced Dry Swales	High	Medium	Medium
Bioretention Basins	Medium	Medium	Medium
Enhanced Wet Swales	High	Low	Low
Infiltration Trenches	High	Low	High
Sand Filters	High	Low	High
Dry Detention Basins	High	Low	Low
Wet Detention Ponds	High	Low	Low
Stormwater Wetlands – Level 2	High	Medium	Medium
Stormwater Wetlands – Level 1	High	Medium	Medium
OGFC	Low	Low	Low

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The work performed in this study demonstrated that selected monitored BMPs, a dry swale with sand filter in Forsyth County and bioretention basin in Bartow County were performing within their anticipated level of contaminant removal and were operating with State of Georgia standards. During a stormwater event, both BMPs demonstrated pronounced first flush peak concentrations, with reduction in the inflow contaminant levels within one hour of stormwater flow. The combination dry swale / sand filter successfully treated turbidity, total suspended solids, total dissolved solids, some nutrients, and some heavy metals. The bioretention basin also successfully treated contaminants and showed better performance in the removal of nutrients when compared to the sand filter. The impact of high slope angles on the concentrations of nutrients was monitored in the coastal plain hydrogeology, and analysis of surface water samples for total inorganic nitrogen revealed that the concentration of TIN measured in surface water samples taken at the base of the slopes increased as slope angle was increased indicating that removal percentages for nutrients may be negatively impacted by steeper slope angles.

An in-depth statistical analysis of the performance of sand filters, based on an extensive database collected at the GDOT sand filter in Canton, GA and data drawn from the International Stormwater Database demonstrated that optimization of BMP dimensions for contaminant removal is a complex, multi-constrained problem. Dimensions that were optimized for metal removal did not perform as well for solids removal, and vice-versa; consequently, selection criteria based on optimized BMP dimensions is not feasible at this point in time, due to the complexity of other factors such as regional hydrogeology and precipitation events.

Finally, it is recommended that the selection criteria flowchart for BMPs on GDOT right-of-way be expanded to include criteria for longevity, as well as distinction between short/intermediate term maintenance versus long term maintenance burden.

APPENDIX A: DETAILED SAMPLE CONCENTRATION DATA FOR TESTED STORMWATER BMPS

Table 18. Summary of Stormwater Event 1 Results (Dry swale with a sand filter).

	Inlet		Outlet			
Parameter	**Sample 1 (0 min)**	**Sample 3 (30 min)**	**Sample 5 (0 min)**	**Sample 6 (15 min)**	**Sample 7 (30 min)**	**Sample 8 (45 min)**
Turbidity [NTU]	34.08	32.76	12.92	13.18	12.24	11.92
TSS [mg/L]	43.2	11.3	3.6	3.9	3.7	2.0
TDS [mg/L]	108.14	71.40	61.48	59.29	55.29	59.78
Nitrite [mg/L]	0.255	0.205	0.037	0.033	0.033	0.032
Nitrate [mg/L]	0.829	0.641	0.611	0.558	0.513	0.529
Total Nitrogen [mg/L]	4.220	3.714	3.583	3.504	3.532	3.520
Total Copper [mg/L]	0.0621	0.0196	0.0149	0.0161	0.0135	0.0126
Total Lead [mg/L]	0.1819	0.0379	0.0246	0.0173	0.0171	0.0080
Total Zinc [mg/L]	0.0465	0.0183	0.0101	0.0031	0.0030	0.0032

Table 19. Summary of Stormwater Event 2 Results (Dry swale with a sand filter).

	Inlet				**Outlet**			
Parameter	**Sample 1 (0 min)**	**Sample 2 (15 min)**	**Sample 3 (30 min)**	**Sample 4 (45min)**	**Sample 5 (0 min)**	**Sample 6 (15 min)**	**Sample 7 (15 min)**	**Sample 8 (45min)**
Turbidity [NTU]	97.5	81.26	85.45	77.9	7.08	5.95	12.46	7.88
TSS [mg/L]	40.50	33.25	36.00	25.50	1.00	4.00	1.75	0.50
TDS [mg/L]	165.43	193.64	177.88	118.18	69.42	49.85	58.90	64.11
Nitrite [mg/L]	0.87	0.78	0.61	0.71	0.14	0.12	0.06	0.06
Nitrate [mg/L]	2.32	1.82	1.64	1.65	1.09	0.98	0.95	0.96
Total Nitrogen [mg/L]	8.03	7.11	6.85	6.93	6.7	6.61	6.57	6.63
Total Phosphorus [mg/L]	0.160	0.155	0.134	0.145	0.020	0.030	0.013	0.017
Total Copper [mg/L]	0.101	0.048	0.044	0.038	0.033	0.025	0.027	0.025
Total Lead [mg/L]	0.225	0.060	0.047	0.035	0.03	0.025	0.020	0.027
Total Zinc [mg/L]	0.090	0.040	0.035	0.031	0.021	0.023	0.017	0.021

Table 20. Summary of Stormwater Event 3 Results (Dry swale with a sand filter).

	Inlet				Outlet			
Parameter	**Sample 1 (0 min)**	**Sample 2 (15 min)**	**Sample 3 (30 min)**	**Sample 4 (composite)[1]**	**Sample 5 (0 min)**	**Sample 6 (15 min)**	**Sample 7 (15 min)**	**Sample 8 (composite)[1]**
Turbidity [NTU]	50.38	47.62	36.03	15.93	8.74	7.24	9.42	12.15
TSS [mg/L]	54.75	52.00	42.75	27.50	8.67	3.33	5.33	7.00
TDS [mg/L]	85.26	83.97	81.21	51.56	34.67	26.67	38.00	45.09
Nitrite [mg/L]	0.37	0.30	0.34	0.22	0.12	0.09	0.12	0.83
Nitrate [mg/L]	1.35	1.11	1.05	1.07	0.78	0.82	0.73	1.53
Total Nitrogen [mg/L]	6.13	5.25	5.18	5.31	4.92	4.85	4.91	6.62
Total Phosphorus [mg/L]	0.052	0.044	0.062	0.023	0.012	0.012	0.009	0.015
Total Copper [mg/L]	0.070	0.028	0.025	0.027	0.020	0.021	0.019	0.035
Total Lead [mg/L]	0.195	0.035	0.030	0.027	0.020	0.015	0.017	0.030
Total Zinc [mg/L]	0.053	0.015	0.017	0.016	0.010	0.012	0.013	0.020

---

[1] Composite sample (45min – 240min)

Table 21. Summary of Stormwater Event 4 Results (Bioretention basin).

	Inlet				Outlet			
Parameter	**Sample 1 (0 min)**	**Sample 2 (15 min)**	**Sample 3 (30 min)**	**Sample 4 (composite)[1]**	**Sample 5 (0 min)**	**Sample 6 (15 min)**	**Sample 7 (15 min)**	**Sample 8 (composite)[1]**
Turbidity [NTU]	38.41	23.53	23.66	26.11	8.80	8.63	8.87	9.14
TSS [mg/L]	37.50	18.75	12.75	19.25	12.25	7.50	10.25	11.50
TDS [mg/L]	147.42	82.72	65.96	38.79	74.32	91.08	90.29	84.71
Nitrite [mg/L]	0.229	0.158	0.168	0.122	0.073	0.083	0.069	0.119
Nitrate [mg/L]	0.758	0.635	0.623	0.630	0.593	0.578	0.585	0.562
Total Nitrogen [mg/L]	4.032	3.753	3.802	3.766	3.598	3.577	3.483	3.506
Total Phosphorus [mg/L]	0.044	0.033	0.032	0.030	0.009	0.019	0.016	0.016
Total Copper [mg/L]	0.053	0.028	0.025	0.026	0.021	0.023	0.018	0.020
Total Lead [mg/L]	0.158	0.048	0.038	0.042	0.030	0.032	0.028	0.026
Total Zinc [mg/L]	0.038	0.021	0.019	0.017	0.013	0.015	0.010	0.011

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[1] Composite sample (45min – 240min)

APPENDIX B: HYDRAULIC CONDUCTIVITY OF GDOT TOPSOIL MIX

DETERMINATION OF HYDRAULIC CONDUCTIVITY OF GDOT TOPSOIL MIX

GDOT requested testing of the specified topsoil mix for development of the Supplemental Specification Section 893-Miscellaneous Planting Materials. A laboratory based investigation was performed with a soil created to meet the grain size distributions of the specified non-organic portion of the topsoil (Table 22 and Figure 88). For the fine-grained soil, 10% of the material was kaolinite (clay) and 90% of the material was Piedmont soil (silt).

Table 22. GDOT Grain Size for Topsoil (Inorganic).

Sieve Size	Percent Passing by Weight
Passing 2 inch (50mm)	100
Passing 1-½ inch (37.5 mm)	100
Passing No.10 (2mm) sieve	83
Passing No.40 (425 um) sieve	60
Passing No. 60 (250 um) sieve	45
Passing No. 200 (75 um) sieve	18
Clay Size (<2 um)	0

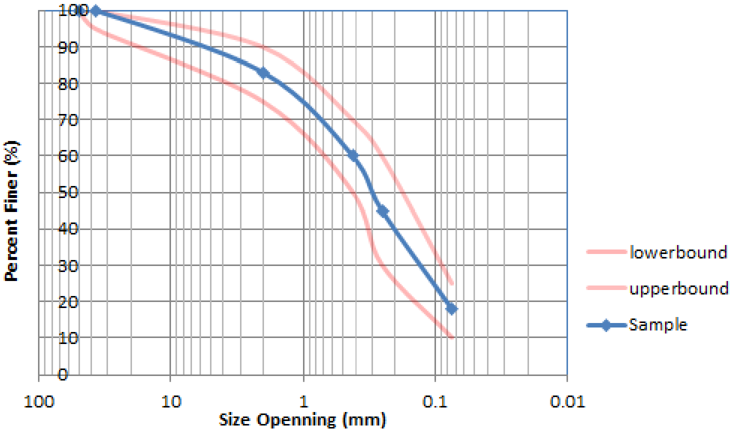

Figure 88. Graph. The grain size distribution curve for the inorganic portion of the topsoil.

Materials and Methods

The inorganic materials used for the test included gravel, Ottawa 20-30 sand, FS 50-70 sand, F 75 sand, Piedmont soil, and kaolinite. These soils were mixed together in specified proportion and sieved to create a specimen for testing that met the Department's grain size requirements. In addition to the soil minerals, organic material was added to the topsoil mix (7.5% by mass).

Commercial cow manure was purchased and used to add organic carbon to the controlled soil mixture. Organic carbon content was determined using a total organic carbon analyzer (Shimadzu).

A series of hydraulic conductivity tests were performed in a falling head hydraulic conductivity test, with flexible membrane (ASTM D5084). All test specimens were back pressure saturated to dissolve discrete air bubbles into the water phase. The B coefficient was monitored until it reached a level of 0.95, while adjusting target effective stress during back pressure saturation. All tests were performed at effective stress levels of 5 psi, 10 psi, and 15 psi.

Results

The cow manure was sampled eight times to obtain a representative measure of its organic carbon content. Organic carbon content ranged from 10.7% - 20.3%, with an average value of 15.8%, which was used to determine the mass of organic included in the topsoil for hydraulic conductivity testing (Table 23). Six samples of cow manure were also tested to determine moisture content in the as received condition, resulting in an average moisture content of 44% by mass (Table 24).

Table 23. Organic Carbon Content Commercial Cow Manure.

Sample ID	Organic Carbon Content (Current)
1	16.9%
2	19.4%
3	12.4%
4	15.7%
5	10.7%
6	14.7%
7	16.6%
8	20.3%
Average	15.8%
Median	16.2%
Standard Deviation	3.01%
Maximum	20.3%
Minimum	10.7%

Table 24. Moisture Content Commercial Cow Manure.

Sample ID	Moisture Content (%)
1	42.7%
2	45.8%
3	46.5%
4	42.8%
5	43.1%
6	43.1%
Average	44.0%

A series of samples were prepared for hydraulic conductivity testing of the fine-grained soils. In these soils, it is especially critical to ensure saturation of the samples. If the sample is not saturated, unconservative values of hydraulic conductivity may be reported. Tests were performed to ensure the samples reached a B value equal to 0.95 (Figure 89). Hydraulic conductivity for the soil with only inorganic minerals was approximately 1 – 2 x 10^{-5} cm/sec. Inclusion of the organic carbon phase increased the hydraulic conductivity of the specified topsoil by approximately one order of magnitude to 2- 5 x 10^{-4} cm/sec (Figure 90 - Figure 91).

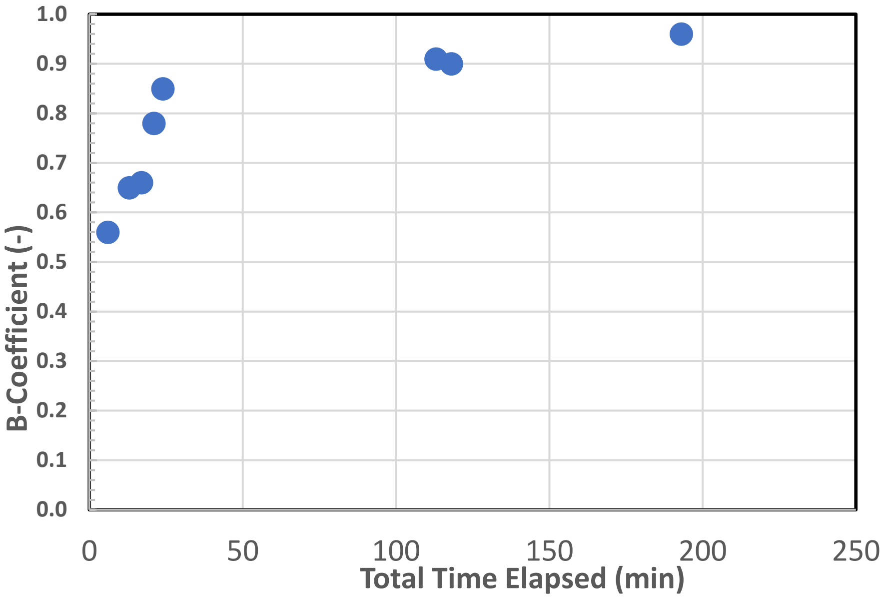

Figure 89. Graph. B value measured for specified topsoil hydraulic conductivity sample.

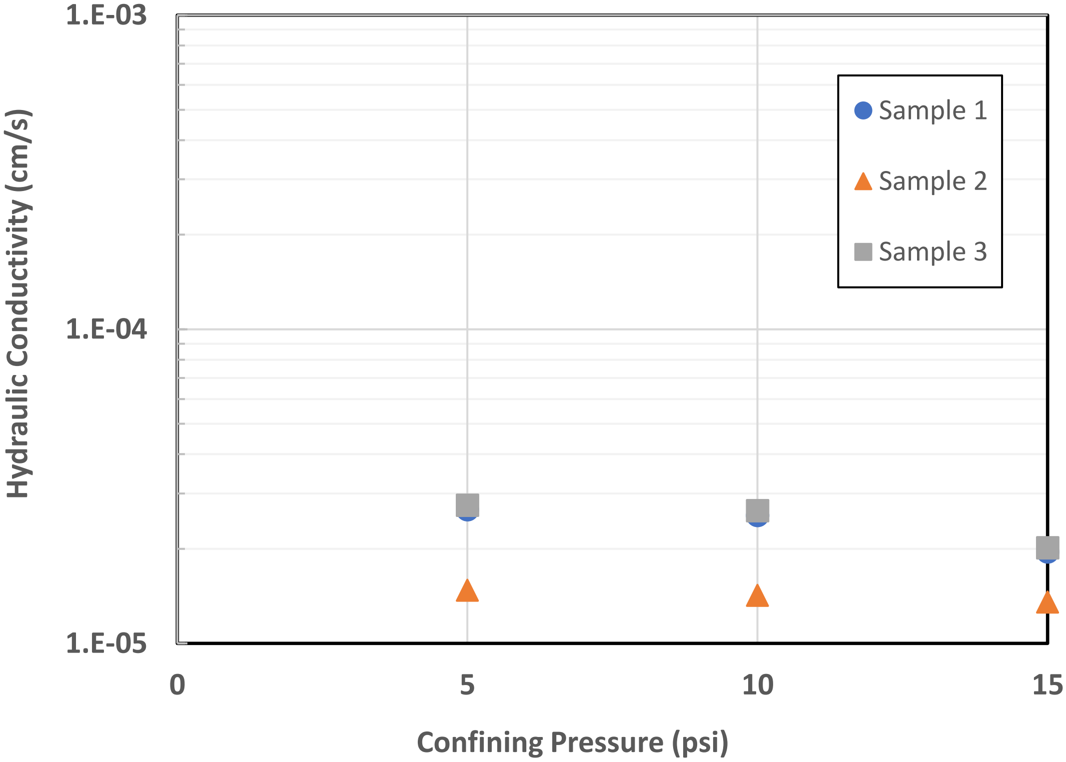

Figure 90. Graph. Hydraulic conductivity of specified topsoil with only inorganic minerals (no organic matter included).

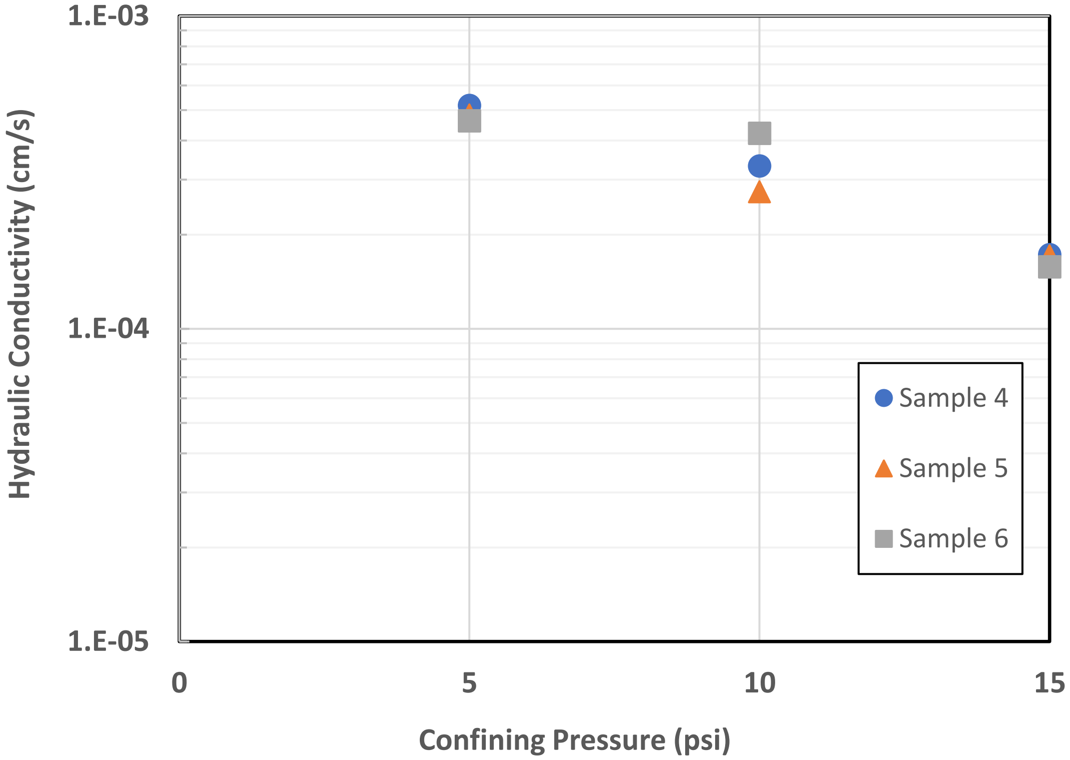

Figure 91. Graph. Hydraulic conductivity of specified topsoil with both inorganic minerals and organic carbon.

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