RESEARCH & DEVELOPMENT

Swale Design Optimization for Enhanced Application and Pollutant Removal:

Vegetated Swales

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16. Abstract

The goal of this study was to evaluate the effects of three key design parameters and two storm sizes on swales' hydrologic and water quality performance. Three design factors with two levels were evaluated for their effect on the performance of swales: swale length (33ft or 10m, 100 ft or 30m), shape (triangular and trapezoidal), and longitudinal slope (1% and 4%). The impact of small-medium (19mm) and large (36mm) rainfall depths, and seasonal differences were also evaluated. Eight grass swales were constructed in Raleigh, North Carolina to collect empirical data in controlled plot-scale studies. Water from an onsite reservoir was used to generate synthetic runoff. Hydrologic performance was measured as reduction in runoff volumes. The pollutants tested under this study included total suspended sediment (TSS), nitrogen, phosphorus, and four heavy metals (copper, lead, zinc, and cadmium). Synthetic runoff simulations were spiked with typical highway pollutant concentrations. Water quality performance was measured as a reduction in mass load of total suspended sediment, nutrients and total metals between swale inflow and outflow.

Swale length, slope, shape, and storm-size were all statistically significant factors influencing runoff volume reduction. The maximum runoff volume reduction was provided by the 30m, trapezoidal swale constructed at 1% longitudinal slope during small-medium storms. Excessive compaction of the swale bed during construction negatively influenced runoff volume reduction ability of swales.

For water quality improvement, the overall results indicate that grass swales are an effective stormwater control measure for conveying runoff and treating pollutants (sediments and metals), if designed for the water quality storm (typically 19-25mm). Swales runoff volume and pollutant load reduction ability is slightly reduced for larger storms (up to 36mm), but not fully eliminated. Swale length was a significant factor for all pollutants except for dissolved phosphorus. The runoff volume and pollutant load reduction benefits from a 30m versus the 10m swale suggests that designers should maximize the swale length to maximum extent practicable for optimizing swale performance. A trapezoidal cross-section should be the preferred swale shape to achieve stormwater treatment goals. For nutrient removal in roadway runoff, swale alternatives such as bioswales or wet swales should be considered.

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List of Abbreviations

DOT	Department of Transportation
EMC	Event Mean Concentration
mg/L	Milligrams per Liter
NCDEQ	North Carolina Department of Environmental Quality
NCDOT	North Carolina Department of Transportation
NPDES	National Pollution Discharge Elimination System
SCM	Stormwater Control Measure
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
μg/L	Micrograms per Liter

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Executive Summary

The goal of this study was to evaluate the effects of three key design parameters and two storm sizes on swales' hydrologic and water quality performance. Three design factors with two levels were evaluated for their effect on the performance of swales: swale length (33ft or 10m, 100 ft or 30m), shape (triangular and trapezoidal), and longitudinal slope (1% and 4%). The impact of small-medium (~0.75 inches or 19mm) and large (~1.4 inches or 36mm) rainfall depths, and seasonal differences were also evaluated. Eight grass swales were constructed in Raleigh, North Carolina to collect empirical data in controlled plot-scale studies. Water from an onsite reservoir was used to generate synthetic runoff. Hydrologic performance was measured as reduction in runoff volumes. The pollutants tested under this study included total suspended sediment (TSS), nitrogen, phosphorus, and four heavy metals (copper, lead, zinc, and cadmium). Synthetic runoff simulations were spiked with typical highway pollutant concentrations. Water quality performance was measured as a reduction in mass load of total suspended sediment, nutrients and total metals between swale inflow and outflow.

Swale length, slope, shape, and storm-size were all statistically significant factors influencing runoff volume reduction. The maximum runoff volume reduction was provided by the 30m, trapezoidal swale constructed at 1% longitudinal slope during small-medium storms. Excessive compaction of the swale bed during construction negatively influenced runoff volume reduction ability of swales.

For water quality improvement, the overall results indicate that grass swales are an effective stormwater control measure for conveying runoff and treating pollutants (sediments and metals), if designed for the water quality storm (typically 19-25mm). Swales runoff volume and pollutant load reduction ability is slightly reduced for larger storms, but not fully eliminated. Swale length was a significant factor for all pollutants except for dissolved phosphorus. The runoff volume and pollutant load reduction benefits from a 30m versus the 10m swale suggests that designers should maximize the swale length to maximum extent practicable for optimizing swale performance. A trapezoidal cross-section should be the preferred swale shape to achieve stormwater treatment goals. For nutrient removal in roadway runoff, swale alternatives such as bioswales or wet swales should be considered.

1. Introduction

Water pollution has long been recognized as an important issue globally. In the United States, significant improvements have been made to address both point and nonpoint sources of pollution since the Clean Water Act of 1972, which has resulted in improved water quality (Subramanian, 2016). The Clean Water Act requires industrial, municipal, or transportation agencies to obtain a National Pollutant Discharge Elimination System (NPDES) permit to discharge any pollutant to the surface waters.

With a continued increase of population in urban areas, the water demand for human consumption is also increasing. This is changing the traditional perspective of viewing stormwater as a nuisance or only requiring flood control to now considering stormwater as a valuable resource that can be used to satisfy increasing water consumption demands (Fletcher et al., 2013; Heaney and Sansalone, 2009). As a result, there is a paradigm shift from efficient routing and conveyance of stormwater to treatment and reuse. As an alternative to traditional stormwater control measure designs, low-impact development and green infrastructure principles are incorporated to manage stormwater runoff at the source by storing and infiltrating water (Dietz, 2007). This approach allows for filtering of pollutants and groundwater recharge, making stormwater available for reuse. Examples of such practices are permeable pavements, raingardens, rainwater harvesting systems, green roofs, and vegetated swales.

Swales, also referred as engineered open channels have been used historically for urban drainage and stormwater conveyance around the world (Burian and Edwards, 2002). As part of the urban landscape, swales can provide aesthetic benefits and mimic natural hydrological processes, thereby preserving the pre-development hydrologic functions of the site, if designed and constructed properly (Ahiablame and Shakya, 2016; Dietz, 2007). Extensive research is being conducted worldwide to advance swale design and examine their effectiveness in treating urban runoff (Ahiablame and Shakya, 2016; Dietz, 2007; Jia et al., 2016; Yu et al., 2013).

Swales and roadside drainage systems date back to the Roman Empire, which was known for its superiority in roadways with proper drainage (Burian and Edwards, 2002). The purpose and design of roadside drainage has evolved over time from combined sewers for simple flood control to runoff water quality treatment for protecting the receiving waters. Swales are a common stormwater control measure (SCM) used by the North Carolina Department of

Transportation (NCDOT) and other Departments of Transportation (DOTs) to manage stormwater runoff due to their unique application in linear environments with limited rights-of-way, and low construction and maintenance costs (CALTRANS, 2004). Despite their widespread use and historical role in stormwater management, the influence of design parameters (such as channel length, slope, and shape) on effectiveness of swales is not yet fully understood and limited design guidance is available for water quality treatment swales leaving room for further improvement in swale design (Fardel et al., 2019). Yu et al. (2001) specifically identified the need for a comprehensive controlled study involving systematic data collection to better understand the effect of design parameters on water quality treatment. The need for such research that can be used to improve swale design criteria becomes more critical as swales become increasingly popular for stormwater management.

Many studies have shown the efficiency of swales in treating small and medium storms (below 25mm) (Davis et al., 2012; Pitt, 1987; Yu et al., 2001), but their performance under large storm events (25-38mm) needs further research (Horwatich et al., 2018). The runoff volume reduction capability of a swale is largely dependent on the infiltration rate (Davis et al., 2012; Revitt et al., 2017; Yu et al., 2001), which may be influenced by temperature or seasons. Unfortunately, previous research on this topic is conflicting. Emerson and Traver (2008) examined two infiltration SCMs and suggested a strong seasonal influence on infiltration rates, while Ahmed et al. (2015) examined roadside swales and concluded that there was no statistically significant difference in infiltration between Fall and Spring. For water quality, swale performance was observed to be substantially better in the summer season for sediment, total nitrogen and total phosphorus (Yuan et al., 2019). Swales' reduced ability to remove nitrogen (especially nitrate) and sporadically even release nitrogen has been attributed to seasonal differences (Li et al., 2016; Stagge et al., 2012), as this pattern was observed more in the summer. Stagge et al. (2012) noted that a swale's behavior as a nitrogen source during summer may be due to an increase in nitrogen supply from organic materials (grass clippings etc.) due to increased mowing frequency. A better understanding of the differences in swale performance due to seasonal variations is important for making management decisions about swale inspection and maintenance frequency.

It is evident that there are significant knowledge gaps and additional research is needed to understand swale performance and advance existing swale design guidance for effectively treating highway runoff. Thus, the following research questions were posed in this study:

1) What is the effect of key design parameters (length, slope, shape) and storm size on the hydrologic performance of a swale?
2) What is the effect of key design parameters (length, slope, shape), and storm size on the water quality performance of a swale?
3) How does the hydrologic and water quality performance of a swale vary in summer compared to other seasons?

Chapter 2 provides a literature review of the existing body of knowledge and identifies research opportunities. Chapter 3 presents the specific objectives, methods and results of field study examining the influence of design parameters and seasons on the hydrologic and water quality performance of a swale.

2. Literature Review

Highway Stormwater Management

Common pollutants in roadway runoff

Highways and roads are largely impervious surfaces that quickly generate runoff volumes after a rainfall, and can wash off a variety of pollutants that may have negative impacts on water quality (Barrett et al., 1998b; Han et al., 2006), including toxicity to aquatic organisms (Kayhanian et al., 2008). Common pollutants in roadway runoff that have been studied include total suspended solids (TSS), total dissolved solids (TDS), nitrate+nitrite (NO_2-NO_3), ammonia (NH_3-N), total kjeldahl nitrogen (TKN), ortho-phosphorus (OP), total phosphorus (TP), carbon, oil and grease, arsenic, chromium, nickel, copper, cadmium, iron, lead, and zinc (Barrett et al., 1998a; Han et al., 2006; Kayhanian et al., 2007; Wu et al., 1998). Most pollutants occur in either particulate or dissolved forms; the latter are most bioavailable causing a quicker response by the aquatic biota (Kayhanian et al., 2012). Thus, an understanding of partitioning between particulate and dissolved phases is critical to design effective stormwater control measures and prevent toxic effects to aquatic life in receiving waters (Huber et al., 2016).

An extensive literature review to characterize the occurrence and fate of heavy metals in different traffic areas showed that zinc, copper, nickel, and cadmium occur mainly in the dissolved phase while lead and chromium are mostly particulate-bound (Huber et al., 2016). In another review focused on highway runoff, monitoring data revealed that most metal pollutants (except copper, nickel, and zinc) and phosphorus are primarily associated with particulates (Kayhanian et al., 2012). A previous study conducted to partition nutrient loads from an urban road surface in Australia showed that the dissolved component for TN ranges between 20-50% in comparison to 20-30% for TP (Vaze and Chiew, 2004). A recent field monitoring study at different road sites in North Carolina showed that 53-84% of TP occurred in the particulate or particle-bound form (Winston and Hunt, 2017). In contrast, nitrate (NO_{2-3}), a dissolved constituent, was a relatively small fraction (16-29%) of TN (Winston and Hunt, 2017). Regardless of the variations in the fraction of dissolved pollutants among studies, researchers have agreed upon the importance of treating dissolved pollutants in order to protect downstream water quality (Huber et al., 2016; Kayhanian et al., 2012).

Highway runoff constituents have been characterized and quantified by several researchers worldwide but significant knowledge gaps exist on their occurrence and fate (Opher and Friedler, 2010). Table 1 presents a summary of typical highway runoff pollutants and basic statistics of the observed event mean concentrations (EMCs). The units are in mg/L unless otherwise stated.

Table 1. Summary of typical highway runoff pollutant concentrations

Type of Pollutant	Range	Mean	Location	Source
Total Suspended Solids (TSS)	32-771	283	Charlotte, North Carolina	(Wu et al., 1998)
	9-221	93		
	4-113	30		
	157-190	173.5	Austin, Texas	(Barrett et al., 1998b)
	15-166	71	Lulea, Sweden	(Bäckström et al., 2006)
	8.8-466	67.7	Los Angeles, CA	(Han et al., 2006)
	1-2,988	112.7	California	(Kayhanian et al., 2007)
	6-312	72	North Carolina	(Luell, 2011), Unpublished data
	-	13	North Carolina (Site A)	(Winston et al., 2012)
Total Phosphorus (TP)	0.24-0.55	0.40	Austin, Texas	(Barrett et al., 1998b)
	0.1-8.2	0.9	Los Angeles, CA	(Han et al., 2006)
	0.03-4.69	0.29	California	(Kayhanian et al., 2007)
	0.03-0.53	0.17	North Carolina	(Luell, 2011), Unpublished data
	0.07-0.17	0.13	North Carolina	(Winston and Hunt, 2017)
	-	0.08	North Carolina (Site A)	(Winston et al., 2012)
Total Nitrogen (TN)	0.30-2.80	1.05	North Carolina	(Luell, 2011), Unpublished data
	1.26-1.69	1.48	North Carolina	(Winston and Hunt, 2017)

	-	1.48	North Carolina (Site A)	(Winston et al., 2012)
Total Copper (Cu)	0.01-0.036	0.025	Lulea, Sweden	(Bäckström et al., 2006)
	0.0012-0.27	0.0478	California	(Kayhanian et al., 2007)
Total Zinc (Zn)	0.129-0.347	0.238	Austin, Texas	(Barrett et al., 1998b)
	0.05-0.135	0.100	Lulea, Sweden	(Bäckström et al., 2006)
	0.0055-1.68	0.187	California	(Kayhanian et al., 2007)
Total Lead (Pb)	0.093-0.138	0.115	Austin, Texas	(Barrett et al., 1998b)
	0.004-0.017	0.011	Lulea, Sweden	(Bäckström et al., 2006)
	0.001-2.60	0.0478	California	(Kayhanian et al., 2007)
Total Cadmium (Cd), μg/L	0.2-30	0.7	California	(Kayhanian et al., 2007)

Since, highway pollutant characteristics are influenced by local conditions such as climate, traffic load, vegetation (Barrett et al., 1998b; Kayhanian et al., 2007), NCDOT has developed typical median EMCs for typical land use that are unique to the roadway environment based on research studies in North Carolina. From the research dataset, primary roadways had a median TSS of 28 mg/L, TN of 1.39 mg/L and median TP of 0.19 mg/L (personal communication, NCDOT, July 30, 2018), while secondary roads had a median TN of 0.54 mg/L and TP of 0.10 mg/L. The median concentrations for dissolved metals are: 10.95 μg/L (copper), 69.2 μg/L (zinc), 2.57 μg/L (lead), and 0.1 μg/L (cadmium), (personal communication, NCDOT, February 9, 2017).

Stormwater Control Measures

A variety of stormwater control measures (SCMs) are available for the watershed managers to manage stormwater runoff and protect the receiving waters. These tools can be broadly classified as non-structural and structural. Examples of non-structural SCMs include the following: enhanced ordinances focused on pollution control, public education, good housekeeping practices, street sweeping, and illicit discharge detection and elimination (Urbonas, 1994). Structural SCMs include but are not limited to detention basins, constructed wetlands, bioretention basins, sand filters, level spreaders, filter strips, and vegetated swales (Urbonas, 1994). Each SCM has its own advantages and disadvantages that are unique to a specific application. For example, a wetland may be better suited for treating runoff from larger drainage areas, while a bioretention basin may be the optimal SCM for smaller drainage areas in limited urban spaces such as parking lots.

Design guidance and available credits

The current design guidance used by NCDOT for swales recommends a trapezoidal or V-shaped cross-section with side slopes of 3:1 or less, and longitudinal slopes between 0.3 and 4.0%, maximum base width of 6 feet, length of 100 feet per contributing acre of drainage area, maximum design velocity of 2.0 feet/sec for a two-year recurrence interval storm (Q_2) and a permissible velocity of 4.0 feet/sec for Q_{10} (NCDOT, 2014). These design criteria along with a minimum six inches of freeboard requirement can assist the engineers to design a hydraulically efficient swale to convey the stormwater. However, no firm guidance on designing a swale to treat the runoff for typical highway pollutants is provided. Rock check dams are included as an alternative design when site constraints do not allow the required slopes or velocities. However, the effectiveness of rock check dams to provide water quality benefits is questionable, as most studies show little to no benefit (Davis et al., 2012; Jamil and Davis, 2009; Powell, 2015). In contrast, Yu et al., (2001) has suggested that including check dams can enhance swale performance. Until recently, swales received a removal credit of 35% for TSS and 20% for nitrogen and phosphorus, which was lower than other SCMs. The current crediting system considers swale research conducted in North Carolina and provides an event mean concentration ($EMC_{effluent}$) for a dry swale of 1.1 mg/L and 0.14 mg/L for TN and TP, respectively (NCDEQ, 2018). A reduced $EMC_{effluent}$ of 0.82 mg/L and 0.11 mg/L for TN and TP are provided for a swale under wet conditions (NCDEQ, 2018). Since the design of required controls are influenced by local conditions such as climate, traffic load, and native vegetation (Barrett et al., 1998b), NCDOT has developed typical EMCs for SCMs based on research studies in North Carolina that are unique to the local roadway environment. Existing North Carolina research suggested that grass swales have an effluent EMC of 0.57 mg/L for nitrogen and 0.11 mg/L for phosphorus. The recent guidance from NCDEQ (2016) discussed above considers swales as a secondary treatment device, which is in agreement with Yousef et al., (1987), but more recent research recommends that swales should be treated as a primary treatment device (Backstrom, 2003).

Swale hydrologic performance

Small-storm hydrology and effectiveness of swales in treating runoff from small storms is well studied in the literature (Pitt, 1987). In a recent USGS study of grass swale effectiveness in treatment of stormwater runoff from highways in Wisconsin, the results suggested that examining larger precipitation events is important, since rainfall depth is the primary factor in determining runoff volume from swales (Horwatich et al., 2018). Five rainfall groupings are presented in terms of rainfall depth impacts, and defined as follows Pitt (1999):

1. extra-small (<5 mm or 0.2 inches)- these events usually produce no runoff
2. small (5-13 mm or 0.2-0.5 inches)- these events produce little to no runoff
3. medium (13-25 mm or 0.5-1.0 inches)- these events produce moderate runoff
4. large (25-38 mm or 1.0-1.5 inches)- these events produce majority of annual flows
5. extra-large (>38 mm or 1.5 inches)- these are the events that produce flooding

Grouping rainfall by depth can help stormwater managers evaluate effectiveness of grass swales in infiltration, attenuation, and conveyance of runoff for different stormwater performance standards (Horwatich et al., 2018).

In accordance with this concept, swale performance was described by three rainfall regimes depending on the size of the rainfall event. Under small or minor rainfall, swales can achieve complete infiltration and there is no runoff; for moderate or intermediate (23-33mm) rainfalls, hydrologic abstractions by the swale (primarily infiltration) reduces the amount of potential runoff; and for large rainfall events, swales primarily function as conveyance systems with low attenuations of runoff volumes and peaks (Davis et al., 2012; Rujner et al., 2018). In a field study in Maryland, the runoff volume reduction was observed to be significant during small storm events with rainfall less than 3 cm (Davis et al., 2012). Swales were able to completely infiltrate the smallest 40% of the storms, whereas for the largest 20% storm events the swales essentially performed as a stormwater conveyance system. In Virginia, Yu et al. (2001) demonstrated a 275m grass swale provided complete infiltration of runoff for small storms (less than 12.7mm). Willis et al., (2013) also observed a frequent attenuation of small rain events for roads served by a swale system when compared to the roads drained by traditional curb-and-gutter system. Numerous other researchers have provided evidence of the runoff volume reduction benefits of a swale. For example, in Australia, Lucke et al. (2014) showed that a 30m long swale can attenuate the average flow volume by 52%. Similar runoff volume reductions between 33-66%

were obtained in a field study with 5-10m long swales in Sweden (Backstrom, 2002). A 23% runoff volume reduction benefit from a 10m long highway grass swale was observed in the Piedmont region of North Carolina (Knight et al., 2013). However, the optimal swale length needed for a defined volume reduction is not clear.

Since runoff volume reduction in a swale is primarily dependent on infiltration processes, a change in season can affect the performance. In a study of two infiltration-based SCMs in Pennsylvania, Emerson and Traver (2008) reported strong association between the infiltration rate and temperature with summer season showing higher hydraulic conductivity. In another study in Minnesota, researchers did not find a significant difference in mean saturated hydraulic conductivity values of roadside swales between fall and spring (Ahmed et al., 2015). In Sweden, a swale with low initial soil moisture conditions (typical of summer conditions) was shown to provide up to 82% runoff volume reduction, but the benefit reduced to only 15% when the initial soil moisture was high (Rujner et al., 2018). In summary, the effect of season on swale performance has been noted in previous research but not fully quantified yet.

The runoff volume reduction performance of swales is also influenced by flow retardance, which is a function of channel roughness, grass height, and grass density (Backstrom, 2002; Deletic and Fletcher, 2006). When the flow depth is less than grass height, it experiences higher resistance slowing down the velocity and allowing for sedimentation and filtration to occur (Winston et al., 2017). Most design guidance available for swales focuses on stormwater conveyance and erosion control, which is typically a higher amount of flow. In an attempt to provide additional guidance for designing "water quality swales" where the flow depth is less than the grass height, Kirby et al., (2005) developed small-flow retardance curves for three different grasses to supplement the Stillwater retardance curves. However, the curves were only applicable to the transitional flow regime, which was an advancement from the turbulent flow regime of Stillwater curves. Further research is needed on the role of vegetation for complete design guidance (Kirby et al., 2005).

Swale water quality performance

The most common ways SCM effectiveness is measured is either using the percent removal method or the effluent event mean concentration (EMC). Urbonas (1994) presented a range of pollutant removal for seven structural SCMs based on a review of literature and input from stormwater practitioners. They suggested that vegetated swales were not highly effective in pollutant removal compared to other structural SCMs, but swales may provide greater than 80% TSS removal, if the flow velocities were less than 0.15m/s and slope less than 3%.

In a separate study, Yu et al. (2013) evaluated performance of six different SCMs (grass swales, constructed wetlands, vegetated filter strips, hydrodynamic devices, media filters, and infiltration trenches) in Korea. Their results suggest that in Korea grass swales performed moderately well by removing an average of 58% TSS and 36% TP but performed poorly for TN removal, an average of 4.5% when compared to other SCMs. A comparison with the International BMP database values showed that the average removal efficiency of TSS and TN by grass swales was higher in USA than in Korea, while swales in Korea were more effective in removing TP. Water quality treatment benefits of swales are well documented with field data collected worldwide (Backstrom, 2002; Barrett et al., 1998b; Stagge et al., 2012). Pollutant removal in swales has been shown to be a function of their length, slope, and channel shape (Lucke et al., 2014; Yu et al., 2001). Lantin and Barrett (2005) present results from swale test sites in Texas, where most of the pollutant removal was observed to occur on the side slopes of the swale instead of the main channel. Typical research has investigated the efficiency of a swale to reduce pollutants that are common in stormwater runoff, such as total suspended solids, heavy metals, nutrients, and hydrocarbons. The results of swale performance for common stormwater pollutants have been summarized in Table 2 (TSS), Table 3 (TP), Table 4 (TN), Table 5 (Cu), Table 6 (Zn), Table 7 (Pb), Table 8 (Cd). These values have been adapted and modified from Lucke et al., (2014).

Table 2. Summary of TSS removal performance of swales

Study Type and Location	Swale Performance for TSS Removal (%)		Source	TSS Measurement Method
	Range	Mean (Median)		
Field Site, Texas, USA	85-87	86	(Barrett et al., 1998b)	Event mean concentration (EMC) reduction
Field, Taiwan	67.2-86.3	N.A.	(Yu et al., 2001)	Mass removal
Field, Virginia, USA	29.7-94	N.A.	(Yu et al., 2001)	Mass removal

Lab and Field, Sweden	79-98	N.A.	(Backstrom, 2002)	EMC reduction
Field, California, USA	N.A.	49	(CALTRANS, 2004)	EMC reduction
Field, MD, USA	44.1-82.7	N.A.	(Stagge et al., 2012)	Mass load mean reduction
Field, NC, USA	N.A.	(81)	(Knight et al., 2013)	Median EMC reduction
Field, Australia	50-80	65	(Lucke et al., 2014)	Average concentration
Field, France	(-76)-264	-71	(Leroy et al., 2016)	EMC reduction
Field, China	92-99	N.A.	(Li et al., 2016)	EMC reduction

Table 3. Summary of Total Phosphorus (TP) removal performance of swales

Study Type and Location	Swale Performance for TP Removal (%)		Source	TP Measurement Method
	Range	Mean (Median)		
Field, Texas, USA	34-44	39	(Barrett et al., 1998b)	EMC reduction
Field, Florida, USA	3-25	14	(Yousef et al., 1987)	Average concentration
Field, Taiwan	28.8-76.9	N.A.	(Yu et al., 2001)	Mass removal
Field, Virginia, USA	73.4-98.6	N.A.	(Yu et al., 2001)	Mass removal
Field, California, USA	N.A.	(-106)	(CALTRANS, 2004)	EMC reduction
Field, MD, USA	(-49.2)-68.7	N.A.	(Stagge et al., 2012)	Mass load mean reduction
Field, NC, USA	N.A.	(-21)	(Knight et al., 2013)	Median EMC reduction

Field, Australia	20-23	21.5	(Lucke et al., 2014)	Average concentration
Field, France	(-304)-64	-114	(Leroy et al., 2016)	EMC reduction

Table 4. Summary of Total Nitrogen (TN) removal performance of swales

Study Type and Location	Swale Performance for TN Removal (%)		Source	TN Measurement Method
	Range	Mean (Median)		
Field, Florida, USA	(-7)-11	2	(Yousef et al., 1987)	Average concentration
Field, Taiwan	13.8-23.1	N.A.	(Yu et al., 2001)	Mass removal
Field, California, USA	N.A.	30	(CALTRANS, 2004)	EMC reduction
Field, MD, USA	(-25.6)-85.6	N.A.	(Stagge et al., 2012)	Mass load mean reduction
Field, NC, USA	N.A.	24	(Knight et al., 2013)	Median EMC reduction
Field, Australia	0.0	0.0	(Lucke et al., 2014)	Average concentration

Table 5. Summary of Total Copper (Cu) removal performance of swales

Study Type and Location	Swale Performance for Cu Removal (%)		Source	Cu Measurement Method
	Range	Mean (Median)		
Field, Florida, USA	8-17	12.5	(Yousef et al., 1987)	Average concentration
Field, California, USA	N.A.	63	(CALTRANS, 2004)	EMC reduction

Field, MD, USA	42.3-81.1	N.A.	(Stagge et al., 2012)	Mass load mean reduction
Field, NC, USA	N.A.	(-147)	(Knight et al., 2013)	Median EMC reduction
Field, France	(-110)-79	4.4	(Leroy et al., 2016)	EMC reduction

Table 6. Summary of Total Zinc (Zn) removal performance of swales

Study Type and Location	Swale Performance for Zn Removal (%)		Source	Zn Measurement Method
	Range	Mean (Median)		
Field Site, Texas, USA	75-91	120.5	(Barrett et al., 1998b)	EMC reduction
Field, Florida, USA	62-86	74	(Yousef et al., 1987)	Average concentration
Field, California, USA	N.A.	77	(CALTRANS, 2004)	EMC reduction
Field, MD, USA	18-92.6	N.A.	(Stagge et al., 2012)	Mass load mean reduction
Field, NC, USA	N.A.	(72)	(Knight et al., 2013)	Median EMC reduction
Field, France	(-323)-80	-58	(Leroy et al., 2016)	EMC reduction

Table 7. Summary of Total Lead (Pb) removal performance of swales

Study Type and Location	Swale Performance for Pb Removal (%)		Source	Pb Measurement Method
	Range	Mean (Median)		
Field, Texas, USA	17-41	29	(Barrett et al., 1998b)	EMC reduction
Field, Florida, USA	0-57	28.5	(Yousef et al., 1987)	Average concentration
Field, California, USA	N.A.	68	(CALTRANS, 2004)	EMC reduction
Field, MD, USA	26.7-61.6	N.A.	(Stagge et al., 2012)	Mass load mean reduction
Field, France	46-116	-24	(Leroy et al., 2016)	EMC reduction

Table 8. Summary of Cadmium (Cd) removal performance of swales

Study Type and Location	Swale Performance for Cd Removal (%)		Source	Cd Measurement Method
	Range	Mean (Median)		
Field, Florida, USA	-	43	(Yousef et al., 1987)	Average concentration
Field, MD, USA	41.4-71.6	N.A.	(Stagge et al., 2012)	Mass load mean reduction
Field, NC, USA	N.A.	(19)	(Knight et al., 2013)	Median EMC reduction
Field, France	BDL	BDL	(Leroy et al., 2016)	EMC reduction

BDL: Below Detection Limit

In addition to treating common stormwater pollutants, swales have other likely benefits that have not yet been investigated in detail. For example, a recent study demonstrated that the vegetated swales may also provide the benefit of carbon sequestration, an important ecosystem service for addressing climate change (Bouchard et al., 2013).

Factors affecting swale performance

As evident from this review of literature, there are wide ranges in reductions observed for each pollutant, from negative reductions when swale is acting as a pollutant source, to substantial positive reductions when the swale is removing pollutants acting as a pollutant sink. This variation is due to a myriad of factors affecting swale performance such as seasons, channel length, slope, shape, particle size, and underlying soil properties. These factors are further discussed below:

Seasons

Swale performance was observed to be substantially better in the summer season for sediment, total nitrogen and total phosphorus (Yuan et al., 2019). A reduction in the ability of a swale to remove nitrogen (especially nitrate) and sporadically even resulting in the release of nitrogen has been attributed to seasonal differences (Li et al., 2016; Stagge et al., 2012), with this pattern seen more in the summer. A swale's behavior as a nitrogen source during summer may be due to nutrient sources as a result of increased mowing frequency or other organic material (Stagge et al., 2012).

Variability in environmental field data is common, and swale studies in the literature are limited by heterogeneity, due to differences in geography; timeframe of data collection; differences in analytical methods; and varied swale characteristics, such as age, length, slope, and geometry (Fardel et al., 2019). This variability reduces confidence in the performance results of swales collected from field data, making it difficult to compare results across different studies and to synthesize an optimal swale design. Therefore, the need for controlled plot-scale studies where empirical data can be collected systematically to evaluate the effect of different design parameters was emphasized by Yu et al., (2001).

Swale Channel Length

Existing literature shows that the majority of pollutant removal, especially TSS, occurs in the first 10-15 m of swales (Li et al., 2016; Lucke et al., 2014). Diminished removal performance with length but continued treatment of particulate form has been observed by several researchers (Backstrom, 2002; Lucke et al., 2014; Mohamed et al., 2014; Yu et al., 2001). To remove dissolved forms of sediment, however, a longer swale length or downstream treatment system with settling and filtration mechanisms is recommended (Fletcher et al., 2002). In Australia, Lucke et al., (2014) showed that a 30m long swale can attenuate the mean flow by 52% and peak flow by 61% providing runoff reduction benefits. They also observed that the first 10m of the swale effectively removed 50% to 80% of TSS and 20%-23% TP between inlet and outlet. This conclusion was supported by another study which found high sediment removal performance of swales within the first few meters, and recommended that construction of a swale longer than the required effective length may be unnecessary and is not a cost-effective solution for TSS removal (Mohamed et al., 2014). However, the findings from these research studies have not been successfully translated to design criteria. For example, the NCDOT swale design criterion of 30m (100 feet) of swale length per 0.40 ha (1 acre) of drainage area is anecdotal and needs to be tested.

As demonstrated above, the optimal length of a water quality swale is a complex question. Yu et al., (2001) recommend a minimum 75m swale length, but design length may depend on the ultimate management goal. Specifying flow attenuation or water quality treatment goals will result in different answers. Beyond this, identifying specific targets, such as TSS, metals, or nutrients may also change the necessary parameters.

Swale Channel Slope

Several researchers have suggested that the swales should be built with reduced or mild longitudinal slopes to achieve higher pollutant reduction (Hwang and Weng, 2015; Winston et al., 2017; Yousef et al., 1987), but very limited field data have been collected to identify an optimal slope. Yu et al., (2001) recommended a maximum design slope of 3% for swales to provide pollutant removal. Results from a laboratory-scale study using hydraulic tilt flumes showed that any negative effects of steeper slope (higher sediment concentration, erosive velocities) can be mitigated by good vegetative cover in grassed waterways (Mishra et al., 2006). The benefits of good grass cover in reducing sedimentation and increasing infiltration were notable with an increase in longitudinal slope.

Swale Channel Shape

Barrett et al., (1998) suggested that triangular (V-shaped) channels are the optimal cross-section for highway median when pollutant treatment is desired. In contrast, more recent studies based on field experiments (Fiener and Auerswald, 2005) and modeling (Hwang and Weng, 2015; Winston et al., 2017) suggest that a trapezoidal shape may be the optimal channel shape to provide pollutant removal when compared to triangular (V-shaped) channels, as this provides a larger cross-section and greater hydraulic retention times. Based on these conflicting conclusions, an optimal swale geometry is still undefined.

Particle Size

The performance of a swale is dependent on the particle size, sediment fate and transport processes occurring through the treatment system, because sedimentation or particle settling is the primary mechanism for pollutant removal (Backstrom, 2003; Deletic, 2001; Deletic and Fletcher, 2006; Winston and Hunt, 2017; Yu et al., 2001). Consequently, many researchers have attempted to quantify the particle size distribution and understand the processes that affect the pollutant buildup and washoff in roadway runoff worldwide (Han et al., 2006; Kayhanian et al., 2008, 2007; Li and Barrett, 2008; Li et al., 2005; Sansalone et al., 1998; Vaze and Chiew, 2004, 2002; Winston and Hunt, 2017; Yuan et al., 2017; Zanders, 2005). Particles in highway runoff may originate from a variety of sources, such as tire abrasion, brake pad wear, fluid leaks, atmospheric deposition, and roadway maintenance activities (Barrett et al., 1998a; Gunawardena et al., 2013; Li et al., 2005; Zanders, 2005). The gradation of materials collected from roadway surfaces can span a large range, from smaller than 1μm to greater than 10,000μm, but the majority of particle sizes that are associated with the first flush runoff from the pavement are the finer fractions between 2-8μm (Sansalone et al., 1998). Another study from a low-traffic volume roadway in Australia showed that almost all the load was finer than 3000μm, about 70% finer than 1000μm, and 10% load finer than 100 μm (Vaze and Chiew, 2002). A subsequent study by researchers showed that although more than half of surface pollutant load from roadways was greater than 300μm, the dominant particle size in stormwater that carried almost all particulate nutrients (TP and TN) was between 11 and 150μm (Vaze and Chiew, 2004). They concluded that for effective removal of TP and TN, the SCMs should be designed to remove pollutant size down to 11μm. In a field monitoring study conducted at multiple road sites in North Carolina to characterize road runoff, the median particle size varied between 32-167μm and d_{90} ranged between 72-591μm (Winston and Hunt, 2017).

It is difficult for a roadside swale to trap the smaller particle sizes below 6-25 μm (Bäckström et al., 2006; Deletic, 2005; Deletic and Fletcher, 2006), a difficulty that can be attributed to limited hydraulic retention times in the rights-of-way (Winston and Hunt, 2017). The smaller-sized particles are known to carry the majority of nutrient and metals loads, due to their larger surface area available for binding (Vaze and Chiew, 2004; Zanders, 2005); these findings, highlight the importance of trapping finer particles for runoff treatment. Despite the available information on particle sizes, site-specific particle size is not always considered in SCM design, leading to either ineffective devices that cannot provide treatment, or oversized facilities that require unnecessary capital investment and increased maintenance (Vaze and Chiew, 2004, 2002). In light of this, Selbig et al., (2016) used an urban pollutant loading model, WinSLAMM to demonstrate that incorrect assumptions on the particle size entering an SCM can significantly affect the design and performance. They emphasized the use of site-specific particle size distribution instead of a single value to represent all runoff conditions for designing cost-effective SCMs and avoiding under-or-over-sizing for treatment.

Soil properties

Another key process that affects swale performance positively is infiltration rates of underlying soils (Barrett et al., 1998a; Yousef et al., 1987). In urban development areas, soils can be either compacted intentionally for augmenting soil strength, inadvertently due to use construction equipment (Gregory et al., 2006), or because of improper construction techniques (Brown and Hunt, 2010). Unfortunately, compaction experienced during construction can severely limit a soil's ability to infiltrate and provide key runoff volume and pollutant removal services (Gregory et al., 2006; Pitt et al., 2008). Soils can be defined as severely compacted if cone penetrometer readings exceed 2070 kPa (300 psi) at a depth of 7.5cm (3 in) (Knight et al., 2013; Murdrock et al., 1995; Pitt et al., 2008).

Other factors that influence infiltration rates are soil type, initial saturation, and ponded water depth. Initial soil moisture conditions, however, have shown mixed results on swale performance (Ahmed et al., 2015; Rujner et al., 2018). In a field study of five swales, results showed higher field saturated hydraulic conductivity than expected, and the authors hypothesized that this was likely due to the grass roots creating macropores, breaking up the soil for infiltration (Ahmed et al., 2015). The benefits of vegetative cover in improving soil infiltration rates were also shown by Mishra et al., (2006). The conventional practice of tillage was recently shown to be a viable option for increasing infiltration rates and reducing bulk density in compacted urban soils of North Carolina (Mohammadshirazi et al., 2017). Authors also attributed the improvement in infiltration rates to vegetation, as the roots grow deeper creating macropores that enhance water movement.

Knowledge gaps/research opportunities

The overall goal of this project is to advance the existing swale design guidance available for highway stormwater runoff treatment by conducting comprehensive systematic research. This field study was conducted with a goal of filling the following knowledge gaps identified in the current literature:

- Data on hydrologic and water quality functions of swales have been collected from case-studies worldwide with widely varying results (Backstrom, 2002; Barrett et al., 1998b; Lucke et al., 2014; Yu et al., 2001). Location, climate, design parameters, swale age and watershed characteristics all affect swale function, making a comparison between these datasets difficult. Thus, there is a need for a comprehensive controlled study to systematically collect empirical data that can be used for enhancing the water quality swale design as swales become increasingly popular for stormwater management (Yu et al., 2001). No such controlled studies have been identified in the literature, which has examined the influence of key design parameters (length, slope, and shape) on grass swale performance with the experimental units constructed side-by-side to reduce heterogeneity.
- Small-medium (<25mm) storm hydrology has been studied for decades, and swales' effectiveness in treating small storms is well-documented (Davis et al., 2012; Pitt, 1987; Willis et al., 2013); however, the call for examining the role of larger precipitation events (25-38mm) is recent (Horwatich et al., 2018).
- The difference in performance of swales by seasons is not well-understood. For water quality, an increase in organic matter due to a higher mowing frequency during summers has been identified as a nitrogen source in swales (Stagge et al., 2012). It is unclear if a greater infiltration of runoff volume during summer accommodate for a temporary increase in temporary nutrient loads without impacting downstream waters. A difference in seasonal performance can have an impact on swale inspection and maintenance policy development.

3. Effect of Key Design Parameters on Swale Hydrologic and Water Quality Performance in Controlled Experiments

Objectives:

The goal of this research project is to evaluate the influence of three key swale design parameters (length, slope, and shape) on the hydrologic and water quality performance of a grass swale. The impact of different storm size (defined here as precipitation depth) and season on swale performance are also examined. For the scope of this research, hydrologic performance was defined as the reduction in runoff volume by a swale as measured at the inlet and outlet. The specific objectives and associated research hypotheses (significance level, α=0.05) for examining the hydrologic performance are as follows:

1. Conduct controlled plot-scale experiments to investigate the effect of channel length on the hydrologic performance of grass swales

   Hypothesis: A longer swale (30m) will provide significantly greater runoff volume reduction when compared to a shorter swale (10m).

2. Conduct controlled plot-scale experiments to investigate the effect of channel slope on the hydrologic performance of grass swales

   Hypothesis: A swale with flatter longitudinal slope (1%) will provide significantly greater runoff volume reduction when compared to a swale with steeper slope (4%).

3. Conduct controlled plot-scale experiments to investigate the effect of channel shape on the hydrologic performance of grass swales

   Hypothesis: Trapezoidal swales will provide significantly greater runoff reduction when compared to that of triangular (V-shaped) channels.

4. Conduct controlled plot-scale experiments to investigate the effect of storm size on the hydrologic performance of grass swales

   Hypothesis: The reduction in runoff volume generated from a small-medium size storm (~19mm) is significantly greater than from a larger-size storm (~36mm). In other words, a swale receiving large rainfall events will function mainly as a conveyance channel with small attenuation of runoff volume.

5. Conduct controlled plot-scale experiments to investigate the effect of seasonal difference on the hydrologic performance of grass swales

   Hypothesis: The runoff volume reduction will be significantly greater in the summer season than Fall and Spring seasons. The two seasons (Fall and Spring) are combined due to similar temperatures and no data was collected during winter months.

The goal of the second part of the research project was to evaluate the influence of three key swale design parameters (length, slope, and shape) and storm size on the water quality performance of a grass swale. Water quality performance is defined as follows: (i) the reduction in concentration of pollutants of concern "pollutants" by a swale, i.e. difference in the influent and effluent event mean concentrations; (ii) reduction in mass load of pollutants by a swale, i.e. difference in the influent and effluent pollutant loads. The pollutants considered for this research include sediment (as total suspended solids), total nitrogen, ortho-P, total phosphorus, and four heavy metals (copper, zinc, lead, cadmium). The specific objectives and associated research hypotheses for investigation of water quality performance (significance level=0.05) are as follows:

1. Conduct controlled plot-scale experiments to investigate the effect of channel length on the water quality performance of grass swales.

   Hypothesis: A longer swale (30m) provides significantly greater pollutant removal when compared to a shorter swale (10m).

2. Conduct controlled plot-scale trials to investigate the effect of channel longitudinal slope on the water quality performance of grass swales.

   Hypothesis: A swale with flatter longitudinal slope (1%) will provide significantly greater removal of sediment and other pollutants of concern compared to a swale with steeper slope (4%).

3. Conduct controlled plot-scale trials to investigate the effect of channel shape on water quality performance of vegetated swales.

Hypothesis: Trapezoidal swales will provide significantly greater reduction of sediment and other pollutants of concern compared to triangular (V-shaped) channels.

4. Conduct controlled plot-scale experiments to investigate the effect of storm size on the water quality performance of grass swales

   Hypothesis: The reduction in pollutant loads from a small-medium size storm (~19mm) is significantly greater than from a larger-size storm (~36mm). In other words, a swale receiving large rainfall events will function mainly as a conveyance channel with small attenuation of pollutant loads.

5. Conduct controlled plot-scale experiments to investigate the effect of seasonal difference (summer vs other seasons) on the water quality performance of grass swales

   Hypothesis: Swales will remove a significantly greater amount of pollutants in the summer season than Fall and Spring seasons.

Methods:

Eight grass swales (experimental units) were designed and constructed at the Sediment and Erosion Control Research Facility (SECREF), North Carolina State University, Raleigh, NC, to test the hypotheses. Swales were built with different configurations of channel shape, slope, and length to systematically evaluate the role of these key design parameters in swale performance. Two different synthetic runoff volumes were generated to test the effect of storm size on swale performance. To evaluate seasonal effects, samples were collected from two swales in different seasons. Three experiments for each simulated storm size (2) are proposed for each swale (8), totaling 48 simulations. The methods are described in more detail below.

Field Survey and Design

Topographic survey data were collected to develop construction drawings and design documents for the swales. Due to limited land availability and funding, replicate swales were not constructed. Instead, multiple runoff simulations will be conducted at each swale.
Survey data were collected in February 2017 using Sokkia SET530R prismless surveying total station and Carlson Explorer data collector. The survey focused on the areas that were available for construction and included points on existing irrigation valve, fence line, ditch line and

general spot elevations along the site that characterized the topography. These survey points were imported in AutoCAD Civil 3D 2017 software to create a topographic surface. This existing surface was used as a starting point for designing the swales. A preliminary layout was created and approved by the SECREF personnel and the North Carolina Department of Transportation, the funding agency for this project. Table 9 provides a summary of the design configuration.

Table 9. Design configuration of constructed grass swales

Swale No.	Length (m)	Slope (%)	Side Slope (H:V)	Bottom Width (m)	Channel Shape
VS-1	30	4	3:1	0	V
VS-2	30	4	3:1	0.9	Trapezoidal
VS-3	10	4	3:1	0	V
VS-4	10	4	3:1	0.9	Trapezoidal
VS-5	30	1	3:1	0.9	Trapezoidal
VS-6	30	1	3:1	0	V
VS-7	10	1	3:1	0.9	Trapezoidal
VS-8	10	1	3:1	0	V

Once the preliminary layout was approved, final construction drawings and bid documents were prepared and submitted to NCDOT for final approval. NCDOT approved the final design in December 2017. In February 2018, the project was advertised for bids, and swale construction was completed in April 2018. Design drawings including site layout, swale design and profiles, construction details are provided in Appendix A.

Construction

Site Preparation and Swale Construction

Prior to construction, a silt fence was installed on the site perimeter to prevent sediment runoff downstream. A small dike/berm was created around the perimeter of the upper swale section to divert run-on from adjacent lands to the construction site during precipitation events. The excavation began from the higher elevation areas in a descending fashion, so that the highest elevation of the site was excavated, graded, and stabilized before the lower areas to avoid sediment wash off from exposed upstream soils during heavy rainfall events. Figure 1 shows a typical grading process for swale construction. Native soils were used for conducting the field experiments, therefore, compaction in the swale beds and main channels was avoided as much as practically possible to limit its impact on infiltration. Soil samples from the bottom of the swale were also collected for analysis and findings are discussed in the results section.

Figure 1. Grading operation for construction of Grass Swale#1 (VS-1)

Once the grading was completed, tall fescue sod was installed in each swale (Figure 2). After the sod was installed in each swale, irrigation was started using sprinkler systems to help establish the grass. Due to the large area that needed to be irrigated, a pump was used to supply water via a 5 cm (2-inch) water hose and the swales were flood irrigated. A ball valve was used at the end to control the pressure from the hose. The grass was considered established once the roots had grown beyond sod mats into underlying soils.

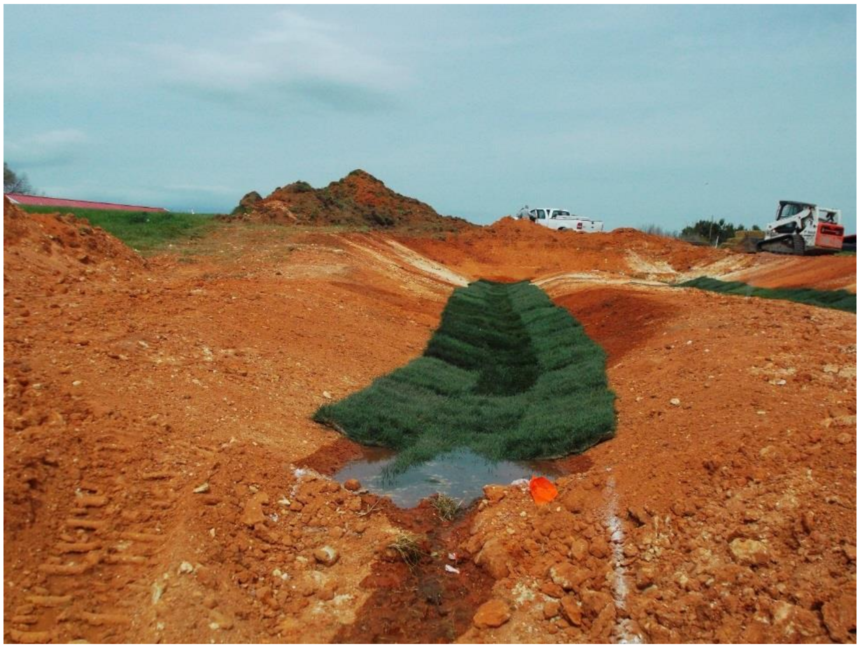

Figure 2. Sod installation for VS-1

Once the swale grading and sod installation was complete, the prefabricated wooden outlet monitoring boxes constructed by the NCSU Stormwater group were placed at the downstream end. The monitoring boxes were constructed from plywood and 1.2mx1.2mx0.6m (4 ft x 4 ft x 2 ft, LxWxD) in dimension. The box included a 60° V-notch weir to collect the water samples and measure stage to determine the flow at the swale outlet. A 20 cm (8-inch) PVC drainage pipe was attached at the outlet end of each monitoring box to discharge the water collected from simulation experiments or rainfall events. The soil below the bottom of these boxes was well compacted with a “jumping jack” or tamper to achieve stability and prevent buoyant forces from dislodging the monitoring boxes (Figure 3).

Figure 3. Installation of outlet structure/monitoring box at VS-5

Once the outlet boxes were installed, all surrounding areas were reseeded, Figure 4 shows a site with substantial completion of construction.

Figure 4. VS-1 completed with sod and outlet structure; surrounding areas reseeded

Site Maintenance

The swales received routine maintenance (mowing) and attempt was made to maintain the grass height between 4-6 inches (100-150mm), typical of water quality swales in the right-of-way. Mowing was performed using a push mower inside the swale to minimize compaction. One swale (VS-3) experienced erosion at the downstream end which was repaired by installing a small piece of erosion control fabric. No fertilizer, herbicide, or pesticide application was performed in or around the swales during the construction and experimental phase. Any weeds were removed using a physical device.

Site and Soil Characterization

To capture existing soil characteristics of the constructed swale site, soil properties such as hydraulic conductivity, bulk density, and soil compaction were measured. Grass height and initial gravimetric water content in each swale was also measured prior to each sampling event.

Infiltration

A constant head permeameter well (single-ring infiltrometer) was used to collect infiltration data from each swale in June 2018. Three locations were selected in each of the eight swales to collect infiltration data. The locations were at swale inlet, mid-point, and exit, before the swale discharges into the monitoring box (Figure 5).

Figure 5. Infiltration tests in the swales at SECREF

The measuring cylinder (21.5 cm^2 area) was inserted straight into the ground to a depth of 4-10 cm. Scraping, leveling or other disturbance of the soil surface was avoided inside the cylinder to maintain soil's hydraulic properties (Dane, 2002). To avoid any leakage, the contact between the soil and inside surface of cylinders was lightly tamped. An infiltrometer tank was inserted in the ground next to the cylinder to provide water supply. The infiltrometer tank was then filled with water to maintain a constant head of water inside the measuring cylinder, and the rate of infiltration was measured until a constant rate was achieved. The time varied between different swales and locations within the swales. The field-saturated hydraulic conductivity was calculated as explained by Dane (2002).

Bulk Density

Since there is significant variation reported in infiltration data even at small spatial scales, another common indicator, bulk density was also measured. Soil samples were collected from the upper 10 cm of the soil using a core sampler (6-cm in diameter). The sampler was inserted in the ground near the infiltration sites at the swale inlet, mid-point, and exit. Soil samples were collected, cut in slices, and preserved in a plastic bag for transport back to the laboratory for processing of bulk density.

Compaction

A cone tipped penetrometer (Field scout SC900, Spectrum Technologies, Inc., Aurora, IL) equipped with a 1.27cm diameter tip was used to measure penetration resistance at three locations within each swale: inlet, mid-point, and exit. Since soil moisture content greatly affects penetrometer data, the measurements were made at least 1-2 days following a rain event so that soil moisture conditions are consistently wet for all swales. Measurements were made before the beginning of field experiments in summer 2018. Cone penetrometer readings exceeding 2070 kPa (300 psi) at a depth of 7.5cm (3 in) were used as a threshold value to identify excessively compacted soils (Knight et al., 2013; Murdrock et al., 1995; Pitt et al., 2008).

Soil Moisture

To account for the effects of antecedent moisture conditions and explain the possible variations in swale performance, soil moisture data were collected each time a sampling event was conducted. A steel auger was inserted at three different locations (inlet, mid-point, and exit) in the swale to a depth of approximately 7-10 cm. The auger was pulled out gently and the soil sample was placed in a plastic bag, wrapped tightly and transported back to the NC State University Soil Science laboratory for analyses.

Grass Height

Previous research has demonstrated that the optimal grass height for providing water quality treatment is between 10 cm-15 cm (4 inches-6 inches). Thus, average grass height was also recorded using a ruler at the swale-inlet, mid-point, and the exit at the beginning of each simulation experiment. A certain tolerance 7.5 cm-20cm (3 inches-8 inches) was allowed for grass height, due to the time constraints and logistics of scheduling mowing before a runoff simulation was conducted.

Plot Experiments

The controlled plot-scale experiments were conducted at the Sediment and Erosion Control Research Facility (SECREF) at North Carolina State University, Raleigh. Data were collected between October 2018-August 2019.

Hydrology

Historically, small-medium storm events have demonstrated more effective treatment by swales than medium and large events. However, recent research has also called for examining large precipitation events since rainfall depth is the primary factor in determining swale runoff (Horwatich et al., 2018). They provide five rainfall groupings in terms of rainfall depth impacts as defined by Pitt (1999): extra-small (<5mm or 0.2 inches), small (5mm-13mm or 0.2-0.5 inches), medium (13mm-25mm or 0.5-1.0 inches), large (25mm-38mm or 1.0-1.5 inches), and extra-large (>38 mm or 1.5 inches). For the purpose of this study, medium (~19 mm) and large (~36 mm) rainfall events are proposed because storms between 12mm-38mm (0.5in-1.5in) are typically responsible for about 75% of the runoff pollutant discharges and should be considered for maximum possible capture of runoff volume. This range includes the current “water quality design storm” of 25 mm (1 inch), also referred to commonly as the “first flush”. Thus, results from this study can be easily applied for use by the design and regulatory communities.

Two synthetic runoff simulations that generated runoff volumes from a medium and large precipitation depth were used to test for the hydrologic performance of swales. The historical rainfall data analysis (when greater than 2.5 mm or 0.1 inch with a 6-hour antecedent dry period) showed the antecedent dry periods in Raleigh-Durham to be approximately 3.9 days. This minimum duration was maintained between conducting experiments in the same swale to the maximum extent practicable. Flow data was recorded by the ISCO 6712 sampler and ISCO 730 bubble module at the inlet and the outlet (Figure 6). A 30º V-notch installed inside the inlet structure and a 60º V-notch inside the outlet structures were used to measure flow. Appropriate weir equations were used to convert stage to flow rate using a stepwise function (derived from V-notch and broad-crested weir equations) as described by Grant and Dawson (2001) for inlet and outlet, respectively:

$$Q = 0.6760 \times H^{2.5} \quad (8)$$

$$Q = 1.443 \times H^{2.5} \quad (9)$$

Design flow volumes to generate runoff simulations were developed using a simple method for a drainage area representing a typical highway environment. The NCDOT anecdotal rule for swale design of 30 m (100 ft) long swale for 0.40 ha (1 ac) of drainage area was used to estimate runoff volumes from both medium and large events. Due to limitation on the available water volume and drainage appurtenances the maximum flow represented runoff from approximately 0.31ac. Thus, the 10m swales were sized per the current NCDOT standards while the 30m swales were “oversized” by 3x.

Initial trial runs were conducted to develop flow volumes that will be generated from this hypothetical drainage area. Multiple swales (VS-5, VS-6, VS-7, VS-8) were selected for pilot testing and a time step duration of 10 min, 20 min, and 30 min was used to release flows from the upstream water supply pond. The flows were released by turning the valve at seven different turns: 0.25, 0.50, 0.75, 1.0, -0.75, -0.50, -0.25, 0.0 with varying time step durations between each step. These fixed turns were primarily selected to reduce human error in turning the valve to values that are not well-defined. The runoff volume measured during each event was used to back-calculate the precipitation depth in a typical 0.12 ha (0.31 ac) highway drainage area as cross-verification of the method. To simulate the rainfall-runoff events, the water valve was turned every 10 minutes for medium storms and 20 minutes for large storms, as they approximately provided the desired runoff volume. An effort was made to fill the water supply pond to approximately the same level each time, since small variations in water levels were observed to cause a variation in the flow volume. However, this was not always possible to due to scheduling issues.

Figure 6. Monitoring setup at the outlet boxes

Water Quality Sampling

For preparing the pollutant spikes, onsite soil from a stockpile (leftover from different construction projects) was collected and brought to the laboratory. The sediment was dried in an oven (Thelco, Model 17; Precision Scientific) for 24 hours. The sediment was mixed well to break any conglomerates of fine particles with a mortar and pestle. The sediment was then sieved through ASTM #25 sieve to obtain particles less than 500 µm (Figure 7).

Figure 7. Sieve setup to reduce particle size of sediment for runoff simulation

The pollutant dosing was determined based on typical concentrations observed in highway runoff in North Carolina. NCDOT has developed typical median EMCs for typical land use that are unique to the roadway environment based on research studies in North Carolina. From the research dataset, primary roadways were shown to have a median TSS of 28 mg/L, TN of 1.39 mg/L and median TP of 0.19 mg/L (personal communication, NCDOT, July 30, 2018). The median concentrations for dissolved metals are: 10.95 µg/L (copper), 69.2 µg/L (zinc), 2.57 µg/L (lead), and 0.1 µg/L (cadmium), (personal communication, NCDOT, February 9, 2017). These values fall within the range observed in the literature.

For water quality tests, ambient pond water was spiked with synthetic pollutants to reflect median highway runoff concentrations in North Carolina. In addition to sediment (TSS), other water quality parameters that were measured under this study are TKN, $NO_{2\text{-}3}$-N, O-PO_4^{3-}, TP, dissolved Cu, dissolved Pb, dissolved Zn and dissolved Cd. The typical highway concentrations and runoff volumes from the hypothetical drainage area were used to estimate the dosing amount for each pollutant to mimic the pollutant concentrations observed in actual conditions. The dried and sieved sediment were weighed for each time step and other reagents mixed to form the dosing mixture and carried to the field site in labeled Ziploc bags. A 50-gallon plastic tank with a stirrer/mixer was used for spiking and dosing as shown in Figure 8 below. The tank was filled with ambient pond water, spiked with known concentrations of synthetic pollutants (sediment, nutrients, and metals) as described above, and discharged from the tank into the inlet box at a constant rate for each selected time step duration. To simulate the hydrograph, the water valve was turned every 10 minutes for medium storms and 20 minutes for large storms.

Figure 8. Synthetic runoff simulation and monitoring setup at the inlet box

Surface water quality samples were collected at the inlet and outlet of swale by an ISCO 6712 automatic sampler with ISCO 730 bubbler module flowmeter. The samples are flow-weighted composite samples per USDOT requirements. Once the test was completed, the composite samples were transferred into appropriate lab-supplied labeled bottles and stored on ice for transport back to the laboratory and stored in a refrigerator. The samples were then transported on ice within 24 hours of sample collection to the analytical laboratory. Metal samples were analyzed at the NCDEQ Water Sciences Laboratory, and the sediment and nutrient samples were analyzed at the NCSU Center for Applied Aquatic Ecology laboratory using the standard methods (APHA, 2012). Table 10 presents the details on the methods.

Table 10. Analytical methods, reporting limits, and sample hold times

Pollutant of Concern	Matrix	Analytical Method	Reporting Limit	Sample Hold Time
Total Kjeldahl Nitrogen (TKN)	Water	EPA Method 351.2	280 µg/L	28 days
Nitrate+Nitrite Nitrogen (NO_2-NO_3), NO_X	Water	Std. Method 4500 NO3 F EPA Method 353.2	5.6 µg/L	28 days

Ortho-Phosphate (PO_4-P)	Water	Std. Method 4500 P F EPA Method 365.1	6 µg/L	48 hours
Total Phosphorus (TP)	Water	Std. Method 4500 P F EPA Method 365.1	10 µg/L	28 days
Total Suspended Solids (TSS)	Water	Std. Method 2540D	-	7 days
Copper (Cu)	Water	EPA 200.8 Rev. 5.4 EPA 200.9 Rev. 2.2	2.0 µg/L	6 months
Lead (Pb)	Water	EPA 200.8 Rev. 5.4 EPA 200.9 Rev. 2.2	2.0 µg/L	6 months
Zinc (Zn)	Water	EPA 200.8 Rev. 5.4 EPA 200.7 Rev. 4.4	10 µg/L	6 months
Cadmium (Cd)	Water	EPA 200.8 Rev. 5.4 EPA 200.9 Rev. 2.2	0.50 µg/L	6 months

Samples were also collected at the inlet and outlet for particle size distribution (PSD) analysis, which was performed by the NCSU sedimentology laboratory in Raleigh, North Carolina. A Beckman-Coulter 13-320 Laser Diffraction Particle Size Analyzer equipped with a Universal Liquid Module. The equipment can measure particle size in the range of 0.04-2,000 µm.

Quality Assurance Samples

Field duplicates are used to assess precision, and field blanks assess whether sample contamination has biased sample accuracy. Field duplicates or replicate samples are used to conduct repeated analysis for each parameter, which can help indicate any potential issues with sampling and laboratory analysis procedures. Field blanks are commonly samples of high-purity distilled water that are filtered, stored, labeled, and analyzed according to the sampling procedure documentation. Since a composite sample is being collected in a 10L bottle to capture the entire storm event, placing a bottle for field blank is not feasible. Hence, a modified field blank sampling procedure was used. Distilled water was placed in a similar 10L HDPE bottle and transported to the field monitoring site. The bottle was left capped and placed close to the sample collection area near the inlet ISCO. Once ISCO finished sample collection, the water from composite bottle was distributed in appropriate pre-labeled, pre-preserved bottles for laboratory analysis. Similarly, the distilled water was distributed in appropriate bottles for laboratory analysis and transported in the same ice cooler. If analysis of field blanks indicates measured values greater than detection limits, contamination is likely occurring in the sampling, handling, or analysis process. Table 11 below shows the QAQC measures and performance standards.

Table 11. Quality Assurance Quality Control Parameters

Measure	Frequency
Field blanks/trip blanks	1 per 5 sampling events (20% of samples)
Method blanks	1 per digestion batch for metals
Field duplicates	1 per 5 sampling events (20% of samples)
Laboratory duplicates	1 per 10
Matrix Spikes	1 per 20 for NO_2+NO_3 and Ortho-P

Prior to water quality tests, the ambient concentration of water in the pond was also tested periodically for the background concentration. A total of 20% of samples (1 in 5) across the monitoring period were proposed for field duplicates and additional 20% samples (1 in 5) for field/trip blanks. The QC samples were collected at the inlet or outlet box location. To measure precision of the sample collection and analysis, relative percent difference (RPD) was estimated for the field duplicate samples as follows:

$$RPD = \frac{|X_1 - X_2|}{\left(\frac{X_1 + X_2}{2}\right)} * 100$$

Data Analysis

Historic rainfall data were obtained from North Carolina Climate office (NCCO) from June 1, 1982-September 30, 2018, for two stations-Lake Wheeler and Raleigh-Durham International Airport. The rainfall data (when greater than 2.5 mm or 0.1 inches with a 6-hour antecedent dry period) was analyzed in R to estimate median rainfall amount and antecedent dry periods. The statistical analysis of data collected via field experiments will be conducted using a suite of tools such as Microsoft Excel and JMP (a SAS software). The field experiment to test objectives 1-4 is a 2^4 factorial design and can be defined statistically as follows:

- Treatments-16 (2^4), Replications-3 per treatment

- Factors (4): Length, Slope, Shape, Storm Size
- Levels (2):
  - Lengths-10m, 20m
  - Slope-1%, 4%
  - Shape-Triangular, Trapezoidal
  - Storm Size-Medium, Large
- Experimental Units (8): Each swale of different design configuration
- Response/Measurement Unit: Flow volumes for hydrologic performance and event mean concentrations (inlet and outlet) for each pollutant

Any non-detect data was planned to be substituted with ½ -the-detection limit but no substitutions were required for the laboratory results. To test the overall research goal of identifying the most influential design parameter on the hydrologic and water quality performance of the swale, an analysis of variance (ANOVA) with significance levels, α of 0.05 was used. Residual plots were examined visually. If the ANOVA assumptions were not met, appropriate data transformation (logarithmic or square root) was conducted and the model was re-fit. A comparison of least square means from within the ANOVA model was also conducted using Tukey's Honestly Significant Difference (HSD) test to identify the differences in mean responses. Factors such as grass height and soil moisture were assumed to potentially affect the responses (runoff volume reduction or pollutant load reductions) and were measured as covariates. The analysis of covariance (ANCOVA) test was conducted with significance levels, α of 0.05.

For testing research objective 5 (seasonal difference in swale performance), data from VS-5 and VS-6 collected in summer and other seasons was used to conduct a two-sample t-test. The two experimental units were treated as comparable units since they have same length and slope (different shapes were ignored for this analysis).

Results and Discussion

The field study involved examining the role of multiple factors in optimizing swale design. A variety of data were collected for analysis, the results and discussion are summarized in the order of site characteristics, runoff volume, particle size trapping efficiency, and water quality. Statistical analysis is included in pertinent sections while complete data sets are provided in appendices.

Site Characteristics

The site characteristics of swales are presented in Table 12. The average field saturated hydraulic conductivity shows a wide variation between swales but is typical of highway swales (Ahmed et al., 2015). Bulk density values in swales are well below the threshold values that can restrict root growth (Brady and Weil, 2002). These values also suggest that the swales were not severely compacted during construction. Detailed compaction values are presented in Appendix A.

Table 12. Site characteristics of swales

Swale	Sand %	Silt %	Clay %	USDA Classification	Field Saturated Hydraulic Conductivity (cm/h)	Bulk Density (g/cm3)
VS-1	62.6	14.3	23.1	sandy clay loam	1.4	1.26
VS-2	54.8	11.4	33.8	sandy clay loam	8.5	1.30
VS-3	57.5	15.7	26.9	sandy clay loam	0.6	1.41
VS-4	48.0	15.1	36.8	sandy clay	1.4	1.40
VS-5	64.2	11.9	23.9	sandy clay loam	5.0	1.33
VS-6	49.0	15.4	35.6	sandy clay	2.9	1.29
VS-7	51.7	14.0	34.2	sandy clay loam	11.5	1.40
VS-8	46.7	16.6	36.7	sandy clay	2.0	1.35

Soil Moisture and Grass Height

Soil moisture and grass height were measured each day prior to runoff simulation since they have the potential to influence runoff volume and pollutant reduction ability of a swale. Figure 9 shows the grass height measurements prior to each runoff simulation. The variability in grass height between and within swales is primarily due to the time of mowing, which was not controlled. Grass height exceeded 2.4 in (6 cm) for all but one measurement, while 3.2 in (8 cm) was a more typical height.

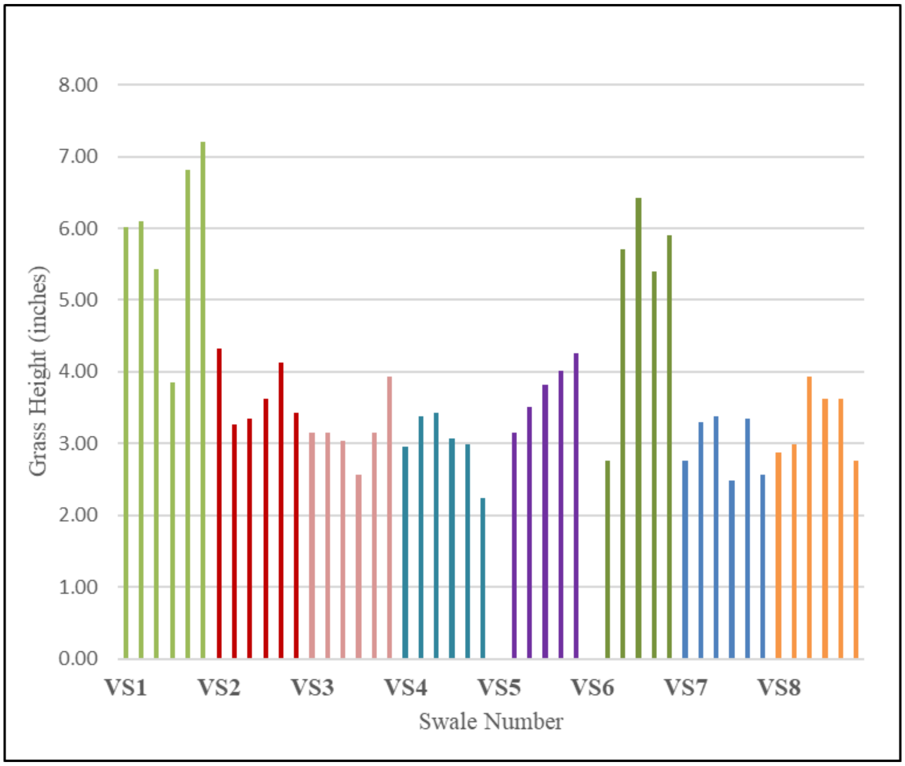

Figure 9. Measured grass height for each sampling event

The soil moisture prior to each runoff simulation was measured as the gravimetric water content (g/g), which is multiplied by the bulk density for each swale to obtain the initial volumetric moisture content. The gravimetric water content showed a similar pattern across swales based on the time of the year (season). The highest gravimetric water content was observed in the Fall season (0.23-0.25 g/g) followed by summer (0.12-0.20 g/g). The lowest water content was observed in the spring (0.08-0.18g/g), March-June) or the growing season when grass roots utilize the most water available in the soil. Detailed grass height and water content results are presented in Appendix A. Both parameters (grass height and water content) were measured as a possible covariate for improving the statistical model to conduct the analysis of covariance (ANCOVA) test, discussed later in the statistical analysis section.

Runoff Volume

The runoff volume through the swale system matched typical hydrograph shapes in runoff simulation studies for both small-medium storms (Figure 10) and large-size storms (Figure 11). Similar hydrographs were reported by Yousef et al. (1987), who conducted runoff simulation studies for grass swales along highways in Florida.

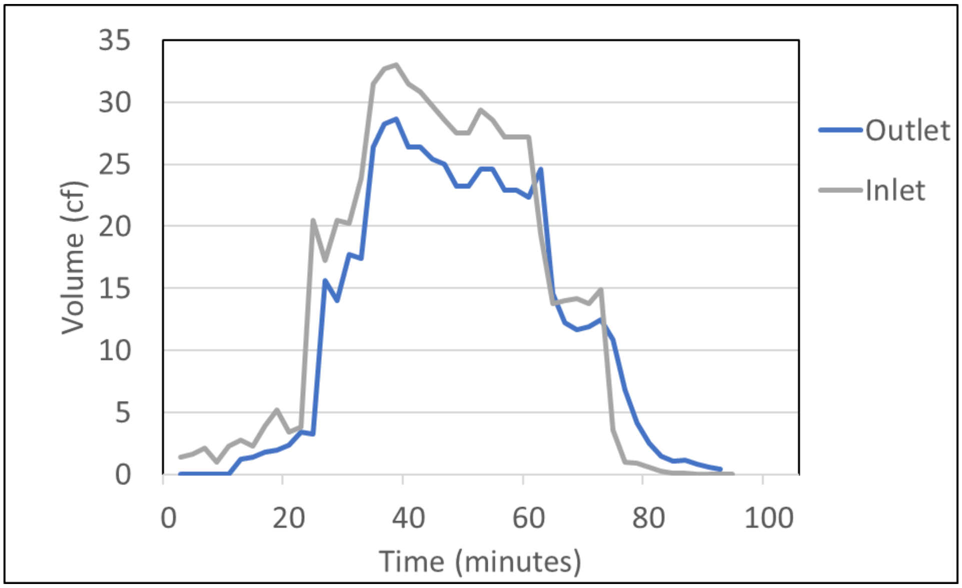

Figure 10. Typical simulated runoff hydrograph for a medium storm

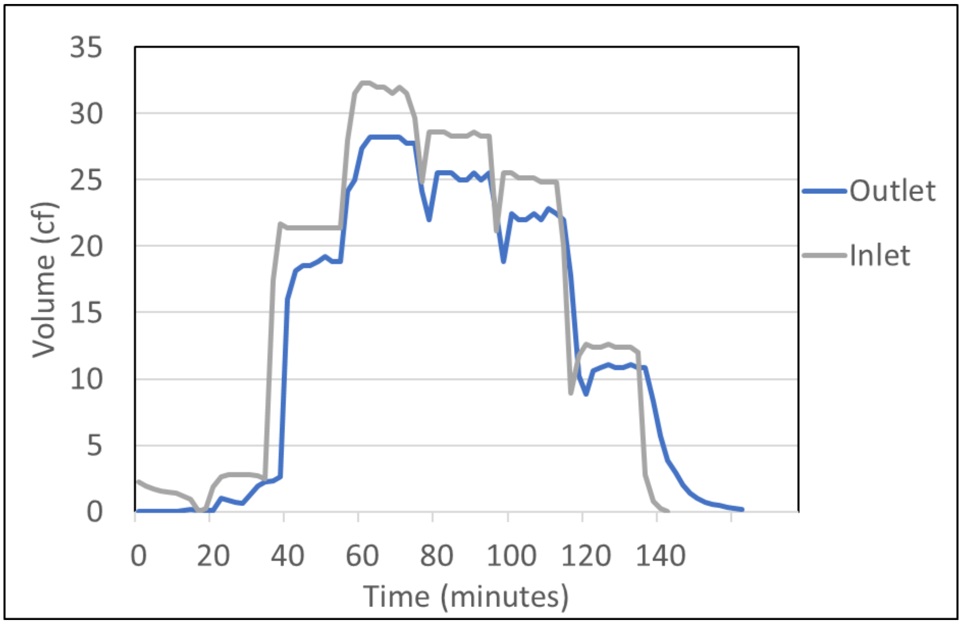

Figure 11. Typical simulated runoff hydrograph for a large storm

The runoff volume reduction obtained by each swale during each simulation event is presented in Appendix B. The inflow runoff volume showed some variability among events, which can be attributed to the challenge in maintaining constant water levels in the supply pond due to water use for other experiments. In addition, human error in operating the water valve and the different travel distance of water to the swales likely influenced runoff volumes reaching the swales. The difference in distance and pipe length can cause a potential change in the amount of runoff delivered to the swale as water travels over different lengths and slopes. The number of fittings used to connect sections of pipe and corrugations also increase with pipe length, thereby increasing chances of energy losses and potential leaks.

Average runoff volume percent reductions for each swale under different storms are summarized in Table 13. Overall, these results agree with previous work demonstrating runoff volume reduction benefits of grass swales (Davis et al., 2012; Knight et al., 2013; Rushton, 2001; Yousef et al., 1987).

Table 13. Summary of average percent reduction in runoff volume

Swale	Configuration	Storm Size	No. of events (n)	Volume Reduced (%)
VS-1	V, 30m, 4% slope	Medium	3	23
		Large	3	14
VS-2	T, 30m, 4% slope	Medium	3	53
		Large	3	41
VS-3	V, 10m, 4% slope	Medium	3	18
		Large	3	14
VS-4	T, 10m, 4% slope	Medium	3	13
		Large	3	12
VS-5	T, 30m, 1% slope	Medium	3	61
		Large	3	44
VS-6	V, 30m, 1% slope	Medium	3	39
		Large	3	25
VS-7	T, 10m, 1% slope	Medium	3	6
		Large	3	9
VS-8	V, 10m, 1% slope	Medium	3	28
		Large	3	25

With the exception of shorter swales, trapezoidal swales provided greater percent reduction of runoff volumes than triangular-shaped swales. The maximum (VS-5) and minimum (VS-7) runoff volume reduction benefits in this study were observed in trapezoidal swales constructed at 1% slope. The greatest runoff volume reductions in VS-5 can be attributed to the swales' long channel length (30m) and because it was the least compacted swale (61psi). Similarly, the lowest runoff volume reduction in VS-7 (trapezoidal) may be due to the short length (10m) available for infiltration, and the highest soil compaction (246psi), which likely impacted infiltration processes (Pitt et al., 2008). The adjacent 10m triangular swale, VS-8, had the second highest reported compaction levels, but provided a greater runoff volume reduction benefit. The runoff reductions in other 10m swales, constructed at 4% slopes (VS-3 and VS-4) do not seem to differ substantially, but once again the less compacted VS-3 (triangular swale) infiltrated more water. The two short triangular swales (VS-3 and VS-8) could provide better runoff attenuation because the greater flow depth and higher hydraulic head may be driving infiltration faster than in a trapezoidal channel. Overall, swale length and compaction level in swales appear to be the most influential factors affecting runoff volume attenuation.

In general, small-medium storms (~19mm) had more runoff volume reduction than large storms as previously observed by Davis et al. (2012), Pitt (1987), Winston et al. (2018), and Yu et al. (2001). The results do differ from Davis et al.(2012) and Rujner et al. (2018), suggesting that although the swale runoff volume attenuation ability during large storms (~36mm) decreased, it was not eliminated.

The findings from this study support continued construction of swales as a green infrastructure practice and stormwater control measure for runoff reduction from a water quality design storm, typically <25mm (Winston et al., 2018).

Statistical Analysis of Runoff Volume Reductions

A full-factorial analysis of variance (ANOVA) test was conducted to determine the most significant factors influencing runoff volume reductions (significance level, $\alpha=0.05$). Table 14 shows the factors that were statistically significant at different α values. Typically, a water quality swale is designed for small-medium size storms; thus, a reduced model with only swale design factors (length, slope, and shape) was also examined. However, the results did not reveal any deviations from the full model. The coefficient of determination for the regression model ($R^2=0.77$, adjusted $R^2=0.67$) suggested that much of the variability in runoff volume reductions (response) was explained by the factors selected for the study.

Table 14. Analysis of variance (ANOVA) results for percent runoff volume reduction

Factor	p-value
Channel Length***[3]	<0.001
Channel Shape**[2]	0.034
Storm Size**[2]	0.024
Channel Slope*[1]	0.052
Length x Shape Interaction***[3]	<0.001
Length x Storm Size Interaction*[1]	0.054
Slope x Shape Interaction*[1]	0.079

The ANOVA results indicate that swale length, swale shape, storm size and (length x shape) were all significant at the pre-determined significance level of α=0.05. Slope, (length x storm size), (slope x shape) become significant at α=0.10 level. The Least Squares Means (LS Means) values for each factor suggested that higher runoff volume reduction was attained by a longer (30m) swale, a flatter (1%) slope, and trapezoidal shape, for small-medium storms. Further, pairwise comparisons were made using Tukey's Honestly Significant Difference (HSD) test to detect means that are significantly different from each other (Table 15).

Table 15. Least Squares Means Comparison for different experimental factors from Tukey's Honestly Significant Difference (HSD) test.

Level	Tukey Grouping[a]					Least Square Mean
Medium,30,1,T	A					61.5
Medium,30,4,T	A	B				53.4
Large,30,1,T	A	B	C			44.1
Large,30,4,T	A	B	C	D		40.7
Medium,30,1,V	A	B	C	D		38.6
Medium,10,1,V		B	C	D	E	28.0
Large,30,1,V		B	C	D	E	24.9

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* Statistically significant at α=0.10; **Statistically significant at α=0.05, 0.10; ***Statistically significant at α=0.01, 0.05, and 0.10;

[a] Levels not connected by same letter are significantly different **(α=0.05)**

Large,10,1,V		B	C	D	E	24.7
Medium,30,4,V		B	C	D	E	23.3
Medium,10,4,V			C	D	E	17.9
Large,10,4,V			C	D	E	14.3
Large,30,4,V			C	D	E	14.2
Medium,10,4,T			C	D	E	12.7
Large,10,4,T				D	E	11.8
Large,10,1,T				D	E	9.5
Medium,10,1,T					E	6.2

Channel Length

A comparison of the LS Means values from Table 15 suggests that the longer, 30m swales provided approximately 2.5x-10x more runoff volume reduction than a 10m swale. Although this study had much larger inflows, the volumetric reductions of over 50% in 30m long swales were similar to those obtained by Lucke et al. (2014). Thus, in contrast to the conclusions of Davis et al. (2012), this study demonstrated that swales can provide substantial runoff volume reduction for larger storms, when the swale length was extended beyond the current design criteria. For this field experiment, the (33 ft) 10m swales were sized per the current NCDOT standard of 100 ft length per 1 ac (0.40 ha) of drainage area with roadways or largely impervious surfaces. Hence, the (100 ft) 30m swales were "over-sized" per current standards, but the runoff volume reductions improved with an increase in swale length. However, the parameter estimates do indicate a pattern of diminishing returns for increasing swale length (approximately 10% reduction in benefit for every 10m increase in length), suggesting that the benefits of runoff volume reductions may "cap-out" after certain lengths. Extending swale lengths beyond the contributing road surfaces can also be challenging for design, and impractical as very few developers would choose to install, for example, a 1000 ft (approximately 300m) long swale (Winston et al., 2017). Modifying the current NCDOT swale design criteria to a 300 ft (or 90m) swale length per acre of contributing drainage area may be a more feasible option to consider. The pairwise comparison results showed the swales VS-5 (30m, trapezoidal, 1% slope) and VS-7 (10m, trapezoidal swale, 1% slope) had highest and lowest runoff volume reductions, respectively for small-medium storms. They are also statistically significantly different from each other and all other swale configurations. As discussed earlier, the compaction levels in these two swales also represent the two extremes from this study, emphasizing the importance of proper construction techniques that can minimize soil compaction and augment infiltration (Brown and Hunt, 2010).

Channel Slope

The runoff volume reduction benefits of flatter longitudinal slopes in a swale were observed to be marginal, but present, in this study. The ANOVA (p-value=0.052 for slope and p-value=0.079 for slope x shape interactions) suggest that slope could be a significant factor, if experiments were repeated and more data were collected, or if a higher significance level (e.g., α=0.10) were considered. Another plausible explanation masking slope as a significant factor may be the influence of variables such as soil compaction, which may be confounding the real effects of slope. In the main, a flatter swale demonstrated enhanced runoff volume reductions in this study.

Channel Shape

The effect of channel shape in providing runoff volume reduction benefits was significant (p-value=0.034). The LS means comparison suggest that the trapezoidal swales can provide approximately 7.5% more reduction in runoff volume than a triangular swale. These results agree with previous modeling studies, which have suggested that a flat-bottom/trapezoidal swale can enhance runoff volume reduction ability (Fiener and Auerswald, 2005; Winston et al., 2017).

Storm Size

ANOVA results indicated that storm size was a significant factor for runoff volume reduction in a swale (p-value=0.024). A least square means comparison showed that runoff volume reduction benefits were approximately 7% higher during a small-medium storm than a large-size storm. The effectiveness of swales for small-medium storms (<25mm) is well-established (Davis et al., 2012; Rujner et al., 2018; Winston et al., 2018; Yu et al., 2001). However, this study provided evidence that swales may not be a "conditionally effective SCM" as mentioned by Davis et al. (2012), and are still able to mitigate runoff volumes during larger storms up to 36mm.

Overall, these results suggest that swale length and compaction levels in urban swales may be more important than the channel slope or shape. These findings highlight the importance of proper design and construction techniques for a water quality swale. Notwithstanding the limitations of field studies, this study suggests that a swale that is (1) longer than the current standard per acre of drainage area, (2) with a trapezoidal cross-section, and (3) built on flatter longitudinal slopes effectively mitigated runoff volumes from small-medium size storms

(<19mm). Furthermore, grass swales not only effectively convey the larger storms (~36mm) but also provide some volume mitigation (albeit somewhat less than that provided for smaller events).

Effect of Seasons on Runoff Volume Reduction

A two-sample t-test (with a significance level of 0.05) was conducted for examining the effect of seasons on runoff volume reduction. Swales VS-5 and VS-6 (30m long at 1% slope) were selected for this limited analysis. Their performance was assumed similar despite different shapes, and storm-size was also ignored for this limited analysis. Six storms were simulated in the summer season (June 20, 2019-September 30, 2019) and another six in the Fall and Spring (October 1, 2018-June 19, 2019). The two-sample t-test results suggest that there is no seasonal difference in runoff volume reduction ability of a swale. These results agree with Ahmed et al. (2015) who concluded that the soil moisture content and season have no significant effect of the mean field-saturated hydraulic conductivity of swales, which is key for runoff volume reduction.

Particle Size and Trapping Efficiency

The median particle size (d_{50}) at the inlet of each swale is shown in Figure 12. The mean and range of sediment particle size used to spike the inflow to the swales are presented in Appendix C. The mean particle size for each gradation was consistent throughout the simulations with a slight variation, which is common in simulation studies (Mohamed et al., 2014). Human error in sieving and sample preparation, wind velocity on day of experiment, and occasional change in the function of the mixer pump are speculated as possible factors causing this variability.

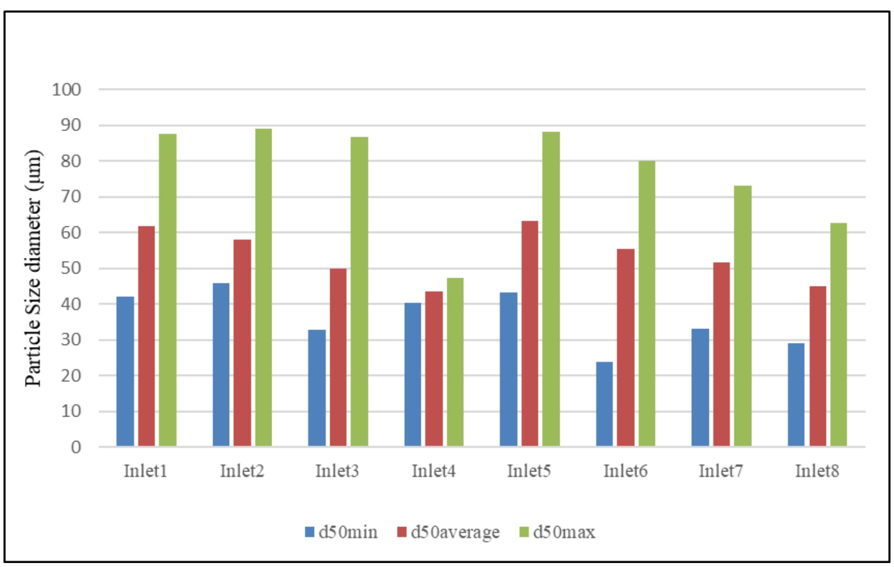

Figure 12. Range of particle size for median (d_{50}) particles at inlet of each swale

Particle size that can be trapped by a grass swale is a key parameter in evaluating its efficiency. As defined by Backstrom (2002), particle trapping efficiency was estimated as the difference between inlet and outlet particle concentrations divided by the inlet concentration. Figure 13 shows the trapping efficiency for each of the eight swales for the different particle sizes.

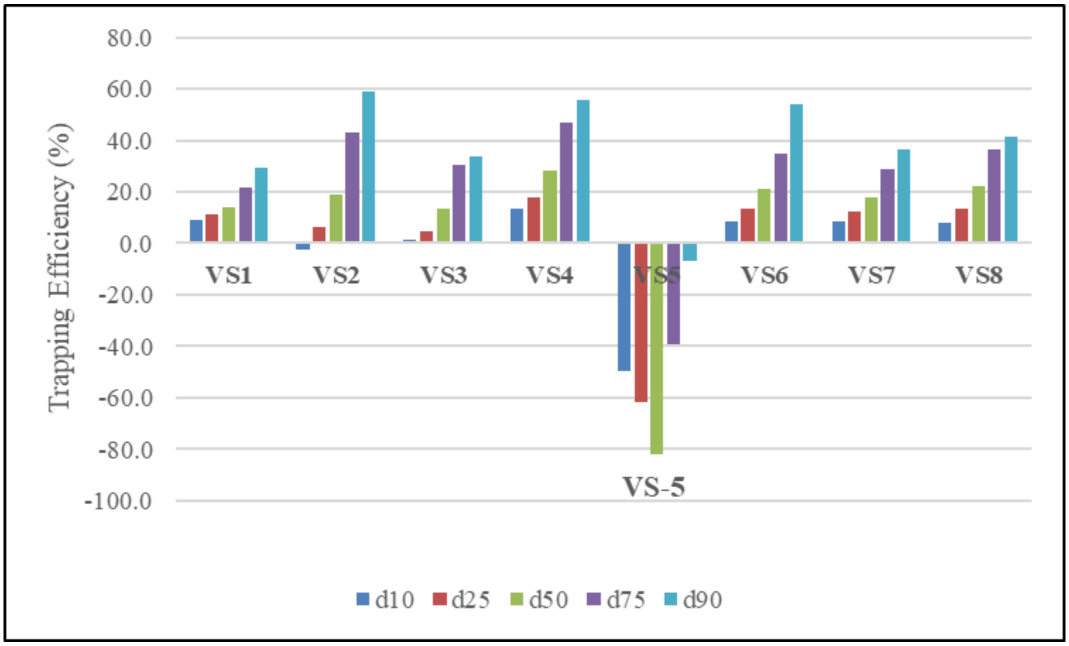

Figure 13. Average Particle Trapping Efficiency for Grass Swales

In most cases, the swales reduced particle size between inlet and outlet suggesting trapping within the swale. However, in 25% of the total simulations, the median particle size (d_{50}) leaving the swale was higher. Outflow particle size (d_{50}) greater than the inflow d_{50} generally occurred in the short (33ft) swales indicating the importance of swale length for increased sediment trapping. The most contradictory results were noted for VS-5, a 30m trapezoidal swale at 1% slope, where in four of the six events d_{50} at the outlet was greater than that of the inlet. This stark negative trapping efficiency and increased particle size at the swale outlet is likely due to the sparse grass density at the inlet of this swale. The sparse grass density allowed larger size sediment to be deposited at the swale inlet (Figure 14), which was then likely re-suspended and exported during runoff simulation. During the first runoff simulation, VS-5 trapping efficiency was 13%, 32%, 42%, 55%, and 67% for different particle size gradations (d_{10}, d_{25}, d_{50}, d_{75}, d_{90}), respectively. The two subsequent runoff simulations resulted in negative trapping efficiency (significantly higher export of sediment), most likely due to “flush” of the swale. The fourth simulation again provided positive trapping efficiencies of 6%, 18%, 45%, and 62% for d_{25}, d_{50}, d_{75}, d_{90}, which may be because previously deposited sediment was already flushed out of the system. The hypothesis of sediment deposition and resuspension due to low grass density is further supported by negative trapping efficiencies observed for the last two simulations.

Figure 14. Sparse grass cover and sediment deposition at the inlet of VS-5 swale

For effective particle trapping in a swale, it is recommended to have a fully developed dense turf (Backstrom, 2002) with tall and stiff grass blades (Ree, 1949; Temple, 1987). Thus, increased particle size leaving the swale in absence of sparse grass density and low grass height in this study emphasizes the importance of proper vegetation establishment and routine maintenance of swales for optimal water quality performance.

Other likely reasons for the increase in particle size are: (i) growth of organic matter in stored samples before the analysis was conducted; (ii) particle aggregation or dissolution that may occur when samples are stored at room temperature (Li et al., 2005). These factors are possible due to the significant time difference (several days to weeks) experienced between sample collection and analysis, due to logistics. To avoid organic matter growth in future studies where particle size distribution is being analyzed, the samples can be pretreated with hydrogen peroxide, if an extended time period is anticipated between sample collection and analysis.

However, it is considered unlikely that this effect would only substantially impact the results from one particular swale (VS-5). For preventing possible particle aggregation during storage, the samples are recommended to be analyzed within 6 h of collection (Li et al., 2005).

Water Quality

Like runoff volume and particle size, concentrations of inflow pollutants in swales also showed some variation as they are attached to the particles and conveyed with the runoff. Other possible factors that can contribute to variation in concentrations include human error in sample weighing and preparation, duration between sample preparation and simulation, and dilution due to greater runoff volumes in large-sized storm simulations. Despite the variation, the inlet concentrations (Appendix C) were well within the range observed in highway runoff pollutants selected for this research. Due to generally lower nutrient influent concentrations, the effluent EMCs from this study should be used with caution to draw inferences when comparing with expected TN (1.10 mg/L) and TP (0.14mg/L) effluent concentrations from the NCDEQ SCM credit document (NCDEQ, 2018). Similarly, the metal concentrations in the mixture had to be spiked at a higher proportion for the laboratory to be able to detect pollutants. As such, the effluent concentrations may appear higher than typical roadway concentrations, but it is not generally representative of swales' effectiveness.

In general, effluent quality is a better predictor of SCM effectiveness than the percent removal metrics (Strecker et al., 2001). However, the pollutant removal mechanisms in a swale are highly dependent on infiltration, thus, pollutant mass load reductions may be a better predictor than EMCs to evaluate swale performance (Lenhart and Hunt, 2011), and are used in this study. The average percent load reductions for all pollutants during different storm sizes is shown in Table 16 followed by a discussion for each pollutant category of sediments, nutrients, and heavy metals. The EMC values for each pollutant and simulation event are presented in Appendix C.

Table 16. Average percent pollutant load reduction (%)

Swale	Storm Size	TSS	Total P	Ortho-P	Total N	Copper	Zinc	Lead	Cadmium
VS-1	Medium	81	32	8	13	30	69	49	70
	Large	78	27	(-4)	12	19	58	40	42
VS-2	Medium	92	49	29	48	62	85	70	79

	Large	90	47	19	35	52	78	64	75
VS-3	Medium	70	19	2	11	21	52	35	47
	Large	67	15	(-15)	16	9	49	39	43
VS-4	Medium	76	1	(-16)	6	34	63	44	61
	Large	71	15	(-9)	9	24	48	35	47
VS-5	Medium	95	61	49	61	78	91	85	92
	Large	85	26	(-101)	39	13	76	61	73
VS-6	Medium	88	24	1	33	46	73	65	77
	Large	88	19	(-22)	36	40	56	42	49
VS-7	Medium	78	5	(-9)	(-1)	10	50	33	51
	Large	76	22	4	8	11	46	39	36
VS-8	Medium	73	24	19	16	27	55	38	54
	Large	71	34	21	19	32	42	39	41

Sediment Reduction

The TSS concentration and load reduction benefits of a grass swale from controlled experiments agree with previous studies in both field and controlled plot-scale swales (Backstrom, 2002; Bäckström et al., 2006; Lucke et al., 2014; Mohamed et al., 2014; Wu and Allan, 2018). The removal efficiencies of a swale on a mass load basis is generally reported to be greater than on a concentration basis throughout the literature. This is primarily attributed to infiltration, which accounts for reduced runoff volumes used in mass load calculations (Rushton, 2001; Wu and Allan, 2018). This study followed similar patterns when comparing load reductions and EMCs for each swale. Sediment mass load reductions ranged between 67-95% with 30m swales generally providing greater reductions than 10m swales. The influent EMCs varied between 30-49 mg/L and the effluent EMCs ranged between 5-16 mg/L, achieving up to 61-84% reductions. The SCM credit document (NCDEQ, 2018) summarizes total suspended solids (TSS) data for seven (7) pollutant removal swales in North Carolina. Three (3) swales receiving influent concentrations below 20mg/L were not considered for analysis as those were considered too low or irreducible. The other four swales with reductions between 45-71% were noted as “passed”, which can be described as achieving more than 29% removal efficiency when the median TSS influent concentrations were greater than 20mg/L. These reductions are lower than the results from this controlled study. The objective of this study was to eliminate the heterogeneity in factors (location, geology, swale age, timeframe of studies, design parameters: length, slope, shape) impacting swale performance (Fardel et al., 2019), and thus results are expected to be a better comparison of how various design factors impact swale function.

Longer swale lengths, flatter slopes, and shallow flow depths are the primary factors for enhanced sediment reductions in grass swales (Gong et al., 2019). The results from this study support these conclusions from previous research. The 30m long trapezoidal swale at 1% slope (VS-5) provided higher TSS load reductions for both medium and large storm size when compared to 30m trapezoidal swale at 4% slope (VS-2). When comparing concentrations, however, VS-2 performed slightly better for large storms. Similarly, VS-6 (30m long, triangular swale at 1% slope) provided better TSS removal (both concentrations and mass loads) than VS-1 located on a 4% slope. These comparisons point to the benefits of flatter slopes for TSS removal. When comparing the shapes, the trapezoidal cross-sections (VS-2 and VS-5) sequestered more sediment than swales with triangular cross-section (VS-1 and VS-6). In all cases, the 30m swales provided higher TSS removal than shorter 10m swales, emphasizing the importance of appropriate swale length to allow for the primary processes of filtration and sedimentation for pollutant removal in swales (Stagge et al., 2012). Swale performance was also slightly better during small-medium storm simulations when compared to the large storms.

While these findings support the conclusion that properly engineered swales can be an effective SCM for low-intensity storms (Yu et al., 2001), they also provide new evidence that the effectiveness of swales, while reduced, is not completely lost during somewhat larger storms. This suggests that water quality swales as a standalone device may be able to treat runoff from larger storms than previously thought by Davis et al. (2012). Thus, additional design features such as check dams, filter strips, and treatment through side slopes may not be required to enhance swale performance (Stagge et al., 2012). This further reduces the overall operation and maintenance costs of swales, supporting their continued use as an effective SCM for linear roadway environments.

Nutrient Reduction

An increase in nutrient concentrations exiting the swale is a common phenomenon noted by previous researchers, while a reduction in nutrient loads is often observed because this calculation considers the reduction in inflow volume (Barrett et al., 1998b; Deletic and Fletcher, 2006; Stagge et al., 2012; Winston et al., 2012; Yousef et al., 1987; Yu et al., 2001). Figure 15 presents the average percent reduction in event mean concentration (EMC) for nutrients. A negative percent removal indicates increase in swale outlet concentrations.

For most constituents, the EMC percent reduction varied between -25 to 25%, with a notable exception of ortho-P for which the export (indicated by negative percent reductions) was substantial. The largest export of ortho-P concentrations occurred in VS-5 (30m, trapezoidal swale at 1% slope) during the spring runoff simulation. The increase in concentration of ortho-P during that simulated event was nearly 5-fold. A field duplicate sample was also collected for that event, verifying the increase in ortho-P concentration. An increase in phosphorus concentrations and mass loads from runoff traveling through grass swales was also observed by Rushton (2001), with residual grass clippings cited as the likely reason. Due to a higher mowing frequency in the Spring, this could be the likely cause in this study as well.

The influent average TN EMC was approximately 1.0 mg/L and the influent average TP EMC was approximately 0.10 mg/L. After flowing through the swales, the average effluent EMCs was essentially unchanged for TP (reduced to approximately 0.094 mg/L) and TN (reduced to approximately 0.98 mg/L) for large storms. For the small-medium storms, both TN and TP effluent EMCs generally showed an increased effluent concentration.

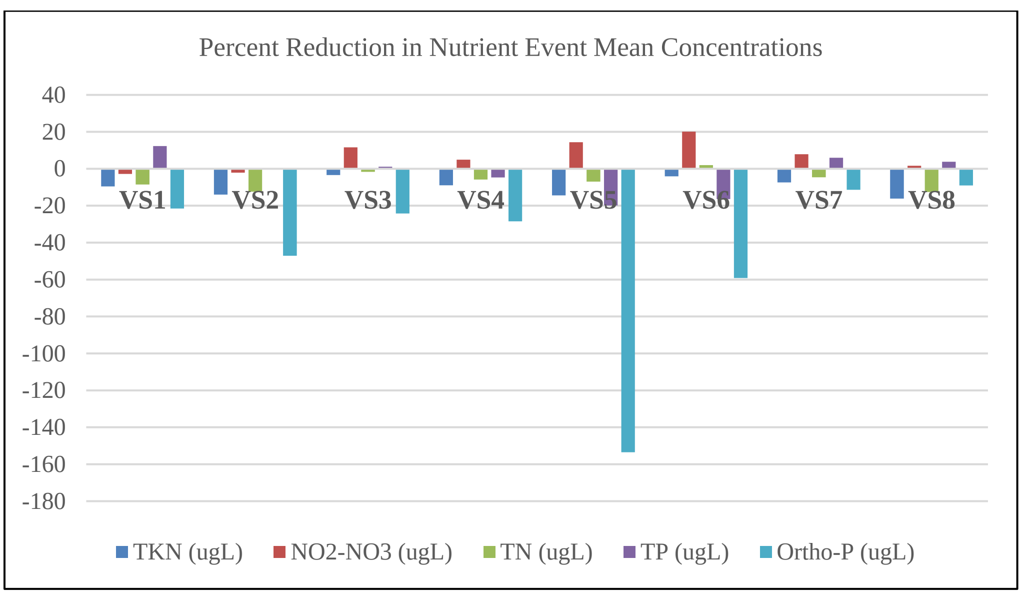

Figure 15. Average Percent Removal in Nutrient Event Mean Concentrations (EMCs)

Yousef et al. (1987) had reported an increase in concentration for both organic and inorganic forms of nitrogen after flowing through the swale length; however, mass loads were reduced.

Similarly, Wu and Allan (2018) reported that the total and ortho-P EMCs did not change when flowing through a swale, but a 60% reduction was estimated on a mass loading basis, indicating the importance of good infiltration for swales to effectively reduce nutrients.

In agreement with previous studies, the mass load of nutrients (Figure 16) showed a positive reduction for all pollutants except ortho-P, primarily due to the high concentrations during the spring simulation event. The average load reductions for phosphorus ranged between 24-61% for medium storms and between 19-47% for large storms in the 30m swales. In the 10m swales, the load reductions ranged between 1-24% for medium storms and between 15-34% for large storms. It was clear that the longer 30m swales with a trapezoidal cross-section performed better than other swale configurations. It is noteworthy that the 30m swales were designed to be 3x the current NCDOT standards (100ft/1ac). Thus, the increased benefit of phosphorus load removal by extending the length and providing a trapezoidal shape may be an important design consideration in phosphorus-limited watersheds.

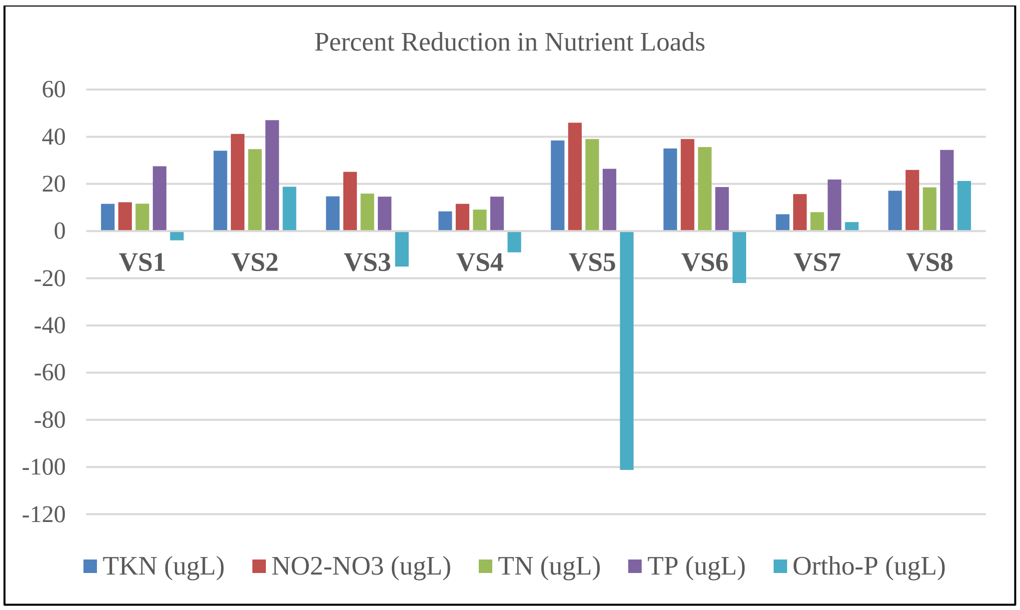

Figure 16. Percent Removal in Nutrient Mass Loads

With one exception (VS-7), total nitrogen loads were reduced between 6-16% for small-medium storms and 8-19% for large storms in the 10m swales. The longer 30m swales, showed 13-61% reductions for small-medium storms and 12-30% for large storms. The 30m swales with trapezoidal cross-section (VS-2 and VS-5) provided highest load reductions for small-medium storms (48 and 61%) and large storms (35 and 39%), with the flatter swale at 1% slope (VS-5) performing slightly better. As with phosphorus, the 30m, trapezoidal-shaped swale constructed

on flatter slope provided highest reductions in nitrogen loads. Although the benefit may be small, these simple design considerations when designing water quality swales along roadways may substantially improve water quality benefits in nitrogen-impaired watersheds.
As evident from these results, the changes in nutrient levels after passing through a grass swale show a mixed pattern similar to previous studies. The findings highlight the importance of revisiting the swale design criteria or considering alternative swale types (e.g., bioswales) for increasing nutrient removal benefit. Results also suggest that including bagging of grass clippings as part of the maintenance protocol may improve a swales nutrient removal ability (or at least reduce export). However, a more specific research study should be conducted before recommending such a policy change.

Metals Reduction

The average percent reduction in metals (zinc, lead, and cadmium) concentration was positive for all swales during both small-medium and large storm simulations (Figure 17). Zinc concentrations were reduced between 38-72% for small-medium storms and 23-63% for large storms. Lead EMCs were reduced between 14-55% for small-medium storms and 20-39% for large storms. Cadmium EMCs were reduced between 35-76% for small-medium storms and 21-58% for large storms.

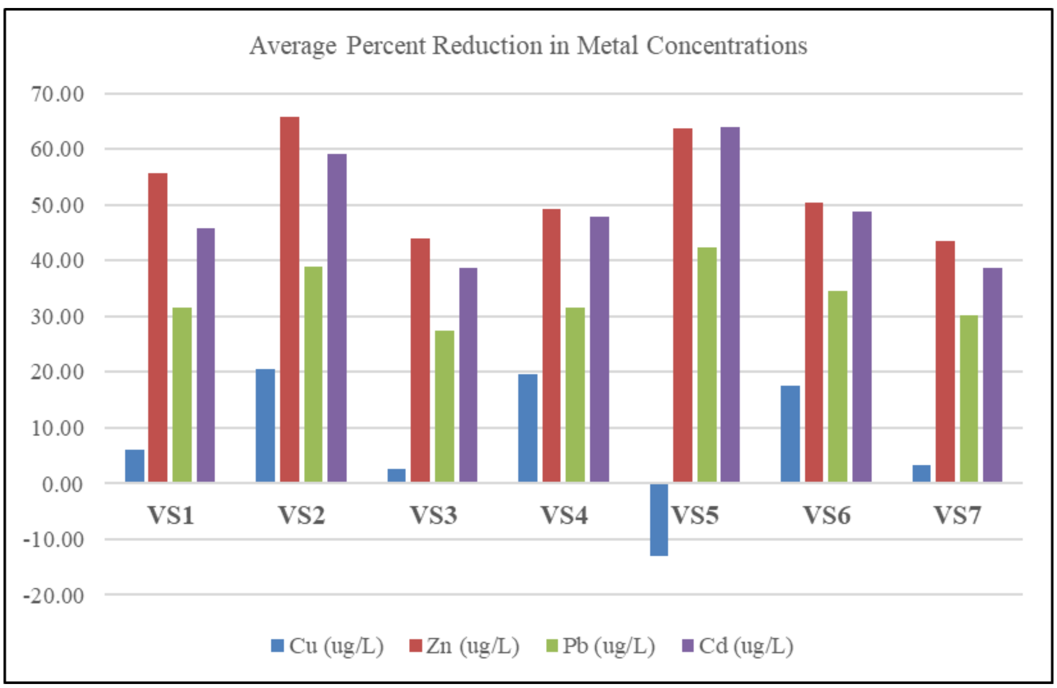

Figure 17. Average Percent Removal in Metal Event Mean Concentrations (EMCs)

Copper showed an increased outflow EMC in VS-8 (10m, triangular shaped, 1% slope) for small-medium storms and in VS-3 (10m, triangular shaped, 4% slope) and VS-5 (30m, trapezoidal shaped, 1% slope) for large storms. The average increase in effluent copper concentrations from VS-5 (60%) for large storms was heavily influenced by the spring simulation events of 2019 (164% and 27% increase). These events in May-June of 2019 also had an increase in particle size and a net export of other pollutants evaluated in this study. As discussed previously, resuspension of previously deposited sediment in the inlet box, conveyance system, and the sparse grass density in the swale could be the potential contributing factors. In general, the metal concentrations were best reduced during small-medium storm simulations in the 30m long swales.

When examining using a load perspective, all metals (copper, zinc, lead, and cadmium) were reduced (Figure 18). The percent load reductions for copper ranged between 10-34% for small-medium storms and 9-32% for large storms in the short swales. In the longer 30m swales, reductions were generally higher ranging between 30-78% for small-medium storms and 13-52% for larger storms. The highest reduction in copper load of 78% was noted for VS-5 (despite increased EMC's), because this swale had the highest average runoff volume reductions, again underscoring the importance of infiltration as a tool to improve swale performance.

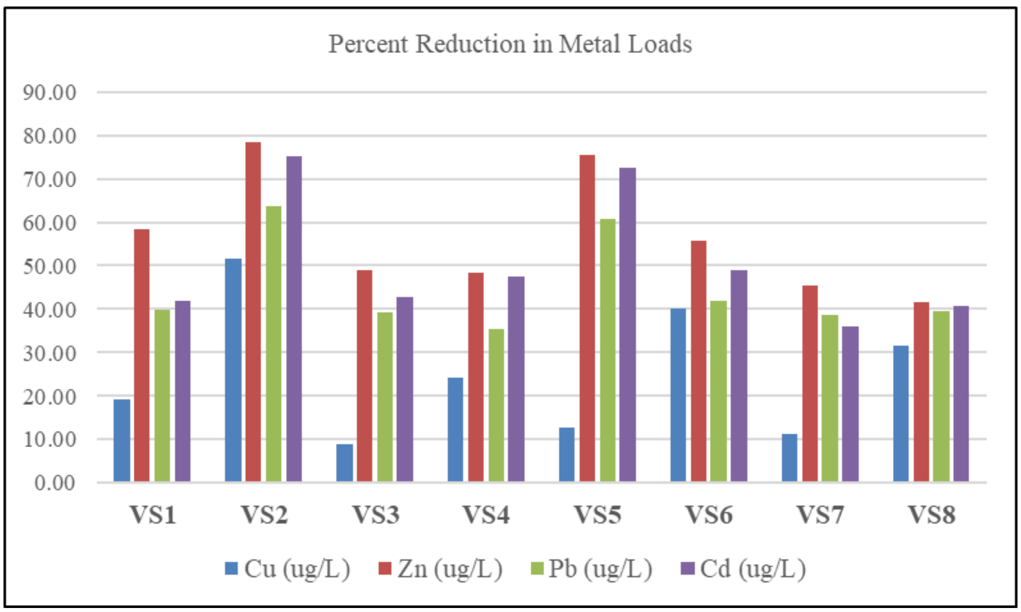

Figure 18. Percent Removal in Metals Mass Loads

Zinc loads were reduced by 50-63% for small-medium storms and 42-49% for large storms in the short (10m) swales. In the 30m swales, load reductions substantially increased to 69-91% for small-medium storms and 56-78% for large storms. The highest zinc load reductions for both storm sizes were achieved by the two 30m trapezoidal swales, VS-2 and VS-5, respectively. Similarly, lead and cadmium loads were best reduced by VS-5 (85 and 92%) followed by VS-2 (70 and 79%) for small-medium storms.

Overall, the observations from this research are consistent with previous studies in removal of metals from swales. In a runoff simulation study conducted in two field swales, the average percent removal of dissolved heavy metals ranged between 77-93% for zinc, 56-76% for lead, 49-70% for copper, and a 63% reduction in cadmium on a total mass basis (Yousef et al., 1987). On the contrary, Backstrom (2003) observed swales to be a source of metals (copper, lead, and zinc), particularly when the influent concentration was low. Reduced effectiveness of swales during low influent concentrations for a variety of pollutants has been reported by other researchers (Fardel et al., 2019; Knight et al., 2013; Lucke et al., 2014; Winston et al., 2012; Wu and Allan, 2018).

In general, these findings suggest that the longer (30m, oversized for current NCDOT standards) trapezoidal swales provided best metal load reductions. The difference in metal load reductions between swales of different shapes (reductions of 1.5x-3x) and different lengths (up to 8x) is substantial, and NCDOT may consider updating their swale length design criteria, if receiving waters are impaired by metals.

Statistical Analysis of Pollutant Load Reductions

An analysis of variance (ANOVA) test was conducted to further test the effect of each factor individually and their interactions on pollutant load reductions. Table 17 presents a summary of the ANOVA tests showing the factors and interactions that were statistically significant.

Table 17. Analysis of variance (ANOVA) results for pollutant load reduction

Factor	p-value
Length* **	<0.0001
Storm Size* **	0.00028
Length x Shape* **	0.00031
Shape* **	0.00171
Slope* **	0.00895
Storm Size x Length **	0.01131

Length x Slope**	0.01316
Slope x Shape**	0.01825
Storm Size x Length x Slope**	0.02403
Storm Size x Length x Shape**	0.04111
Storm Size x Slope x Shape*	0.06593

Because infiltration is a key mechanism of pollutant removal in swales, another ANOVA model was fit with the runoff volume included. This model represents the comprehensive swale runoff and pollutant removal mechanisms that are activated during and after a rain event to convey and treat stormwater. Table 18 presents a summary of the ANOVA tests showing the factors and interactions that were found to be statistically significant.

Table 18. Analysis of variance (ANOVA) results for runoff volume and pollutant load reduction

Factor	p-value	Statistically Significant at α
Length***	<0.0001	0.01, 0.05, 0.10
Length x Shape***	<0.0001	0.01, 0.05, 0.10
Storm Size***	0.00028	0.01, 0.05, 0.10
Shape***	0.00171	0.01, 0.05, 0.10
Storm Size x Shape***	0.00188	0.01, 0.05, 0.10
Slope***	0.00895	0.01, 0.05, 0.10
Slope*Shape***	0.00933	0.01, 0.05, 0.10
Storm Size x Length**	0.01131	0.05, 0.10
Length x Slope**	0.01316	0.05, 0.10
Storm Size x Slope x Shape**	0.02091	0.05, 0.10
Storm Size x Length x Slope**	0.02403	0.05, 0.10
Storm Size x Slope**	0.03757	0.05, 0.10
Storm Size x Length x Shape**	0.04111	0.05, 0.10
Length x Slope x Shape*	0.06287	0.10

* Statistically significant at α=0.10; **Statistically significant at α=0.05, 0.10; ***Statistically significant at α=0.01, 0.05, and 0.10;

Although the main factors (length, storm size, shape, and slope) remain statistically significant for both ANOVA models, a greater number of interactions become significant in the comprehensive model that considers runoff volume. This improvement in the significance levels and increased number of significant factors validate the important role of runoff infiltration in enhancing pollutant load removals from a swale. The following discussion of design factors significance is based on the improved ANOVA model. Table 19 summarizes the ANOVA results showing the design factors that were statistically significant (α=0.05) for each pollutant.

Table 19. Summary of ANOVA results for each pollutant by design factors[1]

Study Factors	TN	TP	Ortho-P	TSS	Cd	Cu	Pb	Zn
Length	Y	Y		Y	Y	Y	Y	Y
Storm Size			Y	Y	Y	Y	Y	Y
Length*Shape	Y	Y			Y		Y	
Shape				Y	Y		Y	Y
Slope				Y				
Length*Storm Size		Y	Y				Y	
Slope*Shape						Y		
Length*Slope			Y					
Storm Size*Shape								
Storm Size*Slope								
Length*Slope*Storm Size			Y					
Length*Shape*Storm Size			Y					

[1]Y indicates when a factor is statistically significant(α=0.05). Total Nitrogen (TN), Total Phosphorus (TP), Ortho-P (Ortho-Phosphorus), Total Suspended Solids (TSS), Cadmium (Cd), Copper (Cu), Lead (Pb), Zinc (Zn)

Swale Length

Swale length was statistically significant for all pollutants except ortho-P, but the apparent anomaly in the spring simulation data for VS-5 may influence that result. Early swale researchers had suggested that the benefit of treatment via side slopes or filter strips was substantially greater than the length of a swale (Barrett et al., 1998b). However, a drawback of their study was the location along a highway median with a greater than typical length of swale channel and sheet flow through side slopes. More recently, Gong et al. (2019) concluded that pollutant removal efficiency of a swale is enhanced when runoff enters the swale as concentrated flow and travels the entire swale length. In another study, Fardel et al. (2020) conducted a pilot test of swales under controlled conditions and concluded that lateral diffuse inflow provided significantly higher pollution reduction when compared to longitudinal, concentrated inflow. These mixed findings on runoff entry point to the swale provides flexibility to the designer depending on site limitations. Thus, designers can consider the runoff entry point to be as far as feasible from the end of the swale to maximize treatment at locations where opportunity for lateral diffuse inflow is limited.

Channel Shape

Results from this study suggest that shape is an important factor if TSS and heavy metals removal is a design goal. Least squares mean comparison suggests that trapezoidal swales tend to perform better than triangular (or V-) shaped swales for pollutant removal. The results from this study are in agreement with previous modeling studies that have suggested a flat-bottom/trapezoidal swale can enhance both runoff volume reduction (Fiener and Auerswald, 2005), and pollution control (Hwang and Weng, 2015; Winston et al., 2017) abilities of a swale. However, these findings differ from Barrett et al. (1998b) who recommended a V-shaped cross-sectional geometry as the optimal shape for treating highway runoff pollutants. This latter field study was conducted over a highway median and not a typical swale.

Channel Slope

The benefits of flat slopes are not as well-documented via field studies, but throughout the literature a flatter slope is recommended for enhanced pollutant removal (e.g., Yousef et al., 1987). However, if flow depth exceeds grass height, the water quality benefits may be reduced (Gong et al., 2019; Hunt et al., 2020).

ANOVA results for this study indicate channel slope to be statistically significant only for TSS removal. For all other pollutants, the slope does not appear to play a significant role. This statistical finding is supported by raw percent reductions, where a difference between the 1% and 4% slopes did not appear to impact runoff volume or pollutant loads substantially.

Storm Size

Storm size was a significant factor in sediment and metal load reductions. Comparison of least squares means suggest that small-medium storms (<19mm) were better treated than large storms (~36mm). Total nitrogen and phosphorus loads were not significantly reduced for the two storm sizes. However, if TSS removal is enhanced during medium-size storms then a greater treatment of attached or particulate nutrients can be expected (Lucke et al., 2014).

In addition to the ANOVA, the variables measured as covariates (grass height and water content) were included in the statistical model and an analysis of covariance (ANCOVA) test was conducted (significance levels, $\alpha=0.05$). However, the ANCOVA results did not show any notable improvements in the model and thus it is not discussed further. A separate bivariate analysis showed a positive but weak relationship between the two possible covariates and responses (runoff volume reductions and pollutant load reductions).

Effect of Seasons on Water Quality

For examining seasonal differences, VS-5 and VS-6, two 30m swales at 1% slope, were selected for statistical comparison. The shapes of these swales are different, but their performance was similar for this limited analysis. A total of six storms were simulated in the summer season (June 20-September 30) and another six in the Fall and Spring (October 1-June 19). The summer season simulations comprised two medium-sized storms and four large storms. The Fall and Spring simulations comprised two large storms and four medium-size storms. Difference in storm-size was also ignored for this limited analysis. Results of average percent pollutant reduction by season are presented in Table 20.

Table 20. Seasonal difference in average percent pollutant load reduction (%)

Season	TSS	Total P	Ortho-P	Total N	Copper	Zinc	Lead	Cadmium
Summer	91	45	9	47	53	72	61	69
Fall/Spring	88	24	(-27)	39	36	75	66	77

The average percent reduction for pollutant loads of TSS, TN, and TP is (sometimes marginally) better in summer than that of the shoulder seasons. Copper was better removed in summer, but zinc, lead, and cadmium were better reduced in Fall and Spring seasons. Grass swales' better removal of TSS, TN, and TP removal in summer than winter season were also reported by Yuan et al. (2019). The removal rates were reported to be approximately 90%, 32%, and 20% in summer compared to 34%, 57%, and 13% (winter) for TSS, TN, and TP, respectively, in that study.

The most notable difference in this study is for both total and dissolved phosphorus. Overall, the two-sample t-test indicated that there was no significant difference in swale performance due to seasons. These results agree with previous research by Wu and Allan (2018), but different than others where nutrient levels increased in summer possibly due to leftover grass clippings from higher frequency mowing (Stagge et al., 2012). Despite non-uniformity of findings in the literature, it is reasonable to infer that under ideal circumstances, where grass clippings are bagged after mowing, it is possible to see greater pollutant removals.

In Spring and summer (i.e., early- to mid-autumn), the grass root systems are stronger, and grass blades are healthier and stiffer. This likely enhances biological activity, soil porosity, infiltration, and adsorption. In winter months, however, the grass may become dormant and experience withered blades that can negatively affect the processes of infiltration and biological activity essential for pollutant removal (Yuan et al., 2019). Therefore, it is likely that the pollutant removal mechanisms of a grass swale are augmented in summer months.

Correlation Analysis

A correlation analysis was also conducted to identify any significant relationships between the percent reductions in responses (runoff volume and each of the pollutants). Spearman's correlation values are presented in Appendix D. The weak association of dissolved phosphorus (ortho-P) with almost all pollutants as well as the runoff volume was a key finding of this limited analysis. This suggests that a greater reduction in runoff infiltration does not imply a significant reduction in dissolved phosphorus. In roadway runoff, approximately 80% of phosphorus is sediment-bound (Kayhanian et al., 2012; Vaze and Chiew, 2004; Winston and Hunt, 2017), but treating dissolved pollutants is critical to protect downstream water quality (Huber et al., 2016; Kayhanian et al., 2012). This may require consideration of other SCMs that are effective in removing phosphorus while also being suitable for linear roadway environments. In a recent study, Purvis (2018) showed significant reductions in both dissolved and total phosphorus loads when using bioswales. Therefore, swale alternatives such as bioswales that use an engineered media should be considered to treat stormwater runoff in nutrient-impaired watersheds.

Conclusions:

This controlled field research suggests that grass swales provide both runoff volume reduction and effective stormwater treatment for sediment and heavy metals generated from roadway runoff. The findings from this research support previous recommendations that swales can be used as part of a treatment train (Yousef et al., 1987), where they provide initial treatment and convey stormwater to another SCM for further pollutant removal. More importantly, this research also provided evidence that grass swales can provide substantially greater treatment than previously thought - serving as a primary control for highway runoff treatment (Barrett et al., 1998b). The following conclusions are drawn for grass swale design and performance based on the results from this study (and supported by related field studies):

1) Longer (30m), trapezoidal swales, constructed at 1% longitudinal slope provided greatest runoff volume reductions for small-medium storms. During large storms, the swales runoff volume reduction ability was reduced but not eliminated.
2) Excessive compaction of swale beds during construction activities should be avoided to protect their runoff volume reduction capability.
3) Inadequate grass density and improperly maintained swales with sediment deposition from previous storm events can negatively impact trapping efficiency of a swale.
4) Treatment length appears to be a significant design parameter that improves the swale performance for most pollutants. To utilize maximum treatment length in a swale, the runoff entry point in form of concentrated flow should be considered during the design process. When feasible, designers should consider maximizing the swale length beyond minimum design criteria of 100 ft (or 30m) per acre of contributing drainage area.
5) Trapezoidal swales performed better than triangular swales for sediment and metals removal due to their greater surface area for runoff infiltration through the swale bed. This increased infiltration opportunity in trapezoidal swales greatly limited runoff volumes and will likely improve nutrient removal compared to a triangular swale.
6) There was no significant difference in pollutant load reductions (except for sediment) due to the longitudinal slopes (1% and 4%) evaluated in this study.

7) Pollutants borne during a small-medium storm size (<19 mm) are treated more effectively than those of a somewhat larger storm size (~36 mm) due to shallower flow depths. Shallow flow depths allow water to travel through the vegetation, maximizing the treatment opportunity. Thus, grass swales can continue to be an effective SCM and a valuable part of green infrastructure when designing for water quality storms.
8) There is no seasonal difference in swale performance for runoff volume or pollutant reductions
9) Swales are an effective treatment measure for sediment and heavy metals. However, as observed in previous studies, they are not as effective for treating nutrients and can often act a source of nutrients for downstream bodies. For roadway runoff treatment in nutrient-impaired watersheds, swale alternatives such as bioswales may need to be considered.

Recommendations for Future Research:

Swales are a complex stormwater system that employ physical, chemical, and biological treatment processes for stormwater conveyance and treatment. Due to the relatively low cost of construction, operation and maintenance, swales will continue to be a key SCM in highway environment. Many future research opportunities remain to optimize swale design and performance, a few recommendations are listed as follows:

1) Controlled field research such as the design of this study is quite effective in eliminating many sources of uncertainties and variables (geographical location, soil type, age of swale, maintenance regime). However, the pressure head of available water supply and hydraulic distance of spiked water to each swale was variable. A mobile water supply to each swale should be considered in future experiments to further eliminate these sources of uncertainties.
2) Optimal design and treatment potential of swales for other highway pollutants (e.g., dissolved metals, polycyclic aromatic hydrocarbons, bacteria) should be investigated under a controlled study.
3) A broader range of longitudinal slopes (0.5-10%) and perhaps a “middle” length (e.g., 20m) should be evaluated under controlled settings to further understand the impact of slope and length on swale performance.

4) Underlying soil in a roadside swale plays a key role in runoff treatment. However, pollutant adsorption by soil particles may impact their long-term efficiency. Evaluating swale sediment samples for pollutant accumulation may help engineers and designers better understand maintenance needs and potential of groundwater contamination.
5) Influence of key design parameters (length, shape, slope) and other factors (season, storm size) should be investigated for infiltration swales, bioswales, and wet swales.
6) Different types of swale-linings (e.g., different rock gradations, different grass and vegetation) and density of vegetative cover should be investigated for their runoff volume reduction and water quality benefits. This may expand the design toolbox for engineers to address watershed-specific concerns.
7) The effects of regular maintenance versus limited maintenance on swale performance should be investigated under controlled settings to enhance swale inspection and maintenance policies. Such a study should also include the impact of leaving the grass clippings from routine mowing in the swale versus the benefits of bagging and removing grass clippings in improving nutrient removal ability of a swale.

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Appendix A

A.1. Swale Compaction

The penetrometer data was recorded for each swale at the inlet point, middle, and exit. Compaction for each swale with depth is represented in Figures 17-24 for each swale.

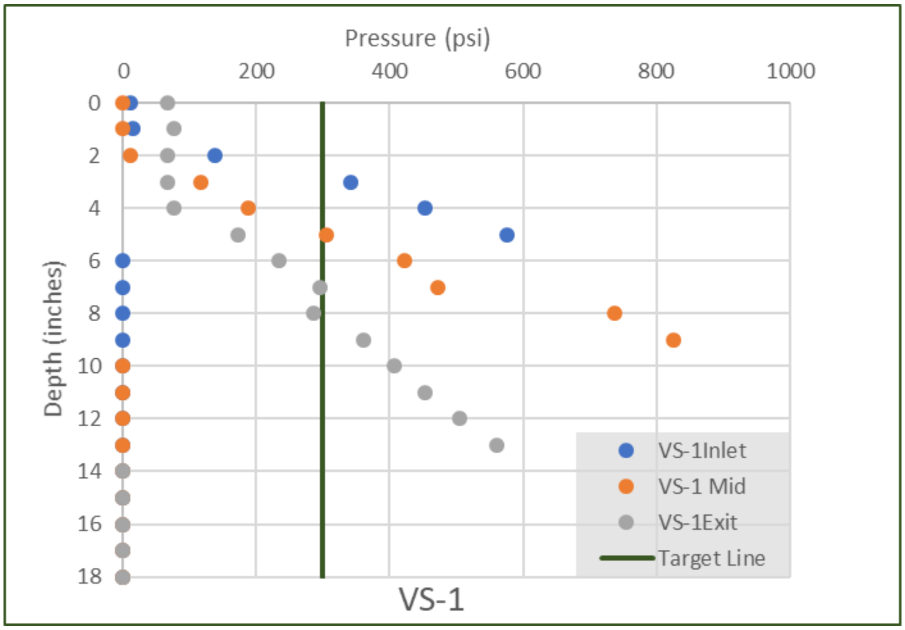

Figure 19. Soil Compaction (psi) in VS-1

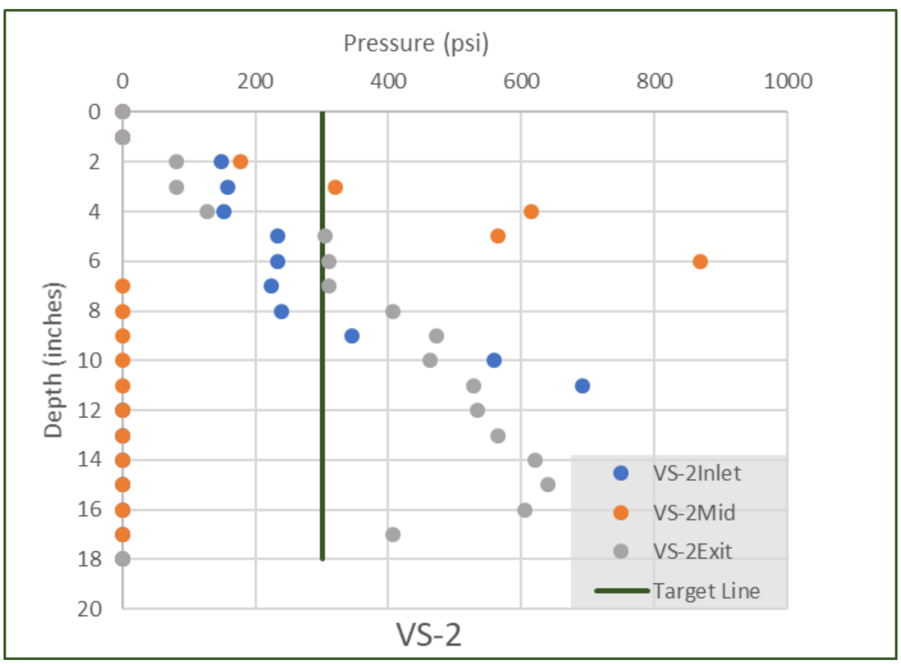

Figure 20. Soil Compaction (psi) in VS-2

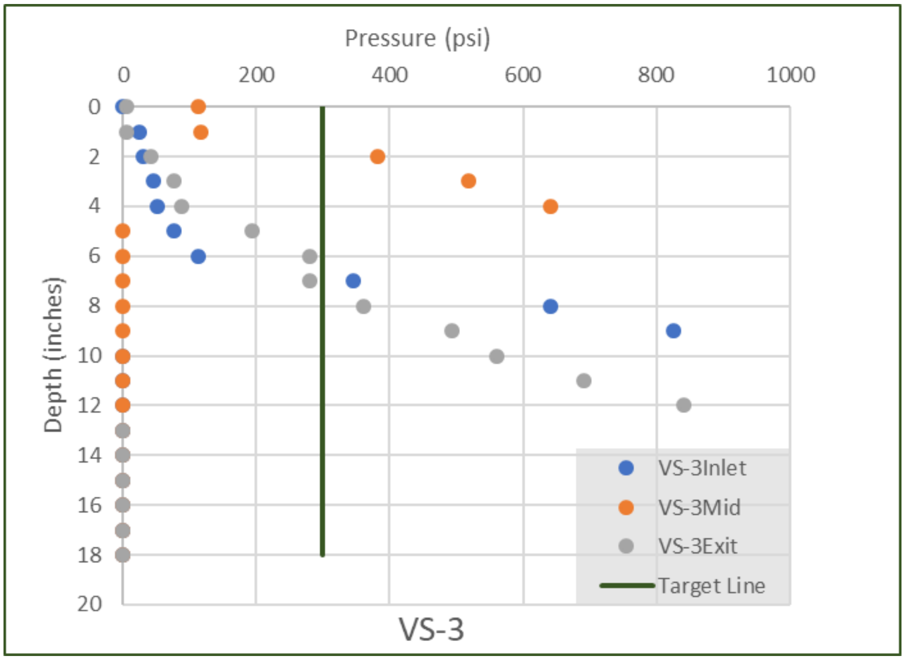

Figure 21. Soil Compaction (psi) in VS-3

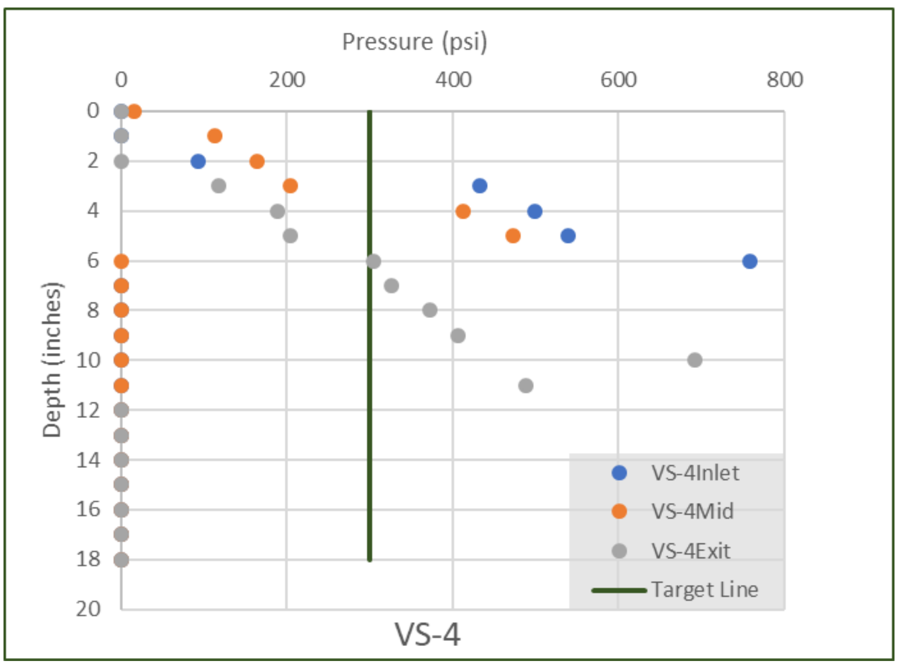

Figure 22. Soil Compaction (psi) in VS-4

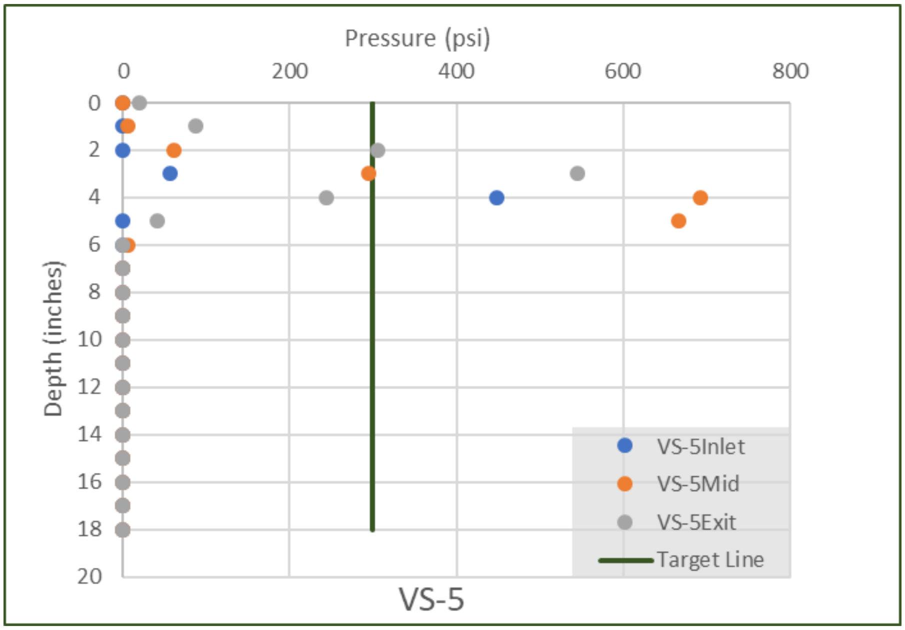

Figure 23. Soil Compaction (psi) in VS-5

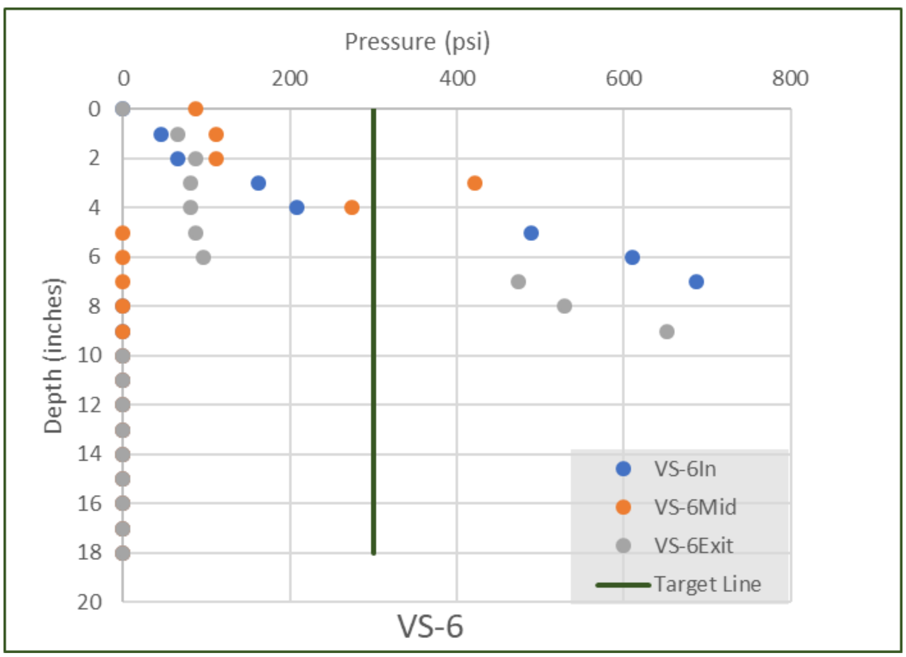

Figure 24. Soil Compaction (psi) in VS-6

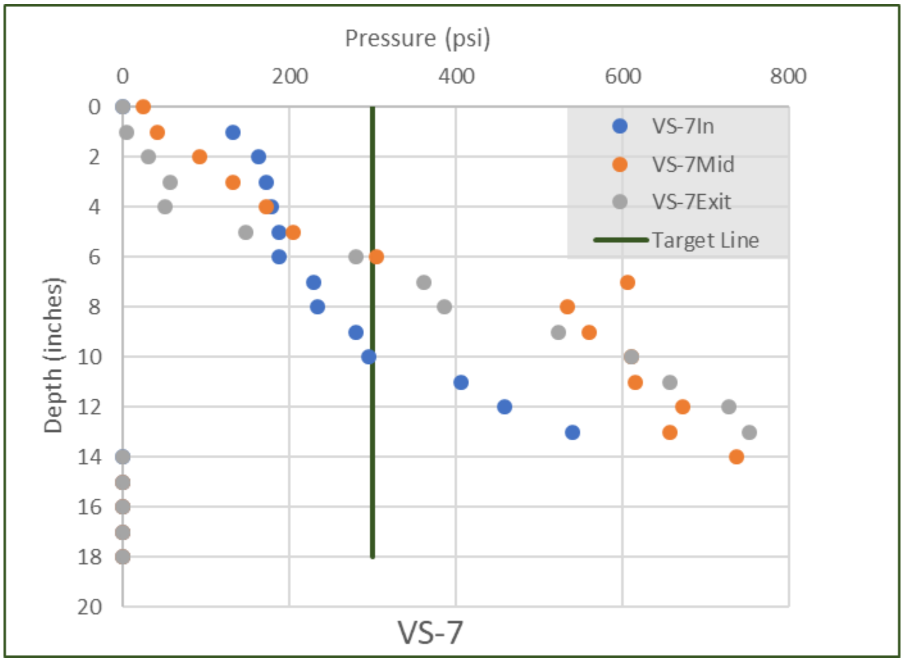

Figure 25. Soil Compaction (psi) in VS-7

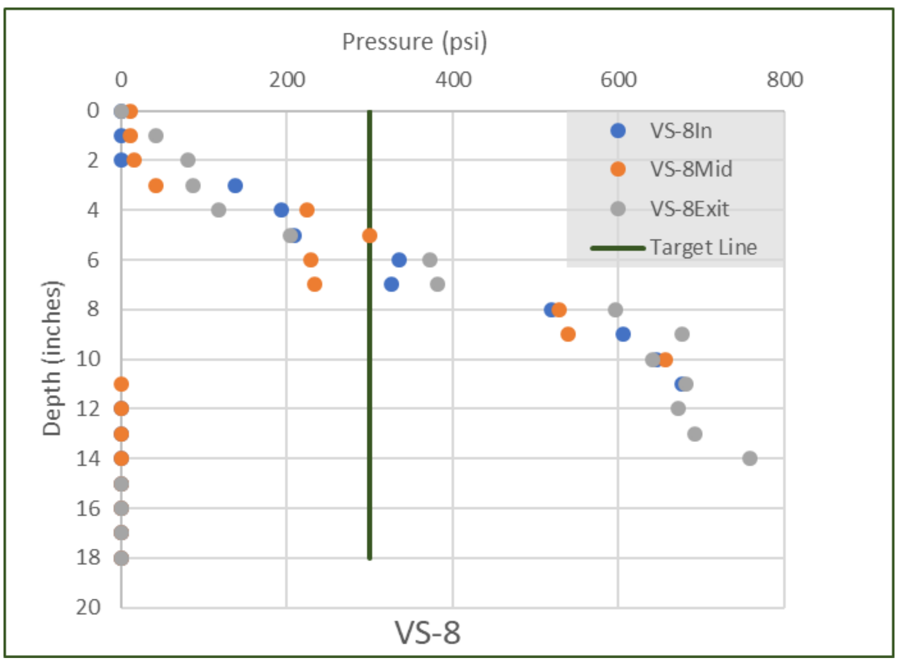

Figure 26. Soil Compaction (psi) in VS-8

The average soil compaction was measured to be highest in VS-7 (246psi) with values consistently above the threshold of 300psi after 6-inch depth past the inlet sampling point. Adjacent swale, VS-8, also showed high average soil compaction values (218psi), but values exceeding threshold at 6-inch depth included the full length of swale. Both VS-7 and VS-8 are the 10m swales located at 1% slope and it is likely that construction technique was not uniform with other swales resulting in increased compaction. The third highest average compaction value (210psi) was observed in VS-2, the 30m swale constructed on 4% slope. The middle and outlet part of the swale appeared to be most compacted with values exceeding 300psi threshold beginning at 4-inch depth. The average compaction in all remaining swales was below 150psi, with VS-5 and VS-6 being the least compacted.

A.2. Swale Moisture and Grass Height

Grass height and initial soil moisture (measured as gravimetric water content) were recorded prior to each sampling event. The gravimetric water content was converted to volumetric water content by multiplying with soil bulk density of each swale. Table 21 presents the daily observations for these variables.

Table 21. Covariates (grass height and water content) measured on sampling days

Sample Date	Swale ID	Average Grass Height (cm)	Gravimetric Water Content (g/g)	Bulk Density (g/cm^3)	Volumetric WC
10/4/2018	VS5	-	-	-	-
10/4/2018	VS6	-	-	-	-
10/15/2018	VS7	7.00	0.21	1.40	0.29
10/15/2018	VS8	7.30	0.24	1.35	0.33
10/24/2018	VS3	8.00	0.18	1.41	0.26
10/24/2018	VS4	7.50	0.19	1.40	0.26
10/29/2018	VS4	8.60	0.21	1.40	0.30
10/29/2018	VS8	7.60	0.26	1.35	0.36
10/31/2018	VS3	8.00	0.26	1.41	0.36
10/31/2018	VS7	8.40	0.22	1.40	0.30
11/4/2018	VS4	8.70	0.25	1.40	0.35
11/4/2018	VS8	10.00	0.24	1.35	0.32
11/11/2018	VS7	8.60	0.24	1.40	0.33
11/11/2018	VS8	9.20	0.26	1.35	0.35
11/21/2018	VS3	7.70	0.25	1.41	0.35

11/21/2018	VS4	7.80	0.24	1.40	0.33
11/28/2018	VS7	6.30	0.22	1.40	0.31
11/28/2018	VS8	9.20	0.26	1.35	0.35
12/5/2018	VS4	7.60	0.24	1.40	0.33
12/5/2018	VS7	8.50	0.24	1.40	0.33
12/19/2018	VS4	5.70	0.26	1.40	0.37
12/19/2018	VS7	6.50	0.26	1.40	0.37
12/19/2018	VS8	7.00	0.27	1.35	0.36
3/19/2019	VS6	7.00	0.22	1.29	0.29
5/28/2019	VS5	8.00	0.09	1.33	0.12
5/29/2019	VS3	6.50	0.08	1.41	0.11
5/29/2019	VS6	14.50	0.12	1.29	0.15
6/17/2019	VS6	16.30	0.21	1.29	0.27
6/20/2019	VS5	8.90	0.14	1.33	0.18
6/25/2019	VS5	9.70	0.18	1.33	0.24
6/25/2019	VS6	13.70	0.22	1.29	0.28
6/26/2019	VS2	11.00	0.13	1.30	0.17
6/26/2019	VS3	8.00	0.14	1.41	0.19
7/3/2019	VS2	8.30	0.13	1.30	0.16
7/3/2019	VS3	10.00	0.10	1.41	0.14
7/10/2019	VS5	10.20	0.18	1.33	0.24
7/10/2019	VS6	15.00	0.19	1.29	0.24
7/11/2019	VS1	15.30	0.21	1.26	0.26
7/11/2019	VS2	8.50	0.18	1.30	0.23
7/16/2019	VS1	15.50	0.16	1.26	0.20
7/16/2019	VS2	9.20	0.19	1.30	0.24
7/25/2019	VS1	13.80	0.24	1.26	0.31
7/25/2019	VS2	10.50	0.24	1.30	0.31
7/30/2019	VS1	9.80	0.15	1.26	0.19
7/30/2019	VS2	8.70	0.19	1.30	0.24

7/30/2019	VS5	10.80	0.17	1.33	0.23
8/16/2019	VS1	17.30	0.22	1.26	0.27
8/20/2019	VS1	18.30	0.19	1.26	0.24

Appendix B

B.1. Runoff Volume Reduction in Individual Swales

The runoff volume reduction obtained by VS-1 swale (4% slope, 100-ft length, and triangular shaped channel) is presented in Table 22. Runoff volume results show that the swale VS-1 (30m long, 4% slope, V-or triangular shape) provided a greater runoff reduction for a medium-size storm (~19mm) than a large-size storm (~36mm). A 23% average reduction in runoff volume was observed for medium-sized storms compared to only 14% for large storms.

Table 22. Runoff volumes inflow, outflow, and percent reduction at VS-1

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	07/11/2019	17,761	11,793	34
	2	07/25/2019	19,701	13,967	29
	3	07/30/2019	18,206	16,877	7
Mean			**18,556**	**14,212**	**23**
Large	1	07/16/2019	40,739	37,446	8
	2	08/16/2019	36,940	30,365	18
	3	08/20/2019	35,756	29,782	17
Mean			**37,812**	**32,531**	**14**

The inflow and outflow runoff volumes of VS-2 (same length and slope as VS-1 but with a trapezoidal shape) are presented in Table 23. The runoff volume reductions in VS-2 (trapezoidal shape) were greater than VS-1 (V- or triangular shape), for both medium-size storms and large storms. In addition to greater average runoff volume reductions, runoff reductions for each storm simulation events in VS-2 (trapezoidal shape) was also substantially greater than VS-1 for both medium and large storms.

Table 23. Runoff volumes inflow, outflow, and percent reduction at VS-2

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	06/26/2019	21,058	5,297	75
	2	07/03/2019	18,834	10,987	42
	3	07/16/2019	18,057	10,158	44

Mean			**19,316**	**8,814**	**53**
Large	1	07/11/2019	35,813	21,394	40
	2	07/25/2019	35,297	23,507	33
	3	07/30/2019	37,651	19,389	49
Mean			**36,253**	**21,430**	**41**

Results from two swales constructed on similar slopes as VS-1 and VS-2 but a much shorter length (10m) and different shapes are presented in Table 24 for VS-3 (triangular shaped) and in Table 25 for VS-4 (trapezoidal shaped).

Table 24. Runoff volumes inflow, outflow, and percent reduction at VS-3

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	10/24/2018	18,497	11,120	40
	2	10/31/2018	18,958	17,251	9
	3	11/21/2018	18,103	17,251	5
Mean			**18,519**	**15,207**	**18**
Large	1	05/29/2019	35,632	35,442	1
	2	06/26/2019	38,135	33,661	12
	3	07/03/2019	41,561	28,785	31
Mean			**38,443**	**32,630**	**14**

Table 25. Runoff volumes inflow, outflow, and percent reduction at VS-4

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	10/24/2018	17,404	14,212	18
	2	10/29/2018	18,160	15,509	15
	3	11/21/2018	17,752	16,820	5
Mean			**17,772**	**15,514**	**13**
Large	1	11/04/2018	30,492	27,184	11

	2	12/05/2018	33,697	31,468	7
	3	12/19/2018	36,347	29,840	18
Mean			**33,512**	**29,498**	**12**

Like the longer swales (VS-1 and VS-2), a greater runoff volume reduction is observed for medium storms compared to larger storms. However, the magnitude of difference is much smaller between two storm sizes. This is likely due to the short swale length as the runoff volume benefits were again observed to be higher in the other two longer swales, VS-5 and VS-6, as shown in Table 26 and Table 27, respectively.

Table 26. Runoff volumes inflow, outflow, and percent reduction at VS-5

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	10/24/2018	16,645	9,076	45
	2	06/25/2019	21,407	8,666	60
	3	07/10/2019	16,675	3,435	79
Mean			**18,242**	**7,059**	**61**
Large	1	05/28/2019	40,944	21,897	47
	2	06/20/2019	39,149	20,126	49
	3	07/30/2019	37,716	23,731	37
Mean			**39,270**	**21,918**	**44**

VS-5, the trapezoidal swale provided up to 61% runoff volume reduction for medium storms and 44% for large storms, which are the largest reductions for each storm type observed in this study. The next highest benefits are provided by VS-2, which is same length and shape as VS-5 but has a steeper longitudinal slope (4%). The runoff volume reduction in VS-6, a triangular-shaped swale is lower than both trapezoidal swales of same length. The lowest runoff volume reductions for 30m swales for both medium and large storm size were observed in VS-1, at 4% slope.

Table 27. Runoff volumes inflow, outflow, and percent reduction at VS-6

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	10/04/2018	17,011	9,303	45
	2	03/19/2019	21,805	14,493	34
	3	05/29/2019	18,638	11,748	37
	Mean		**19,151**	**11,848**	**39**
Large	1	06/17/2019	37,427	28,865	23
	2	06/25/2019	38,512	26,497	30
	3	07/10/2019	34,457	26,983	22
	Mean		**36,799**	**27,598**	**25**

The two remaining swales in the experimental design, VS-7 and VS-8, both of 10m length were constructed on the flatter 1% longitudinal slopes. The average runoff volume reduction observed in VS-7 and VS-8 is presented in Table 28 and Table 29, respectively.

Table 28. Runoff volumes inflow, outflow, and percent reduction at VS-7

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	10/15/2018	16,744	15,311	9
	2	11/11/2018	17,317	17,252	0
	3	11/28/2018	16,908	15,280	10
	Mean		**16,990**	**15,947**	**6**
Large	1	10/31/2018	37,891	34,436	9
	2	12/05/2018	35,048	31,429	10
	3	12/19/2018	36,628	33,349	9
	Mean		**36,522**	**33,071**	**9**

The runoff reduction results for VS-7 (trapezoidal) and VS-8 (triangular) are somewhat inconsistent with the general phenomenon observed in other swales. Triangular swale (VS-8) reduced substantially more runoff volume than the trapezoidal swale.

Table 29. Runoff volumes inflow, outflow, and percent reduction at VS-8

Storm Size	Event	Date	Inflow Volume (L)	Outflow Volume (L)	Percent Reduction (%)
Medium	1	10/15/2018	16,475	11,795	28
	2	10/29/2018	18,066	13,167	27
	3	11/04/2018	15,784	11,279	29
Mean			**16,755**	**12,080**	**28**
Large	1	11/11/2018	31,678	21,490	32
	2	11/28/2018	36,789	30,152	18
	3	12/19/2018	38,267	29,076	24
Mean			**35,578**	**26,906**	**25**

Appendix C

C.1. Particle Size Distribution at Inlet

The mean particle size for each gradation was consistent throughout the simulations with a slight variation, which is common in simulation studies. The variability observed in this study can be attributed to a change in sediment source, human error in sieving and sample preparation, wind velocity on day of experiment, and occasional change in the function of the mixer pump.

Table 30. Inlet mean particle size distribution with ranges (µm)

Inlet	d_{10}	d_{25}	d_{50}	d_{75}	d_{90}
VS-1	14.40 (9.98-18.56)	31.96 (22.22-41.39)	61.86 (42.00-87.66)	114.34 (85.40-162.90)	194.83 (151.00-318.70)
VS-2	13.36 (9.90-18.28)	29.49 (21.88-43.03)	57.97 (45.72-88.87)	130.44 (81.05-161.20)	273.33 (131.60-350.60)
VS-3	11.66 (6.07-21.22)	25.52 (15.46-45.22)	49.95 (32.70-86.75)	102.36 (64.95-142.60)	204.50 (121.30-260.90)
VS-4	8.81 (7.35-9.78)	20.85 (18.67-22.45)	43.55 (40.28-47.22)	101.44 (78.97-133.40)	197.10 (139.40-279.40)
VS-5	14.30 (10.58-18.96)	31.14 (22.81-42.12)	63.22 (43.33-88.04)	135.76 (99.85-185.40)	264.10 (157.90-370.90)
VS-6	13.05 (6.15-19.04)	28.13 (13.04-41.59)	55.56 (23.81-79.88)	114.08 (42.08-162.90)	225.25 (127.20-307.30)
VS-7	10.24 (7.43-18.84)	23.53 (16.93-35.03)	47.93 (33.23-64.03)	100.11 (65.07-142.90)	185.37 (126.40-259.20)
VS-8	9.12 (6.03-13.77)	21.56 (14.75-31.75)	44.95 (29.14-62.71)	101.87 (56.95-133.20)	209.58 (118.90-336.30)

C.2. Pollutant Concentrations at Inlet

The inlet mean pollutant concentrations for large storms is presented in Table 31. The most notable observation in the inlet concentrations occur for VS-5 with a significantly higher average concentration for metals. Upon examining individually, the metal concentrations during the first runoff simulation event on October 4, 2018, were an order of magnitude higher than other subsequent simulation events for VS-5 and other swales. The high concentrations from this first event resulted in a high average concentration for this swale.

Table 31. Inlet mean pollutant concentrations for medium size storm

Inlet	TSS (mg/L)	TP (mg/L)	TN (mg/L)	Cu (µg/L)	Zn (µg/L)	Pb (µg/L)	Cd (µg/L)
VS-1	41.26	0.14	0.95	12.33	60.67	7.53	3.70
VS-2	44.54	0.13	1.03	13.33	64.67	8.03	3.27
VS-3	32.88	0.11	1.01	10.13	65.33	6.90	3.07
VS-4	45.03	0.11	0.95	14.00	82.00	9.60	4.17
VS-5	48.77	0.17	1.02	22.00	130.67	15.73	7.03
VS-6	39.41	0.14	1.06	16.00	85.00	11.77	4.70
VS-7	44.55	0.10	0.81	10.63	68.67	7.60	3.77
VS-8	41.48	0.09	0.84	10.80	65.67	7.40	4.43
Average	**42.24**	**0.12**	**0.96**	**13.65**	**77.83**	**9.32**	**4.27**

The most notable observation in the inlet concentrations occur for VS-5 with a significantly higher average concentration for metals. Upon examining individually, the metal concentrations during the first runoff simulation event on October 4, 2018, were an order of magnitude higher than other subsequent simulation events for VS-5 and other swales. The high concentrations from this first event resulted in a high average concentration for this swale.

The inlet mean pollutant concentrations for large storms is presented in Table 32. A higher than average zinc concentration was noted and can be pointed to the last simulation event on July 3, 2019 when the zinc was reported to be 120µg/l (2x higher than other events). These higher concentrations noted during individual simulation events may have occurred either due to human error while sample mixing and preparation or a possible laboratory reporting error. A possible consequence of such high influent concentrations can be a higher than usual removal rate by the swale.

Table 32. Inlet mean pollutant concentrations for large size storm

Inlet	TSS (mg/L)	TP (mg/L)	TN (mg/L)	Cu (µg/L)	Zn (µg/L)	Pb (µg/L)	Cd (µg/L)
VS-1	32.10	0.10	0.97	9.97	55.67	5.03	1.60
VS-2	29.92	0.10	0.92	9.50	56.67	4.93	1.83
VS-3	37.67	0.11	1.14	11.67	82.67	6.80	2.13
VS-4	31.41	0.08	0.83	7.70	42.67	5.03	2.60
VS-5	30.42	0.11	0.98	9.47	51.00	4.90	1.63
VS-6	40.35	0.10	1.19	10.30	70.00	5.23	1.73
VS-7	40.28	0.08	0.92	8.17	61.67	5.47	2.00
VS-8	40.92	0.08	0.83	7.50	43.00	4.83	2.03
Average	**35.38**	**0.10**	**0.97**	**9.28**	**57.92**	**5.28**	**1.95**

It is noteworthy that the average inlet concentrations were slightly lower for TSS and heavy metals for large storm runoff simulations. This can be attributed to possible dilution of spiked samples due to the substantially higher amount of water passing through the inlet sampling point during large storm simulation.

C.3. Event Mean Concentrations

Inlet and outlet EMCs, and percent removed for all pollutants measured at each swale are presented below. For both medium and large storms, nutrients are shown in one table and sediments and metals are shown in a separate table.

Table 33. Inlet and outlet nutrient concentrations (μg/L), percent reductions, for medium storms

	TKN	NOX	TN	TP	Ortho-P
VS-1					
Inlet1	819.14	133.65	952.80	143.95	47.93
Outlet1	951.98	138.15	1090.13	130.04	60.66
Percent Reduction (%)	-16.03	-3.39	-14.17	8.72	-23.18
VS-2					
Inlet2	890.18	137.82	1028.00	130.83	45.38
Outlet2	1024.80	144.70	1169.50	144.34	71.08
Percent Reduction (%)	-16.93	-5.11	-15.02	-10.41	-55.85
VS-3					
Inlet3	853.77	153.06	1006.83	106.89	40.77
Outlet3	931.93	145.31	1077.24	105.65	48.82
Percent Reduction (%)	-9.38	7.15	-7.45	0.45	-20.50
VS-4					
Inlet4	742.11	204.34	946.46	111.28	55.38
Outlet4	848.15	181.45	1029.61	125.11	73.84
Percent Reduction (%)	-13.81	10.12	-8.51	-12.84	-33.24
VS-5					
Inlet5	773.05	247.83	1020.87	171.08	101.53
Outlet5	912.73	138.55	1051.28	176.69	121.83
Percent Reduction (%)	-18.24	25.06	-4.56	-7.40	-45.73
VS-6					
Inlet6	812.93	243.88	1056.81	136.75	83.72
Outlet6	963.84	188.67	1152.51	171.72	83.70
Percent Reduction (%)	-21.10	21.31	-9.86	-25.16	-56.48
VS-7					
Inlet7	641.46	169.07	810.53	98.40	53.10
Outlet7	718.97	152.61	871.58	98.25	61.07
Percent Reduction (%)	-12.34	8.79	-7.60	-1.72	-16.49
VS-8					
Inlet8	691.18	146.07	837.25	88.33	45.58
Outlet8	830.51	143.32	973.83	92.91	51.66
Percent Reduction (%)	-22.10	1.54	-16.87	-5.48	-13.15

Table 34. Inlet and outlet nutrient concentrations (μg/L), percent reductions, for large storms

	TKN	NOX	TN	TP	Ortho-P
VS-1					
Inlet1	870.21	102.57	972.79	103.30	18.67
Outlet1	896.03	104.72	1000.75	86.98	22.28
Percent Reduction (%)	-2.99	-2.10	-2.90	15.96	-19.84
VS-2					
Inlet2	827.00	94.04	921.04	104.44	25.85
Outlet2	922.43	93.24	1015.68	93.22	35.36
Percent Reduction (%)	-11.01	0.83	-9.85	10.71	-38.40
VS-3					
Inlet3	1012.70	124.77	1137.47	108.57	24.29
Outlet3	944.97	95.36	1040.33	105.88	30.48
Percent Reduction (%)	2.66	16.07	4.20	1.75	-27.91
VS-4					
Inlet4	664.20	162.82	827.03	77.61	27.43
Outlet4	692.30	163.46	855.76	73.59	33.91
Percent Reduction (%)	-4.07	-0.23	-3.17	3.52	-23.68
VS-5					
Inlet5	891.85	87.94	979.79	106.83	19.85
Outlet5	984.00	84.94	1068.94	141.12	67.69
Percent Reduction (%)	-10.55	3.63	-9.29	-32.41	-261.18
VS-6					
Inlet6	1081.58	108.31	1189.89	100.99	29.15
Outlet6	922.47	87.14	1009.61	105.00	47.90
Percent Reduction (%)	12.95	18.94	13.84	-7.60	-61.74
VS-7					
Inlet7	751.34	164.44	915.78	83.75	27.69
Outlet7	774.09	154.79	928.88	71.06	29.17
Percent Reduction (%)	-2.52	6.91	-1.55	13.71	-6.20
VS-8					
Inlet8	694.4733	139.7367	834.21	82.75667	29.38
Outlet8	765.35	137.9367	903.2867	71.36333	30.42667
Percent Reduction (%)	-10.254	1.64432	-8.33002	13.15826	-4.94386

Table 35. Sediment and metals inlet and outlet concentrations, percent reductions, for medium storms

	TSS (mg/L)	Cu (µg/L)	Zn (µg/L)	Pb (µg/L)	Cd (µg/L)
VS-1					
Inlet1	41.26	12.33	60.67	7.53	3.70
Outlet1	10.03	11.73	24.33	5.07	1.47
Percent Reduction (%)	75.63	6.50	60.03	33.16	60.17
VS-2					
Inlet2	44.54	13.33	64.67	8.03	3.27
Outlet2	7.56	10.33	20.33	4.90	1.33
Percent Reduction (%)	82.83	22.82	68.54	39.12	60.56
VS-3					
Inlet3	32.88	10.13	65.33	6.90	3.07
Outlet3	12.96	9.30	35.67	5.23	1.73
Percent Reduction (%)	57.55	8.35	46.17	24.90	43.82
VS-4					
Inlet4	45.03	14.00	82.00	9.60	4.17
Outlet4	12.05	9.73	33.33	5.83	1.77
Percent Reduction (%)	73.25	25.15	57.53	36.51	55.47
VS-5					
Inlet5	48.77	22.00	130.67	15.73	7.03
Outlet5	6.77	12.00	24.00	4.97	1.08
Percent Reduction (%)	85.58	33.83	71.55	54.81	76.26
VS-6					
Inlet6	39.41	16.00	85.00	11.77	4.70
Outlet6	8.20	12.80	30.00	5.40	1.20
Percent Reduction (%)	80.69	14.02	58.25	45.56	64.16
VS-7					
Inlet7	44.55	10.63	68.67	7.60	3.77
Outlet7	11.08	10.17	37.00	5.43	1.97
Percent Reduction (%)	76.16	4.53	46.94	28.07	47.94
VS-8					
Inlet8	41.48	10.80	65.67	7.40	4.43
Outlet8	15.66	10.37	40.33	6.33	2.80
Percent Reduction (%)	62.39	-0.98	37.52	13.78	35.47

Table 36. Sediment and metals inlet and outlet concentrations, percent reductions, for large storms

	TSS (mg/L)	Cu (µg/L)	Zn (µg/L)	Pb (µg/L)	Cd (µg/L)
VS-1					
Inlet1	32.10	9.97	55.67	5.03	1.60
Outlet1	8.18	9.40	27.00	3.53	1.13
Percent Reduction (%)	74.44	5.70	51.52	29.89	31.48
VS-2					
Inlet2	29.92	9.50	56.67	4.93	1.83
Outlet2	5.20	7.77	20.67	3.03	0.78
Percent Reduction (%)	82.59	18.39	63.25	38.66	57.65
VS-3					
Inlet3	37.67	11.67	82.67	6.80	2.13
Outlet3	14.02	11.67	45.33	4.77	1.40
Percent Reduction (%)	62.31	-3.20	41.78	30.09	33.77
VS-4					
Inlet4	31.41	7.70	42.67	5.03	2.60
Outlet4	10.55	6.60	24.67	3.70	1.47
Percent Reduction (%)	66.69	14.02	41.17	26.53	40.31
VS-5					
Inlet5	30.42	9.47	51.00	4.90	1.63
Outlet5	8.32	15.10	22.33	3.43	0.79
Percent Reduction (%)	72.58	-59.65	56.10	29.88	51.54
VS-6					
Inlet6	40.35	10.30	70.00	5.23	1.73
Outlet6	6.51	7.93	27.00	3.80	1.01
Percent Reduction (%)	83.81	20.95	42.51	23.56	33.28
VS-7					
Inlet7	40.28	8.17	61.67	5.47	2.00
Outlet7	9.95	7.60	29.00	3.53	1.37
Percent Reduction (%)	73.21	2.12	39.98	32.28	29.36
VS-8					
Inlet8	40.92	7.50	43.00	4.83	2.03
Outlet8	15.92	6.73	32.33	3.80	1.57
Percent Reduction (%)	61.00	9.45	22.99	20.15	21.44

C.4. Quality Assurance Samples

Several samples were collected as part of the quality assurance project plan (QAPP) developed for this project. This included collection of background samples from the water supply pond (5 events), field blanks (7 events), and random field duplicates (11 events) for samples at the inlet and outlet. Additional quality control measures such as method blanks, laboratory duplicates, and matrix spikes were conducted by the analytical laboratories.

The background or baseline water quality in the water supply pond varied between samples as it was dependent on a larger pond that serves as the source of water. The larger pond is possibly impacted by fertilization upstream in surrounding turf grass research fields. Other factors such as adjacent conditions, season (e.g., more vegetation debris after mowing events or winter when grass was dormant) also potentially affected the water quality results.

The field blank samples were carried to the field, stored on ice, and analyzed in the same analytical laboratories. Field blanks were analyzed for heavy metals on four (4) sampling days; and for TSS, nitrogen (total kjeldahl nitrogen, NO_3-NO_2, and TN), and phosphorus (PO_4-P and TP) on seven (7) sampling days. Almost all field blank sample results were flagged as non-detects or below the reporting limits with a couple of exceptions. On March 19, 2019, the sample detected NO_3-NO_2 levels (16.99µg/L) that exceeded the reporting limit of 5.6µg/L. One field blank sample of July 30, 2019 detected TP concentration of 12.57µg/L that was above the reporting limit of 10µg/L. These two exceedances can be explained by a possible cross-contamination of the sample containers while in ice-cooler with other samples, via air, or a likely human error in the laboratory.

The field duplicates were collected only when enough sample (2x) was available in the ISCO bottles. Relative percent difference of field duplicates was calculated to estimate precision in sample analysis (Table 37). The sample location column denotes the swale number and whether the duplicate sample was prepared from the ISCO sampler at the inlet or outlet location. The RPD is within acceptable thresholds (less than 30% as listed in NCDOT QAPP), for all samples except in two cases where the TSS concentration showed a greater discrepancy between the actual sample and field duplicate.

Table 37. Relative Percent Difference (RPD) for field duplicate samples (%)

Date	Sample Location	TSS	TP	PO_4-P	TKN	NO_2-NO_3	Copper	Zinc	Lead	Cadmium
10/31/18	VS3 In	9	3	6	11	3	-	-	-	-
10/31/18	VS3 Out	3	3	0	14	1	-	-	-	-
11/21/18	VS3 In	32	6	4	9	0	-	-	-	-
12/05/18	VS4 In	58	1	1	12	1	0	0	2	0
12/05/18	VS4 Out	10	4	3	3	1	0	0	3	0
12/19/18	VS8 In	11	9	6	3	1	4	0	5	0
12/19/18	VS8 Out	0	5	1	21	2	2	0	3	0
05/28/19	VS5 In	5	4	15	2	1	4	0	2	0
05/28/19	VS5 Out	14	2	0	0	3	4	0	0	4
07/25/19	VS2 In	5	14	4	12	1	10	2	2	0
07/30/19	VS5 Out	0	6	6	1	1	3	0	0	1

Appendix D

D.1. Statistical Analysis

This section presents supporting information for the statistical tests conducted in this study.

Table 38. Spearman's Correlation coefficients

Variable	by Variable	Spearman ρ
TKN	Volume	0.8274
NOX	Volume	0.9303
NOX	TKN	0.8061
TN	Volume	0.8729
TN	TKN	0.9804
TN	NOX	0.8728
TP	Volume	0.6856
TP	TKN	0.6898
TP	NOX	0.614
TP	TN	0.6852
OrthP	Volume	0.4634
OrthP	TKN	0.397
OrthP	NOX	0.4489
OrthP	TN	0.4498
OrthP	TP	0.7145
TSS	Volume	0.7721

TSS	TKN	0.6871
TSS	NOX	0.8079
TSS	TN	0.7391
TSS	TP	0.535
TSS	OrthP	0.3252
Cd	Volume	0.7629
Cd	TKN	0.5865
Cd	NOX	0.7254
Cd	TN	0.6477
Cd	TP	0.4523
Cd	OrthP	0.3073
Cd	TSS	0.8076
Cu	Volume	0.7071
Cu	TKN	0.6937
Cu	NOX	0.7247
Cu	TN	0.7449
Cu	TP	0.6246
Cu	OrthP	0.5812
Cu	TSS	0.7339
Cu	Cd	0.7169

Pb	Volume	0.8408
Pb	TKN	0.7218
Pb	NOX	0.804
Pb	TN	0.7847
Pb	TP	0.6569
Pb	OrthP	0.4331
Pb	TSS	0.8139
Pb	Cd	0.8609
Pb	Cu	0.7784
Zn	Volume	0.7644
Zn	TKN	0.6476
Zn	NOX	0.7382
Zn	TN	0.701
Zn	TP	0.5686
Zn	OrthP	0.3871
Zn	TSS	0.8624
Zn	Cd	0.9139
Zn	Cu	0.7937
Zn	Pb	0.9116